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HARNESSING HYDROGEN

Is hydrogen the answer, and if so, which technologies? Here we present an overview of "everything you need to know" about this promising new global energy source.

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The global energy system is undergoing significant technological change. This holds true for each of its basic modules (or subsystems): from the breakdown of the primary energy sources being harnessed (the "energy mix" of fossil fuels, nuclear and renewable sources), through the technologies converting primary energy into usable forms (electricity, heat, new fuels, cooling, mechanical energy), to the technologies used in its transmission, distribution, and consumption by end users. The optimization criteria for the transformation process, alongside the basic technical and economic functions (efficiency, generation costs), also need to account for functions reflecting the ecological challenges (climate protection, reducing atmospheric pollution, protecting fuel resources, etc.).

The current climate policy of the European Union

In the wake of the Paris Agreement (COP 21, Paris 2015), insisting upon the need to limit global warming in the current century to within 2°C (with a goal of 1.5°C) above pre-industrial levels, it became necessary to plan appropriate projects to ensure the decarbonization of industry and transport and facilitate the EU's attainment of climate neutrality by 2050. Recall

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that the EU has adopted the following objectives: to reduce greenhouse gases by at least 20% (by 2020), 40 percent (by 2030), and 80 percent (by 2050) as compared to 1990 levels and to achieve an at least 32% share of renewable sources in gross final energy consumption, as well as to increase energy efficiency by 32.5% and bring the establishment of the EU internal energy market to completion. Moreover, at its meeting on 10 and 11 December 2020, the European Council endorsed a new EU target to reduce net greenhouse gas emissions in the EU by at least 55 percent by 2030 compared to 1990 levels. In so doing, it called upon its members to include this new target in the proposal for a European climate law and to adopt it quickly. This poses a significant challenge for all EU countries, for Poland in particular. The complexity of this challenge is further exacerbated by the need to maintain sufficient security in an energy system with an ever-larger share of capacity drawn from renewable sources, which by nature involve a degree of randomness.

The role of hydrogen

In the search for rational solutions to this problem, there is now intense discussion about what role hydrogen can play in the processes of decarbonization of the economy and transportation, in the decentralization of highly efficient generation, and in the delivery of final forms of energy, as well as about how to initiate change in many industries. Today, there often talk about developing a new "hydrogen economy" or, in a somewhat narrower sense, about "hydrogen energy." These terms are understood to embrace a set of processes and technological modules that include the stage of producing hydrogen (it is not a fuel that can be drawn directly from natural resources), its storage, transportation and conversion into desired forms of energy (mainly electricity, mechanical energy, and also new fuels). All of these are important in the overall tally of technical, economic, and ecological efficiency. More specifically, the following are identified as areas where technological, economic, ecological and socio-organizational solutions need to be sought to facilitate hydrogen energy (the hydrogen economy):

- producing hydrogen from various energy carriers, including coal, other hydrocarbon fuels, and nuclear power,
- new technologies for renewable hydrogen generation: electrolysis, thermal decomposition of water (such as thermolysis, cyclic thermochemical

processes, hybrid thermochemical decomposition processes), photocatalysis,

- hydrogen as a propellant for vehicles,
- high-efficiency fuel cells,
- the systemic impact of hydrogen on the technological structure and management of the power industry and on changing the industrial infrastructure – the integration of hydrogen energy technologies with large-scale hydrocarbon-based power generation,
- social-political conditions for investment security in the hydrogen economy.

Perspectives

We are already observing a steady increase in demand for hydrogen. Between 1975 and 2018, its consumption in the world increased from roughly 29 million to 115 million metric tons (Mt) per year. It is to be expected that due to the emergence of new application areas for hydrogen (e.g. in transport), its production will increase intensively. On the feedstock side (2018) of the dedicated production of pure hydrogen (73 Mt), natural gas accounted for the largest share (196 Mtoe – million metric tons of oil equivalent = 41.86 10^9 J), followed by coal (75 Mtoe), others being oil (2 Mtoe) and electricity (2 Mtoe). The remaining demand for hydrogen is met by processes that produce the gas as a by-product. Hydrogen is mainly used in the production of ammonia, methanol, and in refining processes.

Nowadays, there is a widespread conviction that hydrogen has an important role to play in the energy transformation. This has been confirmed by many studies, analyses and programs developed in many countries. According to the scenario presented in the publication *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition* by the Hydrogen Council initiative, the share of hydrogen in the final energy demand in 2050 will be 18%, making it possible to eliminate 6 Gt of carbon dioxide emissions by using appropriate technologies for its utilization in various sectors of the economy and transport (Figures 1, 2). Under the presented scenario, the dissemination of hydrogen technologies will be most rapid in the decade 2040–2050. Between 2015 and 2050, the annual demand for energy from hydrogen should increase approximately tenfold, from 8 to 78 EJ, whereas between 2040 and 2050 alone an increase from 28 to 78 EJ is predicted (1 Exajoule ≅ 277.8 TWh). The projected sectoral breakdown of hydrogen utilization in 2050 includes consumption of 10 EJ in areas of the economy where it is used today, 9 EJ in new industrial processes (carbon capture and utilization – CCU, direct reduced iron – DRI), 11 EJ in municipal economy and housing, 16 EJ in the industrial energy economy, 22 EJ in transport and 9 EJ in electricity generation processes (such as buffering, strategic reserves, storage). This indicates the great potential of hydrogen technologies in decarbonizing the transport sector and improving industrial processes. All the scenarios are optimistic and should be considered as pointing to the possible potential. They also show that the transformation may stretch out over decades. Indeed, the introduction of hydrogen into the energy system adds complication to the system (Figures 1, 2), requiring the introduction of new technologies – including energy storage and information technologies that optimize system functions with a large share of renewable sources with random electricity generation.

Technologies

The development of hydrogen technologies and a global, sustainable hydrogen energy system offers a real opportunity to address three major challenges facing the global energy industry. These are as follows: the need to meet the growing demand for clean gaseous and liquid fuels and electricity; the need to

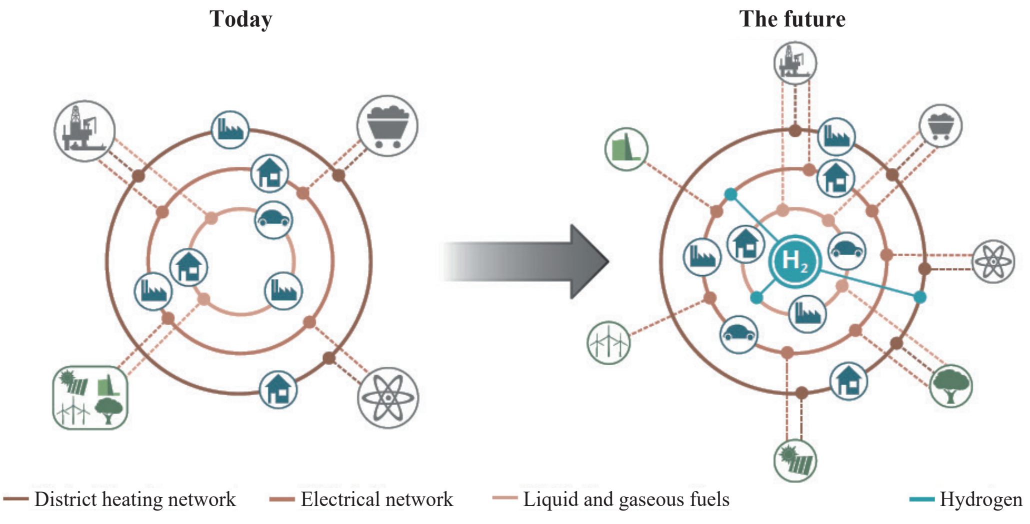

Fig. 1
The changing structure of the economic system due to the introduction of hydrogen (based on the IEA publication *Technology Roadmap: Hydrogen and Fuel Cells*, Paris 2015)

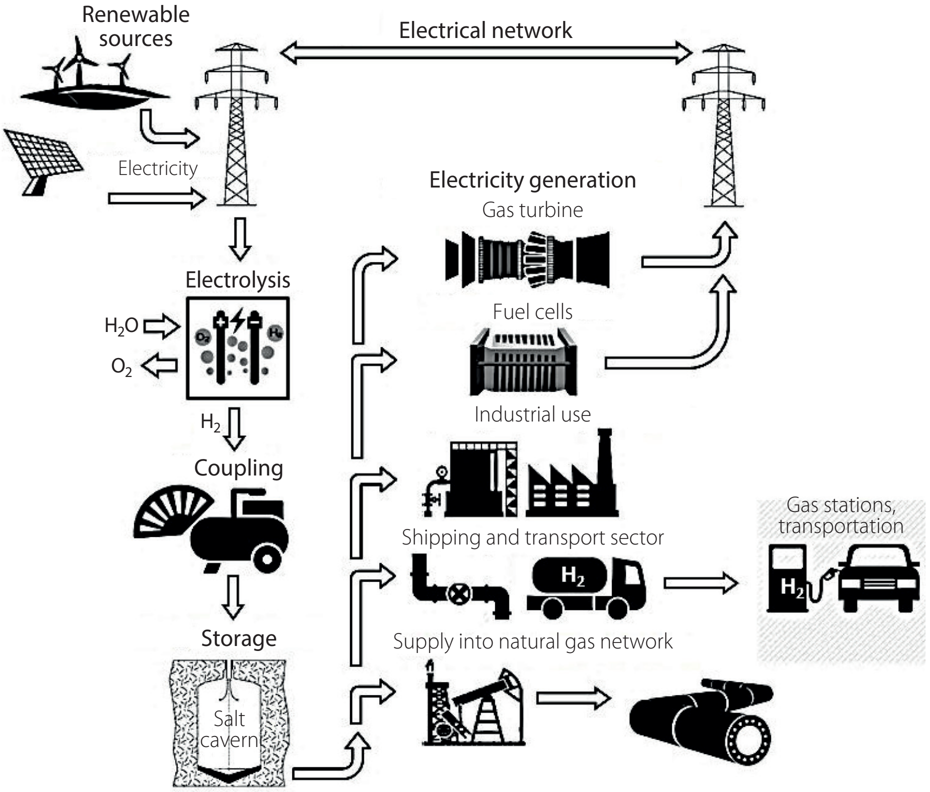

Fig. 2
Modules of the hydrogen economy (after Chmielniak & Chmielniak 2020)

increase the efficiency of fuel and energy production; and the need to minimize harmful emissions to the atmosphere, including greenhouse gas emissions, at the final stage of energy use.

The technologies developed are usually grouped according to schemes: power to power, power to gas (H_2 + CH_4 mixture, methanation), and power to liquid. These are characteristic pathways of hydrogen generation from renewable sources and its conversion to other forms of energy. They do not exhaust all the possibilities for organizing the hydrogen economy. There are also solutions for using low-emission fossil fuel technologies (coal and gas with CO_2 separation) and nuclear fuels that may prove to be competitive with renewable technologies (depending on their stage of development). These, too, need to be factored into the search for the optimal path of development of hydrogen technologies and their use in the whole economy and energy sector, in line with the adopted economic criteria and ecological constraints. In the long run, however, the main technology will probably be the decomposition of water into hydrogen and oxygen and the generation of hydrogen in biomass and waste conversion processes.

On an industrial scale, hydrogen is currently produced mainly from natural gas using the steam methane reforming (SMR) process, which is currently the cheapest option for hydrogen production. In addition, commercially available technologies for the production of hydrogen from natural gas include partial oxidation (POX), catalytic partial oxidation (CPOX), or a combination of these two, as well as autothermal reforming (ATR), catalytic dehydrogenation, pyrolysis, and electrolysis. Also at various stages of development are photocatalytic processes, plasma reforming, membrane reactors, and biological processes.

There are many technologies available for the decomposition of liquid or gaseous water into hydrogen and oxygen. They differ in terms of the type of driving energy, as well as its source and the parameters and organization of the main and auxiliary processes. In general, the following methods are distinguished: electrolysis, thermal decomposition of water (thermolysis, cyclic thermochemical processes, hybrid thermochemical decomposition processes), and photocatalysis. For electrolytic methods the main type of energy supplied to the process is electricity (an external source of direct current), for the group of thermal decomposition methods the driving energy is heat (usually at high temperatures), while for methods in the third group the source is electromagnetic radiation from the Sun.

The state of advancement of each group of technologies varies. Electrolytic methods using two types of electrolyzers (alkaline electrolyzers at medium temperatures, proton exchange membrane electrolyzers at low temperatures) have reached industrial maturity, whereas electrolyzers with oxide membrane (operating at high temperatures) are currently at the pilot study phase. In the group of methods involving the thermal decomposition of water, work is underway on analyzing processes of direct thermal dissociation of water (at a process temperature of about 2500°C), cyclic thermochemical processes, and hybrid processes using different modes of conversion (e.g. electrolysis with chemical conversion). At least 300 thermochemical and hybrid processes are known that can be carried out at different temperatures; they are selected to seek the lowest possible temperature and highest process efficiency. They are often considered in the context of using high-temperature nuclear reactors and solar energy as heat sources. Sulfur-iodine and copper-chlorine processes are currently receiving much attention. The efficiency of the electrolysis process is relatively high:

- alkaline electrolyzers (2018: 63–70 percent, 2030: 65–71 percent, after 2030: 70–80 percent);
- polymer electrolyzers (2018: 56–60 percent, 2030: 63–68 percent, after 2030: 67–74 percent);
- oxide electrolyzers (2018: 74–81 percent, 2030: 77–84 percent, after 2030: 77–90 percent).

Costs

In terms of the costs of producing hydrogen from fossil fuels and biomass, the greatest thermodynamic and economic efficiency of gas and oil use has been confirmed to be achievable through steam reforming technologies. Improvements in this class of hydrogen generation methods should, in addition to increasing economic efficiency, include reducing carbon dioxide emissions from generation processes. Hydrogen production costs vary by geographic region and country, and by the use or non-use of CCUS (carbon capture utilization and storage) in the production processes. The geographical variation mainly derives from the fact that the main cost component is the price of the available fuel (feedstock). For example, the price of hydrogen from natural gas reforming without CCUS facilities in the United States is about \$1/kg H_2, rising to \$1.5/kg H_2 after carbon capture. The corresponding prices for the EU are \$1.7/kg H2 and \$2.35/kg H_2. For China, the level can be assumed at \$1.75/kg H_2 and \$2.4/kg H_2, whereas in the case of Russia and the Middle East, prices are comparable to those in the US. Investment costs are within \$500–900/kWH$_2$ for systems without CCUS and \$900–1600/kWH$_2$ for CCUS. In Poland, the price of hydrogen generation by steam reforming is about 7 PLN per 1 kg of hydrogen, at a gas price of 1200 PLN per 1000 m^3 (without CO_2 separation). The cost of producing hydrogen from coal depends on the gasification technology used, the price of the raw material, and whether or not carbon dioxide separation is used in the gasification process. Available sources cite values in the range of \$0.71–3.13/kg H_2. Data from the Chinese and US markets fall within \$1.1–1.34/kg H_2 without and \$1.47–1.63/kg H_2 with CO_2 sequestration. According to Polish analyses carried out for various coal gasification installations, the cost without CO_2 sequestration is 5.5–6.5 PLN/kg H_2. This is comparable with steam reforming at a gas price in the range of 930–1100 PLN/1000 m^3.

Hydrogen energy applied to the household

The costs of hydrogen generation by electrolysis and thermolysis processes are evaluated in terms of the costs of individual installation modules. These are difficult to verify in practice, due to the lack of operating results for large capacity installations. In 2019, the capacity of operating alkaline electrolyzers exceeded 45 MW, and the capacity of electrolyzers of the PEM type (polymer electrolyte membrane electrolysis, a class of electrolyzers that has recently attracted the greatest interest) exceeded 38 MW. The total capacity of installations with SOEC electrolyzers (solid oxide electrolysis cells) did not reach 1 MW. The total number of installations exceeded

Hydrogen energy being harnessed at a household

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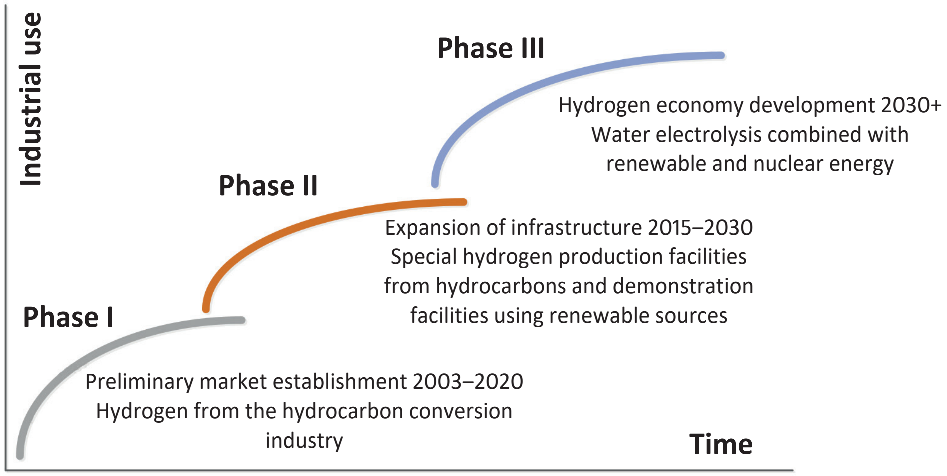

Fig. 3
Possible scenarios of hydrogen economy development (after Ściążko et al. 2018)

the value of 180. The average power per single installation commissioned in 2015–2018 was about 1 MW. Numerous feasibility studies are underway to build 5 and 100 MW installations using alkaline electrolyzer stacks and PEM. In Australia, for instance, a hydrogen production system integrated with a wind and solar farm with a total capacity of 400 MW is under preparation, meant to be capable of producing about 20 t of hydrogen per day by electrolysis of water. One of the directions of application of this gas is the production of ammonia as an energy storage and possibly fuel, with a significant part being intended for export, in particular to Japan.

Based on the results obtained from demonstration installations and assuming a high degree of uptake for this class of technology, it is estimated that in 2030 the cost of hydrogen generation will be \$4.84/kg H_2 in Europe by electrolysis powered by electricity from the grid (with emission cost of \$40/t CO_2), or \$2.87/kg H_2 in the case of renewable energy sources (with renewable energy cost of \$40/MWh). Competitiveness with natural gas steam reforming could be achieved with an electricity price of less than \$40/MWh and an emission allowance price of about \$50/t CO_2. Currently, the cost of generation is high, requiring efforts to improve all modules of its generation and also consistency in climate policy.

An important factor differentiating between the various hydrogen generation technologies is the accompanying carbon dioxide emissions. Renewable driving energy corresponds to zero emissions production (so-called "green" hydrogen). "Grey" hydrogen, in turn, is that generated in processes harnessing fossil fuels (coal gasification emits about 20 kg CO_2/kg H_2, natural gas reforming emits about 9 kg CO_2/kg H_2). There is also talk about "blue" hydrogen, produced in technologies using non-renewable energy sources and raw materials, albeit with the use of CCUS (coal gasification with CCUS emits about 2 kg CO_2/kg H_2, natural gas reforming emits about 1 kg CO_2/kg H_2 – these figures assume the capture of 90% of carbon dioxide). The production of hydrogen by electrolysis processes using grid electricity is burdened by particularly high carbon dioxide emissions (for gas-fired electricity generation, emissions are about 18 kg CO_2/kg H_2, for coal-fired generation, about 40 kg CO_2/kg H_2).

In essence, therefore, we are today in the age of grey hydrogen. It is difficult at this point to determine whether blue hydrogen technologies will be disseminated on a large scale or whether we will move straight into the era of green hydrogen technologies, which would guarantee the achievement of EU climate policy goals and climate neutrality after 2050 (Figure 3).

Application

Hydrogen has great potential for mid- to long-term applications in energy and many industries (Figure 2). In the power industry, there are many opportunities to use hydrogen and fuels generated from this gas. Co-combustion of ammonia in coal-fired units is possible in the near future. Hydrogen and ammonia can be flexible fuel options for fuel cells and gas turbines. For small loads, hydrogen at a price of about \$2.5/kg has strong competitive potential. The main competitive options are natural gas with CCUS and biogas. In the long term, hydrogen may play a major role in large-scale power generation (hydrogen turbines) and as an energy carrier in energy storage systems. For the dissemination of hydrogen energy technology, the development of fuel cells is important. Their competitiveness in the transport sector depends on the cost of the cells and on the construction and operation of hydrogen charging stations. For automobiles, it is fundamental to reduce the cost of the cells and the hydrogen tank in the car. This should make them competitive with batteries and provide a range of 400–500 km, or even 1000 km. For trucks, in turn, lowering the price of hydrogen delivery is key. In the heating sector, the greatest opportunity in the short to medium term for increasing hydrogen consumption lies in admixing hydrogen into the existing gas infrastructure. In 2030, 4 million tons of admixed hydrogen is expected to be consumed. The potential is particularly significant for multi-family residential buildings and public buildings. In the long term, fuel cells and hydrogen boilers are expected to be used in the heating sector. Transportation, power generation, and public utilities have the potential to make use of hydrogen if its production and disposal costs are less than other options.

The complicated issue of the development and diffusion of hydrogen technology makes a well-understood support policy essential. Further endeavors are needed to improve electrolyzers and other methods of producing hydrogen. The search for optimal hydrogen utilization and storage systems is important. Given that rational hydrogen energy largely depends on the local potential of renewable sources (as well as on the fuel structure of energy and transport), national-level programs for the development of hydrogen energy need to be developed. Many countries have drawn up appropriate strategies in this area and formulated research and development programs based on them. Priority directions need to be selected for investment in pilot and demonstration installations.

Barriers

The successful development of the hydrogen economy could significantly contribute to the achievement of a climate-neutral status. However, many challenges and barriers can be identified in this transition process. Apart from the technical and economic challenges, many legal and logistical problems still remain unsolved. Inadequate raw material resources may prove to be an important obstacle to the rapid dissemination of hydrogen technologies. In general, the barriers and accompanying challenges are as follows:

- Hydrogen is now almost entirely generated from natural gas and coal. Despite technological advancements, this generation is responsible for large amounts of carbon dioxide emissions. More work is needed to develop technologies for hydrogen production using renewable energy, as well as carbon capture in fossil fuel processes.
- Hydrogen production using low-emission driving energy is currently expensive. Although the price of hydrogen produced using renewable electricity may decrease as the cost of renewable energy falls and hydrogen production scales up, this process may not proceed quickly enough to make this mode of hydrogen generation competitive.
- The development of hydrogen infrastructure has been slow, which has not been conducive to its uptake. This affects the price of hydrogen for consumers, which is highly dependent on the number of refueling stations and the reliability of supply. Solving this problem requires planning and coordination at the international and national levels, as well as the involvement of local governments and authorities, as well as industrial institutions and private investors. Work on a hydrogen law is also underway in Poland.
- Current regulations restrict the development of the clean hydrogen industry. Among other measures, it is necessary to develop common international safety standards for the transport and storage of large quantities of hydrogen and to track the environmental impact of different hydrogen supply technologies. Work on norms and standardized solutions for hydrogen generation and use is ongoing in the EU and in individual countries.
- The rapid deployment of hydrogen technologies may be hindered by the high raw-material intensity of renewable energy installations (for instance, installing the 25 TW wind power capacity envisaged in 2050 will require more than 50 million Mg of copper, or four times the annual copper production for 2010, and 3.6 million Mg of neodymium, or 180 times the current annual production, as well as large quantities of other materials, including cement and steel). It also entails significant increases in the demand for precious metals (which play a role in catalysts, electrodes, collecting plates), stainless steel, and other substances necessary for the construction of electrolyzers, fuel cells, pipelines, and cables. These industries therefore require significant development if they are to be able to supply the necessary materials for the anticipated widespread adoption of the hydrogen economy.

The following can be considered the priorities for Poland in this regard, from the research perspective:

- identifying studies being conducted in various areas related to hydrogen energy and attempting to coordinate them to a greater degree (including plans for pilot installations),
- laying forth the assumptions for a research agenda, covering issues with high application potential given the conditions in Poland,
- parallel studies on the role of hydrogen in the decarbonization of the transport sector (production of liquid fuels, use of fuel cells in transport), the energy sector (combined heat and power systems with fuel cells, gas turbines, integration of wind and solar energy with hydrogen production technologies, biomass technologies, the role of fossil fuels in the development of hydrogen energy) and the possibility and desirability of its methanation (i.e. conversion of hydrogen to methane) for use in natural gas networks. ■

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