Gravity Storage.

A **new solution** for large scale energy storage.

www.heindl-energy.com

Engineered by HEINDL ENERGY

Heindl Energy.
Gravity Storage in brief.

Gravity Storage

Dear Reader,
Renewable energy from wind and solar sources is now making a rapidly increasing contribution to global power supplies, with a growth rate of over 20% per year. Solar energy, in particular, is available in sufficient quantities in many regions around the world, and can currently be converted into electricity at a cost between 30 and 40 USD/MWh. After depreciation, in fact, a photovoltaic farm typically produces energy at a cost of less than 10 USD/MWh. This will change our energy supply system as we know it:

- Excess power from renewable sources needs to be shifted to times of little or no production in order to take full advantage of PV and wind.
- Fluctuating generation will force grid operators very soon to rethink how they balance power and control frequency.
- Power grids will need to be developed in such a way that enhances their ability to receive the excess energy generated from fluctuating sources.

The ability to store power on a large scale will be an essential feature of any sustainable and reliable future energy supply system.

Gravity Storage is the answer.

After analyzing the development of the solar industry for many years, Eduard Heindl came to the conclusion that a complete energy transition will only succeed when renewable energy generation is combined with cost-effective storage. As a physicist, it was a short step for him to utilize the power of gravity in addressing this challenge.

Also known as Hydraulic Rock Storage, Gravity Storage is a new concept for storing power on a multi-GWh scale. We believe that Gravity Storage will be a game-changing solution for the world´s energy supply, as photovoltaic (PV) and wind power become the cheapest source of electricity and the demand for power continues to increase rapidly.

Gravity Storage makes possible the reliable 24-hour supply of renewable power at steady, predictable costs.

It will also play a part in increasing and ensuring the resilience and reliability of the power grids to which Gravity Storage plants are connected.

How does the technology work?

A piston of rock of diameter 100 m or more is separated from the natural surrounding rock. In times of excess power generation water is pumped under the piston, raising it and thereby storing potential energy.

When the stored power is needed, water is released from beneath the piston, allowing the piston to lower, and used to drive turbines.

Generators are then used to produce electricity, which is fed into the power grid. With each doubling of the diameter, storage capacity increases at a rate that is roughly proportional to the fourth power of the diameter while construction costs only increase at a rate that is roughly proportional to the second power of the diameter. This fact, a result of the applicable laws of physics and geometry, is of groundbreaking significance for the cost efficiency of Gravity Storage. It has a round-trip efficiency of over 80%, similar to pumped hydro. Unlike Pumped Hydro Storage, Gravity Storage does not require any elevation difference. Suitable geological conditions are required, but these can be found in many regions around the world.

Gravity Storage plants can be built using proven technologies from mining and tunnel construction, and can be expected to have a service life of 60 years or more.

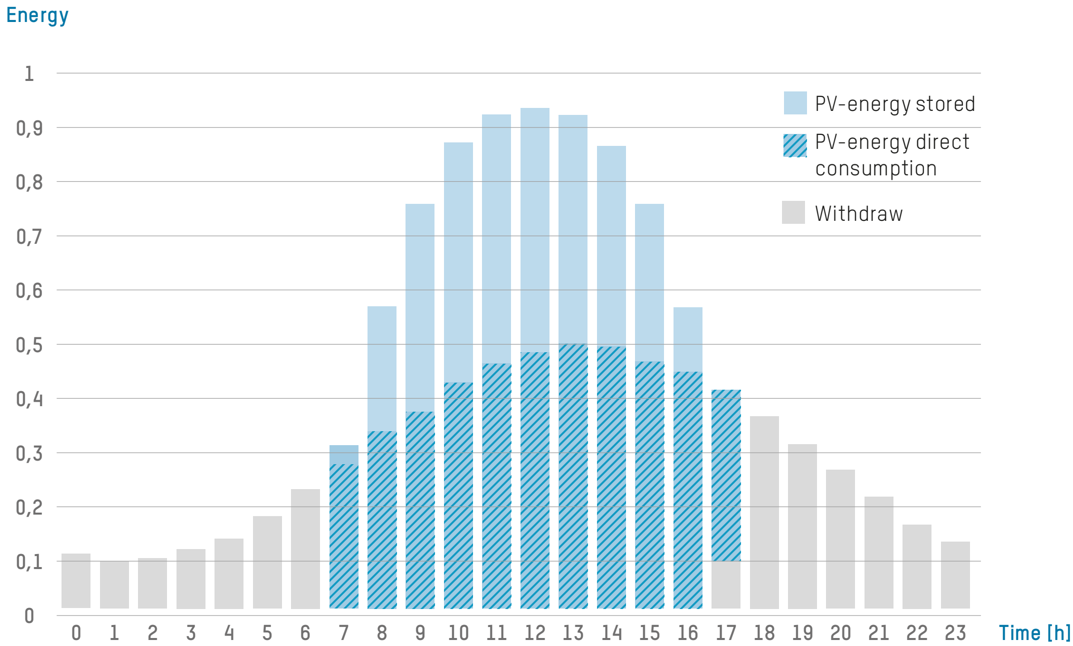
No chemicals or other hazardous substances are used during operation, with water and rock being the key materials required. Applied on a large scale (e.g. 8 GWh), Gravity Storage can be built at a total capex of less than 200 USD per kWh of storage capacity. At Heindl Energy, we have developed the promising Gravity Storage technology with a diverse team of engineering and geology specialists.

With this brochure, we invite you to take a closer look.

Sincerely,
Professor Eduard Heindl

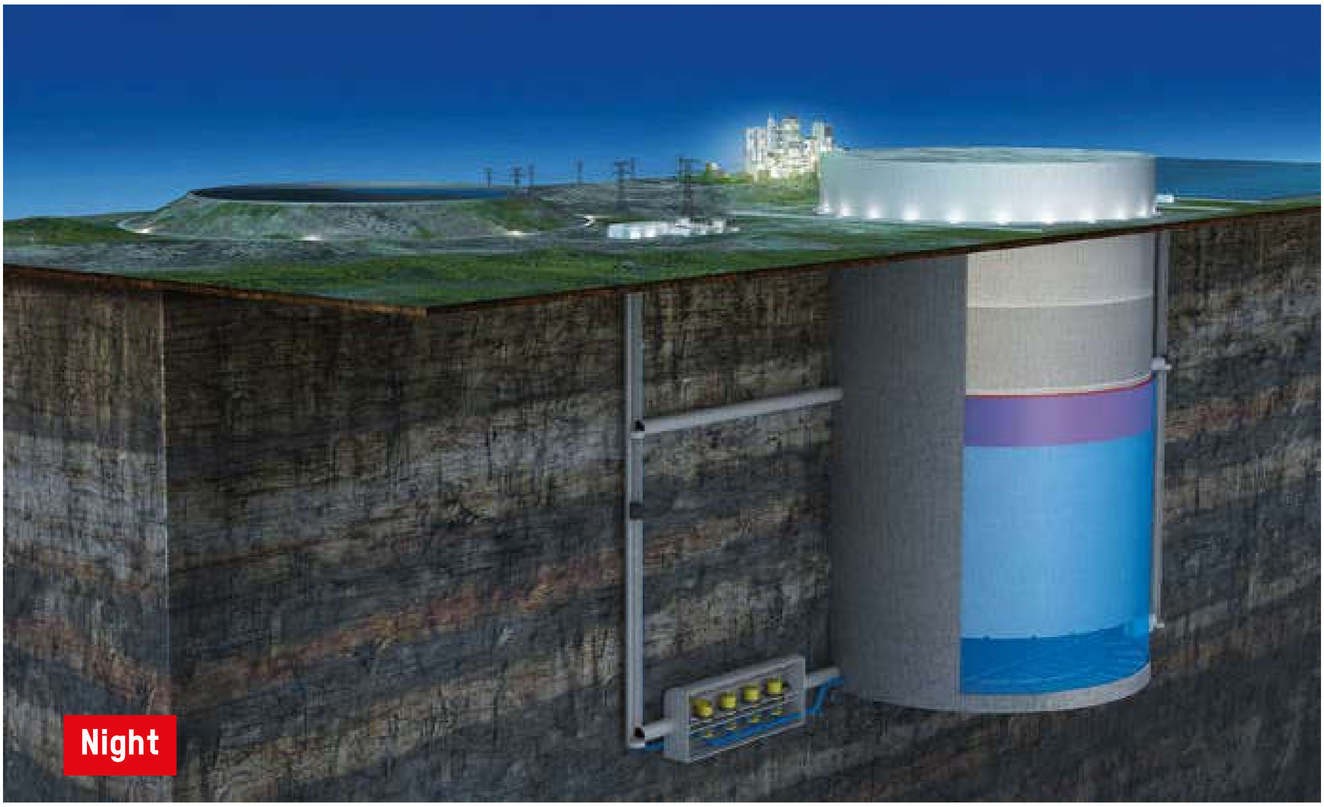
Gravity Storage applications.

In the long run, renewable energy sources combined with suitable storage solutions will ensure a **reliable, sustainable energy supply**.



Example of the continuous energy supply with a large PV system and a Gravity Storage plant of suitable diameter.

Fluctuating, renewable energy sources have a very promising future. But large-scale solar and wind energy generation requires large-scale energy storage solutions in order to provide continuous power, day and night. The increasing ability of PV to directly meet daytime energy needs will increase the need to balance out fast-changing loads in the system. This will also increase the demand for stored energy in the years ahead.



Gravity Storage has much to offer

- in regions where PV energy or wind power is expanding and large-scale storage is required
- in energy markets with a particularly high demand for supply security and ancillary services, and
- in areas where the traditional alternative, Pumped Hydro Storage, is not feasible due to a lack of elevation difference in the local terrain.

Physical principle.

Gravity Storage has **enormous technological potential** as an efficient energy storage solution.

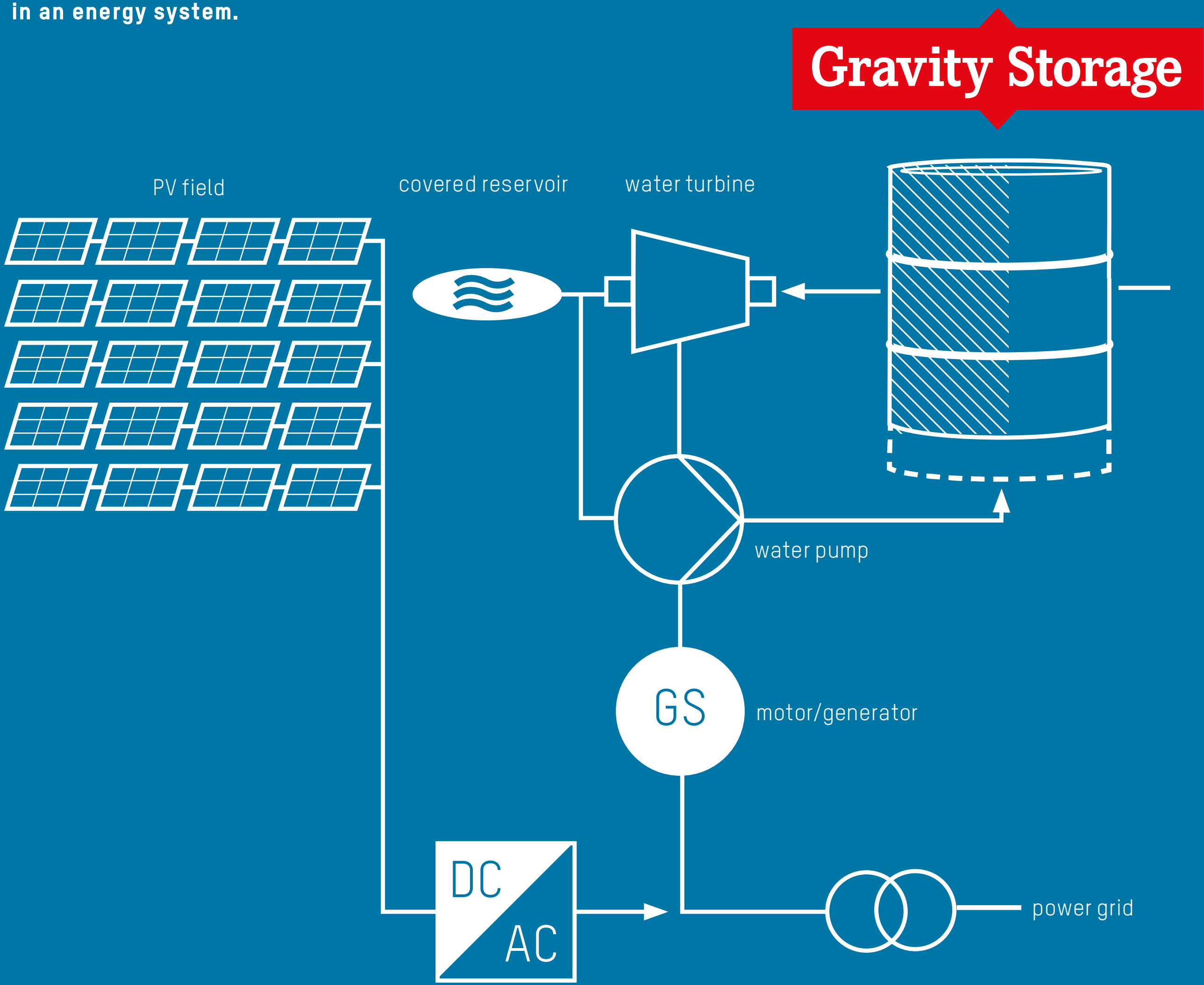
Gravity Storage operates on the principle of converting electrical energy into potential energy by lifting a large mass of rock by pumping water underneath it, and converting it back into electrical energy when required by using the high-pressure water to drive a turbine.

The mass of rock is in the shape of a large piston that has been detached from the surrounding bedrock, creating also the cylinder inside which the piston can move up and down. Both the piston and the cylinder are sealed against water loss by means of a suitable lining, as done in the tunnel construction industry. The water that is pumped under the piston is retained by a high-performance rolling membrane which connects the piston to the cylinder, right around the piston's circumference. A pump, driven by excess electricity when available, forces water beneath the rock piston, lifting it. When electricity is required, the pressurized water is directed through a turbine to generate alternating-current electricity that can then be fed directly into the supply grid. This process has a round-trip efficiency rating of over 80%. The amount of energy that can be stored is proportional to the piston's weight and the height by which it can be raised. As a remarkable consequence, increasing a piston's diameter and height by a factor of two causes its energy storage capacity to increase by a factor of 16. But since the cost of construction of a Gravity Storage plant is heavily dependent on the cost of separating the piston from the surrounding rock, it can be estimated that the same increase in piston size only causes construction costs to increase by a factor of four. In other words, Gravity Storage quickly becomes much more cost-effective as piston size increases. For example, if the diameter doubles, the cost per kWh reduces by a factor of four (to just 25%).

This correlation between energy storage capacity and construction cost clearly favors the construction of large Gravity Storage plants rather than smaller ones. A diameter of approximately 150 m is recommended, corresponding to a storage capacity of one GWh. When used in combination with PV energy generation, such a Gravity Storage plant can ensure stable, highly competitive production costs for many years.

Usable Storage capacity (GWh)	1.0	3.0	8.0	80.0
Diameter [m]	150	200	250	500
Volume of water [1000m³]	1,340	2,380	5,990	38,580
Pressure [bar]	41	67	71	105

Electrical scheme of Gravity Storage in an energy system.



Gravity Storage plant construction.

Built using **advanced construction technologies** from the mining and tunnelling industries.

Construction steps:
- Drilling/excavation of access shafts and tunnels
- Excavation/separation of walls and base
- Sealing and strengthening of excavated surfaces using concrete
- Installation of rolling membrane seal around piston
- Installation of machinery and electrical plant
- Construction of reservoir
- Connection to power grid

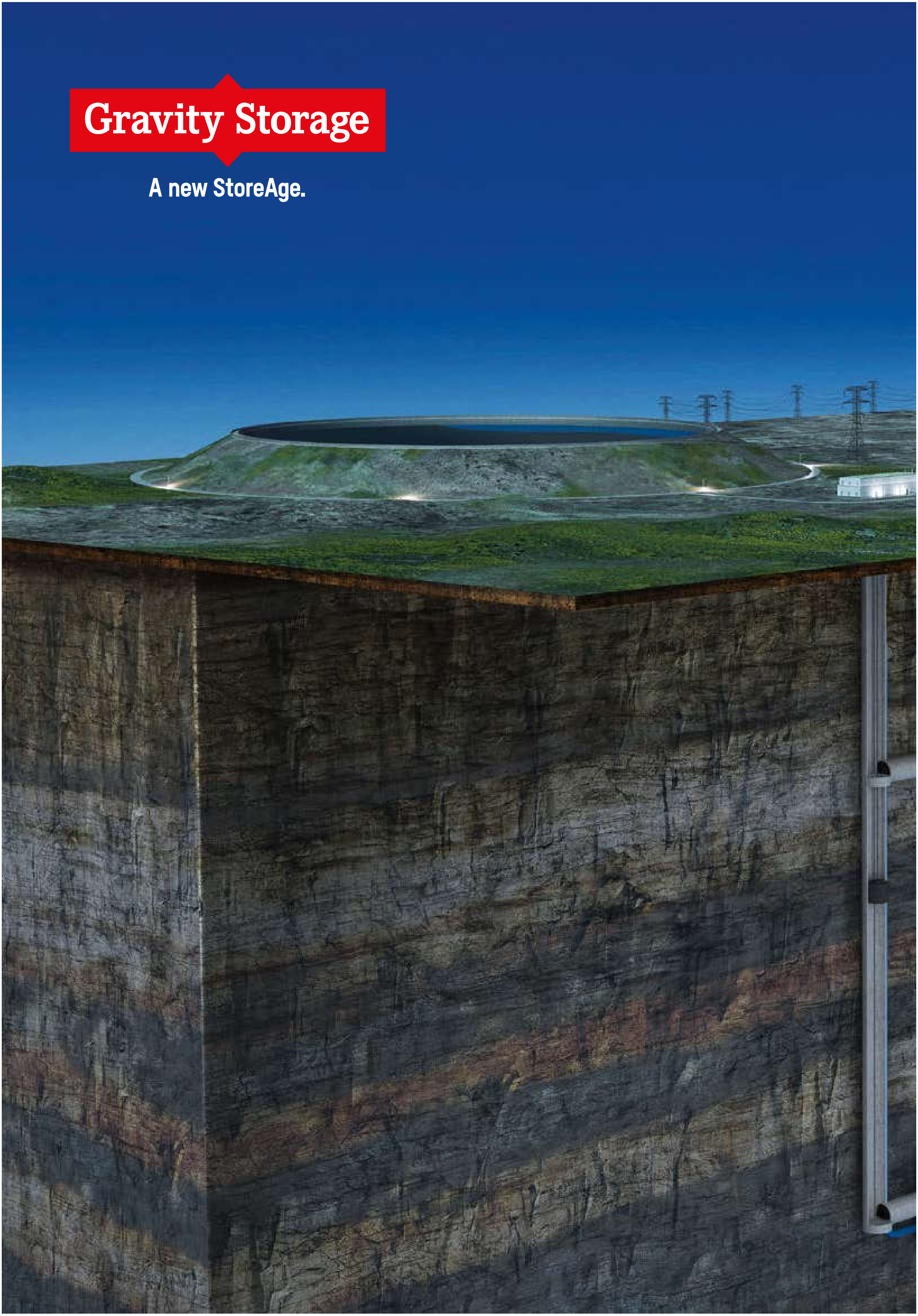
Well-established mining and tunnelling techniques are used to construct a Gravity Storage plant. Two access shafts are excavated, right down to the base level of the planned cylinder. Then the excavation of the ring-shaped space between the cylinder and the piston can be executed in parallel with the separation of the piston base from the rock beneath. Separation of the piston's side from the surrounding rock, downwards from the surface, can be done using classical drilling and blasting or alternatively using sophisticated cutting techniques, with newly developed rock-cutting machines offering high progression rates. As an alternative method also rock cutting techniques using diamond wire saws are investigated. In the process, all exposed surfaces are sealed with geomembrane or metal sheeting to protect against deterioration and water ingress. Where required to stabilize the excavated rock surfaces, various rock anchoring techniques can be employed, depending on the type of rock encountered.

At the same time, all other required elements, including a subsurface chamber for pumps and turbines and an access shaft to serve it, are constructed. Construction on site might be expected to last approximately five years in total.

The operating life of the system is practically unlimited, since its main component – the rock mass – is extremely durable. The operating equipment, such as pumps, turbines and generator, can be designed for a service life of 60 years or more, and can then be replaced as required.

One method for separating the piston from the surrounding rock is using hard rock cutting machines like the reef miner illustrated above.
Pictures: Sandvik AB, www.sandvik.com

The separation of the piston base from the underlying rock is a particular challenge. It is based on the well-established "bord and pillar" method of mining/extraction, with a series of parallel tunnels excavated as a first step (the remaining rock between the tunnels supporting the weight of the piston). Reinforced concrete pillars, split at mid-height to allow the piston to be raised in service, are then constructed at regular intervals along each tunnel, enabling the remaining rock to be excavated thereafter. As an alternative to the excavation of the whole rock mass beneath the piston, where appropriate for the given geological conditions, the remaining rock between the tunnels may be split at midheight as illustrated in center fold.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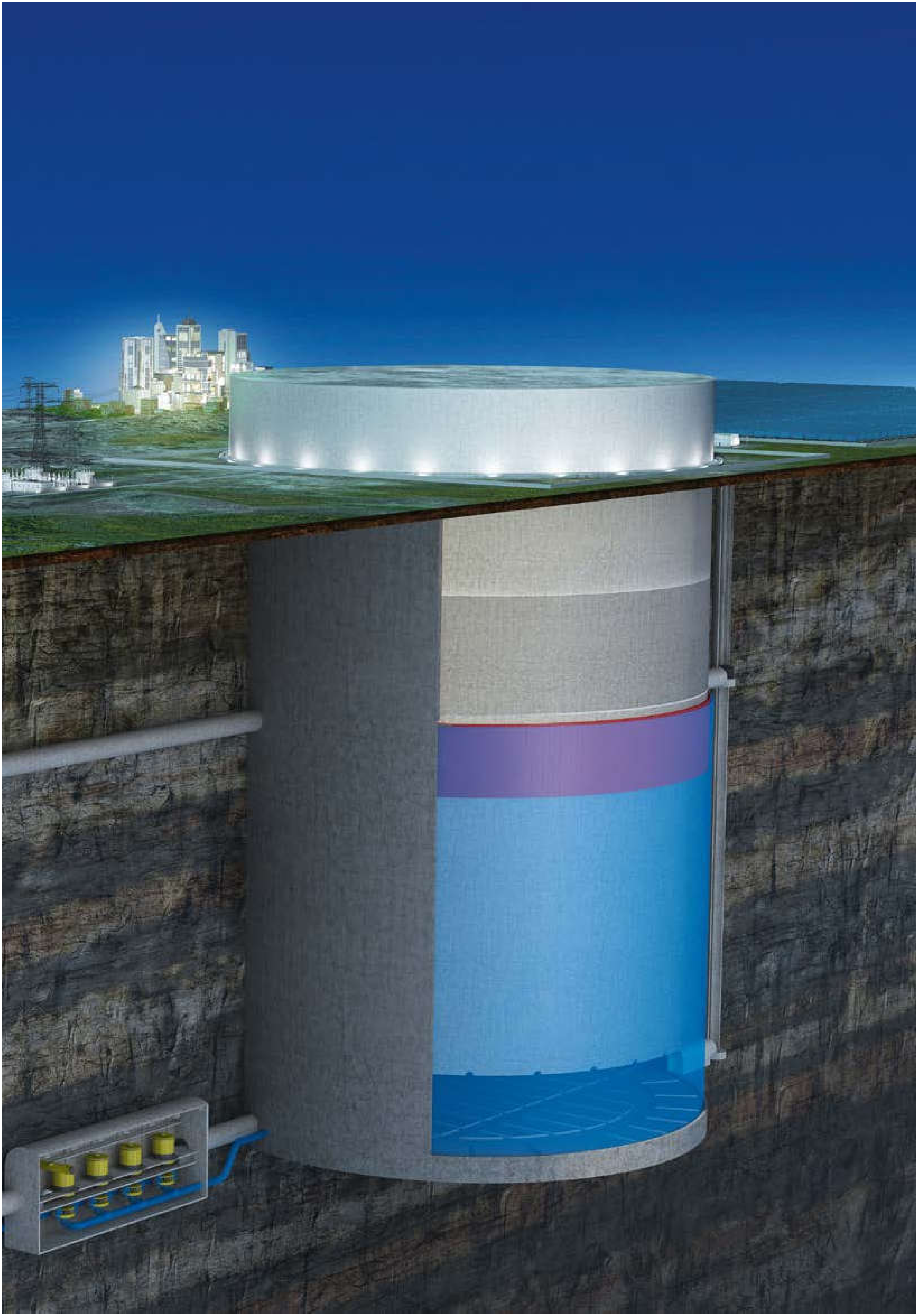
A new StoreAge.



A Water reservoir

Water is used as a hydraulic medium to lift the piston and, when routed through the turbines, to generate electricity. The volume of water needed is much less than is required by a pumped hydro storage plant of the same storage capacity.
For example, a Gravity Storage plant of capacity 8 GWh requires only approx. 6 Mill. m3.

B Water for hydraulic lifting

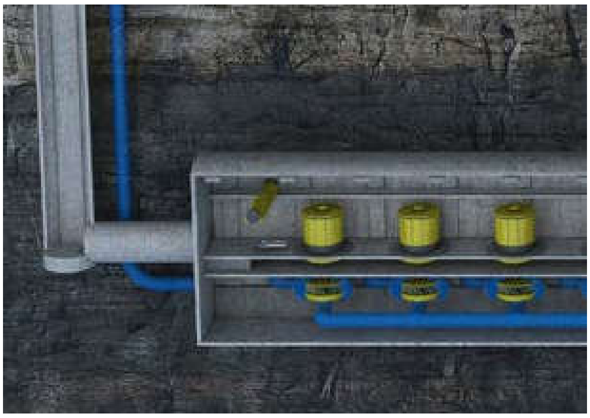
In order to store the water, a reservoir must be constructed nearby – unless a natural basin or lake can be used. To minimize loss of water due to evaporation, the reservoir can be covered with floating sheets of suitable material.

C Stabilization system and surface protection

Around the top of the piston, a multi-chamber ballast tank is provided, the chambers which can be filled with water as required to balance the piston if needed.

D Machine cavern

The turbines, pumps, generator and transformer can be located at the surface or underground in a specially constructed cavern. In principle, these items of plant are used in very much the same way as they are used in pumped hydro storage plants.

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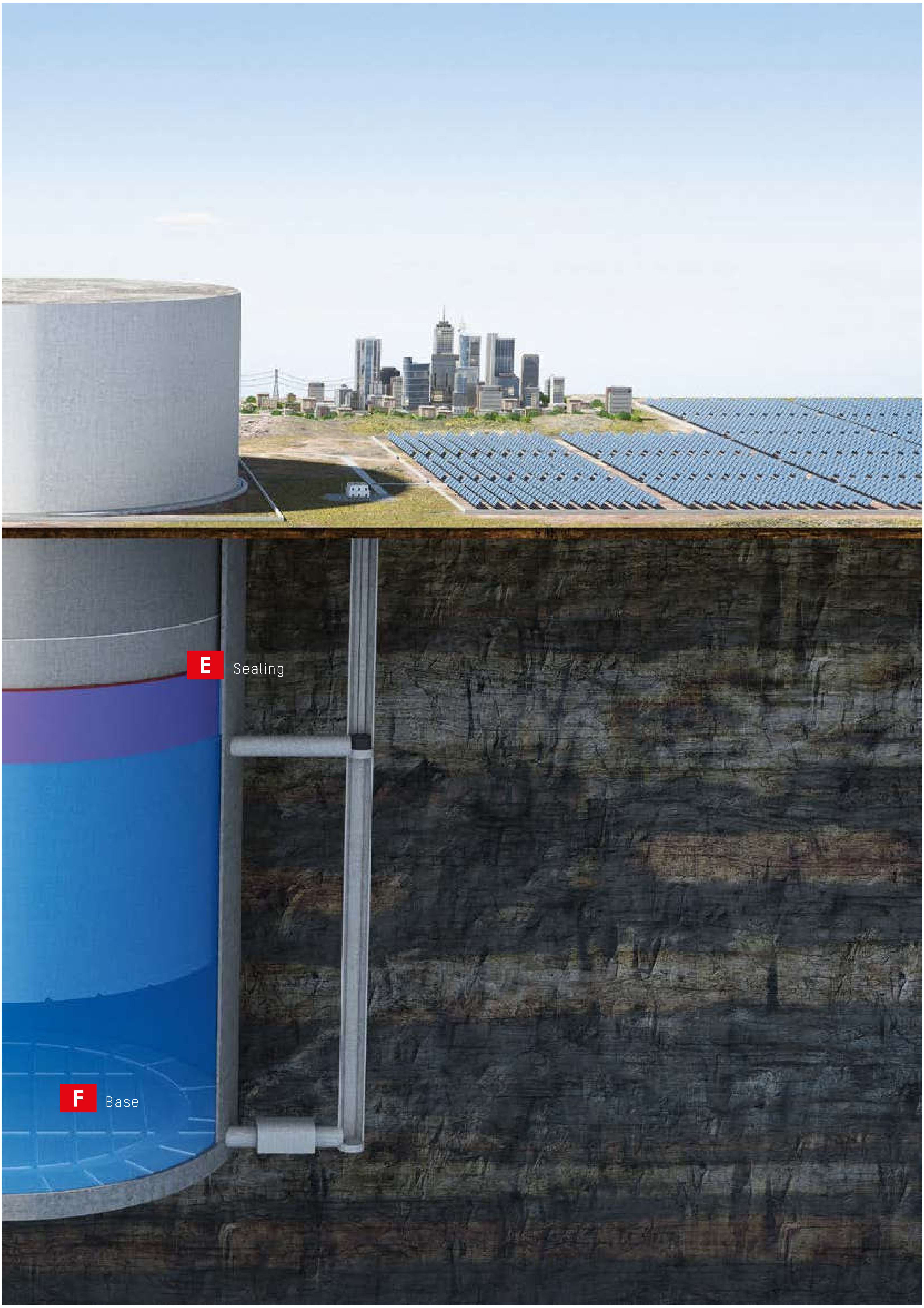
C Stabilization system and surface protection
A Water reservoir
B Water for hydraulic lifting
D Machine cavern


E Sealing
F Base

E Sealing

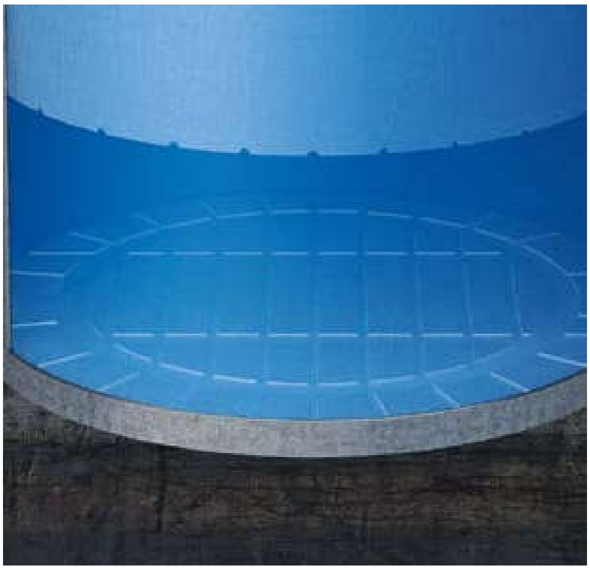
The solution to the key challenge of sealing the gap between the piston and the cylinder, retaining the highly pressurized water below, is a "rolling membrane" which is securely connected to both piston and cylinder. The rolling membrane is assembled in situ from individual membrane elements that connect radially from the piston to the cylinder. The membrane elements, similar to conveyor belts as used in the mining industry, consist of vulcanized rubber reinforced with steel cables or aramid fibers.

Features and design requirements

- Typical pressure at rolling membrane: 50 to 60 bar
- High resistance to abrasion
- Adaptable to the piston's fluctuating position
- Self-centering
- Full access possible for maintenance

F Base

At the base of the cylinder, a network of pillars - either cut from the rock or constructed from concrete - will support the piston when all water is removed (e.g. for maintenance purposes).



The business case for Gravity Storage.

Gravity Storage completes the business case of large-scale production of **energy from renewable sources**.

An illustration of Gravity Storage of 8 GWh in real scale.

The basic business model for Gravity Storage (described for the case of solar): Excess power from PV plants is stored (purchased) during the day and discharged (sold) at night. The demand for storage is guaranteed by the requirement for utility companies and PV farm operators to provide a reliable power supply at all times of day or night. Grid operators also need bulk storage to balance out fast-changing loads in the system. The basic business model for Gravity Storage combined with wind power generation is analogous.

Total investment costs

Plant construction cost depends primarily on the size of the piston and the geological conditions at the specific location. It is estimated that total investment costs (including planning, grid connection, etc.) for a plant of 8 GWh storage capacity (with diameter approximately 250 m) will typically amount to 200 USD/kWh in Europe. In other regions the costs will be even lower. The investment can be expected to give a return for at least 60 years, and maintenance costs are very low.

Revenue models

The design of the Gravity Storage plant, in terms of pump and turbine dimensions, etc., depends on the operator´s intended application. There are several revenue models that may then be applied, which can be combined with each other if desired:

1. **PPA (Power Purchase Agreement),**
   combining production and storage capabilities, is particularly promising – delivering 24-hour electricity at a fixed price for 20 years or more. Such PPAs, including "production + storage", are ready for market as soon as a low-cost bulk storage solution is available. This type of supply requires daily storage of 6 to 14 hours to ensure a 24-hour supply.

2. **Provision of ancillary services,**
   such as
   - frequency regulation,
   - voltage support,
   - black start capability and
   - spinning reserve capacity.

   These services require storage solutions for periods from a few seconds up to several hours. In this case, the return will come from specific service fees and grid charges.

3. **Provision of balancing power,**
   when intermittent generation requires fast ramping capabilities. An ideal storage solution must be cost-efficient,sustainable and reliable. Gravity Storage satisfies these requirements.

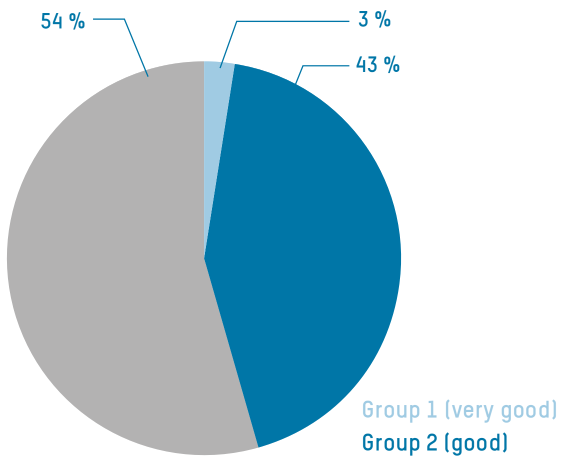
Location factors and geological potential.

Gravity Storage requires **suitable geological conditions** but no elevation difference.

Gravity Storage plants should be located in areas with solid bedrock. The most favorable sites have stable, little-faulted rock such as granite or compact layers of otherwise solid rock material. The geological conditions must first be assessed in detail by a team of geologists. Heindl Energy provides all services required to evaluate potential sites.

In order to estimate how widespread suitable geological conditions for Gravity Storage might be, Heindl Energy has conducted a study analyzing different types of magmatic, metamorphic and sedimentary rock. A total of 117 globally distributed sites where analyzed, and a classification performed based on the internationally recognized Rock Mass Rating (RMR) system. The suitability of the geological conditions for construction of a Gravity Storage plant was found to be "very good" (RMR I) at 3% of the evaluated sites, and "good" (RMR II) at 43%. The remaining sites would require extensive, expensive rock stabilization measures, or would be suitable only for a relatively small Gravity Storage plant.

Geological suitability of evaluated sites for construction of a Gravity Storage plant (corresponding number of sites in brackets).



In addition, a large volume of water (depending on the size of the Gravity Storage – e.g. around 6 million cubic meters for a piston with a diameter of 250 m) must be available. This water is constantly re-used, and thus must only be provided once.

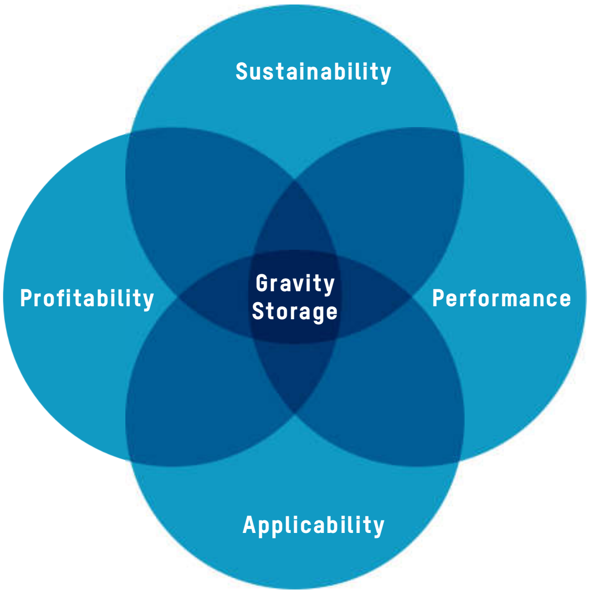
Advantages of Gravity Storage.

Profitability

- Gravity Storage is economically superior to all other energy storage solutions: Low investment costs of approx. 200 USD/kWh storage capacity (for an 8 GWh solution, based on German prices)
- Low running costs of less than 1% of capex per year

Sustainability

- Minimal raw material requirements ("just rock and water")
- Requires much less water than pumped hydro storage
- Small land footprint per kWh
- No chemicals required
- Long service time beyond 60 years



Applicability

- Gravity Storage requires no elevation difference (suitable for flat terrains, unlike pumped hydro storage)
- It can be easily integrated into any high voltage transmission grid
- More than 40% of the continental surface is basically suitable for Gravity Storage

Performance

- The system buffers fluctuating energy on a GWh-scale and maximizes use of excess energy by enabling it to be used during periods of low generation
- High round-trip energy efficiency of 80% or more
- Provides a variety of system services: dispatching, black start capability, rotating masses
- Fast and steep load ramping comparable with that of any modern pumped hydro system
- Discharging time can be tailored to each operator's individual needs

The Mission.

Heindl Energy´s mission is to transform the world's energy storage landscape, paving the way towards a sustainable, clean power supply.

By solving the energy storage challenge in this way, we aim to support the development of reliable power supply systems that are 100% based on production from renewable sources.

The concept of Gravity Storage was invented by Professor Eduard Heindl and has since then been continually developed by the Stuttgart-based company Heindl Energy GmbH, supported by a team of civil engineering, geology, mining and geophysics specialists.

Shareholders of Heindl Energy are Professor Heindl and the Swiss-based financing company HTG Ventures AG.

References
Picture p. 3: ©Thomas Klink
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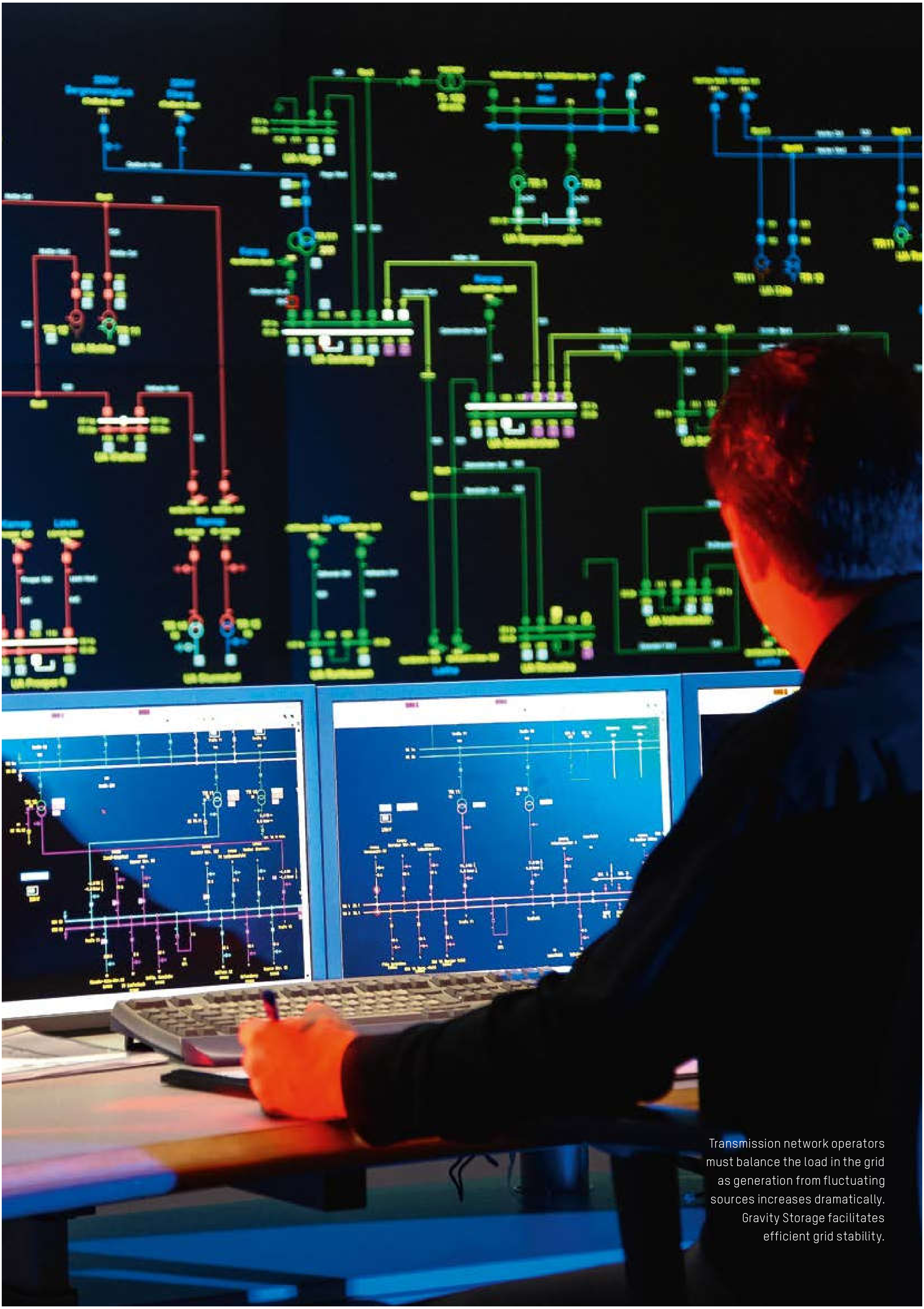
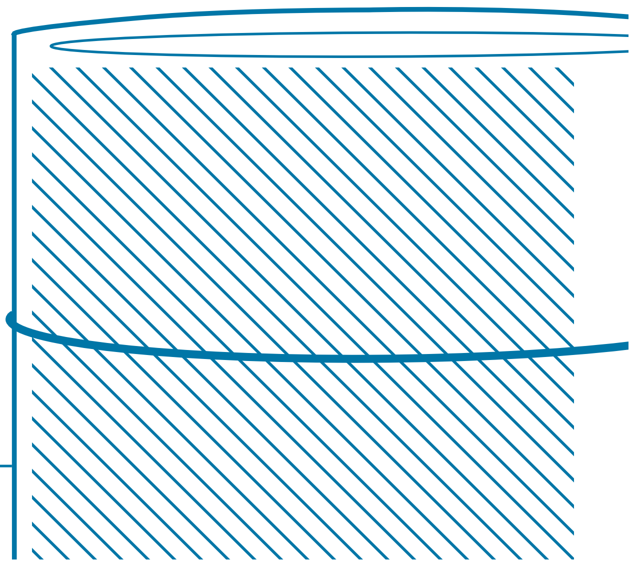
Illustrations: Max Kulich,
www.maxkulich.com



Transmission network operators must balance the load in the grid as generation from fluctuating sources increases dramatically. Gravity Storage facilitates efficient grid stability.



Contact

Heindl Energy GmbH
Am Wallgraben 99
70565 Stuttgart
Germany

Phone +49 711 6569689-0
info@heindl-energy.com