The cleanest energy carrier ever.
Hydrogen Solutions from Linde Gas.

Linde Gas

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Contents.

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Hydrogen + oxygen = energy + water.
The energy formula of the future.

People in the industrialized countries today enjoy more comfort and convenience than ever before. However, they also consume ever-increasing quantities of energy. Even in developing and newly industrializing countries, energy consumption is increasing steadily. At the same time, this is increasing the strain placed on our environment. In discussions about the future of our energy supply – particularly in connection with regenerative energy sources – today one term is used right from the start: hydrogen (H_2). The reason for this is simple: as a storage medium for energy, hydrogen is "polyvalent", i.e. it fulfils several requirements concurrently, proving it to be the most environmentally friendly energy carrier ever – because the only "waste gas" released when using it is water vapor. Moreover, hydrogen's special characteristics render it the ideal storage medium for electricity generated from renewable energy sources, making it the most important link in a sustainable energy value chain which is completely emission-free from beginning to end. This is because hydrogen is the element most commonly found in nature – i.e. unlike fossil fuels such as crude oil or natural gas, it will never run out. Plus: stored hydrogen can be used both to generate electricity and directly as a fuel, which makes it highly suitable for mobile applications in the transportation and shipping sectors.

It is true that hydrogen has to be produced before it can be used as an energy carrier. However, in recent years, decisive technological steps have been taken to make hydrogen production more efficient and environmentally friendly. The vision of a sustainable hydrogen energy cycle is now within reach. It is now important to further develop existing hydrogen technologies from the testing phase to applications suitable for everyday use under economical aspects. Linde, one of the world's leading hydrogen plant constructors, is a major driving force behind this development. This is because the set-up of a global hydrogen energy supply not only holds tremendous economic potential for the future, it is also a real crossgeneration project which in the end will affect all levels of society. And more: it is a commitment which will have an immense influence on the future of our energy supply, and consequently the future of our children and our children's children. Linde will face up to this responsibility. With innovative technology for producing, storing and distributing hydrogen – and with efficient solutions for revolutionary hydrogen applications.

Dr. Aldo Belloni
Linde Gas & Engineering
Member of the Executive Board of Linde AG

Hydrogen – the energy carrier for the 21st century. Opportunities and challenges.

Hydrogen is everywhere: it is not only found in water, but also in all living beings as well as in primary energy sources such as natural gas, crude oil and coal. When hydrogen (H_2) reacts with oxygen (O_2), the end product is water (H_2O). During this process, energy is released. This can be used for mobile electricity generation or for transformation into mechanical energy, for example.

With pure hydrogen, mankind would have the perfect energy source at its disposal. Unlike gasoline, for example, hydrogen does not give off harmful emissions. Moreover, hydrogen – unlike fossil fuels, which will run out at some time – is available in practically unlimited quantities.

In nature, hydrogen occurs in a large number of compounds. However, energy has to be applied in order to obtain hydrogen in its elementary form and use it as an energy carrier. Until now, this energy was largely derived from fossil fuels such as natural gas, crude oil or coal. In future, global research and development work will concentrate more on increasing the proportion of renewable energy sources.

Linde's scientists and engineers have therefore spent decades working on efficient and environmentally friendly solutions for hydrogen production. Another important field of activity is the development of effective concepts for the economical storage and use of hydrogen. On the way to a sustainable hydrogen economy, we will use our technological know-how to establish this indispensable energy carrier throughout the world.

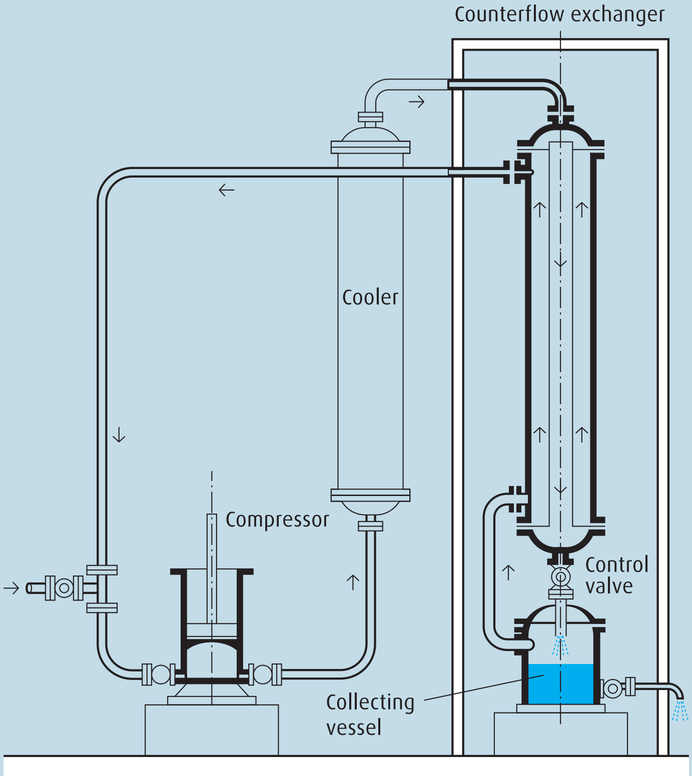
Linde focuses on hydrogen

The existence of hydrogen was discovered back in the early 18th century. Henry Cavendish was able to isolate the element for the first time in about 1766. At normal pressure and ambient temperature, hydrogen is gaseous, odorless and tasteless. Moreover, the gas is non-toxic and much lighter than air, which means that it rises quickly when not contained.

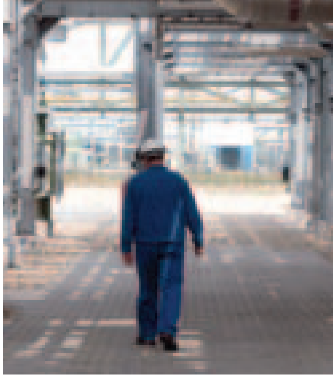
Compounds consisting of hydrogen and air are combustible. The hydrogen flame burns without color and the only "waste gas" released is water vapor. Hydrogen is therefore highly suitable for use as a fuel. However, under normal conditions, the gas has a low density. Storing hydrogen in this state is therefore impractical – the tanks needed would simply be too big.

For efficient, space-saving storage, hydrogen must therefore be pressurized or liquefied through intensive cooling. Around 1900, company founder Carl von Linde was the first to succeed in constructing air liquefaction machines which soon also made possible the liquefaction of large quantities of hydrogen gas. Today, the company is one of the world's leading hydrogen plant constructors and operates Germany's only large industrial hydrogen liquefaction plant in Ingolstadt. Moreover, Linde is a leader in the production and distribution of hydrogen and an international pioneer in the development of innovative hydrogen technologies.

The last 20 years have been marked by intensive research in the area of hydrogen – also and particularly at Linde. It has meanwhile become clear that hydrogen is probably the most promising energy carrier for the future. Moreover, hydrogen can now be controlled safely. Much will therefore depend on how the potential hidden in this energy carrier is utilized in the future.



Plan of the first air liquefaction apparatus, built in 1895.



The driving force. Possibilities of hydrogen production.

At present, hydrogen is produced almost exclusively in one of two ways: firstly thermally, i.e. by heat input, from hydrocarbons. And secondly electrolytically, by the input of electricity, from water. Currently, 98 % of global hydrogen production (approx. 600 billion m^3 per annum) is derived from hydrocarbons, preferably natural gas.
The most effective method of extracting hydrogen from fossil resources is steam reforming, as realized in Linde's industrial plants. This form of production is also environmentally friendly because a good deal of the hydrogen produced in this way comes from water vapor. Because it is so economical, steam reforming is currently the standard hydrogen production process.

Electrolysis: splitting water into its components, oxygen and hydrogen
Hydrogen production through electrolysis offers the possibility of a completely emission-free hydrogen energy cycle. However, the electricity for the electrolysis must be generated from a regenerative energy source such as solar or wind power, biomass or hydropower. A voltage of just 1.5 V is sufficient to release hydrogen gas (H_2) from water (H_2O) by means of electrolysis. The water is first charged with an acid or base in order to enable it to conduct ions. Oxygen (O_2) is released at the positive electrode, hydrogen at the negative electrode. Here a so-called diaphragm between the anode and cathode prevents the two gases from reacting and reverting to water. Moreover, if this process takes place under pressure, the subsequent compression work becomes easier and the energy and space required by the system is minimized. Linde has years of experience with hydrogen electrolyzers as well as the expertise necessary to integrate them into existing hydrogen technology chains.

100,000 m³ of pure energy. Hydrogen production through steam reforming.

By the end of 2004, Linde Gas & Engineering had already built more than 200 hydrogen production plants throughout the world. As a rule, a light hydrocarbon such as natural gas is used to produce hydrogen by steam reforming. At 70–80 %, this process has a high degree of efficiency, i.e. a good ratio of energy used to energy released.

At the first stage, the hydrocarbon is combined with water vapor at a pressure of typically 2.5 MPa and a temperature of 900 °C to form a hydrogen-rich gas mixture which also contains carbon monoxide (CO). At the second stage (the "shift reaction"), the carbon monoxide (CO) is converted to carbon dioxide (CO_2) with water. Here additional hydrogen is extracted from the water in the steam accompanying the process. However, before the hydrogen can be used – e.g. in fuel cells – it must first be purified. This usually takes place in so-called PSA plants (PSA = Pressure Swing Adsorption) in which up to 100,000 m^3 of hydrogen can be purified hourly to qualities of more than 99.999 %.

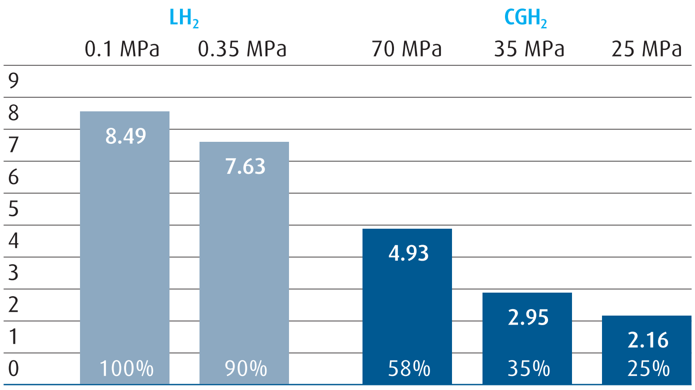
Further techniques for hydrogen production

Partial oxidation can be used as a variation on steam reforming. The process is similar, but involves the input of air or oxygen. With this technique, less pure liquid or solid hydrocarbons (coal, crude oil, bitumen etc.) can be used for hydrogen production. Linde Gas & Engineering has the competence to control complex production processes involving both steam reforming (SMR) and partial oxidation (POX).

Steam reforming plants from Linde (such as this steam reformer in Brunsbüttel, Germany), which supply up to 100,000 m^3 of hydrogen per hour, are constructed for various capacities. Linde exports technology for steam reforming plants throughout the world, e.g. to the USA, the Middle East, Russia, Canada, India, Japan, China and the EU countries.

Hydrogen liquefaction.

Energy content of the states of aggregation (MJ/l)



Energy content of the various states of aggregation of liquid hydrogen (LH_2) and compressed hydrogen gas (CGH_2) at various pressures.

Linde constructs hydrogen liquefaction plants in various sizes. In the picture: the plant in Ingolstadt, Germany, with a capacity of 4.4 tons of LH_2 per day.

In order to store hydrogen efficiently, its "natural state" has to be changed. At present, there are two predominant methods of doing this: firstly, compressed hydrogen gas (CGH_2) can be stored in high-pressure containers at ambient temperature. The second possibility is to store it in liquid form. Extremely low temperatures (-253 °C) and correspondingly isolated containers are necessary for this. The advantage here: cryogenic liquefied hydrogen (LH_2) has a considerably higher energy content per unit of volume than compressed hydrogen gas, and therefore needs less storage space (see diagram).

For liquefying hydrogen on an industrial scale, processes are today used in which the hydrogen to be liquefied is cooled step by step in heat exchangers. Here liquid nitrogen is used as the initial coolant; further cooling is carried out via a closed hydrogen refrigeration cycle, in which the refrigerant capacity is made available by expansion turbines. The actual liquefaction of the hydrogen pre-cooled in this way takes place by throttling expansion in a Joule-Thomson valve; the liquid hydrogen is subsequently fed into a storage tank for further use.

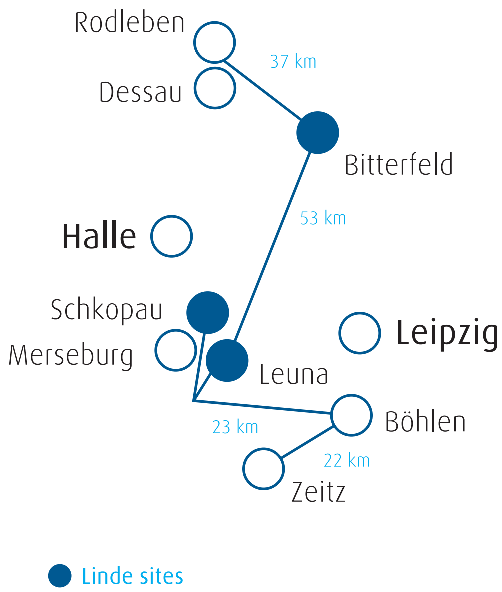
Full steam ahead. Hydrogen distribution by pipeline.

Parallel to the storage of hydrogen, there are also various possibilities of transporting it. One possibility is distribution by pipeline. This method is frequently the best solution, particularly for on-site supply solutions – i.e. when gaseous hydrogen is transported directly from the production site to the consumption site. In order to be able to supply large-scale consumers with the gas quantities required, Linde Gas & Engineering plans, constructs and maintains on-site turn-key plants which can be installed directly on the customer's premises.

Hydrogen can also be transported long distances via pipeline. This is particularly expedient for consistently high consumption, as is the case in industrial areas. Linde operates Europe's most up-to-date hydrogen pipeline in central Germany (Leuna). The pipeline network is more than 100 km long and connects the Zeitz, Böhlen, Leuna, Bitterfeld and Rodleben sites, amongst others.

Moreover, Linde Gas & Engineering has the know-how to make conventional natural gas or town gas pipelines viable for hydrogen transport. Particularly in the current testing phase, this is an important condition for the realization of hydrogen supplies covering a large area and for the construction of a future H_2 filling station network.

The Linde hydrogen pipeline network in central Germany (Leuna).



Clever storage, fast supply.
GH_2 trailers and LH_2 container vehicles.

LH_2 container vehicle for liquefied hydrogen.

Appropriately equipped trucks can be used to transport hydrogen over long distances. In this case, gaseous hydrogen (GH_2) is stored under high pressure in special GH_2 trailers and transported from site to site at ambient temperature.

Even larger quantities of hydrogen can be transported in an LH_2 container vehicle, i.e. a truck with a special tank for cryogenic liquefied hydrogen (LH_2). Here the costs of liquefaction must be taken into consideration, as liquefaction currently accounts for approx. 30 % of the energy stored in the hydrogen. However, as the energy density of LH_2 is considerably higher than that of GH_2, these expenses balance out when transporting larger quantities over increasingly long distances, because fewer journeys are necessary to transport the same quantity of energy.

Current application: modern fuel cell submarines carry hydrogen in metal hydride storage tanks and can remain under water for much longer than conventional diesel-electric powered submarines. Linde equipped HDW AG with the corresponding hydrogen filling technology for this project.

Lots of energy in stock.
Alternative storage.

Current research has shown that there are even more possibilities for storing and/or transporting hydrogen. It can for example be stored in ultra-fine, concentrically arranged graphite tubes (carbon nanotubes) or in stacked wafer-thin layers of graphite (carbon nanofibers). Hydrogen can also be stored in a solution of sodium borohydride ($NaBH_4$) and in polymers (polyaniline, polypyrrole).

The same applies to so-called microspheres – these are tiny, highly pressure-resistant glass balls (Ø < 100 µm, wall thickness 1 µm). Hydrogen can penetrate these at 200–400 °C. These technologies have in part a high degree of development potential, but from the present viewpoint are still at the research stage.

Hydrogen storage in metal hydrides

The only alternative to gaseous or liquid storage actually used at present is storage in so-called metal hydrides: these can store and release gaseous hydrogen in the same way as a sponge absorbs and releases water. This process is already used in some prototypes in the portable systems area (e.g. camcorders, laptops etc.). However, this type of storage is also used in hydrogen-powered fuel cell submarines, which are already being built by HDW AG.

Metal hydride for hydrogen storage.

For better progress tomorrow, you have to break new ground today. Hydrogen opens up scope for a variety of applications.

Many things which once seemed utopian have now become reality. At the beginning of the last century, for example, it would have been difficult to imagine that humankind would actually set foot on the moon. A more recent example of a vision which became a reality a few years later was the development of the Internet, which many believed to be unrealizable.

For a long time, the use of hydrogen as an energy carrier was also believed to be unrealizable, even dangerous. The fact that this idea was not given up is due only to the researchers' thirst for knowledge, the work performed by engineers and the commitment of progressive companies.

In recent years, research into hydrogen as an energy carrier has made tremendous progress. Today, there is a wide variety of applications for almost all energy-relevant areas: with hydrogen, it is not only possible to generate electricity and store it on a long-term basis – hydrogen-powered cars can now also achieve almost the same performance as cars with conventional gasoline or diesel engines. And in the near future, innovative fuel cell technology will make it possible not only to run portable electrical equipment such as laptops or camcorders on hydrogen, but also to supply entire houses with electricity and heat.

In short: the technical conditions for a large-scale, functional, sustainable hydrogen economy already exist today.

Fascinating hydrogen. Mobility without pollutants.

The use of hydrogen in space travel is the background for the futuristic vision of hydrogen-based aviation. Initial attempts in this direction were made back in the 1980s. Picture credit: copyright ESA, CNES, ARIANE-SPACE.

At present, the main industrial use of hydrogen is the manufacture of high-quality products. Hydrogen is employed for example in the production of fiberglass cables, for cleaning microchips, for polishing optical glasses and for processing metals. Hydrogen is also used in the production of fertilizers, for hardening fats, for drinking water treatment and in the production of fuels with low sulfur contents. In space travel, hydrogen has been used as a fuel for rocket engines since the 1960s, and is also used for generating electricity, drinking water and water for general use in space.

In many countries of the world, both hydrogen combustion and hydrogen power generation are currently being tested for their suitability for everyday use. The main focus here is on the mobile use of hydrogen as a vehicle fuel. Linde also concentrates on this area, with good reason. Because, on the one hand, the predicted market volume holds enormous potential for the future. And on the other, the positive effects for humankind and the environment are obvious.

Combustion engines for hydrogen

In their design, H_2 combustion engines are quite similar to Otto engines. This allows the design of bivalent vehicles, i.e. automobiles which can be driven on conventional fuel or on hydrogen as required. Incidentally, it is irrelevant in this case whether the hydrogen is stored as a gas or as a liquid – because for combustion, it is injected into the engine in gaseous form.

Already reality: vehicles with H_2 combustion engines.

Fuel cell technology – versatile, eco-friendly and effective.

H_2 fuel cells need gaseous hydrogen to generate electricity. In principle, they work like batteries in which reverse electrolysis takes place (cf. p. 9). Depending on the energy needed, they can be connected in series, thereby opening up a wide range of portable, mobile and stationary application possibilities. Today prototypes and test facilities already exist for each of these areas. H_2 fuel cells can also be used to generate electricity. Linde, for example, is currently cooperating with a project partner to test H_2 emergency electricity supply for mobile phone antennas.

Using H_2 fuel cells in vehicles

Unlike H_2 combustion engines, H_2 fuel cells power electromotors. Great progress has been made with the development of these systems in recent years. The use of these cells in vehicles is currently being intensively tested in several of the world's industrialized countries – in the USA, Japan, Germany and in other EU countries, for example.

Buses

H_2 fuel cell buses are just as comfortable as conventional buses, but are much quieter and emit no pollutants at all when under way. Moreover, a central filling station is sufficient for filling purposes, as they are always driven back to their starting point at the end of a shift. In this way, local emissions can be reduced particularly in cities and suburban areas.

Fork-lift trucks

Together with its project partners, Linde has developed a new electric fork-lift truck equipped with a particularly high-performance H_2 fuel cell system. Compared to conventional batteries, this innovative technology allows for a significant improvement in the fork-lift truck's drive and lift characteristics; it can also be used without a break, as the time-consuming charging or exchanging of batteries is unnecessary. The fork-lift truck is simply filled, almost like a conventional car.

The existing hydrogen infrastructure at Munich Airport made it possible to test the performance of the new H_2 fuel cell system for fork-lift trucks. One tank of hydrogen keeps the vehicle running for approx. 8 hours in normal operation.

ARGEMUC hydrogen filling station at Munich Airport.

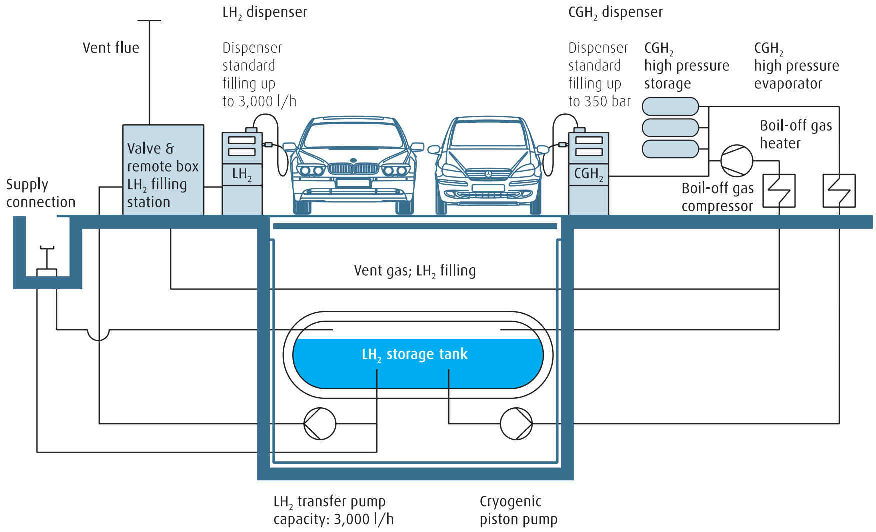
Hydrogen infrastructures in the test phase.

Filling station for gaseous and liquid hydrogen at Munich Airport.

Under the name ARGEMUC (Arbeitsgemeinschaft Wasserstoffprojekt Flughafen München – Munich Airport Hydrogen Project Consortium), a consortium of renowned companies (including BMW, BP/Aral, MAN, Linde and others) has been operating the world's first public hydrogen filling station for gaseous and liquid hydrogen since 1999.

The cryogenic liquefied hydrogen is supplied via LH_2 container vehicles. In contrast, the gaseous hydrogen for the filling station is provided by an on-site supply system installed by Linde. Since 2003, a small steam reformer has been ensuring that GH_2 is produced, cleaned, stored at high pressure and tapped directly at the filling station. Several airport shuttle buses and a test fleet of cars are fuelled with hydrogen at the pumps.

By the end of 2004, the test vehicles had already traveled more than 500,000 kilometers without major technical difficulties; more than 6,000 filling procedures were carried out during this period. The demonstration of a safe and reliable hydrogen supply for vehicles has thus succeeded impressively.



Concept for future hydrogen filling stations for GH_2 and LH_2 with underground storage tanks.

A hydrogen bus at the GH_2 filling station at Munich Airport.

Filling stations for gaseous hydrogen.

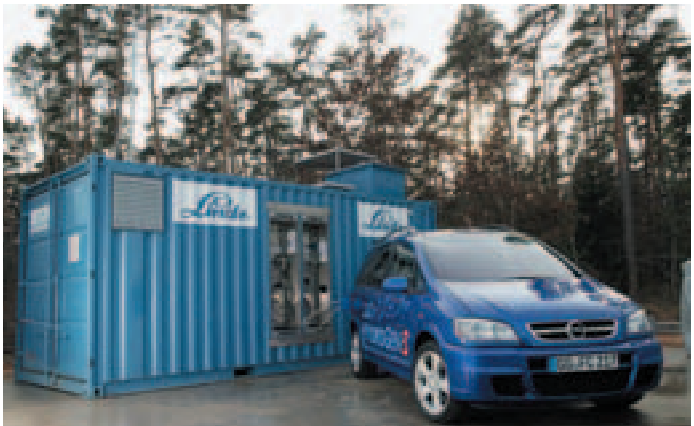
Gaseous hydrogen for filling is usually stored at ambient temperature and a pressure of 350 bar. The complete filling of a vehicle tank, however, is only possible if the filling station builds up a pressure higher than the storage pressure. The higher the pressure, the shorter the filling time.

In recent years, Linde has worked intensively on developing filling stations for gaseous hydrogen. The storage pressure has meanwhile been successfully increased to 700 bar. However, when the gas is compressed to such a degree, the temperature rises considerably. In consequence, the gas cools down after the filling process, causing the pressure in the vehicle tank to drop again.

In order to maintain a constant pressure of 700 bar, it is therefore not only necessary to fill the tank at a pressure of 850 bar, but also to cool the gas down to -15 °C directly before the pump. Linde has developed the corresponding technology for the first 700 bar hydrogen filling station. The filling process now only takes a fast, convenient 3 to 4 minutes.

Special technology is used in integrated GH_2 filling stations equipped with LH_2 storage tanks. Before it is released in gaseous form, a Linde cryo-compressor compresses the hydrogen while it is still liquid to approx. 400 bar, thus ensuring a high degree of efficiency when converting LH_2 to CGH_2. If required, a booster system subsequently increases the pressure to 700 bar.

Filling a hydrogen car at a 700 bar filling station for GH_2.



Delivery of liquid hydrogen for the LH_2 filling station.

Filling stations for liquid hydrogen.

As one of the most important driving forces behind the government-supported hydrogen project at Munich Airport, Linde's responsibilities include supplying the filling station with hydrogen. The liquid hydrogen is produced centrally in Ingolstadt and then supplied by LH_2 container vehicle.

The filling station for liquid hydrogen works with an LH_2 pump developed and patented by Linde. This innovative device enables the tank to be filled especially quickly (50 l/min), thus ensuring the high degree of user-friendliness familiar from conventional filling stations.

Meanwhile, there are now numerous H_2 filling stations throughout the world, for both liquid and gaseous hydrogen, including the Clean Energy Partnership (CEP) project in Berlin, in which Linde is also significantly involved. For this project, Linde provides its entire hydrogen know-how – from production and supply via storage and compression to filling. This portfolio makes the company stand out from competitors which can only cover individual parts of this spectrum.

Filling with LH_2

Until just a few years ago, filling vehicles with LH_2 was relatively time-consuming. One consequence of using cryogenic (-253 °C) liquid hydrogen was that the filling hose and coupler had to be rinsed and warmed before another fuelling procedure could begin.

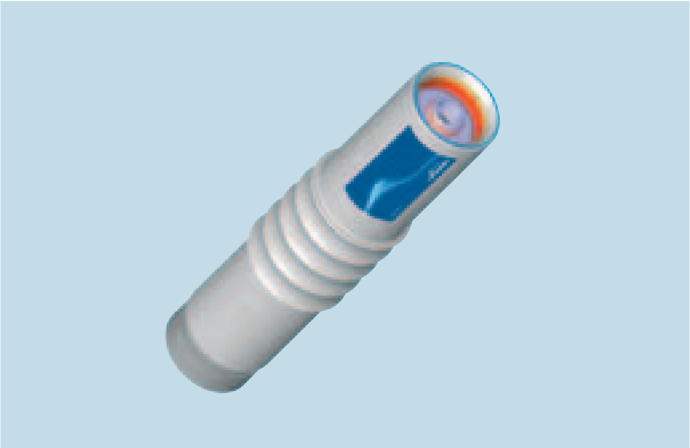
Manual LH_2 coupler

These problems have now been solved: with the new filLH_2™, Linde has developed and patented a manual LH_2 coupler with which fuelling can be carried out quickly and easily. The tank nozzle and filler have valves which only open when connected. This creates a hermetically sealed pipe. A so-called "cold finger" then travels from the tank valve deep into the filler and feeds the liquid hydrogen into the tank. This effectively prevents freezing. An automated LH_2 coupler co-developed by Linde, which is also being tested at Munich Airport, is even more convenient. It carries out the whole process automatically – from opening the fuel tank cap and connecting the LH_2 coupler via the filling process to uncoupling.

In the LOPEX process developed by Linde, which is used with stationary tanks, a heat exchanger is applied to convert gaseous hydrogen back to liquid.

LOPEX process

The LOPEX process patented by Linde counteracts one of the drawbacks of storing liquid hydrogen in stationary tanks for long periods: the slow warming of LH_2 means that some of the liquid in the tank reverts to gas. If no hydrogen is removed, the pressure can increase so much that the gas has to be released via a decompression valve. Here we speak of boil-off losses. With LOPEX, this gaseous hydrogen, which would otherwise be lost, can be converted back to liquid and fed back into the tank. The energy necessary for this process is supplied by a fuel cell which uses a part of the boil-off gas.



The new LH_2 coupler filLH_2™ (patent: Linde).

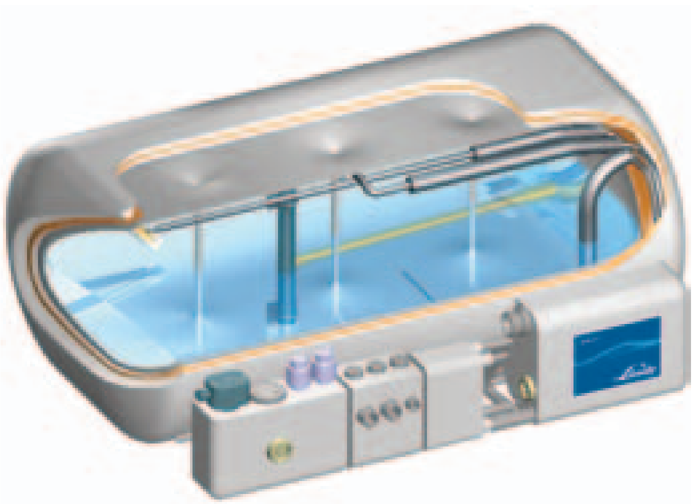
The manual LH_2 coupler in action.

Deep cooling means high efficiency.
LH_2 tank systems.

Linde has developed specially insulated cryotanks for the long-term storage of cryogenic liquefied hydrogen which set new standards for economy and efficiency. The outstanding characteristics of the tanks are due to the double-walled metal container, the innermost of which holds the liquid hydrogen. The inner and outer walls are separated by insulating metal foils interspersed with layers of staple tissue. Moreover, the gap is evacuated and has thermally insulating fixings.

These components guarantee very good insulation, through which the hydrogen can be kept at -253 °C. However, if a hydrogen vehicle remains stationary for a longer period of time, the hydrogen will warm up slowly despite the insulation. After about three days, as soon as the maximum operating pressure (approx. 4.5 bar) is reached and unless the vehicle is used, the excess gaseous hydrogen is released via a special decompression valve.

Increasing holding time with the $cooLH_2$® tank system
Thanks to an innovative recooling system, it is possible to increase the maximum holding time without boil-off loss from three to twelve days, even if the hydrogen vehicle remains absolutely stationary. This is because the $cooLH_2$® system supports the tank cooling by exploiting the coldness contained in the hydrogen. The ambient air is drawn in, dried and liquefied by the energy released by the warming hydrogen. The cryogenic liquefied air thus gained flows through an additional cooling jacket covering the inner tank.



Cross-section of a form-optimized LH_2 tank system.

Hydrogen vehicle design.

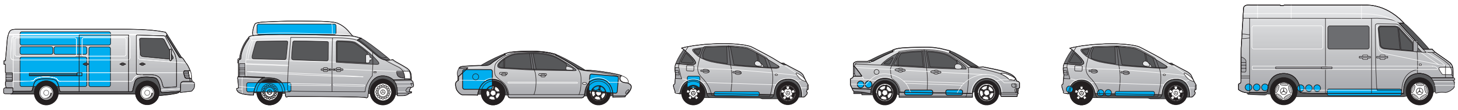
Just a few years ago, an H_2 fuel cell system took up so much space that it could only be accommodated in the loading area of a van. Thanks to the continual development of fuel cell systems and the optimization of hydrogen storage, manufacturers have succeeded in reducing the size of the overall package considerably.

The drive system now hardly influences the performance and loading space of modern H_2 vehicles. The dynamics and suitability for everyday use of these vehicles is today already comparable to that of conventional vehicles. Moreover, the ever smaller fuel cell drive system opens up undreamed-of vehicle design possibilities.

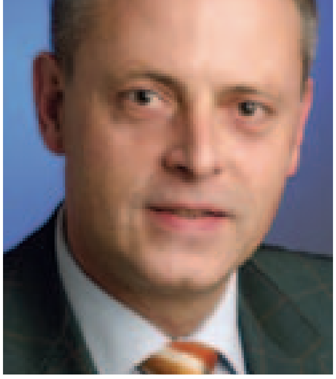
Hydrogen Fuel Injection (HyFI®)

Linde is also able to supply systems to improve the performance of hydrogen engines. One of the most recent developments in this area is the patented HyFI® compressor technology for vehicles with LH_2 tanks and hydrogen combustion engines.

This shoe-box-sized compressor not only optimizes engine performance, it also improves the storage efficiency of cryogenic liquefied hydrogen. This means drivers of hydrogen-powered vehicles can stay on the road much longer before having to make a fuel stop. HyFI® also captures the energy from evaporation and expansion of the liquid hydrogen. This increases engine efficiency from about 30 to 40 percent.



The development of the system size in H_2 fuel cell cars.



Dr. Joachim Wolf

Think hydrogen. The future of energy supply has already begun.

The exploitation of hydrogen as an energy carrier is opening up a multitude of fascinating possibilities. However, it is also raising many complex questions – not least in a political and social context. This is because from a purely technical point of view, many problems relating to the use of hydrogen as an energy carrier have already largely been solved.

Innovative solutions from Linde have made a considerable contribution to making hydrogen applications even safer, more efficient and more user-friendly. Moreover, as one of the largest hydrogen producers, Linde has a complete hydrogen value chain stretching "from well to tank", i.e. from production via distribution to the consumption site.

We can be justly proud of these developments, as they show once again how much can be achieved with purposeful research, entrepreneurial commitment and long-term concepts. And they have shown that the challenges posed by a future hydrogen economy can only be met with the necessary performance, innovation and investment. Because there is one thing that most experts are unanimous about: in the long term, there is no alternative to hydrogen as an energy carrier.

And although there are still hydrogen-related questions which have yet to be answered, we can say even today: where hydrogen is concerned, we have reached the end of the learning phase. Now we have to work fast on realizing an efficient, sustainable, large-scale hydrogen economy. The first steps in this direction have already been taken – and Linde will continue to help the cleanest energy carrier in the world unfold its enormous potential for the future.

Dr. Joachim Wolf
Linde Gas & Engineering
Hydrogen Solutions Executive Director

The first HAT reference project, under way since November 2002: the hydrogen engine and drive chain test center in Garching, near Munich.

We're strongly committed to hydrogen.
Partnerships and projects.

In order to drive on the development of hydrogen technology, Linde is cooperating with renowned, globally active partners in the fields of business and industry. Of decisive importance here are companies active in the fields of mineral oil (e.g. BP/Aral), vehicle construction (BMW), engineering (Siemens) and energy supply (BayernGas).

In joint operations such as the Clean Energy Partnership (CEP) and the Munich Airport Hydrogen Project Consortium (ARGEMUC), Linde is developing the dynamics necessary to carry out hydrogen-based projects efficiently and purposefully. Cooperations such as these, which are also supported and promoted in the political arena – e.g. by the German Federal Government and the Bavarian State Ministry of Economic Affairs, Infrastructure, Transport and Technology – produce synergy effects which enable us to create the technological conditions for an efficient, sustainable hydrogen economy.

HAT – testing with hydrogen

In order to be able to test hydrogen combustion engines and H_2 fuel cell systems, Linde has joined up with TÜV Automotive GmbH and FEV Motorentechnik GmbH for the HAT (Hydrogen Advanced Testing) project. The aims of HAT include the planning and construction of turn-key hydrogen test facilities and the competent execution of corresponding approval procedures. Within this cooperative venture, Linde's responsibilities include the construction and maintenance of suitable gas supply facilities and the production and supply of hydrogen.

Dr. Manfred Stolpe, Federal Minister of Traffic, Construction and Housing, and Dr. Rainer Goedl (r.), member of the Group Executive Board of Linde Gas & Engineering, at the opening of the CEP hydrogen filling station in Berlin (Fall 2004).

The Opel Fuel Cell Marathon crossed Europe in a race from the northernmost town to the westernmost point of the continent.

Throughout the tour, Linde supplied liquid hydrogen for fuel cell operation in the test vehicle HydroGen3.

On the road with Linde.

In order to prove that a hydrogen car is suitable for everyday use, it is not enough to test only locally based vehicle fleets. After all, hydrogen vehicles must be able to travel long distances without running into difficulties. However, at present there is no wide-ranging hydrogen filling station network, and without this, corresponding long-distance testing cannot take place.

Endurance test for fuel cell and tank system

In order to be able to carry out the ultimate endurance test for a hydrogen car powered by fuel cells despite the missing infrastructure, Linde and its partner GM/Opel came up with an idea. At the so-called Opel Fuel Cell Marathon in Spring 2004, the hydrogen filling station was simply sent on the road with the car. In plain language: a hydrogen car based on the Opel Zafira was accompanied by a mobile LH_2 filling station on a 10,000 km marathon journey from Hammerfest in Norway to Cabo da Roca in Portugal. For this project, Linde supplied not only the entire filling technology, but also the liquid hydrogen.

After the six-week journey through a total of 14 countries, one thing was clear: all systems had passed the endurance test successfully. Thanks to Linde's patented LH_2 coupler, it only took around four minutes to fuel the car. And the LH_2 tank system developed by Linde and stowed away under the rear seat of the vehicle functioned absolutely reliably. In this way, both the reliability of the fuel cell drive and the advanced stage of development of Linde's LH_2 filling technology was demonstrated impressively.

Linde's customers will also profit from this experience in future: for long-distance testing on hydrogen-powered vehicles, the company offers the mobile LH_2 filling system under the name mobiLH_2®.

Other projects

Linde is currently involved in two EU projects, the aim of which is to pave the way for a hydrogen-based economy. HyWays is a long-term research project in which all relevant data is being analyzed. The results will enable the EU member countries to make the right decisions for changing to a hydrogen economy. In contrast, StorHy is a consortium of companies and state institutions occupied specifically with the development of H_2 storage technology for the automobile industry. The aim of the consortium is to consistently improve existing storage media, to carry out research into innovative storage technologies and to develop them until they are ready for the market.

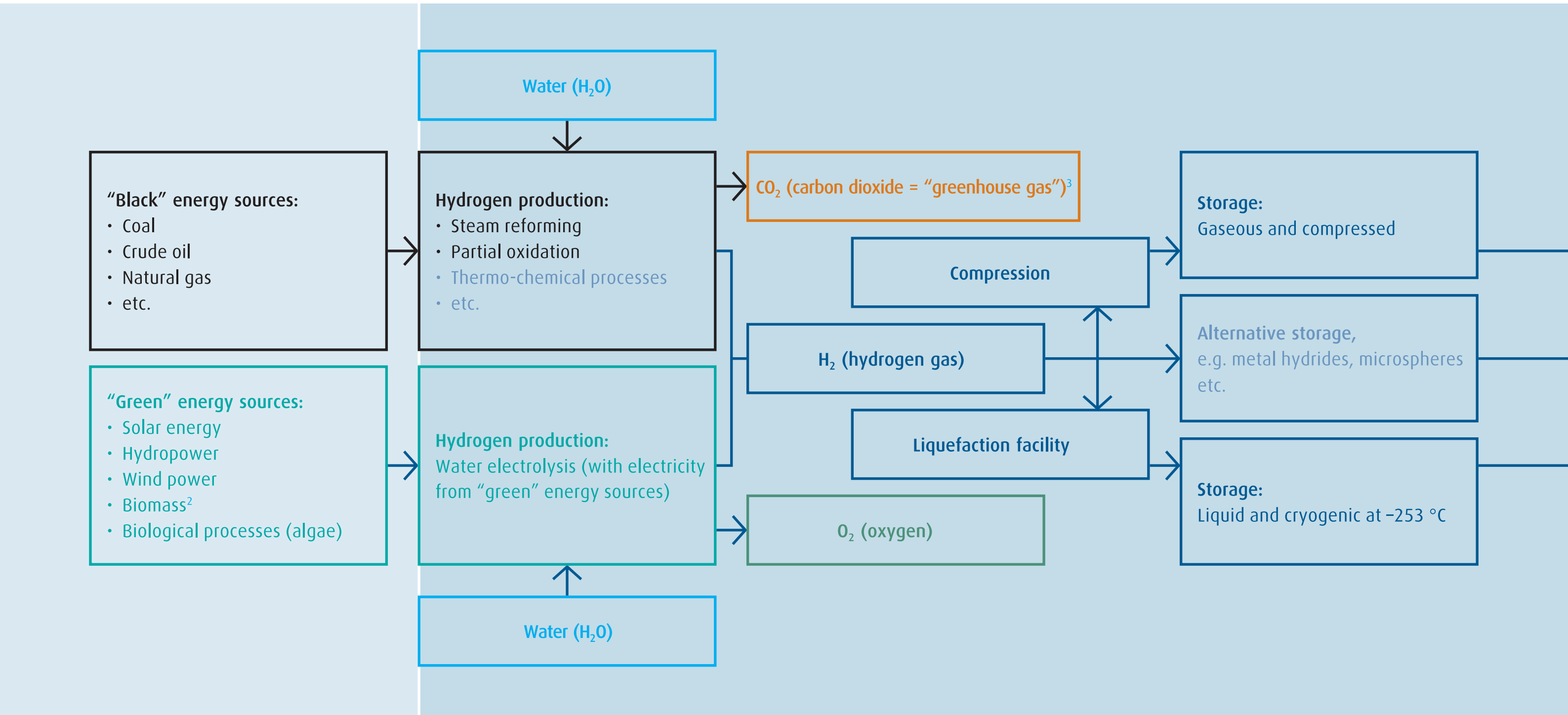
A vision takes shape. The hydrogen society – developments and prognoses.

In principle, all hardware for a functional hydrogen technology chain – from production to application – is already available and ready for use. In order to create an emission-free hydrogen economy, it is actually "only" necessary to change the energy sources for hydrogen production from "black" to "green", i.e. from non-regenerative fossil fuels to regenerative, environmentally friendly energy sources.

Obstacles on the way to a hydrogen society

At present, there are two main obstacles hindering this step forward: firstly, there is still a lack of corresponding infrastructures (e.g. a wide-ranging network of H_2 filling stations). Secondly, the exploitation of conventional energy sources is – at least in the medium term – still distinctly more economical than the exploitation of regenerative energy sources. Therefore, economic factors, political decisions and social developments must be taken into account before hydrogen can make its breakthrough as a widely available energy carrier.

Energy sources **Hydrogen technology chains from Linde[1]**



"Black" primary energy sources
Advantages: economy, efficiency, advanced stage of development, development potential.
Disadvantages: CO_2 emissions, greenhouse effect, global warming, consumption of fossil resources, environmental pollution.

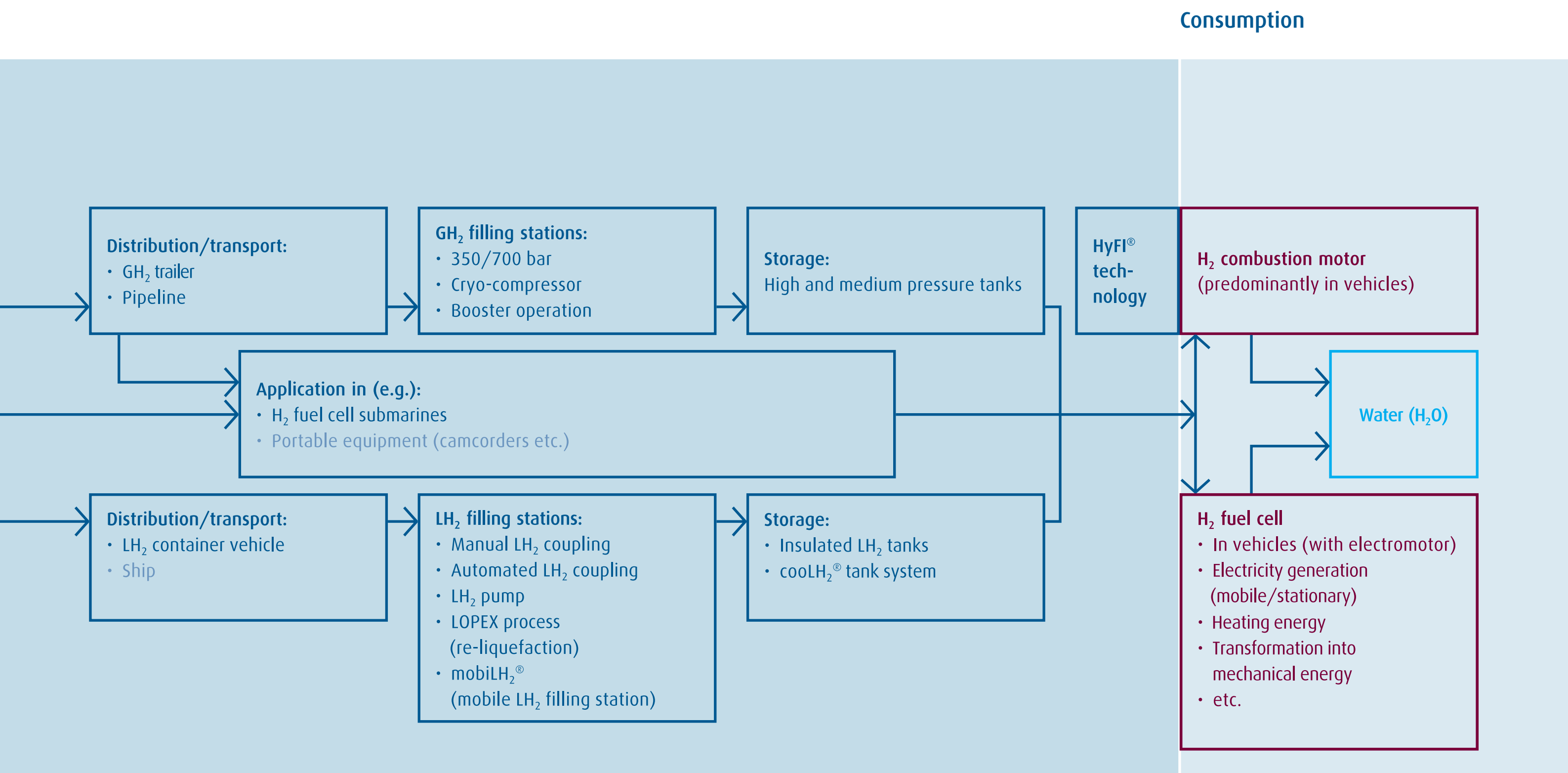
"Green" primary energy sources
Advantages: environmentally friendly, spares fossil resources, renewable energy, availability.
Disadvantages: costs, missing infrastructure, in part lack of social acceptance.

Outlook

The tasks which must be completed on the way to a hydrogen society are varied and demanding. They will continue to pose great challenges for scientists, engineers, entrepreneurs and politicians in the future. Only through international networks, joint efforts in the areas of research and development and an intensive exchange of knowledge will it be possible to reach the targets set – i.e. to make available a clean, practically unlimited energy carrier on a large scale at a price which everyone can afford.

As one of the global market leaders in the hydrogen sector, Linde has been committed to researching this tremendously versatile energy carrier for decades. Moreover, with the construction and export of production and liquefaction plants, the development of innovative transport, storage and filling technologies and the production and distribution of GH_2 and LH_2, Linde has entire hydrogen technology chains in its portfolio.

Through proactive work and successful collaboration with partners and state institutions, Linde is making an important contribution to creating and driving forward the conditions for a sustainable hydrogen economy. However, the fact that it will presumably take years before this technology becomes a matter of course for the general public is no reason for Linde to sit back and relax – on the contrary, the prospect of being able to count on a completely emission-free energy supply one day spurs us on to do our best to make this vision a reality.



[1] ■ Note: Linde is not active in areas marked with this font color.

[2] As combustion takes places when hydrogen is produced from biomass, thereby releasing CO_2, biomass is strictly speaking not a “green” energy source – however, it is still counted as one because it photosynthesizes enough CO_2 into O_2 before combustion to maintain a healthy CO_2 balance. Biological processes and biomass gasification require no subsequent electrolysis, as hydrogen is already available.

[3] In the medium term, so-called CCS (Carbon Capture and Storage) systems are considered to be a possibility of reducing the greenhouse effect. Here the CO_2, released for example from “black” energy sources during hydrogen production, is captured and stored.

Getting ahead through innovation.

With its innovative concepts, Linde Gas is playing a pioneering role in the global market. As a technology leader, it is our task to constantly raise the bar. Traditionally driven by entrepreneurship, we are working steadily on new high-quality products and innovative processes.

Linde Gas offers more. We create added value, clearly discernible competitive advantages and greater profitability. Each concept is tailored specifically to meet our customers' requirements – offering standardized as well as customized solutions. This applies to all industries and all companies regardless of their size.

If you want to keep pace with tomorrow's competition, you need a partner by your side for whom top quality, process optimization and enhanced productivity are part of daily business. However, we define partnership not merely as being there for you but being with you. After all, joint activities form the core of commercial success.

Linde Gas – ideas become solutions.

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