

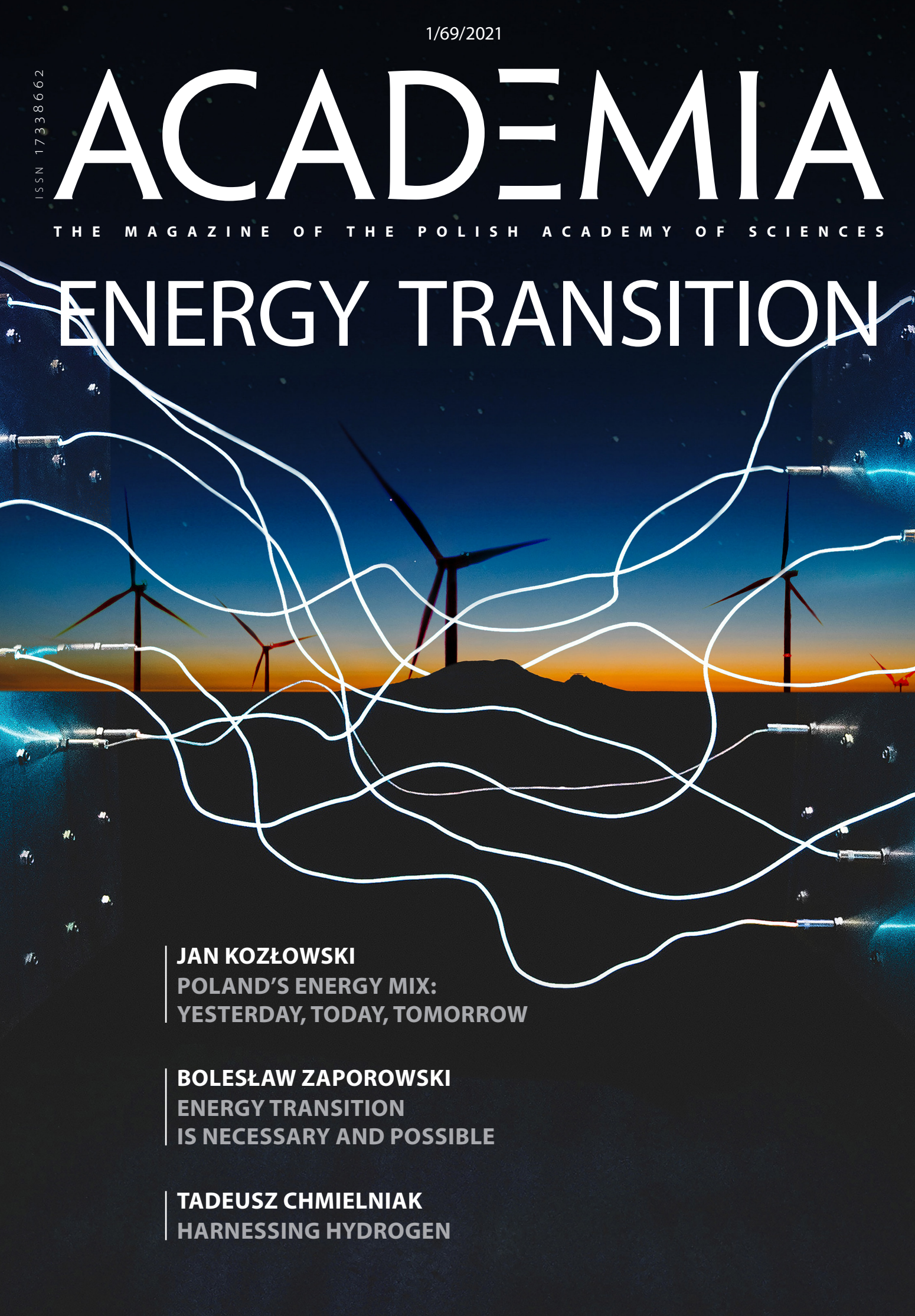
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ACADEMIA

THE MAGAZINE OF THE POLISH ACADEMY OF SCIENCES

ENERGY TRANSITION



JAN KOZŁOWSKI
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YESTERDAY, TODAY, TOMORROW

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IS NECESSARY AND POSSIBLE

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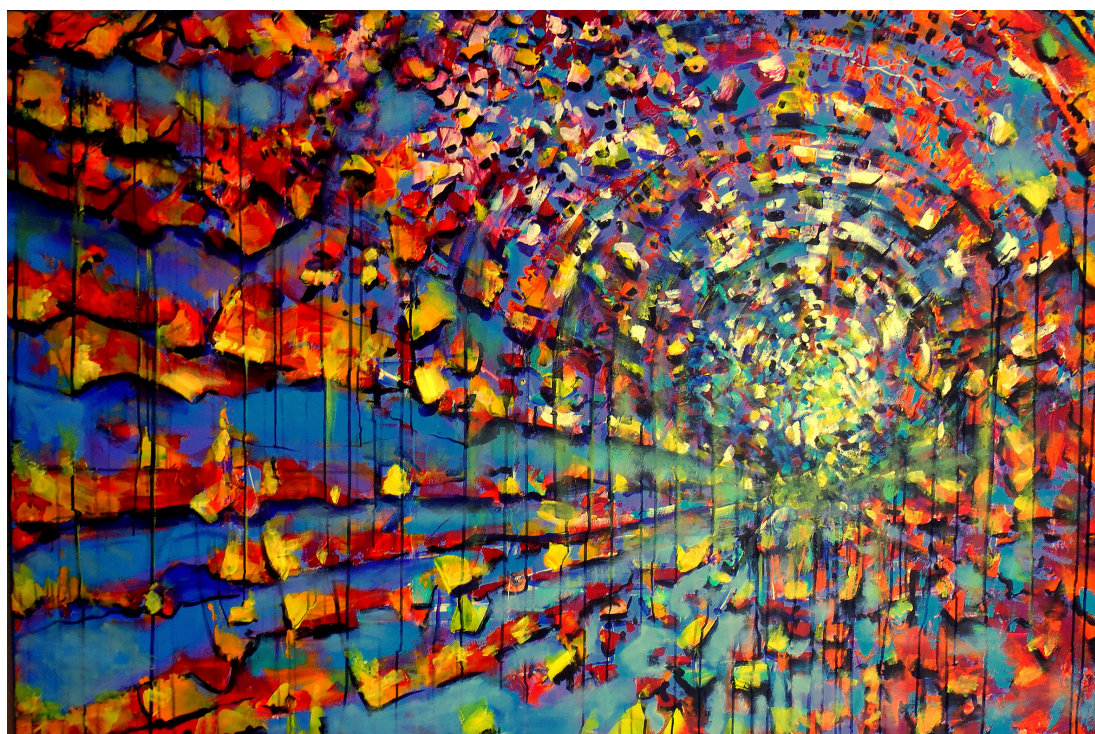
POLAND'S ENERGY SECTOR ON THE BACK OF SCIENTIFIC ARGUMENTS

There can no longer be any doubt that the greenhouse effect, associated with increased CO₂ concentrations in the atmosphere, is caused by mankind's burning of fossil fuels, in conjunction with the gradual deforestation of the globe. In the coming decades, therefore, the Polish economy faces a necessary but difficult energy transition, seeking to ensure the security of energy supplies whilst at the same time striking a balance between socioeconomic development and respect for ecological principles. Moreover, achieving climate neutrality over the next three decades will be further complicated by the long-term impact of the COVID-19 pandemic. For these and other reasons, the prospects for the adoption of an energy transition package have social and political emotions running high in Poland.

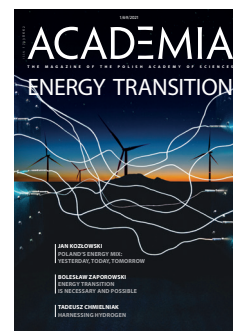
It is our hope that the various scholarly opinions gathered together in this issue of *Academia* magazine will foster thoughtful discussion on the energy transition in Poland, firmly grounded in solid scientific argumentation. In the articles of this issue, a number of Poland's top energy experts discuss various aspects of renewable energy sources and their impact on the country's energy sector, conveying the very latest state of knowledge on a number of sub-sectors. No matter what solutions are implemented, it seems clear that one important consequence that needs to be reckoned with is the social costs of the energy transition borne by society, particularly visible in coal-mining regions.

Several of the authors, as well as the PAS Committee on Power Engineering in its position statement published herein, point out that there is no industrially developed country in the world, with similar natural conditions as Poland, that intends to build a safe and zero-emission power system based solely on renewable energy sources within the next three decades. The overarching conclusion they point to is the necessity of investing in nuclear energy in Poland.

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Lukasz Jankiewicz, "Everything is Energy," 100×150 cm, oil on canvas, Wrocław 2019



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ON THE BRINK OF DISASTER

Transforming the energy sector
is necessary but not sufficient
to prevent a climate catastrophe.



The concentration of carbon dioxide in the atmosphere is rising rapidly. It has already reached 415 ppm (parts per million), up by 48% compared with the pre-industrial era (280 ppm). Such a high level has not been recorded for at least the last 800,000 years (we know this from the air bubbles trapped inside Antarctic ice) and, based on indirect data, probably for the last 10 million years. Carbon dioxide traps the heat that is returning to space after

being delivered by the Sun, so an increase in its concentration causes the Earth's temperature to rise. It is good that some carbon dioxide is present in the atmosphere, because without it the whole of the Earth would be covered by ice. From the perspective of humanity, however, its current concentration is clearly too high. The average temperature on Earth is rising, glaciers are melting, sea levels are rising, hurricanes and floods are becoming increasingly violent, forest fires are increasing, and the precipitation zones are shifting. We are on the brink of disaster, and if we do nothing, our planet faces a very difficult time ahead. According to a report by the Intergovernmental Panel on Climate Change (IPCC), we must do everything we can to stop the temperature from rising by more than 1.5°C compared with the pre-industrial period to prevent a catastrophe and by more than 2°C to prevent a great catastrophe. We have little time left – if we cross the tipping point, there will be no turning back, because we know of no way we might be able to reverse the direction of the changes.

There is no longer any doubt that humans have caused the amount of carbon dioxide in the atmosphere to rise by burning fossil fuels and additionally by cutting down forests. The emissions of carbon dioxide caused by human activity are unbelievably high, reaching 38 billion metric tons a year – two orders of magnitude more than the average amount released by volcanoes. If the carbon contained in this amount of gas (12.2 billion tons) were to be loaded onto the wagons of a train, this train would encircle the equator 47 times. And this is just the level of annual emissions in 2019. An important role is also played by other greenhouse gases, especially methane and nitrogen oxides. Although their emissions are small, the greenhouse effect of each unit of volume is many times larger than that of carbon dioxide. Their final impact is therefore significant, but not as significant as that of carbon dioxide. For this reason, we can only stop the temperature from rising by radically reducing carbon dioxide emissions.

Greenhouse gas emissions

One concept that is important in thinking about climate change is the amount of primary energy contained in coal or lignite, petroleum, and natural gas, the combustion of which leads to the emission of greenhouse gases. Overall, the emissions from these sources, which are used to produce electricity and heat as well as in combustion engines, account for 73.2% of total emissions (<https://ourworldindata.org/ghg-emissions-by-sector>). The remaining emissions are caused by agriculture, deforestation, and waste, as well as the carbon dioxide released in chemical reactions, for example in cement plants. This 73.2% is broken down as follows: industry



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– 24.2%, transport – 16.2%, and buildings – 17.5%. About half of the remaining 15.3% consists of unallocated fuel combustion (not classified as falling within the previous groups), while the rest consists of losses of various types. Of course, some but not all of the energy associated with these emissions is electric power.

Zero-emission energy generation

By various estimates, the power generation sector accounts for 27–40% of total carbon dioxide emissions. Let's assume that this share currently stands at one-third. This fact alone is a major argument in favor of the need to transform the power generation sector towards zero emissions, but there are also other important reasons. Transportation is responsible for approximately 16% of emissions, mainly from the direct combustion of petroleum products, so rapid growth in electromobility will drive up demand for electricity. If hydrogen starts to play a major role in transportation (and this appears likely at least in the case of heavy vehicles), it will ultimately come from electrolysis (green hydrogen), which will consume a lot of electricity. Thus, transportation's 16% share of emissions would eventually shift over to the power generation sector, assuming that it still relies on the burning of fossil fuels. Similarly, buildings are currently responsible for more than 17% of all emissions, largely in connection with heating and cooling, and the growing popularity of heat pumps, which use electricity, will shift some of that 17% over

to the energy sector. We can already observe a rapid change of this type in the case of a small source of household emissions, namely cooking. Moreover, as the Earth's temperature goes up, people will use air conditioning more, thereby requiring more and more electricity. On the road to zero emissions, the use of fossil fuels in industry will drop, whereas the use of green hydrogen will rise, which will likewise require additional electric power. To save the climate, we will most likely need to capture and store some of the carbon dioxide contained in the atmosphere. This, too, will also require significant amounts of electricity. For all these reasons, the power generation sector needs not only to rapidly develop zero-emissions technologies, which will initially reduce and ultimately eliminate fossil fuels, but also to greatly increase power generation capacity.

Energy storage

There can be no doubt that the power generation transition has to bear the brunt of the efforts to achieve zero emissions – or strictly speaking, we should better say “climate neutrality,” because it is impossible to reach zero emissions in full, and some emissions will have to be absorbed or neutralized by the natural environment. Fortunately, the technologies needed to achieve this goal are mature, but we should and we will continue working hard to improve them and bring down their cost. The most serious challenge is posed by the development of energy storage, because the new power generation sector will be largely reliant on wind and solar energy and therefore dependent on weather conditions. In all likelihood, chemical storage in the form of hydrogen will be the most important form of energy storage. The production, storage, and use of hydrogen still require certain improvements. Another challenge consists in adapting the transmission networks to the growing share of distributed energy sources. All countries of the world are lagging behind in this respect, and this is especially true for Poland.

What a year it was!

There is every indication that this is what we will be saying about the year 2020 in the future. Of course, the main reason for this will be the pandemic, which is the pessimistic aspect. Fortunately, there is also an optimistic one – in 2020, most of the economically developed countries pledged to achieve climate neutrality: Norway in 2030, the EU in 2050 (Sweden and Finland in 2045), Japan and Korea in 2050, and China in 2060. Many countries are readying themselves to make similar declarations. The United States withdrew from the Paris Agreement under Donald Trump, but Joe Biden, elected in 2020 on the

Tesla cars parked at the Tesla Supercharger electric vehicle charging station in the Westminster Mall parking lot, California, United States, 22 January 2020



DAVID TONELSON/SHUTTERSTOCK.COM



The first hydrogen-powered train in the Netherlands was shown to the public at the main train station in Groningen on 7 March 2020

back of green policy promises (among other pledges), brought the country back into the Paris deal and signed the document at the beginning of his term. This act was an important symbol. For that matter, it appears that public awareness is changing so rapidly that it will be impossible in a growing number of countries to win elections without pledging an active commitment to the energy transition or, more broadly, action aimed at achieving climate neutrality. Exxon Corporation, which may be one of the strongest bastions of the old order in the energy sector, announced the development of carbon dioxide air capture technologies rather late, namely in January 2021. But Exxon's executive board has not yet managed to bring itself to announce a program for shifting away from fossil fuels, as other oil corporations have (such as BP, Shell, and even Poland's Orlen).

Fair transition

For the time being, these are just declarations. Let us hope that there will be enough determination to put them into effect. However, such declarations of will do seem to be a crucial step for changes beneficial to climate protection to actually come into effect. The energy transition – or, more generally speaking, the transition towards climate neutrality – should be fair. The most affluent countries are currently the biggest emitters of greenhouse gases, and the amount of the greenhouse gases they emit *per capita* is many times larger than that in poorer countries, which want to develop economically and therefore have greater demand for energy. Unless the wealthier countries, which are now transitioning towards

lower emissions, help the poorer ones to prevent their development from following a similar path of high emissions, we will not be able to save the world. In addition, the countries that have pledged climate neutrality should not succumb to the temptation of exporting emissions to other countries by simply relocating emission-intensive industries elsewhere. Climate neutrality achieved in this way may be a propaganda success, but it will not help avert the climate catastrophe, which is a global threat, not a local one.

The last 20%

Transforming the energy sector will not, on its own, be sufficient to save the climate. Why not? Firstly, changes will also be needed in other sectors, above all in industry. Here, technologies are often immature or, still worse, at the stage of laboratory research or prototypes. Implementing low-emission technologies will take a lot of effort. Moreover, there is still the problem of the last 20% or so of emissions, because they cannot be eliminated in full. Does this mean that we will have to store underground large amounts of carbon dioxide captured from the air? Or maybe we will succeed in transforming the previously degraded natural resources in a way that will re-enable them to capture such small emissions? It is certain that the natural environment will not be able to absorb them at their current level, but it may prove capable of capturing the last 20%. This is an important question, and science should be looking to answer it right now – as it will become a crucial issue, hopefully in just a few decades' time. ■



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WHITHER THE ENERGY TRANSITION?

Humanity is being forced to alter how we use energy sources, to move away from fossil fuels and focus instead on renewable, especially solar energy. This transformation may prove to be the long sought-after “holy grail” of energy.



Fig. 1
The three worst “plagues” faced by humanity at the current stage of civilization, affecting our chances of survival. How can we save the Earth, and thereby ourselves? The choices appear obvious, but are extremely hard to put into effect

Jan Kiciński

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Today, we have enough scientific evidence to take it as a proven fact that the ongoing rapid changes to the Earth’s climate, which pose a danger to our civilization, are in large part due to the high emissions and low efficiency of the energy sector. Both the energy sector and climate neutrality are no longer merely problems for politicians, businesspeople, and scientists, but have become challenges faced by humanity itself. The main message of this article, as encapsulated in these introductory remarks, is that a decisive transition from traditional large-scale fossil fuel-based energy generation to renewable ener-

gy-based, distributed generation is very clearly inevitable in the long run.

Figure 1 lists just some of the factors that threaten human development to the greatest degree. We might describe them as the three major “plagues”: harmful gas emissions, intensive farming, and plastic pollution. The fragile balance of the natural environment may be upset as soon as within the coming decade. This may lead to an increase of over 2°C in global warming and disrupt the climate balance. This is explained visually in Figure 2.

Major barriers

We have listed the three major plagues affecting the planet that may lead to humanity’s downfall: not the demise of life on Earth, but the collapse of our civilization as we know it. But in fact, we have more reasons to worry. In order to answer the question of



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A fragile balance

Natural sources (solar activity, natural geologic cycles, biological processes, and volcanoes) account for ninety-seven percent of CO₂ emissions, and this share can be absorbed by oceans and plants. Thanks to this mechanism, the amount of CO₂ in the air has been stable for thousands of years – but this balance is very fragile. Humanity has been upsetting it by emitting huge amounts of CO₂ that cannot be absorbed by the natural environment. That is the essence of the problem.



An illustrative example:

Just a tiny drop of water with a small mass can disrupt the fragile balance of a convex meniscus covering a whole glass.

An increase of over 2°C in global warming may disrupt the climate balance.

Where does the boundary lie?
2°C, or 4°C?

1.5°C

2.0°C

4.0°C

Fig. 2

The fragile balance in the natural environment. Human combustion of fossil fuels emits 37 billion metric tons of CO₂ into the atmosphere each year, and although these amounts account for a very small share of CO₂ in the natural cycle, they remain unsustainable and accumulate. Life on Earth is possible thanks to such natural mechanisms as the carbon cycle and the CO₂ thermostat. The disruption of these mechanisms would turn the Earth into a second Venus or into a snowball. Unfortunately, we are now indeed heading towards such a “Venus scenario”

whether we will survive, we must first identify the most important barriers that prevent us from solving our problems. Attempting to define them, however, leads to some astonishing conclusions.

It turns out that the main obstacles are not posed by the unavailability of relevant technologies, negligence in science, or failure to come up with ideas of how to resolve specific problems. Rather, they turn out to lie in the human mentality and in various geographical/historical factors. These obstacles may be described as people's mindset, climate change denial, and "climate apartheid." Let us take a closer look at each of these in turn.

I. Mindset. We might formulate the most important message for humanity as follows:

If we are to save the Earth, people simply must change their mindset and adopt notions that prioritize sustainable development in harmony with nature, rather than economic development and high consumption at any price.

This is certainly a beautiful idea, but how should we explain to the poorer, developing countries that they should give up their aspirations to attain the standards of living and the level of economic development enjoyed by more developed countries and instead think about the issues of climate change and environmental protection?

A decisive transition from traditional large-scale fossil fuel-based energy generation to renewable energy-based distributed generation is inevitable in the long run.

Across the world, economic development has turned into something of a religion. A key role is played here by the protectionist policies pursued by leaders of some of the world's powers (such as the United States and China) and developing countries (India and Brazil). Also, it is hard to expect that the EU's ambitious climate policy, especially the recent European Green Deal, and the stance promoted by global celebrities (e.g. Al Gore, Bill Gates, Elon Musk, Leonardo DiCaprio) will be enough to inspire all the countries of the world to act.

II. Climate change denial. Why is it so difficult to admit that humans are responsible for progressive climate change? Past fluctuations in the Earth's temperature and CO₂ levels, the relatively low content of

CO₂ in the atmosphere (0.03%) as a whole, and the relatively small impact of anthropogenic factors on the greenhouse effect (0.3%) might lull us into a false sense of security. Consequently, some commentators and even scientists use these facts to promote the opinion that the current rise in temperatures and CO₂ levels is part of the Earth's natural geologic cycle and has little to do with human activity. Indeed, climate change denial has become rampant across the world. Such thinking is clearly a trap (see Fig. 2). How can we win this fight to protect our planet if such an attitude is demonstrated by many members of the public and even by some scientists?

III. "Climate apartheid" is a different aspect of climate injustice. Developed countries (conventionally referred to as the wealthy North) are responsible for most of the emissions and environmental degradation, but it is the inhabitants of the poorest countries (conventionally called the poor South) who will be hardest-hit. This situation is bound to trigger dangerous conflicts, population migrations, and even warfare. It could be resolved through large-scale assistance from the richer countries of the North to the poorer countries of the South, but this appears highly unlikely.

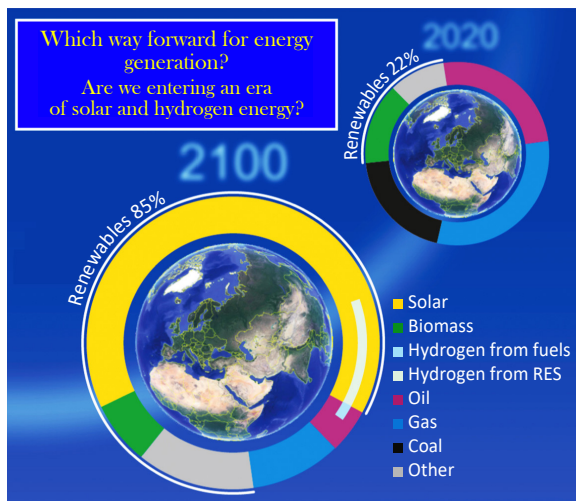
These remarks may lead us to the sad conclusion that as long as the global threats or "plagues" listed above do not directly threaten the very existence of our societies, the support from the global powers and the rest of the world for the EU's climate and environmental efforts will remain moderate or limited only to declarations.

A dawning era of solar and hydrogen energy?

In December 2019, the European Commission unveiled the European Green Deal, an ambitious package of measures meant to bring the EU to climate neutrality in 2050 and enable European citizens and businesses to benefit from a sustainable transition to green energy. In the opinion of many politicians, commentators, and scientists, this is the most ambitious such project ever embarked upon and the most important opportunity and challenge of our era.

Europe has adopted the European Green Deal, but will other countries follow in its footsteps? The questions that arise here are fundamentally important. Do the climate efforts being made by the Old Continent countries actually make sense? Will the costly transition to green energy find allies in other countries of the world? Will Europe not come to be perceived as Don Quixote in this lonely fight?

In answering these questions, we might well quote the statement made by MEP Jerzy Buzek at the last European Economic Congress in Warsaw:



... as Europe, we must show the world – this is the duty of our civilization – that we can move away from fossil fuels, sustain jobs, and remain the most attractive continent for billions of citizens all over the world ... (European Economic Congress Trends, Warsaw, 25 February 2020, <http://www.trends.eecpoland.eu/pl>).

Will this argument be enough? Let us hope so.

Based on an analysis of many research papers, the content published by various companies, and online publications, we may reasonably assume that in the distant future (say, after 2050) we will witness fundamental changes in the structure of the consumption of energy from primary sources (see Fig. 3). In the next century, the dominant source of energy for humans will be solar energy (not nuclear energy, contrary to popular belief). So are we entering an era of solar energy? If so, then technologies related to distributed generation must play a dominant role, and the transition from centralized to distributed energy generation is inevitable.

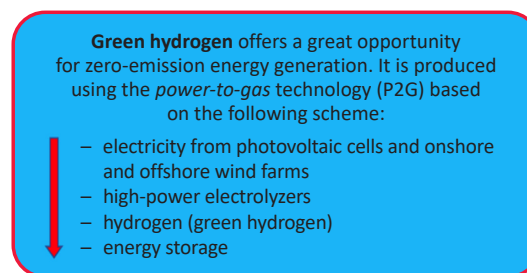
Hydrogen as a fuel of the future

Here, we should stress the role of hydrogen obtained both from renewable energy sources (RES) and from fossil fuels. According to many forecasts, it will come to dominate the structure of primary energy sources at the end of this century, although its exact share is now difficult to estimate.

The production of green hydrogen with the use of renewable electricity is expected to grow rapidly in the coming years. This technology has been relatively well-mastered, but there is still the question of its economic profitability. Today, the unit cost of hydrogen energy is 1.5 to 5 times higher than the cost of energy from natural gas. This will certainly change in the future.

Trends towards producing green hydrogen by electrolysis of water appear promising. Some countries (such as Germany) are already working on high-power electrolyzers. There is no doubt that renewable hydrogen is a technology of the future, although it is currently produced mainly from natural gas and coal (grey hydrogen – approx. 95%).

However, the business models being implemented show that, depending on the location of the electrolyzer and its useful lifespan, e-hydrogen could already be seen as a certain market alternative. However, the future belongs to this technology for reasons related to the expected sharp drop in the cost of producing electrolyzers and the process itself. Thus, e-hydrogen does indeed stand a chance of becoming the fuel of the future (Fig. 4).



Optimistic and pessimistic conclusions

Unfortunately, it is very likely that human societies will mobilize effectively to combat all these “plagues” only when they turn into a direct threat to their existence. At the current stage of human development, it is highly unlikely that all countries of the world will show solidarity in the fight against threats, given the prevalence of the particularistic interests of individual countries and the world of big business.

The situation is somewhat different, however, when it comes to the energy sector itself. The rapid depletion of fossil fuels will simply force us to bring about a profound energy transformation. The only energy source that humanity will never manage to exhaust is the Sun. For this reason, the direction of this transformation is patently evident: away from fossil fuels and towards renewable energy sources. In other words, the next century will be an era of solar and hydrogen energy, resulting from what may be described as a yellow-blue transformation (with “yellow” standing for solar energy, “blue” symbolizing hydrogen).

This puts us in a position to answer the question of “Which way forward for energy generation?” Also, it will open up an even more important question: Have we at long last finally managed to find the necessary “holy grail”? ■

Fig. 3

What will the structure of primary energy consumption be like in 2100? Is the dawn of an era of solar and hydrogen energy upon us? The projected share of energy from renewable sources is anticipated to increase from today's 22% to 85%, with solar energy accounting for the largest share. This means a profound and revolutionary transformation of the energy landscape

Fig. 4

Green hydrogen (e-hydrogen) obtained from renewable energy sources stands a chance of becoming not only a clean fuel, but also a convenient way to store energy. Solving the problem of storing renewable energy is crucially important for distributed energy generation based on local resources

Further reading:

A New World: The Geopolitics of the Energy Transformation, January 2019, www.geopoliticsofrenewables.org.

Global Energy Transformation: A Roadmap to 2050, 2019 edition, www.irena.org/publications.

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END OF THE (MINERS') WORLD?

The social consequences of coal mine closures
in Silesia.



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The fast-approaching end of the era of fossil-based energy poses a particularly huge challenge in Poland's Silesian Voivodeship, given the prevalence of coal mining there. There are numerous significant sociopolitical problems which need to be solved to ensure a successful and socially just transition.

Issues in the coal mining sector

Coal remains the main fuel used to generate power and heat in Poland, with the coal mining sector providing employment to over 83,000 miners across the country. Most of them work at pits in the Silesian Voivodeship, where coal mining is the dominant industry.

There are a number of closely intertwined problems faced by the coal mining sector in Silesia. First of all, in geological terms, most of the shallow deposits have simply been depleted long ago. The grandfathers of today's miners were extracting coal from around 200 meters below ground, their fathers had to descend to around 600 meters, whereas today deposits in many mines can only be found at depths of 1000 meters and below. The high temperatures at greater depths mean a higher danger of methane explosions. Deep mining also means greater distances between coalface and shaft, which translates into increasingly difficult extraction conditions and increased costs.



PAWEŁ SZCZEPANSKI / SHUTTERSTOCK.COM

A second problem is the dwindling profitability of coal extraction in Silesia. The most profitable deposits – those near the surface, the largest and easiest to exploit – have long been depleted, which in turn reflected in efficiency. If the volume of extracted coal decreases faster than the number of miners, that naturally entails lower efficiency. In 2018, Polish miners extracted an average of 0.4 metric tons of coal per hour, compared to 3.5 tons for their American counterparts, meaning that Polish mining simply cannot compete in terms of efficiency. Poland also cannot compete in terms of labor costs, which are significantly lower in developing countries such as Mozambique. As coal prices fall around the globe, mining in Poland is quite simply becoming an unprofitable enterprise. The scheme by which the entire energy and coal industry functions is at the heart of the problem; since Polish thermal coal cannot compete on the interna-

tional market (apart from coking coal), it is mainly used by coal and thermal power plants domestically.

Tensions between the sectors could easily serve as inspiration for another article – in any case, the roots of the problem are political. This is in fact a third main issue concerning coal mining in Poland: the political significance of the industry. The miners and other personnel employed by mining companies, plus their families, comprise a very numerous group; they form the core of the local electorate in what is historically a “swing” province. Making political decisions concerning the mining industry can lead politicians to see a major loss of support in Silesia, as was the case for former Prime Minister Jerzy Buzek and his Solidarity Electoral Action (AWS) coalition back in the 1990s, following the introduction of reforms to the sector prepared by Deputy Prime Minister Janusz Steinhoff. It is hardly a surprise that successive

Facade of a traditional residential building for Silesian worker families (*familok*), Bytom



governments have largely ignored the sector unless forced to by necessity.

Thirty years later

All these elements are of course closely intertwined, and together lead to a fourth problem, rooted in social issues. Poland's coal mining industry has been shrinking gradually since 1990. In 1989, at the end of the communist era, the sector employed over 407,000 people, and the number has been declining with every new reform. By the time the first stage of reform initiated in 1993 was completed, the number fell by over 100,000. The most heavily affected region was the Lower Silesian Coal Basin, where the entire mining industry was wiped out over the period of a decade. Redundancy payouts did not last long, and former miners and the entire region were soon left with no future prospects. The main city in the region, Wałbrzych, became a nationwide symbol of poverty, epitomized by the return of small-scale, "artisanal" mining. Paradoxically, this was in a response to the neoliberal economic discourse dominant in the 1990s, advocating individualism. Local miners simply took matters into their own hands and set about doing what they did best: extracting coal from shallow deposits. Although illegal and highly dangerous, for many former miners it was the only way of surviving the period of transformation.

The closure of the last coal mine in Wałbrzych in 1998 coincided with the launch of the next wave of reform in 1998–2002, popularly known as the Karbownik-Steinhoff Plan. As well as providing redundancy

payouts, it also included additional early retirement options and social benefits. Around 102,600 employees took the option to leave the sector. The plans for closing local mines were new and challenging for the miners themselves, as well as for those in charge of implementing the project. A popular opinion arose that miners tended to spend their redundancy payouts rashly on such things as home improvements or new cars. However, that opinion proves to be largely untrue (although the latter purchases might have been the most evident to nosy neighbors), as according to research by Prof. Marek Szczepański and Dr. Małgorzata Tyrybon from the Institute of Sociology at the University of Silesia in Katowice, most former miners actually spent their redundancy money to pay off debt or to accumulate savings. The paid-leave mechanism, which in reality was equivalent to a generous early pension, meant that the sector lost over 35,000 employees who would have had to work for another twenty or so years in other industries before qualifying for a pension.

As Wałbrzych became the landmark/symbol of the social costs borne by the mining community in the Lower Silesia Basin, Bytom became a notorious symbol of economic restructuring in Upper Silesia. The stories of both towns and their most affected districts are invoked every time rumors of mine closures appear. Local communities fear that they will face a similar fate.

Closing a mine means destroying a local community

For miners, pit closures really do mean the end of the world, bringing everything they have ever known and done to an end. This is because the mining world extends far beyond the pits themselves, including whole local communities. Mining communities have been studied extensively by sociologists in many countries, especially in the UK, and decades of observations have been used to create models of such communities.

Mining communities are socially and spatially isolated; even within large cities mining districts tend to remain distinct social enclaves focused around the mine. The pits provide employment as well as infrastructure such as accommodation, schools, playing fields and even festivals and cultural events. Working down a mine carries a high degree of risk and relies on comradeship and mutual support, giving the profession a distinctive ethos. Since the pits provide extensive infrastructure, the communities show a tendency for passive conservatism and self-containment. Additionally, the culture permeates people's free time, family and neighborly relationships, and the division of labor falls along traditional lines, with men working down pits and women caring for the home and the

Kaufhaus
– a newly renovated,
former ironworks
settlement building
in Ruda Śląska, 2020



NOWAK LUKASZ/SHUTTERSTOCK.COM



PHOTO COLLECTIVE/SHUTTERSTOCK.COM

The town of Wałbrzych, significantly impacted by mine closures

family. This intertwining of professional and social lives makes the mine an omnipresent element of the community's life: it is the subject of conversation at and after work; work colleagues are also neighbors, friends, and relatives.

The British studies concluded that mine closures bring about the destruction of mining communities. The mining microcosm disintegrates; following job losses, the entire infrastructure begins to fall apart. There is no more demand for mining schools, miners lose their jobs and the prestige they once carried. The daily rhythm marked by the stamping boots of miners returning back from the early shift and heading out for the late one is lost. Those able to find other jobs generally need to travel outside the community and eventually leave altogether. Those who are unable to do so end up as "forgotten people" in "forgotten places" (to paraphrase the title of a Polish publication dedicated to mining communities).

Upper Silesia without coal?

Western Europe's experience with coal mine closures predates that of Poland. We could, and sometimes did, learn from the mistakes made and solutions applied as the industry was being restructured in other countries, and can likewise now learn from them in

terms of closing down the industry as a whole. The University of Sheffield carries out periodic research into former coalfields in the UK. The problems involved in shutting down the entire sector eventually boil down to two questions: what will former miners do now, and what will their children do later? The second question turns out to be more pertinent, since the British miners frequently relied on early retirement, support in finding employment and social benefits. Mine closures created vast, permanent gaps in the local economy, and the only realistic opportunities for the children of former miners were minimum-wage jobs driving fork-lifts at warehouses or working in call centers (both industries that soon moved into post-mining regions). The high number of former mining regions in the UK allows researchers to make meaningful comparisons among them, looking for factors conducive to success or failure. The conclusion seems to be that remote regions situated far from major transport hubs, where mining was at the heart of the local economy and employed the majority of the local population, face far greater difficulties following mine closures. Such regions are sometimes referred to as "European rust belts." And it is true that many post-mining regions in Europe have above average levels of unemployment and difficulties in attracting investment; young people leave to seek jobs else-



The Queen Louise Adit passageway – an element of the Coal Mining Museum in Zabrze, 2017

where, and social unrest tends to be higher than in other regions.

Does this mean that Poland's Upper Silesia soon faces a similar fate? Not necessarily. The situation is very different to when the Karbownik-Steinhoff plan was being implemented twenty years ago. There are just twenty mines left out of the original seventy, and unemployment in the region is lower than the national average (4.8% and 6.1% respectively; data as of 30 November 2020). In 2019, coal mining accounted for just 8% of industrial output, down from 20% in 2002. The region has avoided deindustrialization with numerous investments from a range of sectors, and many companies even have to supplement their workforce with staff from Ukraine.

Mining communities are slowly evolving, and today's miners frequently live in a different city than where their mine is located. It is also difficult, in the Internet era, to talk about the social or spatial isolation of mining towns. Today's young miners are no different from their peers, apart from the fact that their smartphones have no signal deep underground. Their wives and partners are far more likely to have jobs of their own, and the former closely-knit nature of the communities is dissipating. Rather than hitting the pub after work with their colleagues, miners now go home to their families. Mining is turning into something of a regular job rather than a whole way of life unto itself. According to studies by the Institute of Structural Research, educational attainment among miners has also changed dramatically: most have completed secondary education, and many have university degrees. Miners operate equipment worth

millions of zlotys and their extensive skills and knowledge are transferrable into sectors such as the machine industry, mechatronics, electronics, renewable energy, transport and construction.

The Silesian city of Katowice has undergone a successful transformation into a city focused on business services. New venues such as the International Conference Centre, National Polish Radio Symphony Orchestra and the Silesian Museum reflect the changes the region is undergoing. Upholding the heritage of the former Kleofas coal mine is a perfect example of preserving the past for future generations. The vision of Silesia as a monolith entirely dependent on coal is disappearing, and public awareness of the health and environmental problems caused by mining is increasing. Communities of many local towns, such as Imielin, Rybnik, Mysłowice and Bytom, have even participated in protests against building or expanding mines and continuing extraction.

"Restructuring" vs. "just transformation"

Restructuring experiments in the region now stretch back some thirty years, and they and the term "restructuring" itself are not thought of fondly. There is a temptation to replace it with the catchier and more attractive concept of Just Transition, but it should be remembered that the processes are not equivalent and Just Transition not a euphemism for restructuring and liquidation. According to the International Institute for Sustainable Development (IISD), Just Transition is a vision and process based on dialogue and plans drafted by employees, the industry, the local community and the authorities which need to be negotiated and implemented in geographical, political, cultural and social contexts. It certainly cannot be boiled down to a tripartite commission making major decisions on restructuring (like in Poland back in the 1990s). When we talk about a "just" transition, we must consider who the target of this justice is, so to avoid making errors in the restructuring process. Former miners should not be favored and supported above other underprivileged groups, since this would simply redistribute unemployment. Focusing exclusively on mine workers ignores workers employed in other sectors in the region.

The prospects for coal mining in Silesia are not great, but the problems are not caused by the EU's decarbonization policies. Quite the opposite: EU programs offer specific funds to finance processes which would need to be completed sooner or later anyway. Should Silesian communities be invited to participate in this transition, solutions will be found. In contrast to coal, the region's resources of ingenuity and creativity are far from being depleted. ■

A CHANGE IN ECONOMIC THINKING



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On ecological economics and its diagnosis of environmental and social challenges and threats.

Your academic interests include the philosophy of science and “ecological economics.” Could you explain the juxtaposition of two apparently antagonistic words in the name of the latter discipline?

EWA BIŃCZYK: Ecological economics – which is not to be confused with environmental economics – creates interdisciplinary models of economic activity that take into account the dependence of the economy on the biosphere. It is a promising field, because such ongoing processes as progressive climate change, the mass extinction of species, growing ocean acidification, and the loss of fertile soils necessitate above all a decisive, pro-environmental change in economic thinking. The history of economics has taken an unfortunate turn. The field is virtually blind to the environmental costs of economic activity. Decision makers and their advisers continue to focus too much on the

narrow aspect of what can be monetized. Big corporations care mainly about profits for their shareholders.

Some prominent economists, such as Nicholas Stern and Andrew Oswald, apologize for the fact that, by paying no attention to environmental costs, mainstream economics has simply let the world down. Responsibility for this situation is attributable to the commonsensical pro-market and pro-growth approach, referred to as “business as usual.” In ecological economics, in turn, there’s discussion about how to sensibly temper growth, with the GDP being replaced with the prosperity index and with environmental costs (such as greenhouse gas emissions) being included in economic governance models. Calls are being made for the creation of “resilient” economies that use redistribution to protect not only what is left of the natural environment but also the most vulnerable individuals.



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What is the role of politics and politicians in all this?

The environmental crisis facing our planet is a profoundly political problem, not just an environmental one. The climate catastrophe has political sources (such as fossil fuel subsidies, the power and influence wielded by oil giants, and the promotion of emission-intensive solutions) and requires decisive reforms. But we keep pretending that we cannot see this. The current epoch of man, referred to as the Anthropocene, is a time of irreversible losses in the stability of the natural environment, yet the most important government ministries are still considered to be those dealing with finance and the economy, rather than the environment. Decision makers are slow to understand the warnings of experts. Citizens and activists have to force them to do so. It seems naïve to think that these priorities can be reversed before it's too late. But we have no other choice if we want to sustain civilization as we know it until the end of this century.

What is the alternative? What do we stand to lose if we remain in this state of lethargy that you so often talk about?

The field of Earth system science and data on the crossing of "planetary boundaries" suggest that we risk disrupting the relative equilibrium of planetary-scale systems that characterized the Holocene. This will entail huge losses for agriculture and the insurance sector, climate migrations, extreme weather events such as heat waves and droughts, struggles for access to water, and political tensions. In Poland, this has been described vividly in the interviews conducted by Dr. Marcin Popkiewicz and Prof. Szymon Malinowski on the website "Nauka o Klimacie" (Climate Science).

We risk losing the future. Trapped in this convenient lethargy, every day we are stealing the future away from our children and grandchildren, from other species, from coral reefs, from tropical rainforests, and from the Arctic.

How much time do we have left?

Unfortunately, we should already have taken up the challenge of decarbonizing already some time ago. After all, we understand perfectly well that a transition away from fossil fuels requires a well-thought-out transformation of most sectors of the economy, not merely the energy sector or housing. We must impose taxes on fossil fuels, but at the same time decarbonization cannot be done in a way that devastates the most vulnerable members of human societies. We need to shift away from long-distance transport, emission-intensive industrial agriculture, emission-intensive forms of entertainment, and so on. We need to build our cities differently, stop fostering hyper-consumerism in developed societies, and put a damper on the advertising sector, which stimulates hyper-consumerism. In the 21st century, the world's countries, especially members of the OECD, should undertake the ambitious mission of transitioning to low-emission economies (we are the biggest emitters and we have the highest consumption of resources). Mankind has altered about 75% of the biosphere, used up 90% of fish stocks. We are consuming 50% of available water and degrading 50% of fertile soils.

What are the economic and social costs of the energy transition that Poland must undergo?

It's a mistake to think of this transition in terms of cost. In fact, investments in renewable energy sources

Strike for the Climate,
Szczecin, 15 March 2019



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Aerial photo of the Turów coal mine

have the highest rates of return! Polish medium-sized companies have competences that are perfectly suited to the renewable energy sector. It is a shame that the renewable energy revolution didn't happen much earlier, because our politicians were too short-sighted. Reports that take into account the costs of soil, air, and biodiversity degradation show that most sectors of the economy are in fact unprofitable. But we don't see this, because polluters don't pay. We live in an era of monstrous neglect, and its costs will be borne by future generations. We are functionally dependent on the biosphere, and no financial markets can hide this. Planetary-scale systems will become destabilized regardless of how many more campaigns of denialism and disinformation are funded by the oil and automotive sectors.

Moreover, a pro-environmental shift towards resilient economies doesn't necessarily imply sacrifices or social costs. This has been described by such prominent researchers as Tim Jackson, Peter Victor, Kate Raworth, Jason Hickel and Jonathan Symons. Unless we worry so much about the losses of the oil sector and the fact that the richest individuals will have to share their fortunes to a small extent. Ecological economics and degrowth economics talk about systemic and gradual redistribution as well as the continued "development" of societies, but towards more free time, better social welfare systems, a world of emission-free types of entertainment, and a dense fabric of social trust. This also takes into account the fact that some sectors will still have to grow, and so will

developing economies, in which living standards still don't guarantee security.

Are the catastrophic visions that get sketched out by scientists not counter-effective? Do they not prompt people to deny facts and think that "everything will sort itself out in the end, because things can't possibly be that bad"?

Indeed, we are caught up in a trap. The warnings raised by scientists and their reports are already so depressing that they paralyze us. But I don't think that censoring scientists is the answer, and neither is the suppression of the Youth Strike for Climate and the attempt to drag its participants through the courts, as is unfortunately the case in Poland (appeals in this case have been made by the Climate Coalition, among other institutions). Passivity and lethargy have such strong and well-institutionalized foundations that we think that it's not worthwhile for humans to survive and to preserve the way of life we know from the Holocene. This makes us realize how pathological the so-called "common sense" really is. It needs to be reshaped. Also, as soon as possible the public debate must incorporate positive and constructive visions of a resilient, low-emission world that is safe for the remnants of the natural environment that we have managed to preserve for us. A world in which not only the most privileged individuals can live comfortably.

INTERVIEW BY MARCIN PIETRAS, PhD

OPPORTUNITIES FOR COAL MINING REGIONS



Miners demonstrating
against pit closures,
"Budryk" Coal Mine
in Ormontowice,
3 February 2015

The concept of a socially "just transition" should not only guide the redevelopment of coal mining regions, opening up the way to technological progress. It is also a chance for the rest of Poland to improve the quality of life and attain carbon neutrality.

What does the term “just transition” mean?

ADAM DROBNIAK: The concept has become a popular political and economic slogan, and it carries a number of expectations. First of all, just transition is mainly associated with comprehensive restructuring of the coal mining industry and conventional power generation. It is seen as one of the EU’s socioeconomic policies bringing significant changes to Poland’s energy and fuel industries. It is also closely linked with major changes in the labor market and production structure, both of which cause a shift in cultural identity and development, in particular in coal mining regions. Finally, the concept describes a change in which high-emission technologies are gradually replaced by low-emission variants, which should provide employment for people affected by job losses in the wake of mine closures.

To make more sense of these ideas, let’s try to define the notion of “just transition”. It is rooted in the concept of fair, sustainable development, formulated in the UN’s Agenda 2030. That document, adopted in 2015, laid out broad perspectives for sustainable development, just transition and integration of a wide range of processes. Just transition features among the 17 Sustainable Development Goals and refers to a transformation towards zero emissions by applying environmentally friendly solutions while limiting social costs.

Agenda 2030 is reflected directly in the European Green Deal (EU 2019). It focuses on three processes: just transition, sustainable resource management and fair distribution, and social justice. The Green Deal stresses the need to change the direction of sustainable economy by shifting away from traditional dividing lines – between the economy, society and the environment – towards an integrated, adaptive approach which adjusts to the environment rather than simply utilizing it. This cannot be achieved without social justice, including equal and fair access to resources (such as clean water and air, green spaces, employment, and infrastructure), eliminating developmental inequalities, and stimulating developmental potential in the long run. Such a change should be implemented through the process of just transition and take into account all social groups participating in the green revolution. This is why it’s so important to support workers and local communities affected by the processes of transformation and environmental protection.

In this context, just transition means a shift away from thinking purely in terms of restructuring traditional industry (profitability vs. liquidation), heading instead towards transformation (decarbonization of the economy and creating new opportunities for development) while taking account of social factors. It also means a shift away from thinking purely in terms of technological indicators (such as energy mix

and efficiency) and economic ones (costs, benefits, profits) towards social factors, such as preventing social costs, creating new attractive jobs, and providing opportunities for development in former coal mining communities.

What’s the difference between just transition and energy transition?

Just transition is accompanied by a shift towards a green economy, including technological solutions focusing on a sustainable relationship between the economy and ecosystems. The main goal of a greener economy is to minimize damage to the environment. This means that technological processes in green economies are selected on the basis of environmental and social aspects in all sectors of the economy.

The key elements of a green economy are renewable energy, sustainable transport, green buildings made using energy-saving materials, waste management (circular economy), water management (blue economy), and land management, including reclamation of post-industrial areas and rational urban management.

A „Just Transition” means a shift away from thinking purely in terms of restructuring traditional industry, heading instead towards transformation, also taking account of social factors.

Branches of the green economy can also be treated as “technological carriers” of Agenda 2030 and the Green Deal. Their aim is to provide solutions helping us adapt to the changing climate. In a broader context, the energy transition is particularly relevant to renewable energy, but it is also important in sustainable transport and green buildings.

A long-term goal of the energy transition is achieving a zero-emissions economy. In Poland, this means reducing the reliance on coal for power generation in order to meet the goals of the Paris Agreement. This requires preparing and implementing new climate policies forming a part of economic development policies, policies supporting innovation and policies supporting the development of industry and services on the national scale.

The main differences between “just transition” and “energy transition” are how they impact society and how both types of transition are prepared. Another



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key difference is that energy transition policies affect the country as a whole, while just transition mainly concerns coal mining regions.

Coal mining regions will experience the greatest social and economic impact of just transition due to pit closures or scaling back activities of mines and related organizations, conventional power stations, and manufacturers and suppliers of materials and equipment for mining activities. This is why such regions will receive aid from the EU through the Just Transition Fund and the InvestEU Programme – an initiative of EIB Group and the European Commission aimed at boosting the economy through mobilizing private financing for strategic investments. For example, the goal of the Just Transition Fund is to stimulate investment in start-ups and SMEs to bolster the diversity of their activities. It will also finance projects involved with research and innovation in tech transfer, investment in renewable energy and green buildings, investments supporting circular economy (minimizing the use of new resources and generation

of waste by recycling), revitalization of post-industrial regions and helping employers of phased-out sectors find new jobs.

Which regions in Poland are affected by just transition?

The Just Transition Fund is aimed at coal mining regions in many European countries. In Poland, the European Commission has preliminarily qualified nine subregions in the Silesian (Bielsko, Bytom, Gliwice, Katowice, Rybnik, Sosnowiec and Tychy), Wielkopolska (Konin) and Lower Silesia (Wałbrzych) voivodeships. Additional activities in the mining industry and conventional power generation are also carried out in the Lubelskie (Lublin subregion with Bogdanka), Łódź (Piotrków-Belchatów) and Małopolska (Western Małopolska) voivodeships. In the Lower Silesian voivodeship, the town of Bogatynia in the Zgorzelec region is also being considered.

Further afield in Central Europe, coal mining regions are also found in Czechia (the Moravian-Sile-

sian, Ústí nad Labem and Karlovy Vary regions), Hungary (the town of Heves and Baranya County), Romania (the towns of Hunedoara and Galați and Gorj, Dolj, Prahova and Mureș counties) and Slovakia (the cities of Trenčín and Košice). However, the Silesian voivodeship remains the largest EU region in terms of coal extraction and direct employment in mining (over 80,000 employees or almost 50% of all EU miners).

Has a just transition been carried out successfully anywhere?

It is currently difficult to give a clear answer to that in the context of a strict definition of a just transition and its planning – for instance, under the framework of the Just Transition Fund, whose current budget is set for between 2021 and 2027. Additionally, note that the “just transition” concept formally dates to policies and development programs from around 2015/2016.

Nevertheless, since the 1980s, many countries and regions of Western Europe have been making attempts to restructure traditional industry (including coal mining and steelmaking) while maintaining the importance of traditional industrial regions. However, as shown by regions which have shifted from being industrial to post-industrial regions – such as the Ruhr Valley, Saxony and Saxony-Anhalt (Germany), Nord-Pas-de-Calais (France), western Scotland and north-western England (the UK), Limburg (the Netherlands) and Wallonia (Belgium) – efforts at creating new paths to development have involved major financial burdens, taken many years and have not been entirely successful in maintaining the regions’ socioeconomic status.

In any case, positive experience cannot be transferred directly from one region to another, due to different conditions and situations which preceded the transition in any given region, particularly notable between the countries and regions in Western and Central Europe. A decisive role may have been played by the very different levels of the knowledge base, productivity and the ability of local industries to adapt to new technologies and activities. Another key aspect is the competencies of local employees and their willingness to adapt and shift professionally. Yet another important element of implementing changes as complex as just transition and energy transition is the country or region’s institutional potential. Polish regions are institutionally vertical and fragmented (e.g. they have low numbers of R&D institutions, science and technology parks, business centers and financial and technological support institutions and weak models of collaboration and co-management), which hinders the development of networks and effective functioning of regional innovation systems. This is made particularly clear through studies into what is known as the “regional innovation paradox”: the

combination of major demand for innovation funding in regions which lag behind (i.e. those dominated by traditional industry and low productivity) together with relatively poor capacity to actually utilize such funds earmarked for innovation. All this means that in Polish coal mining regions implementing a just transition alongside an energy transition will be a major challenge requiring radical socioeconomic, cultural and institutional changes.

What does “just transition” actually mean for the average Pole?

First and foremost, we have to clarify the difference between the impact of just transition and that of energy transition. The former, as noted earlier, overwhelmingly affects coal mining regions. In such regions, people who are involved with the mining sector, mining-adjacent industries and conventional power generation will need to adapt professionally. Organi-

For the average Pole, and for residents in coal regions with no ties to mining, the energy transition will be more significant.

zations in the mining sector will need to diversify or adapt their previous activities, perhaps to focus on the green economy. It is also important for children and young people in coal mining regions to be given alternative career choices.

For residents in coal mining regions who have no ties to traditional industry, just transition will have little significance. However, the decarbonization that goes with it will mean they may have to upgrade heating systems in their homes to something more environmentally friendly; on the flipside it will greatly improve their living conditions, for example by eliminating air pollution and smog.

Similarly, for the average Pole energy transition will be more significant. Decarbonization is a key process in achieving climate neutrality and improving the quality of life and wellbeing in Poland. As such, we can look at energy transition through the prism of preventing deaths caused by cardiovascular and respiratory disease due to air pollution or increasing healthcare costs due to poorer health in society. This is particularly important given that 36 of the 50 cities in the EU most heavily polluted (in terms of PM_{2.5}) are in Poland.

INTERVIEWED BY JUSTYNA ORŁOWSKA, PhD

THE EARTH'S CLIMATE SYSTEM AS A RESOURCE



Prof. Mirosław Miętus, PhD, DSc

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The climate as we know it is a natural resource that is becoming depleted due to the rising demand for energy. The most emission-intensive sectors are those providing for our comfort and welfare. We discuss these issues with **Prof. Mirosław Miętus** from the Institute of Meteorology and Water Management.

Why are we so afraid of emissions from fossil fuels?

MIROSŁAW MIĘTUS: Fossil fuels are, of course, fuels that we extract from the interior of the Earth. From the perspective of the climate, such fuels are harmful. Why? We only need to look at the Earth's energy balance. The model that explains the related processes dates back over 100 years and is very simple. From the perspective of energy transfer, the Earth, treated simply as a sphere, is situated within the stream of solar radiation. For the climate system to be in equilibrium, the amount of energy that reaches the Earth from the Sun must be equal to the amount of energy that leaves the system.

How does this happen?

The Earth takes in shortwave solar radiation in an amount defined by what is referred to as the "solar constant" (the amount of solar energy per unit of time per unit of area measured on a surface perpendicular to the rays at the Earth's mean distance from the Sun – editor's note). Some of this energy is reflected back out to space, with the exact amount depending on the planet's albedo (the ratio of reflected radiation to incident radiation). This means that the climate system in fact takes in an amount of energy proportional to 1 minus the albedo, multiplied by the solar radiation flux. The planet absorbs shortwave radiation, which causes it to warm up, and then emits thermal energy back out of the system. For the

climate system to remain in equilibrium, the amount of energy emitted must be equal to the energy that reaches the system from the Sun. This second type of radiation is longwave radiation (also called thermal radiation, it corresponds to the radiation of a body whose temperature is about 300 K), and its energy flux is determined by the Stefan-Boltzmann law. This law states that longwave radiation is proportional to the fourth power of the surface temperature. So we have the value of the energy flux of the shortwave radiation reaching the Earth on one side, and that of longwave radiation on the other. If we assume that Earth's atmosphere is completely "transparent" to the radiation that passes through it, which means that the radiation is not absorbed in any way by the atmosphere, and that the albedo is about 0.3, as has been confirmed by numerous studies, we will obtain an effective temperature of the Earth of about 255 K, which is about -18°C .

And so, if the atmosphere were "transparent" to longwave radiation, the temperature in the lower layer of the atmosphere would be -18°C , and this would be the average temperature near the Earth's surface. However, the atmosphere is not completely "transparent" to radiation and absorbs it partially, so the energy flux of the longwave radiation leaving the climate system is smaller. If we assume that the radiation capacity has this specific value (0.6), we can demonstrate that the effective temperature at the Earth's surface in the lower layer of the atmosphere is about 288 K, which



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means 33 K (and 33°C) more than the temperature that we would have if the atmosphere were “transparent” to longwave radiation.

What role does the atmosphere play in this process?

By interacting with the Earth’s longwave outgoing radiation, the atmosphere absorbs some of this radiation, trapping it in the layer of gases. If there were no atmosphere, this phenomenon would not occur – longwave radiation would immediately leave the climate system, and the Earth would be much cooler. But because we have this layer of gases, the temperature near the surface is 33°C higher. We call this phenomenon the natural greenhouse effect. This happens because the Earth’s atmosphere has numerous bands absorbing the Earth’s thermal radiation. The atmosphere is composed of natural greenhouse gases, or gases that are present in the atmosphere as a result of natural processes and cause the Earth’s surface temperature to be higher. These gases are carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). This makes life on Earth as we know it possible. We should stress that we are still talking about the average temperature. Even without the presence of gases, the temperature would vary spatially. The average temperature for the whole of the globe is 14–15°C, but the temperature near the equator is more than 10 degrees higher, and the temperature at the poles is tens of degrees lower.

How has the atmosphere and the climate system changed as a result of the emergence of human civilization?

The atmosphere and the climate began to undergo gradual transformations in tandem with the advancement of civilization. The human impact on the Earth’s climate system was initially negligible due to the small population size and a low level of the complexity of social life. With the arrival of the industrial era, however, when the burning of fossil fuels, coal, and wood, intensified, this impact started to grow. This led to the emission of gases, mainly CO₂, which plays a dominant role in the natural greenhouse process. From the early 19th century to the end of the 20th century, CO₂ emissions rose more than twentyfold, and the concentration of this gas in the atmosphere increased from 270 ppm to 415 ppm (parts per million). The concentration of other greenhouse gases has also increased. For example, N₂O is also a product of the burning of fossil fuels, mainly petroleum and its derivatives in engines. In turn, CH₄ emissions result primarily from agricultural activities. Today’s agriculture differs greatly from the agriculture 200–250 years ago. If I were to name just one reason for this situation, it would be the massive rise in the number of people – from less than 1 billion to over 7.5 billion. The intensity of food production increased, and so did CH₄ emissions. These mainly come from the growing surface area of rice cultivation in the world (rice is the staple food for much of

Horse-drawn carriage, 1940



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the world's population) and meat production (we are eating more and more meat).

These last 200 years seem crucially important from the perspective of climate change. What else has changed over this period?

Some of the changes have occurred in the aspects of everyday life that may not be the first things that come to our minds, for example human mobility. Since the beginning of the 19th century, the distance traveled per person per day has increased by more than 1000 percent! Two hundred years ago, a person traveled up to 100 m a day because there was simply no need to travel any further. For example, if people went to work, their workplace was near their home. Today, we travel an average of 40 km per day! Growth in human activity has driven up the demand for energy, and fossil fuels are still its main source.

Road transport, which makes this increased mobility possible on a daily basis, is also a powerful source of anthropogenic greenhouse gases. Burning one liter of gasoline emits almost 2.6 kg of CO₂ into the atmosphere, which means that traveling a distance of 100 km by car translates into the emission of approximately 25.5 kg of CO₂ into the atmosphere (assuming that a car uses an average of 10 L/km). In the case of oil, the emission of CO₂ is approx. 2.8 kg per liter of fuel burned, and this process is coupled with the emission of carcinogenic benzo[a]pyrene.

How do we know that greenhouse gas concentrations are now higher than ever?

From the perspective of the past 800,000 years, we know that the concentration of greenhouse gases is

now higher than ever. We also know that this concentration has grown at the fastest rate over the past 2000 years. There were periods in the Earth's natural history when the concentration of greenhouse gases was nearly comparable to today's levels, but we cannot demonstrate that the rate of this growth was as fast as it is today. This is important, because even if this value was once similar to today's levels, its possible effects, including the climate change at that time, did not affect humans because they did not exist at the time. After all, we look at climate from the perspective of its impact on us. We see it as a natural resource that supports the development potential of our civilization. The ongoing change may cause it to lose these qualities in many regions of the world, which will lead to mass migrations. This will result in a growing population density in the regions where humans will be able to function, which will negatively affect the quality of life, causing problems with the supply of food, access to water, and so on.

The Intergovernmental Panel on Climate Change (IPCC) publishes graphics showing changes in radiative forcing (which means changes in the radiative balance resulting from the anomalies that occur in the climate system) related to the increased concentration of gases that make up the Earth's atmosphere. As a consequence of this increase, a discrepancy arises between the amount of energy reaching and leaving the Earth's climate system. Recent IPCC data from seven years ago show that radiative forcing resulting from the concentration of CO₂ is 1.7 W/m². This value is estimated at 1 W/m² for CH₄ and at 0.17 W/m² for N₂O. When we add these values together, it turns out that the radiative forcing caused by the

three main greenhouse gases is 2.87 W/m^2 . Then there are the gases collectively referred to as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), which appeared as a result of human activity, but they mix well, so their radiative forcing is 0.18 W/m^2 . However, there are also gases that cause the climate system to cool.

Do different greenhouse gases warm the Earth to different degrees?

Each greenhouse gas has a different warming potential. The warming potential of a gas is its capacity to warm the atmosphere compared to that of CO_2 . This means that if the atmosphere takes in the same amount of methane and CO_2 , the warming of the atmosphere caused by methane will be 28 times greater over a period 100 years. In turn, CO_2 has globally the greatest impact on climate change because it is by far the most abundant.

In addition, greenhouse gases have different “lifetimes” in the atmosphere. CO_2 produced today has a lifetime of up to 100 years, while CH_4 survives only around 12 years. The aforementioned chlorocarbons have an even greater warming potential. In addition, they stay in the atmosphere for tens of thousands of years! They include gases called chlorofluorocarbons, which we once identified as being responsible for the degradation of the Earth’s ozone layer and the warming of the atmosphere. One of the most dangerous gases in this group is sulfur hexafluoride, which has the chemical formula SF_6 (a lifetime of about 3,000 years and a global warming potential of approximately 23,000 for a 100-year timescale).

Some gases have short lifetimes in the atmosphere. Examples include carbon monoxide, various nitrogen oxides, aerosols, and ozone. These gases can both warm and cool the climate. Gases that evidently cool the climate include nitrogen oxides (up to -0.15 W/m^2). Since sulfur aerosols cool the climate, it was proposed that they should be used in the fight against global warming. Such ideas came from volcanology, because volcanic eruptions are able to cool the climate for a short period of time. The year 1816 went down as the “Year Without a Summer” because the ash related to the eruption of Mount Tabor in Indonesia blocked access to sunlight for months, causing many weather anomalies even in Europe.

Could the way different greenhouse gases affect the atmosphere change?

Yes, it could change in a significant way if the relationship between their concentrations changes. For example, this may happen if the huge deposits of CH_4 currently trapped in permafrost or deep in the sea are released as a result of global warming. The ocean floor is characterized by relatively stable physical conditions, so the methane trapped there is found in solid

form and should remain there for the time being. But the methane trapped in permafrost is a ticking time bomb, because thawing will release this gas into the atmosphere and it could speed up the warming process in a very significant way. We should bear in mind that CH_4 has a much greater warming potential, and the thawing of permafrost would release huge amounts of this gas into the atmosphere. This methane is natural, but its release into the atmosphere will be caused by human activity.

The effects of modern climate change are multifaceted and are difficult to predict accurately. What are our chances of survival?

Forecasts suggest that the changes resulting from the ongoing climate warming will be rapid and extensive, and they will become real in just a few decades. Also, we should remember that what we know about greenhouse gases and climate change is changing as well. From the perspective of the IPCC’s activity (slightly over 30 years), our knowledge of greenhouse gases in the climate system has evolved. Thirty years ago,

Methane trapped in permafrost is a ticking time bomb, because thawing will release this gas into the atmosphere and it could speed up the warming process in a very significant way.

we stressed that we had a good understanding of the role of the three natural greenhouse gases I mentioned earlier, but we also said that we knew little about other gases and more in-depth studies were needed in this field. Today’s assessment of the level of our scientific knowledge of the role of these gases in the climate system is very different. We know a lot about most of the natural gases, but our knowledge of short-lived gases remains moderate.

The continuance of life on Earth in some form is not in jeopardy, because there are organisms that can survive even in extremely high temperatures, but humans may prove unable to withstand them. The question is, will the current potential of the climate system, which is conducive to the development of civilization, be exhausted slowly and will we manage to slow down these changes to a level that is acceptable and safe for us? Or will the climate change be so rapid and significant that it puts our existence in jeopardy?

INTERVIEW BY JUSTYNA ORŁOWSKA, PhD



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ENERGY MIX: YESTERDAY, TODAY, TOMORROW

A country's "energy mix" typically evokes varying opinions among different groups within society. It also changes over time, at a pace that most energy consumers fail to appreciate. It is shifting even in Poland – certainly not a leader in the energy transition.

The “energy mix” is a concept coming up more and more often nowadays, even in the daily press. Electric power can be generated from different sources: renewable and non-renewable, low-emission and high-emission. The energy mix is the share of each source in power production.

If asked about the source of electric power in our country, the proverbial person-in-the-street will probably answer: coal. As recently as a decade and a half ago, indeed, 95% of Poland’s energy was derived from this fossil fuel, whereas today it is “only” slightly more than 72% (see Fig. 1). Those fighting to protect the climate will take one perspective on the energy mix – what is important to them is that more energy from renewable sources means less CO₂ emissions. Yet those responsible for managing power grids and planning capacity, for instance, will take a very different standpoint – for them, more energy from unstable sources, such as wind and sun, entails more potential problems.

Variability in electricity demand

Our capacity to store electric power is still very limited, demand is highly variable, and major disturbanc-

es in the power grid can lead to a blackout – a major system failure coming suddenly and unexpectedly, causing a prolonged interruption in the power supply over a large area. Fig. 2 illustrates the variability in electricity demand in Poland. Daily variability on weekdays is similar, although the amplitude of daily differences is smaller in months that see more sun-

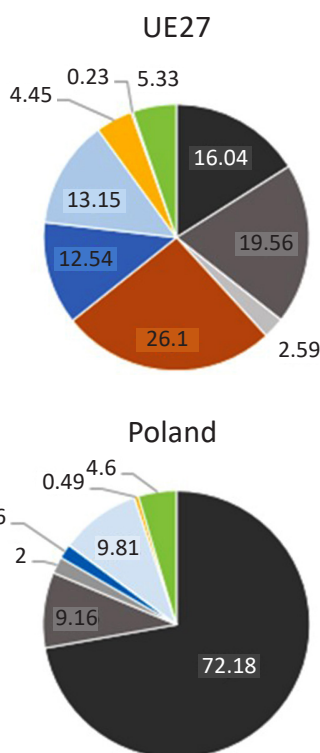


Fig. 1
Share of different sources in electricity generation in 2019, in the EU (excluding Bulgaria, Cyprus, and Malta) and in Poland (according to IEA, <https://www.iea.org/reports/monthly-electricity-statistics>)

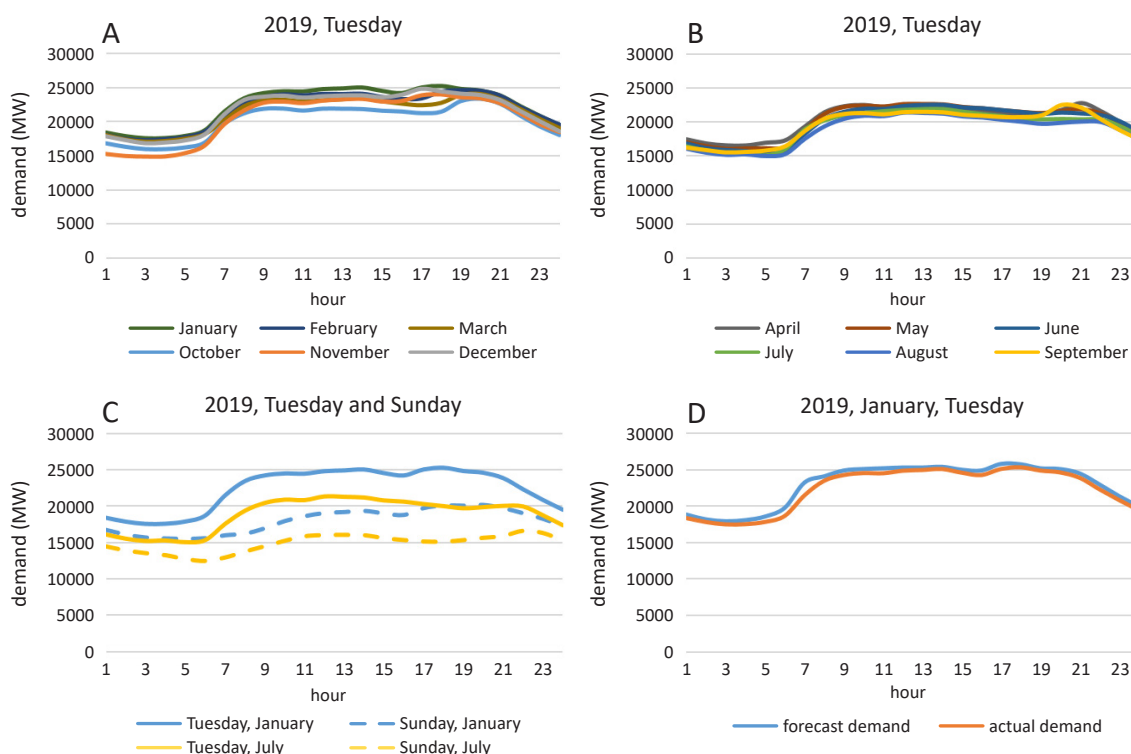


Fig. 2
Diurnal variability of electricity demand in Poland from January to March and from October to December (A); from April to September (B); differences between a weekday (Tuesday) and a weekend day (Sunday) (C); difference between forecast and actual demand on Tuesday, 15 January 2019 (for other dates the situation looks similar) (D). The Tuesdays closest to the middle of each month (A and B) or the Tuesday and closest Sunday in the middle of the month (C) were selected for purposes of comparison. Based on data from PSE



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A bird's eye view of the Solina Dam and hydroelectric power plant, located on the Solina Lake, Poland

shine (see A and B). On the other hand, daily variability does differ significantly between weekdays and weekends (C). Daily and weekly fluctuations are easy to predict based on past experience (D).

The energy mix and network stability

From the perspective of the operator responsible for the operation of the power grid (in Poland, the company PSE), the most convenient sources are known as “dispatchable” sources, such as nuclear, gas or coal-fired power plants. They can be switched on whenever needed, so long as they are not experiencing a failure or undergoing scheduled maintenance. From the operator's point of view, it is also important how fast they can be switched on and off, or more generally, how rapidly their output can be ramped up or down. Coal-fired generators take the longest to start up, so these plants must have a so-called spinning reserve, meaning a reserve of steam that makes it possible to quickly ramp up the output of the generators that are already running; mobilizing their so-called cold reserve, which starts from lighting the furnaces, takes several hours at a minimum, so its utilization needs to be planned well in advance.

It is much easier and quicker to start up a combined cycle gas turbine (CCGT) plant, and especially quick to start up an open cycle gas turbine (OCGT) plant (about 10 minutes) – the difference between these types is discussed further below. OCGT plants are expected to play a greater role in balancing supply and demand in tandem with the rising share of non-dispatchable power sources, namely wind and

solar. Note, however, that the need to ensure sufficient OCGT generation capacity increases the system costs of non-dispatchable sources. These costs are also augmented by the need to use more power from pumped-storage plants – where water is pumped to an upper reservoir at times when there is a surplus of energy, and is then released to flow down to drive generators when there is a shortage of energy. Thus, such plants are not really sources of energy in the final tally, but consume some energy due to unavoidable losses. In 2019, such pumping consumed more than 39 percent of the energy produced by all hydroelectric plants, although on the scale of power generation overall, such consumption was relatively small, on the order of 0.7%.

The growing share of energy from wind and solar poses a challenge to power grid operators. For now, that share is usually small in Poland – at 9.81% from wind, and 0.49% from solar in 2019 – but it will grow. If we compare the period from October 2018 to September 2019 with the period from October 2019 to September 2020, the share of energy from the sun increased in Poland from 0.42% to 1.26% (a threefold increase), whereas the share of wind energy rose only from 9.39% to 10.59% (an increase of just 12.7%), as a result of a reluctant policy on onshore wind energy and starting from a higher baseline. However, instantaneous wind power generation reached its historical peak to date on the night of 27–28 December 2020, at 32.7% of demand – which is already a considerable share, well above Germany's annual average (21%), albeit still far from Denmark's average (55%). This high share was due not only to the favorable weather for wind power, but also to lower energy demand during the nighttime hours.

How should grid operators cope with rapid fluctuations in wind and solar generation? Moreover, they also have to plan for unpredictable spikes in demand and outages. Already today, pumped-storage power plants and spinning power capacity are not enough. When the need arises, we are rescued by exchanging energy with our neighbors, and via their power grids also with still further countries. Fortunately, weather fronts move in a quite predictable way: when the wind blows from the west in France, a little later it will probably blow in Germany and Denmark, and then in Sweden and Poland. As the share of wind and solar power in Europe increases, the exchange of electricity between national grids intensifies. Large cross-border exchanges are not a problem, but ideally each country should have a zero balance of exports and imports over the long term. Poland currently has a significant import surplus (in 2019, we exported 7245 and imported 17,868 GWh; over the same period, Germany exported 73,042 and imported only 40,156 GWh). Sweden is a large exporter of energy (with exports of 34,116 and imports of 8948 GWh), including to Poland.

A number of gas-fired power or combined heat-and-power plants have been or will be put into operation in Poland in the near future. Natural gas is considered a much better raw material from the point of view of CO₂ emissions per unit of energy; however, its production and transport result in emissions of methane, whose greenhouse impact per unit of volume is many times greater than that of CO₂. It is not out of the question, therefore, that as better methods for measuring these emissions are developed, the costs of gas emissions permits will rise drastically, to the point of negating the economic sensibility of investing in gas-fired power generation (with the exception of peak-load power plants, operating occasionally).

There are two types of gas-fired power plants. The first kind is the high-efficiency combined cycle gas turbine (CCGT) plant. Here, heated combustion gases first drive gas turbines, after which they are still hot enough to produce steam for classic steam turbines. Their efficiency reaches 64% (slightly less in practice), which is 84% of the maximum theoretical efficiency for thermal machines. If the heat is additionally used in district heating systems, very little energy is actually wasted. However, we must remember that they emit carbon dioxide, although it is in smaller amounts than coal-fired power plants. And so, gas-fired CCGT plants are a good option for today, but they may be troublesome in just a few decades, and they are slated to have a lifetime of around 30 years. The existing ones will be outdated by 2050, when Poland should attain zero-emissions, at least in terms electricity generation. We therefore need to be cautious about investing in CCGT plants in the future. If built, they should be located near coal mines that can be converted to store carbon dioxide that is captured from the flue gases. Carbon capture may be necessary even sooner, for economic reasons, if carbon fees continue to rise rapidly. Since carbon capture facilities cost money and reduce efficiency, the alternative may be to shut down such power plants even before their operational lifetime expires. The Polish town of Ostrołęka is therefore not a good place to locate a CCGT plant (as is being planned), as it would not be commissioned until a few years from now (the average construction cycle lasts three years) and would be in a location very far from areas where mines are being shut down.

From the point of view of supplementing electricity production in the absence of wind and sun, open cycle gas-turbine (OCGT) power plants are more attractive. They operate in only one phase – the heated combustion gases drive the gas turbines, but there are no steam generators. They are less efficient than CCGTs, but simpler and cheaper to build and can be started up quickly. They do, however, have one very serious drawback: they are unprofitable for investors because they do not operate continuously; it is estimated that they will be used first some 10–20% of the

time, later just a few percent of the time, only after all other options have been exhausted, including importing energy from countries that have temporary surpluses from renewable sources. While there does need to be a network of such power plants, it should not be expected that they will be built purely on market-based principles. However, there should be no trouble obtaining support from EU funds, as there is an understanding in the European Union of the need for such power plants to ensure energy security. In Poland, the national contribution to such investments should be funded by revenues from the “capacity fee”¹ newly introduced on 1 January 2021.

Over time, gas-fired power plants of both types will begin to replace natural gas with so-called green hydrogen, i.e. hydrogen fuel produced by emission-free electrolysis of water. This will first be an additive to gas, then either replace it or be converted into so-called green methane. Methane can easily be converted into hydrogen and carbon dioxide (this produces “blue” hydrogen; “black” hydrogen is produced from carbon and water vapor). The reverse reaction is also

From the perspective of the operator responsible for the operation of the power grid, the most convenient sources are known as “dispatchable” sources, such as nuclear, gas or coal-fired power plants.

possible – hydrogen and carbon dioxide can be converted to methane via the Sabatier reaction. After such green methane is burned, carbon dioxide would have to be captured, so as to cyclically undergo the Sabatier reaction. Eventually, green hydrogen is expected to become the primary energy storage.

There are already mechanisms in place to restore the stability of the power grid if demand exceeds supply, in the form of demand side response (DSR). Companies selected via competitive tendering sign contracts with PSE to reduce, on demand, the amount

¹ The “capacity fee” was introduced in Poland as of 1 January 2021 by the Capacity Market Act of 8 December 2017 (*Journal of Laws* 2018, item 9, as amended). Large enterprises are charged this extra fee for power consumption during peak hours, a measure which aims to encourage them to promote solutions that help flatten out the peak (time shifts in energy consumption, using their own energy sources or means of energy storage, etc.). In the case of individual consumers and small businesses, the fee is a flat-rate levy, the revenue from which is meant to be used to maintain such power generation capacity as to enable uninterrupted supply in the event of fluctuating demand.

of power they draw from the grid. They receive two types of remuneration for this: for readiness and for the actual reduction. Industrial enterprises can perform such a reduction of energy drawn from the grid either by shutting down certain processes or by starting up their own power generators. This is already practiced today, but this service should evolve in the future, in the case of companies with their own generators, enabling them to feed energy back into the grid if it is produced in excess of the company's momentary demand.

In general, power grids are slowly changing their nature: energy production used to be focused at large facilities, from which energy was transmitted unidirectionally to consumers. For some time now, however, distributed generation has been playing a more and more important role, in many EU countries much more so than in Poland, so power transmission is becoming bi-directional.

What if DSR isn't enough? Then we may end up having different levels of power-supply limitation, a situation familiar to the older generation in Poland. Consumers will be cut off in a predetermined order. However, unless major outages occur, this is thankfully still only a hypothetical possibility.

No doubt it is easier to manage a grid when it rests upon a solid base of dispatchable, weather-independent power sources. Let's hope these will be emission-free sources. It is a shame that Poland does not have nuclear power plants. Nevertheless, we should bear in mind that as green hydrogen energy storage becomes better developed, the difference between dispatchable and non-dispatchable sources will gradually

disappear: excess energy from wind and solar will be used to produce hydrogen, which in turn will be used to produce power in times of wind and solar scarcity. Currently, no one can predict when this will happen, which is why the decision to build expensive nuclear power plants is so difficult to make.

Economic conditions

It is difficult to consider shaping a country's energy mix in isolation from economic considerations. Calculating energy costs is a complicated endeavor, as it depends on who's perspective one adopts. They will be different from the investor's point of view, different from the point of view of the network operator responsible for stability and quality of energy supply, and different still from the point of view of the consumer, for whom it is the final price that matters. The investor's costs, also called the levelized costs of energy (LCOE), are calculated taking into account the depreciation period and an assumed, but usually unknown, interest rate on credit. These costs are extremely sensitive to the utilization rate of the power plant over time (the *capacity factor*, as an annualized average). A nuclear power plant will utilize at least 80% of its capacity, a photovoltaic farm no more than a 15% or so. For this reason, a highly efficient CCGT plant is more attractive to an investor than an OCGT plant, as the former will harness its capacity more or less half of the time, while the latter will eventually be included in the system only when there is no more wind and solar energy (i.e. only a few percent of its capacity will be harnessed in the future).

Fig. 3
The price of energy from different sources in 2020, taking into account investment and capital costs and the expected lifetime. These are the so-called investor costs (LCOE), which do not take into account the system costs due to the fact that, unlike nuclear and fossil energy, wind and solar energy are not always available and must be replaced by other sources or imports in case of shortages. The blue bars are the average for 24 countries from different continents. CCS stands for carbon capture and storage

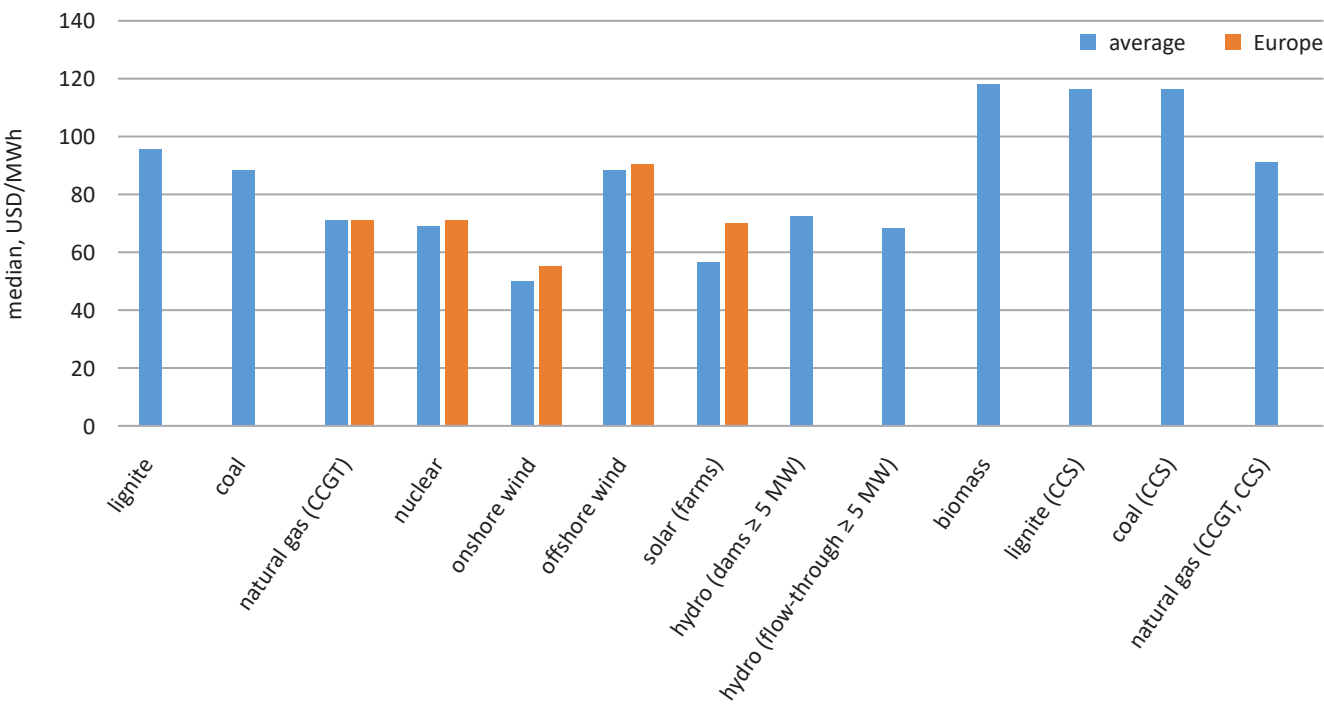


Figure 3 presents the investment costs according to the latest International Energy Agency (IEA) report. It clearly shows that it is currently most profitable to invest in onshore wind power, slightly less in solar farms. Investments in nuclear power and CCGTs are equally profitable on average, although with different risks and different investment timescales – two years for OCGTs, three years for CCGTs, and as long as six years for nuclear plants. The investor's costs increase sharply if the construction period becomes prolonged. For this reason, investing in nuclear power plants is very risky because experience shows that such projects do have a certain "penchant" for becoming delayed. Figure 3 shows that coal is the big loser. Investments in coal-fired units are already uneconomical, and after they are additionally outfitted with CO₂ capture and storage facilities, they would be a complete extravagance.

From the perspective of the grid operator and the consumer, in turn, system costs are important. They depend on the share of weather-dependent energy sources. When this share is small, as in Poland on average, the system costs are negligible. When this share increases, system costs rise faster than linearly, because it is necessary to maintain alternative sources, such as gas-fired OCGT plants, dormant on a daily basis. But assuming there is no turning back from the rising dominance of wind and solar, it still remains unresolved how system costs will be factored in. There are a number of possibilities. For example, a network of OCGT plants could be managed by a company subordinate to PSE, with the ideal being that such plants could be switched on remotely, similar to pumped-storage plants. This subsidiary could also develop hydrogen production capacity, to be ramped up in surplus energy situations (which also pose a threat to grid stability). Initially, hydrogen would be added to natural gas to reduce carbon emissions; in later stages, energy could be produced directly from hydrogen, by fuel cells if they attain competitiveness, by direct combustion, or by green methane production. The subsidiary's other role would be to develop energy storage in batteries as a short-term reserve. The usual limit for this technology is four hours, so it should not be assumed that such batteries will be able to resolve the imbalance of energy production vs. demand on their own.

Contract costs, also known as overnight costs, offer yet another measure of the cost of power. Imagine that a power plant could be built overnight; the value of the contract (hence "contract costs") is then simply divided by the maximum capacity. This is an abstraction, of course, but it illustrates how costs calculated in this way do not take into account the useful lifespan of the investment, the average annual utilization rate of the power plant, or the costs of repaying credit. Costs calculated in this way, as listed

in Resolution No. 141 of the Polish Council of Ministers of 2 October 2020 on Updating the Multi-year "Polish Nuclear Power Program," are extremely high for nuclear power plants (22.3 million PLN/MW) and relatively low for gas-fired OCGT plants (2.3 million PLN/MW). Leaving aside the question of generation start-up time, no one in their right mind would build a nuclear plant only in order to operate it intermittently, during temporary shortages of wind power; instead, they would build an OCGT (currently the cheapest option). It makes more sense for an investor to build a nuclear plant with an LCOE of about \$70/MWh than to build an OCGT with an LCOE of about \$100/MWh if the plant is expected to use 30% of its capacity on average and even higher if that utilization rate steadily declines. Calculating the contract costs allows us to estimate what expenditures will be needed to build reserve capacity in the form of an OCGT with financing from the state budget or European funds. Estimating the necessary reserve in this form and the spread of investments over time is obviously a complicated question.

In conclusion, it is impossible to define universal system costs for all power grids, as they depend on the particular system in place. The system, in turn – assuming that the priority should be to reduce carbon emissions and assuming that the stability of energy supply is taken as a prerequisite – needs to be optimized to minimize costs. Such optimization should also take into account external assistance, in Poland's case first and foremost support from the EU's Green Fund.

If the system costs are added to the investor costs and the environmental costs (which are also not easy to estimate) are likewise taken into account, we arrive at the total costs of energy generation. Only then should the prices for domestic consumers be determined. The regulator (in Poland, the Energy Regulatory Office), which approves the tariffs, should avoid a situation where one sector of consumers subsidizes another sector, because this spoils the economic calculations. Moreover, the approved tariffs should include a fair profit that allows for investments in new technologies, with the regulator only able to specify what minimum portion of this profit must be reinvested. If it is deemed necessary to financially support some particular social group (e.g. the poorest individual consumers), this should not be done by shaping special tariffs (i.e. at the expense of the power industry), but rather by means of state monies earmarked for providing social assistance. On the other hand, subsidizing the energy purchase costs of the more affluent portion of society, companies, local governments or the budget sector should be prohibited, because this fails to promote energy savings, spoils the economic calculations and prevents competition on healthy principles. ■

Further reading:

Energy Storage Technology and Cost Characterization Report. Hydrowires, US Department of Energy, July 2019, <https://energystorage.pnnl.gov/pdf/PNNL-28866.pdf>.

IEA, *Monthly Electricity Statistics: Revised Historical Data, with data up to March 2020* (or newer) (<https://www.iea.org/reports/monthlyelectricity-statistics>).

IEA, *Projected Costs of Generating Electricity*, 2020 edition, <https://www.iea.org/reports/projected-costs-of-generating-electricity-2020>.

Resolution No. 141 of the Polish Council of Ministers of 2 October 2020 on Updating the Multi-year "Polish Nuclear Power Program."



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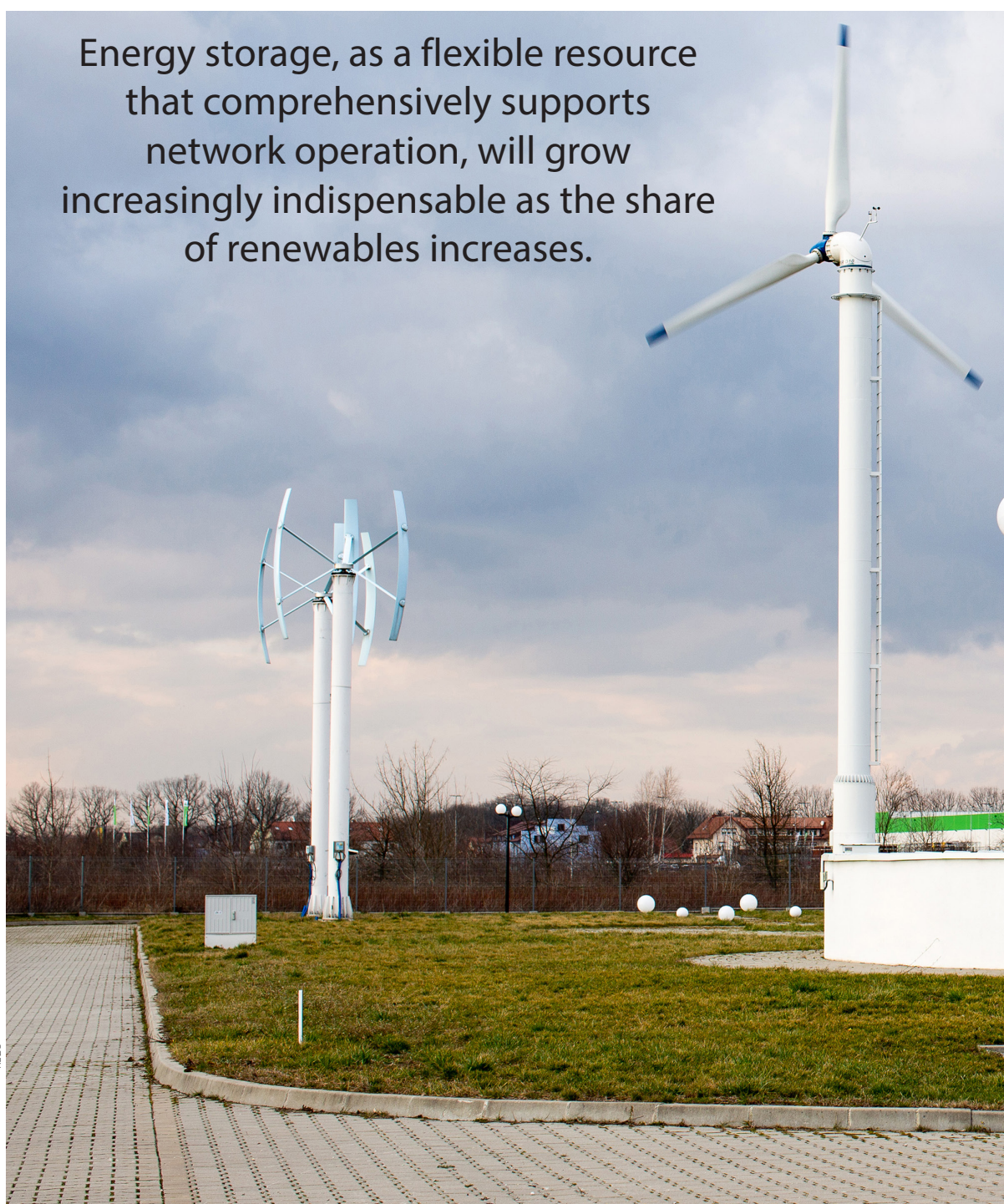


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ENERGY STORAGE – CRUCIAL FOR BALANCE

Energy storage, as a flexible resource that comprehensively supports network operation, will grow increasingly indispensable as the share of renewables increases.



KEZO

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Paweł Grabowski

STAY-ON Energy Management in Puławy

Electric power is becoming the dominant energy carrier, by means of which we satisfy a growing share of our energy needs. This is largely due to its ef-

iciency of long-distance transmission and its ease of conversion into other forms of energy. Thanks to the development of new technologies, such as heat pumps and electric cars, electricity is boldly entering new sectors of use that were once reserved for fossil fuels.

But behind the scenes, reliably supplying electricity to end users requires continuous operation of a whole complex power system, which is like a well-oiled machine in this regard. Maintaining the key parameters of voltage and frequency for the operation of the system is contingent upon preserving the energy balance, i.e. the balance between energy production vs. consumption. For many years, this balance has been regulated by means of regulating the power output of plants burning fossil fuels. This

The Energy Conversion and Renewable Sources Research Centre (KEZO) of the Polish Academy of Sciences in Jabłonna, outside of Warsaw





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An energy storage facility utilizing flow technology, with 260 kW power and 2.2 MWh capacity, in Jeonju, South Korea

has the disadvantage of not only under-utilizing the production potential of such plants, but also detracting from their efficiency.

The twenty-first century has brought new challenges connected with dynamic development of renewable energy sources. The ever-more ambitious climate targets being adopted at the European and global level are stimulating growth in the share of photovoltaic and wind sources in electricity production. However, these sources are relatively capricious, being dependent on the weather and season, so properly balancing them within the larger power system is growing increasingly difficult. Here, of course, is where energy storage systems come in. Their installation increases the flexibility of transmission systems and creates op-

A view inside a vanadium redox flow battery installation, showing the cell stacks



KEZO

portunities for stable operation despite having a large share of renewable sources. It has grown increasingly clear that it will be impossible to meet the ambitious climate goals without large-scale deployment of such energy storage systems.

It should be borne in mind, however, that energy balancing is just one of the many services that energy storage facilities can offer. There may be many more reasons to install them, as they allow for:

- the establishment of micro-scale power systems (microgrids), locally ensuring energy balancing or even complete self-sufficiency,
- ensuring the autonomous (island-mode) operation of such systems, ensuring continuity of power supply in the event of a power outage,
- increased transmission capacity of the current system, by relieving the heavy load on transmission lines, thus taking the place of costly investments in new lines or generation sources,
- improved power quality parameters, by minimizing voltage fluctuations or compensating for reactive power,
- restarting the power system after an extensive failure (called a “black start”),
- taking advantage of energy price differences for the purposes of arbitrage (i.e. charging up with cheap energy during off-peak hours, later discharging it during peak hours),
- minimizing peak power demand, which translates into lower bills or the ability to make better use of available capacity,
- the provision of system services such as frequency regulation and operating reserve.

How to store energy?

The challenge of energy storage has been a subject of study for many years. The first batteries came into use back in the early 1900s, and the first pumped-storage facility was commissioned in 1920. However, it was not until the late 20th century, with the emergence of significant demand for such solutions, that energy storage technologies started to see significant advancement.

There are many methods of energy storage, based on numerous physical or chemical phenomena. The best known and currently used techniques are as follows:

- pressure-based methods: hydraulic peak pumps, compressed air,
- mechanical methods: springs, kinetic solutions, flywheels,
- thermal methods: heat and cold storage tanks,
- electrochemical methods: lead-acid batteries, lithium-ion batteries, flow batteries, and more,
- electrical methods: capacitors, supercapacitors, superconducting coils,

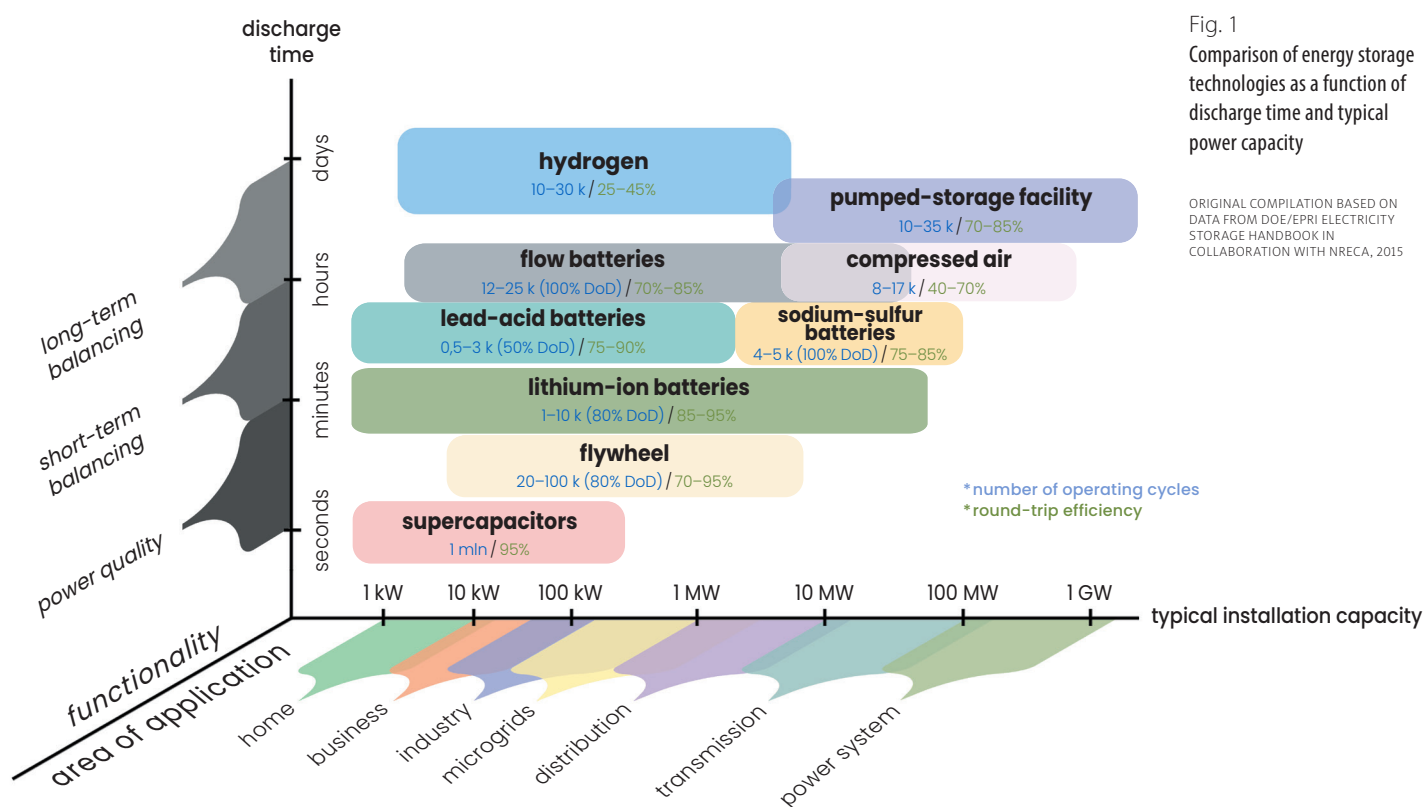


Fig. 1
Comparison of energy storage technologies as a function of discharge time and typical power capacity

ORIGINAL COMPILATION BASED ON DATA FROM DOE/EPRI ELECTRICITY STORAGE HANDBOOK IN COLLABORATION WITH NRECA, 2015

- chemical methods: hydrogen, synthetic fuels, biofuels, and more.

Each of the technologies listed differs significantly, with the most significant performance parameters being:

- available power and overload capacity,
- usable capacity (stored energy),
- round-trip efficiency of the system charge/discharge cycle,
- calendar lifespan and achievable number of operating cycles,
- initial cost (CAPEX) and maintenance cost (OPEX) of the system,
- energy and power density ratios, and the associated mass and building area,
- safety of operation, recyclability,
- environmental requirements, temperature, expansion possibilities.

In general, energy storage methods can be classified into the following types:

- short-term: supercapacitors, superconducting coils, flywheels,
- daily: electrochemical batteries, pumped storage, compressed air, etc.,
- medium- and long-term: hydrogen, biofuels, etc.

Figure 1 compares technologies as a function of discharge time to power. Selecting the right energy storage technology ultimately depends on the user demand and operational parameters, as well as on the

expected functionality. The factors to be considered at the technology selection stage include: the load profiles, the power sources and energy costs (the grid connection conditions, local energy sources), the expected availability of power and capacity, the available space and environmental conditions, the legal conditions, safety of use, financing, and many others.

In light of the above, electrochemical storage technologies – including flow storage – are gaining popularity due to their flexible configurability, i.e., independent power and energy scaling, easy energy access, and

Demonstration installation of hybrid energy storage at the Energy Conversion and Renewable Sources Research Centre (KEZO) of the Polish Academy of Sciences in Jabłonna



relatively lower price per kWh. Therefore, the remainder of this article will mainly be devoted to this technology.

Ubiquitous batteries

Technological advancements and society’s ever-greater demand for cheap and easy energy storage, especially for electric power, have led a very large number of battery technologies to be brought to market in recent years. Energy storage technology using electrochemical batteries is typically chosen because of advantages such as:

- energy conversion by means of the same technology (electrochemistry),
- universal, “convenient” voltage characteristics,
- market availability,
- acceptable dimensions and flexibility of installation (standard shipping-container solutions),

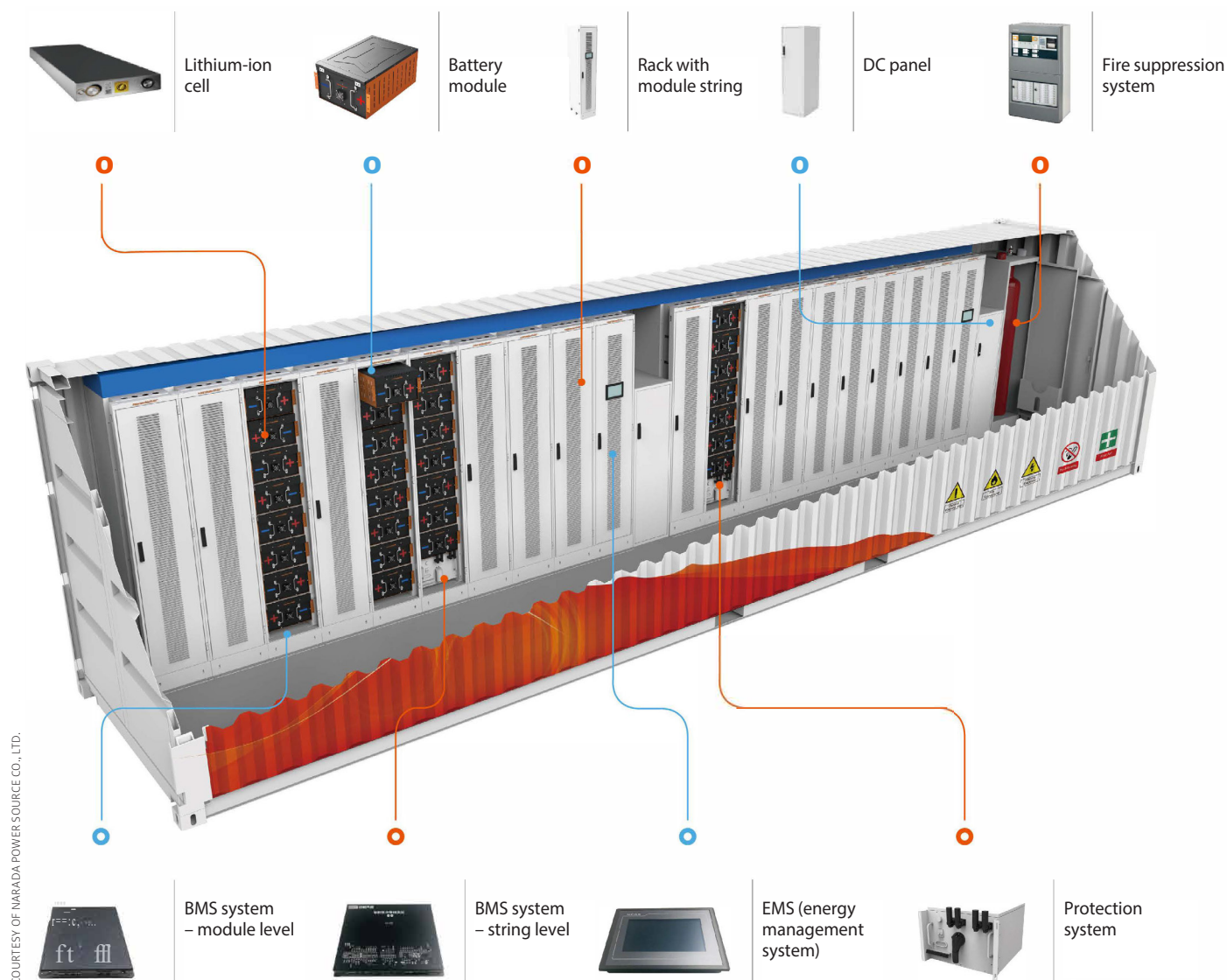
- declining costs,
- maturity of the technology (presence in the market).

Guided by the criterion of technology maturity, commercial availability, and existing large-scale installations, the following technologies are typically applied:

- lithium nickel manganese cobalt oxide (NMC),
- lithium iron phosphate (LFP),
- lithium titanate oxide (LTO),
- vanadium redox flow battery (VRFB),
- lead acid battery (LAB).

Each of these groups is distinguished from the others by certain specific characteristics that make it most suitable for installations of a particular type (and in addition to those listed, many other promising technologies are currently under development in laboratories around the world). Lithium technologies, for

Group	Type	Advantages	Disadvantages
Lithium-ion	NMC	• mature technology • multiple companies manufacturing cells and integrating complete energy storage systems • very high energy density	• technology considered dangerous (requires special attention in terms of explosion and fire safety) • relatively high price • availability restrictions due to a market priority (whereby electromobility comes first) • costly recycling • medium number of operating cycles
	LFP	• safe • relatively the cheapest option from the lithium group	• costly recycling • depth-of-discharge regime required to maintain warranty • high operating cost for high cycle applications (>1 cycle per day) due to cost of replacing used batteries • degradation • medium number of operating cycles
	LTO	• long service life due to number of cycles • large discharge depth range • safe • high efficiency (not including auxiliary systems)	• relatively high price • limited functionality due to price • costly recycling
	LAB	• very mature, widely available • relatively cheap, offering low CAPEX • mature recycling technology	• very high operating costs (OPEX) due to a very low number of cycles (frequent replacement of used batteries) • severely limited functionality due to rapid degradation at deep discharge
	VRFB	• very low operating cost • safe: non-explosive, non-flammable • negligible degradation • unlimited number of cycles • longevity • scalability (power independent of capacity) • negligible self-discharge (i.e. a charged battery left for a longer period of time will not lose its charge) • 100% recyclable	• few references, given the novelty of the technology • requires more installation space due to relatively low energy density • low currents for charging and discharging (i.e. low ratio of power to storage capacity) limit the choice of functionality



instance, are ideally suited for systems requiring high instantaneous output and fast response. A good example can be found in the plant in Cremzow, Germany, with power of 22 MW and a capacity of 35 MWh. It is mainly used for frequency regulation of the grid, providing services to the so-called primary regulation market.

Different roles in the system are played by long-duration technologies, such as flow batteries. One example is a 260 kW, 2.2 MWh installation in the South Korean city of Jeonju. Located at a paper mill, it is used for arbitrage: at night it is charged with cheap off-peak energy, then during the day it powers the paper machines. Additional incentive programs launched in South Korea reward such flattening out of the daily load curve, turning energy storage an additional source of revenue.

Hybrid, meaning what?

Clearly, energy storage systems can serve a variety of functions. It seems natural, therefore, that an investment in energy storage will be most profitable in cases where one installation has multiple functions,

providing several sources of income or savings. But how to choose the right technology in such a case, so as to ensure the right versatility? The solution to this problem may involve the use of a hybrid storage method, combining two or more storage technologies in a single installation. In principle, these should be technologies with complementary properties, e.g. one with high instantaneous power plus another with long retention time.

One such installation was launched in 2020 at the Bystra wind farm in Poland (in the municipality of Pruszcz Gdański): a hybrid energy storage facility combining 1 MW lithium-ion batteries with 5 MW lead-acid batteries. The facility is used to stabilize wind energy production and to support the local transmission grid. In this case, the technologies used, including the control and conversion system, were supplied by the Japanese.

Independent work on developing hybrid energy storage methods is being carried out by a team at the PAS Institute of Fluid-Flow Machinery. At the Energy Conversion and Renewable Resources Research Centre (KEZO) in Jabłonna near Warsaw, a demonstration installation of a hybrid energy storage system has

Cross-section of a lithium-ion energy storage facility

been in operation since 2018. The system has a total power of 60 kW and a capacity of 180 kWh. It employs four battery technologies:

- vanadium redox flow – 12 kW/100 kWh,
- lithium iron phosphate – 24 kW/24 kWh,
- lead carbon – 12 kW/24 kWh,
- lead acid – 12 kW/32 kWh.

This hybrid energy storage facility supports the research center's internal microgrid by balancing its photovoltaic and wind power generation and the power consumption by its offices, laboratories, electric vehicle charging and heat pump (among other things). Another topic of research is battery technologies operating under operational conditions. The research

where the charging and discharging processes must be individually tailored to the distinctive characteristics of each battery in the system. A solution for this issue is being developed by the KEZO team under the framework of the HyStore project ("Hybrid Energy Storage Management System"). Its stated objective is to develop an EMS system specially tailored for hybrid energy storage.

Energy storage comes to Poland

Looking at the experience of other countries, we can conclude that the large-scale integration of energy storage capacities represents the second wave of the energy transition, right after the rise of renewable sources.

Among technologies available today, lithium-ion batteries are attracting the most public attention. At present there are also many other technologies ready for large-scale deployment, such as flow batteries. It seems that the only obstacle to their development is the lack of positive examples of large-scale installations (i.e. with a capacity above 100 MWh). The story is similar for hybrid installations – despite their undoubted advantages, properly selecting, integrating, and operating them is more complex, and that fact may discourage investors.

Of course, the cost of creating an energy storage facility is also an important factor. Currently, batteries are mainly installed in places where grid stability is threatened, and they can also successfully take the place of costly investments to expand the grid and generation infrastructure. In some European countries where the market for system services has been deregulated, battery storage facilities are successfully earning money from frequency regulation. Battery costs are coming down to what is considered a watershed boundary of \$100 per kWh, which will open up many business models – involving, for instance, price arbitrage or the creation of hybrid sources harnessing renewables, featuring a high rate of energy availability.

In Poland, legislation dealing with energy storage remains underdeveloped and does not offer attractive business models for investors. However, the first pilot projects related to energy storage installation are being undertaken. These include a project by the operator Energa in the seaside town of Puck, demonstrating the potential of local energy balancing by means of storage facilities, and a storage facility by the grid operator PGE in Rzepedź (Podkarpacie region) designed to support the distribution system. In the coming years, energy storage may become a source of interesting innovations and many new jobs in Poland.

The project "Hybrid Energy Storage Management System" is funded by the National Center for Research and Development under the 10th edition of the Leader program.

It will be impossible to meet the ambitious climate goals without large-scale deployment of such energy storage systems.

team's goal is to develop a methodology for selecting a hybrid storage configuration that will provide maximum investor benefits for a given mode of operation while ensuring a long service life of the component batteries.

Energy management

The ongoing development of distributed, predominantly renewable energy sources and energy storage systems is changing the traditional energy flow in power systems. In many cases, energy storage is a key enabler for establishing an energy cluster, microgrid, or local balancing area. These terms are often used interchangeably for logically separate sections of a power system, ensuring maximal energy self-sufficiency. Their efficient operation depends not only on the existence of sources and storage, but also on the use of appropriate control methods.

In all energy microgrids, Energy Management Systems (EMS) are a key layer. An EMS primarily provides capabilities for monitoring and controlling energy resources. In addition to the obvious function of managing the charging and discharging of energy storage systems, it can also provide the ability to manage controllable loads, curtail the power generated by renewables if it becomes excessive, maintain optimal operating conditions for combustion-based sources, or use these techniques to ensure island-mode operation (functioning autonomously, without connection to the power system).

The issue of energy storage management becomes more complicated in case of hybrid energy storage,

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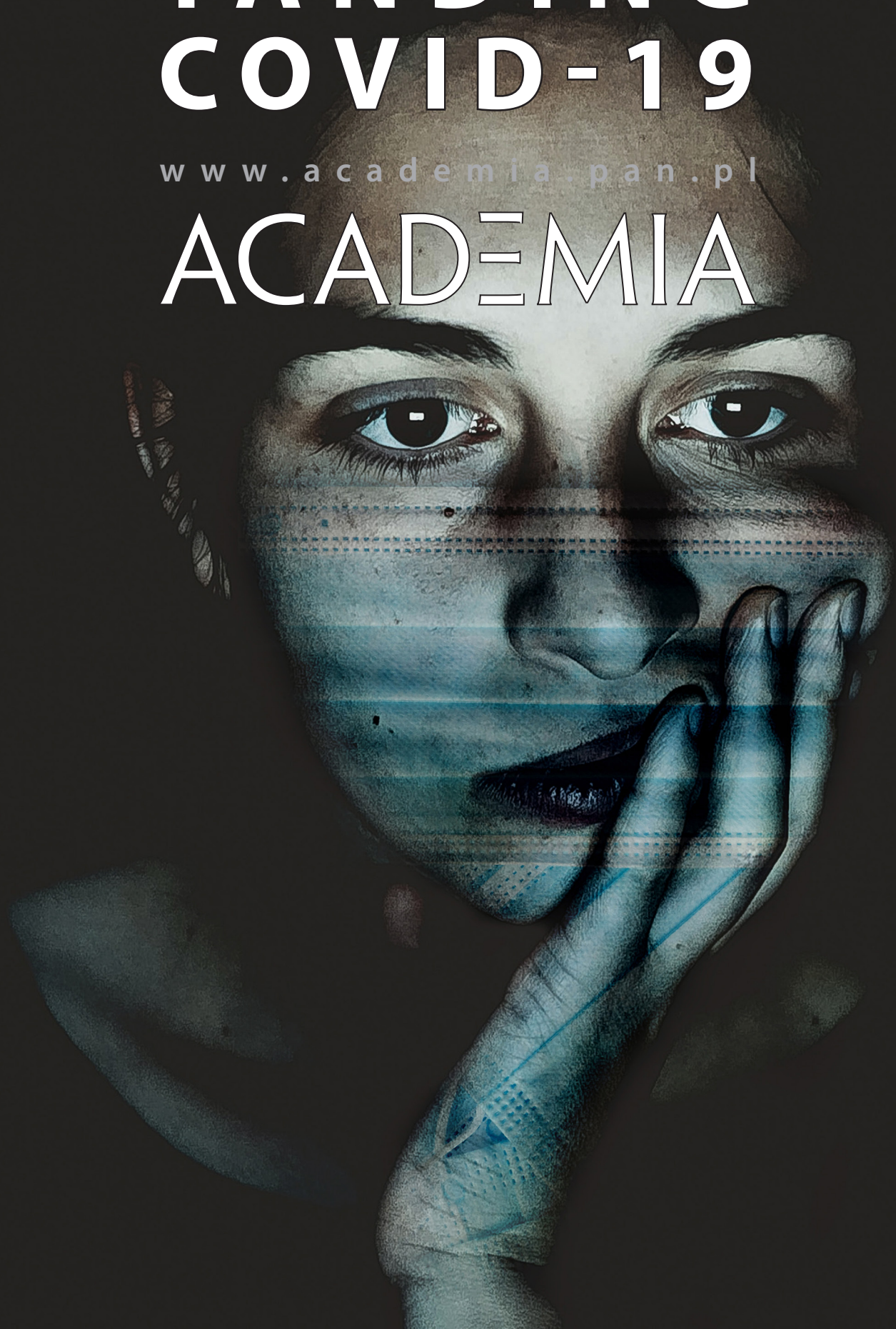
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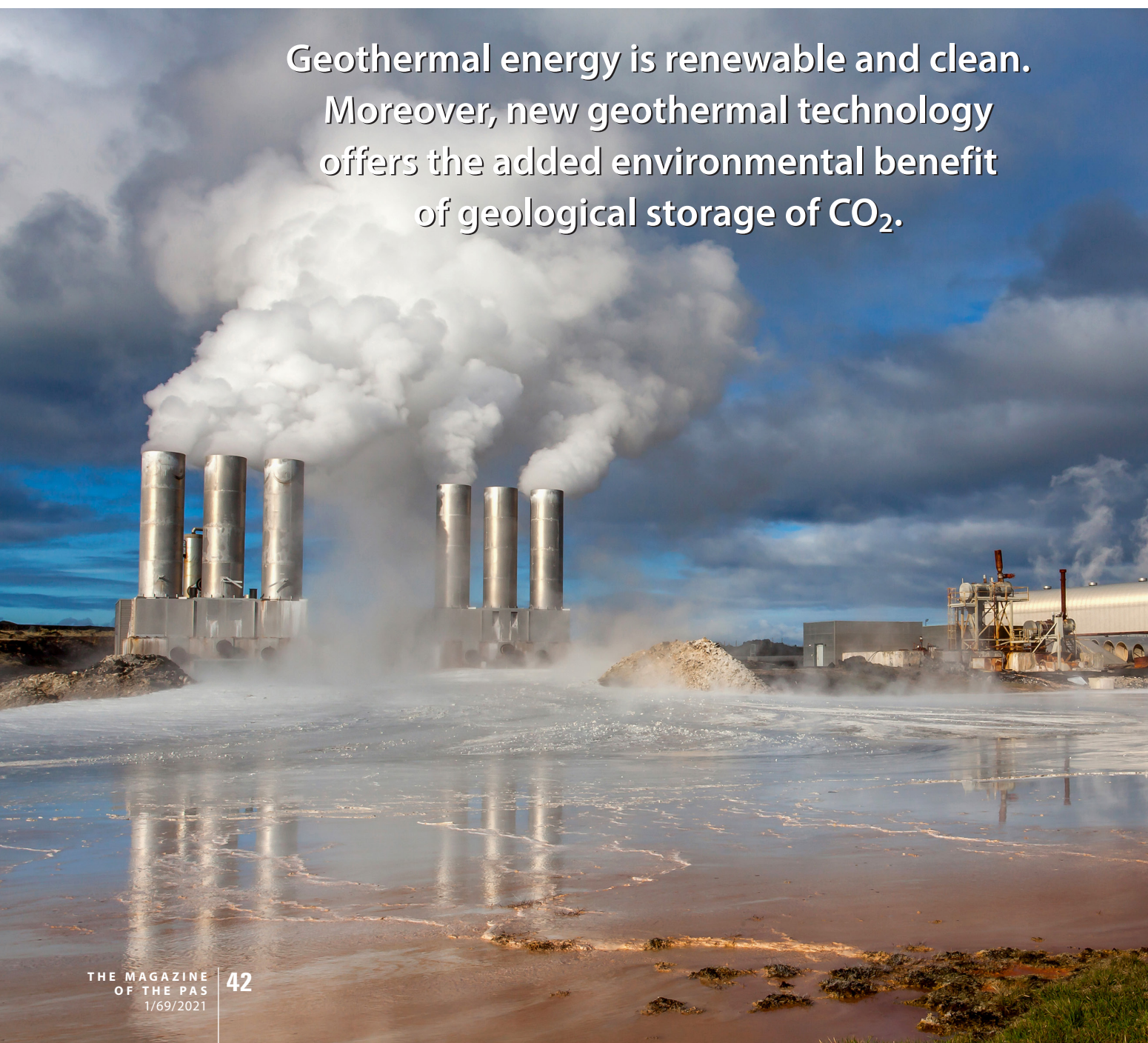
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HOPE FOR A BETTER TOMORROW

Geothermal energy is renewable and clean.
Moreover, new geothermal technology
offers the added environmental benefit
of geological storage of CO₂.



Anna SowizdzałAGH University of Science and Technology
in Kraków

Poland is grappling with a serious air pollution problem, resulting largely from the combustion of solid fuels, which are still the country's primary energy source. Alternative and competitive technological and systemic solutions therefore need to be actively sought and developed in order to satisfy the population's energy demand while simultaneously taking proper care of the natural environment. Boosting

the use of renewable energy sources, including geothermal energy, is an extremely important and necessary element of producing energy in an ecological way.

State support

Geothermal energy is another name for the Earth's internal heat, stored in rocks and in the groundwater that fills rock pores and cracks. Geothermal waters have been utilized since ancient times, but with the development of technology and drilling techniques this type of energy began to be harnessed on a larger scale to meet energy needs. Classical hydro-geothermal systems use existing underground water as the energy carrier, exploited via boreholes, whereas petrogeothermal systems harness hot dry rocks by using a liquid medium (typically water) introduced through boreholes.

Particularly favorable conditions for high-energy geothermal systems, potentially best suited for industrial use, are present within the plates of the lithosphere. In such zones, the geothermal vapor deposits found in reservoir rocks can be harnessed to generate electricity in geothermal power plants. Such deposits occur in areas of modern or recent volcanic or tectonic activity. Countries where such high-temperature geothermal energy is utilized include the Philippines, Mexico, New Zealand, the United States, Japan, Italy, and Iceland. However, on the global scale, such high-temperature geothermal areas are relatively scarce. Low-temperature deposits, with geothermal water deposits at temperatures below 150°C, are much more common – for them, the key sector of development is heating, with electricity production being of local importance.

Geothermal energy is a renewable energy source, and increasing the share of renewables in the national energy balance is crucial for improving the quality of the environment, and thus the health and life of Poland's residents. But despite the many advantages associated with the use of geothermal resources, geothermal energy is still in last place among renewable energy sources in Poland. However, events of recent years seem to justify a certain degree of optimism that the pace of development of the geothermal sector may pick up and the number of geothermal projects in Poland may increase. The national system of subsidies, including those provided by the Polish National Fund for Environmental Protection and Water Management, aims to increase the use of geothermal resources. Its support for geothermal drilling has led to investments located in a number of places in Poland, including Turek, Tomaszów Mazowiecki, Sieradz, Koło and Sochaczew, and more are in the pipeline, at various stages of implementation. New geothermal boreholes stand a chance of laying the foundations for the construction of more geothermal heat plants.



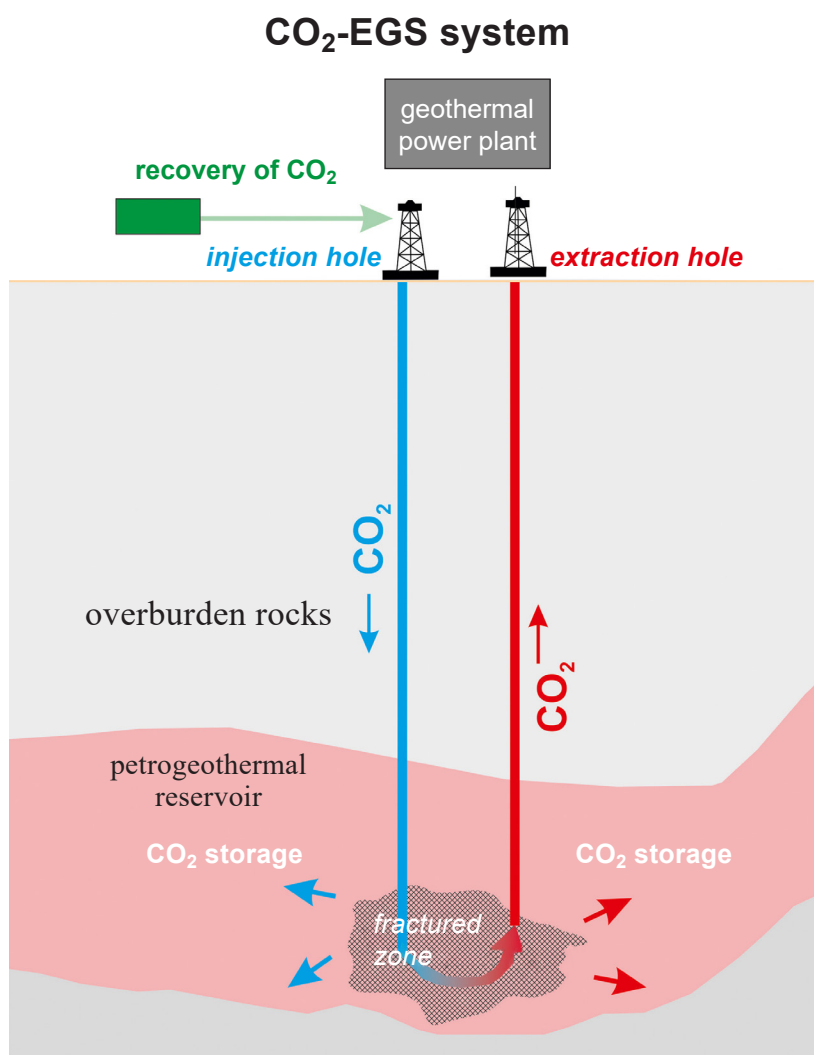
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JOHANN RAGNARSSON/SHUTTERSTOCK.COM

Conceptual diagram of how
a CO₂-EGS system works



Other support systems, such as the Polish Geothermal Plus program and the “Making Thermal Waters Accessible in Poland” program, provide opportunities for the development of geothermal projects and the harnessing of existing resources. Geothermal energy has been included as one of the renewable energy sources listed in the draft “Energy Policy of Poland Until 2040,” a very important document from the perspective of the sector’s development.

At present, geothermal resources in Poland are not being harnessed to a great extent. Such resources are being utilized effectively at six geothermal heat plants (in Poddębice, Stargard, Uniejów, Mszczonów and Pyrzyce in the Polish Lowlands, plus in the southern region of Podhale where the country’s largest and the oldest geothermal heat plant exists) as well as in recreation and balneological centers (balneology is a branch of spa medicine that focuses on the therapeutic properties of underground waters and peloid muds). However, the potential for geothermal energy in the country, as confirmed by scientific research conducted over many years, is clearly much greater.

As Poland is located in an area of low-temperature geothermal resources, it is the heating sector that is the key sector for their development. However, research work is now underway to pave the way towards building Poland’s very first geothermal power plant.

Polish research

Geothermal research has been carried out in Poland since the 1980s. From the very outset, such research has aimed to identify the country’s hydrogeothermal potential – the capacity to utilize geothermal waters with parameters adequate for various purposes, especially for heating, recreation, or balneology. Initial research yielded satisfactory results which led to the construction of the first geothermal installation (in Podhale) and then subsequent ones in Poland. Research on the potential for harnessing hydrogeothermal energy in Poland was summarized in a unique series of geothermal atlases published under the editorship of Prof. Wojciech Górecki in 2006–2013. This work points out possibilities of using hydrogeother-

mal resources for utilitarian purposes, especially in heat engineering, which is so far the key sector for the utilization of geothermal waters in Poland.

Potential

The technology involved in classical geothermal systems is already quite mature, enabling groundwater stored in hydrogeothermal reservoirs located at various depths below the Earth's surface to be exploited. However, there is also tremendous geothermal potential inherent in low-permeability, low-porosity rocks characterized by anomalously high temperatures. This potential can be exploited by means of unconventional systems, known as enhanced geothermal systems (EGS). EGS harness the geothermal energy associated with hot, dry rocks that have low natural permeability and low groundwater saturation. This type of system extracts energy from the rock by artificially increasing the hydraulic capacity of the geothermal reservoir, introducing a working fluid, the energy carrier, into the reservoir thus enhanced, and then channeling it to a power plant to generate electricity. These systems make it possible to harness geothermal energy when the hydrogeothermal conditions of a particular location rule out sufficiently high borehole yields, making potential locations for EGS much more plentiful than for classical hydrogeothermal systems. There are two working fluids used in EGS systems: the first and most commonly used one is water, while the second is carbon dioxide (CO₂). Although the first solution is definitely more common, EGS systems using CO₂ as a working fluid (CO₂-EGS) are very interesting due to both the thermodynamic properties of carbon dioxide and the need to reduce its emissions to the atmosphere. Such systems have indeed attracted much interest because of the added environmental benefit of geological storage of CO₂ during the power generation process. Existing research conducted worldwide has also demonstrated significant advantages of using CO₂ as a working fluid, including its favorable transport properties and low chemical activity.

The EnerGizerS Project

Studying the effectiveness of this innovative technology is the aim of the EnerGizerS project (CO₂-Enhanced Geothermal Systems for Climate Neutral Energy Supply), launched in October 2020 under the framework of the POLNOR 2019 Polish-Norwegian research projects, funded by the Norwegian Financial Mechanism Programme 2014-2021. The operator of the program is Poland's National Center for Research and Development, and it is co-financed from the state budget. It will be carried out until 2023 by a consortium led by the AGH University of Science and Technology in Kraków, partnered with three re-

search institutions – the PAS Institute of Mineral and Energy Economy, SINTEF Energi AS and the NTNU Norwegian University of Science and Technology – as well as the company Exergon.

Researchers from Poland and Norway have thus joined forces in the EnerGizerS project to analyze the efficiency of unconventional geothermal systems using CO₂ as working fluid. The proposed solution aims to help protect the climate by harnessing clean and green geothermal energy while also reducing CO₂ emissions from burning fossil fuels. Unconventional geothermal systems are attracting ever more interest worldwide, mainly due to the possibility of geological storage of CO₂ in tandem with the process of electricity and heat production. This technology has the potential to become a new sustainable renewable energy source of great importance for the implementation of international efforts aimed at mitigating anthropogenic climate change. These solutions are innovative on global markets and have not yet come into widespread use.

Under the EnerGizerS project, our consortium of scientists is working to identify and characterize in detail the potential of various geological structures in Poland and Norway to serve as locations for CO₂-EGS systems, satisfying combined requirements for geothermal and CO₂ sequestration technologies. Due to the differing geological, legal, and environmental circumstances in the partner countries, each of the cases considered will be characterized by different parameters. This research work will lay the basis for a technical, economic, and environmental assessment of the potential for the proposed technology to be brought into use in the Polish and Norwegian energy systems. Comprehensive laboratory tests will be carried out on samples of drill cores taken from relevant geological structures, evaluating their petrophysical, thermal, and mechanical properties. The obtained results will serve as the basis for advanced mathematical modeling, including structural modeling of the reservoir, modeling of the fracturing process in the rock medium, and 3D multivariate simulations of CO₂ injection and production with forecast projections of reservoir behavior over time. The project also involves experimental determination of the properties and behavior of CO₂, as well as mathematical modeling of CO₂-based surface systems for heat and power production.

Overall, the findings of the project will help determine the viability of combining two technologies, EGS and CO₂ sequestration, to both reduce CO₂ emissions and generate energy in an environmentally friendly as well as economically viable manner. Another key benefit from the project will be the exchanging of experience and deeper cooperation between Polish and Norwegian partners, helping to determine the best framework for the analyzed technology and thus reduce risks for future geothermal investments. The final results of the project will be publicized in 2023. ■

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BUILDING BRIDGES TO THE FUTURE

Bonn – the capital
of climate negotiations

Prof. Anna-Katharina Hornidge of the German Development Institute (DIE) draws on a systems-theory perspective to show how politicians, voters, companies and countries can be addressed to take climate change and environmental challenges of the future seriously.

Science has provided many practical solutions in human history – what role does it have to play in solving today's biggest challenges, e.g. climate change?

ANNA-KATHARINA HORNIDGE: If you look at the history of the Western concept of science – spreading from the Enlightenment period in Europe and North America and slowly all over the globe – we can see that science has acted, and still acts, as the engine of economic and social development. It facilitates technological development, which translates into economic growth. If we compare the GDP of countries with their investment in science, research and

education, we see that the societies that have mature science systems are the ones that have grown economically the most rapidly and continuously. With a certain simplification, there is an overall correlation between the development of science systems, and the size of economies.

That means the science system so far acts as engine of linear growth. It has brought us prosperity, but unfortunately, it has driven us to the very limits of our planet, contributing to climate change. Therefore, if we want to get to the root of the problem, it is our science systems that must become engines of circular wealth creation and empowerment.



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How do we do that?

Change is not easy; however, the discussion is ongoing. At the moment, our science systems are calling for a great transition towards a circular economy, a transformation within society and a changing of behavioral patterns. But rather than pointing in a normative direction and urgently calling for societal transformation, it is the job of the science system to show *how* that can be done – *how* we can develop technologies that enable circular wealth creation, and shape institutions and governance systems that enable the redistribution of wealth.

The Sustainable Development Solutions Network (SDSN), Germany, drawing on the *Global Sustainable Development Report* of the UN, speaks of “transformation fields” and “transformational levers” – the latter being leverage points that can accelerate transformation towards sustainability. Energy production, nutrition, and transport are examples of fields where we can see that the technological development and expertise required exists and the sectors indeed can be transformed towards CO₂-neutral wealth creation.

So now the task is to implement these steps – to get the governmental systems and incentive mechanisms right, but also to create regulations that push our energy system away from fossil fuels and towards renewable energies, towards solar and wind (and, where appropriate, towards water).

We recognize that we will need some natural gas to offset certain fluctuations in the system as we transition to power generation through renewables. But, energy consumption is a field where our science systems have already generated enough technological advancements for us to implement. This has of course been underway for years, but it needs to be accelerated, as we have not yet reached the level where we can feed our economies and societies solely on renewable energy.

So, to get back to your question on the role of science, it is clear that science is the engine and accelerator of our economies and societies, as it has been for the past 200 years. The countries that are strong enablers, good at developing technologies but also institutional innovations that enable the use of these technologies, have experienced more dynamic economic and social developments than those that do not invest in their science system. Therefore, science is key for transforming our societies and economies towards circular wealth creation.

Science has been aligned with the paradigm of constant growth. What if this paradigm is no longer valid?

Indeed the linear growth paradigm is not valid anymore. We have hit the limits of our planet and climate, of biodiversity, of nature in general. We need to find ways of maintaining and redistributing wealth, across geographical regions but also across social groups, and ways of reusing resources. That is the challenge of the twenty-first century.

How could we define the main areas in which the world scientific community could support government authorities in the energy transition to a more sustainable model?

Early last year, we, within SDSN Germany, put together a paper for German governmental bodies (legislative and executive), drawing on the *Global Sustainable Development Report* of the UN, in which we strove to identify key areas of transformation and key leverage points in them, key tools for facilitating their transformation. The question is as follows: It is clear that we need to transform our society towards a circular economy, but where should we start? For instance, in fisheries, or perhaps in agriculture?

We identified several key sectors: energy, the building and construction sector, the transport sector, and the agricultural and food-producing sector. These are the four key economic powerhouses that need to find



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ways to continue wealth creation, albeit in a CO₂-neutral and resource-neutral manner. These sectors are key for the overall transformation towards sustainability.

Next, within these sectors, we ask what are the leverage points, what are the instruments that can act as levers to accelerate the transformation? Within this process, governments are of course always at the core. So the question arises, how do we create regulatory systems and incentive mechanisms that push for their CO₂-neutral and resource-neutral transformations?

In addition, finances also play a significant role, a good example right now being the anti-coronavirus stimulus packages. It is crucial for such packages to be used to help us to stabilize our economy in the current crisis, but in a way that modernizes the economies towards CO₂-neutral and resource-neutral transformations. These packages must not now strengthen the coal industry and nuclear power, which would be backwards-looking, but instead these packages must be future-oriented. Consequently, R&D and innovation are relevant as these sectors contribute to the digitalization of our society. And following the sectors in general, societal acceptance within the transformation process is also very important – we certainly cannot

as well. That of course requires a strong voice from Europe, from all its different regions. It is not enough for Brussels to say something, or certain players within the EU. We need all of Europe onboard.

That is why we say that international dialogue is another “lever.” Germany or a different country might come up with all kinds of aims and goals, but it is irrelevant if there is not enough support within the European context, without strong allies such as the United States or, within the climate context, China onboard.

It appears that cooperation between government and science with respect to the climate is going very well in Germany, under the pro-active Federal Minister for the Environment, Ms. Schultze. However, my own experience working for a Polish ministry for two years opened my eyes to the gulf between the climate scientists and the whole complex political situation. How can we do a better job at building bridges between theory and practice?

We do indeed feel very fortunate with our environmental ministry, which is very active in Germany, open for exchange, and reaching out to society. At the same time, however, we must recognize that this does not resolve some of the more fundamental contradictions between the logic of science, as we might call it, and the logic of politics. When things come down to this underlying difference, it is no longer down to any particular individual. There are differences that cannot easily be bridged without a number of coincidences coming together.

Politics is concerned with situations that require majorities; it is about having a majority of voters behind you. That is a very different logic than in science, the logic of listening to the data analyzed in research. To put it bluntly, what is right from a scientific point of view is not necessarily what will win votes. This especially comes into play during certain times of the electoral process. As elections draw closer, scientific advice is increasingly perceived only in terms of whether it can generate votes.

The Fridays for Future movement was still very strong early last year, but since the start of the coronavirus pandemic, the media presence of the movement decreased. That is problematic because what we see at the moment is that the pandemic dominates a lot of the political discussions. The demographic setup of German society is such that corona is the key topic for a large share of voters, because we quite simply have an older society.

Climate is a topic for younger generations.

Well yes, climate change is a topic of the future, whereas the coronavirus is a problem for a large share of the voters right now – at least within the German context. So, at the moment we have the difficulty of how

We need to find ways of maintaining and redistributing wealth, across geographical regions but also across social groups, and ways of reusing resources.

transform society without mobilizing and bringing citizens onboard, and that entails a need for public discourse on CO₂-neutral and resource-neutral transformations.

Lastly, international cooperation is crucial, in that such transformations are not a national mandate but rather a purpose that we have to do as a world society. This will take place at different speeds across the globe, but we need to work on meeting climate targets together. The Glasgow climate negotiations later this year will play a crucial role in ensuring that the coronavirus recovery funds are created and applied in a way that stabilizes our economies, but at the same time contribute to the climate targets. Jointly, as a world society, we need strong players onboard.

China has pledged to be CO₂-neutral in 2063, which is a positive example. We are fortunate that the Biden administration in the United States is clearly oriented towards international cooperation. However, Europe has to step up and play a prominent role



to position the topics of the future – climate change, biodiversity loss, a whole range of resource-degradation related topics, as well as research and education. They stand in a certain competition to the coronavirus issue, which is now heavily focused on. Here we see different logics of time across the demographic setup of voters, creating a challenge.

It's important to show the connections between the two issues, to show how epidemics are not random but rather are connected to climate change in a certain way, or that the coronavirus crises is parallel to the climate one.

That is precisely why the “recover forward” discussions, which now gained traction within the German governmental context and also at the European level with the Green Deal discussions, are so important. If we start separating the coronavirus recovery from the climate crisis, we will definitely lose, because the larger voter group is focused on the corona topic. We have to bring climate change topics and environmental degradation issues into the corona restoration and recovery. We have to strengthen the concept that recovering from the coronavirus has to modernize our economies, making CO₂-neutrality possible to achieve – say, by 2030.

In what ways can cooperation between science, business, and government be improved?

To the logic of truth in science, and the logic of majorities in politics, we have to add the logic of making a profit in the private sector. The private sector is not bound to the idea of generating majorities, but of generating demand. As far as climate-change related advice is concerned, the economics of it all are becoming more important than whether it is politically relevant and resonates with voters.

At this point it becomes relevant within politics and policy-making to create regulatory frameworks and incentive mechanisms that make the transformation of our economic sectors financially viable. The Race to Zero Campaign, for instance, is a significant initiative. It calls for self-formulated pledges from companies, but also from countries and regional organizations such as the European Union, stating, “we want to be CO₂-neutral” by 2040 or so. I want to see more automotive industries signing up to these kinds of initiatives – Porsche has formulated its pledge, so has Mercedes, so has Volkswagen, so slowly there is a kind of competition emerging. Others are realizing that if they do not go with the flow they might lose out.

So getting back to the main idea of how to build bridges between science and politics or the private sector, we have to very carefully reflect on what are the operating logics of these very different sectors. From a systems-theory perspective – whereby science is about truth, politics about majorities, the private sector about profits – the question is how do we build bridges, how can we contribute to overlapping logics. If the goal is CO₂ neutrality, it has to be achieved in a way that gains traction with voters and is also profitable. Here science has a key role to play. Our job is not just to say, “we need to be CO₂-neutral” – that is an important normative statement, but by now this is clear. Now it is much more about showing how this is possible. That is the challenge of today. Quite a number of answers develop over time, so I think we are taking the right steps. But, we are taking them too slowly, and Glasgow will be very important for reaffirming the climate goals, generating political will and mobilizing societies and economies.

A demonstration of the “Fridays for Future” (School Strike for Climate) movement in Germany

INTERVIEW BY JUSTYNA ORŁOWSKA, PHD



KAMIL MASZEWSKI

The Bełchatów
power plant in Poland
– the largest thermal
power station in Europe

ENERGY TRANSITION IS NECESSARY AND POSSIBLE

Is climate neutrality an attainable goal for Poland? What does the term mean, and what challenges does it pose to human civilization? These and other questions are addressed by **Prof. Bolesław Zaporowski** of the Institute of Electric Power Engineering, Poznań University of Technology.



What was the immediate cause for the attention now being paid to the threat posed to humanity by high consumption of fossil fuels?

BOLESŁAW ZAPOROWSKI: In the wake of World War II, in particular after 1950, most countries of the world enjoyed very rapid economic development – driven by a natural desire to recoup the losses suffered both during the war and earlier, during the Great Depression in 1929–1933. This entailed a substantial increase in the consumption of natural energy sources (primary energy), especially fossil fuels such as coal, oil, and natural gas. Their combustion led to a very rapid increase in CO₂ emissions into the atmosphere – from approximately 6 billion metric tons of CO₂ in 1950 to approximately 43 billion metric tons of CO₂ in 2019. Consequently, the equilibrium between the emissions of CO₂ and its absorption by ecosystems was disrupted, and the concentration of CO₂ in the atmosphere rose from 315 ppm (parts per million) in 1950 to 415 ppm in 2019. By comparison, back in 1900, regarded as the beginning of the period of widespread electricity production and use, the emissions of CO₂ into the atmosphere had been about 2 billion metric tons, and the atmospheric CO₂ concentration about 288 ppm.

Initially, the rise in the concentration of CO₂ in the atmosphere and its impact on climate were not widely

noticed. It was not until 1988 that the World Meteorological Organization (WMO) and the United Nations (UN) set up the Intergovernmental Panel on Climate Change (IPCC) to examine the problem more closely.

The 14th World Energy Congress, held in Montreal in 1989 with the motto “Energy for Tomorrow,” posited that the directions of the development of the energy sector should be considered in three aspects: their energy effectiveness, their impact on the environment, and their economic effectiveness, abbreviated as 3E (efficiency, ecology, economy). The important shift here consisted in adding new aspects alongside energy effectiveness, which had been previously the most important factor.

In 1990, based on an IPCC report, the UN General Assembly adopted a resolution that began the intergovernmental negotiating process to combat climate change. On 9 May 1992, at the UN headquarters in New York, an international team of specialists from 35 countries, including Poland, finished its work on the United Nations Framework Convention on Climate Change (UNFCCC), which was opened for signature on 4 June 1992, during the UN Conference on Environment and Development (UNCED) in Rio de Janeiro. The Convention was signed on behalf of Poland by Foreign Minister Andrzej Olechowski on 21 March 1994 and ratified by President Lech Wałęsa on 16 June 1994. The Convention entered into force on 24 October 1994, and it is a binding international legal act (*Dziennik Ustaw* of 1996, No. 53, Item 238). It starts with words demonstrating that the world’s leaders understand the gravity of the problem: “Acknowledging that change in the Earth’s climate and its adverse effects are a common concern of humankind (...).”

The Convention’s supreme decision-making body is the annual Conference of the Parties (COP). At the cyclical COP meetings, governments meet to discuss the content of documents determining the implementation of the obligations arising from the Convention by individual countries. Its primary goal is to stabilize the concentration of CO₂ in the atmosphere at a safe level. So far, there have been 25 such conferences, from 1995 to 2019 (2020’s meeting was cancelled due to the COVID-19 pandemic). Representatives of governments are scheduled to meet at the 26th conference in Glasgow in late 2021. Poland has already hosted three Conferences of the Parties: COP 14 in Poznań in 2008, COP 19 in Warsaw in 2013, and COP 24 in Katowice in 2018. The most important decisions were taken at COP 3 in Kyoto (1997), where the Kyoto Protocol was adopted, and at COP 21 in Paris (2015), where the Paris Agreement was reached.

The Kyoto Protocol required the countries that ratified it to reduce their greenhouse gas emissions below a certain “base level” over 2008–2012. This base level was determined by the emissions in 1990 for



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most countries, and in 1988 in Poland's case. Poland obliged itself to reduce its emissions by 6% against that level. The Kyoto Protocol entered into force on 16 February 2005. By the end of 2005, the document had been ratified by 157 countries, which thus became parties to the Protocol. It was the first step towards proper international negotiations on climate change. However, the world had to wait for their outcome until COP 21, held in Paris in 2015 – when the first-ever universal, legally binding climate agreement was concluded. The deal stands a chance of protecting the world against the effects of climate change. Its implementation is expected to curb the average rise in the Earth's temperature to below 2°C compared with pre-industrial levels. However, efforts are being made to prevent this rise from exceeding 1.5°C. In Europe, observations, data collection, and analyses in the field of climate change are carried out by the EU's Copernicus Climate Change Service (C3S), among other frameworks. The findings and data are utilized by such institutions as the European Centre for Medium-Range Weather Forecasts (ECMWF). The Copernicus Climate Change Service has reported that 2020 (along with 2016) was the warmest year

Most countries, including the EU member states, intend to reach climate neutrality by 2050.

since records first began to be kept, and the average temperature on Earth in that year was 1.25°C above the pre-industrial levels.

The Paris Agreement was adopted by 196 countries by consensus on 12 December 2015, the last day of the Paris Conference. Poland signed the agreement at the UN Headquarters in New York on 22 April 2016, and the Sejm passed an act to ratify it on 6 October 2016. The agreement entered into force on 4 November 2016, following its ratification by 55 countries, accounting in total for over 55% of global CO₂ emissions. Before COP 21, countries submitted plans to reduce CO₂ emissions by varying amounts. At later conferences, however, they were unified in the form of a commitment to reach climate neutrality, or a state of equilibrium between CO₂ emissions and absorption. Most countries, including the EU member states, intend to reach this status by 2050. Globally, this means reducing CO₂ emissions from the current level of about 43 billion metric tons to about 4.5 billion tons in 2050. Countries are expected to achieve this goal by reducing CO₂ emissions substantially in

all areas of transportation, industry, and agriculture and to zero in electricity generation and almost zero in heat generation. In 2019, electricity generated from coal accounted for more than 73% of all electricity generated in Poland, compared to only about 15% in the case of renewable sources.

We already know that the energy transition is necessary not only due to climate goals and commitments, but also because of market requirements. Do you think such transformation is possible?

The answer to this question depends on what part of the planet we are referring to. The Paris Agreement refers to the whole of the world. The condition of the power generation sector in different regions of the world varies and remains closely linked to the economic situation of those regions and their natural resources (primary energy sources). The condition of the power generation sector in individual countries is best characterized by their national energy systems. Every year for the past 10 years, the World Energy Council has rated the performance of national electric energy systems in more than 130 countries of the world using three criteria: energy security (the security of energy supplies), energy equity (ease of access to electricity as gauged by electricity prices in relation to *per capita* national income in each country), and environmental sustainability (the impact on the environment).

The top-ranking country in the 2020 ranking list was Switzerland, followed by Sweden. In 2019, 98.8% of electricity in those countries was generated from zero-emission sources, including 30–40% in nuclear power plants. Ranking next on the list are France, Brazil, Finland, Canada, Slovakia, Belgium, Slovenia, Hungary, and Spain. The share of electricity from zero-emission sources in these countries ranges from 59.2% in Spain to 88.8% in France. The energy transition in those countries should be relatively swift and should not generate very high costs.

The 2020 ranking of electric energy systems put Poland 41st in the world and 26th in the EU (followed only by Cyprus). This indicates that the energy transition in Poland will be a long and capital-intensive process. An additional difficulty is posed by the fact that while Poland is a major producer and consumer of electricity (ranking fifth in the EU and 25th in the world), in fact we lag behind in this area, because in terms of economic potential measured by annual GDP Poland actually ranks higher, at 21st in the world.

Energy transition is possible in Poland, but this transformation will require significant funding for the development of zero-emission electricity generation technologies. That said, we should bear in mind that the economic situation of many countries in the world is much worse, and Poland can additionally count on



assistance under the EU's "just transition" framework. As is the case with other EU countries, this should help us to successfully transform our energy sector. On a global scale, as part of the solidarity policy, the Paris Agreement provides for the establishment of a special fund to assist developing countries in their energy transition. At the beginning of 2020, however, Poland was already classified as a developed country.

What technological conditions have to be met in the energy sector, for Poland to be able to attain climate neutrality?

The most important issues that have to be resolved in the coming months for the door to climate neutrality to open up for Poland are to implement "The Energy Policy of Poland Until 2040," adopted by the Government on 2 February 2021, and to reach agreement with the European Commission on the "National Energy and Climate Plan for 2021–2030," submitted to Brussels in December 2019. These documents set forth a path for the long-term strategy of building a safe and zero-emission electric power system, ensuring the country's electricity supplies security, and making major reductions in CO₂ emissions in all branches of the economy. This problem is addressed in the "Opinion of the Committee on Electrical Engineering, Polish Academy of Sciences, on the implementation of nuclear energy in Poland." It argues that given the lack of sufficient hydropower sources in Poland able to support the construction of major hydroelectric plants, building a secure and zero-emission electric power system has to be based on renewables and on zero-emission nuclear power plants. Poland's attaining climate neutrality around 2050 will be possible if the decisions are made, among other things, to build a secure and zero-emission electric power system, and to make major reductions in the CO₂ emissions in heat generation, transportation, and all branches of the industry and agriculture.

Apart from its reliance on coal, how else does the Polish energy market stand out from the rest of Europe?

If we understand the energy market broadly, as a sector of the economy that deals with generating and supplying electricity and heat for industry, transport, services, and households, as well as fuels for land transport and aviation, the Polish energy sector has several distinguishing traits as compared with the rest of Europe. The first of these is the subsector of generating and supplying heat. All the large and medium-sized cities in Poland, most of the small ones, and also many industrial facilities have their own district heating schemes, which together comprise the National District Heating System. In a district heating scheme, heat is generated centrally, then supplied to end-users by means of a district heating network. In most other European countries, individual heat generation is predominant.

Heat that is centrally generated and supplied to end-users by means of a district heating scheme is known as network heat. Each year, the amount of system heat generated in Poland is around 480,000 TJ, in other words around 133.3 TWh. In 2019, for instance, the figure was 475,477.8 TJ (132.1 TWh). Around 65% of the system heat in Poland is co-generated in conjunction with electricity. For a thermal system to be described as energy-effective, the amount of heat co-generated together with electricity should be at least 75%. Potentially, 50% of system heat should be generated from renewable energy sources. The co-generation of electricity and system heat takes place in what are called cogeneration power units, which function simultaneously in the National Electric Power System and in one of the hundreds (around 400) of separate district heating systems, of varying thermal power. Cooperation between the National Electric Power System and the National District Heating System places additional demands upon the for-

Offshore wind farm



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Nuclear power plant

mer in terms of operating continuity and stability, and hence security. The most important criterion for the functioning of a cogeneration unit is operating at a level of thermal power generation that is consistent with the demand for thermal power in the district heating system, which in most types of cogeneration units also requires working at the proper level of electric power generation in the National Electric Power System. This demands that the electric power being generated at other units operating with in the National Electric Power System be regulated so that the sum of the electric power of all the generation units is at every moment equal to the demand for electric power.

Moreover, the Polish Electric Power System has relatively poor network links to the power systems of neighboring countries, which in emergency situations poses an obstacle to utilizing their assistance.

The Polish energy sector unfortunately stands out against the European backdrop also in terms of the quite antiquated generation units operating at its power plants and combined heat and power (CHP) plants. Of the 91 hard coal and lignite fired steam units at the power plants, as many as 41 have been operating in the National Energy System more than 40 years. The cogeneration steam units at the CHP plants have been in operation for even longer on average. The past 30 years have seen little continuity in efforts to renew the infrastructure of generation units. After 1988, there was a certain interruption in the process of building new power plant units, which lasted all the way until 1994. In 1994–1997, four new units were placed into

service at the Opole power plant. After this investment, there was again an interruption until 2008, when a new steam unit with supercritical parameters was placed into service at the Pątnów power plant. In the past 12 years, only six steam units with supercritical parameters have been placed into service. This discontinuity in investing in generation sources in the Polish power industry has caused a disruption in the regular aging process of power-generation units and their being taken offline, and also the occurrence at certain times of shortages of available power in the National Power System, especially from centrally dispatched generation units (CDGUs). At present we are now facing a culmination in the aging of generation units and a need to take a large number of them offline within a short period of time. The energy transformation of generation sources in the Polish electric energy industry is therefore necessitated not only by the emerging problem of climate change, but also by the aging of the existing power generation infrastructure.

Another trait that distinguishes the Polish power sector from the sectors of most European countries is the relatively low *per-capita* electricity consumption, even compared with countries with similar national incomes. In the EU Member States, this figure was 6305 kWh in 2019, as compared with 4477 kWh in Poland. The highest *per-capita* consumption was seen in Sweden, at 16,779 kWh. This, too, could cause give rise to increased demand for electric power in the National Electric Power System in the coming years.

Are there any technological limitations to adding nuclear power into Poland's energy mix?

Implementing nuclear power in any country poses a major technological, economic, and developmental challenge. The related problems were more serious in the initial period of its development in the world, more specifically in the latter half of the twentieth century. With more than 440 nuclear power units now operating across the world with total capacity of more than 493,390 GW, we can talk about there being considerable experience in constructing and operating of nuclear power plants. Over the past 20 years, modern and safe generation III+ pressurized water reactors (PWR) have been designed, and experience has been gained on how to best construct and use operate them.

These external conditions are favorable for Poland, which is preparing to introduce nuclear power. However, the domestic industry and industrial construction sector are faced with the great responsibility of preparing for tasks related to implementing the nuclear power program. About two-thirds of the related investment tasks can be performed by Polish companies. This holds true in particular for many construction tasks related to laying the foundations for the reactor and the turbine building, the containment building, and the cooling system. Such tasks can be successfully

completed by Polish construction companies, such as Polimex-Mostostal SA, Mostostal Warszawa SA, and Budimex SA, which are highly qualified and experienced in constructing 1000 MW power units. In addition, we have considerable design and construction potential when it comes to the steam generators at Rafako. Ensuring the safe operation of nuclear power units is a new task that requires many years of preparations. In my opinion, our country's technological, economic, and developmental level and the size of the National Electric Power System will allow Poland to perform these tasks with success.

Are today's renewable energy production and distribution technologies enough to ensure energy security for inhabitants of Poland and its industry?

It is the responsibility of the state to ensure the security of electricity supply to industry, transport, services, and households. To fulfill this obligation, the state must have an efficient and secure National Electric Power System. In this new energy reality, which started with the adoption of the Paris Agreement by almost all countries, modern electric power systems must meet three criteria, namely: the security of electricity supply, moderate electricity prices (which depend on low production costs), and environmentally sustainable electricity production. This means that a modern electric power system must be characterized by high operational safety, zero-emission electricity sources, and high economic effectiveness. In other words, such a system must be safe, produce zero emissions, and provide electricity to consumers at possibly low prices. This is exactly the electric power system that must be built in Poland within the next 30 years.

Is it possible to build such a system based exclusively renewable energy sources? The PAS Committee on Electrical Engineering has concluded that this goal cannot be achieved in the required time frame in light of the natural conditions in Poland and the absence of significant hydroelectric power resources.

For the purpose of generating electricity, both Poland and most countries now use – and will continue to use in the future – primarily wind and solar energy, whereas hydroelectric energy and biomass are used to a much smaller extent. Electricity sources that use wind and solar energy as primary energy are characterized by relatively low utilization time of nominal electrical capacity (capacity factor values). In the meteorological conditions that prevail in Poland, these values are as follows: about 3400 hours per year for offshore wind power plants, about 1900 hours per year for onshore wind power plants, and about 950 hours per year for photovoltaic power plants. If the electric power system only had power plants with these conti-

nity parameters, it could not supply consumers with electricity in a continuous way (without disruptions). The difficulty lies in storing electricity in amounts that will allow the electric power system to work in a safe and stable way. This can only be achieved through the conversion of electricity into other forms of energy, preferably hydroelectric or chemical energy, in the form of pumped-storage hydroelectric power plants or electrochemical or hydrogen storage facilities. Building pumped-storage power plants requires natural conditions suited for the construction of upper and lower reservoirs and considerable financial resources. In the case of electrochemical energy storage facilities, especially hydrogen storage facilities, the energy losses in multiple energy conversion processes and the cost of the equipment needed for energy conversion mean that, for the purposes of cooperation with the electric power system within the time limit required for the energy transition, they will not, in my opinion, reach commercial maturity, especially when it comes to the criterion of economic effectiveness. On

For now, no industrially developed country with similar natural conditions as Poland intends to build a secure zero-emission power system using only renewable energy sources.

the other hand, electrochemical storage technologies have already been used in transport and, to a lesser extent, in electricity distribution networks. In addition to being used in industrial technologies, hydrogen technology is making its way into transport. In the future, this technology may also be used in distributed energy systems. For now, therefore, no industrially developed country with similar natural conditions as Poland intends to build a secure zero-emission power system using only renewable energy sources. The one exception is Germany, which nonetheless intends to a considerable extent to use power plants fired by natural gas. Its use for electricity generation purposes causes emissions at the level of 45% of CO₂ emissions from coal-based sources – in other words, this is not a zero-emission technology. Large water energy resources are the only renewable energy source that would allow the electric power system to operate in a continuous and safe way. But Poland does not have such resources. In Europe, such conditions can be found in such countries as Norway.

INTERVIEW BY JUSTYNA ORŁOWSKA, PhD

WIND FARMING IN THE BALTIC

On power generation and the future of Polish offshore wind farms.

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Air moves with respect to Earth's surface as a result of the uneven distribution of heat over major landmasses, with sunlight being absorbed to different degrees by land and oceans, and due to the

rotation of the globe. Temperature and atmospheric pressure variations over different regions cause the flow of air which we call wind. Wind carries kinetic energy which humankind has been harnessing as a source of power for millennia, for example in sailing. Windmills are first mentioned in the Code of Hammurabi back in the 18th century B.C., where they are described as devices for pumping water and irrigating fields.

Today, wind power is used as a renewable resource for generating electricity by wind turbines which are designed for maximum efficiency. Their most important elements are blades which are turned by the aerodynamic force of airflow. The general principle at work here is the same as for aircraft wings, helicopter blades and sails. The flow of air causes a pressure



differential over the blade surface which generates lift and resistance. Carefully setting the position of the blades relative to wind direction drives the rotor connected to the generator (either directly or using gears) to convert the kinetic energy of wind into electrical energy. Wind farms can be located on- or offshore.

Why offshore wind power?

It is universally known that climate change is the main factor driving the loss of biodiversity. Rising temperatures all over the globe are leading to damage and destruction of land and marine ecosystems. Wind power generated by offshore farms is widely regarded as a fundamental means of low-emission power generation in Europe, since it should help re-

duce the emission of greenhouse gases and preserve biodiversity.

Under an EU directive from 2009, energy from renewable sources was meant to contribute 20% of all energy used in the EU by 2020. In 2018, the European Parliament adopted an amended version of the renewable energy directive setting the goal for the EU as at least 32% by 2030. Another key goal is the reduction of greenhouse gas emission by at least 40% in comparison with 1990.

Wind power is the largest contributor to low-emission, renewable energy in the EU, and forecasts predict that this will continue in the coming decades. In 2018, wind power contributed 18.4% of the total potential of electrical energy generated in the EU with 170 GW from onshore and 19 GW offshore farms.



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Assuming that energy from renewable sources may constitute 50% of total power generation in the EU by 2030, wind power (on- and offshore) could contribute 21% of total energy.

In December 2019, the European Commission launched the European Green Deal. It outlines a clear vision of Europe reaching climate neutrality and decarbonizing the power generation system by 2050, stressing the key role of renewable energy sources, in particular offshore wind farms, in reaching this goal. Climate neutrality (also known as carbon and emission neutrality) describes a net-zero emission of greenhouse gases (including CO₂) – that is, achieving a balance between the emission and absorption of greenhouse gases.

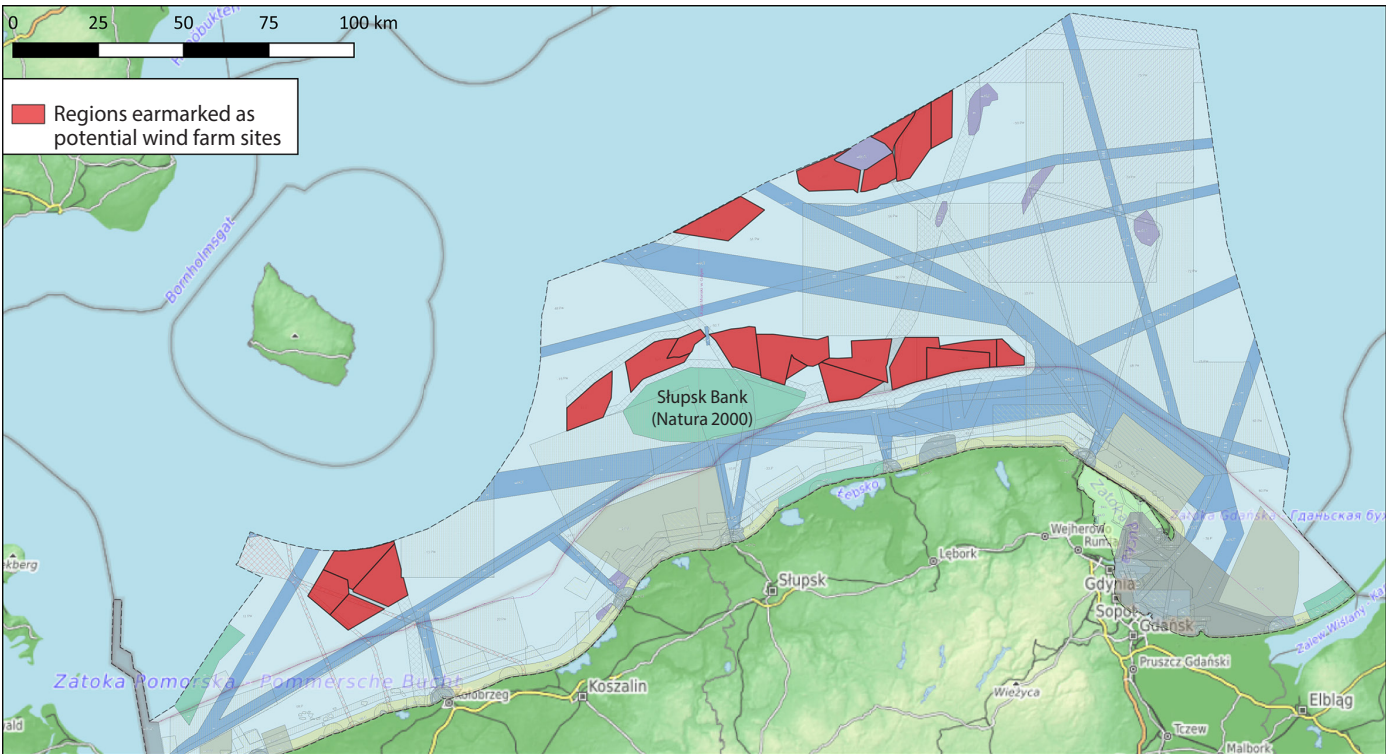
In order to meet these targets, the wind power sector needs to grow significantly. According to the most optimistic scenario of the long-term strategy of the European Green Deal, the total energy generated offshore in Europe will rise to 450 GW, 85% of which will originate from the Atlantic coastal regions of France, Ireland and the UK (85 GW), the North Sea (212 GW) and the Baltic (83 GW). In order to generate 380 GW, the total area dedicated to wind farms would need to be 76,000 km² (assuming 5 MW/km²), that is around 2.8% of the total area of the northern sea basins.

An important element of the planning process is identifying optimal locations for wind farms. Currently, offshore wind farms are built in shallow waters (depths of up to 60 m) at a safe distance from the

coast and shipping routes. According to the Wind-Europe report published in February 2019, European wind farms are at an average distance of 33 km from the coast (41 km in 2017) and at an average depth of 27.1 m. The first offshore wind farm was built in Vindeby in Denmark in 1991; the UK generates 45% of all wind energy in Europe (measured in MW), followed by Germany (34%), Denmark (8%), Belgium (7%) and the Netherlands (5%).

The proposed locations of wind farms in Poland's exclusive economic zone are shown in Fig. 1. The sites are in relatively shallow regions (20–50 m) at a safe distance from shipping routes (min. 2 nautical miles) and do not interfere with areas protected for environmental or defense reasons or used to extract aggregate or hydrocarbons. The total area of the selected locations is approx. 2,245 km², which – assuming a density of turbines of around 8 MW/km² – means a potential total energy generation of approx. 18 GW. The real potential may end up being lower due to environmental limitations in and around the wind farms. Reasons might involve creating bird migration corridors or having to refrain from erecting some of the turbines due to adverse geological conditions. This is why governmental planning reports estimate that offshore wind farms in Polish waters will generate a total of between 8 and 11 GW by 2040. However, according to the report published by the wind energy industry association WindEurope, the optimistic scenario indicates that Poland's region of the Baltic has the potential to generate up to 28 GW. This would

Fig. 1
Proposed locations
for offshore wind farms
within Poland's exclusive
economic zone



SOURCES: VERSION 4 OF THE PZPOW PROJECT; TOPOGRAPHIC OVERLAY: OPENS TREEMAPS

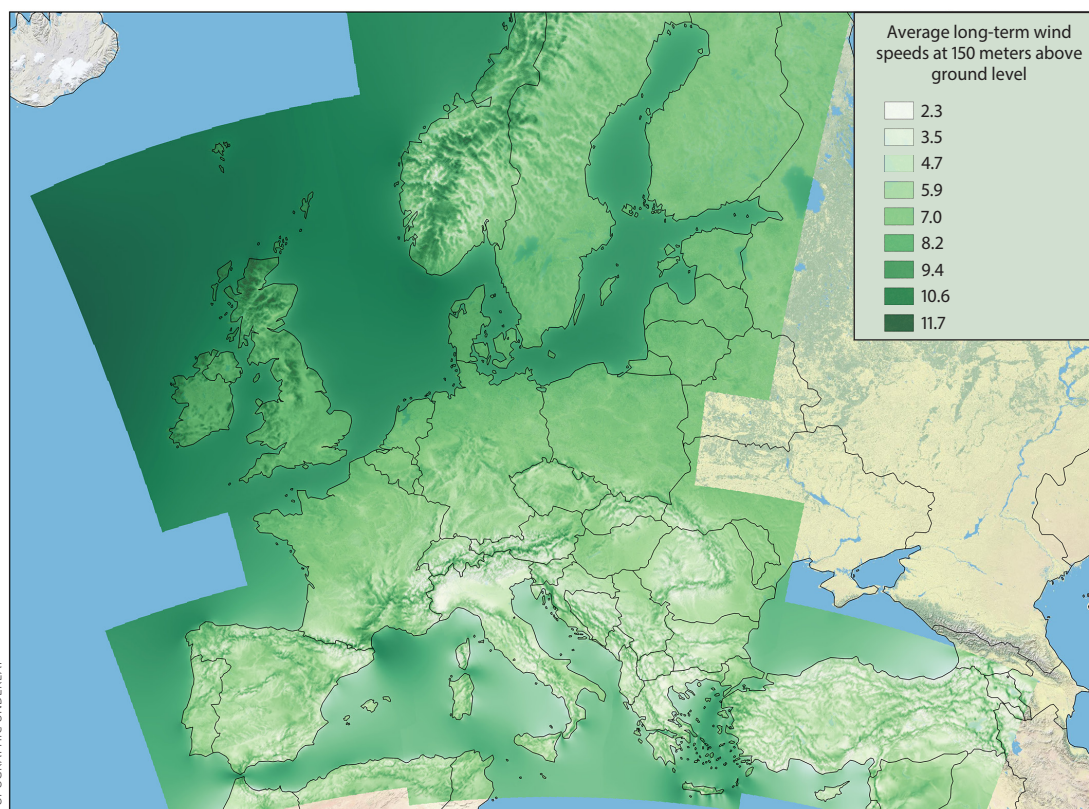


Fig. 2
Average wind speeds in Europe and Turkey at 150 meters above ground level



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require identifying new regions for development of wind farms, for example in the eastern reaches of Poland's economic zone. Since this part of the Baltic is deeper, however, such wind farms would likely need to be built on floating platforms.

Figure 2 shows a map of average wind speeds over several years in Europe at 150 m above ground level. Marine regions typically feature no obstructions and are expansive and flat with low friction coefficients, meaning that wind speeds at a given height are faster (by approx. 1.5–2.5 m/s) than over nearby land, making offshore wind farms more efficient. Better wind energy resources justify the construction of offshore wind farms in spite of their being more complex and expensive. Although wind conditions in Polish waters are not as favorable as those of the North or Irish Sea where first wind farms were built, they are still sufficiently good to justify building offshore wind farms.

Another important factor is the fact that a single construction project results in the creation of a powerful, efficient wind farm. A single offshore wind farm can generate power of up to 1.5 GW, while on-shore farms in densely populated areas generate just 100–200 MW.

The main limitation to developing offshore wind farms is the difficulty in building permanent structures at depths greater than 60 m. However, the development of floating platforms could significantly expand our capacity for generating wind power. Examples include the Hywind project off the Scottish

coast and Windfloat off the coast of Portugal. An important element of the development of renewable energy technologies is bringing together offshore wind power with processes such as hydrogen production and energy storage, which would help wind power make a greater overall contribution.

Wind turbines in energy production

The wind energy sector, both on- and offshore, is dominated by horizontal axis wind turbines (HAWT). Although alternative configurations exist (such as vertical axis wind turbines, VAWT), the development of material technologies and design and production methods have all contributed to a marked improvement in the efficiency and power of HAWTs. The power of a turbine depends on the diameter of the rotor; therefore, it is directly linked to the total area of the blades able to capture the kinetic energy of wind and transfer it to the generator. Increasing the diameter of the rotor and the height of the turbine results in greater power being generated due to the greater windspeeds higher above sea level. This is due to the distribution of speeds in the atmospheric boundary layer. Another advantage of offshore wind farms is the uniform terrain lacking obstacles such as forests or built-up areas and a lower level of turbulence at the turbine, making the conditions more stable.



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SIEMENS GAMESA

Mold of a 75 m blade for a Siemens B75 turbine, at a factory in Hull

Currently, the largest offshore turbines can generate up to 9.5 MW (MHI Vestas); their diameter is 164 m and the top of the blade in the upright position soars to 187 m above sea level. The blades of such turbines are longer than the wingspan of an Airbus A380 and the height of the entire structure, including the section below the water level, exceeds the height of Warsaw’s landmark building, the Palace of Culture and Science (237 m). As their dimensions increase, their power rating increases accordingly; in 2019 this was 7.8 MW, up by 1 MW on the previous year. In the wake of the ongoing development of methods of

designing and manufacturing turbines, in 2020 General Electric and Siemens Gamesa unveiled a range of new solutions which will be gradually introduced in the coming years. Both turbines, General Electric’s Haliade-X and Siemens Gamesa’s SG 14-222, use rotors with diameters of approx. 220 m to generate up to 14 MW of power.

The efficiency of offshore wind farms is the function of wind conditions, the technology used by the turbines, and their relative distribution within the farm. Wake loss is an important consideration, since it can cause losses of up to 40% of the energy generated when one turbine is positioned behind other turbines on the windward side (Fig. 3). The aerodynamic wake effect can be reduced by selecting the optimal distance between turbines in the dominant wind direction at the design stage or by applying innovative technologies making it possible to move the turbines during operation. Since wakes extend for many kilometers beyond offshore wind farms, the effect must also be taken into consideration when planning the locations for new farms in Polish waters to avoid positing overly optimistic forecasts of the amount of renewable energy being generated, as was the case in Germany.

Under the wind conditions found in the Polish region of the Baltic, contemporary wind turbines of the 12-14 MW class will generate energy at an efficiency of approx. 40-45% (theoretical maximum power while operating non-stop). Power generation will depend on the number of turbines erected in a given farm, its size and layout and the presence of other wind farms. As-

Fig. 3
Visualizations of the wakes stretching out behind wind turbines, caused by condensation in humid air. The Horns Rev wind farm



CHRISTIAN STEINSS/VATTENFALL

suming the more optimistic variant (45%), the 11 GW of energy generated by offshore wind farms planned as part of Poland's energy policies by 2040 should meet approx. 25% of the country's energy demand as of 2020. This value is equivalent to the annual demand of around 17 million households in Poland. However, by the time the farms are operational in 2040, both the average energy demand and the way the energy market operates will be very different due to increased efficiency, the prosumer movement, distributed generation, development of new ways of storing energy, ongoing digitalization and all the social changes that go in tandem with these. All this means that the figures mentioned above should be seen as rough estimates.

Environmental impact

Placing wind farms offshore has a significantly lower impact on the landscape and causes no noise concerns (apart from noise during installation). According to legislation governing the use of offshore areas, building artificial islands, structures and installations harnessing sea waters, currents and wind to generate electricity is only permitted within economic zones (Fig. 1). On most days of the year, wind farms are almost invisible from shore; they can be spotted if atmospheric conditions are particularly clear or at night, due to the blinking warning lights atop the turbines.

There are currently no wind farms in Polish waters, although surveys and measurements are ongoing to determine environmental conditions in regions marked for development. The data will be used to prepare reports on the potential impact of wind farms on the environment to make the best decision for the given location.

Using wind power to generate electricity does not use water or cause air, soil, or water pollution. However, unsuitably located or designed wind farms can pose a danger to sensitive habitats and species. This is why, prior to the construction of offshore wind farms and the laying of electricity cables, construction companies conduct extensive surveys and measurements in order to prepare an inventory of biotic and abiotic resources at the proposed site and along the cable route. In terms of the abiotic components, the surveys explore the geological features of the terrain (including geophysical and geological studies, collecting soil samples and testing sediment for traces of pollutants), determine the contour of the seabed, and test for major changes in depth. Hydrological studies measure the direction and speed of sea currents and examine the chemical and physical parameters of water at the site. The local weather conditions are also measured, including wind speeds, temperature and humidity. Biotic components include the local fauna such as fish, birds, bats and protected mammals such as porpoises. Organisms living in the benthic zone (near the seabed), including



WOJCIECH SULARZ

Grey seal taking a rest on a beach near Dębki

phytobenthos and zoobenthos, are also considered. These studies determine the extent to which the site is used by the given species, environmental conditions and any actions which need to be taken to minimize impact. All these results are used to prepare a report on the environmental impact of the proposed wind farm. Such a report lists any measures which need to be taken to minimize the environmental impact at each stage of the construction and operation of the farm. For example, underwater noise generated when drilling foundations into the seabed can be mitigated by using bubble curtains. It should also be noted that as well as the natural environment, the surveyors also investigate any anthropogenic objects found at the site, including those related to cultural heritage, as well as checking for any unexploded ordnance.

When planning the development of wind farms in the southern Baltic, it is important to assess their potential cumulative impact as well as that of individual farms. This is especially important when considering bird habitats. Figure 1 shows the Natura 2000 region at the Słupsk Bank, which is a feeding and wintering site for seabirds such as long-tailed ducks, black guillemots, red-throated loons, and black-throated loons. Any wind farms on the northern or north-eastern slope of the bank would create a barrier for birds flying to the site. Wind farm development plans show that dense spacing of wind farms would make parts of the region uninhabitable for seabirds; this means that it is essential to leave undeveloped corridors interspersed among the farms to provide birds unobstructed access to the Słupsk Bank. Another major issue is noise pollution during the construction stage.

The issues outlined above show the importance of carrying out thorough and accurate survey work when identifying locations suitable for wind farms, so as to prevent local damage, protect wildlife habitats and minimize environmental impact. ■

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WOODY BIOMASS FOR ENERGY PRODUCTION

Is the burning of woody biomass
climate friendly?

The role of forests in climate change mitigation is twofold: sequestering carbon and acting as a source of renewable energy

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Based on how the topic of combusting woody biomass for bioenergy production is presented in the media, most of us are probably quick to imagine a massive, beautiful tree, almost large enough to be declared a natural monument, being cut down, chopped into pieces and thrown into the furnace of a combined heat and power plant.

Such a vision sparks outrage for obvious reasons and prompts a number of questions. How many years will it take for a tree planted today to grow to the size of the one that has just been cut down? What about carbon neutrality? After all, emitting carbon dioxide (CO₂) takes just minutes, but its reabsorption takes years, if not decades. How much CO₂ do we emit during the transportation of woody biomass to the place where it is burned? Hidden behind all these dilemmas the most fundamental question: can woody biomass actually be classified as a renewable energy feedstock?

In recent months, the media have spread numerous half-truths or outright misrepresentations about bioenergy produced from woody biomass, often playing on the emotions of the audience by linking images of massive trees being fallen to the ground to satisfy the growing use of biomass in the energy sector. Unfortunately, the real situation is often obscured by catastrophic language ("biomassacre"), misleading oversimplifications ("electric cars to be powered by burned forests"), or – as it was the case with a certain highly-publicized article in Britain's *The Guardian*¹ – combinations of unrelated but very emotional stories about environmental activists fighting to protect specific forests and sweeping generalizations about the blame allegedly attributable to the EU legislation and about an imminent environmental disaster.

¹ <https://www.theguardian.com/world/2021/jan/14/carbon-neutrality-is-a-fairy-tale-how-the-race-for-renewables-is-burning-europes-forests>

The situation has been worsened by letters of support and scientific articles written by individuals who do not typically deal with such issues as biomass, bioenergy, or assessing the life cycle and carbon footprint of wood products. This may mislead the public not merely about the scale but also about the very nature of the issues related to the use of woody biomass for energy production. In response to such reports, numerous articles have been published to explain the misunderstandings on this topic.

In the remainder of this article, we will try to identify and clarify these misunderstandings.

Objective: decarbonization

Reducing greenhouse gas emissions currently poses a key global environmental problem. The role of forests in these efforts is twofold: sequestering carbon (capturing it from the atmosphere) and acting as a source of renewable energy.

Overall, the use of woody biomass in the EU has grown by 20% over the past two decades. This means that we are faced with the challenge of reconciling increased demand for woody biomass (while being aware of its advantages in replacing non-renewable materials and fossil fuels) with sustainable forest management, including the protection and restoration of the forest ecosystems. The European Green Deal is a fairly ambitious plan, and its success will largely depend on how we use natural resources to produce energy.

What is biomass, and how is it used?

Woody biomass is not the same thing as forest biomass. In short, woody biomass includes both forest biomass (unmerchantable trees, branches, logs, and logging residues) and wood processing residues from the wood industry (for example in the sawmilling industry), as well as post-consumer wood (such as old furniture). Also, biomass is sometimes categorized into prima-

ry biomass (forest biomass) and secondary biomass (wood processing residues plus post-consumer wood).

Only the biomass from the forests managed in sustainable manner can be classified as renewable, and this is one of the issues regulated by the revised EU Renewable Energy Directive (RED II) of 2018.

Biomass (e.g., forest biomass, agricultural biomass) currently accounts for approximately 60% of total renewable energy in the EU. This applies to primary energy and, by the same token, comprises the energy used both in the heating sector and in the electricity sector. The total share of biomass is dominated by the biomass originating from the forest sector (forestry and the wood industry). Its share equals 60%, while the remaining 40% consists of agricultural biomass and waste, among other types.

According to the latest estimates, nearly half of the woody biomass in the EU used for bioenergy production comes from the wood processing residues or post-consumer wood, with primary woody biomass accounting for the other half. Around 20% of all forest biomass used for energy production comes from small-diameter logs (half of which are logs that come from coppice forests in the Mediterranean Basin), while 17% comes from other woody components (branches, tree tops).

Contrary to the suggestions made in the media, a vast majority of bioenergy in the EU is used in the heating sector, and not for power generation (in the electricity sector). From a global point of view, firewood is the most frequently used wood type in the world (approximately 1.9 billion m³). The same amount is used by practically the whole of the world's wood industry.

Bioenergy, emissions, and "carbon neutrality"

It is argued that bioenergy is carbon neutral, and those who raise this argument in discussions point out that the CO₂ emitted during wood combustion



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Forests can support the achievement of numerous different objectives, including the production of timber and ecosystem services



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Photo 1

An example of the use of pulpwood in the production of woody biomass for energy purposes (wood pellets), the United States

Photo 2

Almost half of the woody biomass used for bioenergy production is a by-product of the production of high-value wood products

had to be earlier absorbed from the atmosphere during tree growth. This is a major oversimplification, and the term “carbon neutrality” used here is misleading because we should consider emissions in the whole of the supply chain and their impact on the level of CO₂ sequestration in the forest. For this reason, when we quantify the benefits from the use of woody biomass for bioenergy production, we should consider the question of whether the use of forest biomass leads to a reduction in forest carbon stocks or to the weakening of the forest ecosystem’s CO₂ sequestration capacity. Also, we should take into account all the emissions that arise in the supply chain (such as these associated with production, processing, and transportation). After that, the scenario of the use of woody biomass for bioenergy production should be compared with another scenario, namely one that uses alternative energy sources, to determine which energy source emits less greenhouse gases. For this reason, bioenergy should be considered not in terms of carbon neutrality, but in terms of the climate benefits that it brings compared with other energy sources (such as coal).

Alarmist publications use confusing and very emotional language, for example by mentioning “burning forests” in the context of woody biomass. Considering only the tree stand level, much of the carbon that was absorbed in a tree stand during the growth of trees is suddenly removed from ecosystem when wood is harvested and transported to the bioenergy facility. In order to reach the same level of CO₂ absorption, this tree stand must again reach the felling age. In Poland’s forest-growing conditions, this may take even more than 100 years. The scenario presented in this way will always lead to the conclusion that the use of forest biomass for bioenergy leads

to net CO₂ emissions (more CO₂ is released to the atmosphere than absorbed). However, on the scale of the landscape (which includes many diverse tree stands), CO₂ losses in mature stands are offset by CO₂ absorption in younger stands. This is why it is very important that we analyze the levels of CO₂ release and sequestration on the scale of the landscape, as opposed to individual trees or tree stands. The factors that influence the level of carbon (C) stock on the landscape scale include, for example, growing conditions, current and past forest management practices, the ownership structure of forests, and changes in demand for and supply of wood products. Although this may seem counterintuitive, an increase in demand for woody biomass may lead to an increase in the forest area in a given region. This is because growing demand drives up the price of wood products, which encourages private forest owners to reforest new areas, which consequently increases the CO₂ sequestration at the landscape level.

In addition, we must remember that forests can support the attainment of numerous objectives, which include not only the production of timber, but also provision of ecosystem services (such as improving air quality, stabilizing soil, maintaining biodiversity). Timber is typically used to produce high-value products (such as lumber and engineered wood), for which the seller can charge much higher prices per cubic meter than for the biomass intended for bioenergy purposes. For this reason, during the production of lumber (which in many countries replaces more emission-intensive construction materials such as steel, concrete, and aluminum), woody biomass is produced as a by-product that is used for bioenergy purposes. In turn, if such biomass (for example in the form of wood pellets and wood chips) replaces more



1



2

RAFAŁ CHUDY (2)



In the EU, less than 20% of the primary biomass used for bioenergy comes from logging debris

emission-intensive and non-renewable fossil fuels, then we can talk about further increasing the climate benefits of woody biomass.

Finally, we should stress that the burning of woody biomass produces emissions that are part of the biogenic carbon cycle, unlike the burning of fossil fuels, which releases the CO₂ that has been trapped in the ground for millions of years. Other greenhouse gases, such as sulfur dioxide (SO₂), are also emitted, which additionally contributes to air pollution. In other words, the burning of fossil fuels increases the level of carbon in the atmosphere-biosphere system when the burning of woody biomass takes place within that system. If the carbon stocks stored in forests remain at the same level, the levels of CO₂ in the atmosphere due to forestry practices do not increase. Therefore, claiming that burning wood emits more CO₂ into the atmosphere than coal, because we have to burn more wood to achieve the same level of energy, is a serious misunderstanding.

Long-distance transportation of woody biomass and CO₂ emissions

It might appear that the importing of wood pellets across the Atlantic, from North America into Europe, negates the climate benefits gained from the burning of woody biomass for reasons related to its transportation. However, research shows that the energy produced from fossil fuels in the biomass supply chain is generally low compared with the content of energy in wood products even during international transport. Transporting wood pellets between North America and Europe increases supply chain emissions by 5 g CO₂/MJ. To put this into perspective, contribution to CO₂ emissions in the chain of coal supply and combustion are about 115 g CO₂/MJ. Transporting wood pellets from the United States to Europe, therefore, does not nullify the climate benefits achieved by the

replacement of fossil fuels with biomass from managed forests.

Summary

So, is the burning of woody biomass climate friendly? The answer is: it depends. Mainly on whether the biomass is produced in a sustainable way and used efficiently, which is extremely important for keeping forest ecosystems in healthy condition. The literature clearly shows that efficient use of woody biomass for energy production can help mitigate the climate change which is considered the most serious environmental challenge facing the world in the 21st century.

The main added value that bioenergy offers in mitigating climate change will involve a gradual shift away from fossil fuels and other emission-intensive products to alternative feedstocks. Wood, which is a renewable material sourced from plantations and managed forests, will help us achieve this goal.

Woody biomass may be an important solution that will help Poland increase energy security while implementing the EU climate policy targets. Since forests make up one-third of the country's land area and the wood industry is booming, sustainable forest management and the production of woody biomass may be part of a suit of scalable solutions allowing the achievement of climate neutrality in the future. Bioenergy has the potential to fill gaps in both the heating sector and the electricity sector, where multiple woody biomass biopower systems distributed across the country could supplement in an important and sustainable way the energy mix, which by necessity will be largely reliant on intermittent renewable sources.

We must also remember that burning good quality wood, which may be a side effect of poorly constructed mechanisms for supporting renewable energy sources, is not an optimal solution either for the forest sector, or for forest ecosystems, or for the national economy. ■

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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, Koźienice, Jaworzno, and Turów). Therefore, it is only natural that we should ask what will take the place of all these decommissioned 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



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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 m², such a power station would have to cover an area of 7 km². 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

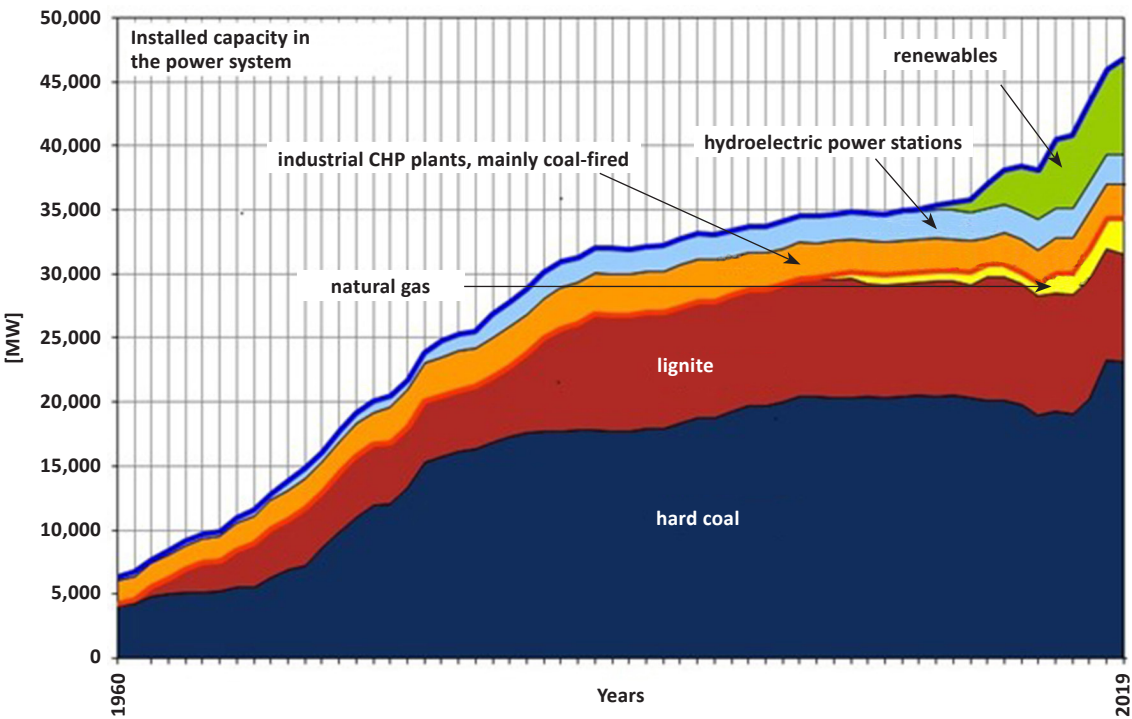


Fig. 1
Development of capacities in the National Power System by fuel types

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.

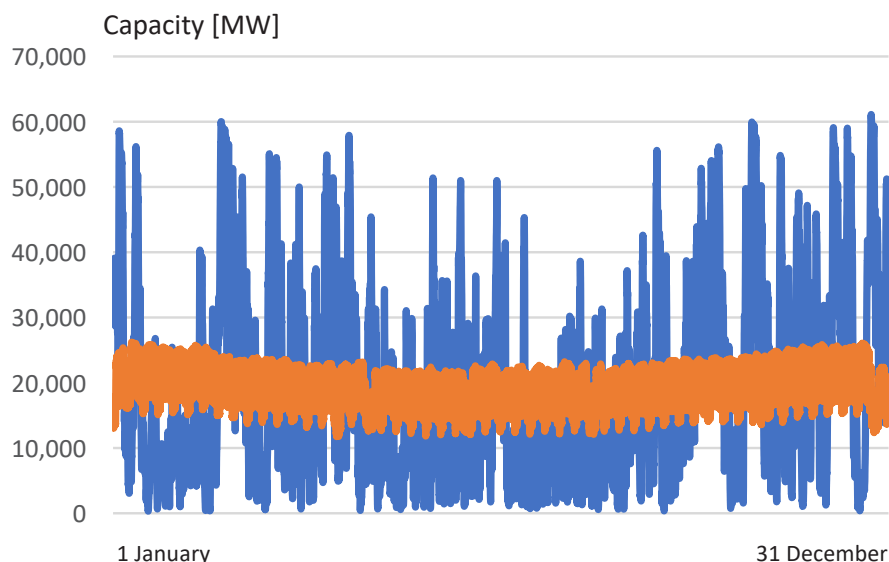
This is the future. Today, however, power plants powered by fossil fuels, primarily coal and natural gas, play the role of sources responsible for balancing out the demand for electricity and its supply, and this situation will continue at least for the next 20 years. For reasons related to the decommissioning 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 CO₂ emissions for climate change-related reasons.

But this situation has now changed. Generation capacities must be renewed as quickly as possible, while CO₂ 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 CO₂. 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



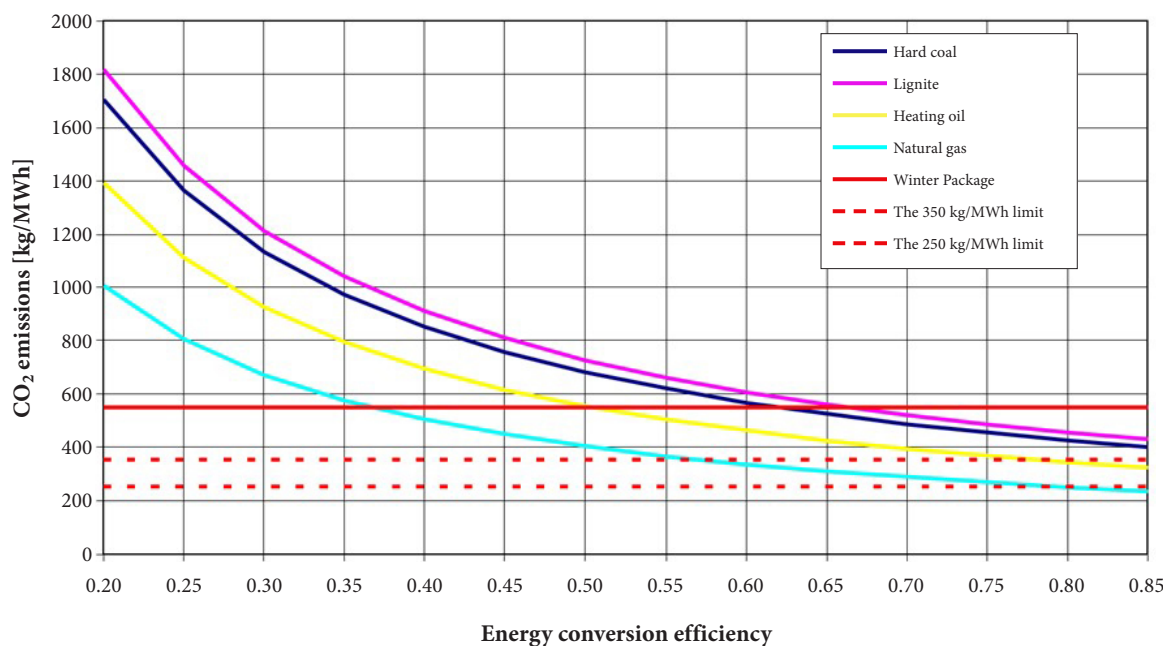


Fig. 3
Specific CO₂ emissions in relation to the amount of energy generated for typical fossil fuels as a function of energy conversion efficiency. The red line (the Winter Package) marks the 550 kg/MWh threshold above which pursuant to the EU law no public aid will be available from mid-2025

atom for every four atoms of hydrogen. The product of its combustion is a mixture of water vapor and CO₂. 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 CO₂ emissions of about 800 kg/MWh. The efficiency of a similar gas-fired unit is about 60%, and the CO₂ 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 CO₂ 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 CO₂.

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).

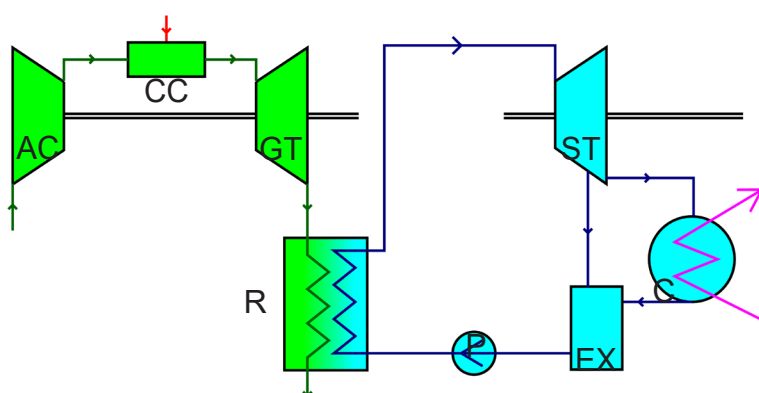


Fig. 5

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 (Schoppsdorf, 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 CO₂ 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. ■

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HARNESSING HYDROGEN



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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



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 hydro-

gen 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 = $41.86 \cdot 10^9$ 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.

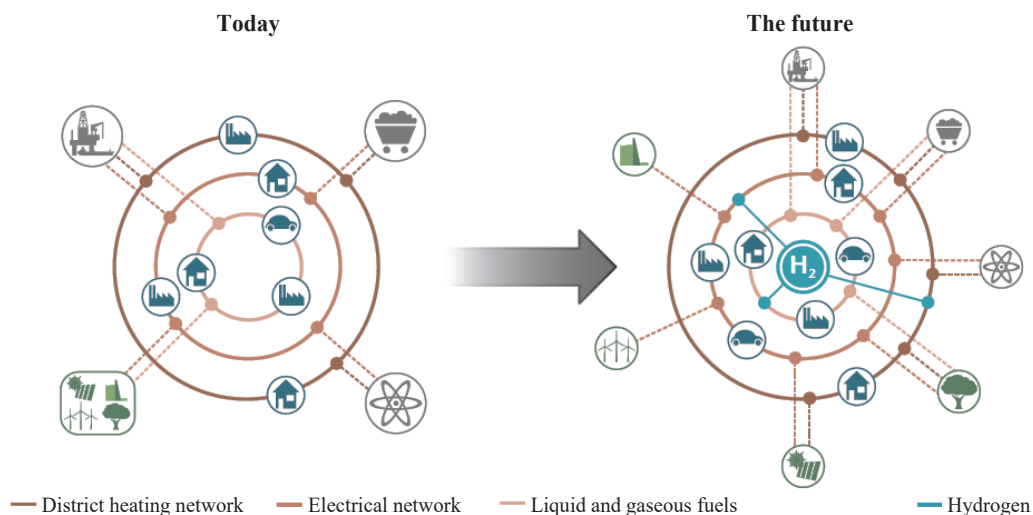
Nowadays, there is a widespread conviction that hydrogen has an important role to play in the energy transformation. This has been confirmed by many studies, analyses and programs developed in many countries. According to the scenario presented in the publication *Hydrogen Scaling Up: A Sustainable Pathway 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 $\cong$ 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)



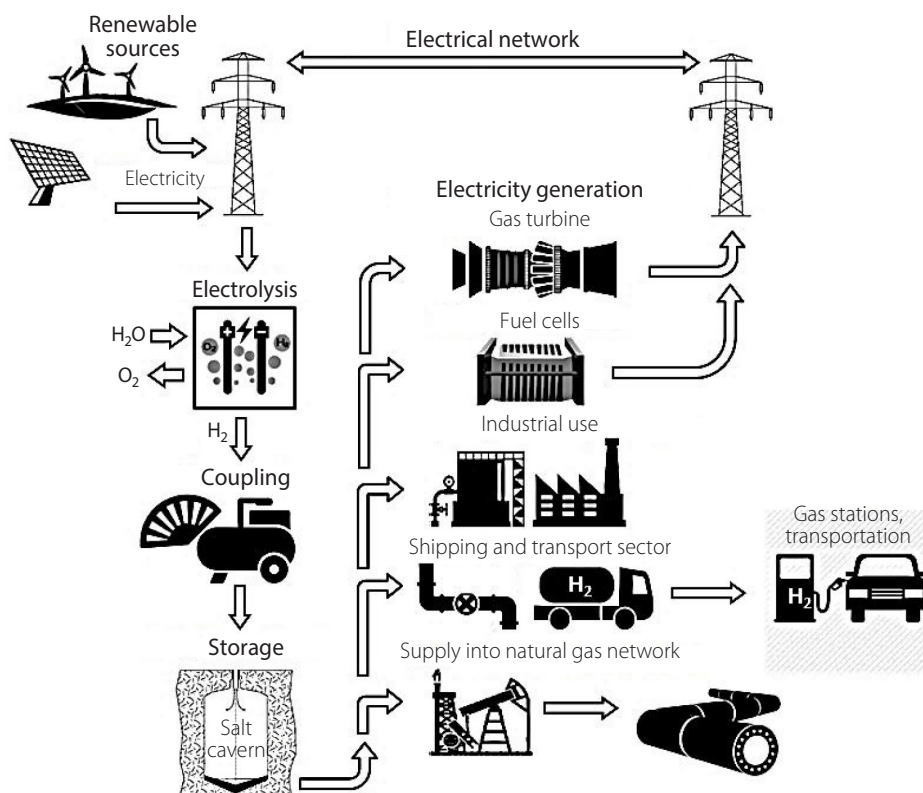


Fig. 2
Modules of the hydrogen
economy (after Chmielniak
& Chmielniak 2020)

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 re-

forming (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 $2500^\circ C$), 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 H₂, rising to \$1.5/kg H₂ after carbon capture. The corresponding prices for the EU are \$1.7/kg H₂ and \$2.35/kg H₂.

For China, the level can be assumed at \$1.75/kg H₂ and \$2.4/kg H₂, whereas in the case of Russia and the Middle East, prices are comparable to those in the US. Investment costs are within \$500–900/kWh₂ for systems without CCUS and \$900–1600/kWh₂ 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 m³ (without CO₂ 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 H₂. Data from the Chinese and US markets fall within \$1.1–1.34/kg H₂ without and \$1.47–1.63/kg H₂ with CO₂ sequestration. According to Polish analyses carried out for various coal gasification installations, the cost without CO₂ sequestration is 5.5–6.5 PLN/kg H₂. This is comparable with steam reforming at a gas price in the range of 930–1100 PLN/1000 m³.

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



ALEXANDER KIRCH/SHUTTERSTOCK.COM

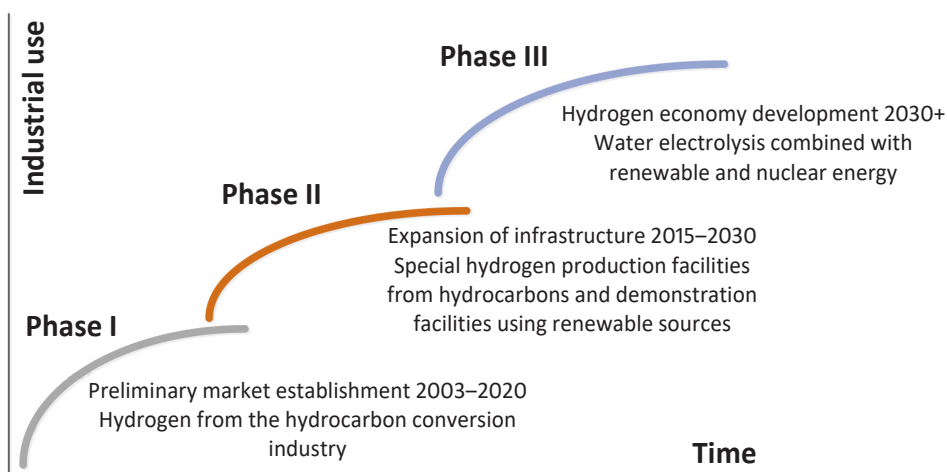


Fig. 3
Possible scenarios
of hydrogen economy
development
(after Ściążko et al. 2018)

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 H₂ in Europe by electrolysis powered by electricity from the grid (with emission cost of \$40/t CO₂), or \$2.87/kg H₂ 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 CO₂. 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 CO₂/kg H₂, natural gas reforming emits about 9 kg CO₂/kg H₂). 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 CO₂/kg H₂, natural gas reforming emits about 1 kg CO₂/kg H₂ – 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 CO₂/kg H₂, for coal-fired generation, about 40 kg CO₂/kg H₂).

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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NUCLEAR POWER: MYTHS VS. REALITIES

Nuclear power was one of the factors underpinning the post-war success of the Euro-Atlantic region. The world is now in great need of a similar step forward

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The history of nuclear power starts at the end of World War II. The speed and momentum with which the liberated portion of Europe was rebuilt was astounding. Nowadays there is certainly inspiration to be drawn from those models, including from the first words of the Treaty establishing the European Atomic Energy Community:

RECOGNISING that nuclear energy represents an essential resource for the development and invigoration of industry and will permit the advancement of the cause of peace, (...) the HIGH CONTRACTING PARTIES establish among themselves a EUROPEAN ATOMIC ENERGY COMMUNITY (EURATOM).

The fight against the COVID-19 pandemic has coincided with global processes related to demographic changes, technological advancements, climate threats as well as the growing position of China and its rivalry with the weakened and alienated United States. Europe and the United States are no longer bound

by a strong alliance. Today's Europe seeks to strike a balance between China and the United States and accepts Russia having a considerable influence over the European energy sector. Emerging economies have growing aspirations, and their rivalry with the most powerful countries is also noticed in Europe. Arguably, the desire to overcome the pandemic may render the upcoming changes turbulent, and key decisions will be made based not only on facts but also on myths. Both facts and myths can be found in the history of nuclear power.

Energy

$E = mc^2$, the iconic equation of nuclear energy, suggests that nuclear reactors make it possible to transform mass into energy and thereby, taking into account the efficiency of thermodynamic cycles, to obtain enough joules of heat from one kilogram of matter to generate more than 8 TWh of electricity – as much as a 1 GW power plant can generate in a year. However, a kilogram of matter will “disappear” from both a nuclear power plant and a coal-fired power station generating the same amount of power. In doing so, however, the coal-fired plant will have to burn several million metric tons of coal delivered by several hundred trains, each with 100 cars filled with 60 metric tons of coal. It is impossible to detect the “disappearance” of this one kilogram of matter after millions of tons of coal are burned in millions of tons of oxygen. A nuclear power plant, in turn, will use about 30 tons



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of fuel, a ton of uranium and plutonium nuclei will be split, and one kilogram of matter will “disappear” from that ton, on balance, because the mass of the nucleus before being split is one tenth of a percent greater than the combined masses of the fission products. This amount is measurable but it is insignificantly small and has no impact on the design of reactors.

Here, it should be explained that the energy released by nuclear fission is well-described by electrostatic repulsion between the two smaller nuclei that arise from splitting the larger nucleus. The high-speed nuclei are then slowed down inside matter, chiefly through interactions with electrons, and their kinetic energy is transformed into heat. Many important details of nuclear fission are described by quantum physics, which explains why a few kinds of atomic nuclei, such as uranium-235 and plutonium-239, often split into two smaller nuclei after capturing a neutron, and why this process releases two or three neutrons that can sustain a chain reaction of atomic fission. A landmark moment for the energy sector came when it was demonstrated that it is possible to regulate the number of fissions per unit of time, which means controlling the power of the reactor, by slowing down neutrons and capturing them with the help of non-fissionable isotopes (the amount of these present in the reactor core is an adjustable parameter).

The formula $E = mc^2$ could be therefore described as a founding myth that not only placed nuclear power within the “relativistic realm” of mass-energy equivalence and sparked off more myths, but also

underscored the enormous density of energy in the reactor fuel.

Safety

Debates on nuclear power always include considerations on the risks posed by spent fuel. As we have noted above, the mass of such fuel is small compared to the amount of the energy generated, but it takes several hundred thousand years for its radiotoxicity to fall to the level of that of uranium ore – a fact that fosters the myth that storing spent fuel poses an insurmountable problem. However, only “fresh” spent fuel poses a threat in and of itself. It must be stored in durable, cooled containers because it produces significant decay heat and is highly chemically active. Nuclear facilities usually store spent fuel in on-site pools at least for the first 10 years. As time passes, radioactive decay becomes less intensive and small enough for well-constructed storage casks. After several hundred years, the spent fuel will no longer contain mobile radioactive isotopes such as cesium-137, which has a half-life of 30 years. After a few thousand years, in turn, there is no risk of mobile radioactive isotopes being released into the environment, and leaks in the casks caused by mistake or by accident will not lead to contamination at a distance of more than a few kilometers. This has been shown by studies of the remains of the natural nuclear reactor at Oklo (Gabon, Central Africa), which spontaneously came into existence two billion years ago in deposits of uranium ore that were



Nuclear power plant in
Ulju-gun, South Korea,
May 2020

flooded with water. Consequently, what poses a challenge is the construction of safe storage sites that will last several thousand years and in the longer run only offer protection against the intentional use of “old” spent fuel for malicious purposes.

The Three Mile Island, Chernobyl, and Fukushima disasters showed that nuclear power could be dangerous, but the steps taken following those disasters improved its safety. In the disaster that took place at Three Mile Island (in the United States) in 1979, safety procedures failed, the reactor core melted down, but there was no contamination of the environment. After the accident, passive safety systems were introduced and emergency procedures were improved. The disaster that took place in Chernobyl (in the Soviet Union) in 1986, the reactor was destroyed, resulting in numerous casualties and significant environmental contamination. This led to a full-blown revival of the myth about the possibility of a reactor explosion of a magnitude comparable to that of a nuclear bomb. Such a scenario is impossible for many reasons, and this was shown in practice by the disaster in Chernobyl, where an uncontrollable power surge resulted in a chemical explosion that destroyed the reactor core, ruling out any possibility of a nuclear explosion. Analysis of the disaster showed that the reactor design had serious flaws, and emergency procedures permitted the operators to make risky decisions. Currently, reactors with such defects cannot be constructed or used. The disaster that took place at Fukushima (Japan) in 2011 exposed our human helplessness in the face of a major

natural disaster. The powerful Indian Ocean tsunami in 2004 had been a wake-up call for such power plants as Fukushima. For several years, attempts were made to convince Japan to better protect power plants against tsunamis. Unfortunately, however, the recommendations were not put into effect at the time.

There is no doubt that ensuring safety is a task of overriding importance, but we must not mythologize it or let it obscure the assessment of the economic utility of reactors. In the past, numerous attempts were made to implement various technologies, but very few of them made their way into the energy sector. Despite several expensive attempts, high-temperature reactors, sodium-cooled fast reactors, lead-cooled fast reactors, and molten-salt reactors all proved unsuccessful. Modern nuclear power technology allows for the fission of only a few percent of the uranium in the reactor fuel, which is the primary motive driving research into the possibilities of making better use of such fuel. Efforts are being made to design reactors that will be able to reprocess the spent fuel from existing nuclear power plants into a less radiotoxic material. This is why, despite costly failures, attempts to construct novel reactors continue to be made from time to time. Examples include the ongoing construction of a power plant with two high-temperature reactors in China. China and Russia have demonstration sodium-cooled reactors, and the United States has recently decided to build a test reactor using this technology and start preliminary design work on other solutions. France, in turn, which probably has the most experience in

designing, building, and maintaining sodium-cooled reactors, has recently dropped plans to implement a similar project. It is likewise worth bearing in mind the importance of developing reactor technologies for special applications, such as the construction of nuclear rocket engines, for example in the past in the program Nuclear Engine for Rocket Vehicle Application (NERVA) in United States and currently in the National Strategy for Space Nuclear Power and Propulsion, or the use of small reactors in extremely remote tundra regions in Siberia, and for the purpose of exploring Mars and the Moon.

The market and costs

Since the Fukushima disaster, the only reactors built for power generation purposes have been large light-water nuclear reactors (pressurized water reactors, or PWRs) with generation units of over 1 GW. One exception is India, which is building 700 MW units with heavy-water reactors, but this project has yet to make its way into the global markets. Only a few PWR projects have attracted investors, and

high costs. In turn, the two EPRs being constructed jointly by France and China in the United Kingdom may be closer to success than failure.

Smaller PWRs, with energy units of less than 1 GW, have been driven out of the global market by economies of scale. Such considerations are commonly found for various technologies – for example in the refrigerator market (two small refrigerators are more expensive than one that is twice as large). However, economies of scale have their limitations. In the nuclear power sector, the first of these limitations results from the technological barriers to the production of large and durable vessels for PWRs and, more generally, from the small size of the market of providers of the critical, expensive, and heavy components.

The vessels in which the uranium reactor core is placed are currently so large that they can only be made by several companies in Japan, China, Russia, South Korea, and possibly one in France. The market is shallow and easily influenced, and the prices can be high. In the plans to build several reactors (just like the six reactors being planned in Poland), all the vessels have to be delivered over two or three years, because a typical production line produces a few vessels per year. For this reason, it is almost impossible to optimize the implementation of a small program. If units are built one by one, the last vessel delivered (the sixth vessel in the Polish program) will have to wait even more than a decade to be installed. Alternatively, the power plants could be built concurrently, which is costly in a small program.

For this reason, we can see a clash between economies of scale and the depth of the market of reactor buyers, and winning a contract to build 20 or more large reactors is not easy. In recent years, Russia has achieved success in this area with its VVER-1200 reactor, China will most likely succeed with the Hualong One reactor, and it is evident that India's heavy-water reactor has potential. In turn, the order books for the construction of new AP1000, EPR, and APR-1400 reactors have been empty for many years. Russia and China are efficiently handling the construction of large reactors. In Poland, this has given rise to a myth about the availability of well-proven large reactors, including ones for which there is zero demand.

Korea's APR-1400 reactors went out of the market when the country decided to phase out nuclear power several years ago. The phase-out program is spread over many years and provides for the completion of four reactors, but plans to build more reactors have been halted.

It appears that an opportunity to create a large market of buyers of AP1000 and EPR reactors was missed several years ago. The factors behind this situation included business failures and the strategic decisions made years ago by France and the United States. The Fukushima disaster slowed down the develop-

Ensuring safety is a task of overriding importance, but we must not mythologize it or let it obscure the assessment of the economic utility of reactors.

all of these projects are similar. In turn, the power plants being constructed with such reactors vary greatly in terms of the assessment of their economic utility. For years, we have observed delays and rising construction costs in all nuclear power plant projects, but the construction of four plants and the launch of the first Korean APR-1400 reactor in the United Arab Emirates should be treated as successes for nuclear power. The APR-1400 projects in South Korea and all of the projects with Russia's VVER-1200 and China's Hualong One have been similarly successful. In addition, the construction of four US AP1000 reactors and two French EPRs in China was completed quite efficiently. On the other hand, the abandonment of the construction of two AP1000 reactors at the Virgil C. Summer Nuclear Power Station (in the United States) was a business failure that caused losses of up to \$10 billion. Other failures include the construction of two AP1000 reactors at the Vogtle Electric Generating Plant in the United States (with costs exceeding \$25 billion) and the construction of one French EPR in Finland and another one in France, which were characterized by delays of many years and absurdly

ment of the nuclear power sector. In 2013, however, China and Russia already showed signs of recovery, and France attempted to win new contracts. In order to consolidate its position, it invited China to take up one-third of the shares in the planned construction of two EPRs at the Hinkley Point C nuclear power station (in the United Kingdom). At the time, China was building two EPRs (which are already in operation), and the new contract in fact gave a green light to the development of the Hualong One reactor, which is modeled on French reactors. France and China are now bound together by joint investments in the UK, which makes it difficult to create a market of EPR buyers because this is not in the interest of China, which has its Hualong One reactor.

The construction of four AP1000 reactors in China was a flagship project in the vision of close collaboration between the United States and China. The reactors are already operational, but a coolant pump failure resulted in one of them being shut for almost the whole of 2019, and there are many signs that these pumps remain a weak point of the AP1000 project. The Americans, just like the French, have sought China's support. In 2013, the conclusion of a deal paving the way for China to become the global supplier for the AP1000 reactors was hailed as a success. Simultaneously, China obtained the right to build clones of the AP1000, dubbed the China Advanced Passive 1000 (abbreviated as CAP1000), and their scaled-up versions named CAP1400. History has shown, however, that construction of an AP1000 reactor using Chinese components has not been launched anywhere in the world, and the Hualong One reactor is supplanting clones of the AP1000 in China's plans.

With the COVID-19 pandemic intensifying the rivalry between China and the United States, it is now evident that the decisions made years ago are making it difficult to create a market of AP1000 buyers because no clones of these reactors are being built in China and the country will not be a global supplier of their components.

Another barrier to the expansion of large reactors is posed by the fact that the size of the buildings designed to accommodate them means that they are erected gradually as the construction of such reactors progresses. This means that many tasks must be carried out one after another, which extends the time needed to complete the project and results in ever-growing delays. The division of the project into parallel paths with small and medium-sized companies participating is likewise rendered more difficult.

These shortcomings might lead us to the conclusion that it is a good idea to build smaller reactors. However, Westinghouse Electric Company's experience with the AP600 and AP1000 projects shows that such solutions are not popular. Westinghouse initially designed the AP600 and completed the licensing pro-

cess in the United States, but no investor was found for the reactor. The company noticed interest in larger reactors and quickly developed the AP1000, essentially by simply scaling up the AP600, and quickly found buyers for the design. Shortly before the Fukushima disaster, there appeared to be a chance for the construction of up to 50 reactors in China, the United States, India, and the UK. Currently, however, competitors are taking over the foreign market, and the United States will most certainly not launch the construction of a new AP1000 in the wake of the August 2020 decision to sell off the components for the two AP1000s in the abandoned Virgil C. Summer project.

It is doubtful that the world will ever return to smaller reactors such as the AP600. Although Poland's nuclear program might consider replacing the planned six 1200 MW units with 12 smaller units, the idea of building 120 power units of 60 MW each in Poland will always be unreasonable. Economies of scale on this level of power output (20 times smaller) argue strongly in favor of large reactors, and good ideas are needed if mass-produced small reactors are to become competitive. One of these ideas involves

It is doubtful that the world will ever return to smaller reactors such as the AP600, though Poland's nuclear program might consider replacing the planned six 1200 MW units with 12 smaller units.

building large nuclear units consisting of a dozen or so modules, with each module powered by its own small reactor, but with many systems shared by at least several modules. The most advanced design in this category has been created by the company NuScale Power in the United States. The first 924 MW unit consisting of 12 modules powered by integrated small PWRs is expected to be launched in Idaho in 2030. The US regulator has already approved the placement of these modules within a single building, which was possible because each NuScale reactor has an individual containment vessel. It is evident that this design has a lot of potential, especially thanks to its dry cooling system, which uses only a few percent of the water drawn by the cooling towers. Several years from now, at the latest, we will know if NuScale is just yet another nuclear power myth or a project that will attract investors with billions of dollars at their disposal. Either it will create a true alternative to the Russian and Chinese reactors, or it will join the mythical family of proven large PWRs that no country except for Poland now wants to build. ■

RENEWABLE ENERGY SOURCES AS PART OF A GREEN DEAL

Renewable energy aims at reducing greenhouse emissions, supplying the growing demand for electricity, and diminishing consumption of fossil fuels – these are the basic elements of the New Green Deal, heading towards carbon neutrality. However, renewables have negative impacts on the electricity network's operation, leading to reduced power system stability.



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The EU's list of renewable energy sources includes energy generated by (i) on- and off-shore wind turbines, (ii) solar energy, mainly from photovoltaic (PV) panels, (iii) biomass and biogas, and (iv) wave and tide power. Currently, solar and wind power are the primary sources of renewable energy. They have similar technical characteristics: the energy is dispersed and not always available. The use of biogas can be beneficial to agriculture, utilizing its waste. Biomass as a renewable resource is controversial as it leads to deforestation.

The minimum shares of renewables in the European energy production set by the European Commission stimulate new investments despite high costs

and limited dispatch ability. The current limit of renewables for 2030 is 32%, possibly increasing to 50% towards 2050.

The main drawback of renewables from the continuity of supply point of view is their limited availability. Onshore wind farms' operation with rated power does not exceed 2,300 hours annually, while offshore wind farms' electricity production time amounts to 3,500 hours at the Baltic Sea and 4,500 hours in the North Sea. Such periods of wind farm operation are relatively short, as compared with the need for 8760 hours of continuous electricity supply.

The maximum theoretical efficiency of a wind turbine does not exceed 59%, and it strongly depends on the area circled by its propellers. In practice, the efficiency of wind turbines is about 40–45%. Advancements in wind turbine technology have led to larger towers, reaching 220m for 9–12 MW plants. Onshore wind towers are significantly smaller, generating 3 MW at over 100m with blade lengths between 60 m and 70 m. Most turbines in Poland are low-power, with the size of their towers not exceeding 40–50 m.

Reference prices for energy from renewable sources in 2020, in PLN per MWh

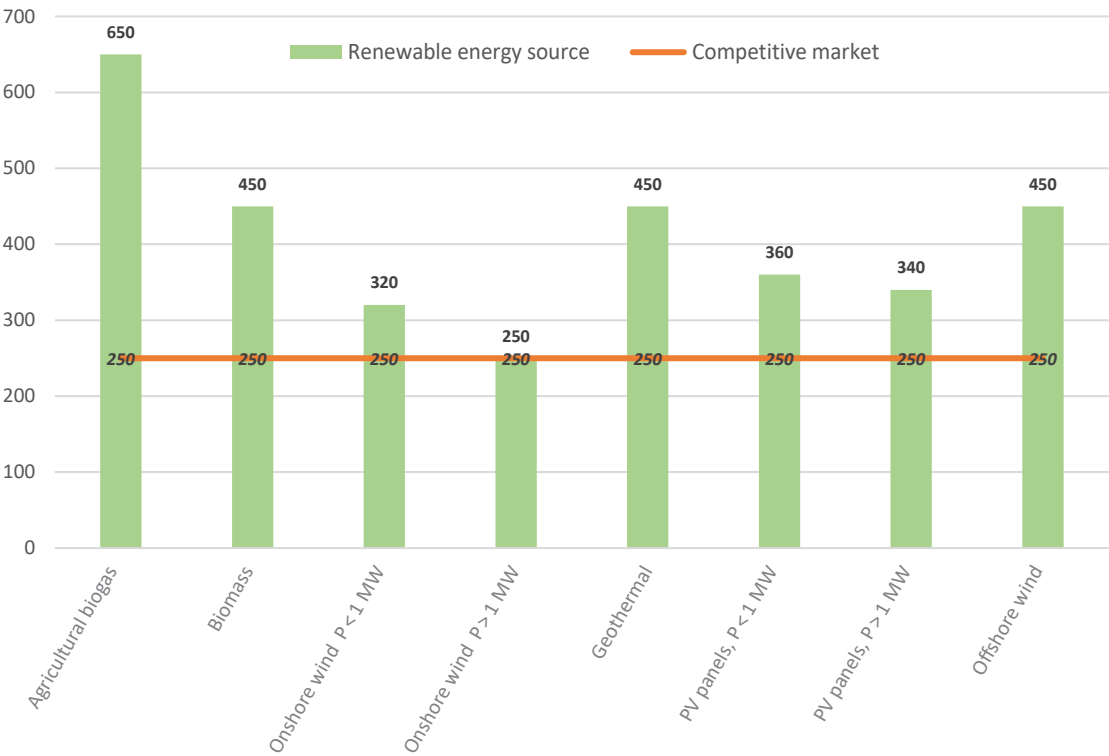


Fig. 1
Reference prices for
renewable energy auctions

They are mainly imported, second-hand, from Western Europe, much like used cars.

Solar-powered electricity generation is dominated by mono- and polycrystalline PV panels. Black monocrystalline cells can reach an efficiency of up to 20% with the maximum theoretical value of about 30%, while distinctive blue polycrystalline panels have smaller efficiency, amounting to 15%. In Central Europe, effective operation time with the rated power by PV panels does not exceed 1000 hours per year. Solar energy in the region is around 1 kWh/m², which means large power PV installations require significant land area. In addition, this technology is highly sensitive to cloud levels, with PV electricity generation being low in the autumn and winter months.

While wind farms are almost entirely commercial installations due to their size, PV panels can also be commercial plants when their rated powers exceed 50 kW, but there are also small household installations operating in the prosumer model (see below).

Renewable energy in Poland

The development of renewable energy sources (RES) in Poland is dependent on subsidies. From 2005 to 2015, the green certificates issued for renewable energy production provided additional income for RES

producers, which could also sell all electricity produced to the distribution companies at competitive market prices. Such double revenue, reaching 200% and more of market prices, allows for very profitable production. Significant profits from RES businesses attracted new investments leading to a boom in RES construction projects and consequently a rapid increase in subsidies, which place a significant burden on consumers, amounting to more than 5 billion PLN per year.

Since 2015, the new subsidy system has been in operation, based on auctions conducted with the use of reference prices. A renewable energy producer can obtain a 15-year contract with auction prices usually well over market prices (Figure 1). The RES subsidies have been increasing year by year to reach the mounting targets of the European Union. Estimates indicate that Poland's average annual direct subsidies for renewable energy sources will amount to 8-10 billion PLN (approx. €1.75-2 billion). The total costs of renewable energy include direct subsidies and costs of maintaining power reserves, which provide electricity when renewable sources are unavailable because there is no wind or sunshine.

Fully dispatchable electricity production plants include only three conventional technologies: (i) coal power plants, (ii) gas-fired power installations, and

(iii) nuclear power generation. However, increasing renewable production causes conventional power plants, on which energy security depends, to produce less and less energy, mainly serving as a power reserve for renewables.

Hence, reduced output of conventional power plants and lower sales revenues lead to new subsidies for dispatchable installations, including coal power stations. These new subsidies introduced in 2015 are called the *capacity market* and will operate in Poland until 2030, charging approximately €1.2 billion per year to energy consumers (2021). Furthermore, contracts established at the capacity market will remain in effect until the early 2040s. Therefore, the capacity market is an indirect subsidy for renewable energy paid to conventional power plants for reserving RES production.

Prosumer programs

Another way to increase production from renewables involves prosumer programs. These allow anyone who owns installations of PV panels to enter subsi-

energy cost-savings while professional producers gain from large-scale electricity sales at favorable prices compared to the competitive market.

Since PV panels can generate power only during daylight, prosumers still have to be connected to electrical networks allowing for energy purchase from outside sources for the rest of the day, especially in winter. Furthermore, the energy produced during daylight has to be stored for evening hours. Energy storage is very expensive. Therefore, a prosumer receives yet another subsidy covering the additional costs of energy storage.

Such a subsidy is called *net-metering*, allowing for the injection of prosumers' energy into the power grid during energy excess from PV panels in daylight and its withdrawal during evenings and nights. Conventional power plants are employed to perform the function of electricity storage. Thus, such installations reduce production when prosumers have energy overplus and increase generation when they withdraw electricity from the grid. The fee paid by prosumers for such storage equals 20% of the electrical energy fed into power networks.

Despite the numerous subsidies, prosumer programs are not cost-effective, and professional economic calculations using the discounted flow method show prosumer losses of 30 percent compared to the case when they solely purchased electricity from the grid. However, the government supports prosumer programs as they provide more RES electricity production. In addition, a certain role in the decision to become a prosumer may be played by a desire to be a part of fashionable trends, including a wish not to stand out among neighbors who have already purchased such RES installations.

It is estimated that the average annual direct subsidies for renewable energy sources in Poland will amount to 8–10 billion PLN.

dy schemes. Prospective prosumers should also have the ability to finance PV installations. These subsidy schemes target the wealthiest groups of energy consumers, owners of houses, able to participate in upfront costs amounting to about 20,000–30,000 PLN (approx. €4,000–7,000).

The main difference between a renewable energy producer and a prosumer is that a professional producer must have an appropriate license to generate electricity and operate as a registered business entity, as a VAT payer. The producer's income comes from the electricity sold at preferential prices obtained in renewable energy auctions (Figure 1).

A prosumer, in turn, is a person who produces energy for his or her use and has received appropriate subsidies, such as Poland's "My Electricity" or "Clean Air" schemes. These subsidies amount to around 8,000 PLN (€1,750), with an average installation cost of 25,000 PLN (€5,500). Thus, prosumers profit from

Impact on the National Power System

The major renewable technologies such as wind and solar power depend on weather conditions, so they cannot be included in power balances that determine energy security. Although RES cannot be dispatched on-demand, wind farms and PV panels are easily controlled power sources. PV and wind power plants have output inverters operating in a pulse modulation mode, capable of shaping the frequency, amplitude, and phase of electric currents fed into the grid. Additionally, wind turbines can change the pitch angle of propellers, thus regulating the amount of energy taken from the wind.

While large wind installations are equipped with appropriate inverter controllers, prosumers' PV panel inverters generally have inadequate controllers, usually adapted from electric drives due to their low

costs. In addition, the inverter controllers of prosumers' PV plants are not designed to work with power systems that experience continuous voltage fluctuations. As a result, when larger fluctuations happen, which occur frequently, PV installation inverters shut down their operation, cutting off power supply from these plants. This can lead to serious failures of power systems.

Seeking to cope with such uncontrolled operation of prosumers' PV installations, grid operators have proposed new rules for response to fluctuations in frequency and voltage levels. However, these new operation rules for prosumers' inverters are still waiting at the Polish Ministry of the Climate and Environment office to be introduced as legal regulations. Moreover, their introduction is being slowed down because of the expected significant increase in the cost of inverters for prosumers' PV plants, which would necessitate more subsidies.

Another problem is that renewable energy installations lack natural inertia, an element of stabilization in power system operation. In the case of energy excess in the conventional power system, e.g., a line outage, steam turbine generators weighing hundreds of tons can increase their rotational speed, converting the electricity surplus into kinetic energy of the rotating masses. Conversely, conventional generators slow down their rotation when there is an energy shortage, transferring energy stored in kinetic energy of rotation back into the power system.

The ability to vary the generators' speed is the main advantage of conventional power stations when stabilizing electric grid operation. Unfortunately, renewable sources do not possess inertia ability, and during fluctuations in power systems, they quickly shut down their operation, causing failures in the electric energy supply. The rising installed capacity of renewable sources impels transmission grid operators to search for new inertia sources in power systems – for instance, proposing to employ the generators and steam turbines in old power plants after their coal furnaces are decommissioned, as rotating masses operating in the motor mode. However, this is a highly debatable solution.

Blackout in East England

On 9 August 2019, the power system in the East of England experienced a major failure, leaving more than 1,152,000 consumers disconnected from the grid and without power – including vulnerable consumers such as Newcastle Airport and Ipswich Hospital. Thousands of travelers were trapped in rail carriages, many in underground tunnels. Rail operation was not restored until the following day. The failure's nature and its speed came as a surprise to the grid operators.

Something that should never have happened has become a real threat.

The failure was initiated by spontaneous shutdowns of distributed generation, mainly small PV panels. At the first stage, 500 MW of PV installations disconnected themselves in response to voltage fluctuations in the power grid. Afterward, the Hornsea One offshore wind power plant reduced its power from 799 MW to 62 MW. In the subsequent failure step, the gas-fired power plant in Little Barford (STC1 – 244 MW) shut down its operation because of excessive steam pressure, and then, anticipating that the safety mechanisms would operate, the dispatchers also disconnected the second steam turbine (GT1B – 187 MW). The resulting rapid drop in voltages across electric networks caused spontaneous and uncontrolled shutdowns of subsequent renewable installations, mostly PV panels, leading to a serious outage in the power supply.

The installed capacity of renewable sources, including PV panels, increases every year, resulting in a higher probability of system failures. Additionally, the power industry's energy transformation and closure of conventional power plants lead to diminishing inertia with stabilizing features. Little progress has been noted in artificial inertia research, leaving an open question of whether it is possible to replace natural inertia.

New Green Deal

The New Green Deal is the EU's political program leading to carbon neutrality, which means the ability to balance emission of greenhouse gases with its absorption, including the forests' ability to capture carbon dioxide. Initially, the green deal was expected to be achieved only by renewable energy sources. However, since this has been proven impossible, as RES cannot operate on demand, intensive research is being carried out to develop large-scale energy storage in the form of so-called *green hydrogen* produced from renewable energy. However, more than a century of experience with hydrogen in the energy industry shows that this gas easily escapes through the walls of storage tanks and pipelines, burning explosively. Thus, the hope of achieving carbon neutrality through the widespread implementation of hydrogen in power generation seems to be wishful thinking.

Renewable energy is an important part of energy transformation; however, it is expensive and requires power reserves provided by conventional power generation. Increasing costs of renewables lead to a new *modus operandi* in power systems, in which electricity is a luxury good with limited access. This new way of functioning power systems will be a big challenge for the economy and societies. ■

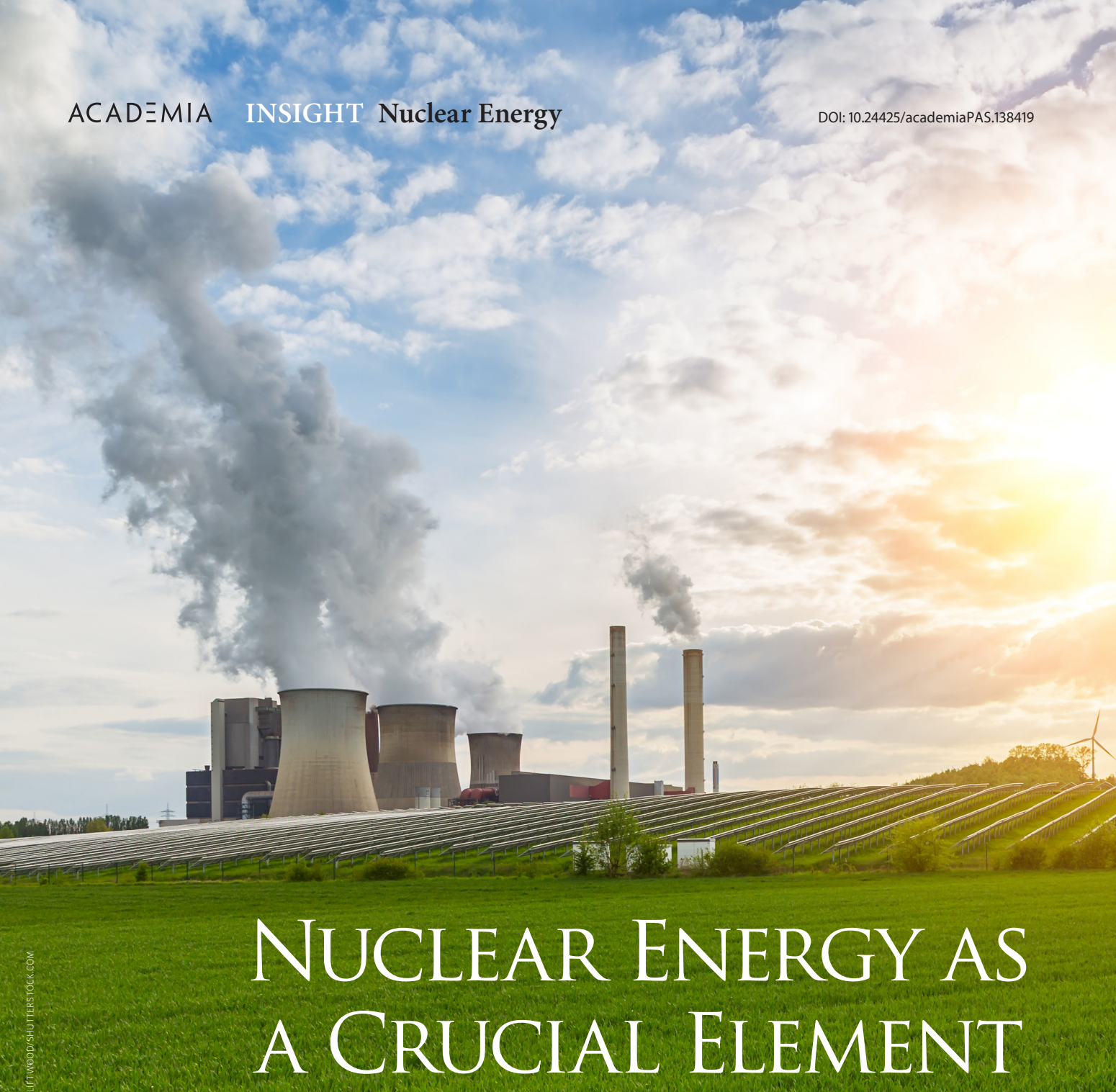
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NUCLEAR ENERGY AS A CRUCIAL ELEMENT

IN POLAND'S POWER SYSTEM

In view of the need to transform the Polish energy sector from a coal-based to a low-emissions industry, can wind and solar power alone provide enough of an alternative?



Andrzej Strupczewski

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Poland needs to build nuclear power plants – at reasonable cost – in order to meet the growing demand for electricity. This conclusion is the result of a number of circumstances:

- Further economic development of the country will require an ever-larger supply of electric power, whose consumption in Poland is currently on one of the lowest levels in the EU.

- We have to meet commitments to reduce greenhouse gas emissions, primarily carbon dioxide.
- Fossil fuel resources are growing depleted, and in Poland in particular, operable coal reserves will last for 20–30 years.
- The acquisition costs and prices of fossil fuels are rising:
 - coal mining volumes are declining year after year, with costs rising,
 - Polish coal is already now uncompetitive, due to high mining and transportation costs,
 - imports of hard coal, mainly from Russia, are on the rise.
- Poland's coal-fired power plants are already outdated and will be decommissioned in the next 10–20 years.
- Air pollution caused by coal combustion results in damaged health and shorter lives for Poles.
- Stricter EU emission standards for sulfur dioxide, nitrogen oxides and particulate matter, as well as mercury, all necessitate either costly upgrades or the decommissioning of old coal-fired power plants.
- Nuclear power plants produce electricity more cheaply than other low-carbon sources.

The main consideration, however, is that given the prospect of introducing large amounts of power generated from unstable and uncontrollable renewable energy sources, i.e. wind and solar, it is necessary to have nuclear power plants that provide reliable electricity generation 24 hours a day, seven days a week.

Electricity is the most perishable commodity; it has to be generated exactly when it is needed. The capacity and technical condition of centrally dispatched generation units are of primary importance for ensuring safe and stable operation of the system. Meanwhile, a significant number of such generation units, with a total capacity of about 10 GW, have been operating in the Polish National Electric Power System (NEPS) for over 40 years, with operating time in excess of 200,000 hours per unit. Therefore, a significant number of them should be expected to be withdrawn from service or slated for modernization in the coming years.

At the same time, the capacity of distributed generation sources, especially those harnessing renewable energy sources, whose operation (power output) is contingent upon meteorological conditions, continues to grow.

Moreover, when planning the future of the national power system, we cannot assume the maximum, or even the average level of power from renewable sources. Being able to ensure that the needs of Polish consumers are met will require us to have sources that guarantee stable operation and regulatable power out-



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put, so that consumers always receive the electricity they need irrespective of weather fluctuations.

Greenhouse effect

Over the past 100 years, the average temperature on the Earth's surface has risen by nearly 0.8°C. The Intergovernmental Panel on Climate Change (IPCC) states that the temperature is rising due to the concentration of greenhouse gases in the atmosphere. The IPCC recommends reducing or eliminating such emissions, and the governments of almost all countries agree with this position.

The European Parliament passed a resolution stating that all available technologies – including nuclear power – are needed in the fight against climate change, which has been described as a global emergency. The European Parliament believes that nuclear energy can play an important role in achieving climate goals because it produces no greenhouse gas emissions and can provide a significant proportion of Europe's electricity production. The EU aims to cut greenhouse gas emissions by 80–95 percent of 1990's levels by 2050.

Poland intends to reshape its electricity system to achieve climate neutrality by 2049. This system will be based on two pillars. The first will be nuclear power, with six reactors of total power 6–9 GW, to be operational starting in 2033. The second pillar will be renewable energy sources, with offshore wind energy occupying a key place in this area.

Would it be a good solution to reduce power generation?

Such a route was proposed to us by anti-nuclear organizations during cross-border consultations on the Polish nuclear power program in 2014–2015. But it turns out that in the countries where such organizations are active, household electricity consumption *per capita* is much higher than in Poland. The figures are 6290 kWh/person/year in Germany, 8006 in Austria, 5720 in Denmark, and 4330 in Poland.

The level of electricity consumption per person in households in Poland is one of the lowest in the EU: only Romania is behind us, whereas in all the other 24 EU countries people have more electricity at their disposal than we do. This is visible in the data from Eurostat, a statistics agency whose work is certainly not guided by any sympathy or dislike for particular countries.

When we consider energy consumption not just for households, but the country as a whole (including industry, transport, etc.), we find that in the group of countries with high total national electricity consumption, the life expectancy of their population ranges from 81.8 years in Finland (14,732 kWh/person/year) to 83 years in Switzerland (7091 kWh/person/year). In contrast, in European countries with low electricity

consumption, life expectancy ranges from 74.3 years in Lithuania (3468 kWh/person/year) to 75 years in Romania (2222 kWh/person/year). In Poland, the average life expectancy is 77.5 years. This suggests that in order to bring the life expectancy of Poles up to the level of the leading EU countries – or even up to the EU average – we need to significantly increase the availability of electric power in Poland.

Can we reduce the energy intensity of our industry?

Electricity consumption per unit of Gross National Income in Poland, as measured in terms of the purchasing power standard (PPS, an artificial currency unit, whereby theoretically one PPS can buy the same amount of goods and services in every country), is not far from the EU average. It is smaller than in the Czech Republic, Austria, Belgium, France, and Slovakia, and slightly larger than in Germany and the Netherlands. Thus, the significant air pollution found over Poland cannot be attributed to low industrial efficiency – rather, the main reason for high carbon dioxide emissions is the use of coal as the main fuel for power plants and households.

Carbon footprints for organic fuels and low-carbon technologies

The carbon footprint of organic fuels is dominated by emissions produced directly, via the combustion of fuels during power plant operation. In the case of solar and wind power, in contrast, significant indirect emissions must be taken into account, which arise during all stages of the “cradle-to-grave” life cycle – i.e. not only during the construction and operation of the power plant, but also during the extraction of construction materials and fuels, their processing and transport, and during the final decommissioning of the power plant and its waste.

In the case of wind, the main emissions are associated with the production of structural materials and concrete for wind turbine foundations. Although illustrations depict wind turbines as lightweight, open-work structures, due to their low per-unit power, the amounts of steel and concrete required per unit of energy produced are quite large.

Images presented by the wind industry show slender towers shining brightly against the landscape or peeking out through distant mists, beautifully surrounded by white clouds. But a typical 1.5 MW wind turbine operating in the United States has a tower standing 80 m high, a rotor assembly (blades and shaft) that weighs a total of 22 t (metric tons), a nacelle plus generator that weighs 52 t, and reinforced concrete used to build the tower comprising a further 26 t



JAGRA/SHUTTERSTOCK.COM

of reinforcing steel and 190 m³ of concrete. Altogether, 100 t of steel is needed to produce a nominal output of 1.5 MW; when the installed capacity factor of 0.34 (achievable only in extremely favorable locations) is taken into account, the actual average output per year is 0.5 MW. This means 200 t of steel per 1 MW of average output. A nuclear power plant with a 1600 MWe EPR reactor needs 71,000 t of steel and iron, so with a capacity factor of 0.9, 49.3 t of steel per MW of average output per year is needed – just one-quarter of the amount demanded by wind turbines!

An objective comparison of the characteristics of wind and nuclear power plants has been carried out by the Institute for Energy Economics and Rational Energy Use at the University of Stuttgart in Germany, and also by the West Pomeranian University of Technology in Poland. The conclusions drawn from these studies are as follows:

- Carbon dioxide emissions when considering the entire construction and decommissioning cycle are twice as high for wind power as for nuclear power.
- Material requirements relative to the total amount of life-cycle energy generated in a power plant are more than twice as high for wind power as for a nuclear power plant! A surprising result: although a nuclear power plant is considered “huge and heavy,” it requires less than half the weight of materials used for “light” and “environmentally friendly” wind power plants per unit of electricity generated.
- The ratio of the cumulative energy expenditure incurred during the construction phase of a wind farm to the total amount of energy produced over the plant’s lifetime is 4.5 times greater for a wind plant than for a nuclear plant.

- The aluminum demand relative to the total installed capacity of the plant is 75 times greater for a wind plant than for a nuclear plant.

There are more such comparisons, all similarly unfavorable for wind energy. Aluminum is a factor worth bearing in mind, as its production involves significant air pollutant emissions. In Poland years ago, this led to the closure of an aluminum plant in Skawina, as the inhabitants of the city of Kraków could no longer withstand the air pollution. This is a good illustration of the importance of emissions that occur well before a wind power plant even starts operating.

Smog over Krakow,
January 2017

Impact of uranium enrichment on carbon dioxide emissions

Carbon dioxide assessments for the nuclear power industry consider the emissions generated when using the diffusion method to enrich uranium. This technique was invented to produce enriched uranium during WWII and was used for 70 years despite the development of newer and more efficient enrichment methods. However, diffusion enrichment requires very large facilities and a great deal of energy, and there are large greenhouse gas emissions associated with it. The centrifuge method, on the other hand, is much more efficient and its greenhouse gas emissions are about 20 times lower. It has already become widely used and it is expected that in the coming years the old diffusion-based facilities will cease to operate, to be replaced by new enrichment techniques, including the centrifuge method, but also the laser method and others.

As is evident, nuclear power clearly offers the best way to reduce carbon emissions. However, such emissions, while currently in the spotlight, are not the

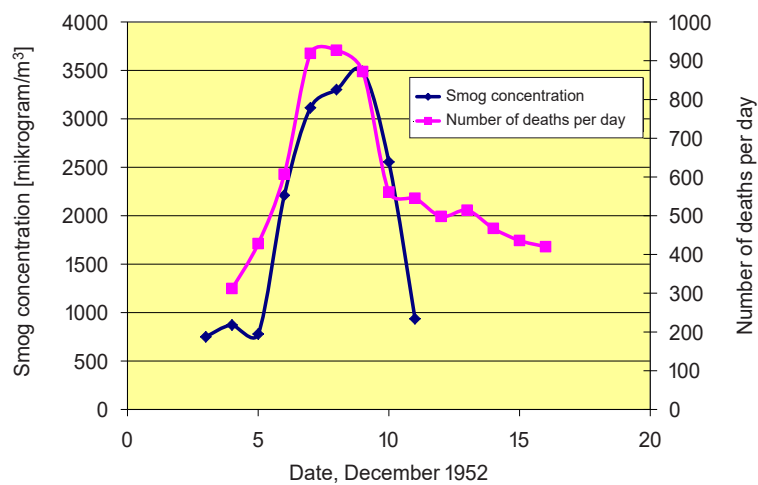


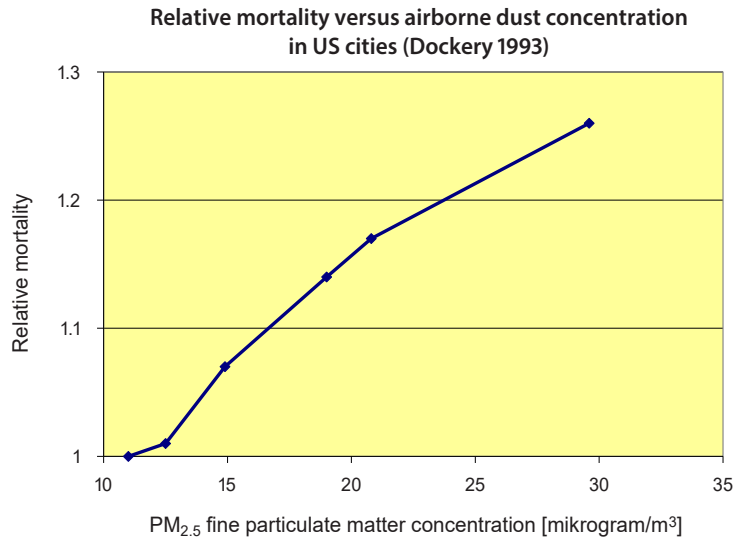
Fig. 1
Air pollution and death rates,
London, December 1952.
Own graph based on data
from Lipfert (1994)

only concern when assessing atmospheric pollution in Poland.

Air pollution in Poland and its impact on health

Apart from and in addition to the urgent need to reduce carbon dioxide emissions, Poles must be aware that air pollution with dust, sulfur dioxide, nitrogen oxides and benzo[a]pyrene poses a direct threat to their health. Particulate matter (PM) consists of a mixture of organic and inorganic substances. It can contain toxic substances such as polycyclic aromatic hydrocarbons (e.g., the carcinogen benzo[a]pyrene), transition and heavy metals and their compounds, and dioxins and furans. PM₁₀ dust is particles less than 10 micrometers in diameter (about one-fifth the thickness of a human hair), able to enter the upper respiratory tract and lungs.

Fig. 2
Relative mortality
as a function
of PM_{2.5} fine dust
concentration.
data from Dockery
(1993), own figure



An even more worrying situation can be observed when it comes to the finer fraction, known as PM_{2.5}. It is particularly harmful to health because, due to its small size, its particles can enter the alveoli of the lungs, from where they can further penetrate the bloodstream. Little heed was paid to air pollution as recently as the first half of the twentieth century, but an “episode” in London in 1952, when the number of deaths was found to increase in tandem with increasing air pollution – as shown in Fig. 1 – caused the alarm to be sounded.

In just one week, the increase in concentrations of dust, soot and smoke in the humid London air, collectively called smog (coined as a combination of *smoke* + *fog*), led to the deaths of 4,000 people and severe health complications in many thousands more. Subsequent studies have shown that respiratory illnesses and deaths are caused not only by incidental high concentrations of pollutants, but also by lower concentrations that occur continuously.

Douglas Dockery’s studies in cities on the American plains found surprisingly large health effects even for pollutant concentrations that lay below the thresholds recognized as permissible by the World Health Organization.

As Fig. 2 shows, already at fine PM_{2.5} concentrations of 20–30 micrograms/m³, there is a marked increase in human mortality. Under Polish regulations, the average value of PM_{2.5} during the year must not exceed 25 micrograms/m³. Unfortunately, in practice this value is nevertheless exceeded in many regions of Poland.

Is building wind turbines and solar panels enough? The need to provide stable power to consumers regardless of weather. Stable and dispatchable nuclear power plants need to be part of in the energy mix to ensure continuous power supply to consumers when there is no wind or sunshine. Experience from Germany and metering data from 14 European countries shows that power generation outages can last for more than 100 hours and can occur simultaneously across Europe.

Wind power fluctuations. Wind is a very unstable and uncontrollable source of energy. The power output of wind turbines increases with the cubic power of the wind speed. Thus, at a wind speed of 4 m/s the output is 39 W/m², at 6 m/s the output increases to 132 W/m² and at 12 m/s the output is 1058 W/m². This means that any change in wind speed causes rapid changes in the amount of power transmitted from the wind turbine to the grid. This creates difficulties in providing a constant power supply to consumers – not just to industry, subway lines, and hospitals, but all of us who expect electricity to be there in the socket whenever we want to use it.

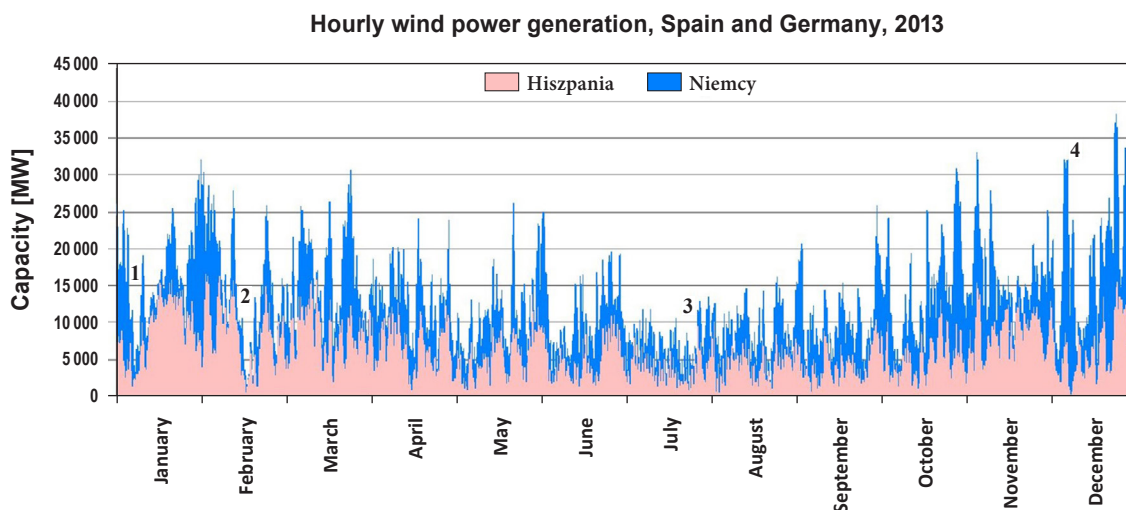


Fig. 3
Annual electricity generation from wind turbines in Spain and Germany in 2013 (compiled by R. Schuster, cited with permission)

Unfortunately, when there is no wind in Poland, we cannot count on necessarily being able to import wind energy from our neighbors. Measurements carried out by independent organizations show that regions of low and high wind power can occur simultaneously over large areas.

Figures 3 and 4 show an aggregate comparison of the changes in wind power through the year in 2 European countries (Spain and Germany) and 14 European countries, respectively, taken from materials of a German NGO, Die Bundesinitiative Vernunftkraft e.V. As is plain to see, increasing the number of countries from which electricity is to be imported

will not compensate for fluctuations in wind power generation. Wind farm capacity across the 14 EU countries varies from 3.7 GW to 78 GW! And the changes occur simultaneously across Europe, from Finland to Spain. The popular claim that the wind is always blowing somewhere is simply not true. And when all 14 countries combined find themselves more than 74,000 MW short below their maximum practical capacity (and even more below their nominal capacity), where should they turn for power?

As Fig. 5 illustrates, the capacity factor for wind and solar power is small. It does not reach 100 percent at any time; the highest-ever capacity equal to 42 per-

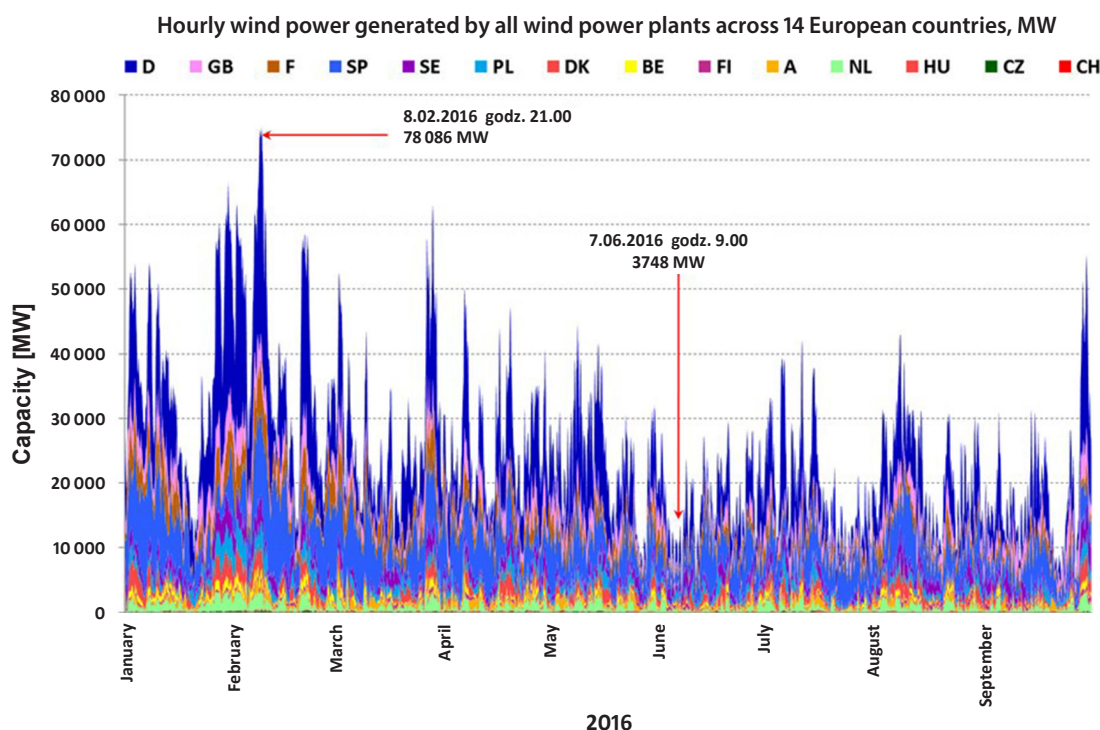


Fig. 4
Annual electricity generation from wind turbines in 14 European countries (compiled by R. Schuster, cited with permission)

Data Source: ENTSOE

Accuracy: hourly data

Drawing: Rolf Schuster

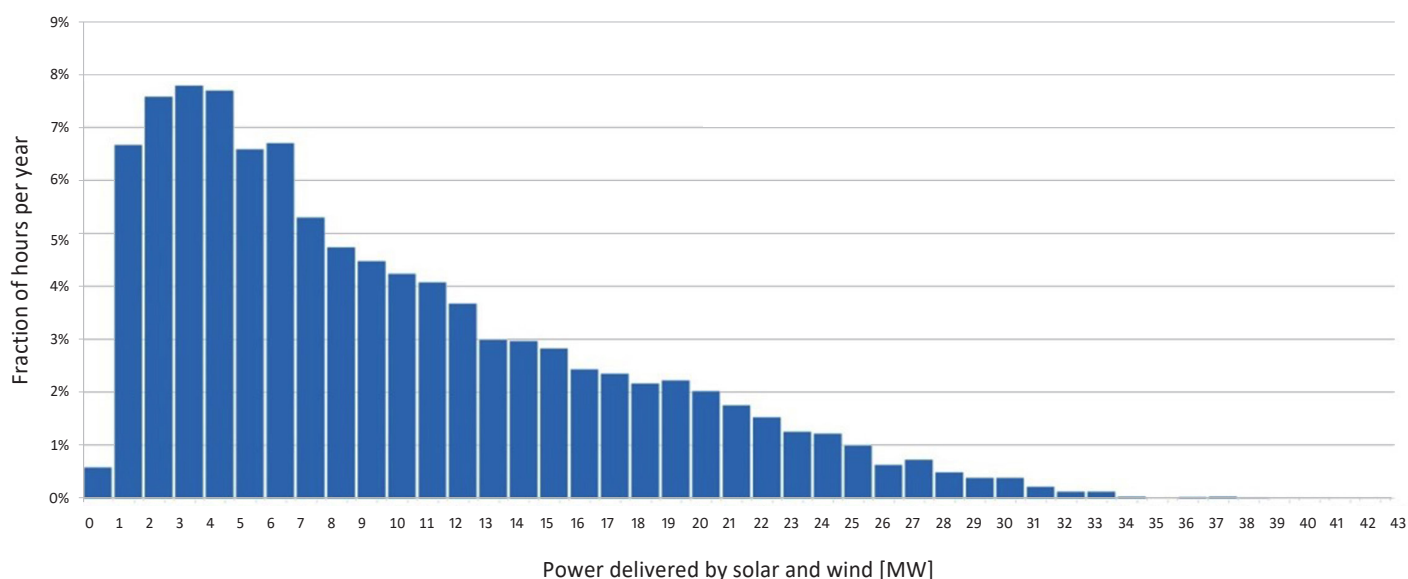


Fig. 5
Time distribution for
capacity utilization levels
at wind farms and solar
panels in Germany
(data from Fraunhofer
Institute, own figure)

cent of the rated capacity (35 GW) was achieved by wind turbines and photovoltaic (pV) panels in Germany in 2014 for one hour, or 0.000114 of the time.

Pumped storage power plants

Without a doubt, pumped-storage hydropower (PSH) is the cheapest way to compensate for wind power fluctuations. Economic evaluations indicate that energy storage in PSH is 20 to 50 times cheaper than other measures. But the energy storage capacity of Polish PSH plants is only about 8 GWh, and building new ones is rendered difficult by geographical and environmental constraints.

How long will the energy reserves in Poland's pumped-storage hydropower plants last in the event of wind silence?

With renewable sources accounting for an 18.2 percent share of electricity production, including 50 percent from wind, wind turbine capacity will average 1.72 GW. In the event of a complete wind silence, therefore, such will be the magnitude of the shortage of capacity faced by the country. Pumped-storage power plants can provide 1.75 GW – but only for a short time.

The total PSH capacity in Poland will cover the lack of onshore wind for 4.5 hours. After that, all the upper reservoirs in the Polish PSH facilities will be empty. What happens next – say, for the next four days?

Building large-scale transmission grids is costly and runs against the concept of distributed power – whereby everyone generates the electricity they need for themselves. Moreover, as can be concluded from data like that shown in Figs. 3, 4 and 5, this will still be insufficient, because fluctuations in wind power occur over large areas simultaneously. And so, backup power needs to be kept available from sources with

regulated capacity, i.e. system power plants. Of these, both coal-fired and gas-fired plants produce carbon dioxide emissions. The only emissions-free source is nuclear power.

Costs incurred by the national power system to ensure continuity of supply to consumers

The costs of a power plant's operation within a broader power system depend on many parameters, including the distribution of energy sources and consumers, the costs of transmission line construction, the expected outages and required reliability of power supply, and in the case of renewable sources – primarily on their share in the overall energy balance of a given system. In general, the higher the share of renewable sources, the higher the system cost of maintaining energy supply security.

This is well illustrated by the example of Germany. A compilation of data for the country, developed by a committee of the OECD, shows the components of the costs of power system cooperation for two levels of participation in energy production: for nuclear energy, coal, gas, onshore wind, offshore wind and solar power for photovoltaic cells. When the share of renewable sources moved from 10 percent to 30 percent, the cost of interfacing with the power system more than doubled. The highest costs were found for solar power, at over \$82/MWh, while lower costs were found for onshore and offshore wind, at about \$43/MWh.

Of course, system power plants also incur costs of interfacing with the power system, but they are much smaller: \$2.25/MWh for nuclear, \$0.97 for coal, and \$0.54 for gas.

Should Poland follow the energy transition path chosen by Germany?

The fundamental problem of renewable sources, which will not be solved even by large reductions in

wind turbine construction costs (and in fact they are not decreasing, as wind power advocates have insisted), is intermittency in electricity production. The production of photovoltaic panels is interrupted every evening (which means 365 times a year), and even during the day their output varies depending on the cloud cover and season. Intermittency of wind turbines is also a problem.

Interruptions in onshore wind farm generation are illustrated in Fig. 6. With a nominal wind turbine capacity of 28,712 MW (in Germany in 2011), the output over seven days was 1,000 MW, or 3.5 percent of nominal capacity. If the share of onshore wind farms in power generation in Poland were 16 TWh, then in case of a 100-hour outage, there would have

to be an electricity reserve of $16,000 \text{ GWh} \times 100 / 8760 = 182 \text{ GWh}$.

And, of course, similar lengths of wind silence occur in Poland as in Germany. An example of such a low-wind period in Poland is shown in Fig. 7.

Consider the case of an offshore wind farm (OWF) contributing 40 TWh per year to electricity generation. In the event of an interruption in the OWF's operation for 130 hours – as for instance happened from 9AM on 4 May 2018 to 7PM on 9 May 2018, when the average output fell to 0.3 percent of nominal capacity, as shown in Fig. 8 – let us assume that the average output of the OWF will be 1% of its nominal output for 130 hours. There will entail an energy shortfall of $40,000 / 8760 \times 130 \text{ h} \times 0.99 = 587 \text{ GWh}$. This entails

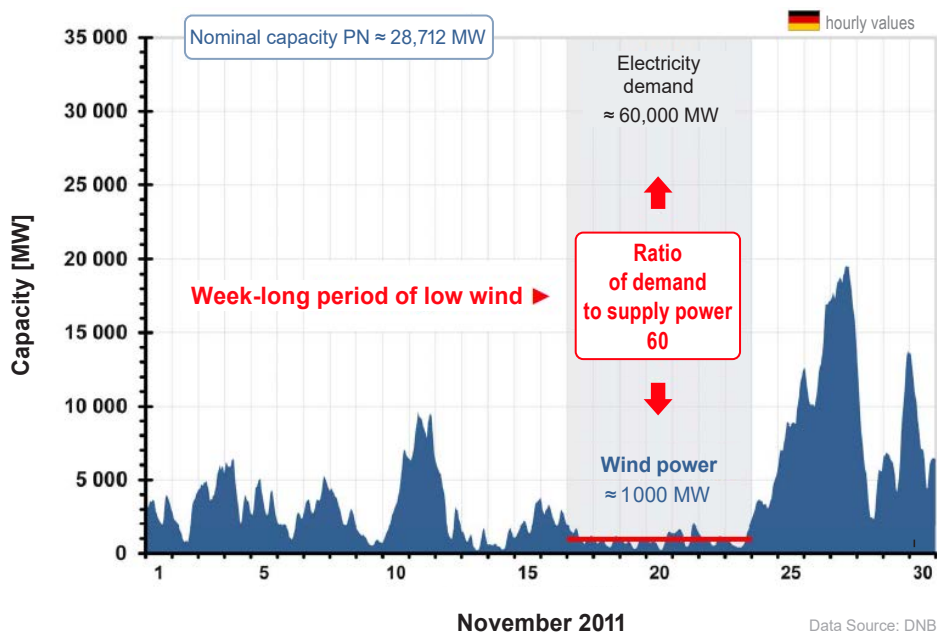


Fig. 6
Break for seven days and nights in onshore wind turbine power generation in Germany

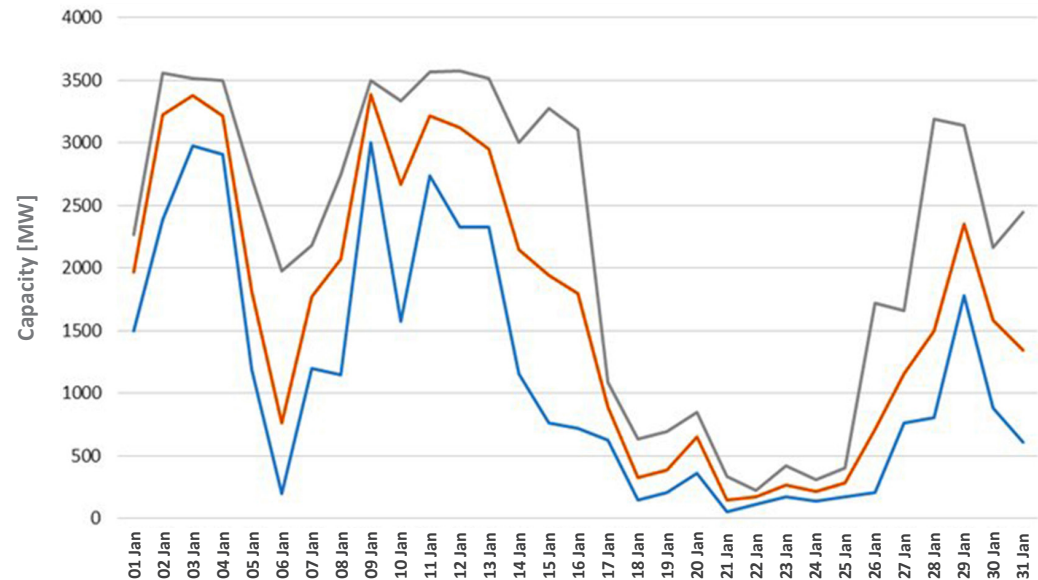
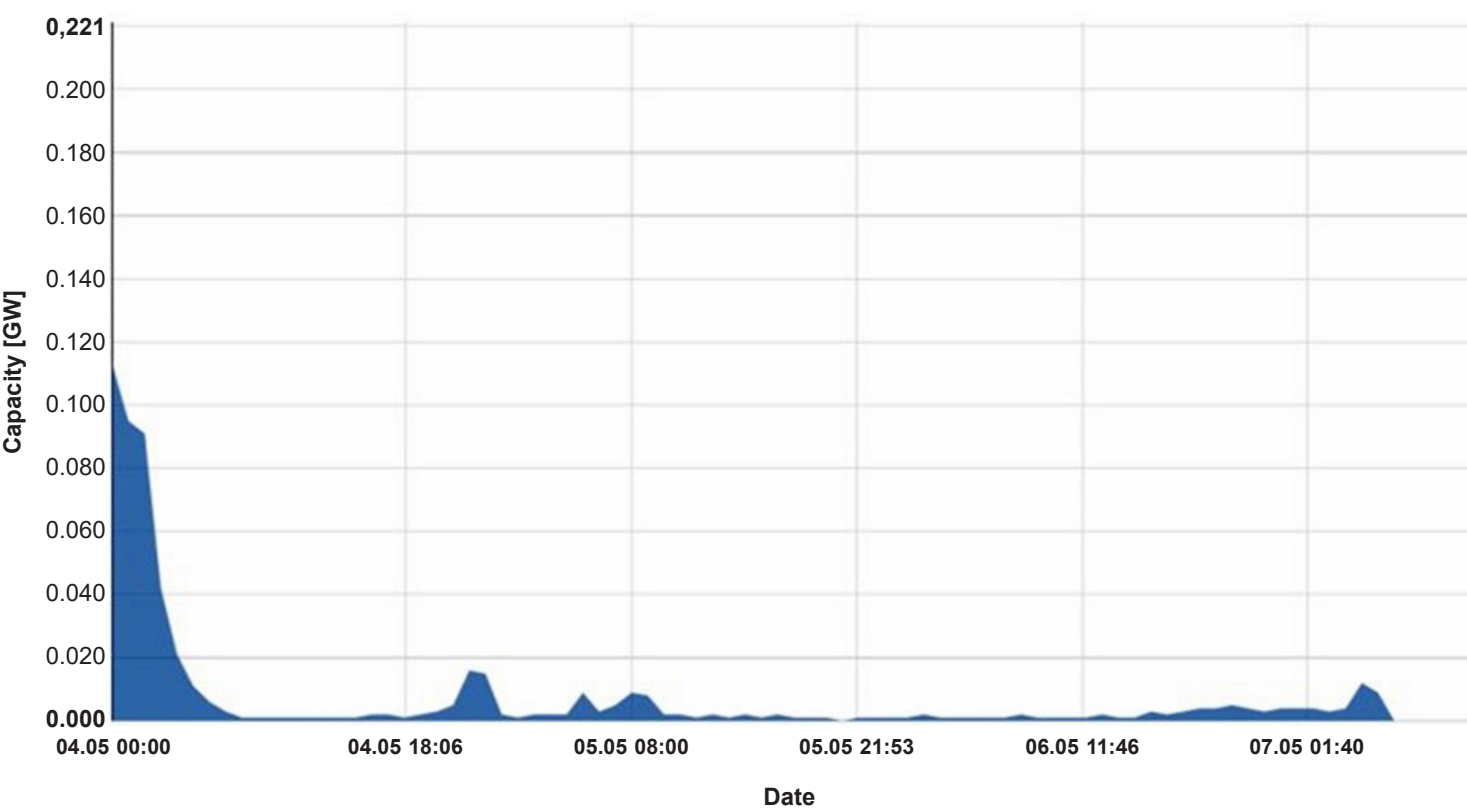


Fig. 7
An example of a low-wind period in Poland is visible on this graph, showing the minimum (blue), maximum (grey), and average (orange) wind generation in January 2015 [MWh].



a need to store 587 GWh of energy just in case such an event occurs. All existing pumped-storage hydro-power facilities in Poland, on the other hand, have a storage capacity of about 8 GWh (1.75 GW for about 4.5 hours)

Maintaining the capacity to balance out fluctuations in wind power is expensive. The costs of compensating for gaps in power supply must be borne by the power system. That means keeping backup power plants either in operation or on standby, able to be brought online quickly to compensate for a lack of wind. At the same time, the transmission grid has to be expanded to accommodate the maximum output of the non-controlled sources. All in all, maintaining a second power system with enough capacity to cover the needs of the whole country is expensive, and since these back-up power plants run at low output or are idle, their efficiency is low and their emissions per unit of energy are higher than if they were running at full output.

A large-scale example is provided by the German experience. At the beginning of the transition in 1998, the cost of the system was only €2.3 billion, and the leader of the Green Party, Jurgens Trittin, promised that the cost of the subsidy for renewable energy sources would be as much as the cost of an ice-cream serving (€1) per person per month. In reality, that burden was rapidly increasing. When Germany's grid operator announced on 23 October 2012 that more than €20 billion would be needed for green energy subsidies in 2013, it came as a shock to the public. Out-

raged industry organizations declared that the burden of green energy subsidies had "reached an unacceptable level, threatening to drive industry away from Germany." Politicians, industrialists and green lobbyists debated who was to blame for the situation. Meanwhile, underestimated forecasts continue to be published. The forecasts prepared by state institutes are presented in Fig. 9. According to them, in 2020, 22 years after the Green Party's beautiful promises, Germany was meant to pay around €29 billion annually to subsidize renewable energy sources. But these forecasts, too, proved to be off the mark. According to the latest data from January 2021, the German grid operators reported that not €29.11 billion, but a record €30.9 billion was paid last year to subsidize power production from renewable sources.

Today, a glance at the data published by Eurostat is enough to discover that the French, who base their energy on nuclear power plants, pay about 17 eurocents/kWh, while the Germans and Danes, who rely on the development of renewable sources, pay about 30 eurocents/kWh. On the scale of the whole country, Germany pays about €30 billion a year to subsidize renewable energy sources, and there is no end in sight to these subsidies. With Germany's population of 80 million people, this means that each German resident pays an annual cost of 375 euros. Do readers who encounter beautiful claims that "the wind blows for free" realize that they entail the prospect that **each Polish family of four will have to pay** an annual

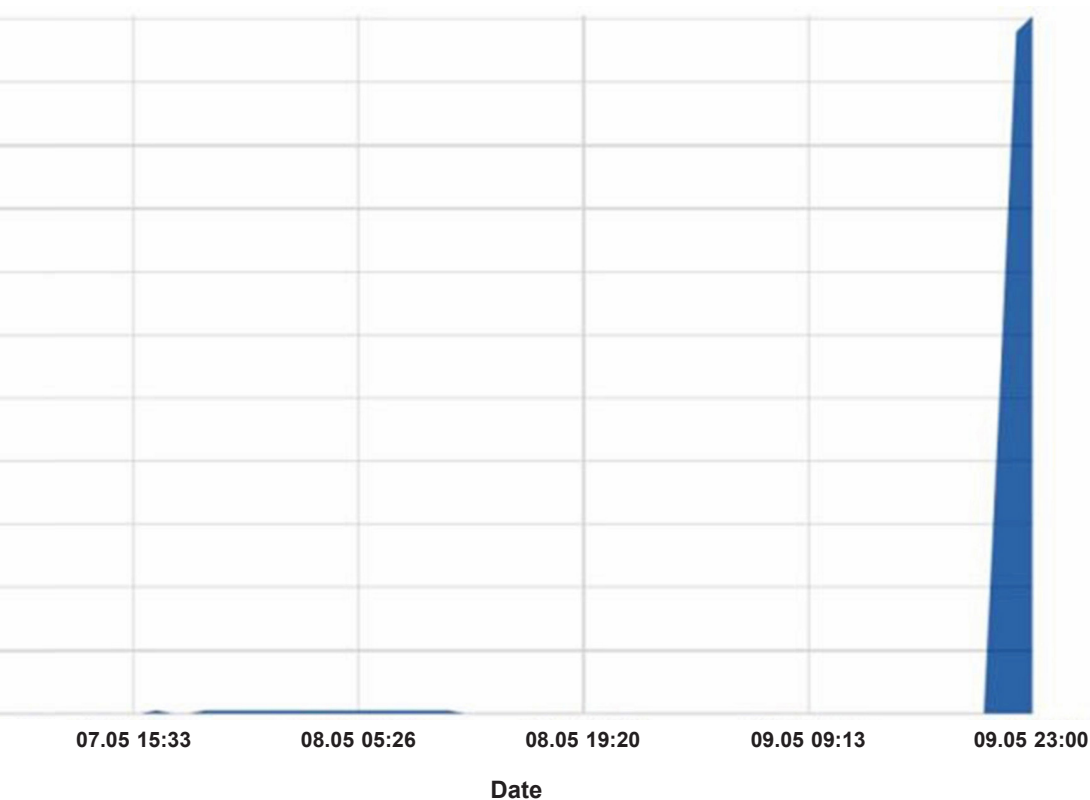


Fig. 8
Offshore wind farm capacity
in the Baltic Sea.
Own figure, source: data for
OWF Baltic 1 and 2

https://energy-charts.info/charts/power/chart.html?l=de&c=DE&year=2017&interval=week&week=18&source=wind_offshore_unit

subsidy of EUR 1,500 × PLN 4.4/euro = PLN 6,600? Are Polish citizens ready for such expenses to be able to boast that they support the development of renewable energy?

Specialists have no doubt that by the end of this decade there will be no technology allowing energy generated from renewable sources to be stored on

a useful scale. As long as it does not exist, controllable energy based on coal, gas and nuclear should be maintained, modernized, and developed. Poland quite simply needs cheap and clean nuclear energy. It is high time not to let ourselves be guided by prejudices or false claims made by nuclear energy opponents, but rather to base our decisions solidly on the facts. ■

● actual outlays in 2020, billions of euros ● Renewable Energy Sources Act (EEG) transformation subsidies, ct/kWh
● total Renewable Energy Sources Act (EEG) transition investments, billions of euros

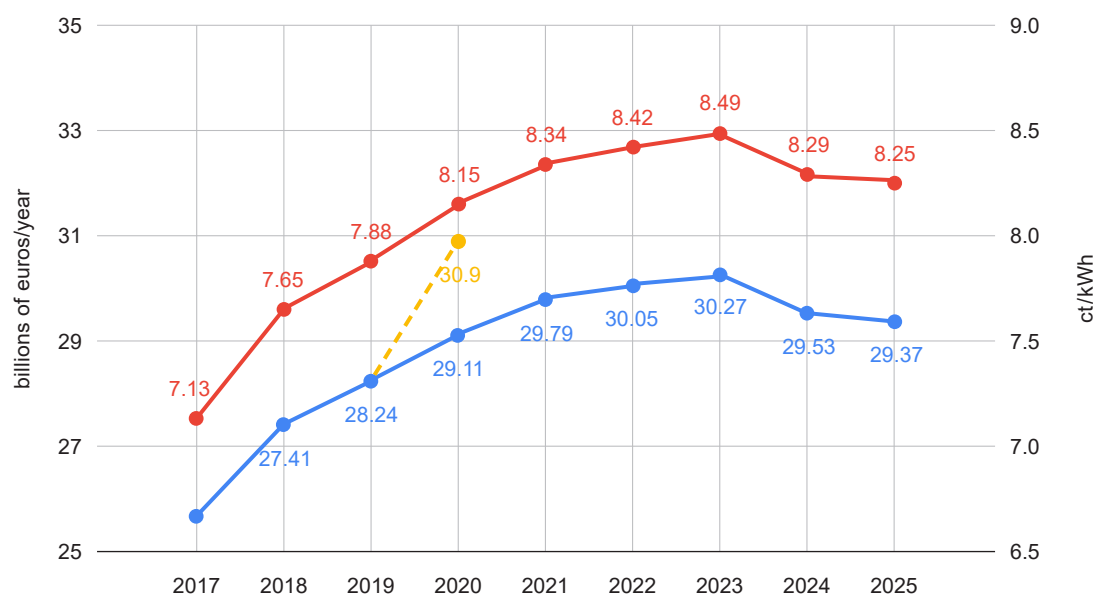


Fig. 9
Total subsidies for
renewable energy sources
and individual energy price
subsidies as forecast by
German institutes vs. actual
total subsidies in 2020



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She works on sites in Poland, Hungary, Germany, and Alaska.

Her research focus is on taxonomy and paleoecology. She uses interdisciplinary methods to reconstruct Jurassic ecosystems.

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WHAT POWERED THE DINOSAURS?

Where did early dinosaurs get their energy from?
Studying fossilized feces reveals certain
secrets of herbivore evolution during
the Jurassic period.



Grzegorz Pacyna, PhD

is a paleobotanist. His current focus is on the taxonomy and evolutionary significance of Silesian conifers from the Upper Triassic and on the taxonomy, evolution, paleoecology, and succession of flora from the Lower Jurassic in Poland's Holy Cross Mountains.

He also studies interactions between plants and animals in the fossil record and biostratigraphy using plant fossils.

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YURI PHOTOLIFE/SHUTTERSTOCK.COM

The large predator
Cryolophosaurus,
likely trackmaker
and coprolite producer
at the Sołtyków site,
a consumer
of herbivorous dinosaurs

Maria Barbacka

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Jadwiga Ziaja

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Jadwiga Ziaja, PhD

is a palynologist studying spores and pollen of Mesozoic plants, mainly from the Jurassic. She uses palynological analysis of rocks to trace changes in the climate and environment in certain regions. She identifies and describes spores and pollen grains in situ, which is an important element in determining botanical relationships between fossil plants.

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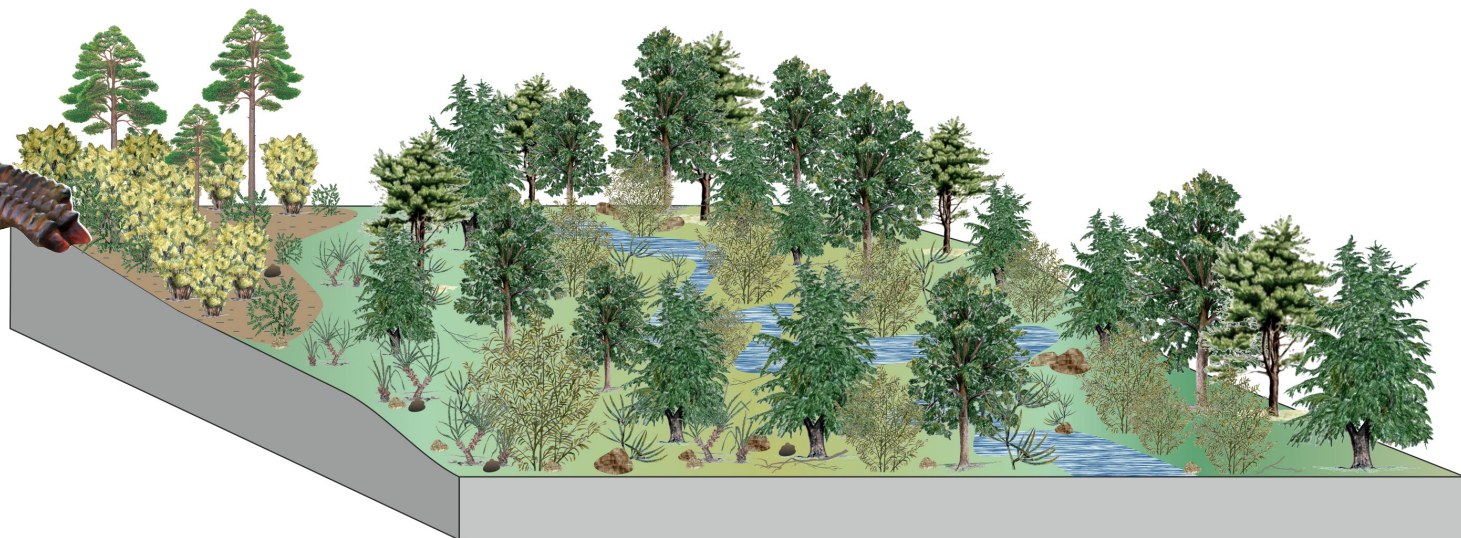


The study of coprolites (fossilized feces) left behind by Jurassic dinosaurs, both herbivorous and carnivorous, at the Sołtyków site in central Poland reveals fascinating information about their diet and habits and about the flora present in the Holy Cross Mountains some 200 million years ago.

The site

Sołtyków (also known as Odrowąż) is a village in Poland's Holy Cross Mountains region, close to the small town of Końskie. Part of a former open-pit quarry, once producing ceramic clay to make bricks, is currently a geological nature reserve (named Gagaty Sołtykowskie). Numerous dinosaur tracks left behind in the boggy soil of the floodplain 200 million years ago have been preserved in the sandstones of the reserve. The most common are mid-sized footprints, most likely made by theropods (early predatory dinosaurs). The largest, spanning up to 50 cm,

Reconstruction of the flora known from coprolites, in accordance with the plants' environmental preferences and the surroundings as reconstructed based on sedimentology studies





Grzegorz Niedzwiedzki, PhD

is a graduate of the Faculty of Biology at the University of Warsaw.

He participates in numerous expeditions studying the Permian-Triassic and Jurassic periods in Poland, Russia, Tunisia, Greenland, and Sweden. He has discovered several sites with preserved tracks and bones of Mesozoic amphibians and reptiles, tracks of early quadrupeds, and dinosaur remains.

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are tridactyl tracks believed to have been left by large early theropods, although their fossilized bones have yet to be found.

The tracks known as *Stenonyx* and *Grallator* were likely made by small *Coelophysis* theropods. There are also numerous footprints spanning up to 40 cm made by sauropods, classified to the *Parabrontopodus* ichnotaxon (an “ichnotaxon” being a taxon based on the fossilized traces of animal activity). The small and medium-sized tracks known as *Anomoepus* and *Delatorichnus* may have been left by early armored dinosaurs or heterodontosaurus. Other tracks offer evidence of the presence of mammal-like reptiles, early mammals or mammaliaforms, lepidosaurs, pterosaurs and early crocodylomorphs.

While very few bones have been found in Sołtyków, dinosaur coprolites are common in the region. Around 300 coprolites have been collected so far, with a handful of them sufficiently well preserved to be suitable for closer study.

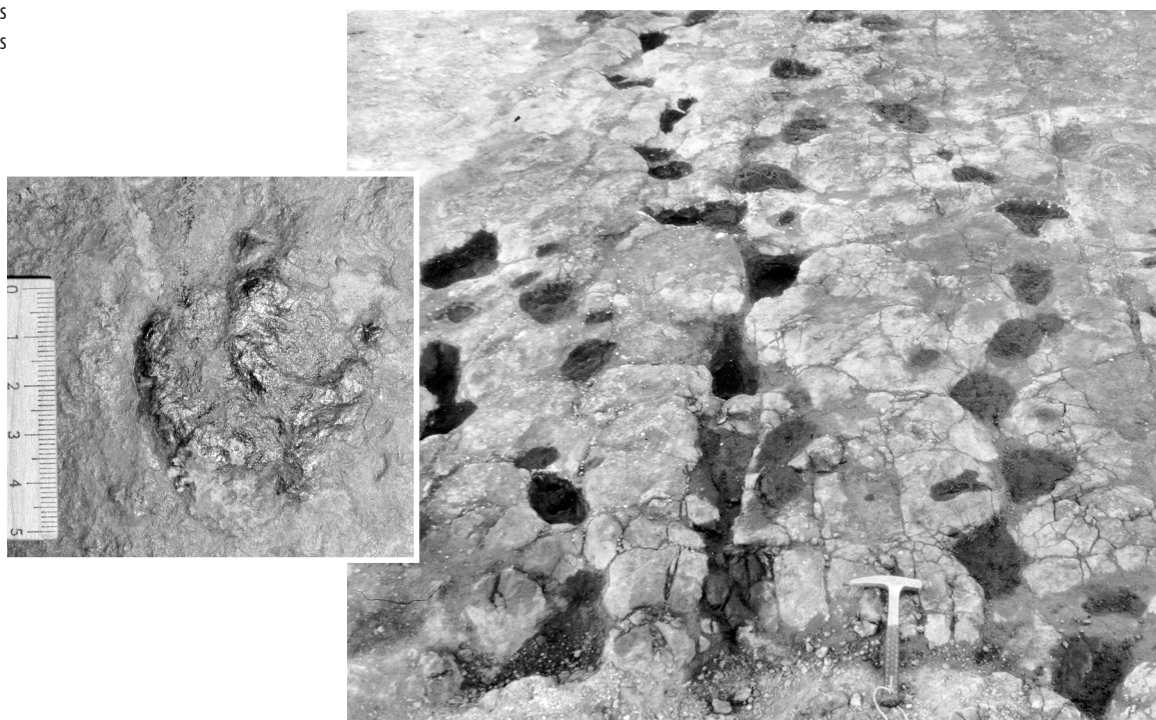
Coprolites

Plant remains may be preserved in the coprolites of both herbivorous (plant-feeding) dinosaurs, as well as carnivores who hunted them. Plant remains and fragments such as bones, insects, shells, etc., also found in coprolites, are an excellent source of information on the real diet of these animals. They also allow us to fill in gaps in our understanding of plants and animals which have not been noted in any other fossil record.

Generally speaking, when the remains of plant cuticles (protective layers made up of lipids, cellulose and pectin on the surface of the epidermis) are found in coprolites, they are present as tiny fragments in digested matter, and are usually identifiable only as plant remains, and more rarely as belonging to a specific group of plants, for example conifers. The coprolites found at the Sołtyków site (both from herbivores and large carnivores) are a unique exception in this regard, in that the leaf fragments are sufficiently large and numerous that some have been successfully assigned to a species, some to a genus, others to a particular systematic group, and in two cases researchers have even been able to describe a new taxon.

We currently do not know why the quality of plant remains is so high in coprolites at this particular site. Early Jurassic sauropods did not have a highly developed mechanism of chewing and masticating food and their teeth only allowed them to tear leaves and perhaps rip branches, so the largely intact food they swallowed was fermented in their stomachs; however, the digestion process was relatively efficient. Some species swallowed rocks (gastrolites) to help break down their food. In carnivores, large plant fragments may have been preserved in feces because they originated from the digestive tracts of their prey at various stages of digestion, and they were not digested further since carnivores lack the appropriate bacterial microflora and enzymes. This means that any plants they ingested were excreted at the same stage of digestion. Large fragments of undigested plant cuticles are highly unusual in herbivore coprolites.

Sołtyków, imprints of tracks left by Sauropodomorphs



Studies

We studied 14 coprolites, seven from large predators and seven from herbivores, most likely Sauropodomorpha. Preliminary treatment involved mechanically breaking down the fossils, dissolving them in hydrochloric acid and soaking in EDTA. After thorough rinsing, organic remains were selected and categorized.

Plant remains extracted from coprolites are preserved in the same condition as those fossilized in sediment: as coalified leaf fragments, or more precisely their cuticles. They are prepared following a classic palaeobotanical method by immersing in Schulze's reagent (concentrated nitric acid and potassium chlorate) and washed in a weak solution of potassium hydroxide. This removes diagenetic carbon, and all that remains is a clean cuticle which is now ready for microscope analysis.

Leaf fragments preserved in coprolites range from a few mm to around 20 mm, with the upper and lower surfaces preserved, allowing us to identify the plants more precisely.

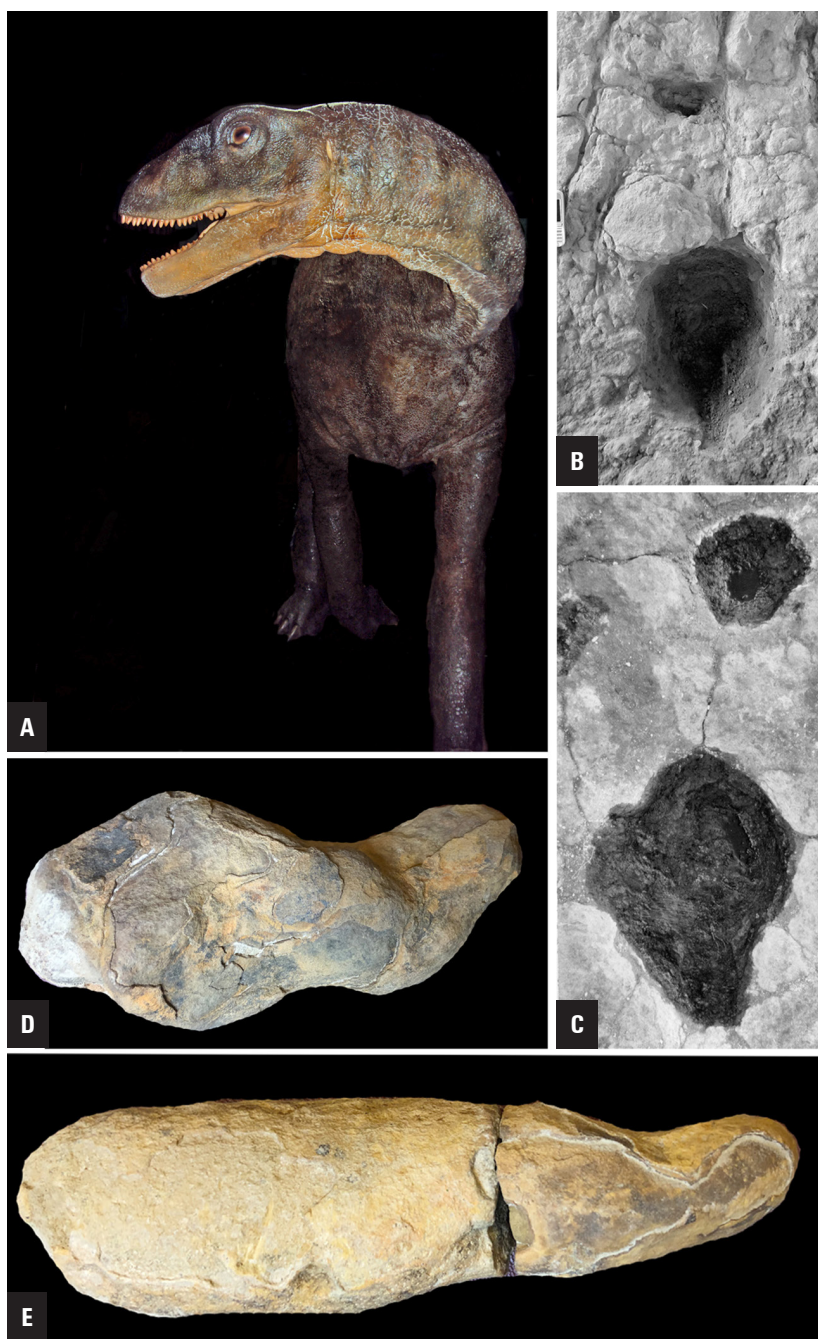
As well as plant cuticles, coprolites may also contain pollen grains and spores, present either in fecal matter (residue) or adhering to cuticles. They also help us identify plants from feeding grounds and to determine the age of research sites.

Interpretation

The plant fragments found in the coprolites of predators, as we have noted, mainly originate from the digestive tracts of their prey. But it is also possible that the carnivores ingested plants accidentally, and we also cannot be certain that the animals may not have eaten them on purpose, since our understanding of the physiology of digestion of Mesozoic reptiles is still very poor. We consider it best to examine these cuticles in the botanical context, leaving conclusions about dinosaur feeding habits focused on herbivores.

Analysis of cuticles from both types of coprolites has revealed the presence of 12 plant taxa, of which five have been assigned to a species, five to a genus, and the remaining two to a higher taxonomic category. Four types of cuticles remain unidentified. In addition to cuticles, we also found one fragment of wood a few millimeters long. The coprolite remains represent three species of seed ferns, one species each of cycad, bennettitalean and ginkgo, four conifer species and two of unknown affinity. Three species had previously been identified near the Holy Cross Mountains, while the others were reported for the first time; thus our knowledge of the local flora has had nine previously unknown taxa added to it.

Analysis of spores present in the coprolites (from bryophytes, lycophytes, and ferns) further rounds out



our picture of the local flora composition in the dinosaurs' feeding area.

Environmental preferences of plants found in coprolites were determined using methods usually used for fossil plants, on the basis of analysis of sediments containing plant fragments and based on the plants' morphology and structure of their cuticles. The majority of taxa found in coprolites are a close match with the reconstructed ecosystem of the Early Jurassic in the region. They are also found at other sites in Europe, mainly in river and delta deposits.

One of the seed fern species found in coprolites shows xeromorphic characteristics, indicating an arid

A. The herbivorous dinosaur *Vulcanodon*, likely trackmaker and coprolite producer at the Sołtyków site. Reconstruction at the Jan Pazar Museum of Natural History and Technology, Starachowice. B, C. Imprints of tracks of smaller and larger individuals, respectively. D, E. Coprolites likely left by a Sauropodomorph

One of the plants found in the coprolites, the seed fern *Pachypteris papillosa* (Thomas et Bose) Harris.

A.

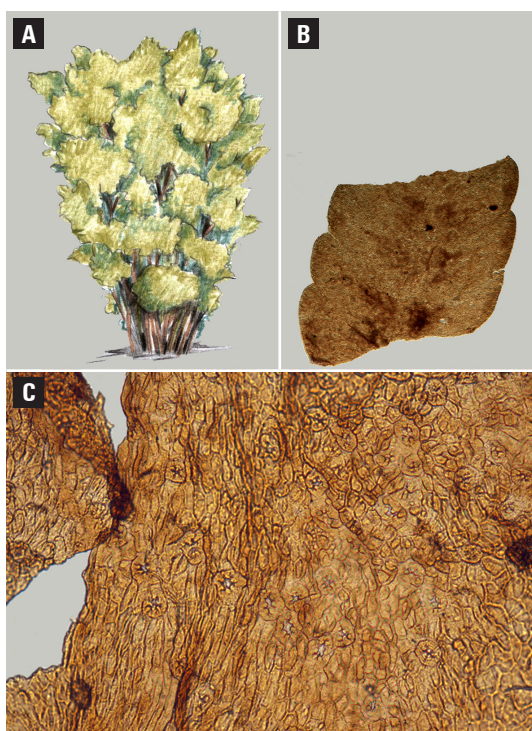
Likely appearance of the plant.

B.

Fragment of a leaf found in the coprolite.

C.

Enlarged cuticle fragment showing stomata regulated by papillae



or saline environment. This means relatively small leaves (compound pinnate), thick cuticles, and stomata protected by papillae. All these features aim to limit evaporation and thus to protect the plant from drying out. Topographic reconstruction of the site does not indicate exposed arid areas, therefore our search for the reasons for xeromorphism turned to local saline sites. This made sense, since the species in question, *Pachypteris papillosa* (Thomas et Bose) Harris, is known from coastal regions and is interpreted as halophytic (salt-tolerant). However, Sołtyków was situated ~700–800 km from the nearest coastline (in present-day Germany). Which means even a large predator could not have covered such a vast distance between feeding and defecating. However, it turns out that at Miłków-Szewna (70 km from Sołtyków), high boron content was found locally, perhaps indicating an ancient saline environment (this is explained by Permian/Triassic evaporate-bearing deposits, which could have delivered salt to springs and soils in the area). A distance 70 km probably was no problem for large animals and reveals some information about the direction of migration of some individuals.

The question remains whether dinosaurs intentionally fed on halophytes, like some contemporary herbivores do, thereby utilizing of the microelements in salt. We currently have no data on whether dinosaurs ingested salt, but given our understanding of present-day reptiles, intentional feeding on halophytes seems unlikely. Recent reptiles which live in salt water (for example crocodiles) have glands which excrete salt. It appears, therefore, that reptiles do not have

a mechanism for utilizing microelements from salt, so feeding on halophytes was most likely incidental.

Judging by the proportion of fragments found in coprolites, the majority of plants eaten by dinosaurs had large leaves and belonged to seed ferns and cycadophytes. Conifers were less numerous, predominantly thuja-like, offering soft, fleshy twigs. Other conifers and ginkgoes were found less frequently. All taxa found in coprolites were trees or large shrubs, which indicates that dinosaurs fed at the canopy level – an interesting detail about feeding behavior.

A complete absence of wood in coprolites (the single microscopic fragment being insignificant in this respect) attests to an abundance of easily digestible, high-energy plant material. A large amount of wood in feces would indicate that animals were forced to feed on material harder to digest, suggesting possible famine conditions.

The taxa from the coprolites we studied likely do not represent the entire diet of herbivorous dinosaurs in the Holy Cross Mountains.

It should be noted that cuticles of many plants, for example large-leaf ferns (which also included tree-like forms) are faint and easily-degrading, while seed plants have cuticles resistant to such a degree that they could pass through the digestive tract undigested – and so, the cuticle fragments in coprolites represent just a small proportion of food which had not been digested for certain reasons. Spores and pollen grains are of no help since they are not equivalent to the species which produced them; they may have simply been found in water or on the surface of plants eaten by the animals.

New information

Overall, the results of our studies of plant fragments in dinosaur coprolites have provided valuable palaeoecological information on a new ecological niche, in particular for the *Pachypteris papillosa* species which inhabited salty inland regions, as well as improving our understanding of dinosaur behavior, diet, and feeding habits. The research has revealed new information on Early Jurassic flora from the northern margin of the Holy Cross Mountains and expanded the number of taxa by nine, including two which had not been described previously at all.

The findings presented here represent the newest results of the research done under the project. Although similar studies have been conducted at other sites all over the globe for many years, none of the materials have been so well preserved or provided so many important data in palaeobotany.

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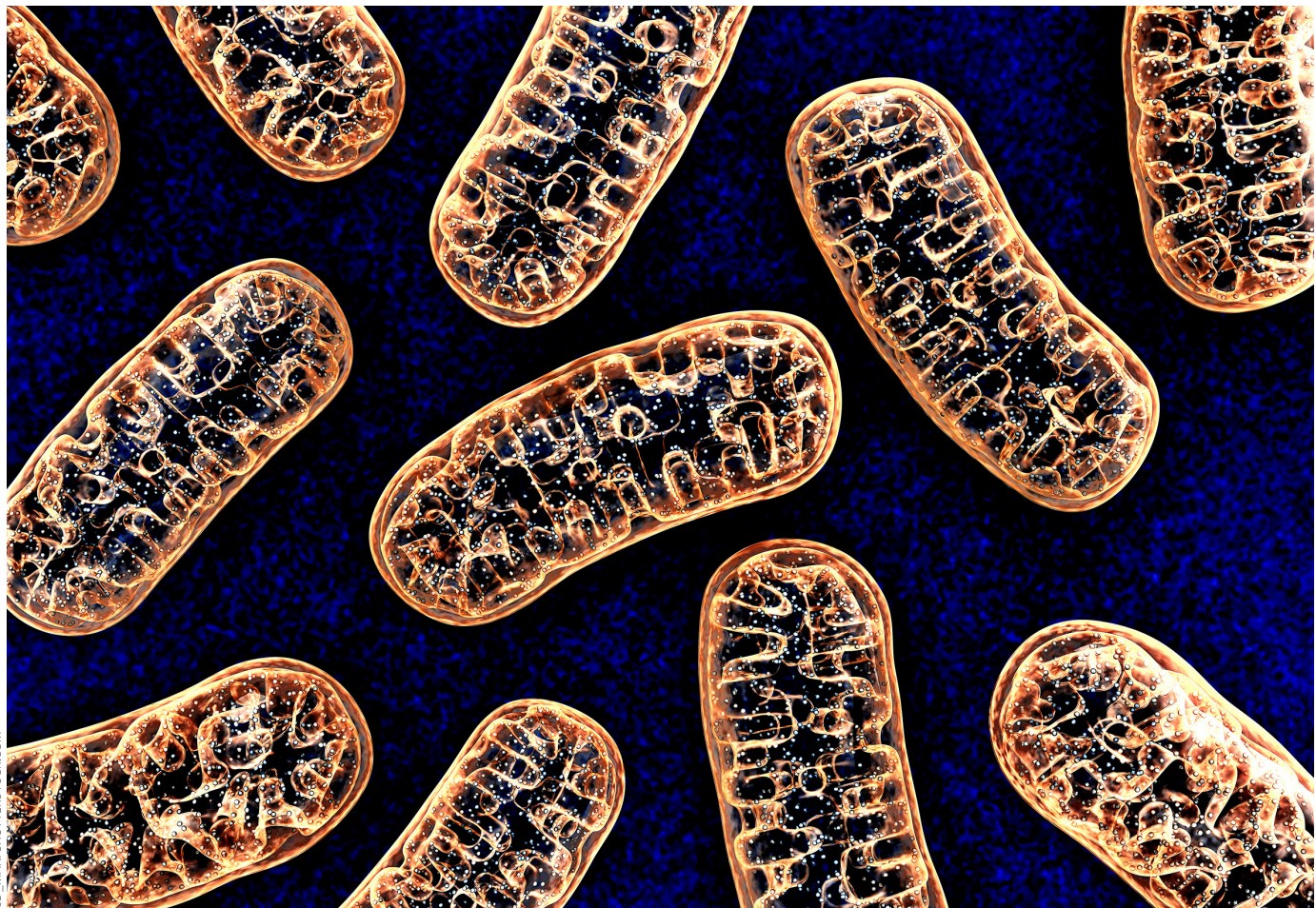
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SEEDS SOUNDING THE ENERGY ALARM



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What do biological powerhouses look like? How do they work? Why does generating a single “dose of energy” demand a highly complicated process? Why do seeds age? Answers to all these questions are to be found in one of the most complex cellular organelles: the mitochondrion.



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In view of their crucial role in energy production, mitochondria are often described as “powerhouses” of the cell. Analysis of the genes coded for in the mitochondrial DNA (mtDNA) indicates that these organelles are descended from a common ancestor – an α -proteobacterium known as the proto-mitochondrion. These findings underpin what is called the endosymbiotic theory, which posits that about 2 billion years ago an anaerobic cell took in a smaller, oxygen-requiring proteobacterium, forming a symbiotic relationship. The “alliance” so forged enabled the anaerobic cell to switch over to an oxygen-related metabolism, allowing it to produce much more energy than before. In the course of evolution, that proto-mitochondrion evolved into a cellular organelle that is today the energy center of the eukaryotic cell – the mitochondrion. In the face of climate change, however, it turns out that these microscopic “powerhouses” may be in serious jeopardy – especially the mitochondria in seed cells.

Structure of mitochondria

The existence of mitochondria was first discovered in the muscle cells of insect wings, by the Swiss scholar Rudolf Albert von Kölliker. We now know that a vast majority of eukaryotes have mitochondria in their cells. These mitochondria are round- or oval-shaped and measure about 2–8 μm in length and about 0.5 μm in diameter. They are surrounded by outer and inner membranes, separated by an intermembrane space. The inside of the mitochondrion is filled with the matrix, which is an aqueous solution of proteins and metabolites used by the organelle in the process of cellular respiration. The inner membrane is the energy center of the mitochondrion. The surface of the inner membrane folds deep into the matrix. These folds, called cristae, increase the surface area in which the production of energy-carrying molecules of adenosine triphosphate (ATP) takes place. These molecules can be described as molecular batteries because they transport and store the energy needed for cells to function.

This energy is stored in chemical bonds and released when these bonds are broken. It is in the mitochondrial cristae that the enzymes associated with what is called the electron transport chain (or the respiratory chain) are embedded. The mitochondria of cells that have different functions differ in terms of the number of cristae, depending on energy needs. Likewise, the number of organelles depends on the type of the organism and the cell. A typical cell contains several hundred to several thousand of these organelles, which divide independently of the cell (Photo 1).

The DNA found inside a cell may take on various forms. In most cases, DNA has the form of a double-stranded linear molecule, but there are exceptions to this rule. In bacterial cells, the genome is circular. Mitochondria also have their own genome, separate from other organelles. For reasons related to their prokaryotic origin, this genome has the form of a circular nucleoid (mtDNA) in which some of the proteins and the RNAs associated with their functioning are encoded. As the proto-mitochondrion evolved into a cellular organelle, the mitochondrial genome underwent numerous modifications, such as the transfer of genes from the proto-mitochondrion to the nucleus of the cell and *vice versa*. Interestingly, animal and plant mitochondrial genomes differ in their structure. In animals, the mitochondrial genome is typically a simple and small circular DNA molecule. The mtDNA of plants, however, has not been studied as well, for reasons related to significant variations in its structure, length, and organization. For the sake of simplicity, the plant genome is pictured as a circular molecule containing all the genetic information of the mitochondrion, which is called the master chromosome.

The functions of mitochondria

The main role that mitochondria play is to produce energy for the cell. But they also have other tasks, which include the regulation of the membrane potential, apoptosis (programmed cell death), and redox regulation.

The production of energy in the form of ATP, known as oxidative phosphorylation, takes place in the inner mitochondrial membrane, where the enzyme proteins of the electron transport chain are embedded. The electron transport chain comprises five major enzymes: NADH-coenzyme Q reductase (complex I), succinate dehydrogenase (complex II), coenzyme Q-cytochrome *c* reductase (complex III), cytochrome *c* oxidase (complex IV), and ATP synthase.

The essence of oxidative phosphorylation lies in transporting electrons through successive elements of the electron transport chain. This occurs through a series of oxidation and reduction (“redox”) reactions. The electrons are supplied by two chemical compounds that are formed elsewhere in the cell,



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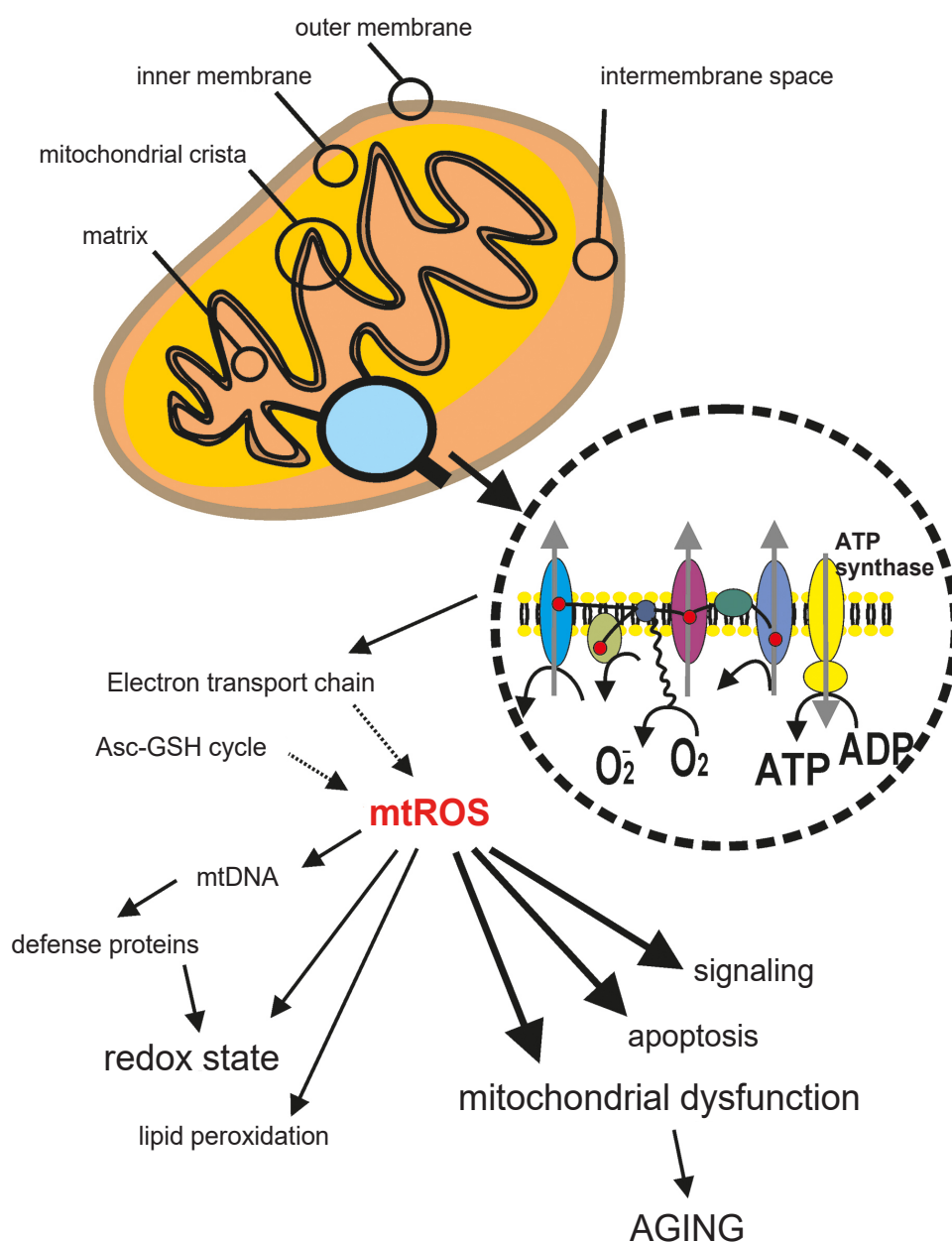


Fig. 1
The relationship between oxidative phosphorylation in mitochondria and the production of reactive oxygen species (mtROS) and their impact on changes in metabolism and the induction of seed aging

namely the reduced forms of nicotinamide adenine dinucleotide (NADH) and flavin adenine dinucleotide (FADH₂). The energy contained in the electrons of these compounds is the driving force behind oxidative phosphorylation. The transport of these electrons by the protein complexes of the electron transport chain produces the protonmotive force, causing protons to be pumped out of the mitochondrial matrix into the intermembrane space. Then, under the pressure of protons flowing back into the mitochondrial matrix, ATP synthase synthesizes ATP molecules (Fig. 1).

An important role in oxidative phosphorylation is played by oxygen molecules, which are the final acceptors of the electrons in the electron transport chain. Because of its affinity for electrons, molecular oxygen produces a significant amount of thermody-

namic drive in the electron transport chain. Partial reduction leads to the formation of hazardous compounds called reactive oxygen species (ROS). They are considered the main instigators of cellular aging – including in the cells of seeds, which are usually associated with a state of dormancy and limited metabolism. Nevertheless, in the course of the long-term storage of seeds, their cells may experience increased ROS production during metabolic changes associated with respiration, which negatively affect their genetic material and the nutrients they store. Mitochondrial DNA is neither protected in any way by protein membranes, nor bound to stabilizing proteins, called histones, which makes it more vulnerable to damage.

Although the mitochondria serve as powerhouses for cell growth and metabolic activity, they are also

one of the major sites of ROS production, formed during electron transport through the complexes in the mitochondrial electron transport chain. Superoxide anion radical ($O_2^{\cdot-}$) is a precursor of most ROS and a mediator in oxidative chain reactions. It can be formed in the electron transport chain as a result of one-electron reduction occurring with flavins (such as vitamin B_2 , which is involved in oxidation and reduction processes) or ubiquinone (mainly known as coenzyme Q_{10} in the cosmetics industry). Superoxide anion radical is formed in complex I, complex II, and complex III (Fig. 1). A balance between the generation of ROS and their removal by a specialized defense system enables uninterrupted energy production in seed cells.

What threats do tree seeds face nowadays?

Trees are long-lived organisms – species exhibiting the greatest longevity, such as the Rocky Mountain bristlecone pine (*Pinus aristata* Engelm.), may live as long as 5,000 years. Such a long lifespan is inevitably linked to continual exposure to stress stimuli at different stages

of the plant's development. Even seeds still maturing on the branches of their parent tree experience stresses of varying type and intensity. The increasing frequency of extreme weather events, such as droughts and heat waves, is the result of factors including high CO_2 concentrations in the Earth's atmosphere. In 2015, CO_2 levels exceeded 400 ppm (parts per million) for the first time since measurements began in 1958, when it was 315 ppm (as a point of comparison, note that in 2021 the CO_2 concentration is already 416 ppm). This has serious implications, not only for species' ability to colonize new areas, but also for the quality of seeds, which ensure the sustainability of forests.

Over the past decades, many surprising observations have been made, especially in the case of species that show cyclical seed production patterns, such as the beech and oak. Such trees recognize an increase in air temperature as a signal to start increased seed production the next season – this next year is then called a seed year. As a result of the rises in average temperatures now being recorded every year, trees are constantly trying to prepare for a seed year. However, the species that produce relatively heavy seeds, such as acorns and beechnuts, need up to eight years to regather the energy necessary for the production of many flowers and fruit. Consequently, seeds are produced every year, but there are far fewer of them, and most do not have a complete embryo – they are “empty” seeds. Not so long ago, however, such trees had a number of years to regenerate between seed years.

Seeds raising the alarm: the initiation of aging

How can we prevent the loss of seed material, which is crucial for forest sustainability? We need to continuously collect and store it in very specific and species-dependent ways, which poses a considerable challenge. All this is due to the molecules we mentioned earlier, namely reactive oxygen species. Studies show that a reduction in the viability of seeds stored for several years is closely linked to an increased concentrations of ROS and the products of the oxidation of storage materials in the form of lipids. This means that the plant material has aged. But what do we even mean by the “aging” of seeds? After all, we associate seeds primarily with the very beginning of new life.

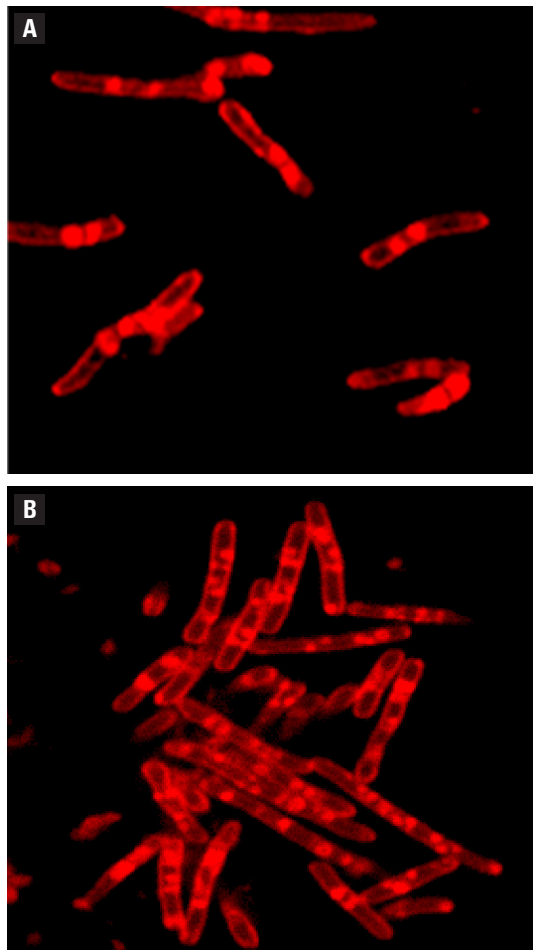
Respiration and other metabolic processes are controlled by the oxidation-reduction potential (the oxidation and reduction systems within the cell), also known as the “redox” state. The matrix of a mitochondrion abounds in a range of defensive compounds involved in this regulation. This system includes many compounds. The most important of these are manganese superoxide dismutase (Mn-SOD), the ascorbate-glutathione cycle (Asc-GSH), catalase, and the

Photo 1

Microscopic observations of mitochondria in beech seeds showed that their ultrastructures change gradually during the aging process

A. Mitochondria isolated from stored seeds are smaller, occurring singly or in small clusters

B. Mitochondria in fresh seed cells are much larger, found in large clusters, elongated in shape, and evidently retain their metabolic activity





JOANNA KUROWSKA-OBERC

proteins of peroxiredoxins (including peroxiredoxin in IIF, important for defining physiological differences between drought stress-resistant and drought stress-sensitive seeds) and thioredoxin. In normal conditions, the level of ROS molecules is effectively regulated, and its slight fluctuations are involved in intercellular communication, acting as transmitters of physiological responses to various phenomena. However, under the influence of such stress factors as drought or heat, ROS are accumulated in excessive amounts and become toxic despite the fact that intracellular messengers play an important role. This happens because ROS have powerful oxidizing properties and therefore change the redox state in different parts of the cell from reducing to oxidizing. They oxidize lipids, which are the main components of cell membranes, including mitochondrial membranes (Photo 1). In so doing, they disrupt the structure of cell membranes (biological membranes), causing changes in their selective permeability and the activity of the proteins bound to them, including antioxidant enzymes. We can determine these changes, for example, by measuring the efflux of electrolytes from the inside of cells into the water in which the tissue being examined has been placed. A state in which the cell cannot detoxify harmful molecules fast enough is called oxidative stress. Its level is determined using lipid oxidation products, typical of tissues under oxidative stress.

Prof. Denham Harman's free radical theory posits that aging is the accumulation of oxidative damage

over time, which gradually increases the risk of death in all living organisms. Seen from this perspective, the aging process directly affects the efficiency of mitochondria and their ability to produce energy. Examples may include elm seeds, in which as many as 48 mitochondrial proteins change in the course of aging. Moreover, these changes have been shown to be related to electron transport and the Krebs cycle, which are processes that form the basis of aerobic respiration. An excess of ROS in mitochondria causes mtDNA damage, which makes it very difficult to preserve genetic information. In turn, the lack of genome integrity impacts negatively on seed viability. All these events taken together translate into the progressive destruction of genetic material and the inhibition of metabolic processes. The cells of aging seeds are unable to produce energy and store it in the form of ATP in amounts enabling the initiation of germination.

For these reasons, we can say that stress caused by changes in climate conditions or improper seed storage leads to the activation of a specific type of intracellular signal – an energy deficit alarm. This signal affects the cell's ability to produce respiration-related mitochondrial proteins such as ATP synthase. Cutting off the supply of metabolic energy needed to maintain the reducing environment in the cell ultimately determines its fate. The cell declares that it is "time to die." In turn, the more cells die, the more "aged" (i.e. unable to germinate) the seed becomes.

Light at the end of the tunnel

Although the aforementioned processes taking part in seeds may have serious consequences, nature has provided seeds with a defense mechanism that protects them from aging. Certain chemical compounds can "switch off" the energy alarm. One of them is proline, an amino acid that has been so far studied intensively in cereal species and other crop plants. Proline accumulation increases in response to environmental stress factors, for example during drought. Proline has the ability to stabilize cell membranes and proteins, which helps reduce water loss and increase the activity of the antioxidant system, causing ROS molecules to be removed more efficiently. For this reason, this interesting amino acid could indicate the level of damage caused by oxidative stress. In addition, it could be used to monitor the conditions of storing seeds to reduce the possibility of oxidative stress in their cells as much as possible. The commercial use of proline may not only protect seeds from aging, but also improve the efficiency of producing seedlings that would be better adapted to changing stress conditions. There is every indication, therefore, that the future will bring an effective solution to the problem of aging – if not for us humans, then at least for seeds! ■

Empty seeds can be observed with growing frequency, such as in the case of sycamore maple trees (*Acer pseudoplatanus* L.)

SYMBOLIC POWER OF THE WINDMILL

Digging deeper into the history and symbolism of Dutch art.



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As you wander through the Rijksmuseum in Amsterdam, amidst the assorted Vermeers, Rembrandts, still lifes and self-portraits, a certain distinctive windmill might initially escape your attention. Once you spot it, however, there is no mistaking it: the tall structure dominates the canvas, set against a cloudy sky painted in subtle greys, blues, greens, and browns. The river and the landscape are almost an afterthought, and there is no doubt as to what the artist wants us to focus on. The towering windmill in Wijk bij Duurstede is the indisputable protagonist of the painting. It is a symbol of the Netherlands, an indelible element of the country's landscape, culture, art, and everyday life.

Upon returning from a trip to the Netherlands in 1921, the Polish artist Tadeusz Makowski wrote: "I travelled slowly through Rotterdam, the famous Haarlem, La Haye. A flat landscape as far as the eye can see, canals crisscrossing the fertile fields and pastureland. Windmills dotting the landscape like wraiths, their ancient silhouettes seemingly sprouting from the soil. Masts and outlines of ships in the distance, cattle and sheep graze the fields. All real, yet looking straight from paintings by old Dutch masters. Fragments from Ruisdael and Vermeer. I admired them from my carriage window," (cited from M. Śniedziwska, *Siedemnastowieczne malarstwo holenderskie w literaturze polskiej po 1918 roku* [Seventeenth-Century Dutch Painting in Polish Literature Since 1918], Toruń 2014).

Much like such Polish artists as Józef Pankiewicz, Jan Cybis, and Józef Czapski, Makowski was fascinated by the observations of the French critic Eugène

Fromentin, author of *The Masters of Past Time*. Polish writings on the art of the Netherlands and discourse on such authors as Fromentin and Johann Wolfgang Goethe have entered the canon of Polish art history and essay writing. Jan Białostocki's annotations to the Polish edition of Fromentin's *Les Maîtres d'autrefois* explains that Dutch painting cannot be separated from the terrain where it was created. This is an important point, since viewers typically attempt to situate paintings in the context of their own reality, examining them much like Makowski admired the lowlands from his train window.

Indeed, the discussions of all Polish and many other scholars of Dutch culture start from the paintings, rather than from the scenery itself. It is the paintings that are the point of departure, the key to polemicizing with the Old Masters. The windmill, on the other hand has a long history of being used for drainage in the Netherlands, making it a common element of the landscape. It was only later that it became popular with artists.

The *Windmill of Wijk bij Duurstede* showcases the classic Dutch motifs: the landscape dominated by the sky, unpredictable weather, waterways, and of course the towering structure itself. The vast scale of the windmill is a conscious attempt to elevate its symbolism, encouraging reflection, comparisons between art and reality, and continuing interpretations of the artwork.

Dutch landscapes

The history of landscape painting dates back centuries, reflecting how people experienced and expressed their relationship with nature in different ways. Depictions of landscapes have varied according to artists' sensitivities, vision and perception of their relationship with the environment. We tend to think that the art of the Middle Ages focuses on spirituality and otherworldly matters and does not depict the beauty of the natural



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world, but this is not always the case. The opulent late-medieval illuminated miniatures, tapestries and frescoes frequently feature intricate elements of nature and humankind's reliance on the rhythm of nature. In later centuries, when the contemporary world gradually became as important to artists as the spiritual sphere, painting started revealing a sensuality closely linked with nature. However, before landscapes became a distinct genre, artists used them as a backdrop for historical, mythical and religious events and as settings for portraits. The natural world was there to enhance emotions and discreetly set the mood.

The realism of *Très Riches Heures du Duc de Berry* (1410-1416) and other "books of hours" made for Milanese and Neapolitan patrons, attributed by some to the van Eyck brothers, soon found its way into easel painting. By the 15th century, the meticulous depiction of details in Dutch landscapes gave them an increasing autonomy. Previously depicted in the background or serving as a setting, landscapes came to the forefront. Artists focused on the impact of light and weather, bringing further realism to their faithful depictions

of nature. By the early 16th century, landscapes had become a fully-fledged genre. Dutch artists were captivated by the beauty of their country; they sought inspiration from Italian landscapes, but they found their idealized style smoothing out irregularities found in the natural world did not feel right in their native Netherlands. Landscapes extended to the entire canvases, with human figures acting as staffage, narrative elements rather than protagonists.

Windmills as symbols of progress

Jacob van Ruisdael, whose *Windmill of Wijk bij Duurstede* (ca. 1668-1670, oil on canvas, 83×101 cm, Rijksmuseum in Amsterdam) we discussed at the outset, was one of the great painters of the Dutch Golden Age. He worked in the wake of the Netherlands regaining its independence, when he and other artists started seeing their homeland as worthy of celebrating and turned their attention to the scenery. This came after

Jacob van Ruisdael,
Windmill of Wijk bij Duurstede, ca. 1670,
Rijksmuseum in Amsterdam

Traditional windmills
in the village of Kinderdijk
in the Netherlands



centuries of Habsburg rule, which had put the Netherlands under powerful influence of Catholic Spain since 1447. While the Holland and Flanders regions were provinces of Habsburg Netherlands, their citizens had no distinct nationality of their own, although northern Netherlands was overwhelmingly Protestant while Flanders in the south was dominated by Catholicism. Independence finally arrived in the early 17th century. Liberation from the foreign rule was a great victory against Spain's military might and brought a widespread sense of personal liberation. The treaty of Antwerp was signed in 1609, putting an end to the Eighty Years' War with Spain and ushering in freedom of religion throughout the Netherlands.

The fact that Dutch landscapes are dotted with windmills is, of course, no romantic accident. Living on land at or even below sea level would have been impossible without continual human intervention. Polders – low-lying tracts of agricultural land – were surrounded by dikes and then drained, in a practice that dates back to the 11th century. The land was prone to flooding by inland waters and the sea, and the local population worked hard to adapt it by building embankments and constructing their dwellings on the highest ground possible. Initially used to grind grain into flour, windmills were soon harnessed to drive water pumps transporting water from lower to higher regions, where it was pumped yet again by still more windmills. The drained ground could then be used for settlement and agriculture. As well as being used for drainage, windmills were also used to mill flour, press rapeseed and sunflower oil, grind mustard seeds, drive sawmills and grind pigments.

Nowadays, windmills are the Netherlands' main tourist attractions, with around 1000 old mills scattered throughout the country, mainly privately owned and sometimes still used as accommodation. This is just a tiny fraction of the numbers dotting the land-

scape three centuries ago. In 1729, the Beemster polder alone was kept drained by a whopping 629 windmills, surrounded by a complex system of dikes and embankments. The Netherlands is home to around four thousand polders of different sizes, ranging from just a single hectare to over 50,000 hectares.

For example, the Flevoland region was once a bay of the North Sea – or rather, of the “South Sea” (*Zuid-erzee*) as the Dutch would have it. The Netherlands' youngest province, it was not drained until the 20th century, when the dike separating it from the rest of the North Sea was built in 1932. Polders were being created up until 1968, serving as settlements for families from overpopulated Amsterdam and its suburbs. The region is still developing rapidly and is a hub of tulip plantations – another symbol of the Netherlands.

Windmills in paintings

During the 1630s, Dutch painting took on an wholly nationalist focus. The landscapes became increasingly monochromatic; the moisture-saturated air diffused the sunlight, giving the world a muted palette of greys. This gave the paintings an intimate aura; the soft contours and blue-grey glaze muting bright colors were seen as superior to the dazzling, detailed Flemish style. This did not make the paintings any less colorful – the Dutch masters were skilled at making the most of the subtle shades. While Flemish landscapes were dominated by the ground and trees, Dutch artists showed a clear preference for the sky. In tandem with the almost monochromatic, nuanced shades, this gave Dutch landscapes a meditative, pensive atmosphere.

During the second half of the 17th century, artists continued to reach for traditions of monochromatic landscapes while turning their attention even more towards contemplation, peace, and quietude. They expressed their personal interpretations of nature and



started specializing in landscapes depicting the sea, fields, forests, and rivers.

Few were as versatile in their work as Jacob van Ruisdael, though not even he could hide his passion for observing the sky. Sunlight changed hue as it pierced through clouds; however, the most important element of his style was a quest for a feeling of drama. He was fascinated by nature and took great pleasure in painting the sea and its destructive power, rapid rivers and even waterfalls, entirely unknown in his native Netherlands. The Dutch landscape artist Allaert van Everdingen travelled to Sweden around 1640 and his subsequent paintings had a major impact on van Ruisdael, who had never seen a waterfall. This impression and inspiration, intertwined with a sense of drama, contributed to his depiction of the exaggerated silhouette of the windmill of Wijk bin Duurstede. The artist imposed his narrative on the painting, bringing to the fore an element which might otherwise have been overlooked.

The painting depicts a landscape around the town of Wijk, near Utrecht. As well as the windmill dominating the scene, the painting is a realistic representation of the area, showing the River Lek flowing through the lowlands under a turbulent sky. The actual windmill was much smaller than shown in the painting. The illusion of depth, perspective and subtle colors come together to create a highly naturalistic vision. As a result, the windmill appears to be of the right proportions, since the other elements of the surroundings all come together at its silhouette. A few women walking along the riverside path, shown as pale shapes, do not draw our attention away from the main element. The town buildings in the distance, the shrubs and the women are all essential elements of the landscape, painted in meticulous detail and enhanced by the diffuse sunlight. The windmill is positioned at the intersection of the outlines of the sky, water,

and land. It is a cylindrical construction with a single small window and a balustraded balcony encircling the building about halfway up. The artistic illusions serve to emphasize the realism; the artist uses them to create a vision of the world in accordance with his imagination.

The nearby coast, ubiquitous waterways, mists and sunlight glowing through the clouds all make paintings depicting the Netherlands of that time extremely intimate artworks. Their atmosphere comes from the diffuse light bringing together all elements of the landscape into an almost monochromatic whole. Van Ruisdael saw the landscape through a veil of mist which blurred contours or distorted them into forms creating an illusion of optical imperfection. He intertwined traditions of almost monochromatic painting with a luminosity bringing warmer tones.

Ernst Gombrich wrote about Jacob van Ruisdael that as he was growing up, masterpieces by Jan van Goyen and even Rembrandt were already widely acclaimed, so they would have influenced his style and choice of subjects: "During the first half of his life he lived in the beautiful town of Haarlem, which is separated from the sea by a range of wooded dunes. He loved to study the effect of light and shade on these tracts and specialized more and more in picturesque forest scenes. Ruisdael became a master in the painting of dark and sombre clouds, of evening light when the shadows grow, of ruined castles and rushing brooks. In short it was he who discovered the poetry of the northern landscape" (E.H. Gombrich, *The Story of Art*, 1950, Phaidon).

Van Ruisdael was also described as a poet of the paintbrush by Goethe¹ and by the great Polish romantic poet, Adam Mickiewicz.² From a scholarly point of view, his paintings are an accurate reflection of the ideas of the era. The regained independence, freedom and right to their land inspired artists to depict the Netherlands as they saw it and as they wanted to show it to the future generations. It is notable that they shied away from portraits of national heroes and historical and battle scenes. The Protestant religion and culture was more attuned to landscape and genre painting. Dutch artists turned their attention to the natural world, creating images of a beautiful land worth preserving for the future. Jacob van Ruisdael consciously chose the windmill as a symbol of the Netherlands. ■

¹ J.W. Goethe, *Ruisdael the Poet*, 181.

² "As for painting: for a picture one requires viewpoints, grouping, ensemble – and sky, the Italian sky! Hence in landscape art Italy was, is, and will be the country of painters. Hence also, except for Breughel – not Van der Helle, but the landscapist, for there are two Breughels – and except Ruysdael, in the whole north where has there been a landscape artist of the first rank?" – A. Mickiewicz, *Pan Tadeusz*, trans. George Rapall Noyes, London and Toronto, 1917.

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Opinion of the Committee on Electrical Engineering of the Polish Academy of Sciences on the implementation of nuclear power in Poland,

adopted by resolution on 25 November 2020 at the plenary meeting
of the PAS Committee on Electrical Engineering

1. Introduction

The need to develop nuclear power in Poland is warranted by the necessity to safeguard, in the long-term, the operational security of the Polish National Electric Power System (NEPS), which in turn is essential for ensuring the continuity of electricity supply to industrial recipients, transport, services and households.

Continuous and uninterrupted supply of electricity is an aspect of national energy security, which comprises one element of national security, alongside territorial, health, food, water, and digital security.

The Climate Agreement, adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris (12.12.2015), and the decision of the European Council of October 2014 on the level of CO₂ emission reductions in the European Union Member States by 2030 pose a serious challenge to the Polish power sector: implementing – in the first half of this century – energy generation technologies that will bring about a significant reduction in CO₂ emissions. Having signed the Paris Agreement on 27 April 2016 at the UN headquarters in New York, Poland is obliged to implement the provisions of both the Agreement and the European Council decision of October 2014. The most important tasks resulting from these agreements concern the electricity generation sector [7, 8].

This opinion attempts to outline a long-term strategy for the development of the Polish power generation sector, including a solution to the CO₂ emission reduction problem. As a starting point for an attempt to solve this issue, Article 5 of the Constitution of the Republic of Poland was adopted. This provision stipulates that Poland ensures environmental protection in keeping with the principle of sustainability. In relation to sustainable development of the power system, this principle can be summed up by stating that the system should safeguard economic development of the country, while protecting the balance of the ecosystem. Taking this into account, the sustainable development of the electric power generation sector should meet the following four criteria: (1) ensure the secure operation of the National Electric Power System (NEPS), (2) ensure the availability of low-cost (generated at the lowest possible cost) electricity that promotes the economic development of the country, (3) ensure economical consumption of non-renewable primary energy resources, and (4) ensure the protection of the environment and prevent climate change by minimizing CO₂ emissions per amount of electricity generated (kg CO₂/kWh) [10].

When searching for a solution to the problem of sustainable development of generation sources in the NEPS, the issue is to strike a balance between the environmental protection goals, the electricity generation costs and the security of its supply.

2. Status of generation sources in the National Electric Power System

As of 31.12.2019 the installed capacity of generation sources in the National Electric Power System (NEPS) was about 46.6 GW, with 36.0 GW of that in power plants and 10.7 GW in combined heat and power (CHP) plants. On the other hand, the generating capacity of generation units operating in power plants and CHP plants was approx. 36.1 GW and 10.3 GW, respectively [3].

The largest generation potential of power plants' installed capacity is offered by condensing steam units, with a total installed capacity of approx. 26.2 GW and a maximum generating capacity of approx. 26.3 GW. These include 6 modern supercritical steam units with a unit capacity ranging from 460 MW to 1,075 MW, fired by hard coal and lignite, 90 subcritical steam units with a unit capacity ranging from 60 MW to 560 MW, fired by hard coal and lignite, 3 subcritical steam units, burning coke oven gas, and 4 subcritical steam units, fired by biomass. A significant generation potential, very important for the NEPS's operation, is represented by 11 units in pumped-storage hydroelectric power plants with a total capacity of 1,413 MW and over 2,500 units in run-of-river power plants with a total capacity of approx. 983 MW. The capacity of the power plants using renewable energy sources (RES), in addition to the capacity of the already mentioned hydroelectric power plants and biomass-fired power plants, comprises the capacity of onshore wind and photovoltaic power plants of 5,898 MW and 1,526 MW, respectively [4].

The second group of generation sources operating in the NEPS consists of combined heat and power (CHP) units. Their total installed electricity capacity is approx. 10.7 GW, which accounts for about 23% of the installed capacity in the NEPS. In 2018 cogeneration generated electricity accounted for about 16.4% of all electricity generation in Poland and for about 21.5% of electricity sold to end users [4], while the share of heat generated in CHP plants in the total production of system heat was approx. 65% [5]. The combined heat and power generation units exhibit significant technological diversity. The largest production potential is offered by CHP steam units, whose electrical installed capacity is approx. 7.9 GW, representing about 73.8% of the electrical capacity of all cogeneration sources operating in the NEPS. These include CHP units fired by hard coal, natural gas, coke oven gas, biomass and municipal waste. The modern CHP units are natural gas-fired gas-steam CHP units, built in 1999–2018, with a total installed electrical capacity of approx. 2,080 MW. They employ gas turbines from leading companies, such as General Electric, Siemens, Ansaldo and Solar Turbines. One interesting group of CHP units are natural gas-fired simple-cycle gas turbine CHP units, with a total installed electrical capacity of about 194 MW.

Cogenerational gas-fired CHP units with gas engines, with a total installed electrical capacity of over 500 MW, are an important and developing technology. These CHP units burn natural gas or gas from mine degassing or biogas produced in the process of biological conversion of biomass chemical energy into biogas chemical energy in biogas plants (agricultural, sewage treatment plants and municipal waste landfills). There are also several biomass-fired Organic Rankine Cycle (ORC) CHP units operating in the NEPS, with a total installed electrical capacity of about 11 MW [4]. Out of more than 760 different types of CHP units operating in the NEPS, only 4 (2 steam units and 2 gas-steam units), with a total installed electrical capacity of approx. 1,380 MW, function to a limited extent as centrally dispatched generation units (CDGUs) in the NEPS.

In recent years, the NEPS has witnessed a significant increase in the capacity of distributed generation sources (non-CDGUs), particularly in the form of RES-based generation units and, to a lesser extent, cogeneration sources whose operation (output) depends on weather conditions or heat demand in district heating systems. The growth of non-CDGU capacity in the NEPS will continue in the coming years. Therefore, in order to ensure security of NEPS operation, it is necessary to simultaneously increase the new capacity of centrally dispatched generation units (CDGUs), whose capacity in the NEPS will be decreasing due to the decommissioning of coal-fired condensing steam units, while demand for capacity in the NEPS will be growing. The CDGUs operating in the NEPS are highly diversified in terms of energy effectiveness, their technical condition and flexibility in responding to load changes. A significant number of them, with a total capacity of about 10 GW, have been operating in the NEPS for over 40 years and their operation time has exceeded 200,000 hours. Therefore, a significant number of them are expected to be decommissioned in the coming years [11].

3. Security of the National Electric Power System operation

The criteria that need to be met by the sustainable development of generation sources in the NEPS were formulated in the above Introduction. The primary objective of sustainable development of the power system is to ensure security of electricity supply to consumers, while protecting the environment. The

overriding criterion of sustainable development of generation sources in the NEPS is therefore that of ensuring its operational security. The security of the NEPS operation hinges on striking an equilibrium between the demand for electric power and the available capacity of generation sources [1]. The capacity and technical condition of centrally dispatched generation units (CDGUs) are of fundamental importance for ensuring secure and stable operation of the NEPS. Their installed capacity in the NEPS as of 31.12.2019 was about 28.1 GW. They consist of the following: condensing steam units fired by hard coal and lignite, with a unit capacity of more than 200 MW, connected mainly to the 440 kV and 220 kV transmission grid and partially to the 110 kV distribution grid, pumped-storage hydroelectric units, two coal-fired CHP steam units and two new CHP combined cycle units of 465 MW and 630 MW, fired with natural gas. Of the total CDGU capacity, 87.6% is represented by coal-fired steam units, of which:

- 8 steam units with a unit capacity of 125 MW and 3 steam units with a unit capacity of 200 MW have been operating in the NEPS for at least 50 years,
- 22 steam units with a unit capacity of 200 MW have been operating in the NEPS for 46 to 50 years,
- 16 steam units with a unit capacity of 200 MW have been operating in the NEPS for 40 to 45 years.

These coal- and lignite-fired units will most likely be decommissioned in the next ten to twenty years. By that time, only two new coal-fired supercritical steam units with a total capacity of 1,406 MW (in Jaworzno and Turów power plants), two condensing gas-fired gas-steam units with a total capacity of 1,400 MW (in Dolna Odra power plant) and two natural gas-fired gas-steam CHP units with a total capacity of 966 MW (in Stalowa Wola CHP plant and Żerań CHP plant) will be added to the NEPS. This will result in a serious shortage of CDGU capacity in the NEPS that will threaten its operational security and, therefore, there will be a need to replace the decommissioned coal-fired condensing steam units with new zero-emission CDGUs characterized by continuity and stability of operation – at present, these can only be nuclear units.

By 2040, only supercritical coal-fired steam units and subcritical steam units with a unit capacity of 360 MW and 500 MW as well as a certain portion of steam cogeneration units are likely to remain in operation in the NEPS and by 2050 the only ones remaining will be supercritical condensing steam units and some cogeneration steam units. Therefore, a very important challenge in the necessary technological transformation of generation sources in the NEPS is posed by the fuel transformation of CDGUs, which are decisively responsible for its operational security.

Poland's scarce domestic resources of natural gas, the limited resources of the fuel globally, the lack of a fully liberal international market for it and its high per-unit energy cost (approx. 30 PLN/GJ) make it impossible, in the long term, to consider natural gas as a strategic fuel for low-emission CDGUs, which are intended to ensure security of the NEPS operation. Moreover, gas-fired condensing gas-steam units are also a source of CO₂ emissions at a level of approx. 45% of emissions from coal-fired power plants. Therefore, from the point of view of NEPS operation security, CDGUs in the form of coal-fired condensing steam units being withdrawn from operation should be replaced by zero-emission nuclear units, and they may only be partially replaced by natural gas-fired gas-steam CHP units. Natural gas in the electric power industry in Poland should be used primarily as a fuel for high-efficiency CHP units whose overall efficiency (conversion of chemical energy of fuel into electricity and heat) exceeds 80% [2].

The required capacity of CDGUs to ensure secure and stable operation of the NEPS depends on the following factors: the electric power demand at the NEPS winter and summer peaks, average annual electric power demand, and the available capacity of non-CDGUs. Projected values of gross electricity consumption, the NEPS load in the winter and summer peaks, the required capacity of CDGUs and the capacity of distributed sources (non-CDGUs) are presented in Table 1, cumulatively for 2020, 2025, 2030 and 2035. The projected values of gross electricity consumption were determined on the basis of an analysis of annual increments in this consumption in the NEPS for 2000–2019, assuming an annual growth rate of 1.27% for 2020–2050. The projected demand for NEPS peak capacity for the winter and summer peaks as well as planned decommissioning of CDGUs was based on a study by the grid operator, PSE S.A. [11].

Table 2 presents a forecast of the desired capacity structure of power plants and CHP plants as well as of electricity production in Poland in 2030, 2040 and 2050. The forecast was guided by the following assumptions: (1) the capacity of CDGUs, required for secure operation of the NEPS, includes the capacity of power units of system power plants, fired by coal and nuclear fuel, the capacity of gas-fired

Table 1.
Forecast capacity balance in the NEPS in 2020-2035

Volume	Year			
	2020	2025	2030	2035
Forecast gross electricity consumption [TWh]	179.1	190.7	203.1	216.4
Projected winter peak demand for peak capacity [GW]	28.0	30.3	32.7	35.2
Projected summer peak demand for peak capacity [GW]	24.8	27.5	30.5	32.7
Planned decommissioning of CDGUs [GW]	1.8	2.5	4.7	13.6
Planned construction of new CDGUs (steam, coal-fired and gas-steam, natural gas-fired) [GW]	1.9	3.8	3.8	3.8
Projected capacity of CDGUs after decommissioning and construction of planned new CDGUs [GW]	28.2	29.4	27.2	18.3
Projected capacity of distributed sources (non-CDGU) [GW]	17.0	21.0	25.0	31.3
Required new capacity of CDGUs [GW]			3.0	6.0

Table 2.
Forecast desired power plant and CHP plant capacity structure and electricity generation structure in 2030, 2040, and 2050

Primary energy type (fuel or RES type)	Forecast desired power plant and CHP plant capacity structure and electricity generation structure in 2030, 2040, and 2050								
	2030			2040			2050		
	GW	TWh	%	GW	TWh	%	GW	TWh	%
Hard coal and lignite	28.3	127.1	62.6	18.5	79.2	34.3	9.5	43.7	16.7
Nuclear fuel				5.0	39.4	17.1	9.0	70.9	27.1
Natural gas	5.0	21.2	10.4	6.8	28.6	12.4	9.4	39.5	15.1
Biomass and biogas	2.6	10.4	5.1	3.0	12.0	5.2	3.8	16.0	6.1
Water	2.5	2.7	1.3	2.7	2.9	1.3	2.8	3.0	1.1
Wind	11.2	29.8	14.7	17.0	47.5	20.6	21.5	63.7	24.4
Sun	12.5	11.9	5.9	22.0	20.9	9.1	26.0	24.7	9.5
Total	62.1	203.1	100.0	75.0	230.5	100.0	82.0	261.5	100.0

condensing and CHP units, with a unit electrical capacity exceeding 200 MW, fired by natural gas, the capacity of cogeneration steam units with extraction-condensing turbines, with a unit electrical capacity exceeding 100 MW, fired by coal, and the capacity of pumped-storage hydroelectric power plants, (2) generation units of small capacity (dispersed sources), due to the required high energy effectiveness (optimal use of primary energy) – with the exception of wind, hydro and photovoltaic power plants – should be built only as CHP units [2], and (3) the projected capacity of nuclear power plants and power plants and CHP plants using renewable energy sources (RES) is based on the capacity needed to ensure the operational security of the NEPS and to fulfill Poland's international commitments to reduce CO₂ emissions, resulting from the Paris Agreement and the decision of the European Council of October 2014.

4. Nuclear power development in the world

As of 31 December 2019, there were 443 nuclear units in operation in 30 different countries around the world, with a total capacity of 392,098 MW. In 2019 they produced 2,586.2 TWh of electricity, accounting for 10.4% of total global electricity generation. The nuclear units currently in operation predominantly employ pressurized water reactors (PWRs), installed in 300 units, boiling water reactors (BWRs) present in 65 units, pressurized heavy-water reactors (PHWRs) – 48 units, gas-cooled reactors (GCRs) – 14 units (only in the UK), light-water boiling reactors (LWGR) – 13 units (only in Russia as RBMK reactors), plus fast breeder reactors (FBR) operating in 3 units (2 in Russia and 1 in China). The number of reactors and the capacity of nuclear power plants and the electricity produced by them in 2019 are shown in Table 3 [6].

Table 3.
Number of nuclear power units in operation and nuclear electric power capacity and production, as of 31.12.2019

No.	Country	Number of units (reactors)	Nuclear power plants capacity [MW]	Electricity generation in nuclear power plants [TWh]	Share of nuclear power plants in total electricity generation [%]
1	France	58	63,130	382.4	70.6
2	Slovakia	4	1,814	14.3	53.9
3	Ukraine	15	13,107	78.1	53.9
4	Hungary	4	1,902	15.4	49.2
5	Belgium	7	5,930	41.4	47.6
6	Bulgaria	2	2,006	15.9	37.5
7	Slovenia	1	688	5.5	37.0
8	Czechia	6	3,932	28.6	35.2
9	Finland	4	2,794	22.9	34.7
10	Sweden	7	7,740	64.4	34.0
11	Armenia	1	375	2.0	27.8
12	South Korea	24	23,172	138.8	26.2
13	Switzerland	4	2,960	25.4	23.9
14	Spain	7	7,121	55.9	21.4
15	US	96	98,152	809.4	19.7
16	Russia	38	28,437	195.5	19.7
17	Romania	2	1,300	10.4	18.5
18	UK	15	8,923	51.0	15.6
19	Canada	19	13,554	94.9	14.9
20	Germany	6	8,113	75.1	12.3
21	Japan	33	31,679	65.7	7.5
22	South Africa	2	1,860	13.6	6.7
23	Pakistan	5	1,318	9.1	6.6

No.	Country	Number of units (reactors)	Nuclear power plants capacity [MW]	Electricity generation in nuclear power plants [TWh]	Share of nuclear power plants in total electricity generation [%]
24	Argentina	3	1,641	7.9	5.9
25	China	48	45,518	330.1	4.9
26	Mexico	2	1,552	10.9	4.5
27	India	22	6,255	40.7	3.2
28	Netherlands	1	482	3.7	3.1
29	Brazil	2	1,884	15.2	2.7
30	Iran	1	915	5.9	1.8
World		443	392,098	2,586.2	10.4

On the other hand, as of 31 December 2019 there were 60 more nuclear power units under construction, with an expected total capacity of 63,271 MW. New nuclear power units are being built primarily in Asian countries (40 units), namely: in China (16), India (9), South Korea (4), the United Arab Emirates (4), Bangladesh (2), Japan (2), Pakistan (2) and Iran (1), and in European countries (16 units), namely: Russia (4), Belarus (2), Slovakia (2), Turkey (2), Ukraine (2), the UK (2), Finland (1) and France (1). The remaining 4 nuclear units are being built in North and South America, namely in the United States (2), Argentina (1) and Brazil (1). In the coming years Bangladesh, Belarus, Turkey and the United Arab Emirates will join the club of nuclear power plant users. Among the 60 new nuclear units under construction, PWRs predominate (49 reactors), the others being as follows: 6 PHWRs (India), 2 ABWRs (Japan), 2 FBRs (China and India) and 1 HTGR (China). The number of units and reactor types under construction are shown in Table 4 [6].

Table 4.
Nuclear power units under construction, as of 31 December 2019

No.	Country	Number of units (reactors)	Reactor types	Total capacity [MW]
1	China	16	10 (Hualong One), 2 (CAP 1400), 2 (ACPR), 1 (HTGR), 1 (SFR 600)	16,600
2	India	9	6 (PHWR), 2 (VVER-1000), 1 (FBR 470)	6,084
3	South Korea	4	4 (APR-1400)	5,360
4	Russia	4	2 (VVER-1200), 2 (VVER-TOI)	4,525
5	UAE	4	4 (APR-1400)	5,380
6	Bangladesh	2	2 (VVER-1200)	2,180
7	Belarus	2	2 (VVER-1200)	2,220
8	Japan	2	2 (ABWR)	2,653
9	Pakistan	2	2 (Hualong One)	2,028
10	Slovakia	2	2 (VVER-440)	880
11	Ukraine	2	2 (VVER-1000)	2,070
12	Turkey	2	2 (VVER-1200)	2,228

No.	Country	Number of units (reactors)	Reactor types	Total capacity [MW]
13	US	2	2 (AP1000)	2,234
14	UK	2	2 (EPR)	3,260
15	Argentina	1	1 (CAREM 25)	25
16	Brazil	1	1 (PRE KONOI)	1,340
17	Finland	1	1 (EPR)	1,600
18	France	1	1 (EPR)	1,630
19	Iran	1	1 (VVER-1000)	974
Total		60		63,271

The largest market shares in building new nuclear units are held by: China – 18 units, Russia (Rosatom) – 17 units, South Korea – 8 units, India – 7 units, and France (EdF) and the United States (Westinghouse and GE) – 4 units each. Chinese nuclear power companies are building 16 units in China and 2 in Pakistan. Russia’s Rosatom is constructing nuclear units in the following countries: Russia (4), Bangladesh (2), Belarus (2), India (2), Slovakia (2), Turkey (2), Ukraine (2), and Iran (1). This company is building nuclear units with several types of PWR power reactors, including the VVER 440, VVER 1000, VVER 1200 and VVER TOI. The Korean Hydro and Nuclear Power (KHNP) company is building 4 units with APR 1400 reactors in South Korea and 4 units with the same reactors in the United Arab Emirates. Nuclear Power Corporation of India Limited (NPCIL) is building 6 PHWR 700 units and 1 FBR 470 unit in India. France’s EDF is building 1 EPR unit in Finland, 1 EPR unit in France and 2 EPR units in the UK. Westinghouse is building 2 AP1000 units in the United States and the US-Japanese group General Electric Hitachi Nuclear Energy (GEH) is building 2 ABWR units in Japan.

In addition to the 60 new nuclear units under construction, many countries are planning further nuclear generation units, most notably China (81), India (36), Russia (32), Turkey (10) and South Africa (8). There are plans to build a total of more than 240 nuclear units worldwide, the vast majority of them with PWRs installed, as the most mature designs and the safest to operate.

Australia is among the countries planning to enter the path of nuclear power development. In 2019 it produced 256.6 TWh of electricity in total, of which as much as 56.39% was generated from coal. The Australian House of Representatives Standing Committee on the Environment and Energy conducted an inquiry and produced a report based on it, entitled “Not without your approval: a way forward for nuclear technology in Australia.” Citing data collected by the Massachusetts Institute of Technology (MIT) among other sources, this report states that the Commission found evidence that nuclear power has the lowest mortality rates of all power generating technologies, namely per PWh of electricity generated from coal it ranges from 15,000 deaths/PWh in the United States to 90,000/PWh in China, from oil – 36,000/PWh, from natural gas – 4,000/PWh, from hydro – 1,400/PWh, from solar – rooftop – 400/PWh, from wind 150/PWh, and from nuclear – 90/PWh. The Commission’s Chair Ted O’Brien, in discussing the results of the inquiry on Sky News, stated that nuclear power “is the safest form of energy.” It should be noted here that Australia is one of the largest producers and exporters of coal in the world.

It is also worth noting that another large producer of electricity from coal (89.06% in 2019), South Africa, already operates two large power units with PWR reactors, with a total capacity of 1,860 MW, and plans to build further 8 large units with PWR reactors, with a total capacity of 10,400 MW. Nuclear power development is also planned by another large producer (3rd in the world), user and exporter (1st in the world) of coal, namely Indonesia, which produces approx. 255 TWh of electricity per year, of which over 58% from coal. The country plans to build 6 Russian nuclear units, VVER 1000 and VVER 1200, by 2030, with a total capacity of 6,800 MW.

An extensive nuclear power development program is also in place in a country similar in scale to Poland, namely in Vietnam. It intends to build one 1,000 MW nuclear unit by 2040, and further 4 units of the same size by 2045, despite the fact that it has significant hydropower capacity that in 2019

produced almost 31% of the country’s electricity. Egypt and Kenya are the second and third African countries, after South Africa, to embark on the path of nuclear power development. Egypt, which is Africa’s second largest electricity producer, has a grand plan to build 8 nuclear units, in two phases of 4 units each, with a total capacity of 9,600 MW. The construction of the first unit is expected to begin in 2021. Kenya’s Nuclear Energy Agency announced on 5 August 2020 that it had applied for approval to build a 1,000 MW nuclear unit expected to come online in 2027, along with plans to increase Kenya’s nuclear capacity to 4,000 MW by 2035.

Several Central European countries, such as Bulgaria, Czechia, Romania, Slovakia, Slovenia and Hungary, are making intensive preparations to start building new nuclear power plants or to increase the capacity of their existing ones.

The impact of nuclear power generation on zero-carbon electricity production in selected countries in 2019 is shown in Table 5. This list includes 12 European Union Member States.

Table 5.
Share of electricity generation from zero-carbon sources in selected countries in 2019

No.	Country	Share of electricity generation from zero-emission sources [%]	Share of electricity production from RES sources [%]	Share of electricity generation in nuclear power plants [%]
1	Sweden	98.91	58.91	40.00
2	Switzerland	98.80	65.50	32.30
3	France	88.82	17.96	70.86
4	Brazil	85.22	82.63	2.59
5	Finland	81.18	47.89	33.29
6	Canada	80.62	65.40	15.22
7	Slovakia	79.63	25.27	54.35
8	Belgium	70.58	21.82	48.76
9	Slovenia	67.54	29.02	38.52
10	Hungary	60.36	11.38	48.98
11	Spain	59.21	38.04	21.17
12	UK	56.63	39.27	17.36
13	Germany	56.35	44.09	12.26
14	Romania	55.64	38.32	17.90
15	Bulgaria	49.04	14.95	34.09
16	Czechia	45.18	12.62	32.56
17	US	36.96	17.60	19.36
18	Russia	36.62	17.93	18.69
19	China	36.23	27.43	3.90
World		37.24	26.89	10.35

All told, there have been three major nuclear power plant accidents in the over 65-year history of nuclear power: 28 March 1979 at the Three Mile Island plant, 26 April 1986 at the Chernobyl plant, and 11 March 2011 at the Fukushima Daiichi nuclear power plant. In all of these accidents, the reactor core melted due to the loss of coolant caused by failures of the primary and emergency cooling systems, as well as erroneous decisions by the operators. Therefore, after these accidents, great attention was paid to

the design of passive backup reactor core cooling systems. No accident in the history of nuclear power has resulted in an uncontrolled nuclear reaction.

The above-discussed accidents have contributed to a slowdown in the development of nuclear power in the world. However, despite the losses incurred, most of the companies involved in building power equipment for nuclear power plants have learned the right lessons from these accidents. New reactor designs were developed, characterized by improved safety of operation, in particular Generation III+ reactors, and conditions were created for a return to dynamic development of this energy sector. At that seemingly critical time, new countries, such as China and South Korea, appeared on the map of nuclear companies. Together with Russia, they are today – at a time when the balance of the ecosystem is under threat – giving new impetus to the development of nuclear power in the world, when the need for zero-carbon, stable sources of electricity to ensure the secure operation of electricity systems has increased significantly.

5. Cost of electricity generation in nuclear power plants

The implementation of nuclear power in Poland involves a number of important issues, including not only societal acceptance but also economic efficiency. The cost structure in nuclear power generation is characterized by heavy financial expenditure on the construction of a power plant, followed by low operating costs, including fuel costs. One of the major economic criteria of an investment project in the field of power generation sources is the projected per-unit electricity generation costs, discounted for the year of project start-up, taking into account the impact of both capital expenditure and operating costs. Calculations of these costs made for the purposes of this opinion support the conclusion that per-unit costs of electricity generation in nuclear power plants, as discounted for 2020, under Polish conditions, are comparable to the same costs (including the costs of CO₂ emission allowances) in system power plants fired by fossil fuels (i.e. in coal-fired steam plants and natural gas-fired combined cycle plants), being on the level of 350–360 PLN/MWh. Significant differences exist in the fuel component of these costs, with the costs of CO₂ emission allowances, as shown in Table 6.

Table 6.
Projected unit electricity generation costs in system power plants (CDGUs),
with costs of CO₂ emission allowances, discounted for 2020

No.	Type of generation unit	Unit electricity generation costs, including the costs of CO ₂ emission allowances [PLN/MWh]	Costs of fuel and CO ₂ emission allowances in unit electricity generation costs [PLN/MWh]
1	Lignite-fired supercritical steam unit	350	181
2	Hard coal-fired supercritical steam unit	355	189
3	Natural gas-fired combined cycle unit	360	218
4	Nuclear unit with Generation III+ PWR	352	49

A sensitivity analysis of the impact of a nuclear power plant’s specific design and operating parameters on its economic efficiency supports the conclusion that unit electricity generation costs in nuclear power plants discounted for 2020 are most affected by unit capital expenditure, the time of use of the installed capacity and the discount rate (cost of capital). The fuel price and power plant lifespan, on the other hand, have a much smaller impact on these costs. A 10% decrease in unit capital expenditure or a 10% increase in the time of use of the installed capacity would reduce unit electricity generation costs by 7.67%, whereas a 10% decrease in the discount rate would lower unit electricity generation costs by 7.38%. In contrast, a 10% increase in the fuel price would increase the per-unit cost of electricity gener-

ation by only 1.45%. This is important in assessing the risks associated with future fuel prices and their impact on electricity generation costs.

These results indicate that at the stage of preparing an investment related to the construction of a nuclear power plant, efforts should be made to seek ways to reduce unit capital expenditure and the discount rate. Experience from nuclear power plants currently under construction in several countries around the world shows that significant savings can be achieved in capital expenditure when constructing two twin units simultaneously, particularly in terms of the labor involved in reinforcing and laying the concrete foundations for the reactor, safety housing and the cooling system. This is why over 80% of current nuclear power plant construction projects involve building two twin units, with a slight time lag of six months to a year between them. Significant savings in capital expenditure can also be achieved through proper preparation of the project, enabling it to be carried out according to schedule, without prolongation. A very important problem with as capital- and time-intensive project as the construction of a nuclear power plant is the cost of capital (the capital discount rate). State involvement, in the form of loan guarantees and purchase of generated electricity at a guaranteed price, has a great influence on lowering this cost. In addition, we are currently witnessing historically low interest rates, making the cost of capital low not only in Poland but worldwide, thus making for a good moment to invest in the nuclear power sector. Experience gained from EdF's construction of nuclear units at the Hinkley Point C power station in the UK shows that almost two-thirds of the value of construction contracts are being carried out by domestic companies. All these aspects, including the Polish State's involvement in the nuclear power plant construction, should be factored into in the project's financial model (financial plan) [9].

Another important issue related to the implementation of nuclear energy in Poland is international cooperation, including among the European Union (EU) Member States. The EU should promote the development of the nuclear industry in its Member States and include nuclear power in the European Green Deal and support programme, alongside renewable energy sources (RES), since without nuclear power it will be unable to meet its climate commitments. Among those to have pointed out this fact is the Prime Minister of Slovakia, who has called for setting up a European alliance of countries using nuclear energy in order to make it easier for the countries which do not yet have nuclear power plants to implement this technology. At present, nuclear power plants are operating in 13 EU Member States, allowing the European Union to achieve the world's largest share of zero-carbon nuclear electricity generation in its total production, namely 25.15% in 2018.

6. Summary

The analyses included in this opinion support the following conclusions:

1. Poland's commitments under the signed Paris Agreement (2015) and the decision of the European Council of October 2014, as well as the condition of generation sources in the Polish National Electric Power System (NEPS), especially of the centrally dispatched generation units (CDGUs), of which several dozen with a total capacity of about 10 GW will have to be decommissioned already in the coming years, pose a serious challenge to the Polish electric power sector in terms of the fuel and technological transformation of generation sources in the NEPS.
2. Technological transformation of generation sources in the NEPS needs to take into account the sustainable development criteria, the most important being to ensure the security of NEPS operation and environmental protection, including striving for climate neutrality. This forces the Polish electric power sector to face the challenge of starting to build a secure, zero-emission power system that should hinge on two pillars: nuclear power plants and power plants using renewable energy sources (RES), including onshore and offshore wind power plants and photovoltaic power plants.
3. A long-term strategy of sustainable development of the electric power system, leading to climate neutrality, in a country that lacks substantial economic hydropower resources that might enable it to construct high-capacity hydroelectric power plants in the power system to ensure its secure and stable operation, can only be based on a combination of RES and nuclear energy development. Without nuclear power, it will not be possible for Poland to achieve the goal of climate neutrality.

4. In recent years, modern Generation III+ pressurized water reactors (PWR), characterized by high safety and operational reliability, such as the AP 1000 (Westinghouse), EPR 1650 (EdF), VVER 1200 (Rosatom), Hualong One (CNNC) and APR 1400 (KHNP), have been launched and integrated into power systems in a number of countries. Thus, the beginning of nuclear power development in Poland will be at a time when the pressurized water reactor technology has reached its full design and operational maturity worldwide.
5. There are two important problems that need to be solved for Poland to embark upon the path of nuclear power development, namely societal acceptance and the economic effectiveness of the associated investment project. Both problems are solvable. A rational, evidence-based debate and development perspective for a particular region should convince the local community that nuclear power based on proven and safe technology is a good solution. Adoption of a financial model for the investment project in which the Polish State will be involved, in consortium with the supplier of reactors and basic power equipment, with guarantees of purchase of produced electricity, should enable – in the shortest time possible – the launch and timely completion of projects related to the nuclear power program in Poland, moving on to safe operation in a long-term horizon, with relatively low costs of electricity generation that remain almost constant over time.
6. The implementation of nuclear power in Poland would contribute to assuring the secure operation of the National Electric Power System, thus improving Poland's energy security, increase fuel diversification in the Polish electric power generation sector, stabilize production costs and thus electricity prices for consumers in the long term, and also significantly reduce CO₂ emissions and bring our country closer to achieving the goal of building a secure and zero-emission power system, and thus to achieving the Paris Agreement goal of climate neutrality.
7. The fuel and technological transformation of generation sources in the National Electric Power System will be a long-term process, spanning about 30 years. During this time, many sectors of the economy, including the hard coal and lignite mining industry, will be able to transform, availing to a large extent of the opportunities created by the development of zero-carbon generation technologies in the power industry.
8. Implementation of nuclear power in Poland will require more intensive training of specialists and the advancement of research work in this field.

Further reading:

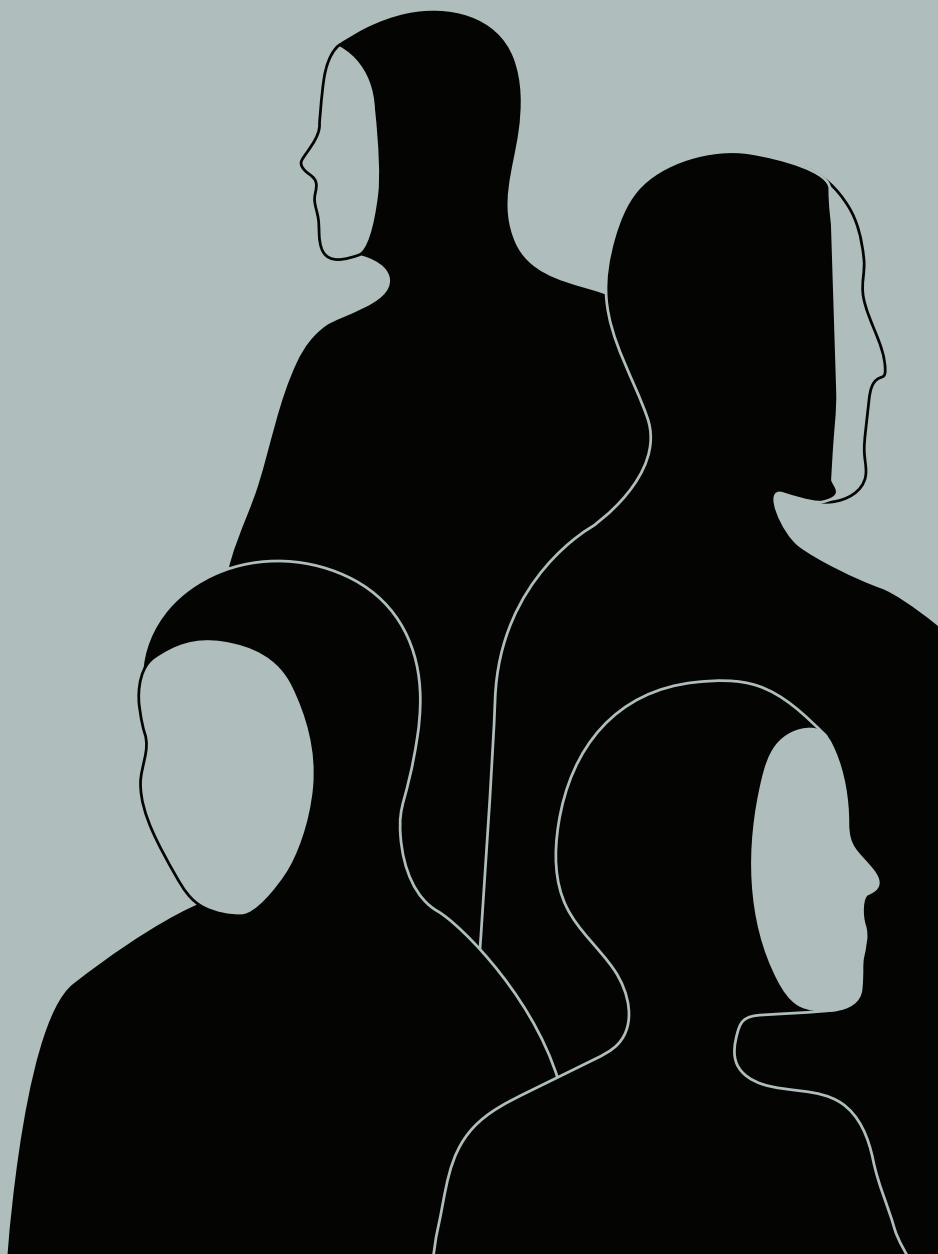
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INDIFFERENCE

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Ενέργεια: From the Potential to the Actual



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Since antiquity, philosophers have wanted to know what the world is made of. But they have also wondered what sets it in motion. Where does this force that effects change, overcomes inertia, and leads to development come from, and how does it operate? Is it inherent in all matter? Does it stem from the way matter is constituted? Or maybe it is external and timeless, preceding and simultaneously shaping all that is material? This force had the power to transform disorder and chaos into a structured order that was at least partially comprehensible.

The story of how the universe was born also merits careful consideration of the nature of the energy precipitating its birth. What triggered this eruption of energy? Was that process random or, on the contrary, marked by purposefulness even before it all began? Is it possible to find and use this primordial energy? Is it present in our everyday lives? What is left of it? What (or maybe who?) is or was it? Who or what was its source?

The concept of energy is one of the central topics raised in Aristotle's *Metaphysics*. Energy (ἐνέργεια) is the vitality, activity, and force thanks to which a being turns from potential to actual. This would make it something formal in nature. Energy could be described as the force thanks to which potentiality, which is contained in primordial matter, starts the process of its actualization, which is accomplished in the process of its achieving form. According to Aristotle, this is because the proper object of study is intrinsic being, which he calls substantial being, whose structure is always composed of matter and form, or hylomorphic. Here, form means the conceptual component of a thing; it refers to those properties of substance that can be defined. As such, it is the essence of a thing, its actuality and reality. It could be said that it is thanks to form that we can say that a pot is a pot, a tree is a tree, and a human is a human. The specifics, in turn, are determined by matter, which contains individual differences that determine that a specific human is me, and not someone else. We can talk about two meanings of "matter": one is narrower and refers to what a specific thing is simply made of (wood, gold, stone), whereas the other pertains to what is not a concrete thing, nor a quantity, nor any category that determines and defines being.

We cannot cognize matter in this primary sense, because it has no concept – it is pure potentiality, undifferentiated possibility. Its individual substances are only extracted from it by the energy of form, and they are what we can cognize. Since activity is the nature of form, Aristotle argues that activity, or energy, is the essence of being. The world is described as the continuous motion from the potential to the actual. This transition takes place within the order of four causes: the material cause, the formal cause, the efficient cause, and the final cause. Each of them can be described using the concept of energy, which is the driving force behind the mechanism of all emerging, doing, creating, and acting. To gain a better grasp of this order, we could use the metaphor of a house in which the material cause is formed by bricks, concrete, wood, and so on, the formal cause by the design made by an architect, the efficient cause by the builders who will build the house based on the design, and the final cause by the purpose it was built to serve, which here means the desire to have a place to live.

Changes taking place in the world are based on the transition from the potential to the actual. This transition is driven by energy, which following Aristotle we can call an "act." The process initiated by energy culminates in the full actualization of potentiality, or entelechy (ἐντελέχεια). If energy is



the driving force behind action, activity, and anxiety, then entelechy is actualization, the moment of perfection, fulfillment. In most cases, it is not permanent: substantial beings do not achieve entelechy in order to stop and persist in that state. The actualizing energy continues to operate, no longer as a factor of development, but as a factor of degeneration. I will mercifully not illustrate this mechanism using a human being as an example, but rather propose to take the example of a rose. In full bloom, it reaches the state of the most perfect actualization of its potentiality, it is a rose in the fullest sense of the word, but only to then wither, die, and rot – all the while preserving its matter, because it is the foundation of phenomena and all of their transformations. Substances are composed of matter, which lasts even when a thing itself falls apart.

We still have to ask a question that is crucially important from the perspective of energy: where does it come from? How did this motion begin, thanks to which potentiality becomes an act? In his description of the world, Aristotle did not assume a notion of infinity. The world has its beginning in time and space – each element must be located in its own sphere, and outside the sphere of the last element there is neither matter nor vacuum. This world can be simultaneously described as a process of causally related events where one by necessity leads to the next. Since this chain of causes cannot be endless, because time is finite, this means that there must be a primary cause of all motion, *venerabilis inceptor*, *primus motor*, the prime mover. Aristotle describes the prime mover as what sets everything in motion yet remains unmoved. It is non-complex and there is only one prime mover – it is the efficient and final cause of the world, because it is the ultimate good towards which the world is moving. The prime mover is the only necessary being, and the actuality of his being is happiness – in other words, the prime mover remains in a state of permanent entelechy.

The figure of the prime mover, which Aristotle sometimes calls reason, became an important inspiration for mystics, who tried to find it in contemplation, and for physicists, who searched for an inexhaustible source of energy. It also proved very helpful to St. Thomas, who had the thankless job of trying to reconcile Aristotle's thought with the dogmas of Christianity. Identifying the prime mover with God was certainly a lot more obvious than trying to reconcile empiricism with Augustinian-Platonic rationalism. It is worth noting, however, that the establishment of this view of energy in culture led to the conviction that the most important source of energy did not come from our world at all. Perhaps this was what gave rise to the Anthropocene's extreme irresponsibility. ■

PROMOTING THE DEVELOPMENT OF WIND ENERGY



An image from a study visit
to the Anholt Offshore
Wind Farm in Denmark
(owned by the Danish
energy company Ørsted)

The Polish Wind Energy Association (PWEA) is Poland's largest organization promoting alternative energy sources, mainly onshore and offshore wind power. It is actively involved in consultations on strategic documents and acts of legislation related to the market of renewable energy sources, alternative fuels, and the energy transition. By working together with decision-makers at the EU, national, and local government levels, it aligns various interests to promote Poland's sustainable development. It organizes events bringing together representatives of the sector and decision-makers, including the annual PWEA Conference – the largest such event in Central and Eastern Europe (<http://konferencjapsew.pl/en/>) devoted to prospects for the development of onshore and offshore wind energy in Poland. The Association initiated the establishment of the RE-Source Poland Hub Foundation (<http://resourcepoland.pl/en/>), which shows businesses how they can become part of the trend towards the green transition and sustainable development. It promotes pro-environmental attitudes and knowledge of the environmental, economic, and social benefits of wind energy in the media, on social media (such as <https://www.facebook.com/psew.pwea> and https://twitter.com/PSEW_PWEA), and during the “Summer with the Wind” family summer picnics (*Lato z wiatrem*) held at the Baltic Sea.

For more information about the PWEA, visit <http://psew.pl/en/>.



Photo 1
A platform with an offshore
transformer station
at the Anholt wind farm
in Denmark



Photos 2 & 3
The “Summer with
the Wind” educational
campaign on the benefits
of wind energy development
in seaside resorts
and the Mazury region

Photo 4
The 2020 PWEA conference
in Serock, bringing together
investors and representatives
of the wind energy industry
as well as decision-makers
and representatives of the
government administration

Photo 5
The Wind Energy Industry
Personality of the Year award
ceremony, held annually in
Serock during the largest
wind energy industry
conference in Central and
Eastern Europe





SLAWOMIR SKUKOWSKI

6



ADRIAN MATRACKI

7



ALEKSANDRA KOSKA

8



ALEKSANDRA KOSKA

9

Photos 6, 7 & 8
Photos submitted in the "We care about wind" competition on social media, organized simultaneously with an educational campaign held in seaside resorts during the summer vacation

Photo 9
During a study visit to the Jarocin-Koźmin Wind Farm (owned by WPD Polska), Ms. Jadwiga Emilewicz (then deputy prime minister) descended from a wind turbine on a rope with the assistance of a belayer (after receiving the appropriate training) as part of the demonstration of evacuation procedures

Energy Distorted in Translation

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The word for “energy” in Polish, *energia*, harks back to the same Greek root as its English counterpart. The related Polish noun *energetyka* (roughly: “energetics”), on the other hand, has a narrow, specialized meaning – referring to the “power sector” (the branch of the economy dealing with energy) or “power engineering” (the science of transmitting, storing, harnessing various types of energy). This noun, therefore, invokes energy only in the specialized industrial or scientific sense (roughly the same scope as this issue of *Academia* magazine).

The ordinary adjective derived from the first noun is *energeticzny*, “energetic.” The somewhat longer adjective derived from the second noun, *energetyczny*, might be expected to be similarly restricted in meaning (“related to the power sector”), but nevertheless turns up nowadays in various kinds of texts on everyday subjects. In a fashion column, for instance, we might read that a “red brooch provides an *energetyczny akcent* (energetic embellishment) that catches the eye,” in press coverage of a celebrity New Year’s Eve party we might find a description of the “*energetyczny występ* (energetic performance) by the singer Zenek,” or a political commentary might describe a leader as “courageous and *energetyczny* (energetic).” Everyone in Poland is familiar with *napoje energetyczne* (energy drinks), even if we do not drink them.

Plainly, the longer adjective *energetyczny*, rather than being limited to the scientific/industrial scope,

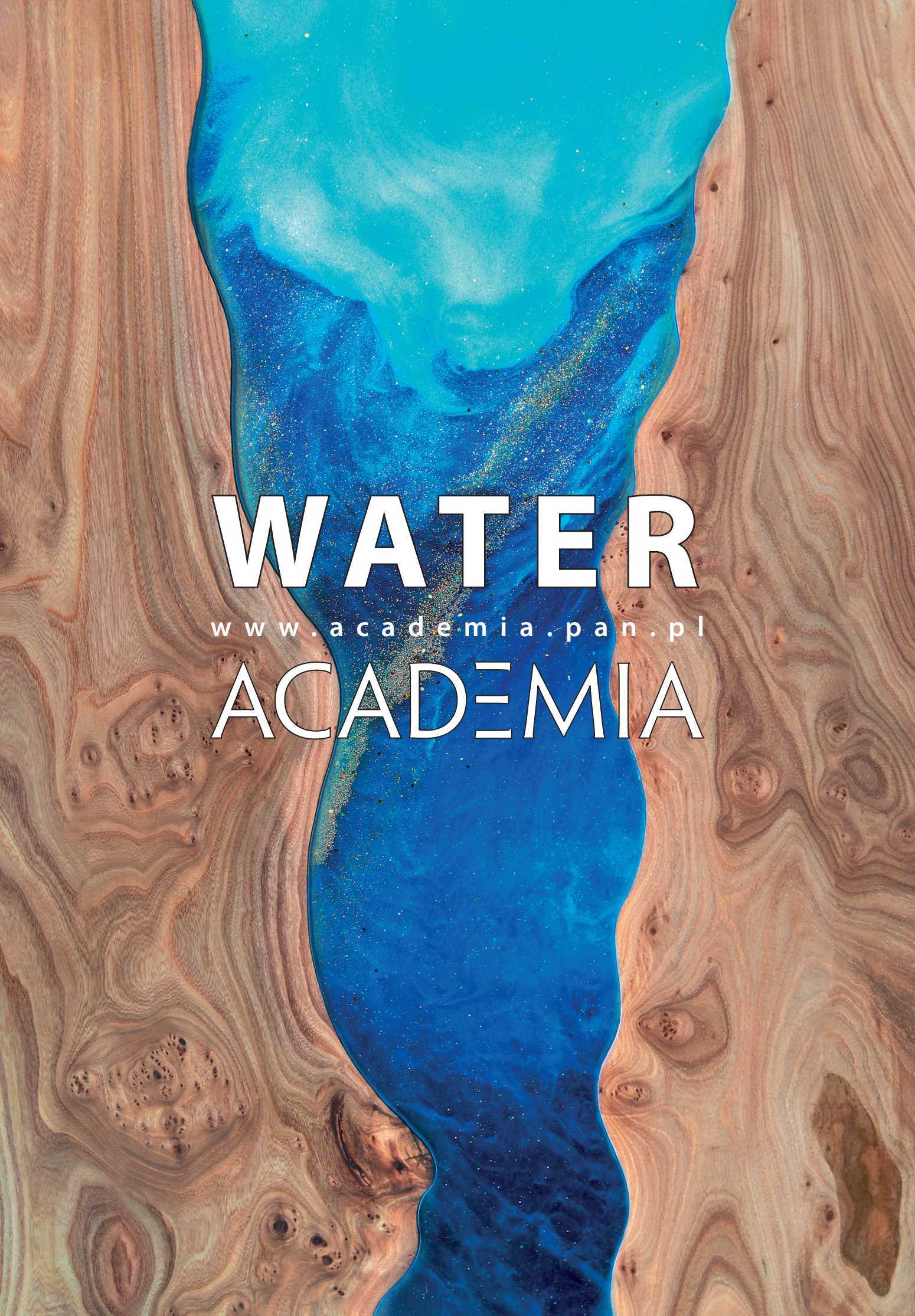
can nowadays describe anything that gives or releases energy (the shorter adjective *energeticzny* still works best in describing behaviors or phenomena that are manifestations of energy, e.g. *energeticzny krok* “energetic step,” *energeticzne działanie* “energetic action”). The puzzle, then, is that in such uses the longer adjective *energetyczny* appears to be derived structurally from *energetyka*, but semantically from *energia*. How did this discrepancy arise?

An answer seems easy to pinpoint: in such uses *energetyczny* is not actually derived from *energetyka* at all, but simply copied from English “energetic,” which means the same as *energeticzny* but is more similar in sound to *energetyczny*. The whole confusion, therefore, is probably due to the laziness of amateurish translators, translating English texts into Polish with insufficient attention (professionals would never fall into this trap). All too often, someone must have simply spotted the adjective “energetic” in a foreign text and, rather than opting for the stylistically better *energeticzny*, settled instead for the knee-jerk reflex of *energetyczny*. Gradually the longer word became entrenched in the language in this meaning.

Moreover, *energetyczny* is not the only such example in Polish. Much the same story could be repeated for the adjectives *technologiczny* (often used to mean “technical” as well as “technological”) and *metodologiczny* (“methodical” as well as “methodological”). ■



EMERALD/MEDIA/SHUTTERSTOCK.COM

The background of the image is a composite of two textures. A central, irregularly shaped area is filled with a vibrant blue liquid, possibly water or paint, which has a slightly grainy texture and some darker, swirling patterns. This blue area is surrounded by a light brown, wood-grained material with prominent, wavy lines and knots, resembling a cross-section of a tree trunk. The overall composition is vertical and symmetrical.

WATER

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