

## Article

# New Uses for Coal Mines as Potential Power Generators and Storage Sites

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**Abstract:** In the context of sustainable development, revitalising the coal sector is a key challenge. This article examines how five innovative technologies can transform abandoned or in-use coal mines into sustainable energy centres. From solar thermal to compressed air energy storage, these solutions offer a path to a more sustainable future while addressing the decline in coal production. This approach not only promotes energy efficiency but also contributes to the mitigation of environmental impacts, thus consolidating the transition to a more responsible energy model. Thus, in this document, the reader can find the explanation of why we have opted for these technologies and not other existing ones. In addition, the economic, environmental and technical feasibility of the different technologies is analysed. Finally, real cases of the successful application of these technologies will be presented once they have gone beyond the project idea phase, and the reasons why we are calling for their transposition to the coal industry in the search for its revitalisation will be explained.

**Keywords:** energy storage; abandoned underground mines; coal mines; renewable energies



**Citation:** Pous de la Flor, J.; Pous Cabello, J.; Castañeda, M.d.I.C.; Ortega, M.F.; Mora, P. New Uses for Coal Mines as Potential Power Generators and Storage Sites. *Energies* **2024**, *17*, 2213. <https://doi.org/10.3390/en17092213>

Academic Editors: Dameng Liu and Susana Torno Lougedo

Received: 19 March 2024

Revised: 24 April 2024

Accepted: 1 May 2024

Published: 4 May 2024



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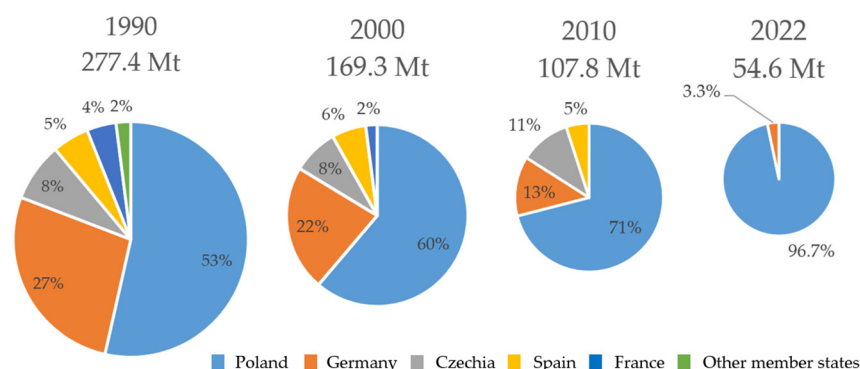
## 1. Introduction

In a world demanding sustainable and environmentally responsible solutions, coal, which has for many years a mainstay of power generation for many years, is at a crossroads. Coal mines, whether operating or abandoned, represent a legacy of the Industrial Revolution but also hold transformative potential. With awareness of the need to reduce greenhouse gas (GHG) emissions and the pressing need to meet growing global energy demand, it is vital to explore new directions for this fossil energy source.

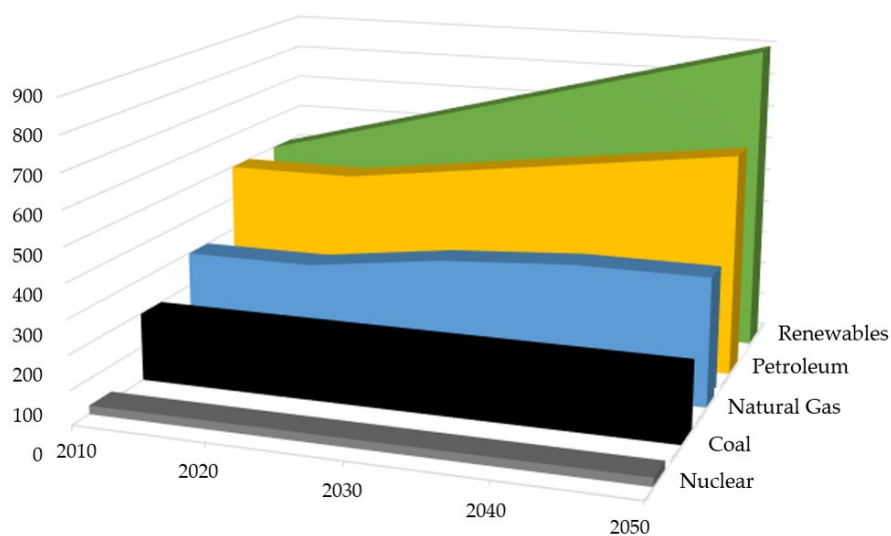
In recent years, we have witnessed a marked decline in favour of coal as an energy resource. As can be seen in Figure 1, in Europe, for example, the production of coal has been declining and has become residual. In fact, coal mining and extraction has been eliminated in countries such as the Netherlands (1970), Belgium (1990), France (2004) and Spain (2018) [1].

This is not limited to the European space; in fact, in recent years, the dominant position of coal in the energy consumption of China, the world's largest GHG emitter, has not changed, but the share of coal in its energy consumption has been decreasing year by year [2], so much so that the share of energy from natural gas and non-fossil fuels increased significantly from 17.9% in 2015 to 25.9% in 2022 [3]. Furthermore, the share of non-fossil energy sources, such as wind, solar and geothermal, increased from 11% in 2015 to 17.5% in 2022 [4].

As discussed above, environmental concerns, driven by coal's significant contribution to global CO<sub>2</sub> emissions, have led to a reconsideration of its role in the global energy mix. However, the growing demand for energy (Figure 2), driven by global population growth and economic development, raises the urgent need to explore innovative and efficient sources.



**Figure 1.** Production of hard coal (Million tons) in the EU, 1990–2022.



**Figure 2.** Global primary energy consumption (quadrillion British thermal units) by energy source (2010–2050).

Despite this scenario of growing demand, coal faces a paradigmatic transition. Its association with high carbon emissions and its status as a non-renewable resource pose fundamental dilemmas in a world increasingly committed to sustainability. As evidence of this commitment, more than 170 countries have agreed on the need to limit fossil fuel emissions to avoid dangerous man-made climate change, as formalised in the 1992 Framework Convention on Climate Change [5].

The need for energy is undeniable, but the challenge lies in how to meet this demand in a sustainable and efficient manner. This is where innovation and the adoption of advanced technologies emerge as catalysts for change. The transition to a circular economy is presented as the way forward, where resources are used efficiently, waste is minimised, and energy solutions that mitigate environmental impacts are sought. In this quest, the energy transition towards a sustainable model committed to by the Organisation for Economic Co-operation and Development (OECD), which ratified the Paris Agreement, should bring environmental benefits [6].

It is in this context that coal mines, whether abandoned or in operation, emerge as strategic assets. Transforming these sites, formerly associated with the extraction of a fossil resource, into centres of energy innovation is a crucial step towards a more sustainable future. The key lies in embracing technologies that not only address energy demand, but also mitigate the environmental impacts associated with production and consumption.

Five revolutionary technologies that can turn coal mines into engines of sustainable energy will be explored in this article. Solar thermal, compressed air energy storage (CAES), mini-hydraulics, gravity underground energy storage (GES) and hydrogen production will

be the protagonists of this journey into the future. These technologies not only have the potential to revitalise abandoned mines but can also improve the efficiency and sustainability of operating mines.

In the following sections, we will dive into each of these technologies, exploiting their specific application in the context of coal mines. From capturing sunlight in vast expanses of open-pit mines, to optimising energy production through compressed air storage in underground mines, these innovations hold the key to unlocking a future where coal, far from being a liability, becomes a renewed resource for sustainability.

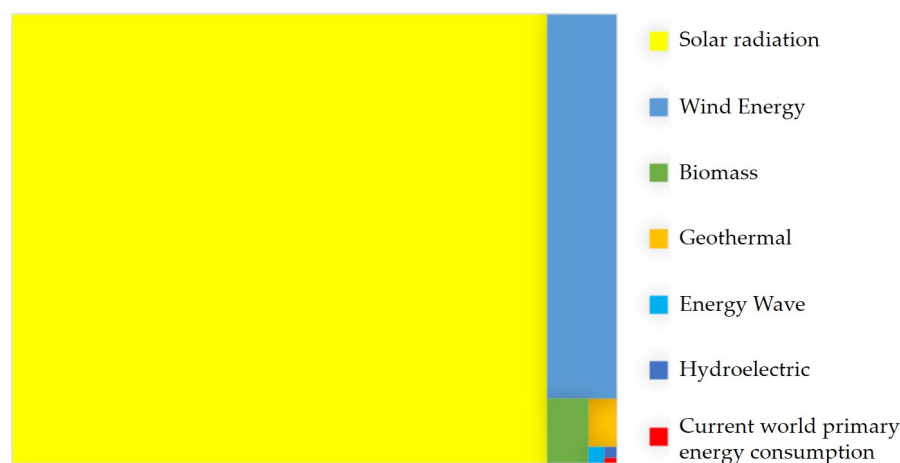
## 2. Materials and Methods

### 2.1. Solar Thermal Power Plants

In the relentless search for sustainable options, solar thermal technology presents itself as an innovative solution for the metamorphosis of open-pit coal mines. This well-known and continuously developing technology harnesses solar energy, transforming it into heat, thus offering a fresh perspective on the energy dynamics of these vast, disused deposits.

The basis of solar thermal technology lies in capturing and utilising the sun's heat to generate energy. Currently, there are three groups of technologies for harnessing solar energy: photovoltaics, solar thermal power plants for electricity generation and, finally, low-temperature solar thermal for heating and hot water [7]. Unlike photovoltaic systems, which convert sunlight directly into electricity, solar thermal technology focuses on harnessing radiant heat.

In order to understand the energy potential of the sun, the amount of energy consumed by humans worldwide over the course of a year is about  $4.6 \times 10^{20}$  J [8]. This energy is supplied by the sun in just one hour. Therefore, we can conclude that the sun can play a fundamental role in the development of energy generation systems capable of sustainably supporting the world's growing demand. In fact, as can be seen in Figure 3, the theoretical physical potential of renewable energies, including solar thermal energy, is practically negligible in relation to current global primary energy consumption.

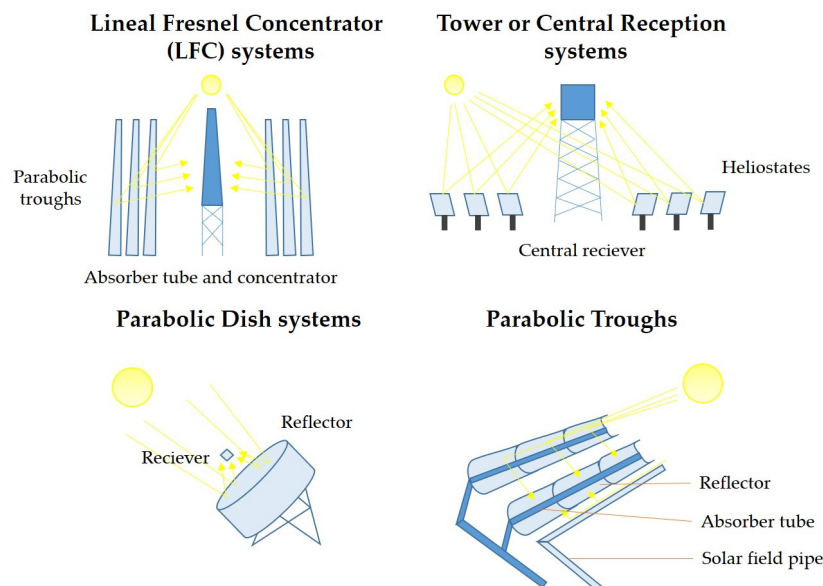


**Figure 3.** Theoretical physical potential of renewable energies.

In the context of open-pit coal mines, the extensive surface area available becomes a favourable canvas for the implementation of these solar collectors. Their strategic arrangement in the previously mined extraction areas creates a perfect synergy between the former function of the site and its new life as a sustainable energy source.

Currently, four technologies are mainly used to concentrate solar power plants (Figure 4). The basis for the classification is the type of system used to concentrate the incident solar radiation. As can be seen in Figure 4, we distinguish the following: tower or central receiver plants, plants with cylindrical parabolic collectors, plants with linear Fresnel-type concentrators and parabolic dish Stirling plants [9]. In the case proposed by this article as a

line of research, of the four technologies used, only the tower or central receiver systems and the parabolic dish would be applicable to open-cut coal mines, as the use of parabolic troughs would not be indicated due to their difficulty of installation, operation and cost in a flat topography such as that of open-cut mines.



**Figure 4.** Main concentrating solar technologies.

Our approach is based on the fact that the open and unobstructed topography of the coal fields provides an ideal setting for solar energy capture. Solar collectors, arranged in the various positions mentioned above, would be strategically placed in areas exposed to the sun for most of the day. These collectors capture the energy from solar radiation and use it to increase the temperature of a fluid [10].

The choice of thermal fluid plays a crucial role in the performance and efficiency of the system. Once heated by solar radiation, this fluid transports heat to a heat exchanger. Here, the heat is used to generate high-pressure steam, which, in turn, drives a turbine connected to an electric generator. This process converts the captured thermal energy into ready-to-use electricity [11].

The injection of electricity into the grid is where we find another point in favour of the transformation and use of abandoned deposits since, in addition to the topographical and geological characteristics, the use of high-voltage mining equipment, such as transformers or mineral extraction equipment, requires good connectivity to the electricity grid. Therefore, in the transformation of open-cast mines to sustainable power plants, the savings that would be made by the existence of a proper connection to the grid to inject the electricity generated is crucial and reinforces our theory that the use of abandoned mines for this purpose can be an immense opportunity.

Finally, the existence of access in the form of former mining towns that have now been converted into population centres, and major road, rail and even air and sea connections, is another reason to argue in favour of the transition from abandoned sites to renewable power plants in pursuit of a net-zero economy and sustainable development.

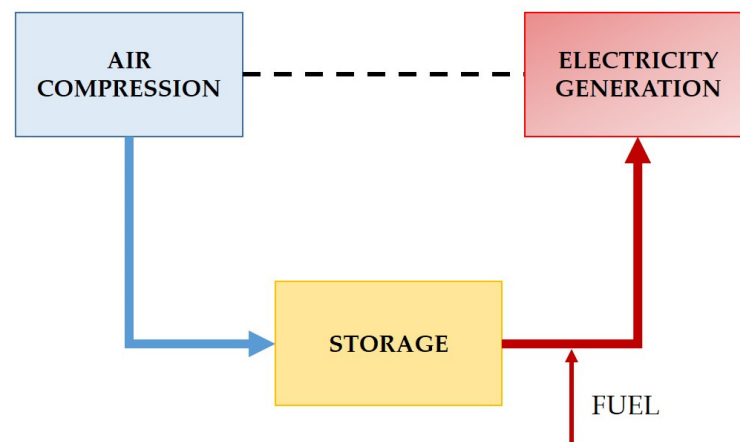
## 2.2. Compressed Air Energy Storage (CAES)

Compressed air energy storage (CAES) technology is mainly based on using electrical energy from renewable energy sources, such as solar or wind power, to store it in the form of high-pressure compressed air underground. The technology consists of two separate parts: charging (compression) and discharging (expansion) of the cavity [12]. During times of excess energy and lower electricity demand, ambient air is stored at high pressures in underground cavities (engine in compressor mode). When the grid requires power to meet

high demand, this pressurised air can be released through the engine (engine in generator mode) to generate electricity.

Despite its integration into the electricity system and, together with pumped hydro, being the only technologies that store energy above 100 MW [13], the key to the development of CAES lies in choosing the ideal storage site and the optimal way of heating the air in the expansion process.

Regarding the thermal performance of the system, the special feature is that in the compression process, the air is heated from atmospheric pressure to a storage pressure of approximately 70 bar [14] and generates a large amount of heat. This heat is lost directly to the atmosphere by cooling the air in the coolers of the compression system to reduce the temperature of the injection air in the cavity to approximately 43–49 °C [15]. As a consequence, in the expansion phase, the air has to be heated (using fossil fuels), and the efficiency of the system decreases to only 50% (Figure 5).



**Figure 5.** Diagram of a diabatic CAES system.

The way in which air is heated has led to research into different types of systems to find the most optimal solution to make compressed air storage technology independent of fossil fuels. We highlight the following: adiabatic CAES, isothermal CAES or bio-caes, among others.

However, at present, little research has focused on the type of site, nor have new alternatives been developed that make it possible to develop CAES in a more efficient and environmentally friendly way. This part of the project is the most decisive when it comes to demonstrating the technical and economic feasibility of the technology, as the site has the following determining factors associated with it [16]:

- Exploratory risk derived from any selection of the underground storage structure.
- The need to invest in an exhaustive geological and mechanical characterisation of the rock mass to ensure the stability and watertightness of the storage facility.
- Types of structure that optimise the technical and economic viability of the project.

At present, only two plants are operating with compressed air storage technology, CAES [17,18]. In both, the cavities chosen for air storage have been salt formations (diapirs). This is due to their interesting physical properties (the elastoplastic property of salt means that the cavity walls are able to maintain their structural integrity even after undergoing compression–extraction cycles) and their low construction cost, as the cavities are formed via solution mining (a simple and cheap method of 2 to 10 USD/kWh).

This is the motivation for the development of this research. It is proposed to develop storage infrastructure for CAES systems in abandoned underground mines (i-CAES), particularly in underground coal mines, on the basis that

- Geological and geophysical studies have been carried out using the mine reports prepared in the exploration phase prior to the ex-operation of any mine, which, in our case, can be used to evaluate the stability of the rock formation, a key part of ensuring the watertightness of the storage structure. In this way, the associated exploration risk is considerably reduced as the information is already available.
- There is no need to create a new cavity since the access galleries to the coal mine are reused for i-CAES confinement. Only a shotcrete lining and sprayable waterproofing sealing membranes need to be invested in. Both techniques are economical, well known in tunnel waterproofing, and prevent both capillary water ingress and air leakage in the pressure and compression cycles.
- In this type of mining, environmental and social impact studies are carried out to assess the possible effects of mining in the area; thus, carrying out a CAES project in an obsolete mine does not have a direct impact; rather, it is an opportunity to reuse a disused resource.
- Storage capacities adequate to the installed power capacity of the area can be achieved by adjusting the demand–production curve and optimising the area. In addition to the capacity requirements of the area, the size of the CAES will depend on the installation area since it is necessary to guarantee a geomechanically stable area, mainly access galleries in non-exploitable rock because they are less porous, more permeable and more structurally resistant.
- The distribution of salt formations in Europe is specific, they are not evenly distributed among all countries and their exploitation is limited by environmental legislation. Thus, abandoned mines become a viable alternative to salt domes.
- Since 2018, as explained in the introduction to this article, in order to meet the commitments arising from the Paris Agreement (Mine Closure Plan by 31 December 2018 set by the EU), the coal mining sector has experienced a significant decline in terms of production and demand as a result of the progressive closure of thermal power plants.

This situation means that the traditional link between energy and the subsoil is weakening, leading to a lack of alternative sectors, depopulation and ageing. However, the infrastructure developed in the last century presents a good opportunity for defining new energy mining in the 21st century: abandoned galleries with large spaces and good stability could be transformed into optimal infrastructure for storing compressed air—iCAES—achieving the economic reconversion of mining regions and introducing a circular economy in the mining sector (which is in the early stages of integration) for a current and necessary purpose.

### 2.3. Mini-Hydraulics

Pumped hydro storage (PHS) has been around for decades and is currently the only fully mature storage technology. It is a very widespread technology worldwide and currently represents approximately 95% of the storage capacity, with more than 160 GW of installed capacity. According to the targets set by Europe, PHS technology will remain an important option, with global storage capacity projected to almost double to 300 GW by 2070 [19].

From a global perspective, China is the leading country in installed hydropower capacity, with a third of the world share. Brazilian electricity production from hydropower has reached 9%, which is understandable given the nation's access to the Amazon and favourable topography. It is followed by Canada (with little evolution due to the continuously flowing Niagara Falls, creating transmission rather than storage challenges) and the United States.

Two water reservoirs, turbines and water pumps are required to run the storage operation. Typically, the power required from the pumps is less than that drawn from the turbines. The two reservoirs must be located at different elevations that are proportional to the amount of energy stored.

The rationale behind PHS is that when demand is high and there is not enough power generation (prices are higher, as demonstrated in the previous section), power is generated by flowing water from the upper reservoir to the lower reservoir (discharge mode) and turning the hydro turbine by virtue of the conversion of the considerable head of water. The coupled electrical generators are responsible for generating electrical energy that is fed into the grid.

On the other hand, when demand is low and there is surplus generation (the price is lower), the surplus energy from the grid is used to run the pump (load–load mode), driving the water upwards.

In this way, a profit is made in arbitrage by selling at more expensive times (discharge mode) and buying at cheaper times (load mode).

The efficiency of this energy storage system is high and is in the range of 70–85%, even reaching 90% depending on the technology used, the plant size, the height difference, etc., as well as the specifications of the turbines and the size of the gates [20].

Although this is a pioneering technology, there are few areas for improvement and there are many drawbacks. The drawbacks include the following [21]:

- They require a very specific location to be installed. On the one hand, they need to be located in mountainous areas to achieve the altitude difference between the upper and lower reservoirs. On the other hand, they need to be installed in river areas, which means that they are limited by water availability and flood control. In addition, they need to be installed in geotechnical locations where avalanches and landslides are not expected. Finally, the site must have access to electricity distribution networks, bearing in mind that efficiency is reduced by having to transport the stored and generated energy over long distances.
- They have the low fast response capacity of conventional systems, which can only be solved by using expensive variable speed systems.
- They require a huge investment for installation. Investment in break-even analysis would be needed to find cost-effective solutions.
- They have high environmental impact and are increasingly constrained by stricter environmental considerations.

In response to all these drawbacks, our research has addressed PHS through closed-loop pumped hydro systems. These systems contain small upper and lower reservoirs (mini-hydro) located in areas away from rivers. In this way, the water circulating between the reservoirs is continuously recycled.

Among the areas evaluated, this work proposes the use of abandoned coal mine galleries as pumped hydro storage reservoirs. Worldwide, some 61,600 sites have been identified as potential closed-cycle pumped hydro power plants. These sites could potentially supply a storage capacity of around 23,000 TWh.

The use of closed pumping circuits solves all the disadvantages mentioned above but has the limitation of not having the water resource provided by the river and being limited to the hollow of the two reservoirs. However, it is proposed as a new innovative technology in the search for the revitalisation of galleries in abandoned coal mines.

#### 2.4. Hydrogen

Hydrogen is going to be a new energy carrier, a statement that is no longer in doubt. However, we must remember that hydrogen has always been a part of the mix of usable energies. Perhaps its price per kilo, which is very high compared to fossil fuels, and the special conditions (mainly temperature and pressure) for its storage and transport have relegated it to second, if not almost last place [22]. The other options on which the market was betting were cheaper because their technologies of use were well known and also

more economical. Under these conditions, it was normal that the use of hydrogen was not developed.

In the current scenario, various reasons, such as the greed of energy and electricity companies in terms of economic results, the growing scarcity of traditional resources or the increased difficulty of exploring and exploiting them, have led to a significant increase in fuel prices. Therefore, hydrogen is becoming competitive, provided it is exploited as a natural resource or produced as green or blue.

Hydrogen technologies stand out as the best option in the quest for a decarbonised atmosphere, as the only by-product they can generate is water, as opposed to the CO<sub>2</sub> emitted during the combustion of fossil resources. All these advantages are leading to a narrowing of the price and cost gap in favour of hydrogen.

Hydrogen is produced in many different ways, each of which gives it the colour attached to its name: grey, brown, blue, pink, turquoise, green, yellow and gold. However, without a doubt, the generation of green hydrogen is the most important goal [23]. In this way, producing hydrogen with renewable energy sources has been and is the great existing goal, as we have hydrogen that comes from the sun or the air, a clean, inexhaustible and free source of energy. These three characteristics constitute the fundamental advantages of green H<sub>2</sub>.

Another advantage is that it can be generated with surplus electricity, mainly from the grid. These surpluses, which can come from any source (nuclear, renewable, fossil fuels, etc.), are produced and not used due to mismatches between production and demand, or due to the conditions of the electricity market. In this way, mines can become storage or on-demand energy production plants, much needed in the grid, and can increase their profits while diversifying into another very lucrative activity.

In short, hydrogen has many advantages: it is generated in energy- and water-consuming electrolyzers, and it can be stored and used in virtually all industrial processes. Hydrogen technologies also exist for all types of engines, cars, trucks, ships and even aircraft. Therefore, it is a great substitute for oil and its derivatives in the world of transport, presenting itself as an alternative energy source. Here, it also plays a role in the process of electrification of means of transport [24].

On the other hand, hydrogen is in demand in different traditional industries, such as steel and fertilisers, but also in new processes such as conversion to ammonia, ethanol or methanol [25]. Currently, the use of methanol combined with CO<sub>2</sub> produces synthetic fuels that are already being integrated into conventional transport systems such as aviation.

However, hydrogen also presents a number of problems that give rise to technological and safety challenges. Among these problems are the current gas pipelines, which cannot withstand more than 5% of this element, as it fragilises the metallic materials of which they are composed. It also presents the problem of explosive atmospheres; its wide range of flammability (between 4 and 75%) makes its use dangerous. On the other hand, let us not forget that its use in burners is still evolving because, although the flame admits a certain percentage of hydrogen, its direct combustion is a challenge. At present, the only advantage in this field is that it can be burned as part of the combustion gas. It would be ideal to enrich the biogases that can be obtained from various current waste treatments, some of them hazardous, with hydrogen [26].

In short, hydrogen is an energy vector that we cannot afford to waste; it is a tangible value in the future energy mix and must, therefore, be present in our mining activities [27].

For this publication, we have proposed that, in current mines, abandoned or in operation, we could find the following:

- Generation areas: wind turbines in elevated areas of the mines, such as mountainous areas, shaft derricks, etc. The installation of photovoltaic panels in disused cuts, in dumps and in areas of the mine where mines pass through, such as warehouses, workshops, plants and stockpiles.



- Production areas: use of H<sub>2</sub> as a fuel for use in production machinery to produce the electricity needed in the mine or to sell to the grid by producing electricity with hydrogen fuel cells.
- Hydrogen storage areas as a stockpile of raw materials for the market, which will demand it on a large scale in the future.

Mines and reservoirs where methane naturally occur show that the gas was confined in nature and indicate that the reservoir was stable until anthropogenic action released the gas. A fundamental parameter that must be measured and controlled when the gas is first extracted is the pressure, as this must not be exceeded in the successive injection processes that may occur of the gas itself or of other gases, such as hydrogen.

Hydrogen molecules are smaller than methane molecules, so their tendency to leak will be greater, although this leakage capacity will be determined by the porosity and permeability of the ground. Therefore, it has been deduced that if an area of the mine is used as a hydrogen storage area, it must be conditioned for the new conditions of pressure, temperature and, above all, to meet the challenge posed by the greater capacity of hydrogen to leak through cracks and pores. The use of waterproof membranes and concrete or the use of resistant steel cladding are technologically acceptable solutions that are currently being studied in numerous projects.

Similarly, the natural production of hydrogen [28] in porous media, both shallow and deep, must be studied. For this purpose, the behaviour of hydrogen with the other existing elements has to be simulated, taking into account the different phases in which they are presumably found in each case under study. The latest advances in this field have been described in the results section of this document.

In conclusion, hydrogen presents itself as a very interesting and promising player in diversifying the economic activities of mining companies for the future, as well as in terms of cost savings and energy self-sufficiency. It also contributes to the desired independence from fossil fuels and to the fight against climate change.

### 2.5. Gravity Underground Energy Storage (GES)

Gravity Energy Storage (GES) systems, also known as gravity batteries, are large-scale energy storage technologies adapted from the Pumped Hydroelectric Energy Storage (PHES) concept developed with the aim of eliminating geological limitations and water requirements. GES systems can have different designs and structures, but, like PHES technology, they make use of gravity for energy storage and generation [29].

A large mass is used which, when lifted, stores potential energy based on the mass of the object and the height to which it is lifted. The higher the height, the greater the potential energy, and the greater the mass, the greater the energy change. The stored potential energy is then converted into electricity by spinning a generator when the mass is lowered to its initial position [30].

The average cost per unit (kWh) generated is competitive: the construction price is around EUR 6 to 8 million (50% cheaper than lithium batteries), and they reach efficiencies above 80% (higher than other technologies), have high durability (according to the promoters, these technologies usually have more than 25 years of operation without degradation and more than 40 years with almost no loss of performance), lower environmental impact (due to the absence of waste in the life cycle as in the case of batteries), great capacity to withstand frequency events at a very competitive cost (with fast responses unlike other technologies such as CAES) and promote the local economy by not requiring raw materials from third countries (as in the case of rare earths for batteries).

Even though these characteristics may currently be competitive with other storage systems, it will be difficult to lower their costs over the years of their operation, making them less competitive with other technologies whose cost decreases over the years due to the economy of scale. Additionally, they are technologies of considerable size and have a slow response time when storing large amounts of energy.

Although there are several ways to develop this technology, the use of underground coal mines is the most competitive option for the following reasons:

- The larger the volume of the mine, the greater the energy storage capacity of the plant and the more efficiently it can adapt to needs.
- It utilises disused space without the need to invest in a new installation, reducing the environmental impact and extending the life of the mine.
- They reuse machinery used in the mine without the need to invest in new assets.
- Maintenance costs are kept to a minimum by using galleries that are already in optimum health and safety conditions.

### 3. Results

Having described the technologies that are the subject of this research, to prove their applicability and current development, the following are real success stories that have been developed, some of which were achieved with the initiative of this research team.

#### 3.1. Compressed Air Energy Storage (CAES)

SMART MINENERGY Project was a pre-competitive development of a safe and efficient compressed air energy storage system using abandoned mine voids.

The project, developed by the research team, was included in the “Co-Collaboration Challenges” line within the State R&D&I Programme. This initiative was oriented towards the Challenges of Society within the framework of the State Plan for Scientific and Technical Research and Innovation of the Ministry of Science and Innovation. The project, with code TRC2019-006874-3, had an execution period of 22 months and an overall budget of EUR 840,399, with funding from the Ministry amounting to EUR 627,182 (Figure 6).



Figure 6. SMART MINENERGY Project.

The SMART MINENERGY Project was carried out in the Iberian Market with the aim of being close to the new energy storage centre, controlling the entire process and having a known business network for the improvement, fine-tuning and maintenance of the installation. In this sense, different reports on the valuation of old mines in the Asturias Basin were used. It was determined that in the province of León alone, there was capacity for an installed power of 3420 MW in 47 abandoned inland mines. This fact marked the project, leading to the selection of the province of León as the target area of the study and its centre of operations. After the application of a multi-criteria algorithm, the Sarita Mine was selected as the ideal location for the prototype.

The achievement of this pre-competitive prototype under the SMART MINENERGY project, together with the adoption of an adiabatic cycle in the compression and decompression of air, would make it possible to achieve a renewable energy storage system with an efficiency of over 70% and at competitive costs.

The initially proposed prototype was 10–30 m long with a cross-section of 10.5 m<sup>2</sup>. This would result in a volume of approximately 105–315 m<sup>3</sup> and a pre-pressure range of 53–124 bar. With these conditions and a compressor sized at 170 kW installed power, 714 kWh of energy would be stored and fed into the grid under adiabatic conditions.

The aim was to preserve the horseshoe section of the original gallery, but the effect of other gallery geometries was also studied. As the original support, a calculated reinforcement of at least 20 cm of shotcrete was completed in order to withstand the new stresses to which the CAES warehouse would be subjected.

The original gallery located in the mining infrastructure of the Santa Bárbara Foundation, in addition to being reinforced in its support, would be sealed with two 3–4 m thick concrete plugs, which would create an airtight volume in which to store the compressed air.

The sealing plug will isolate the confinement from the rest of the galleries. A wedge-shaped design has been defined to withstand the high longitudinal pressures to which it will be subjected. The whole assembly will be completed by a system of sensors to monitor the behaviour of the confinement device.

In conclusion, the SMART MINENERGY project has made it possible to develop a pre-competitive and replicable demonstration prototype for the use of underground infrastructure (tunnels and galleries) as energy storage in the form of compressed air. This storage system will also contribute to increasing the load factor of intermittent renewable sources (solar and wind), thus facilitating the deployment of these energy sources and further reducing external energy dependence and favouring the decarbonisation of the electricity sector.

### 3.2. Hydrogen

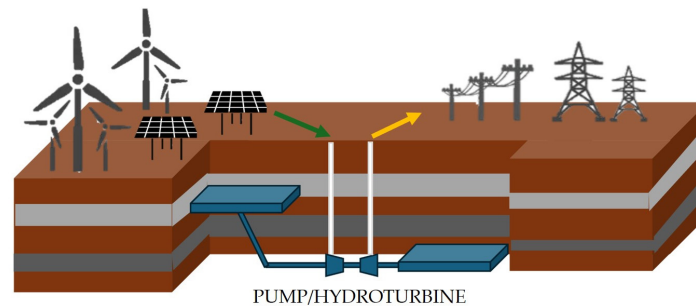
As a result of the application of hydrogen technology, the UNDERGY project stands out. This project, located in southern Spain, has pioneered the idea of injecting hydrogen in place of pre-existing methane into a depleted field. The geological constitution of the deposit has facilitated the process, as it has a depth of about 800 metres, the cover rock is a resistant marl with very little porosity, and the storage rock is a sandstone that is free of other elements, such as iron oxide compounds, carbonates, sulphur and cyanobacteria, the latter of which are susceptible to producing methanisation when hydrogen is introduced.

The development of this project demonstrates that the injection of hydrogen into abandoned deposits and mines can be made a reality and encourages further research in cases such as the one covered in this special feature on coal mines.

### 3.3. Mini-Hydraulics

At present, there are no real cases of hydraulic pumping technology being used in mines (Figure 7), but there are several references worldwide. The most important ones are as follows:

- South Africa: the use of pumped hydro in gold mines has been considered, specifically in the West Rand gold mine [31].
- Germany: it has been reported that the Posper-Haniel coal mine plans to become a 200 MW PHS plant [32].
- Spain: PHS plants were proposed to be developed in more than 30 coal mines in the Asturian Central Basin [33].
- China: the number of closed coal mines has reached 3868, with a production capacity of more than 350 million [34].

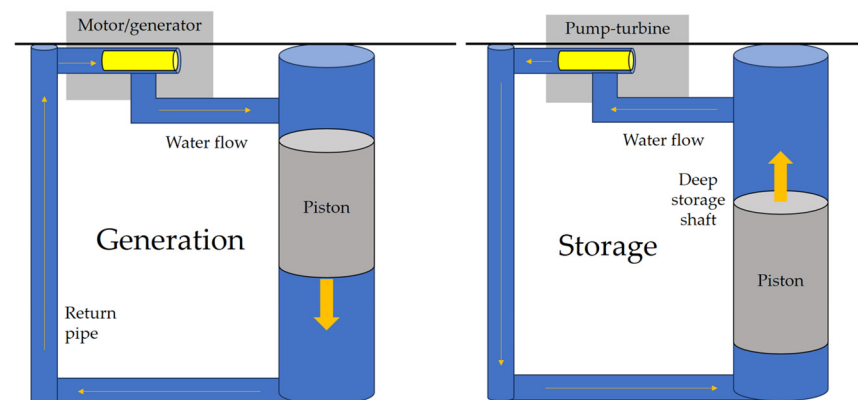


**Figure 7.** Pumped hydroelectric storage system using abandoned coal mines.

### 3.4. Gravity Underground Energy Storage (GES)

There are several references:

Gravity Power Module (GPM): This is a technology developed by the US company Gravity Power, founded in 2021 and based in California [35]. As shown in Figure 8, this system uses a large piston suspended in the shaft of a water-filled underground well with sliding seals that help prevent leakage around it. The system works as a closed loop, which means that the well is filled all at once, mainly at the start of operation.



**Figure 8.** GPM technology scheme.

- Scottish company Gracitricity, founded in 2011, proposes a system that uses the geology of the ground to support heavy weights suspended in a deep shaft by cables attached to winches and store energy in rehabilitated and newly constructed mine shafts (Figure 9).

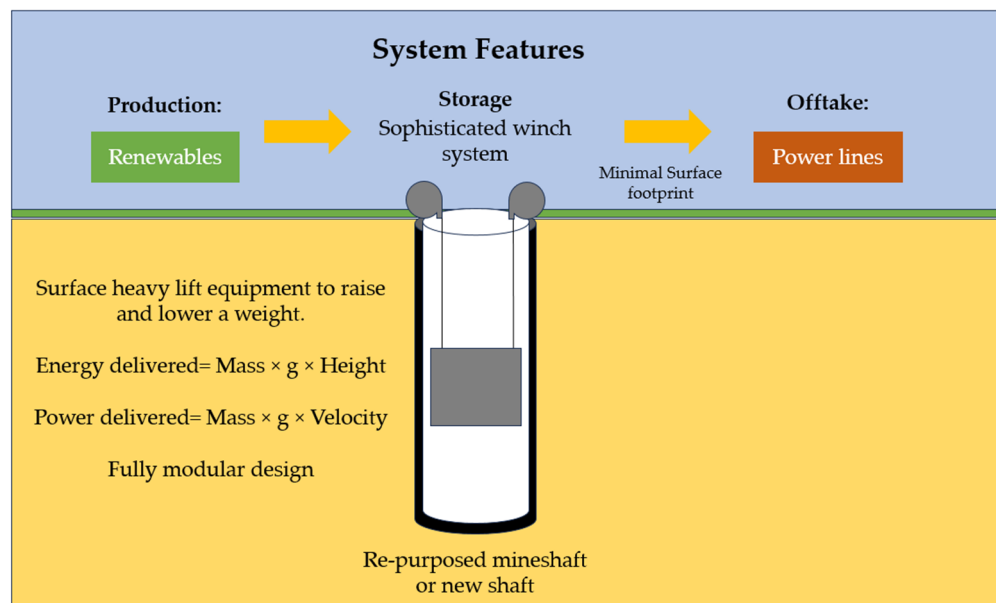


Figure 9. GraviStore technology scheme.

#### 4. Discussion

From the above, the reader will have understood that the application of the different ideas and technologies described in this article will become a challenge for our sector, certainly not without its problems, but with very interesting and novel outcomes.

Table 1 compares the five technologies proposed in the article, giving a picture of their applicability in economic and technical terms. In addition, the maturity and performance of the different technologies can be checked in the table. Additionally, the last column in the table indicates which technologies have been implemented in real cases and which are still at the project idea stage.

Table 1. Comparative table.

Technology	Economic	Technical	Stage	Performance	Projects
Solar Thermal	High costs	Complexity	Concept	Long operation life	No real cases/No references
CAES	Low costs	High capacity	Medium maturity	40–100 years	One project/Few references
Mini-Hydraulics	High investment	High capacity	Great maturity	40–80 years	No real cases/Multiple References worldwide
Hydrogen	High costs	In the future, it will allow high capacities	Under development	Low number of cycles	Few references
GES	Low costs	Medium capacity	Feasible	Long operating life	Several references worldwide

For all technologies, the environmental aspect is key for the following reasons: reusing an infrastructure reduces environmental impact by optimizing the life cycle. Additionally, the social problems caused by the utilisation of coal mine resources are not negative. The infrastructure developed in the last century presents a good opportunity to define new energy mining in the 21st century: abandoned galleries with large spaces and good stability could be transformed into optimal infrastructures to store energy, achieving the economic

reconversion of mining regions with the introduction of a circular economy to the mining sector for a current and necessary purpose.

However, at the technical level, there are still many challenges to completing the projects proposed in this article.

Today, the transformation and modernisation of coal mines has begun. The challenge is to get on board with enthusiasm, modern engineering and, of course, funding. The other option would be to decide that these alternatives are not viable or desirable for society, that they are not useful and modern, and that they are not aligned with the SDGs and, ultimately, with the future.

Faced with this situation, we believe the answer is clear: let us transform our facilities by transferring useful and valid technologies, developing what is necessary to make them a reality in our sector and revitalising our companies and facilities.

## 5. Conclusions

In conclusion, this study has outlined a number of promising technologies for the reuse of underground coal mines, supported by a variety of fundamental justifications. It has been shown that these mines represent versatile spaces capable of accommodating a wide range of activities beyond traditional coal mining. Their value is enhanced by the existence of approved industrial permits and established infrastructure, including serviceable electrical installations, compressed air systems and highly skilled personnel of different disciplines. By taking advantage of these underground facilities, surface space is freed up for other uses, contributing to better land planning and the revitalisation of de-industrialised areas.

Importantly, this initiative is closely aligned with the Sustainable Development Goals (SDGs), addressing key issues such as energy independence, economic revitalisation and job creation. It also provides a unique opportunity to develop economically attractive businesses and attract investment, which could boost economic growth in regions affected by the cessation of mining activity. With a large number of available mines and a clear economic and social potential, this proposal not only contributes to the sustainable development of the mining environment but also promotes energy efficiency and stimulates innovation in coal and energy-related technologies, thus positioning these former mines as pillars of future economic and technological development.

**Author Contributions:** Conceptualisation, J.P.d.l.F.; methodology, M.d.l.C.C.; validation, P.M. and M.F.O.; investigation, J.P.C.; resources, J.P.d.l.F., M.d.l.C.C. and J.P.C.; writing—original draft preparation, J.P.d.l.F.; writing—review and editing, M.d.l.C.C. and J.P.C.; supervision, P.M.; project administration, J.P.d.l.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

**Acknowledgments:** To the collaborators and partners of the Technical University of Madrid.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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