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# Potential Application of RES and Underground $H_2$ Storage in Abandoned Mines †

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**Abstract:** Mining operations, as with all industrial operations, have a significant impact on the environment both through the generation of waste and through landscape change. In view of this, pioneering and sustainable post-mining technologies are demanded to reduce environmental impact. Clean energy can be part of the solution, with emphasis on the penetration of renewable energy sources (RES) for the mitigation of greenhouse gases. RES production is inherently fluctuating, at times being insufficient while others creating energy surpluses. Converting a mining site into a parallel renewable energy generation facility can provide new job opportunities and economic value, as well as contribute to a more secure energy supply. Abandoned mines present a viable option for the installation of such systems, exploiting their underground facilities for safe storage. In this regard, the underground facilities can be exploited for green hydrogen ($H_2$) energy storage systems to be used on-site in times of RES deficits. Underground $H_2$ storage has many advantages over surface storage, including safer storage, smaller footprints, a larger storage capacity, and a lower cost. The re-use of pre-existing infrastructure and land availability for deploying solar parks also offers innovative ways to generate clean energy. This study examines the potential of repurposing abandoned mines in the form of renewable energy generation facilities in order to improve their environmental impact and move quickly towards sustainable and innovative mining throughout Europe.

**Keywords:** renewable energy sources; hydrogen; energy storage; mining



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## 1. Introduction

The transition towards sustainable and low-carbon energy systems is nowadays essential to tackling the issues of climate change and fossil fuel depletion. Renewable energy sources (RES) are key in this effort, accounting for more than 8115.8 TWh, or 28.7% of the global electricity generation in 2021 [1]. Despite this, the intermittent nature of RES results not only in potential energy deficits but also surpluses. Thus, coupling RES with energy storage systems is essential to minimizing energy waste and achieving a stable and reliable energy supply.

In recent years, abandoned mines have drawn attention as potential sites to be repurposed as RES plants and energy storage areas. Indicatively, by 2012, eight projects were ongoing or scheduled in the U.S. only, including the installation of RES on mines [2]. The vast open areas of abandoned mines provide ample space for the installation of RES systems such as wind farms or solar power plants. Considering energy storage, the pre-existing infrastructure, underground networks, and geological characteristics of mines allow for storage capacities as well as the integration of safety systems, besides their own inherent safety due to their enclosed and controlled nature. Especially for the latter, abandoned mines present an excellent candidate for energy storage systems, and the storage of energy carriers requires extensive safety systems and measures.

Hydrogen ($H_2$) is an example of such an energy carrier, seeing a constant rise in popularity in recent years as an alternative fuel of significantly lesser impact than conventional fossil fuels. The majority of emissions of $H_2$ are attributed to its production. $H_2$ produced by water electrolysis requires great amounts of electricity—more than 50 kWh for 1 kg produced [3]. The production method for the electricity used significantly affects the impact of $H_2$ in its overall value chain, with electricity from RES producing the cleanest and most environmentally beneficial $H_2$ (green $H_2$). In this scope, the EU is aiming for the production of 10 million metric tons of green $H_2$ by 2030 [4].

This study aims to examine the potential of deploying RES and underground $H_2$ storage systems for on-site $H_2$ utilization in abandoned mines by reviewing the site and infrastructure requirements and limitations of both RES and $H_2$ production and storage systems and the unique characteristics of abandoned mines as possible solutions. The conclusions of this study will contribute to both the energy production and mining sectors by assessing the benefits of collaboration and its role in achieving the climate neutrality goals of 2050, while also revitalizing abandoned or depleted mines and creating new revenues and jobs. Extensive research also needs to be conducted for the safety of the operation in terms of geomechanics, as overpressure from the equipment installation and operation can result in even fatal structure collapses.

## 2. Potential Application of RES in Abandoned Mines

### *2.1. Site and Infrastructure Requirements for RES*

Sites for the installation of RES plants must meet specific criteria in order to ensure maximum exploitation and energy production, safety of operation, minimization of environmental and social impact, and land conservation. Solar power plants and wind farms specifically require large, open areas without physical or other obstacles. In addition, regulations considering natural landscape conservation and community protection bring down the number of potential sites significantly. For wind farms, Europe implemented in 2016 a "10H" regulation, meaning that the setback distance from inhabited areas should be at least ten times the height of the turbines, an average of 2 km [5]. These strict regulations drastically reduced potential sites for many EU countries, with Poland, for example, having 98% of its territory excluded [5]. While new regulations aim to address the issue by reducing the setback distance to even 500 m, potential sites are still limited. For these reasons, RES plants are typically installed in remote areas.

### *2.2. Repurposing Abandoned Mines for RES*

Abandoned mines in the world account for vast, unexploited areas of unique features and infrastructure that lie dormant. In Europe, flooded mines are estimated to be as many as 30,000 [6]. Repurposing of abandoned mines is essential to not only facilitate the development of other sectors but also balance the impact of their past activities through the reuse of these areas, reduction in greenhouse gas (GHG) emissions from electricity production in their regions, and creation of new jobs.

The large surface areas of mines can be utilized for installing PVs, while elevated locations and strong wind conditions in elevated mine shafts present an ideal site for wind power generation. In addition, these sites often possess existing electrical infrastructure, including grid connections and transmission lines, which reduces the need for costly and time-consuming infrastructure development. Leveraging the inherent advantages of abandoned mines enhances the efficiency and performance of RES systems, increasing generation and grid stability.

These advantages have already been identified by technology providers and energy producers, with various projects seeing the installation of RES, specifically solar power plants in abandoned mines. In 2004, approximately 0.2 $km^2$ of a former lignite-mine ash deposit in Espenhain, Germany, was repurposed as a 5 kW solar power plant with 33,500 solar modules, producing electricity for the German grid [7]. In the same manner, similar projects have seen the development of solar power plants in abandoned mines or tailing sites. For instance, the Questa Mine project has seen the installation of approximately 175 solar panels on 20 acres of the mine's tailing site, with a total capacity of 1 MW [7]. In addition, large-scale hybrid systems, combining diesel with PVs or wind turbines, have also gained ground in recent years. In Australia, two such systems were installed in 2015 and 2016, in Queensland and Western Australia, respectively [8]. These installations had capacities of 26 MW diesel/1.2 MW PVs and 19 MW diesel/10 MW PVs, the latter also including energy storage of 4/1.8 MW/MWh. Two similar systems have also been installed in the northwest territories and Quebec, Canada, in 2012 and 2014, respectively. These installations accounted for 46.8 MW diesel/9.2 MW wind and 21.6 MW diesel/3 MW wind, the latter having a 0.6/4.3 MW/MWh storage capacity.

## 3. Potential Application of Underground Storage in Abandoned Mines

### *3.1. Site and Infrastructure Requirements for $H_2$ Storage*

$H_2$ production and storage systems require extensive infrastructure. The first piece of equipment for these systems is the electrolyser. Electrolysers use electricity to perform water electrolysis, separating $H_2$ from oxygen ($O_2$). These systems are coupled with water supply and treatment systems, providing purified water for the process. After production, gaseous $H_2$ is compressed with the use of reciprocating, rotary, ionic, or centrifugal compressors at high pressures, typically 350–700 bar, and stored in tanks [9,10]. $H_2$ is transferred to the storage tanks or from them to be used through distribution systems comprising steel pipelines similar to those used for natural gas, retrofitted to be suitable for $H_2$ flows [11]. This retrofitting involves implementing robust sealing technologies, such as liners, paints, bulk materials doping coatings, or hard metallic or mixed metallic-ceramic coatings enriched with TiN/TiC prepared by laser cladding, to prevent $H_2$ embrittlement and corrosion in the tanks and pipelines [12,13].

In addition, the volatile and flammable nature of $H_2$ obligates storage sites to have extensive safety and monitoring infrastructures [14]. This involves the installation of fail-safe components, such as valves, as well as gas detectors, smoke and fire detectors, heat sensors, and fire-suppressing systems.

Ventilation systems are also vital to facilitate air circulation and prevent the accumulation of hazardous $H_2$ gases, the lower flammability limit of which is 4% [15]. These units incorporate exhaust systems such as duct airflows and fans to allow air circulation at a rate higher than the lower limit of 0.3 $m^3$ per minute per 1 $m^2$ of solid floor space [16].

### *3.2. Repurposing Abandoned Mines for Underground $H_2$ Storage*

Underground $H_2$ storage in abandoned mines offers significant advantages, considering the aforementioned requirements. The vast underground spaces and extensive networks of tunnels and chambers provide sufficient room for large-scale $H_2$ storage without the need for constructing new storage facilities. Furthermore, the geological stability of underground mines ensures the long-term integrity of the storage infrastructure.

In addition, underground $H_2$ storage in abandoned mines offers various safety advantages. The inherent geological stability of underground mines provides a secure environment for $H_2$ storage, minimizing the risk of external disturbances or natural disasters, and the robust construction of mines, designed to withstand the pressures and stresses of mining operations, provides a solid foundation for safe $H_2$ storage.

Furthermore, controlled and enclosed underground mines, coupled with ventilation systems and gas monitoring technologies, allow the early detection of possible $H_2$ leakages and enable prompt response and mitigation actions. While the enclosed spaces significantly reduce the risk of an accident, monitoring activities are still necessary to ensure the safety of the equipment, $H_2$ stacks, and personnel inside and outside the closed storage space.

The infrastructure requirements for underground $H_2$ storage differ only slightly from those of conventional storage sites. Besides $H_2$ production systems, gas compressors and injection systems are also necessary, connected through proper pipelines to avoid $H_2$ embrittlement or leakages. Another key component is injection wells, which allow the controlled injection of $H_2$ into the underground storage reservoirs. The main differences in infrastructure lie in the required facilities associated with the enclosed nature of the reservoirs. Specifically, shafts or tunnels are required for various reasons, from the connection with production and distribution systems to communication networks and power supply systems to the transportation of personnel and equipment.

## 4. Sustainability of Repurposing Abandoned Mines

While RES present one of the most viable and promising options for decarbonizing electricity production, their overall environmental impact, while drastically lower than conventional production methods such as coal, is still negligible. This impact is heavily attributed to land use and infrastructure requirements. For example, the construction of a 1 MW PV plant requires 4 to 5 acres of land for a daily production of approximately 4000 kWh [17]. Repurposing the open areas of abandoned mines can reduce the net use of previously unused and exploitable lands as well as the need to retrofit said lands for PV installation to a minimum, reducing both the overall environmental impact and construction costs. In the same manner, repurposing existing infrastructure, such as electrical grid connections, etc., also significantly reduces the environmental impact and costs.

In 2014, a 63 kWp solar power plant was deployed at the New Luika gold mine in Tanzania. In its first year of operation, the plant produced an annual 100,000 kWh of electricity, with an estimated fuel saving of 28,000 litters and a $CO_2$ reduction of 67 tonnes [18]. Future plans for the mine aim for a fully operational solar farm with more than 1,000,000 kWh of annual production, an equivalent of 219,000 litters of fuel, and $CO_2$ savings of up to 660 tonnes. In addition, various studies have assessed the sustainability of installing RES in abandoned mines. Bódis et al. examined the potential of PV installation at eight different mining sites in Uzbekistan [19]. The analysis concluded that the installation of a 1 MW PV system would account for an annual electricity production of 1555 to 1685 MWh, resulting in an annual reduction in GHG of 888.2 to 928.5 tonnes of $CO_2$. Considering the financial feasibility, the net present value for the site with the largest energy production, Tebinbuloq, was estimated to be USD 2.217 million. The average revenue from electricity production was estimated at USD 84,000, resulting in almost 13 years of payback time and an internal return rate of approximately 12%.

Considering energy storage, the unique characteristics of underground $H_2$ storage present significant advantages over surface storage in terms of environmental as well as economic sustainability. According to Taylor et al., large-scale underground $H_2$ storage costs only one-tenth, or even less, than surface storage facilities [20].

## 5. Discussion and Outlook

The application of RES coupled with underground $H_2$ storage in abandoned mines presents a promising solution towards increasing both the efficiency and the sustainability of these systems. However, successful implementation relies on joint efforts between the different stakeholders. Industry players, policymakers, and local communities need to engage in collaborations addressing concerns, foster public acceptance, and facilitate the development of regulatory frameworks that support the development of these technologies. This collaboration will allow for the identification of suitable sites for applying RES and underground $H_2$ storage, considering regional variations in geological conditions and the particular needs and priorities of local communities.

The installation of RES coupled with underground $H_2$ storage in abandoned mines is slowly gaining ground in both the scientific and industrial communities. For example, in 2021, Liu et al. examined and evaluated the influential factors of using abandoned coal mines for storing H, based on an improved analytic network process (ANP) [21]. On an industrial level, HyStock is currently working on the first large-scale underground $H_2$ storage facility in the Netherlands [22]. Nevertheless, the dissemination and overall development of this approach are hindered by the relative lack of information considering sustainability. Therefore, future research should focus on conducting techno-economic analyses to assess the cost-effectiveness of RES and underground $H_2$ storage projects. Factors such as capital investments, operational costs, and revenue streams will provide a comprehensive evaluation of the economic viability of these initiatives. Environmental impact assessments should also be conducted to examine the potential advantages or disadvantages of deploying RES and large-scale $H_2$ storage in abandoned mines, including the risks of groundwater contamination, subsidence, and impacts on local ecosystems. Moreover, investigation of optimal strategies for integrating RES and underground $H_2$ storage systems with existing energy infrastructure, grid networks, and demand and response programs is essential to maximize overall system efficiency and increase sustainability.

## 6. Conclusions

This study aimed to examine the potential of applying RES coupled with underground $H_2$ storage systems in abandoned mines. Deployment of RES in these sites increases their overall sustainability, minimizing the need for acquiring and retrofitting lands that could be exploited otherwise, the need for the installation of intricate infrastructure, and the overall cost of the plant, while also producing higher revenues due to the increased efficiency of the RES systems.

Considering $H_2$ production and storage, the unique characteristics of these areas, such as enclosed and control chambers, geological stability, etc., significantly enhance the overall safety, a major concern for systems storing the volatile and highly flammable $H_2$. Considering the sustainability of these systems, minimizing the need for acquiring storage areas, and simplifying the safety network and infrastructure by exploiting mine characteristics significantly decrease both the costs and the environmental impact of this approach.

In conclusion, abandoned mines present excellent sites for both RES and energy storage installations in close proximity. The suitability of abandoned mines for storing $H_2$ specifically further increases the value of this approach, as $H_2$ is nowadays considered one of the most promising green energy solutions, whose development, however, is hindered by safety and regulatory issues. Considering all these, the application of RES and underground $H_2$ storage seems to offer numerous advantages, such as the minimization of the environmental impact of the plants, land conservation, community protection, and the creation of new jobs through the revitalization of mining sites, while also facilitating the dissemination and development of $H_2$ as a powerful asset toward achieving the EU's climate neutrality goals by 2050.

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