



ADELE – ADIABATIC COMPRESSED-AIR ENERGY STORAGE FOR ELECTRICITY SUPPLY

RWE POWER – ALL THE POWER

RWE Power is Germany's biggest power producer and a leading player in the extraction of energy raw materials. Our core business consists of low-cost, environmentally sound, safe and reliable generation of electricity and heat as well as fossil fuel extraction

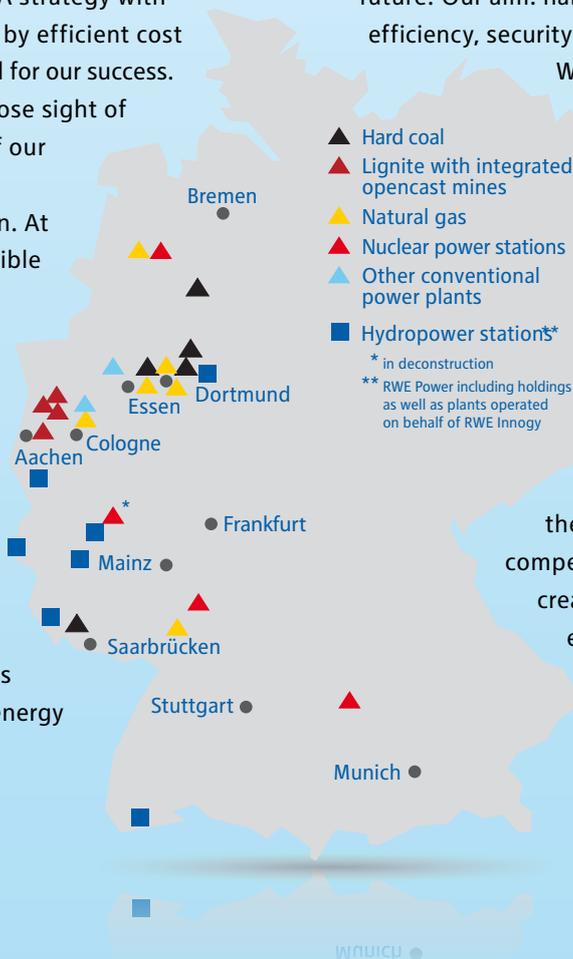
In our business, we rely on a diversified primary energy mix of lignite and hard coal, nuclear power, gas and hydropower to produce electricity in the base, intermediate and peak load ranges.

RWE Power operates in a market characterized by fierce competition. Our aim is to remain a leading national power producer and expand our international position, making a crucial contribution toward shaping future energy supplies. A strategy with this focus, underpinned by efficient cost management, is essential for our success. All the same, we never lose sight of one important aspect of our corporate philosophy: environmental protection. At RWE Power, the responsible use of nature and its resources is more than mere lip service. Our healthy financial base, plus the competent and committed support of some 17,800 employees under the umbrella of RWE Power enable us to systematically exploit the opportunities offered by a liberalized energy market.

In this respect, our business activities are embedded in a corporate culture that is marked by team spirit and by internal and external transparency. With an about 30 per cent share in electricity generation, we are no. 1 in Germany, and no. 3 in Europe, with a 9 per cent share. We wish to retain this position in future as well. And that is where we want to stay. Which is why we are investing our own energy in shaping and designing the energy supply of the future. Our aim: harmonizing the claims of economic efficiency, security of supply and climate protection.

We provide impetus – with our know-how, innovative technologies and considerable investment.

So research and development are of strategic importance for us. Our scientists and engineers are pursuing visions, tapping potentials, implementing ideas. This innovative power strengthens the company in the face of growing competition and on the way ahead. It creates the preconditions for a secure energy supply and economic success. That is what we are working for – with all our power.

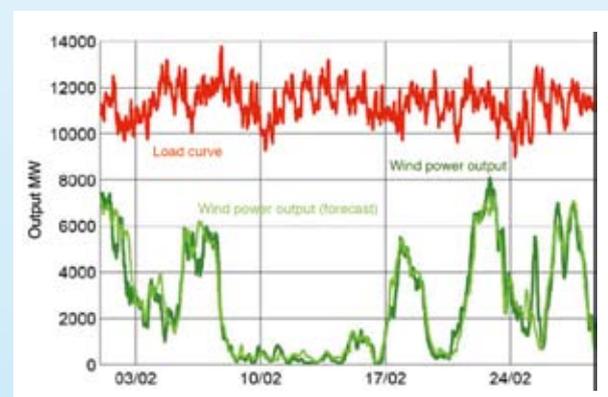


COMPRESSED-AIR ENERGY STORAGE (CAES) AS BUFFER FOR ELECTRICITY FROM WIND AND SUN

The demand for flexible balancing power to maintain grid stability shows strong growth.

By 2020, the share of renewable energy in Germany's power generation is set to rise from today's 15% or so to 30%. The biggest slice of the new-builds required – besides biomass – will be accounted for by wind power and photovoltaics: the renewal of turbines onshore alone and extensions offshore will double the installed capacity of wind power to nearly 50,000 megawatts (MW). The feed-in of wind and solar power is weather-dependent, however, and is extremely intermittent – as experience has shown – between zero and 85% of the max. installed capacity. So if the electricity grid is to remain stable, these fluctuations must be balanced. This is because the amount fed in and the amount consumed must be the same at all times. Today, flexibly deployable, conventional power plants are used for this, as a rule pumped-storage, natural-gas and hard-coal power stations.

In certain weather conditions, their capacities are already nearly exhausted today. Moreover, thanks to



Power consumption and power generation from wind in the VET grid zone (February 2008) (source: VDE study)

the growing share of combined heat and power generation (CHP), they will tend to decline rather than increase. Still, CHP plants, too, are not geared to the electricity demand; their operation follows the demand for heat. Upshot: the need for flexible power-plant capacity, i.e. for amounts of electricity available in the short term, is growing rapidly.

This is where storage technology comes in: whenever supply exceeds demand, e.g. on a windy day, the power can be stored and then fed into the grid again during a calm. If this succeeds on a large scale, the interaction of conventional power plants with renewable resources can be optimized. Storage technologies will not be a panacea, but could gain considerably in importance on tomorrow's electricity market.



ELECTRICITY STORAGE TODAY: PROVEN TECHNOLOGY, NEW APPROACHES

The technology of choice today is the pumped-storage power plant. In an excess power supply, water is electrically pumped into a reservoir on a hill, so that it can be discharged when power demand is high to drive a turbine in the valley.

Efficiency is between 75 and 85%. Today, Germany has pumped-storage power plants producing a total of about 7,000 MW. The expansion potential is severely limited, especially in northern Germany where the balancing need is greatest.

Compressed-air energy storage (CAES) is similar in its principle: during the phases of excess availability, electrically driven compressors compress air in a cavern to some 70 bar. For discharge of the stored energy, the air is conducted via an air turbine, which drives a generator.

Just as in pumped storage, its power can be released very quickly. One merit over pumped storage, however, is that the visible impact on the landscape is low. What is more, the facilities can be built near the centres of wind-power production, especially in central and northern Germany. Today, there are two CAES plants: one in Huntorf (Lower Saxony) since

1978, and another in McIntosh (Alabama, USA) since 1991. The efficiency of the 320-MW plant in Huntorf is about 42%, that of McIntosh around 54%. This means that they are more than 20 percentage points below the efficiency of pumped-storage plants.

What lowers the efficiency: first, the air that heats up during compression must be cooled down again to the ambient temperature before it can be stored in the cavern. Second, the cold air must be re-heated for discharge of the storage facility since it cools strongly when expanding in a turbine for power generation. Today's plants use natural gas for this. Valuable efficiency percentages are lost.

Physical background: when air is compressed, heat, too, is produced, besides pressure. This can be observed when using a bicycle pump, for instance. Conversely, cold emerges when compressed gas escapes and loses pressure. This can be felt, e.g., when refilling a gas lighter.



Herdecke pumped-storage power plant

Turbine hall of the Vianden pumped-storage power plant



ADIABATIC COMPRESSED-AIR ENERGY STORAGE WITH BETTER EFFICIENCY

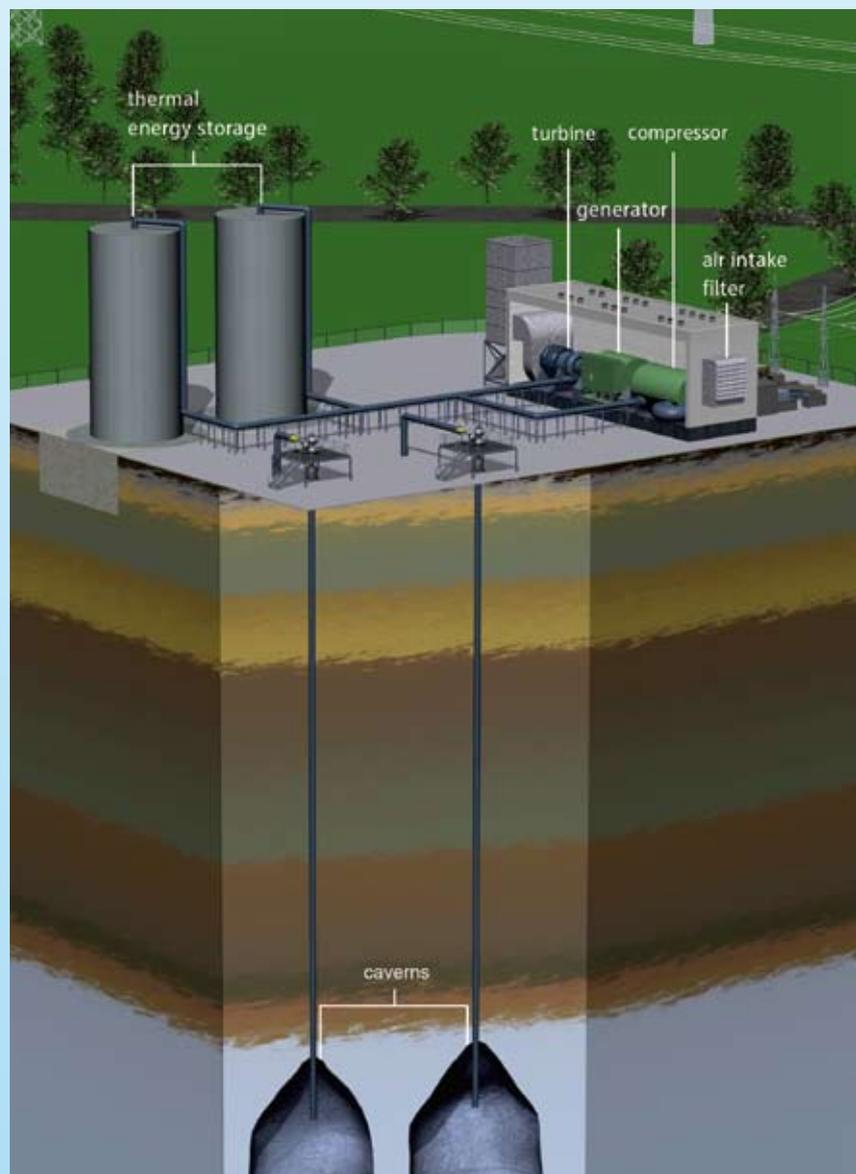
RWE Power is working along with partners on the adiabatic compressed-air energy storage (CAES) project for electricity supply (ADELE). „Adiabatic“ here means: additional use of the compression heat to increase efficiency.

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When the air is compressed, the heat is not released into the surroundings: most of it is captured in a heat-storage facility. During discharge, the heat-storage device rereleases its energy into the compressed air, so that no gas co-combustion to heat the compressed air is needed. The object is to make efficiencies of around 70% possible. What is more, the input of fossil fuels is avoided. Hence, this technology permits the CO₂-neutral provision of peak-load electricity from renewable energy. That this technology is doable has been shown by the EU project Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) and by a study presented by General Electric and RWE in 2008.

The aim of the new joint project mounted by the German Aerospace Center (DLR), Ed. Züblin AG, Erdgasspeicher Kalle GmbH, GE Global Research, Ooms-Ittner-Hof GmbH and RWE Power AG – the project being officially sealed in January 2010 – is to develop an

adiabatic CAES power station up to bidding maturity for a first demonstration plant. The federal ministry for economics has held out a prospect of funding for the ADELE project.



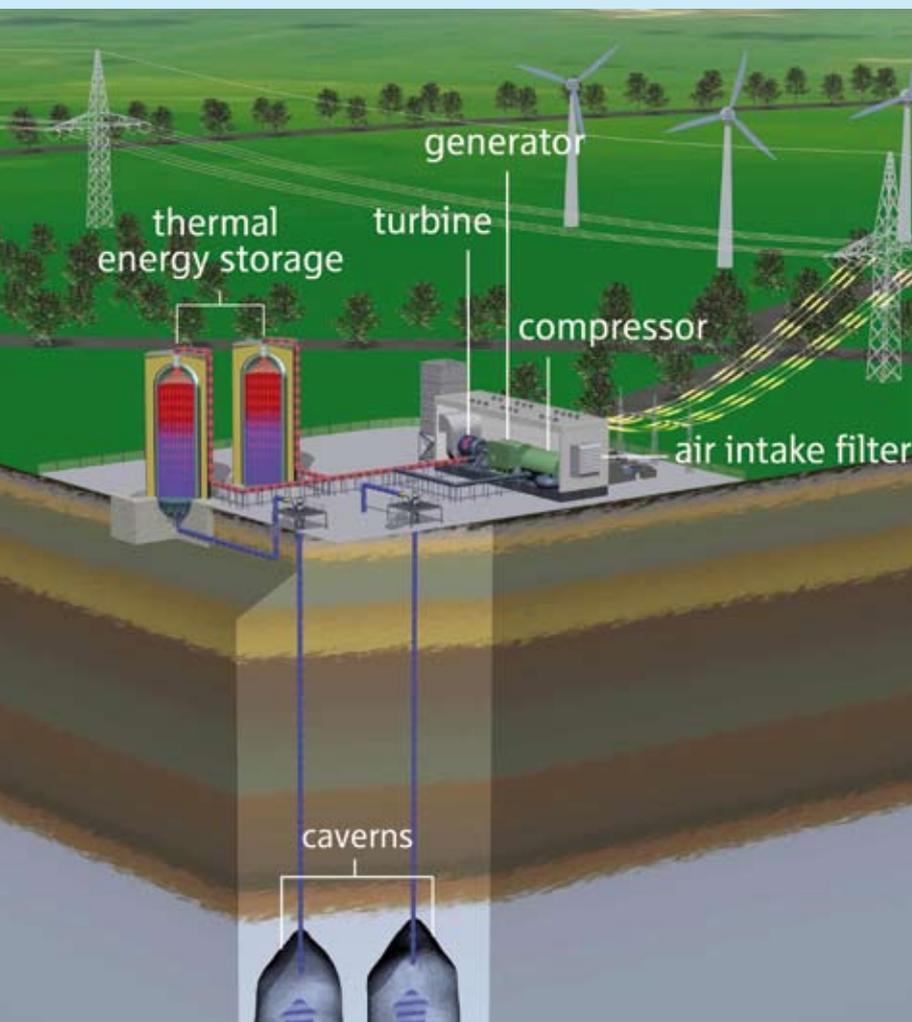
UNRIVALLED WORLDWIDE

Pioneering work: six partners from industry and research want to bring adiabatic CAES technology up to industrial-scale application maturity.

In day-to-day charging and discharging operations, a commercial plant should store some 1,000 MW hours of electrical energy and feed some 300 MWel into the grid for several hours. The demonstration plant, which is necessary as a preliminary stage in the development line and is, in the nature of things, smaller, could probably go on stream in 2016 at the earliest. ADELE is bundling the know-how and experience of a power-plant operator, the manufacturing industry and research in an effort to clarify the open issues of the technology.

RWE Power is coordinating the project. As future operator, it is drawing up the requirement profile. This comprises, among other things, the deployment strategy, availability and operating safety issues. Investigations are assuming day-cycle-based operations geared to the spot market with proportionate provision of balancing energy. The vetting of feasible locations, too, is on RWE Power's work schedule.

The optimal interplay of all technical components, i.e. the system design, is the project's core task. Under the lead management of GE Global Research in Garching, specialists are clarifying the overriding mechanical-engineering and thermodynamic issues and working out the best-possible configuration for compressor, turbine, heat-storage device, cavern and other units. The final result will be a concept ready for bidding that covers the entire plant.

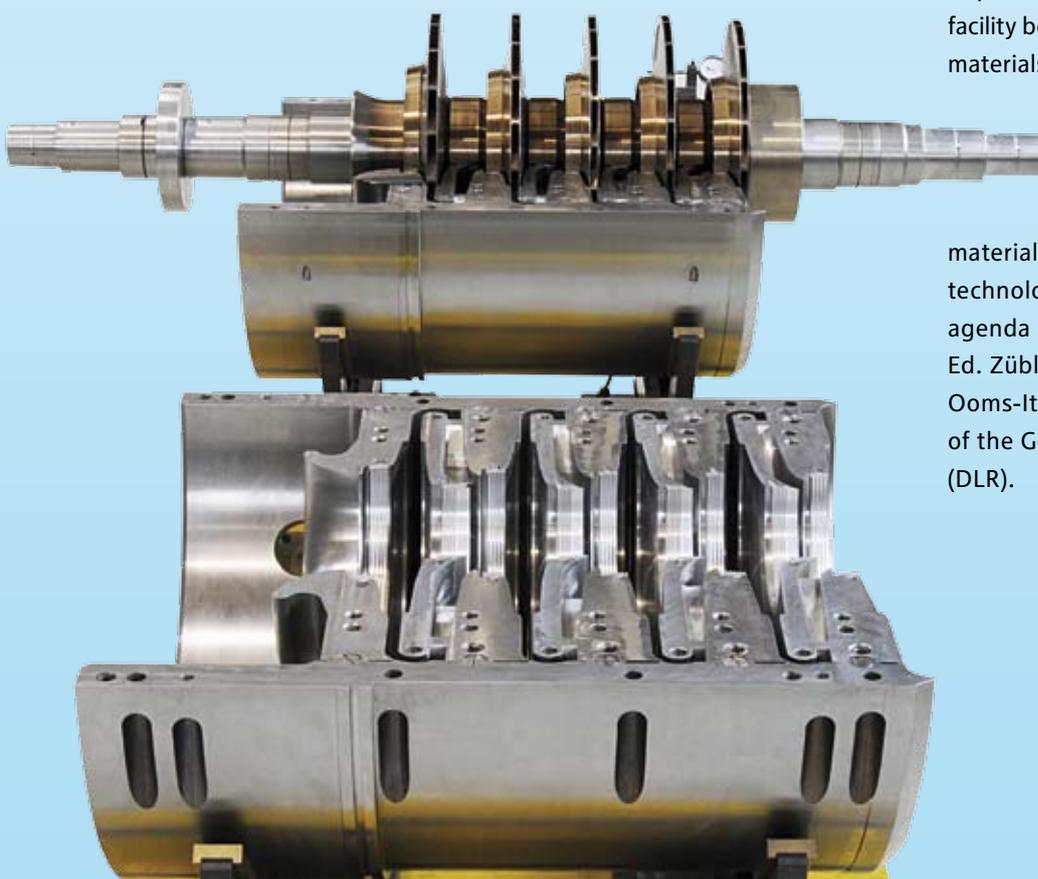


TECHNICAL CHALLENGES OF STORAGE: COMPRESSOR AND HEAT-STORAGE

The ADELE concept places extremely heavy demands on the equipment used: cyclical stresses, temperatures of over 600°C and a pressure of up to 100 bar.

General Electric (GE) is developing the compressor, one of ADELE's core components: driven by an electric motor, the compressor sucks up the ambient air, which is then compressed to up to 100 bar and fed into the heat-storage device as hot compressed air. Nothing is known of the interaction of high pressure and high temperatures at the compressor outlet in relevant industrial-scale requirements. GE must find innovative solutions for the entire compressor train, taking account of the cyclical mode of operation while meeting the demand for part-load capability and still-high efficiencies. GE is producing a preliminary aerodynamic design and the preliminary mechanical compressor design. Details will be clarified in a development project running in parallel with ADELE and financed by RWE

and GE Oil & Gas. The heat of the compressed air – over 600°C – is no waste heat in the ADELE concept. It is stored and, during later discharge, re-used to pre-heat the compressed air. The heat-storage facilities are up to 40-m-high containers with beds of stones or ceramic moulded bricks through which the hot air flows. Which type of heat-storage stone holds on to the heat best and releases it again quickly when required? How must a heat-storage facility be insulated? Which building materials keep the pressure vessel tight? What must the pipelines to and inside the pressure vessel look like? Numerous material, structural and process-technology issues are on the agenda of the project partners Ed. Züblin AG and its subsidiary Ooms-Ittner-Hof GmbH (OIH), and of the German Aerospace Center (DLR).



TECHNICAL CHALLENGES OF DISCHARGE: TURBINE AND CAVERN

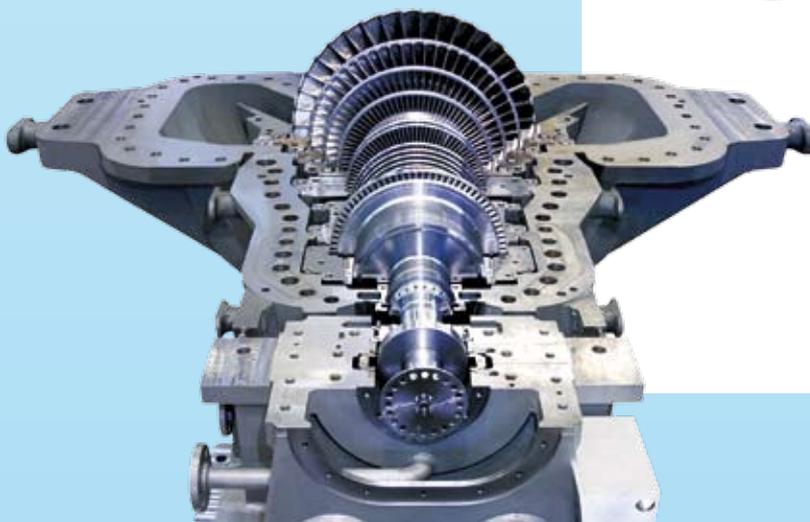
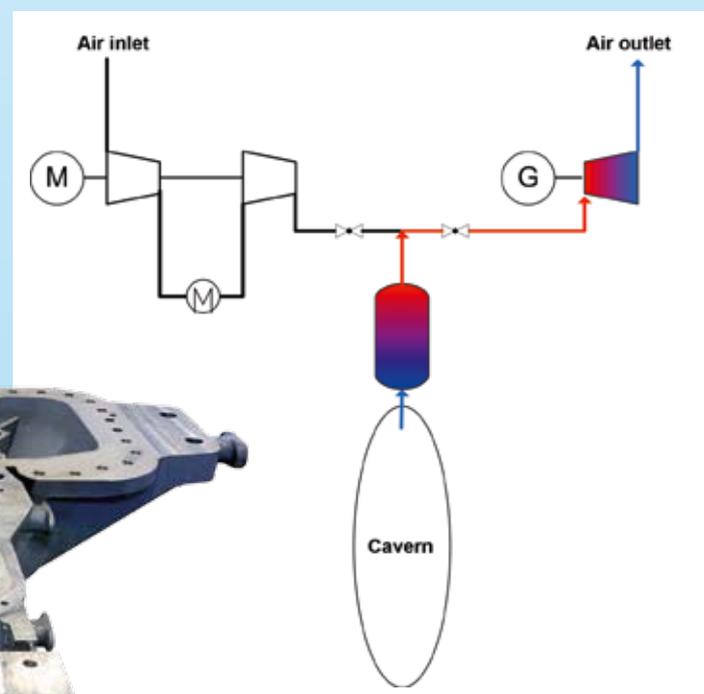
Turbine technology and cavern engineering are being adapted to meet the special requirements of the adiabatic CAES power plant.

Erdgasspeicher Kalle GmbH, a company in the RWE Group, has great experience in the planning, building and operating of underground natural-gas storage facilities. In ADELE's case, however, storing compressed air in a subterranean salt cavern is different from storing natural gas: the air is stored and removed on a daily basis and not over the long term, and the pressure fluctuates accordingly. This has consequences for the size and design of possible caverns. In addition, the humidity can lead to more corrosion of the underground bore-hole equipment, the cavern heads, pipes and fittings. Geology and locational issues, too, must be clarified.

The air turbine is the subject of another GE working package: at a later date, compressed air will flow into this central ADELE component to set it rotating and drive the connected generator. Here, General Electric's engineers are checking how they can adapt

existing turbine technology for use in the CAES plant. The pressures to be expected, for example, far exceed the inlet pressures of today's gas turbines. Moreover, the turbine must cope with the considerable fluctuations in pressures and throughput amounts when the storage facility is discharged.

The turbine is the last link in the charging/discharging chain, so that the aimed-at overall efficiency of some 70% should approximate that of pumped-storage plants for the first time. ADELE would thus provide convincing answers to the questions: where to put the electricity when it does not happen to be needed? Who helps the powering-up peak-load stations to guarantee grid stability if electricity feed-in from wind and sun collapses?



GE – FOCUS ON COMPRESSOR, TURBINE, OVERALL INTEGRATED PLANT



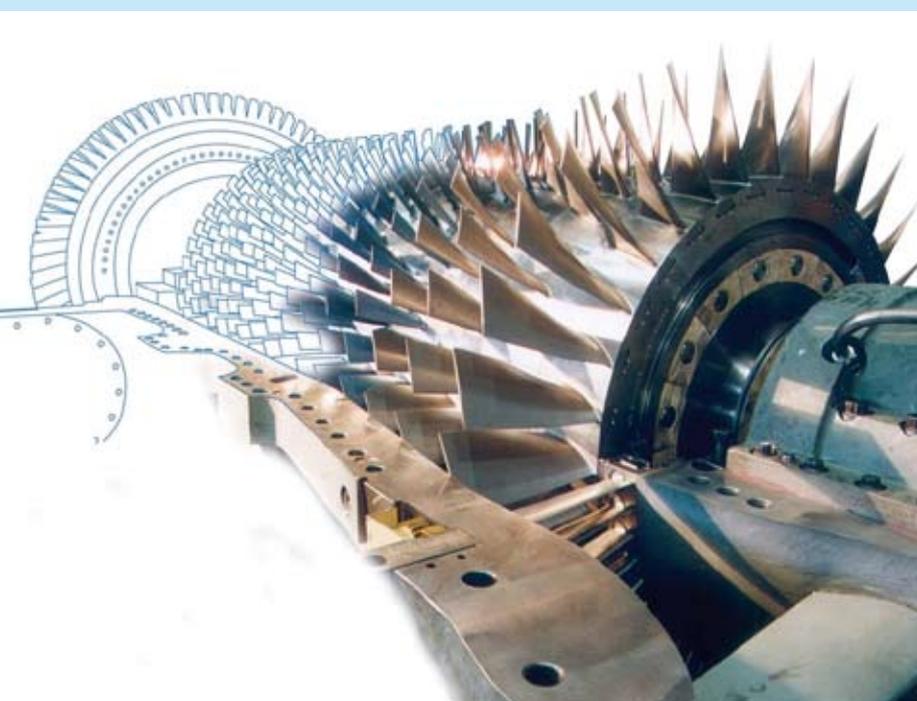
GE imagination at work

From its experience in developing and operating sophisticated energy systems and turbo machinery, GE is inputting comprehensive know-how for system optimization and for compressor and turbine development.

GE Global Research was opened in Garching near Munich in 2004 as the GE group's European research centre. Research focuses are the future energy supply using renewable and environmentally compatible energy concepts as well as increased efficiencies in power plants and turbo machinery. After extensive preliminary work, GE – in the ADELE project and in another parallel project financed by RWE and GE Oil & Gas – will drive forward the development of the CAES technology with focuses on system optimization and on compressor and turbine development. This requires a high degree of integration of all system components. From an application angle, therefore, the technical-economic optimization of the overall system is a key task which must take place in an iterative form

with the development of the components. Besides system optimization, the success of the overall concept will depend crucially on an efficient and low-cost air compressor. The high temperatures and pressures at its outlet – coupled with cyclical stress – are a special technical challenge for which no commercial solutions are available as yet. Which is why ADELE needs innovative approaches in the design of the compressor train involved and the deployment of sophisticated manufacturing processes.

To obtain high overall efficiencies, a suitable air turbine, too, is necessary. Here, existing technology must be adapted especially to the high and temporally varying turbine inlet pressures and volume flows of a CAES plant. GE Global Research and GE Oil & Gas are in charge of developing the core components 'air compressor' and 'air turbine'.



ZÜBLIN AND OOMS-ITTNER-HOF - FOCUS ON HEAT STORAGE



Heat-storage devices, storage material and high-temperature insulation are the working focuses of Central Technology at Ed. Züblin AG and its subsidiary Ooms-Ittner-Hof GmbH.

Ed. Züblin AG is no. 1 in German building construction and civil engineering. At its heart is Central Technology, which bundles its technical competencies. One focus of its work is energy storage, a field in which its engineers have already acquired extensive know-how and numerous patents for solar power stations. For ADELE, they are in charge of developing the heat-storage pressure vessel. To be able to charge and discharge the large amount of heat at the high temperature of over 600°C with low exergy losses, the heat flows through the heat-storage device directly and is stored in inventory stones. Due to the high pressure, it is necessary to develop a pressure-resistant storage vessel specially adapted to the process requirements, and to integrate the sub-components 'high-temperature insulation' and 'storage inventory' to be developed by the project partners Ooms-Ittner-Hof and DLR. The cyclical temperature and pressure stresses and the aimed-at permanence and dependability of the heat-storage device place heavy demands on engineering and require innovative solutions and materials. Ooms-Ittner-Hof is one of the top performers in refractory and chimney construction and handles jobs in both engineering and assembly worldwide. The company has a 150-year tradition in refractory

and chimney construction for industrial plants, like power stations, refineries, glassworks and steel mills. Refractory construction uses tried-and-tested materials that have been further developed across the decades. ADELE poses new challenges for the experts with its boundary conditions of cyclical temperatures, humidity, high pressure and long service lives. For one thing, this requires extensive material tests. Also needed are heat-technology calculations, constructional designs of ceiling and wall elements, anchorage points, assembly concepts, manufacturing and field assembly activity charts, and the dimensioning of the storage stones.



DLR – FOCUS ON HEAT-STORAGE DEVICE



Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

The German Aerospace Center (DLR) has years of experience in adiabatic CAES power plants.

DLR's Institute of Technical Thermodynamics (ITT) in Stuttgart is working on the use of highly efficient energy-conversion technologies and technical solutions for the introduction of renewable energy sources. The spectrum of its work ranges from basic-research-oriented laboratory activities all the way to the operation of pilot plants.

One of the focuses of its work is high-temperature heat storage for power-plant engineering and industrial processes for which it has long years of experience and in-depth involvement in numerous national and European development projects.

Here, adiabatic CAES has been the institute's field of activity for several years now: as early as 2003, initial concepts for the build-up of a high-temperature storage facility for this power-plant type were worked out and assessed together with partners in Europe's four-year „AA-CAES“ project. Further-going contributions were made in a later study commissioned by RWE.

In the federal economics ministry's ADELE project, the state of knowledge on the heat-storage device is being further developed up to demonstration maturity in a division of labour between the partners Ed. Züblin and OIH. The focuses of DLR's contributions are on the concept and on design issues for shaping the storage inventory and the high-temperature insulation which, as core components, crucially mark the performance and cost efficiency of the overall structure.

The work is being supplemented by experimental investigations: functional tests on storage-facility components, for example, are underpinning the designs. For this purpose, existing DLR process-development units are being used. Cyclical testing of materials will answer existing questions on the choice of materials.

Test rig to investigate
high-temperature
storage facilities at
DLR Stuttgart



