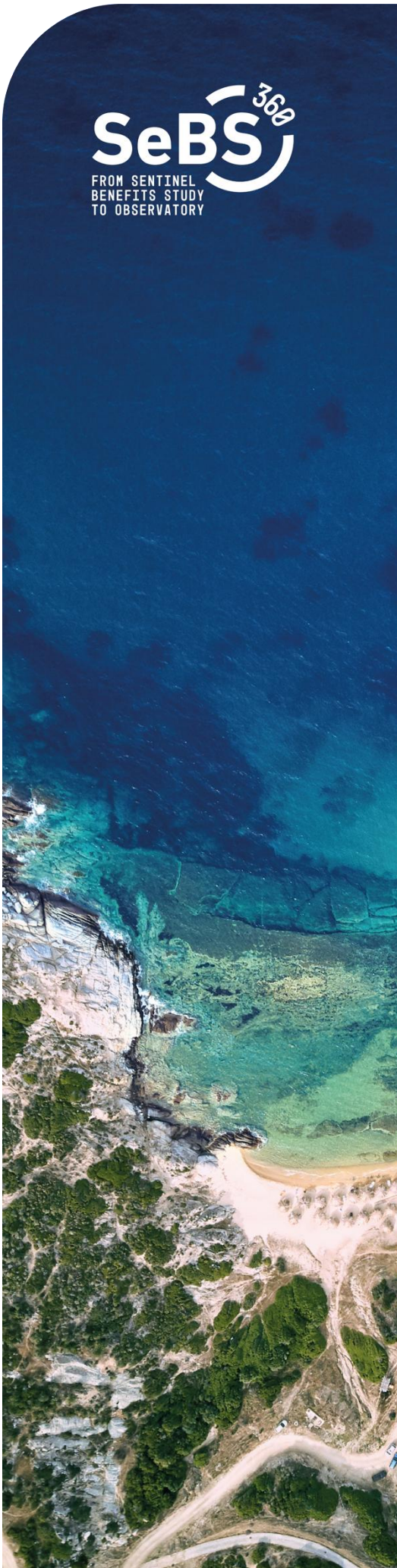
SeBS 360
FROM SENTINEL BENEFITS STUDY TO OBSERVATORY

Underground Gas Storage Facility Monitoring in Germany

Case Study

October 2026



Funded by

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Setting the Scene

Bernd Wessels farms on the western edge of Epe, where the Münsterland flattens out towards the Dutch border. His fields look like any others in the region: maize, pasture, a drainage ditch that needs clearing every autumn. What makes them different cannot be seen from the road. A kilometre down, salt caverns store natural gas, crude oil, and brine, and have done since before he took the farm over from his father.

He remembers the spring of 2014, when crude oil surfaced on a pasture a few kilometres away. No pipeline ran under that field, and for weeks nobody could say where the oil had come from or where it might appear next. The clean-up took years, and the family whose land it was eventually gave up their farm. The question the incident left behind was a simple one: is the ground under his own fields moving too, and if it were, who would notice?



Photo: the Dinkel near Epe, on the cavern field, March 2024. Michielverbeek, CC BY 4.0, via Wikimedia Commons

These days he can check for himself. A public map at monitoring-epe.de shows how the ground across the cavern field moves, measured by a radar satellite passing overhead every few days and sensitive to changes of a few millimetres. He has been to the information evenings in the Gronau town hall, and the old field barn he suggested is now one of the objects inspected monthly alongside the satellite record. He does not look at the map often: it is enough that it exists, and that anyone else can look at it too.

This case study is about how that map came to be, what it takes to produce it, and what it is worth to the operator who pays for it and to the people who live above the field.

Whilst the characters in this story are entirely fictional, the situation is inspired by real events based on our knowledge gained through the case interviews.

Executive Summary

This case examines how radar data from the Copernicus Sentinel-1 mission support the monitoring of ground movement above the Gronau-Epe cavern field in North Rhine-Westphalia, Europe's largest underground gas storage site. A kilometre beneath the fields on the German-Dutch border, 114 salt caverns hold natural gas, crude oil, brine, and helium for ten different operators, in a total cavern volume of close to 4.6 billion cubic metres. The solution mining that created the caverns, their slow convergence under the weight of the overlying rock, and the injection and withdrawal of those volumes all cause the ground above to move, slowly but measurably, in ways that can affect wells, pipelines, watercourses, and property. EFTAS Fernerkundung Technologietransfer GmbH, a remote sensing company based in Münster, processes Sentinel-1 imagery into a near-continuous, millimetre-sensitive picture of how the ground moves across the whole field, with an archive reaching back to December 2015.

The service runs through two parallel chains. The commercial chain connects EFTAS to Uniper Energy Storage GmbH, the field's largest operator with 39 caverns and around 16.9 terawatt-hours of stored energy. Uniper has commissioned ground-movement assessments on a recurring basis for around a decade, embeds the results in its integrity risk-assessment cycle, and has funded follow-on work for 2026/2027. In parallel, a public-interest and research chain developed around cooperation between local authorities, citizens, EFTAS, and academia. The activities originated from a research cooperation between the City of Gronau, the citizens' initiative Bürgerinitiative Kavernenfeld Epe e.V., EFTAS, and the Research Center of Post-Mining at THGA Bochum, **the first arrangement in German mining to embed a citizens' association as a formal scientific partner**.

This study examines the value generated along the value chain across four tiers, looking at six dimensions of benefits. The benefits are assessed against the regulatory baseline: the annual terrestrial levelling survey at a fixed set of benchmarks that Salzgewinnungsgesellschaft Westfalen (SGW), which owns the caverns, is obliged under German mining law to carry out and report. The Sentinel-1 service adds up-to-weekly, area-wide coverage of the 25-square-kilometre field, separates vertical from east-west horizontal motion, and allows the movement history of any location to be reconstructed on demand. Managing these subsurface hazards is critical given the severe consequences of past incidents; for example, a 2014 leak from an oil cavern released 200,000 litres of crude oil, led to the resettlement of a farm, and cost a double-digit million-euro amount to remediate.

The economic value is primarily enabling and risk related. For EFTAS, free Sentinel-1 data make the service financially viable, replacing a commercial-data input estimated at €100,000 to €180,000 per year. For Uniper, obtaining comparable ground-movement information by conventional terrestrial means would cost an estimated €250,000 to €450,000 per year, with a baseline of €350,000, and that avoided cost is attributed in full to the free Sentinel data, because

without them the service would not exist at a price the operator would pay. A second lens, the expected loss from major cavern incidents that earlier detection could avoid, gives around €52,000 per year within a wide range and is reported alongside rather than added. The two tier estimates are distinct and are not summed. The environmental analysis showed that drought-related soil and groundwater dynamics can substantially amplify mining-induced subsidence: at the subsidence maximum, average movement of around 2 cm per year increased to around 3 cm in the dry year 2022, while wet conditions in 2023 slowed subsidence and produced local uplift. 28 areas protected for nature fall within a 5-7 km buffer of the storage facilities analysed here, and as such the mitigation of risk from leaks associated with movement may be considerable nationally. The regulatory benefit is today a complement to the statutory baseline, with radar interferometry moving towards formal recognition in German professional guidance and standards. The innovation and science benefits include a growing product line, two peer-reviewed publications, and an AI-based follow-on project. **The most distinctive value in the case is societal. Participatory monitoring has helped rebuild trust between the operators and local communities.**

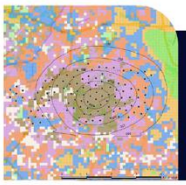
The mechanism transfers well beyond Epe. Germany holds roughly two thirds of its 260 terawatt-hours of gas storage capacity in salt caverns, the European hydrogen build-out will add to the population of cavern facilities that need monitoring, and Epe itself is preparing a hydrogen storage expansion designated a European Project of Common Interest. From 2027, European resilience rules will require storage operators to produce all-hazard risk assessments. **If regulatory recognition of satellite-based monitoring follows, comparable cavern fields could benefit from the approach, subject to their geology, land cover, operating conditions, monitoring requirements and institutional context.**

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The Sentinel Data

Copernicus Sentinel-1 provides free-of-charge, all-weather, day-and-night C-band radar imagery over the Gronau-Epe cavern field, with up-to-weekly coverage across two viewing geometries and an archive reaching back to 2015.



Tier 1: EFTAS (Service Provider)

Sentinel-1 SBAS-InSAR ground movement monitoring of Europe's largest underground gas storage site. Avoided commercial-radar-data cost (~€100,000–180,000/year), a reusable product line in underground storage monitoring, and two peer-reviewed publications.



Tier 2: Uniper Energy Storage (Primary User)

A weekly, field-wide movement picture enabling per-cavern integrity management. Replaces information that would cost ~€250,000–450,000/year to obtain by conventional levelling and GNSS surveys, attributed in full to the Sentinel data, plus better-targeted inspection budgets and evidence in damage claims.



Tier 3: Customers and Gas Owners (Secondary User)

Gas traders, industrial consumers, and transmission system operators booking storage capacity at Gronau-Epe. A more reliable storage service protecting €500–900 million of stored value: lower probability of outage or stranded gas in winter.



Tier 4: Citizens and Society

An independent, public ground movement record for residents, rebuilding trust after the 2014 leak and protecting the farmland, watercourses, and nature reserves above the caverns.

1. Introduction and Scope

1.1 The context of this study

The analysis of the case study 'Underground energy storage facility monitoring' is carried out in the context of the Sentinel Benefits Observatory (SeBS360), an activity of the European Space Agency that builds on and extends the long-running Sentinel Benefits Study (SeBS). SeBS has produced a foundational methodology[1], and a portfolio of case studies documenting how Earth Observation services based on Copernicus Sentinel data deliver value across the value chain to users, society, and the wider economy. The SeBS360 project continues the case-study work and adds a programme-level synthesis layer aimed at extracting sectoral synopsis-type insights found in the benefit patterns the Sentinels generate across sectors and geographies.

The Sentinels form a central part of the European Union's Copernicus Programme, providing space-based observations on a full, free, and open basis. Sentinel data are thus a key component of the Copernicus Services, and a crucial source used by companies to deliver products and services helping different users across the Globe. Data from the Sentinel missions, together with other relevant data sources and complementary information, support a wide range of application areas, including agriculture, forestry, climate monitoring, environmental protection, disaster risk management, and natural resource management. Sentinel data therefore constitutes a key input for the development of downstream products and services delivered by companies and organisations to users in Europe and beyond.

1.2 What is the case all about

This case looks at how satellite radar data from the European Copernicus programme help operators and the public keep watch over Europe's largest underground gas storage facility. The site, the Gronau-Epe cavern field in North Rhine-Westphalia, holds 114 salt caverns roughly one kilometre below the surface near the German-Dutch border. Together they hold a total storage volume of close to 4.6 billion cubic metres, used for natural gas, brine, crude oil, and helium by ten different operators. Creating the caverns by solution mining, their gradual convergence under the weight of the overlying rock, and injecting and withdrawing those volumes year after year all cause the ground above to move, slowly but measurably, in ways that can affect

[1] The previous Sentinel Benefits Study project produced a foundational methodology for the assessment of the impact and benefits the Sentinels have on various aspects of industry, science and society. The methodology is available on the following link: https://sebs360.eu/wp-content/uploads/2026/03/SeBS-Methodology-2024.pdf

pipelines, wells, watercourses, and nearby properties. **Monitoring that movement is both an operational and a public concern.**[2,3]

Uniper Energy Storage GmbH, the largest operator on the site, holds 39 of the caverns and draws on satellite-based ground-movement assessments to manage those risks. The service is delivered by EFTAS Fernerkundung Technologietransfer GmbH, a remote sensing firm based in Münster, using imagery from the Copernicus Sentinel-1 mission. **The output is a near-continuous map of how the ground is moving across the whole cavern field**, sensitive enough to pick up changes of a few millimetres a year. The same movement record remains available to the hydrogen storage expansion planned at Epe, which the European Commission has designated a Project of Common Interest.

Traditional monitoring of the cavern field, performed each year by the salt field owner Salzgewinnungsgesellschaft Westfalen, relies on ground surveys at a small number of fixed points. **The satellite service does not replace that legal baseline but adds a continuous, area-wide picture in places where conventional methods see very little.** The service has also become the technical core of a research cooperation that links the City of Gronau, the citizens' initiative Bürgerinitiative Kavernenfeld Epe e.V., EFTAS, and the Research Center of Post-Mining at the Technische Hochschule Georg Agricola in Bochum. Signed in July 2021, the cooperation **brings a citizens' association in as a formal scientific partner**.[4]

1.3 More about the study

Each case study developed under **SeBS360** focuses on products and services that use data coming from Sentinel satellites and examines how the resulting value is generated across the value chain. The analysis starts from the direct use of Sentinel-derived information by the relevant users in the case and then follows the subsequent links in the value chain in order to understand how benefits extend beyond the immediate user to other organisations, asset owners, and ultimately citizens and society.

In this process, the main aim is to understand and demonstrate the value generated through satellite-based Earth observation, and in particular using data from the Copernicus Sentinel missions. Each case study therefore seeks to assess the benefits attributed the use of Sentinel data. These benefits may include, among others, improved operational efficiency, better-

[2] Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23. doi:10.3390/mining6010023.

[3] Rudolph, T., Goerke-Mallet, P., Homölle, A., Müterthies, A., Perrevort, H., Teuwsen, S., Yang, C.-H. (2024). 'Participatory Geomonitoring for Future Mining—Resilience Management in the Cavern Storage Epe (Germany)'. Mining 4(2):230–247. doi:10.3390/mining4020014.

[4] Forschungszentrum Nachbergbau, THGA Bochum. Research cooperation 'Monitoring Epe' signed July 2021. https://fzn.thga.de.

informed decision-making, reduced uncertainty, economic gains, increased safety, strengthened resilience, and wider societal value.

The evidence generated through these case studies can be useful to different groups. For **decision-makers**, access to a portfolio of concrete and well-documented cases helps demonstrate where and how Sentinel data creates practical value, thereby supporting future investment and policy decisions. For **users**, such case studies move beyond a general understanding of Earth observation and provide clearer evidence of what EO-based services can contribute in comparable operational settings. For **service providers**, robust evidence on the benefits associated with Sentinel-enabled services can strengthen communication, market positioning, and the broader promotion of EO-based solutions.

Within the framework of **SeBS360**, multiple case studies are being developed and documented to build a broader evidence base on how Sentinel data supports operational activities, generates value across different sectors, and contributes to benefits that reach beyond the immediate user.

1.4 Acknowledgements

This case study draws on the time and insight of those who run, study, and advocate for the Gronau-Epe cavern field and its monitoring. A special thanks goes to:

- Roman Przyrowski, Uniper Energy Storage GmbH
- Matthias Borgelt, Uniper Energy Storage GmbH
- Maxim Stein-Khokhlov, Uniper Energy Storage GmbH
- Andreas Müterthies, EFTAS
- Sebastian Teuwsen, EFTAS

Their valuable input during the interviews and the site visit to Gronau-Epe informed the analysis throughout this report. The case also draws on the published work of the research cooperation between the City of Gronau, the Bürgerinitiative Kavernenfeld Epe, EFTAS, and the Research Center of Post-Mining at THGA Bochum.

2. Underground Energy Storage in Germany

The Gronau-Epe cavern field sits at the intersection of three concerns that shape how Europe stores its energy. The first is technical: how deep salt deposits are turned into pressurised storage volumes for gas, oil, and, increasingly, hydrogen. The second is environmental: how the operation of those storage volumes interacts with soils, watercourses and protected landscapes on the surface. The third is societal: how cavern operators, public authorities and the citizens who live above the field build a shared understanding of what is happening underground. This section sets out each in turn before the next section explains what Sentinel data add to the picture.

2.1 Salt caverns and the European energy system

Underground gas storage is a little-noticed part of the European energy system. **Between a quarter and a third of the gas consumed in the European Union in winter is drawn from storage**[5] that was filled in the summer, balancing the seasonal swing between supply and demand and giving traders, distributors, and governments a buffer against shocks. Since the Russian invasion of Ukraine in 2022 and the introduction of the EU Gas Storage Regulation that summer, those volumes have also become a security policy in their own right: **member states must keep their facilities at least 90% full before each winter**.[6]

Most of that storage sits in three kinds of geological structures. Depleted oil and gas reservoirs, the cheapest option, offer large volumes but slow injection and withdrawal rates. Aquifers, used in some northern European countries, behave similarly. Salt caverns are the third and increasingly important kind (Figure 1). Shaped by pumping fresh water into a thick salt layer and dissolving the salt away, a single cavern can hold hundreds of thousands of cubic metres of pressurised gas, withstand frequent cycling, and refill in days rather than months. That speed and flexibility make them particularly valuable as the share of variable renewables grows and as hydrogen begins to be stored at scale.

[5] European Commission, DG ENER, Gas storage. https://energy.ec.europa.eu/topics/energy-security/gas-storage_en: underground storage covers 25 to 30 per cent of the gas consumed in the Union in winter.

[6] Regulation (EU) 2022/1032 of 29 June 2022 amending Regulations (EU) 2017/1938 and (EC) No 715/2009 with regard to gas storage. Sets minimum filling targets of 90% for underground gas storage in EU Member States.

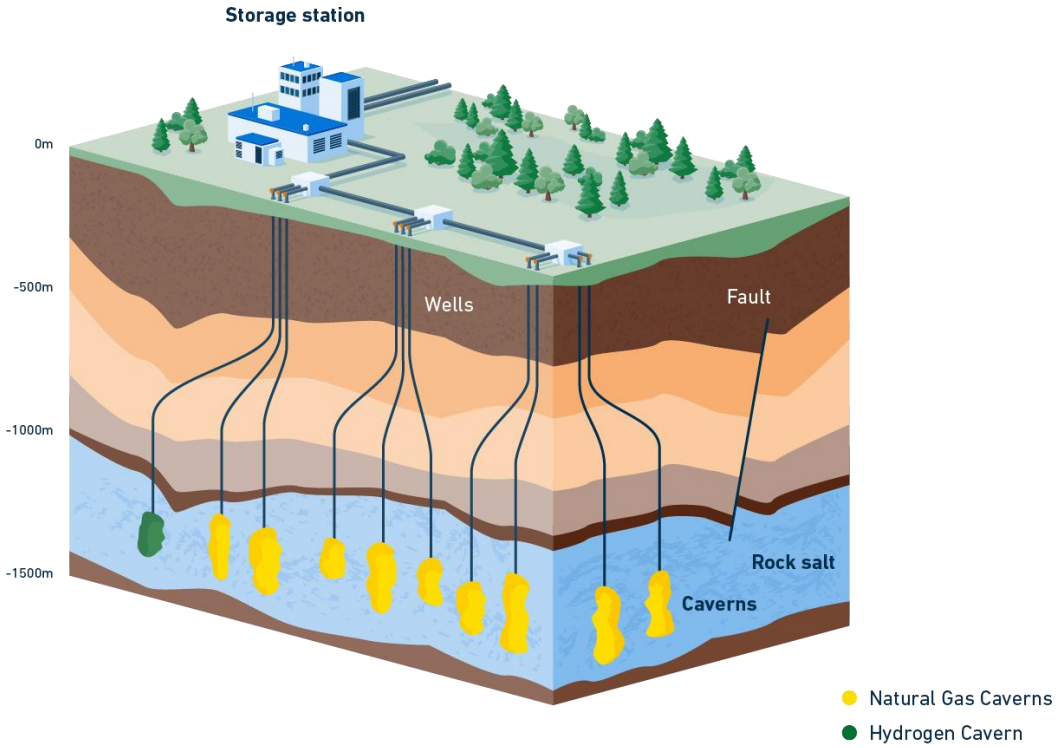


Figure 1 Schematic cross-section of a salt-cavern storage facility: wells from the surface storage station reach caverns leached out of the rock salt at depths of 1,000 to 1,500 metres. Source: Uniper Energy Storage GmbH

Germany has more cavern storage than any other European country, and roughly two thirds of its total gas storage capacity sits in salt. Most of those caverns are in northern and western Germany, where Zechstein salt deposits run shallow and thick (Figure 2). The same geological occurrence that powered Germany's nineteenth-century chemical industry (salt layers hundreds of metres thick) now underwrites its energy security and, increasingly, its hydrogen ambitions. The European Commission has named several German cavern projects, including a hydrogen expansion at Gronau-Epe, as Projects of Common Interest.[7][8]

[7] Initiative Energien Speichern e.V. (INES). Gas Storage Capacities. https://energien-speichern.de/en/gas-storage/gas-storage-capacities.

[8] European Commission, sixth list of Projects of Common Interest and Projects of Mutual Interest, adopted 28 November 2023. Project 'UST Hydrogen Storage Epe' included under the hydrogen storage category.



Figure 2 Map of underground gas storage facilities (Gas Infrastructure Europe, 2021)

2.2 The Gronau-Epe cavern field

The cavern field at Gronau-Epe spreads across an area roughly five kilometres by five kilometres on the German side of the German-Dutch border. All caverns lie on German territory, although the salt deposit itself continues westwards beneath the border towards Enschede. The first well, Epe-1, was drilled on the road from Gronau to Graes on 24 July 1964 in the hope of finding natural gas, after promising discoveries elsewhere in the region. Instead, the drillers found 400 metres of unusually pure rock salt, between 98% and 99% sodium chloride, lying flat and largely uninterrupted by faults or folds at depths between 1,000 and 1,500 metres. The deposit is unique in the Permian salt basin of northwestern Europe.[9]

By the end of 2023, solution mining had produced 114 caverns at Gronau-Epe (Figure 3). The eastern, older part of the field is laid out as a regular grid on roughly 300-metre centres, with each cavern served by a single well at the surface. The western part, where mining is still in progress, uses collective drilling sites with several deviated boreholes from a single pad. Most of the caverns now serve as storage. Five hold crude oil, one stores helium and the remaining 108 hold natural gas. **Working gas capacity across the field totals roughly 3.5 billion cubic metres, equivalent to around 35 terawatt-hours of energy.**

The field is shared between ten different operators. Salzgewinnungsgesellschaft Westfalen mbH & Co. KG (SGW), jointly owned by Solvay, Vestolit, and Bayer, holds the primary extraction rights

[9] Rudolph, T., Goerke-Mallet, P., Homölle, A., Müterthies, A., Perrevort, H., Teuwsen, S., Yang, C.-H. (2024). 'Participatory Geomonitoring for Future Mining—Resilience Management in the Cavern Storage Epe (Germany)'. Mining 4(2):230–247. doi:10.3390/mining4020014.

for brine and acts as the central mine surveyor for the site. SGW produces more than two million tonnes of rock salt per year as brine for its chemical-industry shareholders. **The largest single storage operator is Uniper Energy Storage GmbH, which holds 39 caverns** split between high-calorific and low-calorific gas services. RWE follows with 20 caverns across three regulated entities, then NUON (owned by Vattenfall) with seven, then Trianel, KGE, ENECO and Air Liquide with smaller positions.[10]

Above ground, the landscape is mostly agricultural, with scattered settlement at Kottiger Hook and the small town of Epe at the field's northwestern edge. Four watercourses cross the field from west to east (the Flörbach, Schwarzbach, Rottbach, and Dinkel), the Dinkel being the regional receiving water for the smaller streams. The western edge runs into the Amtsvenn-Hündfelder Moor, a former raised bog now designated as a nature reserve and undergoing rewetting after decades of peat extraction. A second nature reserve, the Epe-Graeser Venn, sits a few kilometres to the south. Both are sensitive to changes in groundwater levels and surface elevation, which makes the interaction between cavern operations and the surface water balance a central concern of any monitoring system. The satellite layer in Figure 3 already hints at that interaction: the largest vertical movement appears not only around the subsidence maximum at the centre of the field but also in its north-western part, most plausibly because of the organic-rich soils there.

[10] Solvay corporate communications. SGW (Salzgewinnungsgesellschaft Westfalen mbH & Co. KG) is jointly owned by Solvay (65%), Vestolit (25%) and Bayer (10%).

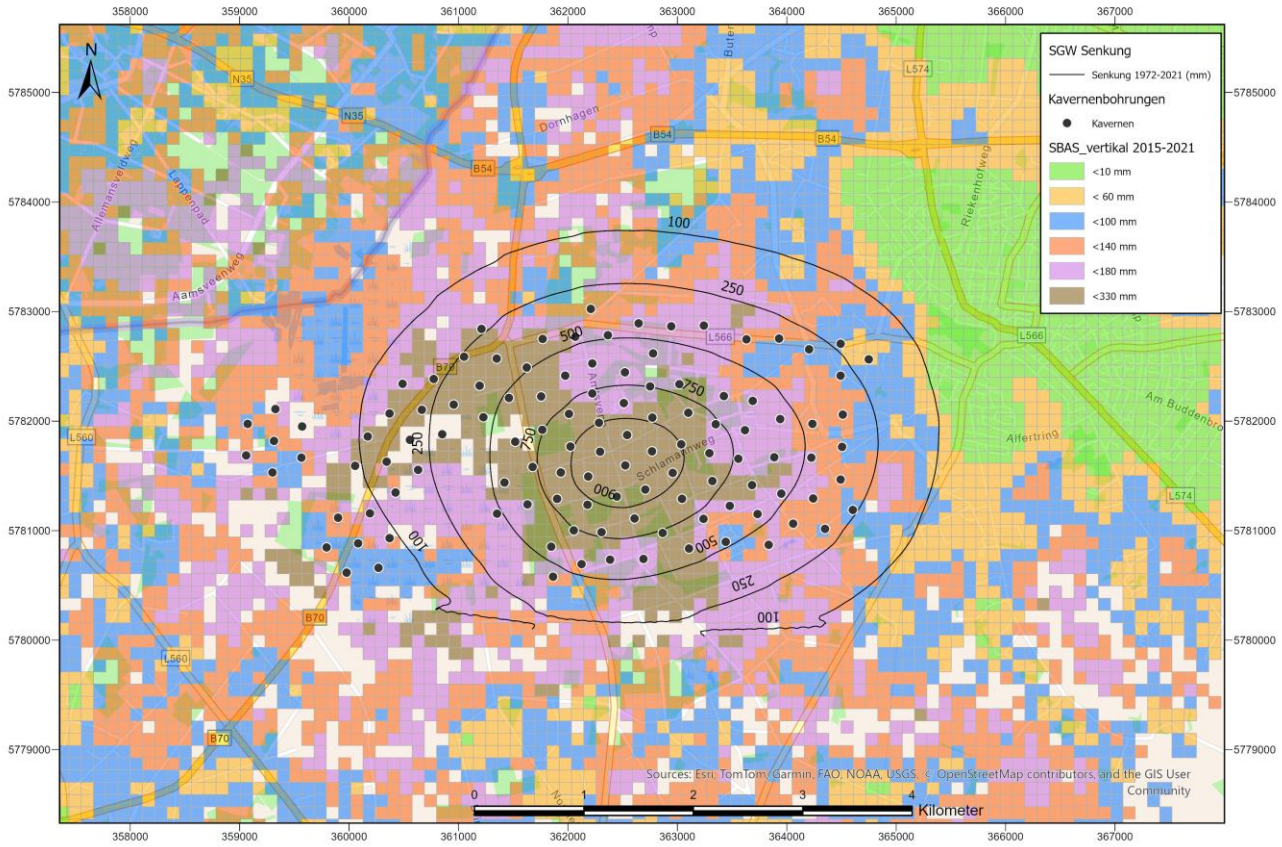


Figure 3 The Gronau-Epe cavern field: cavern wells (dots), isolines of cumulative subsidence from SGW's terrestrial levelling, 1972 to 2021 (mm), and vertical surface movement from Sentinel-1 SBAS interferometry, 2015 to 2021. Source: Uniper Energy Storage GmbH

2.3 Ground movement, public concern, and the 2014 incident

Each injection and withdrawal cycle changes the pressure, the temperature and the residual stress in the surrounding salt. Over months and years, the cavern walls slowly converge: the cavity narrows under the weight of the rock above. For brine production the convergence is typically half a percent to one percent of the cavern volume per year. For gas storage with frequent cycling, it can be twice that. The motion is small at any one cavern, but cumulative across 114 caverns it produces measurable subsidence at the surface. The natural relief stays intact: the ground surface is lowered locally as a whole rather than deformed into a visible depression.[11]

After 50 years of operation, **the centre of the Gronau-Epe subsidence area has sunk by close to 90 centimetres**. The deepest point lies under fields and farmland, where the consequences

[11] Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23. doi:10.3390/mining6010023.

are mostly cosmetic. Closer to the edges of the subsidence area the picture is more complicated. Pipelines, wells and overhead infrastructure can be pulled and pushed by uneven settlement, surface drainage patterns shift, and the relationship between the bogs and the local water table is sensitive to centimetre-scale changes in elevation. None of this is hidden from the people who live above the field. The citizens' initiative that later formed has described the operators' communication before 2014 as less than reassuring, a view the operators do not share: SGW, Uniper, and RWE point to a long-standing practice of open days and direct contact with residents.[12]

The turning point came in 2014. In late February the operators registered a pressure drop in cavern S5, one of the older crude-oil caverns in the eastern part of the field, and on 12 April crude oil was discovered at the surface on a pasture in the Amtsvenn, a few hundred metres away. The oil had escaped through a defect at a riser-pipe connection at 217 metres depth and migrated upwards along geological structures. Up to 200,000 litres leaked, of which around 70,000 reached the surface, contaminating the meadow and a shallow groundwater aquifer. Five cows that drank the oil-water mixture had to be put down, and the affected farm was later resettled. **Remediation ran for more than two and a half years and reached a double-digit million-euro cost**, borne by the operator and its insurers, and the mining authority subsequently required the conversion of the crude-oil cavern pipework to a double-walled casing system at a further double-digit million-euro cost. Regional television, radio and newspapers covered the leak for weeks, and public meetings drew sharp questions.[13,14]

What grew out of the incident is now a distinctive feature of the case. The Bürgerinitiative Kavernenfeld Epe e.V. (BI-K), the citizens' initiative of the Epe cavern field, registered itself formally in 2018 with an explicit list of objectives that included preventing damage to residents from industrial salt mining, promoting civic engagement around the field, and improving the monitoring of ground subsidence and waterlogging on agricultural land. **On 7 October 2020 the Gronau city council passed a resolution calling for an independent measurement programme** to clarify what was happening to the ground. In July 2021 the City of Gronau, BI-K, EFTAS and the Research Center of Post-Mining at THGA Bochum signed a research cooperation that would put the satellite-based monitoring service at the technical core of that programme. The cooperation is the first arrangement of its kind in German mining.

[12] Rudolph, T., Goerke-Mallet, P., Homölle, A., Müterthies, A., Perrevort, H., Teuwsen, S., Yang, C.-H. (2024). 'Participatory Geomonitoring for Future Mining—Resilience Management in the Cavern Storage Epe (Germany)'. Mining 4(2):230–247. doi:10.3390/mining4020014.

[13] Brouard, B., Bérest, P., Hévin, G. (2019). 'Lessons from a salt cavern collapse and a salt cavern abandonment test failure'. Oil & Gas Science and Technology – Revue d'IFP Energies Nouvelles. Documents the 12 April 2014 cavern S5 oil leak at Gronau-Epe.

[14] WDR dossier 'Ölleck in Gronau' (2014 to 2015), https://www1.wdr.de/nrw/muensterland/kreis-borken/oelleck-in-gronau-100.html; Dr. Schleicher & Partner, remediation record 'Ölschaden Epe S5', works essentially complete by December 2016; Landtag NRW Vorlagen 16/2511 and 16/4797 on the mandated double-walled casing conversion.

2.4 Conventional monitoring and its limits

Under the German Federal Mining Act, the operator within the zone of more than 10 centimetres of induced subsidence is legally responsible for surface changes. At Gronau-Epe that obligation rests with SGW as the holder of the original mining rights, and SGW in turn must deliver an annual mine-survey report to the Bezirksregierung Arnsberg, the state mining authority for North Rhine-Westphalia. The historical method for producing that report is terrestrial levelling between a series of fixed benchmarks distributed across the field, supplemented by satellite-navigation (GNSS) measurements at selected points.[15]

Three things follow from that arrangement. First, **the legal baseline is annual, not continuous, and it covers only the points where the survey team chooses to measure**. Second, the coverage is highly concentrated: a handful of benchmarks rather than the entire surface area of the field. Estimates discussed in the Epe research cooperation put **the spatial coverage of conventional measurement at well under one percent of the affected area**. Third, the survey delivers vertical movement only, and within the constraint of where the benchmarks happen to sit. **Horizontal motion, which can matter for pipelines and buried infrastructure, is essentially invisible to the traditional method.**

European and German public services have begun to fill some of those gaps. The Bodenbewegungsdienst Deutschland (BBD), Germany's ground motion service, run by the federal geological survey BGR, provides ground motion data based on Sentinel-1, although in its early years it delivered only line-of-sight displacement rather than decomposed vertical and horizontal motion. The Copernicus European Ground Motion Service (EGMS) has been operational since 2022 and now provides vertical and east-west horizontal motion across the EU, but its underlying processing relies on persistent scatterers (stable, radar-bright objects such as buildings), and the rural land cover at Gronau-Epe gives the algorithm too few of those to work with. The Dutch equivalent, the Bodemdalingskaart, covers the Dutch side of the field with vertical motion only, and shows discontinuities at the border. **None of the public services produces a continuous, area-wide, dual-component picture of motion across the cavern field as a whole.** The EFTAS service covers this gap.

This is the situation the satellite service arrived into: ground that moves slowly but consequentially, a statutory survey that measures it once a year at a fixed set of points, public services that only partly cover the gap, and a community that wants to see the evidence for itself. The next chapter explains how satellite radar measures ground movement and what it can and

[15] Federal Mining Act (Bundesberggesetz, BBergG). The operator within the zone of more than 10 cm of induced subsidence is legally responsible for surface changes.

cannot see, introduces the Copernicus programme that supplies the data, and then describes the operational service that EFTAS has built on top of them.

3. The Use of Sentinel Data

This section examines the technical core of the case: how data from the Copernicus Sentinel satellites are turned into a monitoring service for the Gronau-Epe cavern field, and what the resulting product can and cannot tell its users. The first subsection sets out the advantages and limits of satellite radar interferometry as a method. The second introduces the Copernicus programme and the Sentinel-1 mission that supplies the data. The third describes the operational service EFTAS has built on top of them. The company itself is profiled in section 4.2.1.

3.1 How can satellites help monitor a cavern field?

The question for any site with slow-moving ground is whether satellite measurements can tell operators, researchers and citizens something they cannot get from traditional ground-based surveying. They can, within limits. This subsection sets out the advantages and the limitations in general terms. Section 3.3 shows how they play out in this case.

Before entering the specifics of this case, it is important to understand how satellites can capture changes on the Earth's surface, generating information that supports the monitoring of ground movement and infrastructure.

Broadly speaking, there are two main classes of EO satellite systems (Figure 4):

- **Those carrying passive sensors** able to detect the sun's energy as it is reflected from the Earth's surface. These "optical" satellites are affected by cloud coverage (as it hinders solar radiation) and key data related to vegetation can only be observed during daytime. Typically used sensors in this category are radiometers (incl. imaging and spectro-radiometers) and spectrometers.
- **Those carrying active sensors** capable of emitting their own energy (in the form of electromagnetic radiation) to illuminate the scene (and objects therein) they observe. Such satellites send a pulse of energy from the sensor to the object and then receive the radiation that is reflected or backscattered from that object. Typically used sensors in this category are radar, scatterometers, and lidar. Satellites carrying such sensors – for example, Synthetic Aperture Radar (SAR) satellites – are unaffected by cloud coverage or insolation.

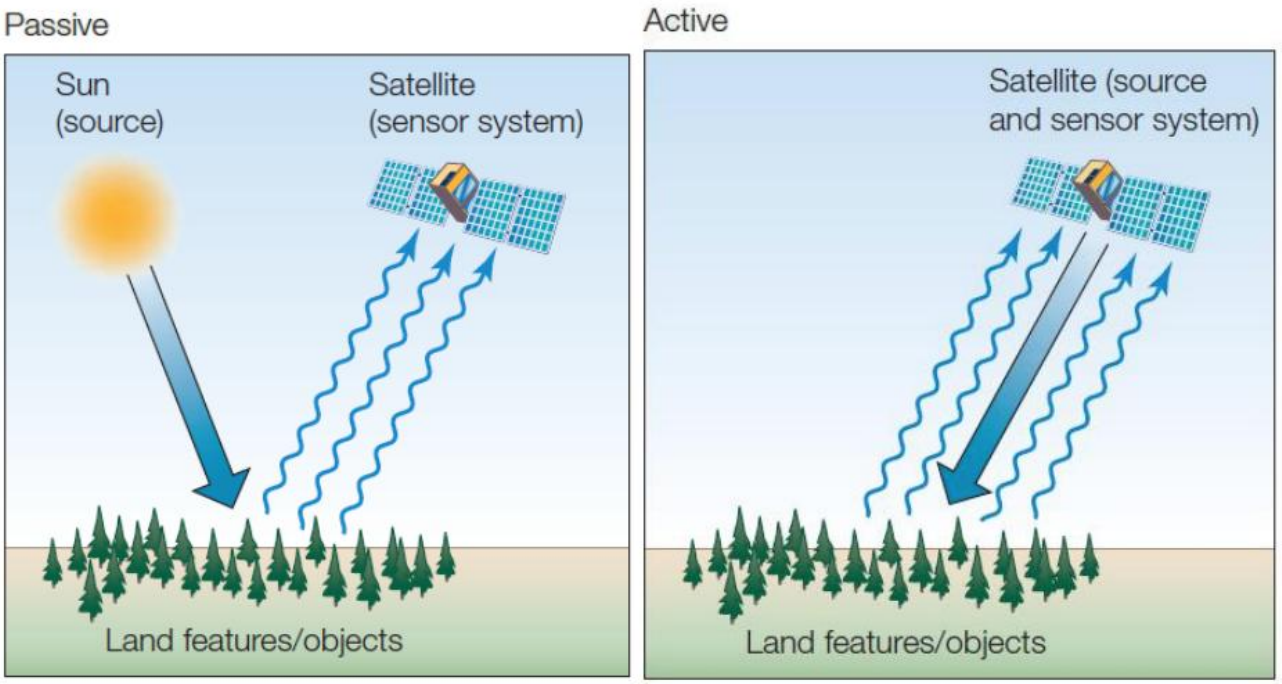


Figure 4 Passive (optical) versus active (radar) Earth observation (ESA EO Science for Society training materials, 2025)

As seen in Figures 4 and 5, active and passive sensors emit/collect electromagnetic signals of different wavelengths. In practice, different materials on the Earth's surface reflect electromagnetic waves in a different manner. These reflectance differences allow EO satellites to distinguish between grasslands, water surfaces, forests, and buildings.

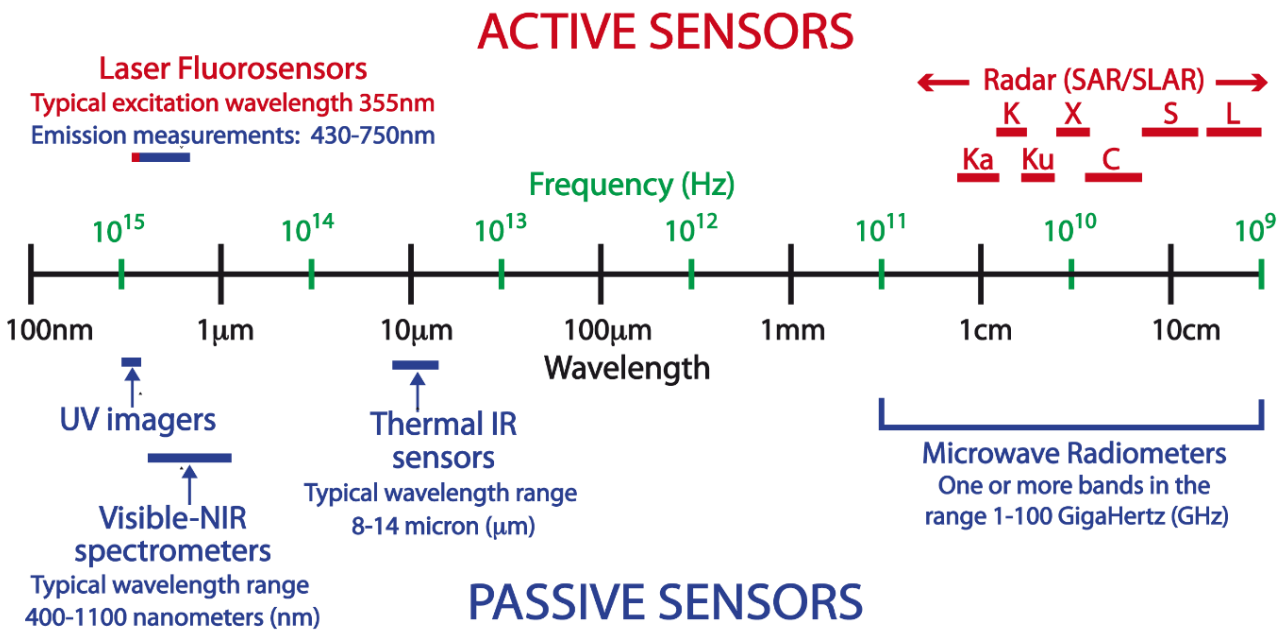


Figure 5 Schematic representation of the segments of the electromagnetic spectrum in which the different Earth observation sensor types operate (ESA EO Science for Society training materials, 2025)

3.1.1 Advantages

The core advantage of synthetic aperture radar interferometry, or InSAR, is that **it measures the position of the ground at millimetre precision without anyone needing to be on site**. A radar satellite passes overhead every few days and records the surface. By comparing two passes from the same orbital position, the processing software detects changes in the distance from satellite to ground to within a few millimetres. Build a time series of such comparisons and the slow movement of the ground above a cavern field becomes visible.

For ground-motion monitoring, that capability translates into five practical advantages over conventional terrestrial surveying.

- **Spatial coverage**. Terrestrial levelling produces measurements at a handful of fixed benchmarks. **A Sentinel-1 acquisition covers the full 25-square-kilometre cavern field in one pass**, with no need to choose where to look in advance. Areas of bog, farmland and protected reserve are measured at the same density as built-up areas around Epe itself.
- **Temporal frequency.** A mine-survey report is produced once a year. **Sentinel-1, operating with two satellites in formation, repeats each orbit every six days, and because adjacent tracks overlap more at higher latitudes, a site in Germany is in practice observed several times in each six-day cycle once ascending and descending passes are combined. A processing chain built on these acquisitions can deliver ground-movement updates at up to weekly frequency,** and the archive allows movement at any location to be reconstructed on demand back to December 2015. Movement that would otherwise have been visible only in retrospect on an annual cycle can be picked up within days.
- **The dimensional split.** Conventional levelling produces vertical displacement only. By combining acquisitions from ascending and descending orbits, an InSAR workflow separates motion into vertical and east-west horizontal components. Horizontal movement matters for pipelines and buried infrastructure, both of which can be stressed by uneven settlement even where the vertical signal looks modest.
- **Cost**. Sentinel-1 data are **free, distributed under the open data policy of the European Copernicus programme.** The marginal cost of adding another year of monitoring is processing time and analyst hours, not the data themselves. That changes the economics of long-running monitoring services in ways that would not be possible with commercial satellites alone.
- **The archive.** Sentinel-1A entered operations in late 2014, so any site can now be looked back over nearly a decade of weekly acquisitions. At Gronau-Epe, for example, the field

has been studied retrospectively across 760 scenes running from December 2015. That kind of historical depth cannot be recovered from terrestrial surveys after the fact.[16]

3.1.2 Limitations

InSAR also has limits that matter at this site. Four limits matter most for Gronau-Epe.

- **Orbital geometry.** Sentinel-1 flies in a near-polar orbit, which means it measures motion along its line of sight from the east and from the west. Combining ascending and descending tracks lets the workflow split motion into vertical and east-west horizontal components, but **north-south motion cannot be resolved**. For most cavern fields that is acceptable. For sites where ground motion is strongly oriented north-south it would be a meaningful gap.
- **Land cover.** The simplest variant of InSAR, Persistent Scatterer Interferometry (PSI), relies on radar-bright objects that reflect the radar signal consistently from one pass to the next. Buildings, pylons and large rocks are good examples. The Gronau-Epe field is overwhelmingly agricultural, with low building density and a mix of bog, woodland and farmland. PSI alone returns too few measurement points to cover it. Sites like this therefore require the Small Baseline Subset (SBAS) method**, which extracts motion information from distributed scatterers** across the surface rather than from individual stable targets. SBAS is more demanding to process and noisier than PSI, but it works on rural land where PSI cannot.
- **Environmental noise.** Some of the soils above the cavern field, particularly the organic-rich Plaggenesch, Niedermoor, Hochmoor and Anmoorgley types in the western part, swell and shrink with soil moisture in ways that register as motion in the radar signal. These movements can mask or amplify the cavern-induced signal. **Distinguishing primary (operational) from secondary (hydrogeological and pedological) drivers requires combining the radar data with soil maps and operational storage information.** That separation is what the multi-criteria layer of the EFTAS workflow is designed to perform, but it is also a constraint on how directly the raw motion map can be used. Figure 6 shows the pattern at Gronau-Epe: the areas of strongest apparent movement in the satellite point cloud coincide with the organic-rich soils in the west of the field, which are rated as highly sensitive to compaction.
- **Resolution.** A Sentinel-1 SBAS product at Gronau-Epe is produced on a 30-metre grid. That is fine for cavern-scale and field-scale analysis. It is too coarse to monitor individual

[16] Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23. doi:10.3390/mining6010023.

buildings or single wellheads in detail. Where that finer view is needed, EFTAS supplements Sentinel-1 with TerraSAR-X data from the German commercial mission, which has metre-scale resolution but costs money. The combination of free Sentinel-1 for wide coverage and TerraSAR-X for targeted detail is a common pattern across InSAR services.

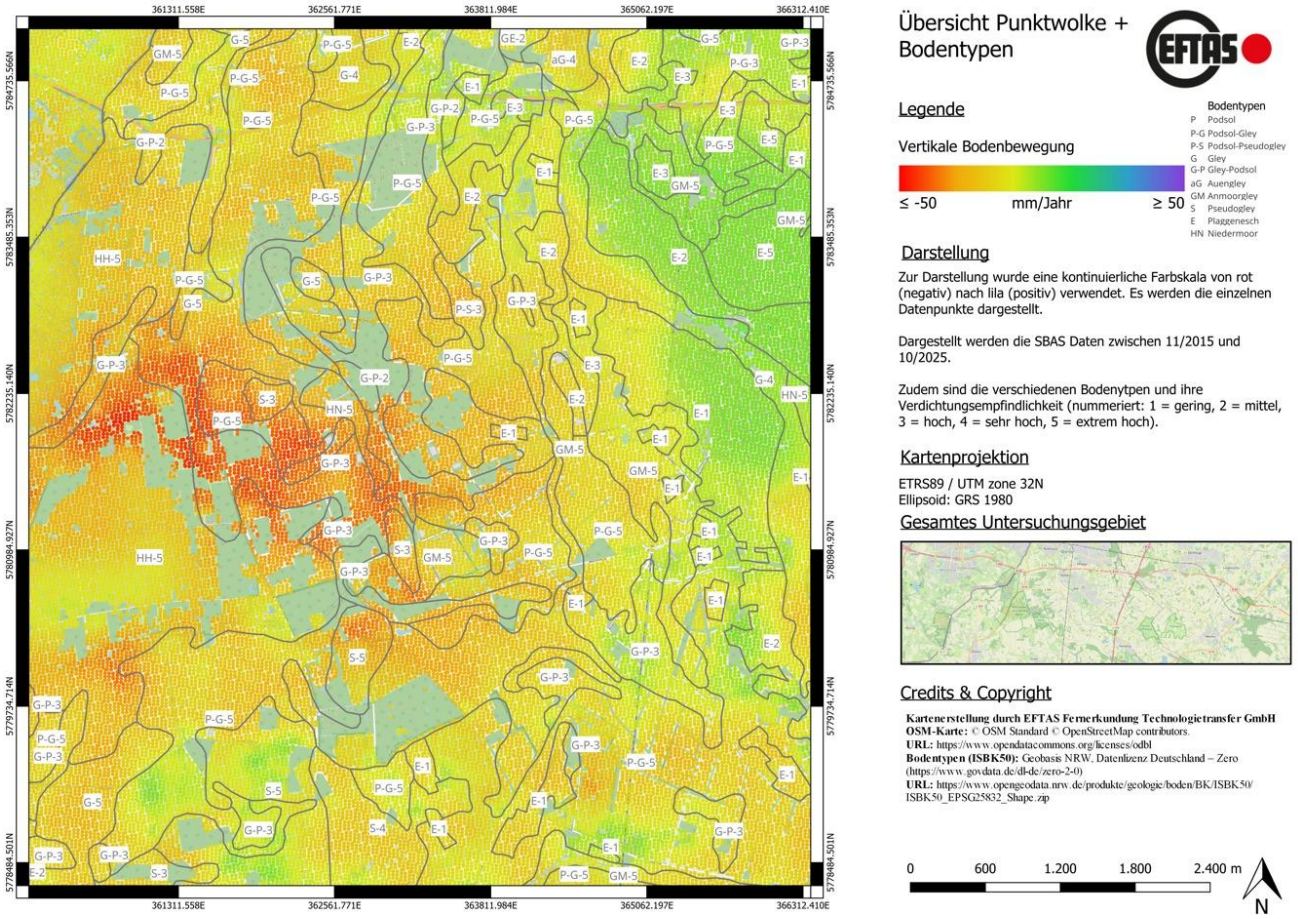


Figure 6 Vertical ground movement above the Gronau-Epe cavern field from Sentinel-1 SBAS point data, November 2015 to October 2025 (mm per year, red for subsidence, purple for uplift), overlaid with soil types and their sensitivity to compaction (1 low to 5 extremely high). Source: EFTAS Fernerkundung Technologietransfer GmbH, soil data Geobasis NRW (ISBK50)

A regulatory point sits alongside these technical limits. **Satellite monitoring is not currently a legal substitute** for statutory terrestrial surveys, in Germany the annual survey required under the Federal Mining Act**.** It complements rather than replaces that baseline. Whether and when state mining authorities will recognise InSAR as a compliance method is an open question, and a likely future driver of commercial adoption across the sector (section 3.3.1).

3.2 Copernicus and the Sentinels

Copernicus is the European Union's flagship Earth observation programme. Owned by the EU and operated jointly by the European Space Agency and Eumetsat, it began life in 1998 as Global Monitoring for Environment and Security (GMES) before being rebranded in 2012. The

programme combines a constellation of satellites with a free and open data policy and a set of thematic services for the atmosphere, marine, land, climate, emergency and security domains. Total European public investment in Copernicus over its operational life runs into the tens of billions of euros.

The space segment is the Sentinel family, currently spanning six mission lines, each tuned to a particular kind of observation (Figure 7). Sentinel-1 carries a synthetic aperture radar that sees through cloud and works at night. Sentinel-2 carries a multispectral optical instrument that produces colour and near-infrared imagery at 10-metre resolution. Sentinel-3 carries instruments for sea surface temperature, ocean colour and land surface temperature. Sentinel-4, an instrument flown on the Meteosat Third Generation sounder satellite, and Sentinel-5/5P measure atmospheric composition. Sentinel-6 measures sea level. Each mission is built around a pair or constellation of satellites to ensure continuity, and the European Commission has confirmed a series of expansion missions, including ROSE-L and CHIME, for the late 2020s.[17]

[17] European Space Agency. Copernicus Sentinel Expansion Missions, including ROSE-L (L-band SAR) and CHIME (hyperspectral imager). https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Copernicus_Sentinel_Expansion_missions.

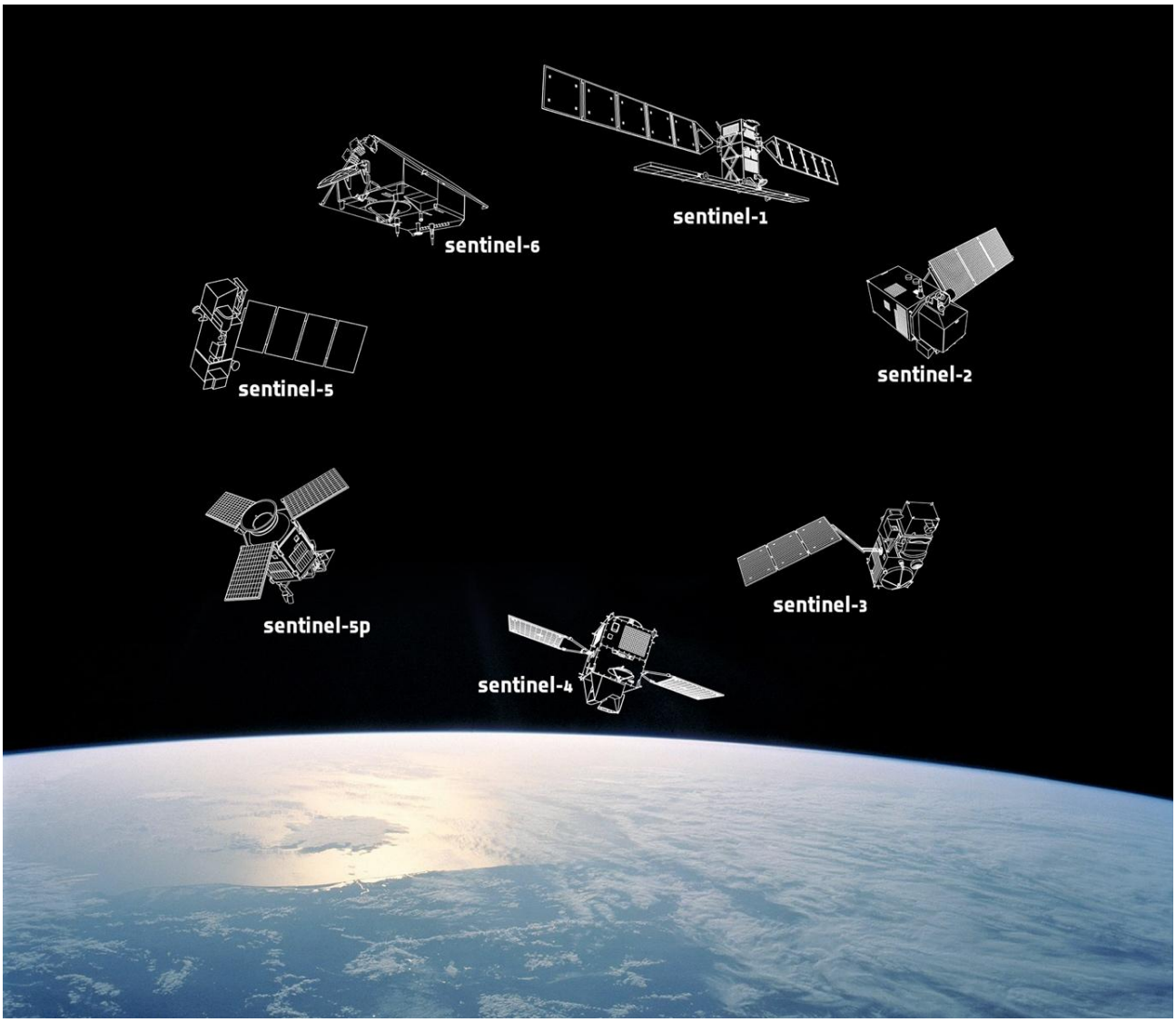


Figure 7 Current suite of Sentinel missions (ESA)

Sentinel-1 is the workhorse for ground motion. It operates in C-band, around 5.4 gigahertz, which strikes a usable balance between vegetation penetration and sensitivity to ground deformation. The active constellation consists of Sentinel-1C (launched late 2024) and Sentinel-1D (launched 2025). Sentinel-1A, which carried the mission from 2014, was retired in June 2026, and the original Sentinel-1B failed in orbit in 2022. With two satellites in formation the repeat cycle is six days. The standard acquisition mode over Europe, Interferometric Wide-swath, covers a 250-kilometre swath at roughly 5-by-20-metre native resolution.[18]

For Gronau-Epe the EFTAS workflow uses Sentinel-1 Interferometric Wide-swath acquisitions in VV polarisation, from both ascending and descending tracks. Sentinel-2 plays a smaller supporting role, supplying multispectral imagery used to map vegetation damage and to

[18] European Space Agency. Sentinel-1 Mission. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1. Sentinel-1A launched 3 April 2014; Sentinel-1B (April 2016, ended in orbit 2022); Sentinel-1C launched 5 December 2024; Sentinel-1D launched 2025.

estimate relative soil moisture, both of which feed into the analysis of ground movement. The combination of the two missions, with their complementary revisit cycles and instruments, is at the heart of what makes the case work.

3.3 The EFTAS Service

The company behind the service is profiled in section 4.2.1. This section describes the service itself: how EFTAS applies Sentinel data to the monitoring problem set out in chapter 2, the processing chain and products it has built, and the platform through which they are delivered.

The Gronau-Epe service sits inside the energy and mining unit. EFTAS leads the radar processing chain, draws on a network of partners for ancillary data and field validation, and is responsible for the operational delivery of monitoring products to the participatory research cooperation and of commissioned ground-movement assessments to Uniper Energy Storage. The processing pipeline runs on in-house infrastructure using ENVI SARscape for the InSAR processing, ESRI ArcGIS Pro for geographic information, and Python for the multi-criteria analysis layer.

The headline technical output is a weekly ground movement product covering the full cavern field on a 30-metre grid, decomposed into vertical and east-west horizontal components. Beneath that headline, the product chain integrates more than 15 open geodatasets, including the 1:50,000 NRW soil map, the official mine survey records from SGW, GNSS measurements from GeoBasis NRW, and operational storage data per operator from AGSI+, the European gas storage transparency inventory. Where higher resolution is needed for specific objects, EFTAS supplements Sentinel-1 with TerraSAR-X. Figure 8 shows the current state of that product, with the movement record now extended to October 2025.

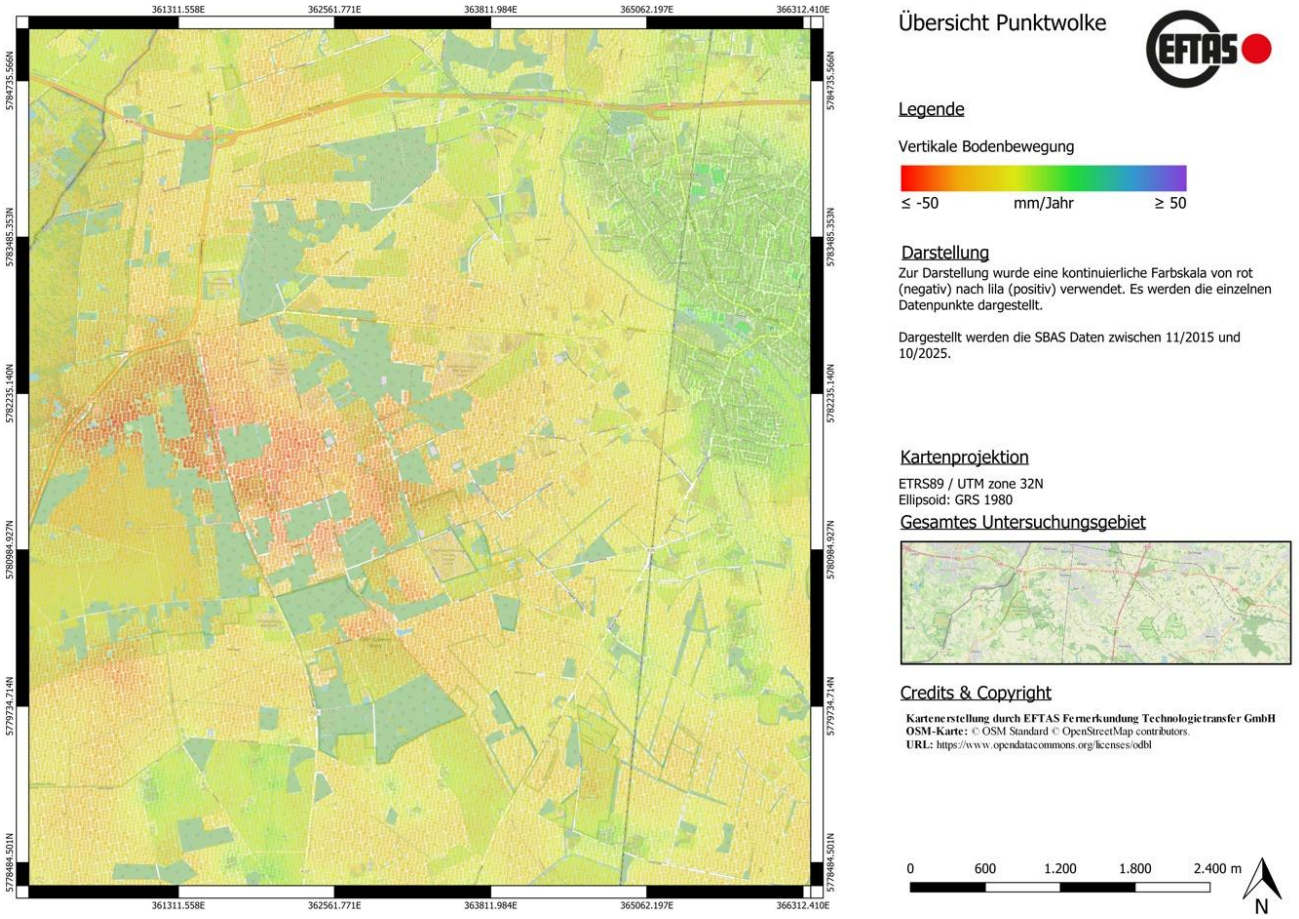


Figure 8 The most recent EFTAS ground-movement analysis for the Gronau-Epe area: vertical movement from Sentinel-1 SBAS point data, November 2015 to October 2025 (mm per year, red for subsidence, purple for uplift). Source: EFTAS Fernerkundung Technologietransfer GmbH

A K-Means spatiotemporal clustering layer, run in a Space-Time Cube within ArcGIS Pro, groups areas of the field by their joint pattern of vertical and horizontal movement. **A multi-criteria decision analysis weighted 60% on ground movement and 40% on soil type, then attributes those clusters to operational (cavern-induced) or environmental (hydrogeological and pedological) drivers.** The methodology is documented in two peer-reviewed papers in the journal Mining (Rudolph et al. 2024 and 2026) and was presented at INTERGEO 2025 in Frankfurt and at the 13th Deutsches GeoForum in Berlin later that year.

The participatory dimension of the service is delivered through a WebGIS platform at monitoring-epe.de (Figure 9). The platform makes selected results and base data publicly visible, supports the public information events held in Gronau town hall, and provides the technical anchor for the formal partnership with the citizens' initiative BI-K and the City of Gronau.[19]

[19] Monitoring Epe research cooperation portal. https://monitoring-epe.de.

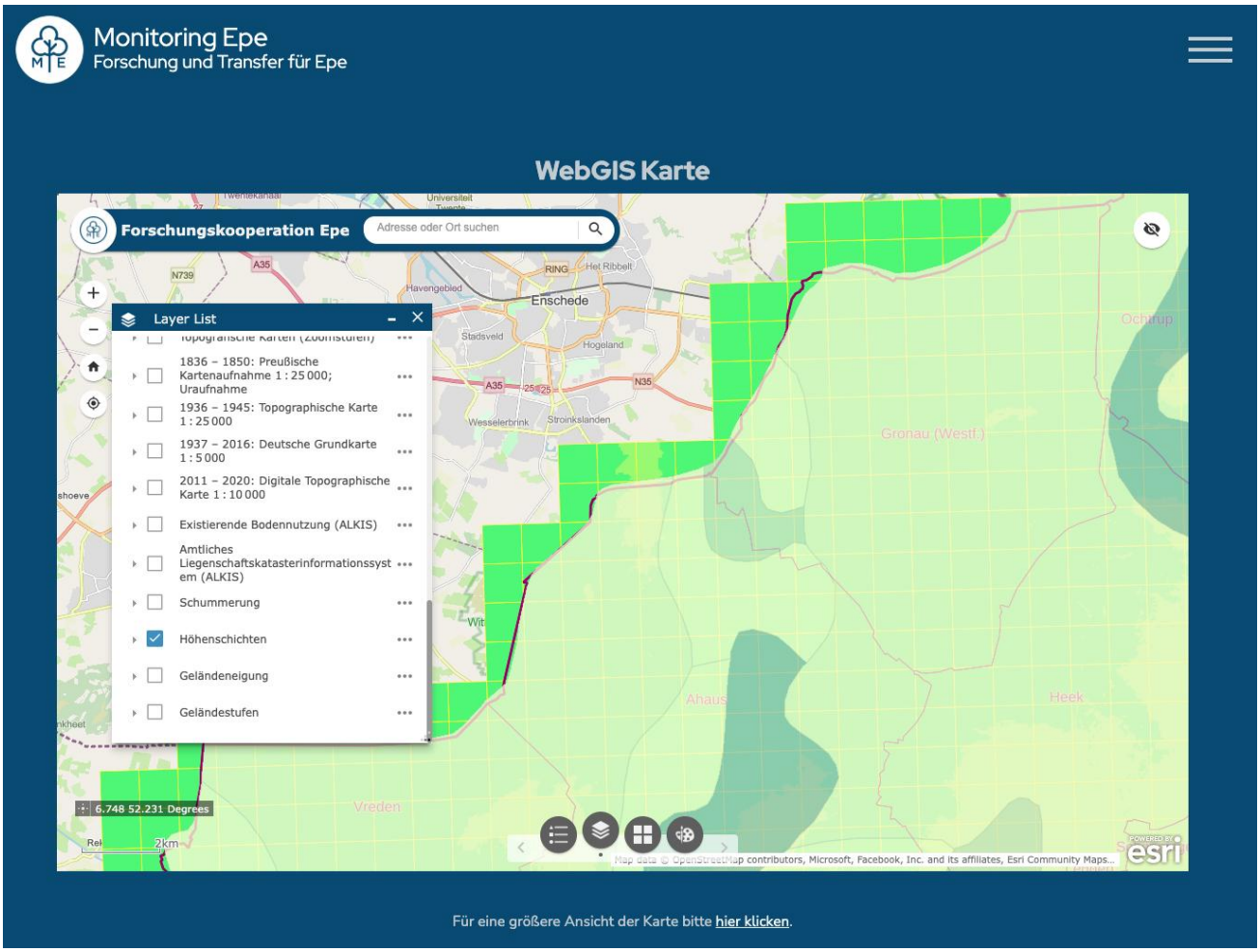


Figure 9 The monitoring-epe.de WebGIS platform

3.3.1 Future evolution of the service

Four threads will shape the service over the next several years.

- **Hydrogen.** Uniper has begun preparing the cavern field for hydrogen storage, starting with a first phase of around 200 gigawatt-hours and scaling to as much as two terawatt-hours, under a European Commission Project of Common Interest designation. For the monitoring itself the conversion changes little: hydrogen is another gas in the same caverns, and the measurement task carries over. What matters is continuity, keeping the movement record unbroken as the expansion comes online.
- **Artificial intelligence.** REWE (Radarfernerkundung Epe W-E-Bewegung) is the Uniper-funded work through which the Sentinel-based assessments are commissioned: it was developed in 2023 on the initiative of THGA and EFTAS, and REWE 1.0 analysed the movement record for 2015 to 2021. The follow-on, REWE 2.0, commissioned for 2026/2027, adds an AI layer to the existing methodology. **The objective is to make the**

assessment of site integrity more automated, particularly the attribution of ground movement to specific cavern operations rather than to environmental drivers.[20]

- **The next generation of Copernicus.** Sentinel-1 Next Generation will provide continuity for the C-band ground motion service into the 2030s. ROSE-L, scheduled for launch in 2028 or 2029, **will add an L-band radar with a longer wavelength that penetrates dry vegetation better than C-band**. Co-located C and L-band acquisitions would improve the separation between vegetation-related motion and ground motion proper, which is exactly the kind of disentangling that matters in the mixed land cover at Gronau-Epe. CHIME, the hyperspectral imager planned for the late 2020s, would add a new dimension to the vegetation and soil moisture work currently done with Sentinel-2.
- **Commercial transfer.** How far the methodology developed here can be applied beyond Gronau-Epe. EFTAS plans the transfer first for the cavern industry, but also intends to take in other underground activities that can cause ground motion, including geothermal energy and carbon capture and storage. EFTAS has flagged underground energy storage as a future hot topic in its own strategy, and the methodology is in principle transferable to any cavern field with similar geological and land-cover characteristics. Other German cavern fields, including Etzel, Krummhörn, Bernburg and Bad Lauchstädt, are obvious candidates. So are the European Commission's other Projects of Common Interest in hydrogen storage. How quickly that transfer happens depends partly on the pace at which mining authorities recognise InSAR as a complement to conventional monitoring, and partly on the commercial moves of the cavern operators themselves.

[20] Forschungszentrum Nachbergbau, THGA Bochum. REWE: Radarfernerkundung Epe W-E-Bewegung. https://fzn.thga.de/en/forschung/rewe-2.

4. Understanding the Value Chain

4.1 Description of the value chain

The Sentinel-based monitoring service at Gronau-Epe sits inside a value chain that runs from the European space programme at one end to the citizens of Gronau at the other. This section sets out the structure of that chain and profiles each of the actors along it.

In SeBS360, the value chain is analysed across four tiers (Figure 10). EFTAS is the Tier 1 service provider, processing Sentinel-1 data into ground motion products. Uniper Energy Storage GmbH is the Tier 2 primary user, paying for the service and using it to manage operational and infrastructure risk on the cavern field. Tier 3 captures the commercial counterparties that ultimately benefit from a more reliable storage service: customers purchasing storage capacity from Uniper and the gas owners whose volumes sit underground. Tier 4 is citizens and the wider society of Gronau and the German-Dutch border region.

Furthermore, **a second strand of beneficiaries sits alongside the commercial chain.** The salt field owner Salzgewinnungsgesellschaft Westfalen (SGW), the City of Gronau, the citizens' initiative Bürgerinitiative Kavernenfeld Epe e.V. (BI-K), the Research Center of Post-Mining at the Technische Hochschule Georg Agricola in Bochum, and the state mining authority Bezirksregierung Arnsberg are all directly involved in the use, governance, or oversight of the service. They are gathered here under the heading "other beneficiaries" but several of them are central to how the service actually functions on the ground.

Two practical features of the chain deserve attention up front. The first is that **the Tier 3 link, in this case, is evidential rather than transactional**. Commercial buyers of storage capacity do not pay EFTAS or Uniper extra for the satellite monitoring component, and the value to them shows up indirectly as a lower probability of stranded gas or supply disruption. The second is that two distinct delivery chains run in parallel. The annual mine survey delivered by SGW to the mining authority is one chain. The Sentinel-1 products delivered by EFTAS to the research cooperation and, through the commissioned assessments, to Uniper are another. Both contribute to monitoring outcomes, but they serve different governance functions, and the SeBS360 analysis here focuses on the second.

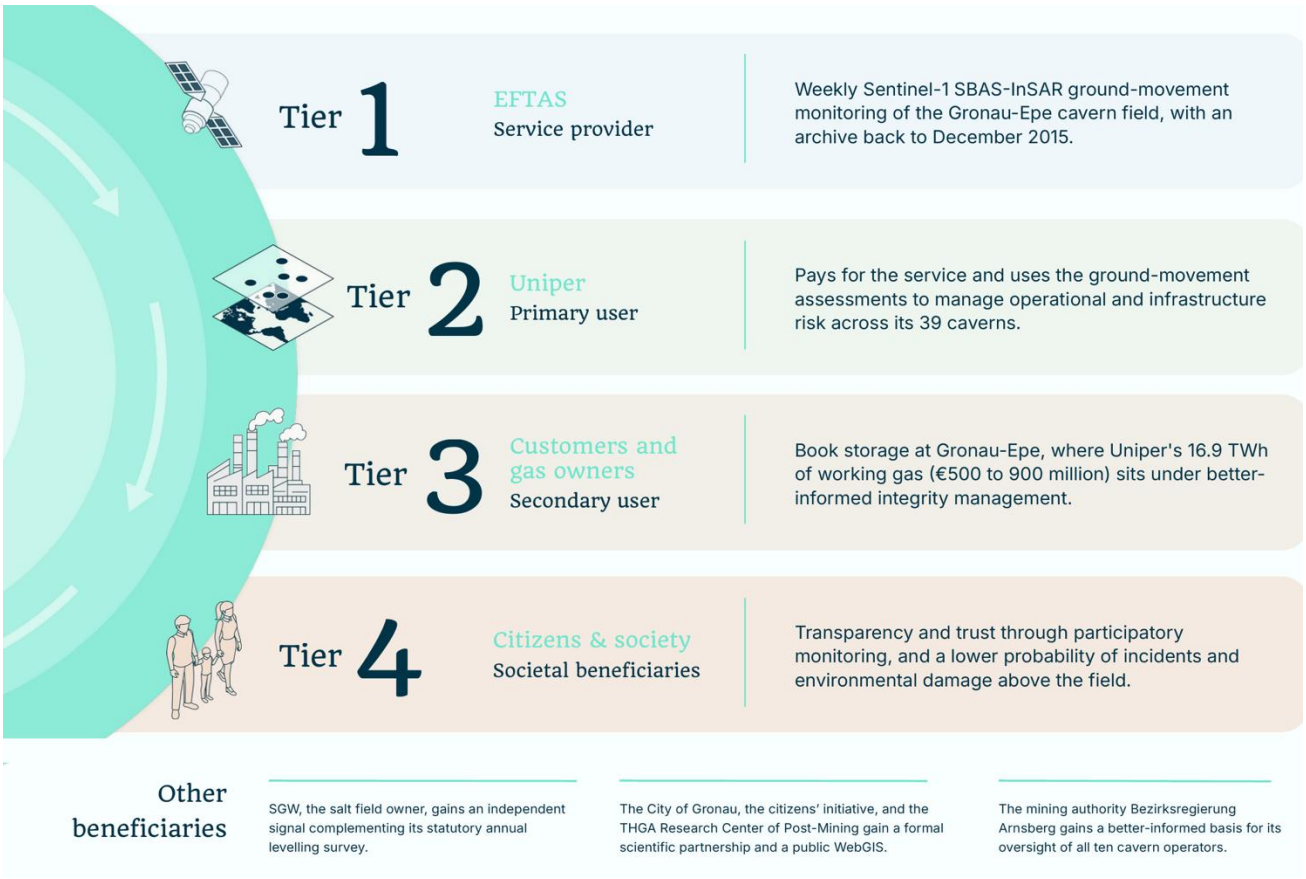


Figure 10 The four-tier value chain of the Gronau-Epe monitoring case, with other beneficiaries alongside

4.2 Actors

The operators and the salt-field owner have been on the field since the 1970s. The citizens' initiative BI-K formed in 2018, in the aftermath of the 2014 oil leak. The city council called for independent measurements in October 2020, and in July 2021 the City of Gronau, BI-K, EFTAS, and the Research Center of Post-Mining at THGA Bochum signed the research cooperation that has organised the public side of the monitoring ever since. Uniper had by then been commissioning ground-movement assessments for its own integrity management for years, and the REWE work later connected that commercial strand to the same methodology. This section profiles each of these actors, tier by tier.

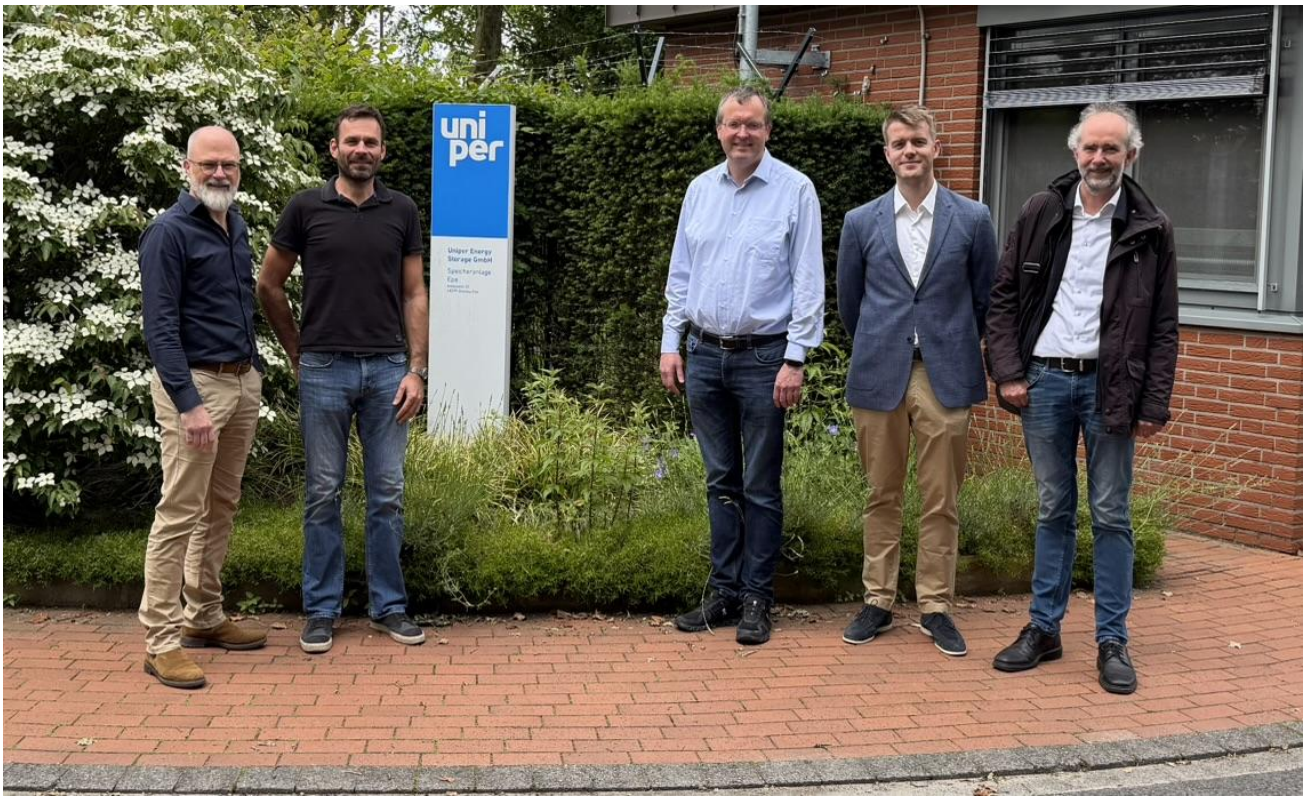


Figure 11 Visiting Uniper facilities with representatives of EFTAS and Uniper

4.2.1 The Service Provider (Tier 1) – EFTAS

EFTAS Fernerkundung Technologietransfer GmbH is a privately held remote sensing and geoinformation company founded in 1988 and based in Münster, in the north-west of Germany. The company describes its core business as customised geoinformation and IT services built on the combined use of satellite, airborne and ground data. It is certified to ISO 9001 and, since August 2025, to ISO/IEC 27001:2022 for information security.[21]

Six application domains structure the company's work: agriculture and forestry, environment and landscape, energy and mining, infrastructure and mobility, public safety, and tourism. Within mining and georesources, EFTAS has run a dedicated unit for more than two decades. For more than twenty years the company has provided commercial Earth observation services to the mining industry and to mining authorities, covering exploration support and the environmental impact assessment and monitoring of active mines and of sites in the post-mining phase. Alongside that commercial work sits a portfolio of research, from EU framework projects on integrated mining impact monitoring, including i^{2}MON under the Research Fund for Coal and Steel and STINGS on workable satellite-SAR systems for mining areas, to subsurface storage applications like the one analysed here.

At the European level EFTAS works regularly with Eurostat, DG Agriculture and DG Environment on continental land cover and biodiversity surveys. Long-running national work in Germany

[21] EFTAS Fernerkundung Technologietransfer GmbH. https://www.eftas.de.

supports the Cologne District Government (Bezirksregierung Köln) on forest monitoring under Waldinfo.NRW, and the company has been a recurring partner in agricultural payment monitoring under the Common Agricultural Policy. Beyond Europe, EFTAS has delivered geoinformation services for UNESCO biosphere reserves, the Algerian national parks system, and a range of African food security and environment programmes. In July 2025 the methodology developed at Gronau-Epe was presented in Riyadh under the UNCCD G20 Global Land Initiative, on an invitation to EFTAS that was taken up by its research partner, the Research Center of Post-Mining at THGA Bochum.

For the value chain, the relevant point is that EFTAS sits at the interface between the European space infrastructure (Copernicus, Sentinel-1, Sentinel-2) and the operational needs of the cavern field. It is responsible for the entire processing chain from the Level-1 Sentinel-1 products distributed by ESA (single look complex scenes) to area-wide ground-movement time series derived from approximately weekly observations, for the integration of ancillary geodata and operational storage information from AGSI+, for the multi-criteria analysis that separates operational from environmental drivers, and for the technical operation of the WebGIS platform at monitoring-epe.de. The commissioned assessment work for Uniper (REWE) sits in this tier, as does the formal partnership agreement with the parties to the research cooperation.

4.2.2 The Primary User (Tier 2) – Uniper Energy Storage GmbH

Uniper Energy Storage GmbH is the German underground storage business of Uniper SE, headquartered in Düsseldorf since 2019. The parent company emerged in 2016 from the demerger of E.ON's conventional generation, trading and energy storage activities. Following the 2022 gas crisis it was stabilised by the German state, which today holds around 99 per cent of the shares and is required to reduce its stake to 25 per cent plus one share by the end of 2028. The storage subsidiary operates eight underground gas storage facilities across Germany, Austria and the United Kingdom with a combined working gas capacity of around 82 terawatt-hours.[22]

At Gronau-Epe, Uniper holds 39 of the 114 caverns, split between high-calorific (H-gas, 29 caverns) and low-calorific (L-gas, 10 caverns) services (Figure 12). **Working gas across the Uniper position amounts to around 16.9 terawatt-hours (roughly 1,916 million cubic metres), making Epe by some distance the largest position** in Uniper's storage portfolio. The site also plays a big role in the company's planned hydrogen storage expansion, the UST Hydrogen Storage Epe project, designated by the European Commission as a Project of

[22] Uniper Energy Storage GmbH. https://www.uniper.energy/energy-storage-uniper. Operates eight underground gas storage facilities in Germany, Austria and the United Kingdom.

Common Interest in 2023, with a first phase of around 200 gigawatt-hours and a target ultimate capacity of up to two terawatt-hours of hydrogen.



Figure 12 Wellhead at Gronau-Epe (Kaverne S78)

Uniper's interest in the satellite monitoring service is operational and economic. The worst-case framing is direct: a single cavern with around a million cubic metres of stored gas becoming inaccessible because of subsurface or surface failure would translate into multi-million-euro consequences, both in lost gas and in recovery and remediation costs. The hundreds of

kilometres of 40-centimetre pipeline that connect the caverns to surface installations are exposed to similar uneven-settlement risk. Uniper is not legally obliged to do its own ground motion monitoring at the field, that obligation sits with SGW, but commissions satellite-based ground-movement assessments on a voluntary, recurring basis to manage its operational risk and to support its licence to operate.

4.2.3 The Secondary Users (Tier 3) – Customers and gas owners

Tier 3 is the part of the value chain where attribution gets indirect. The actors are the commercial counterparties of Uniper's storage business: gas traders, industrial consumers, transmission system operators, and other parties that book storage capacity at Gronau-Epe under Uniper's commercial terms. They do not contract with EFTAS or pay separately for the satellite monitoring component. Gas traders book capacity to move gas between seasons and capture price spreads. Industrial consumers and municipal utilities book it to secure physical supply through the winter. Transmission system operators count on stored gas for balancing and system stability. The benefits this group derives from the monitoring service are assessed in section 5.2.3.

In aggregate, this is a substantial tier. Uniper's Gronau-Epe position alone amounts to around 16.9 terawatt-hours of working gas, equivalent at recent gas prices to roughly €500 million to €900 million of stored value at any given moment. Across the field as a whole, working gas of around 3.5 billion cubic metres is held on behalf of buyers ranging from German utilities to traders supplying the wider European market. The Sentinel-1 monitoring service contributes to that whole, but in proportions that the SeBS360 analysis can only estimate.

4.2.4 Citizens and Society (Tier 4)

The Tier 4 actors at Gronau-Epe are the 47,000 residents of Gronau and the surrounding villages, the agricultural and small-business community of the cavern field, and the broader regional public served by the Westfälische Nachrichten, WDR and the local council. The 2014 oil leak and the subsequent formation of the citizens' initiative BI-K mean that **the relationship between the cavern operators and the local public is very active** for a German mining site.

Tier 4 value arrives in two ways. The first is the participatory geomonitoring cooperation, which makes the satellite data and related geodata publicly visible through the WebGIS platform at monitoring-epe.de and translates them for non-specialist audiences. The concrete forms of that engagement, and the benefits they deliver, are treated in section 5.2.4. The second is the underlying operational benefit shared with Tier 3: lower probability of incidents, lower probability

of disruption, and a more transparent record against which to interpret what is happening underground.

4.2.5 Other Beneficiaries

Five other actors are central to the case.

Salzgewinnungsgesellschaft Westfalen mbH & Co. KG (SGW) is the salt field owner, jointly held by Solvay (65%), Vestolit (25%) and Bayer (10%). SGW holds the primary extraction rights at Gronau-Epe, produces around two million tonnes per year of rock salt as brine for chemical-industry use, and is the legally obliged mine surveyor under the German Federal Mining Act. SGW's annual terrestrial levelling report is the regulatory baseline against which the Sentinel-1 service is positioned as an augmentation, not a replacement.

The City of Gronau is the local authority covering roughly 47,000 residents and the principal civic interlocutor between the cavern operators and the public. The city council passed the resolution of 7 October 2020 calling for an independent measurement programme and is a signatory to the research cooperation contract of July 2021.

The Bürgerinitiative Kavernenfeld Epe e.V. (BI-K) is a registered citizens' association, established in 2018 to advocate for the residents of the cavern field. **BI-K's formal partnership in the research cooperation is the first time a citizens' initiative has been embedded as a scientific partner in a German mining project.** The association is responsible for selecting a portion of the surface objects used for monthly site inspections and for feeding local knowledge into the methodology development.

The Research Center of Post-Mining at THGA Bochum (FZN) provides the scientific anchoring for the research cooperation. It is the home institution of the two peer-reviewed publications documenting the methodology and coordinates the Uniper-funded REWE work (section 3.3.1), whose follow-on, REWE 2.0, adds an AI layer to the existing workflow.

The Bezirksregierung Arnsberg, Department 6 (Mining and Energy in NRW), is the state mining authority responsible for implementing the German Federal Mining Act in North Rhine-Westphalia. The Bezirksregierung receives SGW's annual mine-survey report and oversees compliance for all 10 cavern operators at Gronau-Epe. It is directly involved in the research cooperation in an advisory capacity and is one of the audiences for any future move to recognise satellite monitoring as a compliance method.

5. Assessing the Benefits

The benefit assessment follows a value-chain logic and examines how Sentinel data contribute to operational outputs, user actions, and resulting benefits across the different tiers of the case (Figure 13). The analysis focuses on six benefit dimensions where relevant to the case: economic, environmental, societal, regulatory, innovation/entrepreneurship and science/technology related benefits. Not all dimensions are expected to be relevant or measurable in each tier.

For each identified benefit, the assessment seeks to clarify five elements: (i) the stakeholder experiencing the benefit, (ii) the mechanism through which the benefit is created, (iii) the indicator or proxy used to assess it, (iv) the evidence on which the assessment is based, and (v) the extent to which the benefit can be attributed to the Sentinel-enabled service. Where sufficient evidence is available, models are developed and used to estimate indicative orders of magnitude. Where this is not possible, benefits are described qualitatively and linked to concrete operational effects.

Particular attention is given to attribution. **The report does not assess the value of the overall service in generic terms**, but rather examines the extent to which Sentinel-derived inputs enable, improve, scale, or reduce the cost of the service compared with plausible alternatives or with a situation in which such information would not be available.

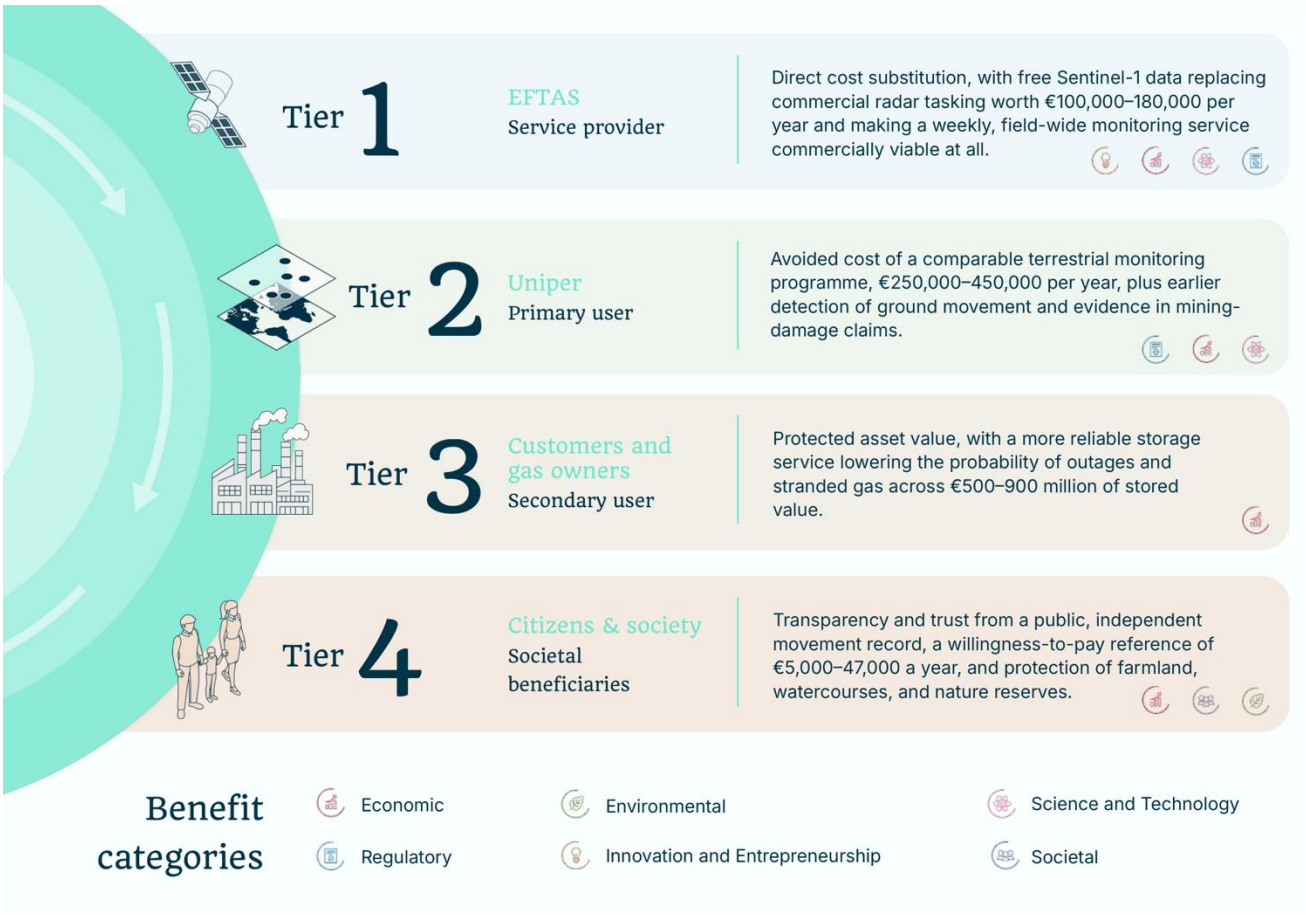


Figure 13 Summary of benefits across the tiers

5.1 Overview

The benefits of the Sentinel-based service at Gronau-Epe are measured against a counterfactual: the monitoring the cavern field would have if the service did not exist. The regulatory baseline is the annual terrestrial levelling survey delivered by SGW under the German Federal Mining Act, which measures vertical displacement at a fixed set of benchmarks once a year. The Sentinel-1 service adds up-to-weekly coverage across the full 25-square-kilometre field, separates motion into vertical and east-west horizontal components, and reaches back across nearly a decade of archived acquisitions. **The benefits assessed in this section are the difference between those two pictures, not the value of ground motion monitoring as a whole. At the primary-user tier the comparison is drawn against the conventional programme Uniper would otherwise have had to procure to obtain comparable information (section 5.2.2).**

The assessment uses tier-specific counterfactuals. At Tier 1, the alternative is either procuring commercial SAR data for a broadly comparable service or not providing the service at its current scale. At Tier 2, the counterfactual is reliance on SGW's annual terrestrial levelling and Uniper's other integrity information without the dedicated Sentinel-based assessment. At Tier 3, it is the corresponding level of storage reliability without the additional information, while at Tier 4 it is

the absence of the Sentinel-enabled public ground-movement record. Annex 2 consolidates these counterfactuals and their assumptions.

Three rules of method apply throughout the benefit assessment across the value chain. First, the benefit assessment is sequential: **value created at one tier is not re-counted at the next**. Second, attribution is conservative and stated for each benefit. Third, where a figure is based on a benchmark transferred from another setting rather than on operational data specific to this case, that is stated at the point of use and revisited in section 6.3. The economic figures rest on the named assumptions set out in Annex 2.

In most cases the dominant benefit is a measurable efficiency saving, such as fewer field visits, crop losses avoided or permits issued faster. **Here the largest economic benefit is the reduced probability of a low-likelihood but high-consequence failure**, and it sits alongside clear environmental and societal benefits. The service also runs through two parallel chains. The first is the commercial chain that connects EFTAS to Uniper and, beyond it, to the customers who book storage capacity. The second is the participatory research cooperation that connects the same data to the City of Gronau, the citizens' initiative BI-K, and the wider public. The assessment that follows traces benefits through both.

In this application the operational tempo is set by the geomechanics. Salt-cavern ground movement develops over months and years, assessing the significance of a movement can take a month or more, the regulatory baseline is annual, and the operator's integrity reviews run on multi-year cycles. **Periodic area-wide assessments, supported by an archive that allows movement at any location to be reconstructed on demand, is what makes the service valuable.** The value of the Sentinel-based service lies in its completeness, its resolution, and that ability to look back, rather than in daily alerting.

The benefits identified are also not all realised at the same point in time. **The benefits that have accrued today sit mainly in Tiers 1 and 2**: the avoided cost of commercial data, the commissioned assessment work, and the use of the results in Uniper's asset integrity approach. The benefits tied to continuous monitoring, to wider adoption across the field's ten operators, and to the hydrogen expansion are future benefits, contingent on decisions not yet taken, and they are labelled as such where they appear.

Where this section puts figures on benefits, it does so as indicative estimates built from transparent assumptions. The value at stake in the storage business is large and reasonably well documented, but the share of it attributable to the satellite service specifically is a matter of judgement. The figures below should therefore be read as order-of-magnitude proxies that frame the scale of the benefit.

5.2 Benefits along the value chain

The benefits set out below follow the four-tier value chain described in section 4. The actors who sit outside the commercial hierarchy, but who are central to how the service works on the ground, are treated together at the end under other beneficiaries.

5.2.1 The Service Provider (Tier 1) – EFTAS

Economic Benefits

The principal quantifiable indicator at Tier 1 is the estimated replacement cost of the Sentinel-1 input. Without free Sentinel-1 data, EFTAS would either need to procure commercial SAR data or provide a less frequent and less extensive service. A weekly service needs 52 scenes per year in each of the two viewing geometries, or 104 scenes in total, because separating vertical from horizontal motion requires both an ascending and a descending view. A single TerraSAR-X StripMap scene covers the whole 25-square-kilometre field, so each acquisition date requires one scene per geometry.[23] At current marketplace tasking prices of around €1,750 per scene (UP42 price list, accessed July 2026, see Annex 2, Assumption 1), a like-for-like replacement would cost of the order of €180,000 per year, or €125,000 to €145,000 with multi-year volume discounts. Previous SeBS case studies provide useful reference points: the Netherlands pipeline-monitoring case and the Portugal motorway case each estimated avoided commercial-data costs of around €60,000 per year. Those estimates were built on a single viewing geometry and therefore describe a less capable programme than the dual-geometry service costed here. **The commercial replacement cost is indicatively estimated at €100,000 to €180,000 per year, with a baseline value of €140,000**. The counterfactual assumed at this tier is therefore a commercial-data replacement of the same weekly, dual-geometry service, at current tasking prices (Annex 2, Assumption 1). Alongside this, EFTAS earns direct revenue from the commissioned assessment work for Uniper and from its role in the research cooperation. In principle that revenue would also exist under a commercial-data counterfactual, but at the data prices above the service would most likely not have been commissioned in this form at all, so in practice the revenue stream is contingent on free and open Sentinel data. The figures are commercially confidential, so the revenue is characterised rather than disclosed. That revenue is a cost to Uniper, so it nets out inside the value chain and is not added to the totals in section 5.3. What is counted at this tier is the avoided data cost, which is money that would otherwise leave the chain altogether, to a commercial data supplier.

[23] EARSC SeBS case reports: Improving Maintenance of Pipeline Infrastructure in the Netherlands (2016) and Motorway Maintenance in Portugal (2024). https://earsc.org/sebs. TerraSAR-X marketplace tasking and archive prices: UP42, https://docs.up42.com, accessed July 2026. Umbra open price list: https://umbra.space/pricing, accessed July 2026.

Three distinct attribution statements sit alongside that figure. The avoided data cost is a cost that exists only if the free Sentinel-1 data is removed, so it belongs to the Sentinel data itself. **The statement that the service would not be economically viable at all without free and open data is an enabling condition, in effect a total dependence.** And the share of the delivered service value carried by the Sentinel data, as distinct from EFTAS's processing chain, clustering, and ancillary geodata, is a third measure. It is not used to discount the counted estimates, since the service would not exist without the data, but Annex 2, Assumption 5 reports its effect as a sensitivity.

Regulatory Benefits

The regulatory dimension is also a Tier 1 benefit. Radar interferometry is becoming formally recognised in German professional guidance and standards: the DMV Grundsätze for geomonitoring were revised in January 2025, and a DIN standardisation process is underway (see section 5.3.3).[24] The benefit observed today is that the Gronau-Epe record supports that process directly, because it is peer reviewed, publicly delivered, and validated against the statutory levelling. The free and open data policy stands behind this: a service that would not exist on paid data has produced the evidence base on which more efficient regulation can be built, which is how applications of a technology become enablers of better rules. For EFTAS the commercial consequence is significant. **The larger benefit is expected rather than already observed: investments will be made at scale once a technique is recognised in the regulatory framework**, a development the company itself expects to drive commercial adoption (see section 3.3.1), and a provider holding a decade of publicly documented cavern-field work is positioned to convert that recognition into demand ahead of competitors without such a reference.

Innovation and Entrepreneurship Benefits

The more durable benefit is that **the Gronau-Epe work has turned a bespoke project into a reusable asset**. The processing chain, the multi-criteria attribution layer that separates operational from environmental drivers, and the WebGIS delivery platform together form a methodology that EFTAS can carry to other sites. The company has itself flagged underground energy storage as a future hot topic in its strategy, and Gronau-Epe is a highly credible reference.

[24] Deutscher Markscheider-Verein (DMV), Grundsätze zur Anwendung der Radarinterferometrie: first edition 16 September 2013, revised edition January 2025. https://www.dmv-ev.de. A related DIN standardisation process has been under way since around 2020.

SAR-based ground-motion services already account for roughly a fifth of the company's business, and the Epe methodology provides a **strong basis for adaptation to other cavern fields** and **future hydrogen-storage projects**, subject to their geological, operational and monitoring conditions.

The free and open availability of Sentinel-1 data is central to the viability and scalability of this business model. Because the input data carry no licence cost, the marginal cost of running and extending the service is processing time and analyst hours rather than data procurement. This makes a weekly, multi-year monitoring product commercially viable, and it allows EFTAS to offer comparable services at a more competitive price.

Science and Technology Benefits

The work has also generated substantial reputational and follow-on returns. The methodology is documented in two peer-reviewed papers in the journal Mining and has been presented at INTERGEO 2025 in Frankfurt and the 13th Deutsches GeoForum in Berlin.[25] In July 2025 the Gronau-Epe methodology was presented in Riyadh under the UNCCD G20 Global Land Initiative, on an invitation to EFTAS that its research partner, the Research Center of Post-Mining at THGA Bochum, took up on behalf of the cooperation. The follow-on development work at THGA Bochum, funded by Uniper, extends the work with an artificial intelligence layer and represents a concrete pipeline of further activity. The work has also generated an initial commercial spillover: EFTAS was invited to a nearby ground-damage case involving a sand-and-gravel operation specifically on the strength of its Gronau-Epe work. Together, these publications, presentations, research activities and commercial opportunities strengthen EFTAS's position in a market it expects to grow.

5.2.2 The Primary User (Tier 2) – Uniper Energy Storage GmbH

Economic Benefits

Uniper is the paying user and the actor for whom the economic benefit is largest and most direct. Its interest is operational risk management. **A single cavern holding roughly a million cubic**

[25] Rudolph, T., Goerke-Mallet, P., Homölle, A., Müterthies, A., Perrevort, H., Teuwsen, S., Yang, C.-H. (2024). 'Participatory Geomonitoring for Future Mining—Resilience Management in the Cavern Storage Epe (Germany)'. Mining 4(2):230–247. doi:10.3390/mining4020014. Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23. Presentations at INTERGEO 2025 (Frankfurt, October 2025) and the 13th Deutsches GeoForum (Berlin, November 2025) as reported by the Monitoring Epe research cooperation, https://monitoring-epe.de.

metres of stored gas becoming inaccessible through subsurface or surface failure would carry consequences in the order of several million to tens of millions of euros once lost gas, recovery and remediation, and lost availability are counted. The hundreds of kilometres of 40-centimetre pipeline connecting the caverns to surface installations are exposed to similar risk from uneven settlement.

Uniper has commissioned ground-movement assessments at Epe on a recurring basis for around a decade. The Sentinel-based work is the latest expression of that practice: the REWE 1.0 procurement covered 2015 to 2021, and follow-on work extending the analysis to 2025 is commissioned for 2026/2027.

The mechanism by which the service delivers that benefit is earlier and better-resolved detection. The annual terrestrial survey leaves a blind spot of up to a year between measurements. Because Sentinel-1 acquisitions accrue weekly, **an S1-powered assessment figures out when and where movement developed and at what rate, information the annual survey cannot provide between campaigns**. This can bring forward the moment of detection by weeks or months and allow a cheaper, smaller intervention before a developing problem escalates. The horizontal component of the measurement, which conventional levelling does not provide, is directly relevant to pipeline integrity, because buried infrastructure can be stressed by lateral ground movement even where vertical settlement looks modest.

Without the Sentinel-based service, Uniper's picture of ground movement would rest on the annual levelling campaign alone. A developing movement could then remain invisible for up to a year, detection would come later, and the interventions available at that point would be larger, more expensive, and harder to plan. Uniper has shown clear proactiveness to avoid these blind spots and has commissioned ground-movement assessments for around a decade and intends to extend them to all of its storage sites. The counterfactual at this tier is therefore not the annual survey alone but the conventional monitoring programme Uniper would have had to procure to obtain comparable information, and the benefit assessed is the avoided cost of that programme (Annex 2, Assumption 7).

Movement that stands out sends Uniper back to that cavern with other instruments, and the maps help decide which cavern to check first and where the technical risk is greatest. Money follows the same logic. Risk budgets at Epe are set cavern by cavern, so a cavern with notable horizontal movement can justify workover spend on a wellhead or a casing that a quiet cavern cannot, and each cavern carries its own evaluation programme covering technical and non-technical factors. The worst case is losing access to a cavern rather than losing the gas in it. Uniper would then need to recover the cushion gas, inject water, plug and abandon the well, and give up the capacity that cavern was selling. That has happened once in roughly fifty years at Epe.

EFTAS measures the movement but stops short of calling it critical, so the judgement stays with Uniper's own geoscientists. Uniper is also candid that it is still testing. The assessments have been done project by project, there is no settled routine for handling the results, and the company says the operational consequences are not yet clear enough to predict. The estimate below rests on better-informed decisions being taken today, and stops well short of assuming a settled rule for acting on the data.

Two figures describe the size of this benefit. The first is exposure: Uniper's Gronau-Epe position of roughly 16.9 terawatt-hours of working gas is worth in the order of 500 to 900 million euros at recent wholesale gas prices of roughly €30 to €55 per megawatt-hour, and the monitoring helps protect access to it. The second is the replacement cost of the information itself. A conventional programme delivering comparable coverage would need monthly precise-levelling campaigns over a densified network of around 450 benchmarks, permanent GNSS stations to recover the horizontal component, and the associated processing and interpretation. Annex 2, Assumption 7 costs this programme at €250,000 to €450,000 per year, with a baseline of €350,000. EFTAS states independently that acquiring equivalent information by conventional means would cost an order of magnitude more than its Sentinel-based service. The fee Uniper pays EFTAS is small against that figure and is not netted off. The avoided cost is attributed in full to the free Sentinel data: EFTAS states that the service would not be commercially viable on paid data, no other source delivers wall-to-wall, dual-component, weekly coverage of this site, and the commercial-data alternative is already valued separately at Tier 1, so discounting Tier 2 again for the processing chain would count the same chain twice. The Sentinel-attributable benefit at this tier is therefore €250,000 to €450,000 per year, with a baseline of €350,000. Annex 2, Assumption 5 reports the effect of a 50 to 60 per cent data-share discount as a sensitivity (€125,000 to €270,000 per year). This follows the information-equivalence approach used in earlier SeBS cases, including the Netherlands and Murcia analyses. The exposure figure describes what is at stake, while the replacement cost is the benefit estimate.

A second lens looks at what the information does rather than what it would cost to obtain: the expected annual loss from major cavern incidents that earlier detection could avoid. Annex 2, section A2.3 sets it out in full. Across Uniper's 39 caverns a major incident has a 0.4 to 2.7 per cent chance in any year, at a consequence of around €60 million, which is an expected loss of €234,000 to €1.6 million a year before the added monitoring. Only 25 to 40 per cent of that is open to influence, the share of failure types that develop slowly enough for area-wide movement data to catch them, and ground-movement monitoring carries 40 to 50 per cent of Uniper's detection capability alongside wellhead pressure monitoring, seismic surveillance, and the statutory levelling. **The expected annual avoided loss is therefore around €52,000 per year, within a range of €23,000 to €330,000.** The figure is shown in Table 1 but not added to the replacement cost, because under the counterfactual adopted here comparable information exists in both scenarios, so the risk reduction it buys is largely common to both and counting it alongside the replacement cost would value the same information twice. No incident at Epe has

yet been averted through the service, so it is a potential risk reduction rather than an observed avoided loss.

The gains below describe what Uniper does with the information, and they would arise under either way of obtaining it. They explain why the information is worth procuring. The benefit counted above is the cost difference between the two ways of getting it.

The clearest recurring gain is better targeting of the integrity budget. Risk management at Epe runs at the level of the individual cavern: some caverns need no special budget or inspection in a given year, while caverns showing notable horizontal movement can justify additional workover spend on wellhead or casing issues. An area-wide movement picture lets that per-cavern evaluation programme direct inspection and workover money to the caverns that warrant it, and supports forward budget planning rather than reactive spending. Better targeting does not mean a smaller budget. Acting on a cavern that the maps have flagged can raise spending in the year it happens, and the return comes as damage that does not occur and as work done at the right time instead of in an emergency. That is why the report carries budget targeting as an indicator rather than as a saving, and puts no figure on it.

A second gain works through evidence rather than prevention. Under the German Federal Mining Act the burden of proof for mining damage reverses inside the statutory subsidence zone, so the ability to show objectively when, where, and at what rate the ground moved carries direct value in damage claims and disputes. **If the data shows that surface movement is not related to operations, Uniper can demonstrate that it is not responsible**, and it considers that insight very valuable. The archive dimension matters here, because questions of causation typically arise years after the movement itself. Under section 120 of the Federal Mining Act, damage within the statutory zone of influence is presumed to be mining damage, and it is the operator that must rebut the presumption.[26] In the German hard-coal sector this regime produces settlement volumes of roughly €84 million per year across more than 20,000 claims, an average of around €4,200 per claim, as reported by RAG for 2022.[27] Those figures come from a different mining context and are not transferred to this case as an estimate, but they give an idea of what is at stake in damage claims wherever the presumption applies, and of what an objective, archived record of when, where, and at what rate the ground moved can be worth to either side.

[26] Federal Mining Act (Bundesberggesetz, BBergG), section 120. Damage occurring within the zone of influence of a mining operation is presumed to be mining damage, and the presumption must be rebutted by the operator.

[27] RAG AG, Bergschadensregulierung. https://www.rag.de/unternehmen/handlungsfelder/bergschadensregulierung. Roughly €84 million paid in 2022 across more than 20,000 claims in the German hard-coal sector, an average of about €4,200 per claim, against a provision of about €2.5 billion.

Regulatory Benefits

Uniper is not the legally obliged mine surveyor, but it reports its voluntary integrity monitoring, including the surface-movement work, at its annual meetings with the mining authority, which views it very positively. The area-wide, time-stamped movement record provides a stronger evidential basis for these discussions, helping Uniper explain observed patterns, their possible causes and the rationale for any follow-up action. Without the Sentinel-based assessment, these discussions would rely primarily on annual point measurements with less spatial and temporal context. This directly results in goodwill and a smoother supervisory relationship. The transparency of the participatory cooperation also reduces the operator's cost of conflict and objection, due to fewer complaints, disputes, and formal objections need to be handled when residents can consult an independent record themselves. The forward-looking pay-off is positioning: German mine surveying has adopted operator-led innovations before, as it did with satellite positioning (GNSS), whose surveying use was pioneered by Uniper's predecessor Ruhrgas before the state system followed, and the trajectory of radar interferometry through the professional guidelines points the same way (section 5.3.3). Starting now positions Uniper as a leader rather than a follower when recognition comes.

Science and Technology Benefits

Uniper also draws a science and technology return from the arrangement. It funds the REWE research line at THGA Bochum, with REWE 1.0 delivered and the 2026/2027 follow-on work commissioned to add an artificial-intelligence layer and to integrate the 2024 three-dimensional seismic survey, and company staff co-author the peer-reviewed publications that document the methodology.[28] REWE 1.0 is built on the 2015 to 2021 Sentinel-1 record, the follow-on extends the same archive to 2025, and it is the free availability of that archive that makes a decade of retrospective analysis affordable as a research undertaking. The return is **early access to state-of-the-art monitoring methods,** applied to and validated on its own field, and **an increasingly explanatory, cavern-by-cavern understanding of ground behaviour that feeds directly back into integrity management** (section 7.4).

A future benefit: the hydrogen expansion

Uniper also plans to store hydrogen at Epe. The UST Hydrogen Storage project, designated a Project of Common Interest by the European Commission in 2023, targets up to two terawatt-hours. The caverns and the monitoring stay as they are, although hydrogen would be cycled more

[28] Forschungszentrum Nachbergbau, THGA Bochum. REWE: Radarfernerkundung Epe W-E-Bewegung. https://fzn.thga.de/en/forschung/rewe-2.

often than methane, which changes the pattern of movement to be tracked. The record is useful in permitting and in the public debate around it, because a decade of published measurements is hard evidence when the safety case is questioned. The benefit depends on the investment going ahead, so no figure for it enters this report.[29]

5.2.3 The Secondary Users (Tier 3) – Customers and gas owners

Economic Benefits

Tier 3 is where attribution becomes indirect. The actors are Uniper's commercial counterparties: the gas traders, industrial consumers, transmission system operators, and other parties that book storage capacity at Gronau-Epe, together with the owners of the gas in the caverns. They do not contract with EFTAS or pay separately for the satellite component, and the benefit reaches them through Uniper's operational reliability. Of the six benefit dimensions, the one at stake at this tier is economic. The security-of-supply dimension that runs alongside it is societal in nature and is counted once, in section 5.3.6. Without the Sentinel-based service, these actors would face the reliability implied by the annual survey alone.

An interruption at the field would not affect these groups in the same way.

Gas traders and wholesale portfolio holders book capacity to move gas between seasons and profit from price spreads. If a position cannot be withdrawn during the weeks when spreads are open, the trading opportunity is gone by the time access is restored. For this group, the monitoring slightly reduces the chance of an interruption in the windows that matter commercially.

Industrial consumers and municipal utilities book capacity to make sure gas is physically there in winter. If booked volumes became unavailable, they would have to replace them at short notice on the spot market, at whatever prices a cold week produces. A lower probability of that situation is what the added reliability is worth to them.

Transmission system operators do not own the gas but rely on the field's deliverability for balancing and system stability. Cavern storage can switch between injection and withdrawal faster than other storage types, and Gronau-Epe's capacity is part of the flexibility the network is planned around. What matters to them is that the capacity Uniper offers remains actually available.

The gas owners hold the value that is ultimately at risk. Uniper's own position amounts to around 16.9 terawatt-hours of working gas, worth in the order of €500 to 900 million at recent

[29] European Commission, sixth list of Projects of Common Interest and Projects of Mutual Interest, adopted 28 November 2023. Project 'UST Hydrogen Storage Epe' included under the hydrogen storage category.

wholesale prices, and the field as a whole holds around 3.5 billion cubic metres on behalf of buyers ranging from German utilities to traders supplying the wider European market.

For all four groups the benefit is real but fractional and indirect. It is a small share of a large, protected value, it reaches them through Uniper's integrity management rather than through any contract of their own, and it is not monetised separately here, to avoid double counting with the Tier 2 estimate.

5.2.4 Citizens and Society (Tier 4)

The Tier 4 beneficiaries are the residents, farmers, and small businesses described in section 4.2.4, together with the broader regional public. For this community the benefit is tangible because the relationship between operators and residents was damaged by the 2014 oil leak (Figure 14). The satellite service, delivered through the participatory research cooperation, addresses that history directly by making the ground movement record publicly visible. Without the Sentinel-based service there would be no such public record: residents would depend on the operators' own statutory reporting, delivered at a handful of benchmarks once a year and not published.



Figure 14 Crude oil at the surface in the Amtsvenn, April 2014. Source: RTV Oost (Nog maar één olielek in Amtsvenn)

Economic Benefits

A willingness-to-pay thought experiment, in the manner of earlier SeBS cases, gives a reference number for the reassurance that the public record gives residents. If each of the roughly 47,000 residents of the City of Gronau valued an independent, continuous record of ground movement at €1 to €10 a year, between the €0.01 to €1 used for flood reassurance in the Ireland case and the €7.75 to €14.30 per connection anchored on a utility compensation tariff in the Netherlands case, the total would be €47,000 to €470,000 a year, of which the 10 per cent satellite share applied in the Netherlands case gives €5,000 to €47,000. The number is indicative and is not added to the economic totals in section 5.3.1.

Societal Benefits

The benefit is principally one of transparency and trust, which is difficult to monetise and is better captured through proxies. A public survey reported by the research cooperation found that 59.1 per cent of responding citizens wanted more information about the research cooperation, evidence that the appetite for transparency outstrips what conventional monitoring delivers.[30] The value can be framed as the confidence that residents and property owners gain from an independent and continuous record, and as the educational return from public engagement. The five public information events in Gronau town hall, the bicycle excursion through the cavern field, and the schools project at the Euregio Gesamtschule Epe that won the GeoIn-MINT Award in February 2026 are concrete expressions of that return.[31] All of this engagement runs on the Sentinel-1 record: the information events present the satellite-derived movement maps, the excursion visited the sites those maps cover, and the schools project works with the open data itself. It also matters for trust that the measurements come from a source none of the parties to the local conflict controls.

Environmental Benefits

The environmental benefit lands at Tier 4 as protection of the lived environment above the field. The surface hosts farmland, watercourses, and the raised bogs of the nature reserves, and the

[30] Figure as reported by the Monitoring Epe research cooperation. Monitoring Epe research cooperation portal. https://monitoring-epe.de.

[31] Monitoring Epe research cooperation, site news: the public information events in the Gronau-Epe council hall, the bicycle excursion through the cavern field, and the GeoIn-MINT Award of the DDGI to the Euregio Gesamtschule Epe project course in February 2026, https://monitoring-epe.de/geoin-mint-award-fuer-projektkurs-umweltmonitoring-der-euregio-gesamtschule-epe/.

2014 leak demonstrated that a cavern failure can reach soil and groundwater, with remediation that took years. The management changes that reduce that risk are made, and counted, at Tier 2 and are not re-counted here.

The benchmark ecoregion in which the storage facilities are located is European Atlantic mixed forests (with the Temperate Broadleaf & Mixed Forests biome); however, the C3S/ESA-CCI 2022 land-cover product identifies the land-cover type where the storage facility is located as class 190 (= 'urban areas'). The mosaic landscape, which combines natural and modified landcover types, contains 28 areas protected for nature within or intersecting with a 7 km distance of the centre of the storage region (i.e. a 5 km search window measured outward from the 2 km target area). These constitute 10 nature reserves, 11 Landscape Protection Areas (LSG), and 7 sites with no additional information (protected-area proximity extracted from the World Database on Protected Areas (WDPA); UNEP-WCMC & IUCN, 2026) (Figure 15A). Of particular importance to nature conservation are EU Special Areas of Conservation (Habitats Directive) and Special Protection Area (Birds Directive), including the *Moore und Heiden des westlichen Munsterlandes* bird protection area, as well as Dutch sites such as *Aamsveen* and *Dinkelland* on the border.

To understand the value of landscape features in the national context, we sampled 500 random pixels of the same land-cover class (190) and ecoregion (European Atlantic mixed forests) across Germany, and calculated Biodiversity Intactness Index (BII) scores. The global biodiversity ranking value of the storage facility region was compared against the sample priority rankings distribution for sampled sites in Germany (mean and 2.5-97.5% percentile interval). We find that for biodiversity alone, the area where the storage facility is located ranks 25 (in the top quartile) for global conservation priority, though close to the median priority ranking value of randomly sampled sites in the same ecoregion and country (Figure 15A).

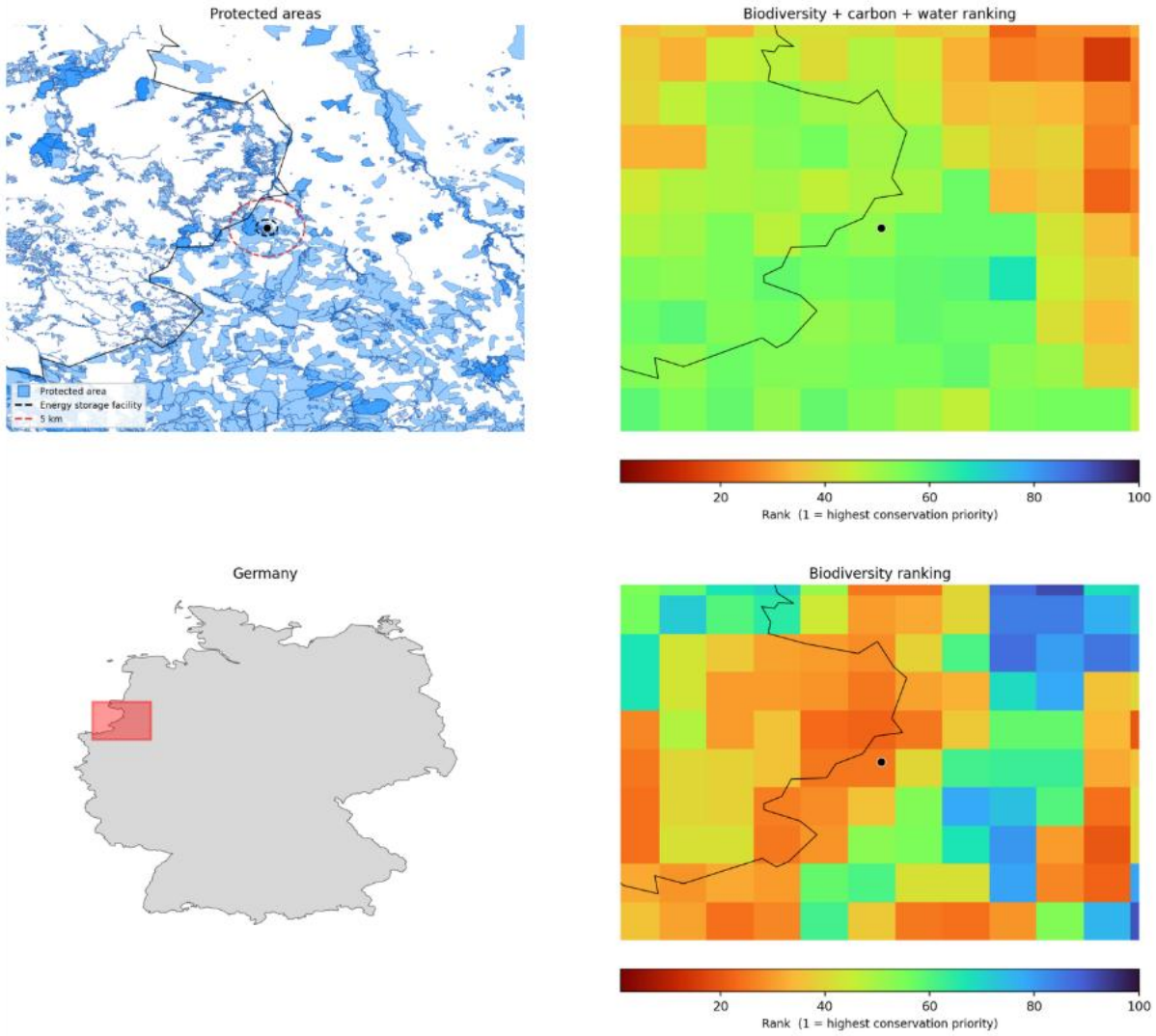


Figure 15 Spatial overview of environmental features within the landscape surrounding the storage facility. (A) protected areas in the wider study area, extracted from the WDPA (UNEP-WCMC & IUCN, 2026). (B) Combined biodiversity, carbon, and water conservation priority ranking. (C) Study area extent (red) within Germany (Dutch border). (D) Biodiversity-only conservation priority ranking (1–100).

A quantitative analysis of the environmental benefits arising from reducing the risk of leakage of stored commodities into landscape features such as these protected areas – as well as interspersed watercourses and farmland – would be highly speculative. However, qualitatively, it can be assumed that the risk mitigation as outlined in section 5.2.2 translates into benefits as far as the integrity and ecological condition of regional habitats is concerned.

What residents gain is **a lower probability of environmental damage to the land they farm and live on, and an independent record that separates operational effects from natural ones**, such as the drought-driven soil movement the analysis identified. This lower probability of damage will translate into local and regional benefits that can be attributed to ecosystem service values associated with the ecological integrity of areas protected for nature.

5.2.5 Other Beneficiaries

Five actors that fall outside the commercial four-tier hierarchy each draw a distinct benefit from the service.

SGW, the salt field owner and the legally obliged mine surveyor, gains a complementary and independent signal that strengthens the regulatory baseline its annual survey provides. The value to SGW lies between campaigns: the weekly Sentinel-derived maps cover the eleven months its own levelling does not, and provide an independent cross-check on its statutory measurements.

The City of Gronau gains a civic instrument that helps its role as interlocutor between operators and the public, and that reduces the burden of handling complaints and uncertainty. The solution works well because the Sentinel record is continuous and public and comes from an independent source.

The citizens' initiative BI-K gains genuine empowerment, as its formal partnership in the research cooperation is **the first time a citizens' association has been embedded as a scientific partner in a German mining project**, with a defined role in selecting surface objects for inspection and feeding local knowledge into the methodology. That role works directly on the Sentinel-based products, since the objects BI-K selects serve as ground reference for interpreting the satellite maps.

The Research Center of Post-Mining at THGA Bochum gains scientific output and funding, including the two peer-reviewed publications and the Uniper-funded REWE 2.0 follow-on that adds an artificial-intelligence layer to the workflow. Both the publications and the REWE research line are built on the Sentinel-1 archive.

The Bezirksregierung Arnsberg, the state mining authority, **gains a better-informed basis for its oversight of all ten cavern operators at the field** and an early view of a method that it may one day recognise as a complement to conventional compliance monitoring.

Taken together, these beneficiaries show that the service generates value well beyond the commercial chain, in the governance and oversight of the field and in the scientific and civic institutions around it.

5.3 Summary of Benefits

The benefits traced along the value chain can be summarised into the six categories. Several benefits appear under more than one heading, which reflects the integrated nature of the case rather than double counting.

5.3.1 Economic

Most of the economic benefit comes from risk mitigation rather than from new revenue, and the figures are estimated in different ways and with different degrees of confidence, so the figures are summarised in Table 1 and are not summed. For EFTAS the quantified line is the avoided commercial-data cost of €100,000 to €180,000 per year, alongside confidential revenue and a growing product line. For Uniper the quantified line is the avoided cost of a conventional monitoring programme delivering comparable information, €250,000 to €450,000 per year, attributed in full to the Sentinel data (Annex 2, Assumption 7). The probability-weighted incident analysis, around €52,000 per year within a range of €23,000 to €330,000, is shown alongside for context and not counted. The unquantified recurring gains, budget targeting above all, arise under either way of obtaining the information and are what make it worth procuring, rather than an addition to this number. Tier 3 holds a thin but real share of that protection, and Tier 4 carries no separate economic line: its value is captured under the societal and environmental headings. The free Sentinel-1 data make the whole chain financially possible, because they remove the data cost that would otherwise make a long-running, area-wide service economically unfeasible. Attribution is the same at both tiers: the avoided data cost at Tier 1 exists only if free Sentinel-1 data are withdrawn, and the avoided procurement cost at Tier 2 is attributed in full under the necessary-condition rule, because the service would not exist on paid data and the data alternative is already valued at Tier 1 (Annex 2, Assumption 5).

Table 1 Economic benefits by tier, with lower, baseline, and upper estimates and attribution

Actor	Economic benefit	Status and attribution
EFTAS (Tier 1)	€100,000–€180,000 per year estimated commercial replacement cost; baseline estimate €140,000; service revenue (confidential)	Quantified from current commercial tasking prices for this site; the cost exists only if free Sentinel data is removed
Uniper Energy Storage (Tier 2)	€250,000–€450,000 per year estimated cost of obtaining comparable information by conventional terrestrial means; baseline €350,000, attributed in full to the Sentinel data; budget targeting and evidence value as indicators	Modelled (Annex 2, Assumption 7), indicative unit rates pending validation; 100 per cent attribution under the necessary-condition rule, with the 50 to 60 per cent data share kept as a sensitivity (Assumption 5); indicators not yet monetisable
Uniper Energy Storage (Tier 2), supporting lens	≈ €52,000 per year expected avoided loss from major cavern incidents (€23,000–€330,000)	Probability-weighted model (Annex 2, section A2.3); reported for context, not summed with the replacement cost, since both value the same information

Customers and gas owners (Tier 3)	Fractional share of the protection of 16.9 TWh (≈ €500 to 900 million) of stored value	Exposure characterisation, not monetised; evidential rather than transactional link; a separate Sentinel-attributable flow is not modelled, to avoid double counting with the Tier 2 estimate

The rows are estimated in different ways and with different degrees of confidence and are not summed. EFTAS's service revenue is shown for completeness but left out of the totals, because Uniper pays it: it moves money between two tiers of the same chain rather than adding any. **Taken together, the annually recurring quantified benefit across the chain is of the order of €350,000 to €630,000 per year, with a baseline of around €490,000, combining the avoided commercial-data cost at Tier 1 and the avoided information-procurement cost at Tier 2, each valued against its own counterfactual. The €500 to 900 million of protected stored value stands behind those flows as the value at stake rather than as an annual benefit.** The future hydrogen de-risking benefit is excluded from the table. Tier 4 carries no counted economic line: what reaches citizens and society is transparency, trust, and a lower probability of environmental damage, which are set out under the societal and environmental headings below. A willingness-to-pay reference number for Tier 4, €5,000 to €47,000 a year, is given in section 5.2.4 and is not added to the totals.



- Tier 1: €140,000 a year avoided commercial-data cost (€100,000–180,000)
- Tier 2: €350,000 a year avoided terrestrial monitoring cost (€250,000–450,000), with €52,000 a year avoided incident loss as a supporting lens
- Tier 3: share of €500–900 million of protected stored value, not monetised
- Tier 4: willingness-to-pay reference of €5,000–47,000 a year, not summed

5.3.2 Environmental

The environmental benefit runs in two directions. The first is the earlier detection of subsidence and other surface effects that could signal developing risks before environmental damage occurs, particularly damage caused by the leakage of stored commodities. This concern was made concrete by the 2014 oil leak and is heightened by the mix of raised bogs, farmland, watercourses, groundwater and protected habitats above and around the field. The second is continuity: **the same monitoring carries over unchanged through the planned transition of the field to hydrogen storage**, keeping the movement record unbroken through the conversion. The supporting use of Sentinel-2 to map vegetation condition and relative soil moisture adds a further environmental dimension to the product.

Consistent with the SeBS360 approach, the environmental benefit is claimed through changes in management rather than attempting to quantify changes in the state of nature, which redirects both public concern and management attention towards the key issue of mitigating risks from leakage. The contribution runs to the management of risk to areas nationally important for biodiversity, as well as the incidental monitoring of the state of areas including two raised-bog reserves and the four watercourses. Specifically in relation to the environmental indicators outlined in the methodology, both are concerned with 'reducing harm to biodiversity', especially in the form of potential harm to specific high value areas for conservation (rated 1 – 3 on the SeBS360 environmental benefits scale, as these are potential benefits through avoided impacts only, though based on known incident occurrence, and highly significant if realised). The latter can also be considered to support efforts on 'reduction of pollution', through ongoing monitoring for divergence from the environmental baseline. The clearest documented information benefit is attributional: the analysis showed that **a substantial share of the observed subsidence signal was driven by drought-related soil dynamics rather than by cavern operations**.[32] The counterfactual makes the attribution clear. Annual levelling measures a fixed set of benchmarks and cannot separate a drought signal from an operational one across a 25-square-kilometre field, so the attributional finding, and the redirection of management attention that follows from it, would not exist without the Sentinel-based service.

- Reduced harm to biodiversity: earlier warning of leakage risks to the bogs, watercourses, and protected habitats
- Reduction of pollution: ongoing monitoring for divergence from the environmental baseline
- Drought, not cavern operations, shown to drive much of the observed movement
- Unbroken movement record through the planned hydrogen conversion

5.3.3 Regulatory

The current regulatory benefit is that the service complements, rather than replaces, the annual terrestrial survey required under the German Federal Mining Act. It provides operators and the mining authority with more frequent and spatially detailed information than the statutory baseline alone. According to Uniper, the mining authority has responded positively to this additional information during the company's annual meetings. **The German mine surveyors' association first proposed radar interferometry as a recognised technique in 2013 and issued revised professional guidelines in January 2025**, with a standardisation process under

[32] Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23.

way.[33] Gas storage is a critical entity under the European Union's resilience rules, and **the German implementing act in force since March 2026 obliges storage operators to run all-hazard risk assessments from 2027**, assessments that satellite ground-motion monitoring directly supports.[34] **Formal regulatory acceptance already exists elsewhere: the Dutch state supervision of mines accepts InSAR in statutory measurement plans, and Italian guidelines have specified InSAR for gas storage monitoring since 2014.** The continuous record also strengthens the evidence base for the permitting of the hydrogen expansion under its Project of Common Interest designation. The recognition process is driven by the profession rather than by any single site, and what the Sentinel-based work contributes is the evidence: a decade-long, peer-reviewed, area-wide record that conventional levelling cannot produce and that would not be affordable if the data had to be bought.

- Complements the statutory annual survey, welcomed by the mining authority
- DMV guidance revised in 2025, DIN standardisation under way
- All-hazard risk assessments required from 2027 under EU resilience rules
- InSAR already accepted in Dutch and Italian statutory monitoring

5.3.4 Innovation and Entrepreneurship

The case is a clear source of innovation. EFTAS combined the Small Baseline Subset method for rural land cover with a K-means spatiotemporal clustering step and a multi-criteria decision analysis weighted between ground movement and soil type, integrating more than fifteen open geodatasets into a single operational product.[35] **The participatory model is itself an institutional innovation**, the first embedding of a citizens' initiative as a scientific partner in a German mining project. The cooperation did not come from the satellite data, it grew out of the 2014 incident and the demand for transparency and independent monitoring that followed. The Sentinel-based service gave it a technical basis that the parties could afford and share. For EFTAS the entrepreneurial benefit is a new product line in underground energy storage monitoring that is transferable to other cavern fields, and the REWE 2.0 follow-on shows the methodology continuing to evolve. SAR-based ground-motion services already account for roughly a fifth of the company's business, and the stated trajectory runs from campaign-based

[33] Deutscher Markscheider-Verein (DMV), Grundsätze zur Anwendung der Radarinterferometrie: first edition 16 September 2013, revised edition January 2025. https://www.dmv-ev.de. A related DIN standardisation process has been under way since around 2020.

[34] Directive (EU) 2022/2557 on the resilience of critical entities, implemented in Germany by the KRITIS-Dachgesetz, in force 17 March 2026, with risk assessments obligatory from 2027. For formal acceptance of InSAR elsewhere: Staatstoezicht op de Mijnen (Netherlands) accepts InSAR in statutory measurement plans, and the Italian ILG guidelines (2014) mandate InSAR for gas storage monitoring.

[35] Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23.

studies towards continuous site monitoring and a subscription product with weekly updates, with interest from other operators. The first spillover has arrived in the form of an invitation to a nearby ground-damage case won specifically on the Epe reference. None of this is attributable to conventional monitoring. The processing chain, the product line, and the participatory model were all built around a free, weekly, area-wide radar archive, and EFTAS states that the service would not be economically viable if that archive had to be procured commercially.



- SBAS, K-means clustering, and multi-criteria attribution across 15+ open geodatasets in one product
- A new EFTAS product line, with a first invitation won on the Epe reference
- A citizens' initiative as scientific partner, on a technical basis made affordable by free Sentinel data

5.3.5 Science and Technology

The scientific and technological benefit is well documented. The methodology is set out in two peer-reviewed papers in the journal Mining and has been presented at INTERGEO 2025 and the 13th Deutsches GeoForum.[36] **Independent validation exists as well**: a separate research group resolved the site's displacement field with Sentinel-1, separated cavern convergence from an operational pressure-cycle response of up to plus or minus 6 millimetres and from groundwater-driven soil dynamics, and showed good agreement with the mine surveyor's levelling.[37] The work advances the practical state of the art in applying InSAR to underground storage on mixed rural land cover, in particular the decomposition of motion into vertical and horizontal components from ascending and descending tracks and the attribution of movement to operational or environmental drivers. The service is also positioned for the next generation of Copernicus, with ROSE-L offering L-band data that should improve the separation of vegetation-related and ground motion, and CHIME adding hyperspectral capability to the vegetation and soil work now done with Sentinel-2. The REWE research line, the two publications, and the independent validation all draw on the Sentinel-1 archive, and no alternative dataset offers a decade of consistent, freely available coverage over which retrospective analysis of this kind could be run.

[36] Rudolph, T., Goerke-Mallet, P., Homölle, A., Müterthies, A., Perrevort, H., Teuwsen, S., Yang, C.-H. (2024). 'Participatory Geomonitoring for Future Mining—Resilience Management in the Cavern Storage Epe (Germany)'. Mining 4(2):230–247. doi:10.3390/mining4020014. Rudolph, T., Pawlik, M.P., Yang, C.-H., Przyrowski, R., Müterthies, A., Teuwsen, S., Hegemann, M. (2026). 'Application of K-Means Clustering for the Analysis of Horizontal and Vertical SBAS-InSAR Ground Movement Data Above Europe's Largest Underground Cavern Gas Storage Gronau-Epe'. Mining 6(1):23.

[37] Even, M., Westerhaus, M., Simon, V. (2020). 'Complex Surface Displacements above the Storage Cavern Field at Epe, NW-Germany, Observed by Multi-Temporal SAR-Interferometry'. Remote Sensing 12(20), 3348. doi:10.3390/rs12203348.

- Two peer-reviewed papers in Mining, presented at INTERGEO 2025 and the 13th Deutsches GeoForum
- Independent validation against the mine surveyor's levelling
- REWE 2.0 (2026/2027) adds an AI layer and the 2024 3D seismic survey

5.3.6 Societal

The societal benefit is the most distinctive feature of the case. **The participatory geomonitoring cooperation rebuilds trust between operators and a community marked by the 2014 oil leak**, gives residents an independent and continuous record of what is happening beneath them, and translates technical data for non-specialist audiences through public events, an excursion, and an award-winning school project. The public survey confirms the demand: 59.1 per cent of responding citizens wanted more information about the research cooperation. In a cross-border community on the German-Dutch frontier, the service demonstrates that satellite data can serve not only the operator who pays for it but also the public that lives above the asset. The shared movement record gives the operator, researchers, public authorities and residents a common reference point for communicating evidence and discussing different interpretations, an accountability benefit that conventional mine surveying does not provide. Without free and open Sentinel data that record would in all likelihood not exist in this form: a service run on commercial data, paid for by the operator alone, would have been neither affordable for a public cooperation nor as readily shared.

A second societal strand is strategic. Underground storage is a pillar of European security of gas supply, an obligation further emphasised by the EU Gas Storage Regulation's filling targets,[38] and in a stress winter the macroeconomic value of stored gas is measured in hundreds of millions of euros per terawatt-hour (Annex 2, Assumption 6). **Monitoring that protects the availability and the public acceptance of Europe's largest cavern storage field therefore carries a strategic value** that this report highlights. Statutory levelling produces a handful of benchmark readings a year, reported by the operator and not published, so the public visibility on which the entire participatory arrangement rests is attributable to the Sentinel-based service.

- Public, independent movement record at monitoring-epe.de
- 59.1% of surveyed citizens wanted more information
- Protects the availability and acceptance of Europe's largest cavern storage field

[38] Regulation (EU) 2022/1032 of 29 June 2022 amending Regulations (EU) 2017/1938 and (EC) No 715/2009 with regard to gas storage. Sets minimum filling targets of 90% for underground gas storage in EU Member States.

6. Key Findings and Final Thoughts

6.1 Key findings

The wide, free, and repeatable coverage of Sentinel-1 is enabling a chain of practical value over Europe's largest underground cavern gas storage field. Radar acquisitions accruing weekly are processed by a specialist provider into an area-wide picture of ground movement, decomposed into vertical and east-west components on a 30-metre grid. **That information serves two audiences**: an operator managing the integrity of 39 caverns holding 16.9 terawatt-hours of working gas, and a community that lives above the field.

In most cases analysed under SeBS and SeBS360, the value of Sentinel data runs down a single commercial path. Here the same data feed two. One is commercial, the recurring assessments Uniper commissions and embeds in its per-cavern integrity thinking. The other is civic, the first research cooperation in German mining to embed a citizens' initiative as a scientific partner. The two reinforce each other: the cooperation gives the operator transparency and social licence, and the operator's commissions keep the methodology funded.

The economic evidence is strongest and most specific at the service-provider tier, where free Sentinel-1 data displace a commercial data cost of the order of €100,000 to €180,000 per year. At the primary-user tier the service replaces information that would cost an estimated €250,000 to €450,000 per year to obtain by conventional terrestrial means, attributed in full to the Sentinel data. A supporting probability-weighted estimate of avoided incident losses, around €52,000 per year within a range of €23,000 to €330,000, is reported alongside but not counted (section 6.3). Unquantified but tangible benefits furthermore include better-targeted integrity budgets, the evidence value of movement records, and the availability value of the storage capacity. The service furthermore helps protect an exposure of €500 to 900 million of stored gas, and the availability of a strategic asset, which explains why the operator commissions the work. That protection is shared with the operator's other integrity instruments: within the supporting incident analysis, the share of detection capability carried by ground-movement monitoring is put at 40 to 50 per cent (Annex 2, Assumption 5), and the €500 to 900 million describes the value at stake rather than a benefit of the service. There is no established rule for how much an operator should spend to protect a value of this size. Insurance pricing is the nearest benchmark: commercial property premiums in the United States run at roughly 0.3 to 0.8 per cent of the insured value per year,[39] and large, well-protected industrial risks are priced below that. The fee Uniper pays EFTAS, roughly a tenth of the conventional cost, is well under 0.01 per

[39] Insureon, How are commercial property insurance premiums calculated, https://www.insureon.com/small-business-insurance/commercial-property/how-premiums-are-calculated, accessed October 2026: base rates of $0.30 to $0.80 per $100 of coverage.

cent of that exposure, and even the costed conventional programme at €350,000 a year would stay below 0.1 per cent.

6.2 The impact of sentinel data

As in most cases analysed under SeBS and SeBS360, the question of attribution arises: what part of the produced benefit can be attributed to the use of Sentinel data? Sentinel data have an impact on this case in three respects. First, the free and open data policy is the enabling condition of the service. EFTAS states plainly that the service would not be economically viable without it, and no commercial C-band alternative offers the same combination of weekly revisit, dual viewing geometry, and a continuous archive. A like-for-like commercial replacement is procurable in principle, but at a data cost of the order of €140,000 per year (Annex 2, Assumption 1) it would consume the economics of a long-running, area-wide product.

Second, the technical characteristics of Sentinel-1 are the foundation of what the service can see. Wall-to-wall coverage measures the bogs, farmland, and reserves at the same density as the built-up areas, where the free public persistent-scatterer services return too few points to be useful. The combination of ascending and descending tracks separates vertical from east-west horizontal motion, and the horizontal component, invisible to terrestrial levelling, matters greatly for the user as this movement directly affects sub-surface infrastructure like pipelines. **The archive, more than 760 scenes reaching back to December 2015, lets the movement history of any location be reconstructed on demand**, which matters when assessing causation.

Third, attribution is higher than in most cases analysed under SeBS and SeBS360: it reaches 100 per cent for the deformation information itself, and 40 to 50 per cent within the operator's wider integrity decisions. **For the deformation information itself there is no practical alternative at this site**. Within the operator's wider decision-making the contribution is deliberately discounted to 40 to 50 per cent, since wellhead pressure monitoring, seismic surveillance, and the statutory levelling inform the same decisions. Sentinel-2 plays a supporting role, supplying the vegetation and soil-moisture layers that help separate operational from environmental drivers of movement. In short, the data are a full substitute at the level of procurement, a 40 to 50 per cent contributor within the operator's integrity decisions, and an indirect, unquantified contributor beyond Tier 2. The counted Tier 2 estimate therefore carries 100 per cent attribution, following the necessary-condition rule applied in the Norway and Greenland cases: the service would not exist without the free data, and the alternative data purchase is already valued at Tier 1. The earlier practice of discounting the replaced programme's value to the 50 to 60 per cent carried by the data rather than by EFTAS's processing is kept in Annex 2, Assumption 5 as a sensitivity, and the supporting incident analysis applies only the 40 to 50 per cent detection-

portfolio share. No quantitative societal benefit is claimed for Sentinel: the trust generated by the participatory cooperation owes as much to the actors' engagement work as to the data.

6.3 Interpretation of results: key assumptions and limitations

The results in this chapter rest on a set of explicit choices and assumptions that should be flagged, and they carry different degrees of confidence. The first is the relationship between the two economic framings used in chapter 5. **The exposure framing, €500 to 900 million of stored value, is not a benefit estimate**: it describes what is at stake, and it explains the operator's approach to monitoring. The benefit estimate at Tier 2 is the avoided cost of a conventional programme delivering comparable information, €250,000 to €450,000 per year, attributed in full to the Sentinel data (Annex 2, Assumption 7). The probability-weighted incident analysis, around €52,000 per year, is reported for context and not counted, to avoid valuing the same information twice. The Tier 1 and Tier 2 estimates are each valued against their own counterfactual, a commercial-data purchase by EFTAS at Tier 1 and a terrestrial procurement by Uniper at Tier 2, and the combined order of magnitude in section 5.3.1 should be read with that in mind.

The avoided commercial-data cost at Tier 1 is built bottom-up from current commercial tasking prices for the Uniper site (Annex 2, Assumption 1). The direction is confirmed by EFTAS's own statements, that the service is not viable without free data and that acquiring equivalent information by conventional means would cost an order of magnitude more.

The incident-frequency and consequence inputs are the best-evidenced parts of the model, drawn from a peer-reviewed worldwide census and from documented incidents, and cross-checked against the site's own history. Their limitations are stated in Annex 2: the frequency estimates answer different definitions of an incident, and the consequence estimates come partly from other jurisdictions and other decades.

The detectability-and-reduction assumption is based on transferred evidence and expert judgement. Some slow-developing failure mechanisms may produce surface deformation that InSAR could help identify, and precursory deformation was detected retrospectively before the Bayou Corne collapse. However, the 2014 Epe leak was first identified through a wellhead pressure drop, and the available evidence does not demonstrate that Sentinel-based monitoring would have detected or prevented it. **No incident at Epe has yet been averted through the service. The model therefore estimates a potential expected risk reduction rather than an observed avoided loss.**

The analysis assumes continuity of the Sentinel-1 constellation. The failure of Sentinel-1B in 2022 showed that this cannot be taken for granted: a single-satellite constellation halves the acquisition cadence and weakens the dual-geometry decomposition on which the horizontal component depends. The launches of Sentinel-1C in December 2024 and Sentinel-1D in 2025

restored the constellation, and Sentinel-1 Next Generation is expected to carry the capability into the 2030s.[40]

In terms of robustness, the most solid result is the avoided commercial-data cost at Tier 1: it is built from observed tasking prices for this site, and it holds for the weekly, dual-geometry specification costed here. The replacement-cost estimate at Tier 2 depends on the specification of the counterfactual programme and on indicative unit rates, and both should be validated against SGW's campaign costs and market quotes. The supporting incident analysis carries wide uncertainty, from around €23,000 to around €330,000 per year, driven by the incident base rate, the consequence cost per incident, and the detectability share. The 40 to 50 per cent attribution share within the operator's decision-making is an interview-based judgement rather than a measured quantity. The societal and regulatory findings are informed qualitative judgements based on interview material and the public record, not measured outcomes against a quantified counterfactual. The environmental findings are similarly framed to societal and regulatory findings, and are informed qualitative judgements, although do build upon data extraction for regional biodiversity values. All results are specific to this site. How far they transfer to other cavern fields is a question for chapter 7, not a claim made here.

6.4 Final thoughts

This case extends the thesis running through the cases analysed under SeBS and SeBS360 in a direction the portfolio has not covered before. Earlier cases analysed under SeBS and SeBS360 have documented the commercial value that freely available Sentinel data, processed by a capable downstream provider, generate for an operator. That the same data can be **placed at the technical core of a formal partnership between a city, a citizens' initiative, a university, and a company, and can help convert a damaged relationship between an industry and the community into a documented model of participatory monitoring, is new**. The most distinctive value in this case is civic, and this is not reflected in the quantitative assessment.

Chapter 7 covers the next question: whether formal recognition of radar interferometry arrives, and how far it would carry the benefits documented here beyond Epe.

6.5 How does this case relate to others

The case sits within a small but growing family of SeBS analyses that apply Sentinel-1 radar interferometry to ground motion problems. Ground Motion Monitoring in Norway examined the use of the nationwide InSAR Norway map by the Norwegian Public Roads Administration for road

[40] European Space Agency. Sentinel-1 Mission. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1. Sentinel-1A launched 3 April 2014; Sentinel-1B (April 2016, ended in orbit 2022); Sentinel-1C launched 5 December 2024; Sentinel-1D launched 2025.

design and maintenance, and is the closest methodological precedent, including its finding that attribution can reach 100 per cent where no practical alternative to the satellite information exists. Infrastructure Monitoring in the Netherlands assessed the use of Sentinel-1 by gas and water utilities around Rotterdam and Gouda to plan pipeline replacement against severe subsidence. Ground Motion Intelligence in Romania, a short report from 2023, captured the use of Sentinel-1 to characterise landslides next to a Romanian mining operation, and comes closest to this case in its liability and attribution questions. Global Oil Industry Activity Monitoring, which examined Sentinel-1 measurements of crude oil tank-roof heights, provides a precedent in the energy storage context, although the application there is commercial market intelligence rather than physical infrastructure monitoring.

The quantified precedents place this case in context. **The Netherlands case remains the closest published benchmark, with national benefits of €15.2 million to €18.3 million per year** and around 30 per cent of the value attributed to Sentinel-1. Motorway Maintenance in Portugal quantified €2.5 million to €3.6 million per year for a Sentinel-1 and Sentinel-2 service extrapolated across the national motorway network. The two aquifer cases in Spain, Murcia and Catalonia, applied the same Sentinel-1 interferometry to groundwater-driven subsidence and carry the largest quantified benefits in the ground-motion family, at €31.7 million to €71.8 million and €11 million to €22.2 million per year respectively.[41] Across the SeBS portfolio the regulatory dimension tends to dominate infrastructure cases. **This case differs from that pattern: the regulatory benefit is today a complement to the statutory baseline, while its distinctive strengths lie in risk-mitigation economics and in a societal dimension that no earlier ground-motion case covers.**

Three features set this case apart from those earlier studies. First, **it is the only one to apply Sentinel-1 interferometry to an underground installation**, and the only one where ground motion is the direct operational consequence of injection and withdrawal cycles managed by the user. Second, the rural land cover at Gronau-Epe forces the use of Small Baseline Subset processing rather than Persistent Scatterer Interferometry, which makes the case methodologically different from the Norway and Netherlands precedents. Third, the participatory research cooperation around monitoring-epe.de extends the value chain into a public-trust dimension that has no equivalent in earlier reports.

[41] EARSC SeBS case reports. https://earsc.org/sebs. Figures taken from the published case reports for the Netherlands, Portugal, Murcia and Catalonia cases.

7. Widening the perspective

7.1 Geographic extrapolation

The mechanism at the heart of this case, free, wide-area, repeatable radar data used to monitor ground movement above underground storage, is geographically general. **It transfers to any cavern field with a similar geological setting**, and the conditions that make it valuable at Gronau-Epe, slow but consequential deformation, mixed rural land cover that defeats persistent-scatterer methods, and assets and people above the field, recur across the salt basins of northwestern Europe.

Germany is the natural first ring of extrapolation. It has more cavern storage than any other European country, with roughly two thirds of its roughly 260 terawatt-hours of gas storage capacity in salt caverns,[42] and the candidate fields are well known: Etzel, Krummhörn, Bernburg, Bad Lauchstädt, and the other fields of the North German basin. Uniper's position at Epe is roughly a tenth of German cavern capacity. A simple scaling of the Tier 2 baseline estimate across the German cavern fleet produces an illustrative figure of around €2.6 to €4.6 million per year. This is an illustrative scenario rather than a national benefit estimate, as it assumes that every field would otherwise procure comparable terrestrial monitoring and that network sizes and campaign costs match Epe's.

The second ring is European and global. Salt-cavern storage operates in the Netherlands, the United Kingdom, France, Denmark, Poland, and Portugal, the hydrogen-storage projects designated across the Union carry the same monitoring logic, and EFTAS has flagged interest in markets beyond Europe. Sentinel-1's global, free coverage means the same economics travel with the method.

7.2 Administrative and institutional transferability

Institutionally, the case demonstrates a governance model as transferable as the technology. One field-wide, operator-independent dataset serves an operator's risk management, a salt-field owner's statutory reporting, a mining authority's oversight, and a community's demand for transparency at once. At Epe this emerged from a specific history, but nothing in the arrangement is site-specific: a city, a citizens' initiative, a university, and a provider can sign the same kind of cooperation over any monitored field, and the Epe cooperation is documented in the peer-reviewed record precisely so that it can be copied.

For authorities, the case offers a template for the oversight of multi-operator fields. The Bezirksregierung Arnsberg participates in an advisory capacity today, and its counterparts in

[42] Initiative Energien Speichern e.V. (INES). Gas Storage Capacities. https://energien-speichern.de/en/gas-storage/gas-storage-capacities.

other German states supervise comparable fields. Section 5.3.3 sets out the two drivers that matter here: the all-hazard risk assessments that storage operators must produce from 2027, which create an administrative demand channel for exactly the kind of evidence this service produces, and the Dutch and Italian precedents, which show what formal acceptance of InSAR within statutory monitoring looks like.

The cavern field straddles the German-Dutch border, and the national ground-motion services on either side stop at it. A service built directly on Sentinel-1 does not, which makes cases like this one an argument for harmonised, cross-border monitoring of shared subsurface systems, a point of direct relevance to the European Ground Motion Service.

7.3 Improved market and user uptake

Within the case itself, the growth trajectory is stated by the primary user. Uniper, which has commissioned these assessments, foresees extending them to cover all of its storage locations within four to five years. EFTAS has similar ambitions, to develop a subscription service with weekly updates, delivered through established workflows in which new data are processed automatically to a dashboard. Interest is not confined to one operator: the field's monthly operators' meeting has begun to engage with the geoscience results, and other storage operators have shown interest in the approach.

The adoption conditions are practical: a robust web-based service that is easy to use, costs that are low and predictable, and results from a complex process made accessible to non-specialist users. The structural barrier is familiar: regulation lags behind technology, **monitoring budgets will become available when a technique is recognised in the regulatory framework**, and until then adoption rests on voluntary, risk-driven commissioning of the kind Uniper has practised at Epe for a long time.

The growth markets are visible. **The European hydrogen build-out will add to the number of cavern facilities that need monitoring**, and the number of post-operational caverns with long-term surveillance obligations will grow substantially as fields age.

7.4 Technological evolution and future service development

The service's next technical step is already commissioned. The 2026/2027 follow-on work described in section 5.2.2 moves **the methodology from describing movement towards explaining it cavern by cavern**.

A further potential development identified by Uniper is the integration of multiple datasets within a digital-twin or data-cube environment. Uniper described this as combining InSAR-derived ground movement with soil, geology and seismicity data, and potentially meteorological and in-

situ information, to identify relevant patterns across datasets that cannot be handled manually. In this concept, Sentinel-1 would provide the area-wide ground-movement layer, while the other datasets would help assess whether observed movement is associated with cavern operations or external influences such as soil moisture. The resulting information could support decisions about which caverns warrant further investigation.

The Copernicus Sentinel Expansion Missions are directly relevant to this case.[43] ROSE-L, under construction for launch around 2028 to 2029, adds an L-band radar whose longer wavelength penetrates vegetation and senses soil moisture, which addresses head-on the two constraints that shape the current service: the rural land cover that forces the more demanding processing method, and the soil-moisture noise that must be separated from cavern-induced motion. Combined C-band and L-band acquisitions would improve that separation significantly. CHIME, the hyperspectral imager planned for around 2030, extends the vegetation and soil analysis now done with Sentinel-2 and opens a path to methane monitoring around storage installations, for which the EnMAP precursor is already in orbit. Sentinel-1 Next Generation secures the continuity of the C-band ground-motion record into the 2030s, highly relevant for a service whose value grows with its archive.

A final, forward-looking point comes from the case's own history. The specification of one of Sentinel-2's bands was driven by mining-sector users, RWE and RAG, in a 2011 mining research project, to detect subsidence-induced vegetation damage, and the sector's engagement with ROSE-L and CHIME requirements can play the same role for the next generation. The users in this case both benefit from the Sentinels and help set the requirements that will shape their successors.

7.5 Extrapolation of the benefits

The preceding sections describe how the service could expand. This section looks at the same question from the benefits side: which of the benefits found at Epe would transfer, and how reliably.

The Tier 1 replacement-cost benefit transfers where a new site requires a comparable frequent, dual-geometry and area-wide radar service. However, the Epe estimate of €100,000 to €180,000 per year should not be multiplied automatically by the number of fields. Scene coverage, acquisition frequency, viewing geometry, shared processing infrastructure and economies of scale would need to be assessed for each deployment. Confidence in the existence of this

[43] European Space Agency. Copernicus Sentinel Expansion Missions, including ROSE-L (L-band SAR) and CHIME (hyperspectral imager). https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Copernicus_Sentinel_Expansion_missions.

benefit is high where comparable service specifications apply, but its magnitude must be recalculated for each site.

The Tier 2 information-replacement benefit transfers where an operator would otherwise need a comparable terrestrial monitoring programme, and its magnitude must be re-estimated for each site, since network size, campaign frequency, and land cover differ. The supporting incident analysis transfers only where surface movement is relevant to cavern or infrastructure integrity, and the illustrative German scaling in section 7.1 assumes that every field would otherwise procure comparable monitoring, with comparable network sizes and campaign costs. These assumptions would require revalidation at each field. Confidence in the direction of the benefit is moderate, while confidence in its extrapolated magnitude is low.

The environmental benefit transfers where cavern-related (and other similar) movement interacts with environmentally sensitive land surface features, groundwater conditions, agricultural soils or protected habitats, and where the resulting information is used to guide investigation or management. The attributional finding set out in section 5.3.2 is the part that generalises. However, the relative importance of these drivers is site-specific and cannot be transferred without local geological, hydrological and land-cover information. Confidence in the informational benefit is moderate; no generalised avoided-damage benefit is claimed.

The regulatory benefit transfers where InSAR is recognised as an accepted complement to existing statutory monitoring or all-hazard risk assessment. The pathway and the existing precedents are set out in section 5.3.3. The institutional principles of the Epe cooperation are also transferable, but implementation depends on local authority roles, funding, data-sharing arrangements and stakeholder participation. Confidence is moderate and depends primarily on regulatory recognition and institutional adoption.

The societal benefit transfers where communities seek clearer, independently interpretable information about movement beneath inhabited or environmentally sensitive areas, and where an organisation is willing to communicate the results transparently. At Epe, the benefit was strengthened by the field's particular history and by the participation of the city, the citizens' initiative, researchers and EFTAS. The technical platform can be replicated, but the resulting trust and engagement cannot be assumed to arise automatically at another site. Confidence in technical transferability is high, while confidence in equivalent societal outcomes is moderate and context-dependent.

The innovation and entrepreneurship benefit transfers with the provider rather than with the site. The processing chain, the attribution layer that separates operational from environmental drivers, and the WebGIS delivery platform are reusable assets, so the second and subsequent deployments cost less than the first and the capability travels wherever the provider does. What does not transfer automatically is the market. Uptake depends on regulatory recognition and on operators holding a monitoring budget, the same barrier described in section 7.3, and a

competent downstream provider has to exist in the target country. Confidence that the capability transfers are high, while confidence in the pace of commercial uptake is low.

The science and technology benefit transfers where a research partner and an operator are willing to work on the same data. At Epe the decisive ingredient was the arrangement rather than the geology: a funded research line, an operator prepared to open its operational data, and an archive long enough to support retrospective analysis. The first two are institutional choices that any field could make, and the third comes with Sentinel-1 everywhere. The methodological results themselves, the decomposition of motion from ascending and descending tracks and the separation of operational from environmental drivers, are published and are therefore available at a new site without being earned again. Confidence in the methodological transfer is high, while confidence that a comparable research partnership form is moderate and depends on local institutions.

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Annex 2: General Approach, Methodology and Economic Model

A2.1 The SeBS360 approach

This case has been analysed within the Sentinel Benefits Observatory (SeBS360), which continues the methodology developed under the Sentinel Benefits Study (SeBS).[44] For each case a value chain is defined that begins with the service provider (Tier 1) and the primary user (Tier 2) and follows the value through subsequent tiers to citizens and society. Benefits are assessed against six dimensions, economic, environmental, regulatory, innovation and entrepreneurship, science and technology, and societal, and for each benefit the assessment identifies the stakeholder, the mechanism, the indicator or proxy, the evidence, and the attribution to Sentinel data. Assumptions are stated, kept conservative, expressed as ranges rather than point values.

The economic analysis is a value-of-information exercise, and its counterfactual is layered. The first step is the regulatory baseline, the annual terrestrial levelling delivered by the mine surveyor, which is annual, vertical only, and covers a very small share of the field. The second step is the free public layer, the BodenBewegungsdienst Deutschland and the European Ground Motion Service, but their standard processing needs fixed structures to measure against, and over the fields and bog of the cavern field they return too few measurement points to be useful. The third step is the EFTAS service itself. **Value is claimed only for the increment that each step adds**, and principally for the increment of the dedicated service over the public layer.

The framework for valuing that increment follows the value-of-monitoring literature, in which **continuous or area-wide monitoring should be compared with intermittent inspection, not with a complete absence of information**.[45] Monitoring then creates value through three channels: earlier detection of developing anomalies, avoided or better-targeted inspection effort, and better-timed intervention. These are the channels through which the assessments in chapter 5 are organised.

A2.2 Economic model and assumptions

The economic assessment takes six assumptions.

Assumption 1, avoided commercial-data cost (Tier 1). The counterfactual data source for a weekly, dual-geometry radar service is commercial SAR. Two SeBS precedents show the order of magnitude: the Netherlands pipeline case carried around €60,000 per year of TerraSAR-X data

[44] EARSC (2024). SeBS Methodology: A Practical Guide for Practitioners, Version 2, July 2024. https://earsc.org/sebs.

[45] Kamariotis, A., Chatzi, E., Straub, D. (2023). 'A framework for quantifying the value of vibration-based structural health monitoring'. Mechanical Systems and Signal Processing 184, 109708. doi:10.1016/j.ymssp.2022.109708.

cost per utility service, and the Portugal motorway case valued the avoided commercial acquisition at around €60,000 per year.[46] The estimate is nonetheless built bottom-up for this site. The requirement is 104 single-look complex scenes per year, the interferometry-grade image product, 52 weeks in two viewing geometries, with one TerraSAR-X StripMap scene of 30 by 50 kilometres covering the field and its surroundings. At marketplace tasking prices of around €1,750 per scene, the like-for-like cost is of the order of €180,000 per year, or €125,000 to €145,000 with the 20 to 30 per cent multi-year volume discounts customary in SAR procurement, and the cheapest openly priced new-space alternative implies around €145,000 per year. A less performant approach at an 11-day repeat costs around €115,000 per year in two geometries, or just under €60,000 in a single geometry, at the price of losing the horizontal component: this was the approach in previous SeBS cases. **Adopted range: €100,000 to €180,000 per year, average €140,000**, for a like-for-like weekly dual-geometry service. The ten-year archive is treated separately: it cannot be procured/tasked retroactively over this site, and it is stated qualitatively rather than monetised. This sits alongside, and must not be confused with, the enabling condition that EFTAS states plainly: **without free and open Sentinel-1 data the service would not be economically viable at all.**

Assumption 2, incident frequency (Tier 2). The model needs the rate at which a major well-integrity incident happens at one cavern in one year. Three sources bear on it, and each is published in a different unit, so the table below restates them on the common basis of incidents per 100,000 cavern-years. The first is the worldwide census of storage-cavern leakages. The second is the United States national estimate, which counts every reportable incident rather than major ones only. The third is the site's own history at Gronau-Epe.[47][48]

Source	As published	Per 100,000 cavern-years
Worldwide census of storage-cavern leakages	About 2 major casing-leak incidents per 10,000 cavern-years, with the severe-consequence subset about a quarter of that	20 major, about 5 severe
United States national estimate	About 1 reportable incident per 1,000 well-years, at any severity	100
Gronau-Epe site history	One serious containment loss in roughly 50 years, in a field that has grown to 114 caverns	22 to 25

[46] EARSC SeBS case reports: Improving Maintenance of Pipeline Infrastructure in the Netherlands (2016) and Motorway Maintenance in Portugal (2024). https://earsc.org/sebs. TerraSAR-X marketplace tasking and archive prices: UP42, https://docs.up42.com, accessed July 2026. Umbra open price list: https://umbra.space/pricing, accessed July 2026.

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[48] Li, Z. et al. (2022). 'A national estimate of U.S. underground natural gas storage incident emissions'. Environmental Research Letters 17, 084013. Around 0.027 reportable incidents per facility-year and about 1 per 1,000 well-years across 387 US facilities, 1940 to 2016.

Each rate is then reduced by a factor of 0.6 to 0.8 for modern completion and monitoring practice. A stronger double-barrier adjustment is not applied, because the retrofit the mining authority mandated after 2014 covers the Epe oil caverns, while the 39 caverns modelled here store gas. Applying the midpoint of 0.7 to the worldwide census rate gives the value used as the baseline, 14 major incidents per 100,000 cavern-years. The site's own history gives 13 to 20 on the same adjustment, which is in line with it.

The scenarios in section A2.3 use 10 at the low end and 70 at the high end. The low end is the site history under a stronger completion adjustment of 0.3 to 0.5. The high end is the United States rate after the same 0.7 adjustment, and it is high because it counts incidents of any severity. The severe-only lower bound of 3 per 100,000 cavern-years is not carried into the scenarios, because pairing it with the severe consequence anchor of Assumption 3 would discount the same severity twice.

Assumption 3, consequence cost per incident (Tier 2). The consequence of a serious incident is assessed based on the components identified by Uniper: loss of access to the cavern, recovery of cushion gas, water injection and plugging and abandonment through a roughly 1,000-metre production string, remediation, and the loss of the storage capacity as lost business (Table below). Three benchmarks further back up the assumptions: the 2014 Epe S5 remediation alone reached a double-digit million-euro figure (section 2.3), the Moss Bluff cavern fire of 2004 cost around 50 million dollars, roughly €60 to 80 million in 2026 prices, including the loss of 1.8 terawatt-hours of gas, and the Bayou Corne collapse generated verified costs in the €200 to 350 million range. **Adopted value: €60 million per incident**, with the collapse case treated as an outlier. The single figure is used in all three scenarios of the A2.3 table.

Component	Basis	Order of magnitude
Lost working gas	Around 430 gigawatt-hours per average Epe cavern (16.9 TWh across 39 caverns), valued at €30 to 45 per megawatt-hour	€13 to 20 million
Unrecoverable cushion gas	Cushion gas is roughly 25 to 35 per cent of the gas in place, around 150 to 230 gigawatt-hours per cavern	€5 to 8 million
Remediation	The 2014 S5 precedent: a double-digit million-euro clean-up over more than 2.5 years (section 2.3)	€10 to 25 million
Plugging and abandonment	A roughly 1,000-metre cavern well with large-diameter casing, brine displacement, and long-term monitoring obligations	€0.5 to 2 million

Repair or replacement	Heavy workover of the casing and liner; a replacement cavern takes around two years of leaching and capital expenditure in the tens of millions	€1 to 5 million
Lost storage business	Around 430 gigawatt-hours at the capacity value of Assumption 6, over an outage measured in 2-3 years (S5 cavern precedent)	€6 to 8 million

The bottom-up assessment above and the inflation-adjusted Moss Bluff benchmark match up to approximately €60m.

Assumption 4, detectability and consequence reduction (Tier 2). Not every failure can be attributable to surface-deformation. The 2014 Epe leak announced itself first through a wellhead pressure drop three weeks before oil surfaced, and its mechanism, casing strain induced by subsidence, is exactly the type of slow-developing process that area-wide deformation monitoring could detect. Ground deformations were also measurable (retrospectively) by radar interferometry before the Bayou Corne collapse.[49] Sudden mechanical failures, by contrast, offer no deformation warning. The model therefore assumes that 60 to 70 per cent of incident types develop slowly enough to be visible, reflecting that the documented failure mechanisms at this site belong to the slow-developing type the monitoring is designed to see, and that earlier and better-resolved detection reduces the consequence of those incidents by 40 to 60 per cent, based on the more than six weeks that passed in 2014 between the first pressure anomaly and the discovery of oil at the surface. Combined detectability-and-reduction factor: 25 to 40%, baseline value 35%.

Assumption 5, attribution. Two attribution questions arise and they are kept apart. The first is the contribution of ground-motion monitoring within Uniper's wider detection portfolio, which also contains wellhead pressure monitoring, seismic surveillance, and the statutory levelling: 40 to 50 per cent is assumed. It applies to the supporting incident analysis of section A2.3 only, where the benefit is a decision outcome rather than a piece of information. The second is how much of the delivered service depends on the free Sentinel archive as distinct from EFTAS's processing and the ancillary data it brings in. The counted Tier 2 estimate (Assumption 7) attributes the avoided procurement cost in full to the Sentinel data, following the necessary-condition rule used in earlier SeBS cases where no practical alternative exists: EFTAS states that the service would not be commercially viable on paid data, no other source delivers wall-to-wall dual-component coverage at this site, and the commercial-data alternative is already valued at Tier 1, so a second discount would count the processing chain twice. As a sensitivity, a 50 to 60

[49] Jones, C.E., Blom, R.G. (2014). 'Bayou Corne, Louisiana, sinkhole: Precursory deformation measured by radar interferometry'. Geology 42(2), 111 to 114.

per cent data share would reduce the Tier 2 estimate to €125,000 to €270,000 per year (around €190,000) and the incident line to €12,000 to €200,000 per year (around €29,000).

Assumption 6, value of storage capacity. The adopted range is €1.4 to €15 per megawatt-hour of working gas per storage year, with a baseline value of €6.4 from the nearest published capacity auction.[50] One day of unavailability of the full Uniper position at Epe is then worth around €0.30 million. The much larger stress-winter figure, around €0.55 billion of avoided macroeconomic damage per terawatt-hour of stored gas estimated for a crisis scenario, showcases the clear strategic dimension in chapter 5 but this is never entered into the expected-value calculations.

Assumption 7, terrestrial-equivalence cost (Tier 2). The counted Tier 2 benefit is the avoided cost of a conventional programme delivering comparable ground-movement information, following the information-equivalence approach of earlier SeBS cases. The costed specification is a densified levelling network of around 450 benchmarks over the 25-square-kilometre field, measured monthly by second-order precise levelling (12 to 20 crew-days per campaign at €1,200 to €1,500 per crew-day, €180,000 to €360,000 per year), four to six permanent GNSS stations to recover the horizontal component (€25,000 to €50,000 per year), benchmark installation and maintenance (€10,000 to €15,000 per year), and processing, adjustment, and reporting (€25,000 to €40,000 per year). The components sum to €240,000 to €465,000 per year, adopted as a rounded range of €250,000 to €450,000 with a baseline of €350,000. Monthly is taken as the practical ceiling of a terrestrial campaign programme, and it matches the operator's own reading that assessing an impact takes a month or more, so a weekly terrestrial equivalent is not costed. The unit rates are indicative, built from typical German engineering-survey rates rather than quotes. The confidential fee Uniper pays EFTAS is not netted off: EFTAS's own statement that equivalent information obtained conventionally would cost an order of magnitude more puts the fee at roughly a tenth of the conventional cost, below the precision of the unit rates. The adopted range is attributed in full to the free Sentinel data under the necessary-condition rule set out in Assumption 5, so the Sentinel-attributable benefit is €250,000 to €450,000 per year, with a baseline of €350,000; at a 50 to 60 per cent data share it would be €125,000 to €270,000 per year. Two caveats bound the estimate. Even a monthly terrestrial programme would not reproduce weekly, wall-to-wall coverage or the 2015 to 2025 archive, so the equivalence understates the service on those dimensions. Assumptions 2 to 5 support the incident analysis of section A2.3, which is reported alongside in Table 1 for context and is not counted in the chapter 5 totals.

A2.3 Probability-weighted estimate of the avoided expected loss (Tier 2)

The avoided expected loss at Tier 2 is estimated as: expected annual avoided loss = number of caverns x incident frequency per cavern-year x consequence cost x detectability-and-reduction

[50] MND Gas Storage capacity auction results, https://www.mndgs.cz/en/auction-results/ (annual product 2024/25 cleared at 6.39 EUR/MWh); Frontier Economics for Uniper (October 2025), study on the value of full gas storage in a stress winter, https://www.uniper.energy/news.

factor x attribution. The table below applies the named assumptions in three scenarios. The consequence cost is the fixed €60 million of Assumption 3 throughout, so the scenarios differ only in frequency, detectability, and attribution. The pessimistic frequency of 10 applies the stronger 0.3 to 0.5 completion adjustment, the one that would hold if the gas cavern completions performed to the double-barrier standard, to the site's own unadjusted history of 22 to 25 per 100,000 cavern-years.

In the baseline scenario the 39 caverns carry an incident rate of 14 per 100,000 cavern-years, which is a 0.55 per cent chance that one of them suffers a major incident in any given year. At €60 million per incident that is €328,000 of expected loss a year before the extra monitoring. About 35 per cent of that is open to influence, being the share of failure types that develop slowly enough for area-wide movement data to catch them and the reduction in damage that earlier warning brings, which leaves around €115,000. Ground-movement monitoring carries 40 to 50 per cent of the detection capability behind that reduction, which gives the €52,000 in the table. The lower and upper scenarios move the same four inputs down and up.

Parameter	Pessimistic	Baseline	Optimistic
Major-incident frequency per 100,000 cavern-years (adjusted)	10	14	70
Annual probability across the 39 Uniper caverns	0.39%	0.55%	2.73%
Consequence cost per incident	€60m	€60m	€60m
Expected annual loss without the added monitoring	€234,000	€328,000	€1,640,000
Detectability and consequence reduction	25%	35%	40%
Share of detection capability carried by ground-movement monitoring (Assumption 5)	40%	45%	50%
Expected annual avoided loss	≈ €23,000	≈ €52,000	≈ €330,000

This analysis is reported as supporting evidence in Table 1 and is not carried into the chapter 5 totals, which use the replacement-cost estimate of Assumption 7. Two further points bound it.

First, the range is wide, from around €23,000 to around €330,000 per year, with a baseline estimate near €52,000 per year, and it is dominated by the two judgement parameters, detectability and attribution, rather than by the comparatively well-evidenced frequency and consequence inputs. Second, it covers a single benefit, the avoided expected loss from major cavern incidents on the existing gas business. It does not cover settlement-driven pipeline and wellhead incidents, for which no frequency data exist, the better targeting of the per-cavern inspection and workover budget, the evidential value of being able to attribute or exonerate the cause of surface movement, the strategic availability value of the storage capacity, or the de-risking of the hydrogen expansion, and it should not be read as a comprehensive valuation of the service.

This model is the counterpart to the indicative exposure-based figure quoted in section 5.2.2, which reads the same benefit as a small probability reduction on a large exposure. The relationship between the framings is set out in section 6.3.

Annex 3: About the Authors

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Tim is a space industry strategy consultant working in collaboration with EARSC and Oxford University on the SeBS360 project. Tim specialises in Earth Observation and the European space sector, with over a decade of experience in the market uptake and commercial exploitation of EO downstream applications across energy, raw materials, and critical infrastructure. Before consulting, he spent six years as Managing Director and CFO of SkyfloX, a European Space Agency spin-off developing airline-based EO payloads. Within SeBS he leads the energy theme, developing benefit case studies that quantify the economic, environmental, and societal value of Copernicus Sentinel data.

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Alejandro is an early-career conservation scientist with over ten years of experience working in academic, non-profit and industry settings. His research is driven by a strong interest in understanding whether and how conservation efforts succeed, as well as in developing remote sensing applications to help monitor these efforts. He has particular expertise in the development of impact evaluation designs for conservation projects operating in nature-based credit markets. As a postdoctoral researcher at Oxford, he works on the ESA-funded projects Leveraging Earth Observation for Nature Finance (LEON) and ESA SeBS360.

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Joe is a Professor at the University of Oxford, and co-founder of the consultancy Wild Business Ltd. He has spent much of the last 25 years trying to understand how businesses impact biodiversity, and how to monitor and mitigate those impacts towards nature recovery. Joe has a BSc in Physics, an MSc in Environmental Technology, and a PhD in Ecology. He leads the ESA-funded project Leveraging Earth Observation for Nature Finance (LEON), and supports the ESA SeBS360.

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Lefteris is co-founder and CEO at Evenflow and CEO of the Committee on Earth Observation Satellites (CEOS). He is a strategy consultant with expertise in programmatic, strategic and business aspects of EU Space Programmes (Copernicus and Galileo). For more than 15 years, Lefteris has been extensively involved in various studies and projects related to the development, market uptake and exploitation of EO downstream applications. He has been contributing to the understanding, measurement and promotion of EO value through multiple activities, most notably the Sentinel Benefits study. He has been advising clients and partners across the full spectrum of the EO value chain, including EU institutions (EC, EEA, SatCen, ESA, EUSPA), universities and private companies.

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