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Natural Gas

A transition fuel on the path from coal to hydrogen.

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The basic generating units in the Polish National Electric Power System (NEPS) are currently steam units burning hard coal and lignite (Fig. 1). Most were built in 1965–1985, and many have been in operation beyond their original design lifespans. Though technically constructed to have an operating life of 200,000 hours, with repairs and modernization they often operate for more than 300,000 hours. However, the need to shut them down and replace them with new generating units is inevitable. Almost half of the current installed capacities in the NEPS need to be decommissioned. Based on the information contained in the preliminary, published version of the document titled "Energy Policy of Poland Until 2040," coal-fired generating units with a total capacity of 3,000 MW were decommissioned in 2015–2020, and it is expected that around 6,000 MW will be decommissioned by 2030 and more than 10,000 MW over the following 10 years. After 2040, only a few coal-fired units placed into service over the last several years will remain operational (those in Opole, Kozienice, Jaworzno, and Turów). Therefore, it is only natural that we should ask what will take the place of all these decomissmioned units.

Power generation and the European Green Deal

From the perspective of the energy policy formulated by the European Union (EU), the year 2050 is posited as an important watershed when the economies of the EU countries are expected to reach climate neutrality. The set of measures aimed at helping the EU countries to achieve this goal is referred to as the European Green Deal. For the energy sector, this means that in 2050 electricity and heat generated for municipal purposes should come from renewable sources, primarily wind and solar energy. Nuclear power has not been ruled out, but other types of energy are preferable. Many other developed countries outside the EU declare that their economies will also reach climate neutrality within a similar timeframe. At a recent UN session, China pledged to become climate-neutral, but over a slightly longer timeframe, namely by 2060.

Wind and solar energy in Poland

In Poland, recent years have witnessed a very rapid increase in wind and solar energy capacity (Fig. 1). However, the increase in the amount of energy produced is considerably smaller. For the purpose of determining the generation capacities of various energy technologies, the *capacity factor* is defined

as the ratio of the actual electrical energy output over a period of one year to the maximum possible output. In Poland, this is about 1,000 hours for solar cells and 2,000–2,500 hours for onshore wind turbines. Power plants using fossil fuels (coal, gas, nuclear fuel) are designed for an expected operating life of more than 7,000 hours per year. This means that, in extreme cases, replacing a 200 MW unit being taken out of service would require the construction of a photo-voltaic power station of 1,400 MW. Since we can obtain an average of about 0.2 kW from a cell of 1 m^2, such a power station would have to cover an area of 7 km^2. The construction of onshore wind farms, in turn, is limited by the legally required minimum distance between the tower of the wind turbine and residential buildings, based on what is referred to as the 10H rule, where H is the total height of the installation. For 2 MW turbines, which are quite common, the installation is around 200 meters high, which means that the turbine must be built at a distance of 2 km from residential buildings. Such sites are hard to find in Poland.

The Lech Kaczyński LNG Terminal in Świnoujście – an import and regasification terminal, December 2016

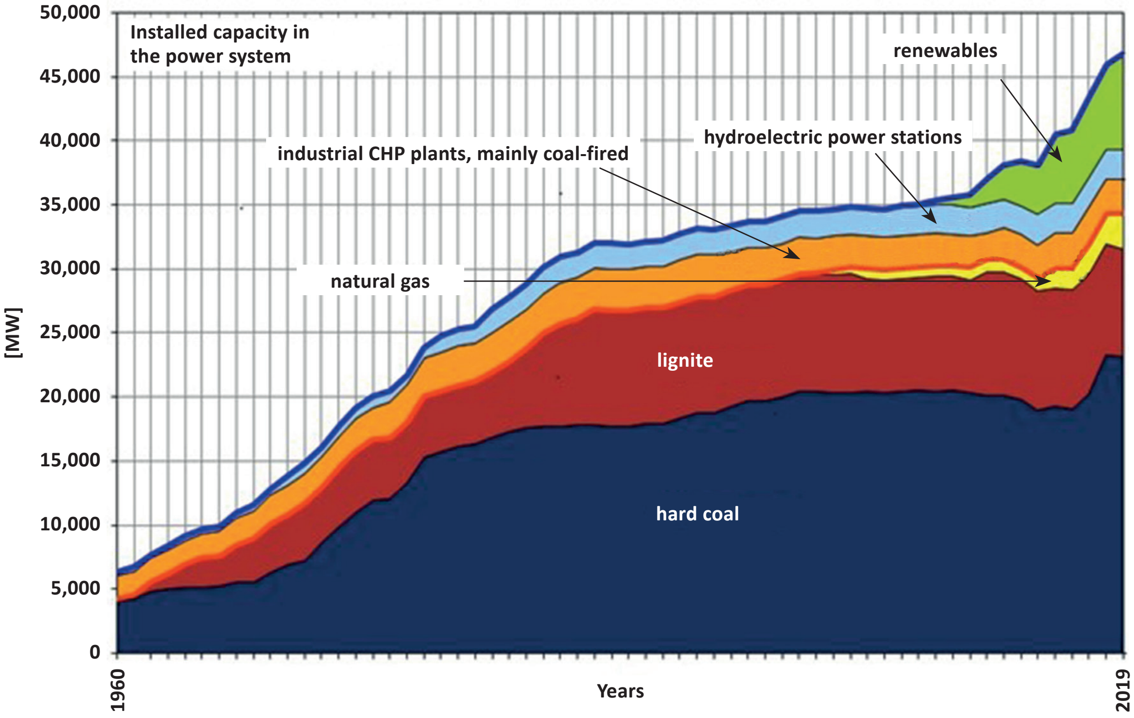


Fig. 1
Development of capacities in the National Power System by fuel types

However, the most important problem for the development of solar and wind energy is posed not by locational constraints, but by the fact that the power they generate depends on the time of day and on the weather. Such factors cannot be controlled, and their intermittent nature is not consistent in any way with demand for electricity. Figure 2 illustrates demand for electricity in Poland and the hypothetical output from wind under a scenario where Poland has only wind farms. These have been scaled so that annual production is equal to demand, using as an example data from 2017, when demand reached 168.38 TWh.

Harnessing solar energy does not make this situation any better. What we need is energy storage, on a very large scale at that. Based on data from the same example, ensuring the availability of energy at all times would require an energy storage facility of about 16 TWh. What does this mean? The peaking power plant in Żarnowiec has a storage capacity of 3.6 GW. Consequently, we would have to build nearly 4,500 such plants in Poland – certainly an unrealistic prospect. Intensive research is being carried out on other energy storage technologies, and we can assume that technologies allowing such large amounts of energy to be stored will have been developed and implemented by 2050. Among the most promising technologies include hydrogen technology. In periods when the electricity generated exceeds demand, the surplus would be used to produce hydrogen (for example through the electrolysis of water). The hydrogen would be then stored and used to generate electricity in the periods when demand for electricity exceeds its supply.

Hydrogen can be converted back into electricity in an electrochemical process in a fuel cell (the reverse of electrolysis) or in a traditional electric generator powered by a hydrogen combustion engine.

This is the future. Today, however, power plants powered by fossil fuels, primarily coal and natural gas, play the role of sources responsible for balancing out the demand for electricity and its supply, and this situation will continue at least for the next 20 years. For reasons related to the decommissioning of old coal-fired units, such countries as Poland actually need to construct another "generation" of classic coal- or gas-fired power plants.

Natural gas in the energy sector

Both these technologies have been known and used for many years. For reasons related to limited access to gas, however, the first gas-fired unit did not appear in Poland until 1999 – it was the combined heat and power (CHP) plant in Gorzów Wielkopolski. Without going into the more technical aspects, if we compare these two technologies, we will see that the important thing was that the unit cost of the construction of a gas-fired power plant (1 MW of capacity) was lower and the efficiency was higher, but the fuel was more expensive. In Polish conditions, the electricity produced from coal remained much less expensive than the electricity generated from gas for many years. Likewise, there were no discussions on the need to reduce CO_2 emissions for climate change-related reasons.

But this situation has now changed. Generation capacities must be renewed as quickly as possible, while CO_2 emissions must be reduced for climate change-related reasons. This is where we can see the first advantage of gas over coal. Gas is less emission intensive. This is quite evident because the heating value of coal is almost exclusively linked to the presence of carbon, and burning coal releases CO_2. In the case of natural gas, which is almost pure methane, there is one carbon

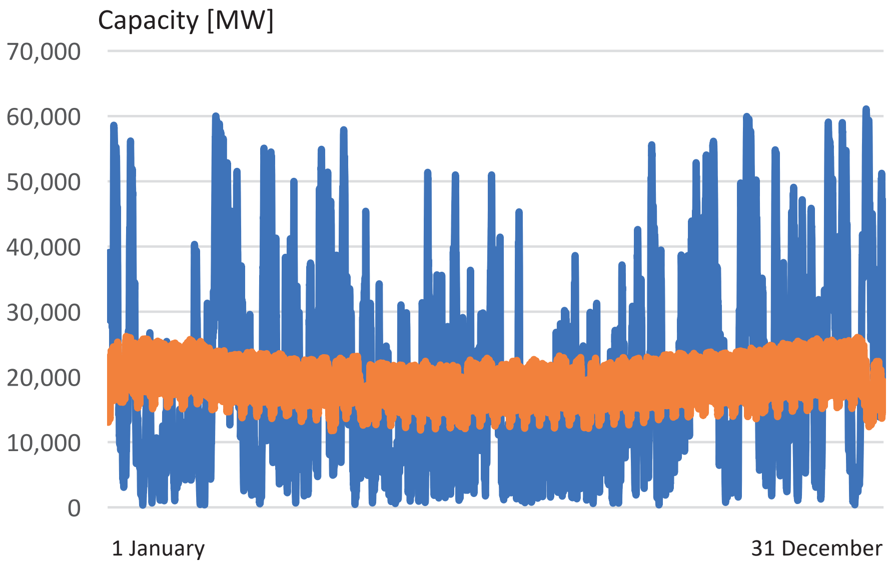


Fig. 2
Changes in demand for electric power (orange line) and the power generated by wind turbines in Poland; the capacity of wind turbines at any given moment (blue line) was adjusted so that annual production would be equal to the national demand in 2017

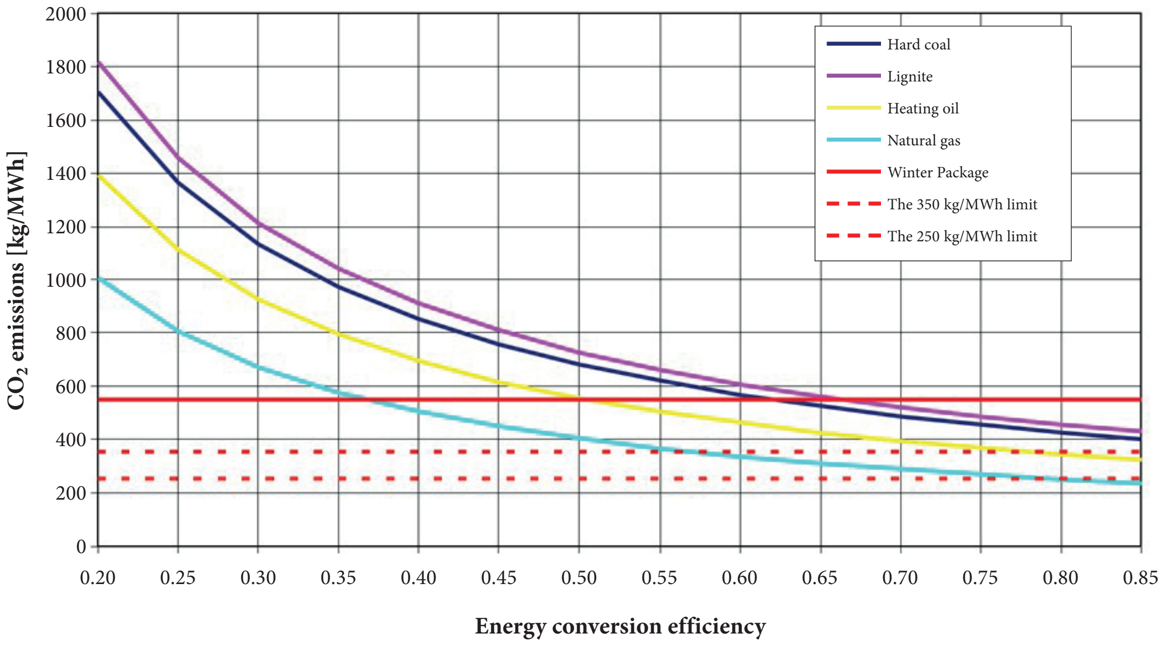


Fig. 3
Specific CO_2 emissions in relation to the amount of energy generated for typical fossil fuels as a function of energy conversion efficiency. The red line (the Winter Package) marks the 550 kg/MWh threshold above which pursuant to the EU law no public aid will be available from mid-2025

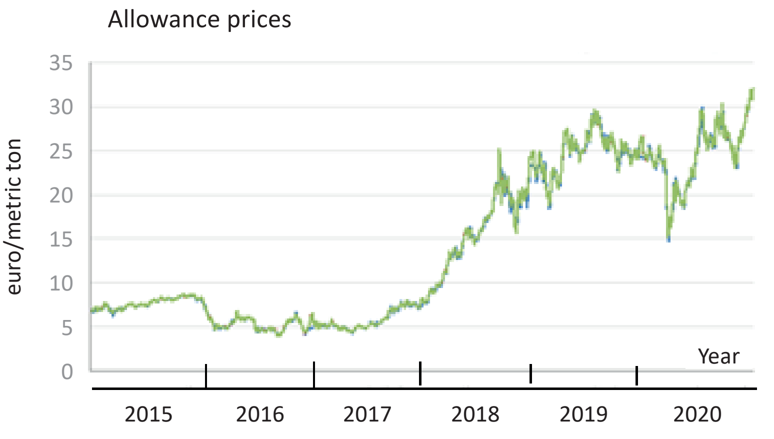
atom for every four atoms of hydrogen. The product of its combustion is a mixture of water vapor and CO_2. A comparison of the emission intensity of these two fuels is shown in Fig. 3.

The efficiency of modern coal-fired units that only produce electricity is 45%, which results in CO_2 emissions of about 800 kg/MWh. The efficiency of a similar gas-fired unit is about 60%, and the CO_2 emissions are about 350 kg/MWh. In the case of power plants that produce both electricity and heat, the efficiencies are over 80%, resulting in emissions of 450 kg/MWh and 250 kg/MWh, respectively. These emission levels are important from the formal standpoint. Pursuant to the existing EU legislation, from mid-2025 onward it will not be possible to provide public aid to generating units with emissions higher than 550 kg/MWh. In practice, this will exclude the use of coal-fired power plants as units responsible for balancing out demand vs. supply. Discussions are ongoing on reducing the emissions limit to 350 kg/MWh or even 250 kg/MWh in the following years. This will also rule out the use of coal-fired CHP plants for this purpose, but it will be possible to use gas-fired power and CHP plants.

Arguments in favor of gas include not only formal restrictions, but also costs. Since 2005, the EU has used the emissions trading system under which emissions allowances can be bought and sold as one of the mechanisms of limiting CO_2 emissions. Allowances were initially allocated to power and CHP plants free of charge, but the number of free allowances allocated directly to producers was gradually reduced in the following years. Allowances were granted to individual countries and energy producers buy them at auctions (the money from the auctions remains at the disposal of each country). In the initial years, allowances cost around a few euros, which was not a significant cost from the perspective of producers. The situation changed at the end of 2017 (Fig. 4), when allowance prices began to rise rapidly. Currently (January 2021), the price is almost 35 euros per metric ton of CO_2.

Allowance prices of over 100 zlotys per ton have altered to a significant extent the relationship between the costs of generating electricity from coal and the costs of generating electricity from gas. At present, the gas price at exchanges is around 110 zlotys per MWh (for easier comparison, the prices are per unit of energy – the product of their mass and heating value) plus about 20 zlotys in the cost of transmitting the fuel to the power plant, which works out as 130 zlotys per MWh, and the cost of fuel in the cost of electricity (generated in a plant with 60% efficiency) is about 215 zlotys per MWh for gas and 40 zlotys for allowances, which works out as a total of around 250 zlotys MWh. In the case of coal, these prices are respectively 100 zlotys per MWh for coal,

Fig. 4
Carbon emissions allowance prices 2015–2020



220 zlotys per MWh of the fuel cost in the electricity cost (assuming that the efficiency of the plant is 45%) and 80 zlotys per MWh for allowances. In total, the fuel and emissions costs in the price of electricity are about 250 zlotys per MWh for gas and 300 zlotys per MWh for coal. We should also remember that the costs of building a coal-fired power plant are at least 60% higher than those of building a gas-fired power plant, despite the fact that its useful life is 50% longer. In general, electricity generated from coal is more expensive than electricity from gas!

Until 1999, Poland had practically no installations that used gas technology. At the few industrial CHP plants that did exist, gas was burned in steam generators. From the perspective of the technology of converting the energy contained in fuel into electricity, however, these generators used steam technology, the same as used in coal combustion.

In the case of gas combustion for the purposes of producing electricity, the basic technology that is used relies on a combined-cycle system that combines a gas turbine set and a steam turbine set (Fig. 5).

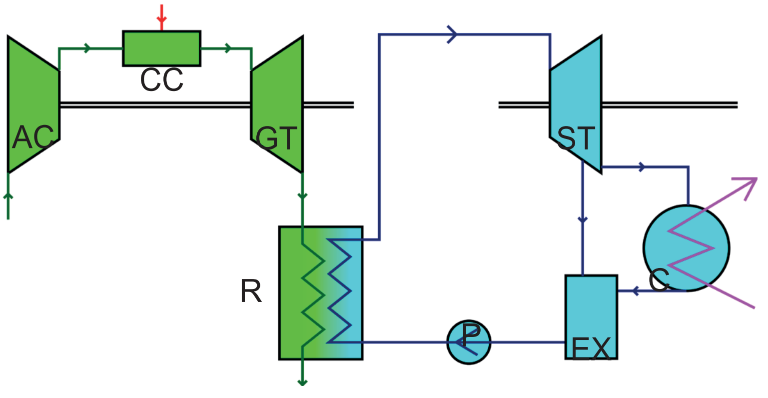


Fig. 5
A simplified diagram of a combined-cycle unit
AC – air compressor,
CC – combustion chamber,
GT – gas turbine,
R – heat recovery steam generator,
ST – steam turbine,
C – condenser,
EX – heat exchanger,
P – pump.
Diagram based on Polish version from https://pl.wikipedia.org/wiki/Uk%C5%82ad_gazowo-parowy

A gas turbine set consists of three components: an air compressor (AC), where air is compressed to reach the pressure of about 1.5 MPa, a combustion chamber (CC), where natural gas is burned in high pressure air, and a gas turbine (GT), where the expansion of the exhaust gas from the combustor takes place at a temperature of around 1,500°C. As a result of this expansion, the turbine shaft rotates, thus driving the electric generator.

The exhaust from the gas turbine whose temperature exceeds 500°C is directed to the heat recovery steam generator (R). It generates steam, which then flows into the steam turbine (ST). The steam is expanded in the turbine and condensed in the condenser (S). The water preheated in the heat exchanger (EX) is pumped (pump P) under high pressure to the generator. The steam turbine, just like the gas turbine, drives the electric generator. The system makes it possible to harness a very wide range of temperatures to convert energy into work (from as little as 30°C to about 1,500°C), allowing for a very high efficiency of the process, even over 60% in the newest solutions.

Gas turbines and the European Green Deal

From the perspective of these considerations, the gas turbine is an important element of the combined-cycle system described above. Since the gas turbine operates at very high temperatures, its lifetime is not long. Throughout this period, the components operating at the highest temperatures are replaced. Nonetheless, the lifetime of a gas turbine is about 25 years, significantly less than that of a steam turbine. This shorter operating life is advantageous from the perspective of reaching the goal of transitioning away from fossil fuels by 2050. The gas turbines built over the next several years will end up being fully depreciated from the perspective of capital expenditures.

In my opinion, gas turbines have yet another advantage, perhaps the most important one. In general, their principle of operation is compatible with the use of any combustible gas, which therefore also means hydrogen.

In practice, however, this is not easily implemented. Natural gas is currently the main gaseous fuel, and gas turbines, in particular their combustors, are adapted to this gas. The properties of hydrogen as a combustible gas are significantly different from those of natural gas (which is almost pure methane), as compared in Table 1.

The only parameter whose value is similar for both gases is the flame temperature. Other parameters differ, often by whole orders of magnitude. The heating value of hydrogen in relation to its mass (MJ/kg) is more than twice as high, so in terms of mass much less hydrogen must be burned assuming the same power, but hydrogen is more than 70 times lighter. Consequently, it is necessary to burn over 30 times more hydrogen in terms of volume, which results in the need for much larger diameters of fuel pipelines and most of all the combustor itself. In the case of hydrogen, the flame speed is almost 10 times greater, the energy needed for ignition is more than 20 times smaller, ignition occurs almost 10 times faster, and the range of concentrations at which the combustible mixture is formed is larger. Safety considerations and prevention of the loss of control over the combustion process pose challenges that have yet to be fully resolved from the technological perspective. However, all major players in the market of gas turbine manufacturers plan to have gas turbines capable of burning pure hydrogen ready for commercial use around 2030. Today's turbines burn a mix of natural gas and

Table 1
A summary of the selected properties of two combustible gases: methane and hydrogen

Combustion without excess air (stoichiometric combustion) under normal atmospheric conditions	Methane CH_4	Hydrogen H_2
Flame speed [m/s]	0.4	3.0
Flame temperature [°C]	~1950	~2150
Flammability limits [% by volume]	5–15	4–75
Minimum ignition energy [mJ]	0.28	0.011
Ignition delay time in the conditions of a combustor (730°C and 1.7 MPa) [ms]	45.6	6.2
Lower heating value [MJ/kg]	50.01	120.33
Density [kg/m^3]	0.657	0.09

hydrogen, and the allowed share of hydrogen is becoming increased in consecutive designs. The newest turbines made by leading manufacturers are capable of burning a mix of gases in which hydrogen accounts for up to 30% of volume. Hydrogen's density is low, so this share is considerably smaller in terms of energy, namely below 10%.

The gas turbine, along with the combustor and the compressor, is only part of the installation. The remaining components remain the same, regardless of whether methane or hydrogen is burned. It will be possible to continue to use them after 2050, when we transition away from natural gas and burn only hydrogen.

The combined-cycle system is not the only technology in the energy sector that uses natural gas. Smaller installations, with a capacity of several MW, use gas engines instead of gas turbines. Smaller capacities are primarily used in the heating sector for the simultaneous generation of heat and electricity. In this case, the exhaust from the engine used to generate not steam, but hot water, which is then directed to the heat network. There is no steam turbine or condenser, and the steam generator is replaced by a water boiler. For such installations, work is ongoing on the combustion of mixtures with a growing share of hydrogen and, in the future, pure hydrogen. The current state of progress of such projects is similar to that of the projects involving gas turbines.

Using a mixture of methane and hydrogen to generate electricity in the transition period has yet another advantage. In some countries, such as Germany, certain regions are characterized by a periodical excess of electricity produced from wind and sunlight over demand. In such cases, the surplus electricity is used to produce hydrogen. How should this hydrogen be put to use, if there are no adequate storage facilities yet? The role of a storage facility is played by the natural gas network. The hydrogen that is produced is pumped into this network. For reasons related to characteristics of hydrogen, the proportion of hydrogen cannot be too high. In Germany, the permissible is norm is up to 10% hydrogen. In specific parts of the network (Schopsdorf, Saxony-Anhalt), work is ongoing on projects using a mixture in which hydrogen accounts for 20% of volume. There is no doubt that the existing network infrastructure for natural gas facilitates the gradual introduction of hydrogen into the economy.

Natural gas: a near-perfect fuel for the transition period?

Globally, a vast majority of countries, faced with evident climate change, appear to have made the political decision that steps need to be taken to radically reduce CO_2 emissions. For the energy sector, this means the need for widespread use of renewable energy sources. Relevant technologies are available, and their cost is acceptable. However, one problem remains unresolved. As yet, we do not have electricity storage facilities on a mass scale and at an acceptable cost, and such facilities are needed to temporarily balance the amount of electricity produced and consumed. Intensive work is underway, but for the next 20 years or so we will be forced to use traditional power and CHP plants as regulating units to cover energy shortages that cannot be compensated by energy obtained from renewable sources. In Poland, in light of the need to decommission existing coal-fired units on a mass scale, replacing them with combined cycle gas and steam units using natural gas is practically the only solution that is technologically and economically justified. Is this a perfect solution? No, mainly because the domestic gas resources remain insufficient. Nevertheless, this is the best solution, even if it is not perfect. ■

Further reading:

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