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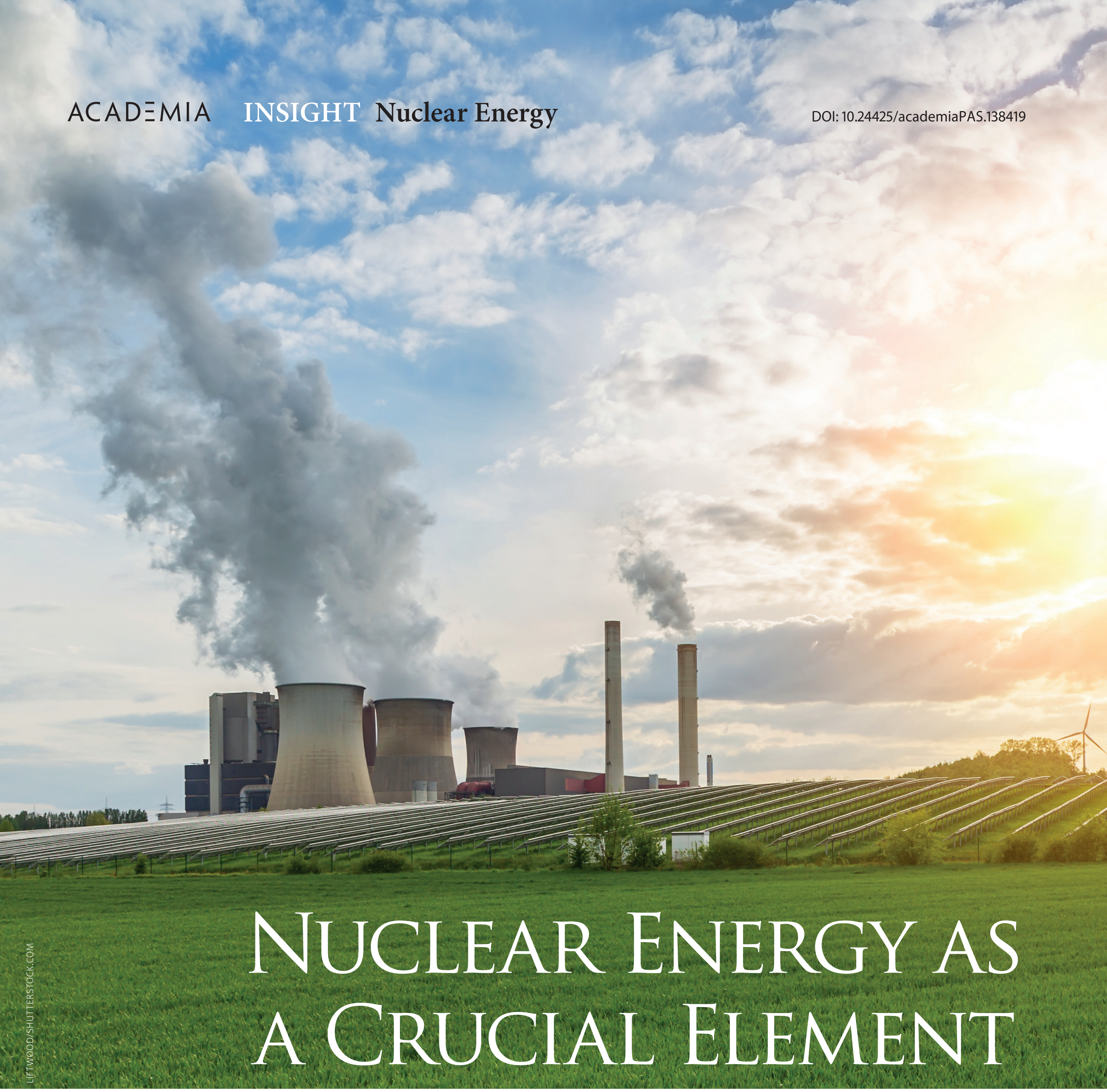

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Nuclear Energy as a Crucial Element in Poland's Power System

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?

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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- Poland's coal-fired power plants are already outdated and will be decommissioned in the next 10–20 years.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, openwork 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

Smog over Krakow, January 2017

of reinforcing steel and 190 m^3 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.

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

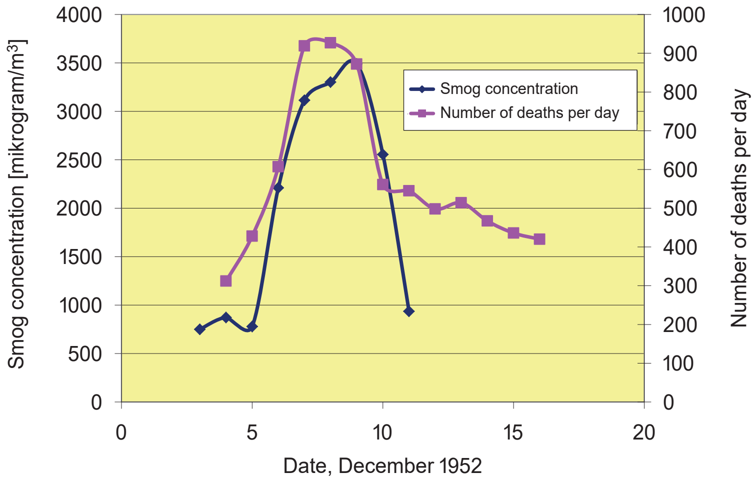


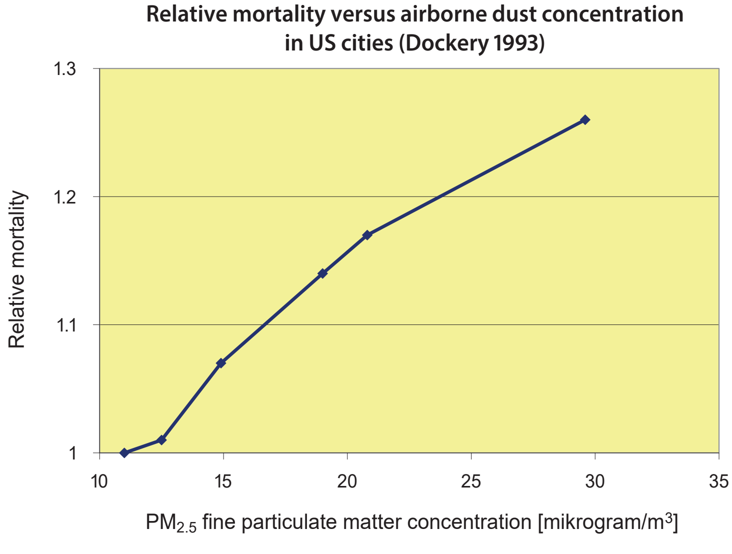
Fig. 1
Air pollution and death rates, London, December 1952. Own graph based on data from Lipfert (1994)

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. PM_{10} 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/m^3, 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/m^3. 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/m^2, at 6 m/s the output increases to 132 W/m^2 and at 12 m/s the output is 1058 W/m^2. 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.

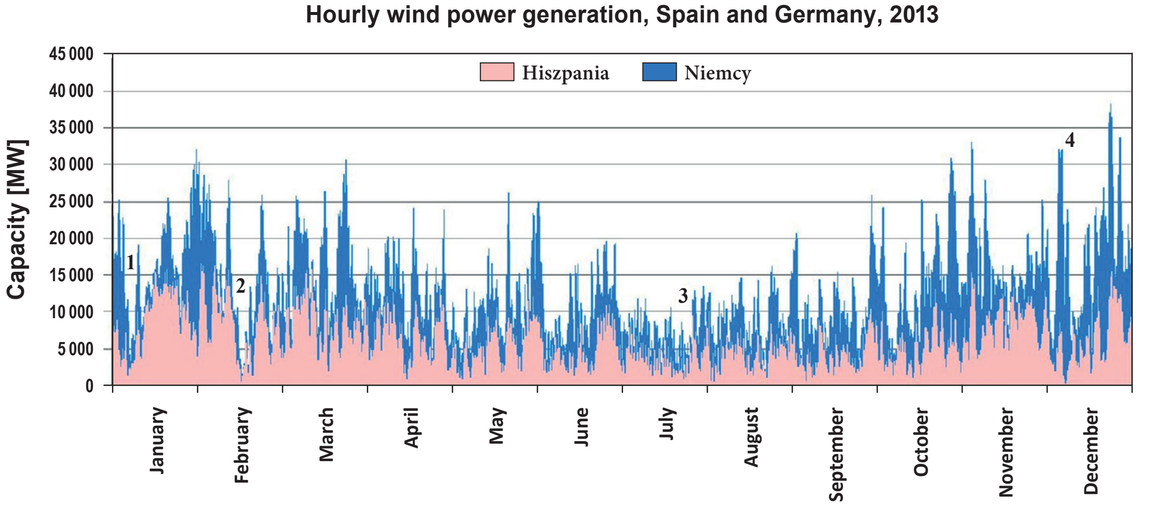


Fig. 3
Annual electricity generation from wind turbines in Spain and Germany in 2013 (compiled by R. Schuster, cited with permission)

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-

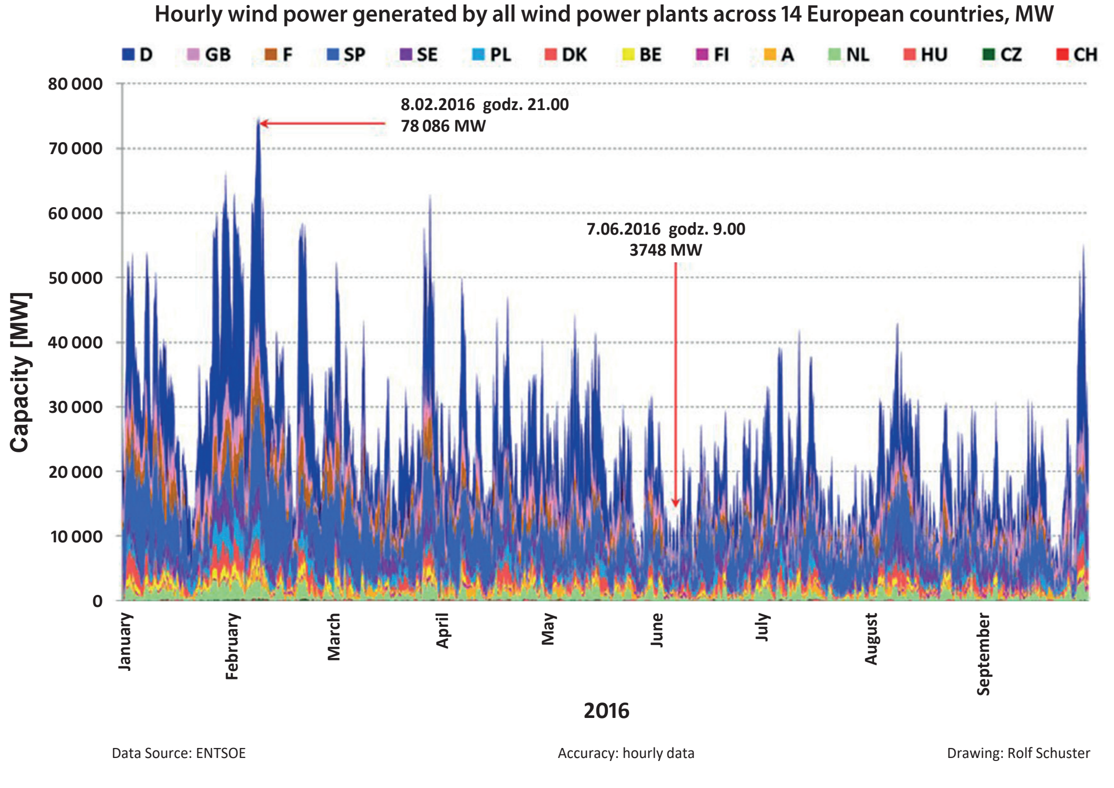


Fig. 4
Annual electricity generation from wind turbines in 14 European countries (compiled by R. Schuster, cited with permission)

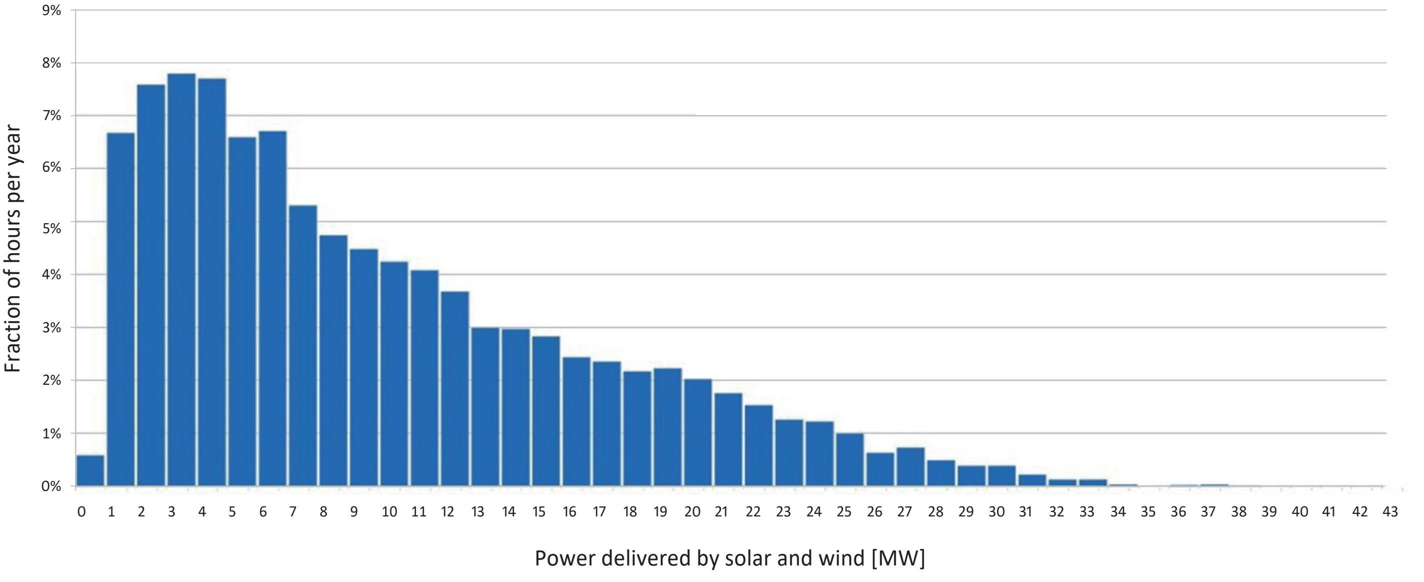


Fig. 5
Time distribution for capacity utilization levels at wind farms and solar panels in Germany (data from Fraunhofer Institute, own figure)

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 GWh × 100/8760 = 182 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 × 130 h × 0.99 = 587 GWh. This entails

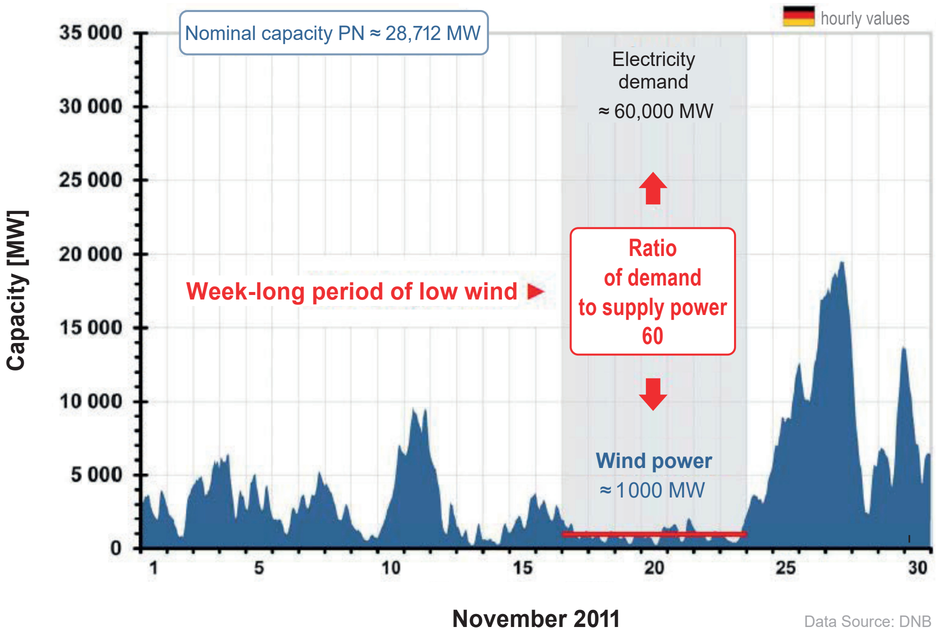


Fig. 6
Break for seven days and nights in onshore wind turbine power generation in Germany

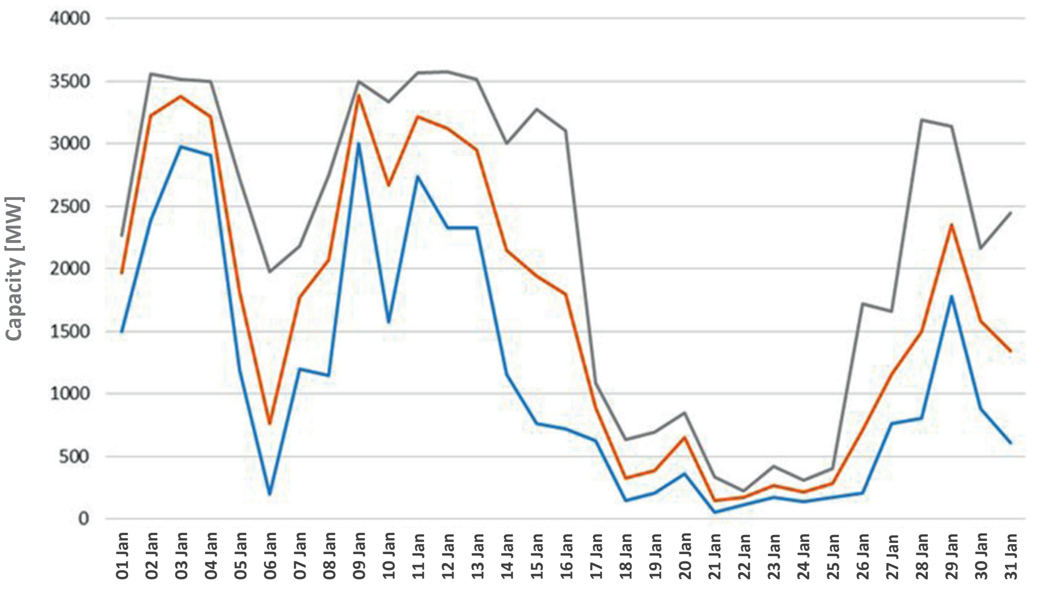
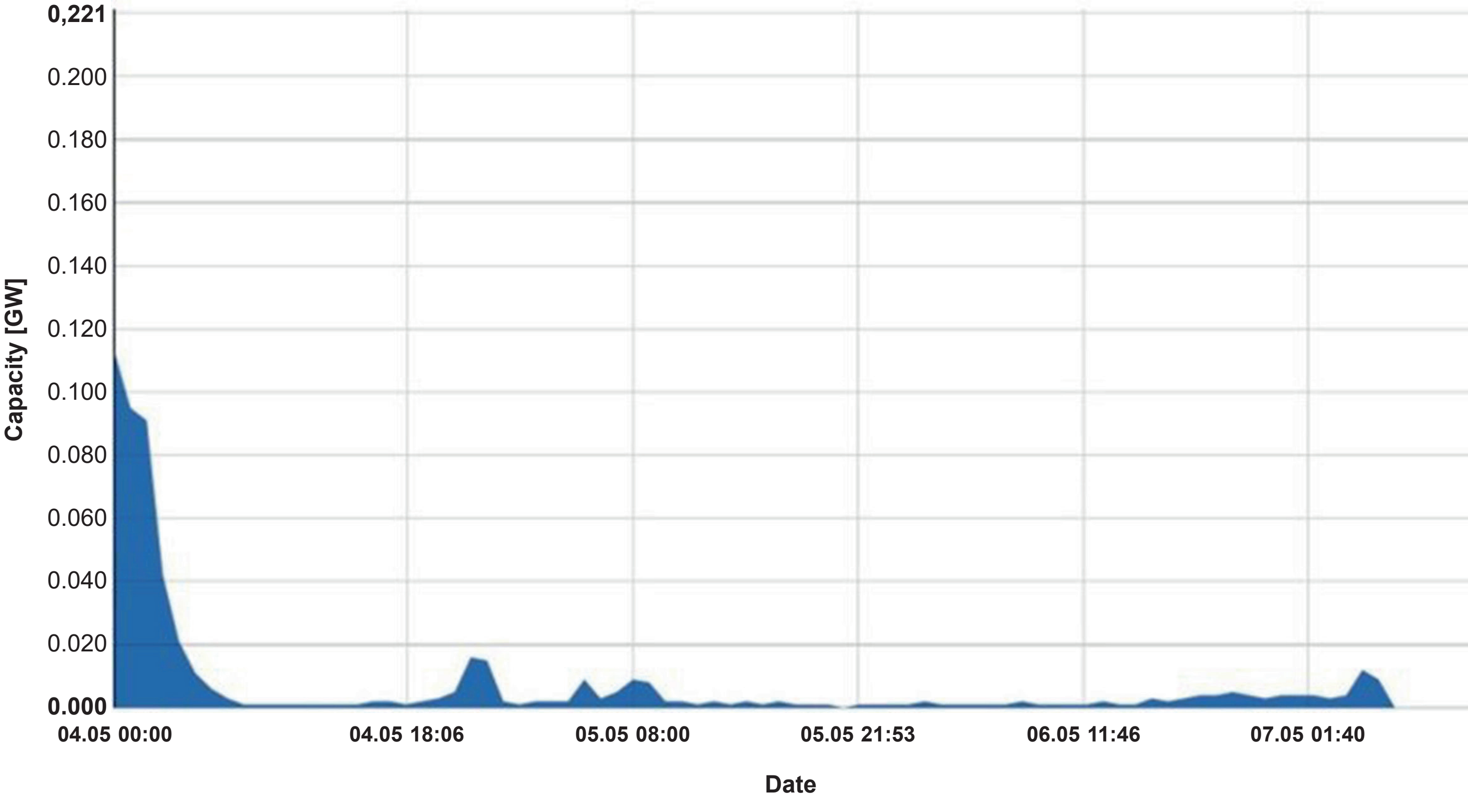


Fig. 7
An example of a low-wind period in Poland is visible on this graph, showing the minimum (blue), maximum (grey), and average (orange) wind generation in January 2015 [MWh].



a need to store 587 GWh of energy just in case such an event occurs. All existing pumped-storage hydropower 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, Jurgen 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. Outraged 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

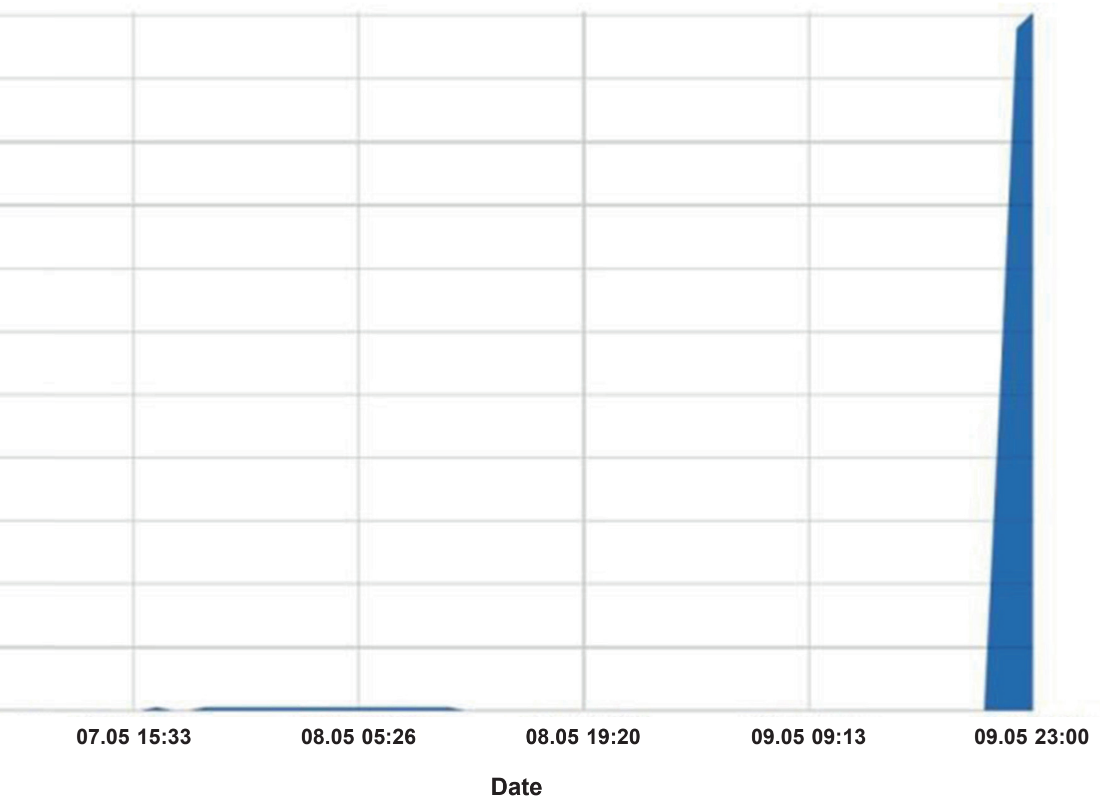


Fig. 8
Offshore wind farm capacity in the Baltic Sea.
Own figure, source: data for OWF Baltic 1 and 2

https://energy-charts.info/charts/power/chart.htm?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. ■

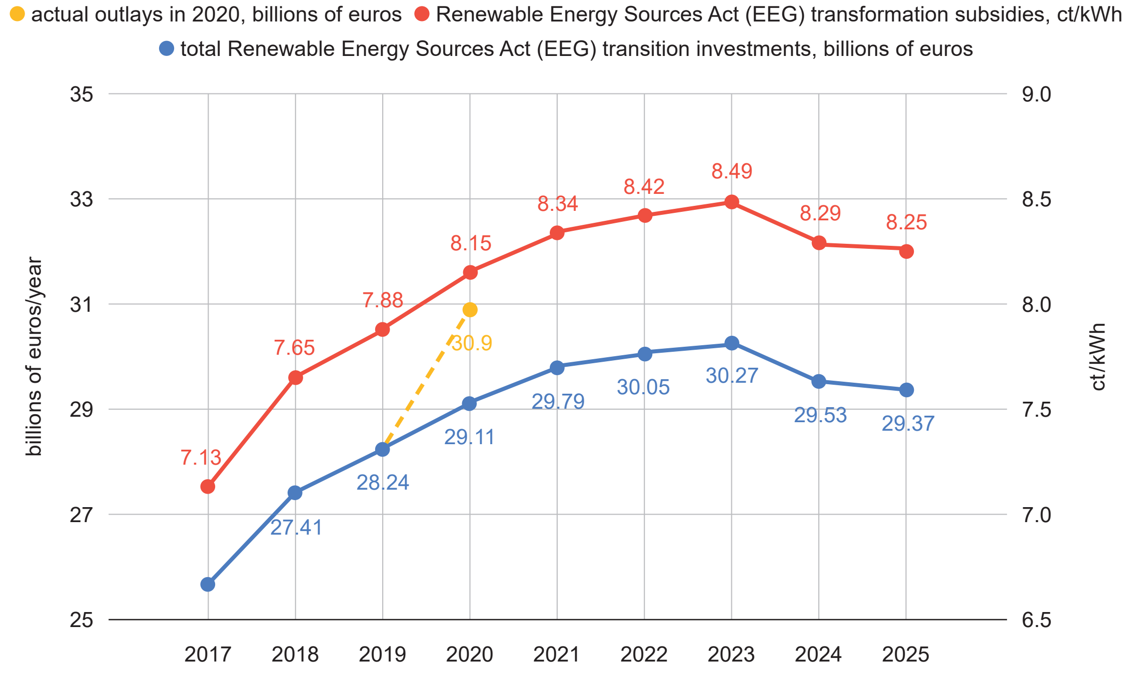


Fig. 9
Total subsidies for renewable energy sources and individual energy price subsidies as forecast by German institutes vs. actual total subsidies in 2020