DOI: 10.24425/academiaPAS.138408

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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.

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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 CO_2 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.

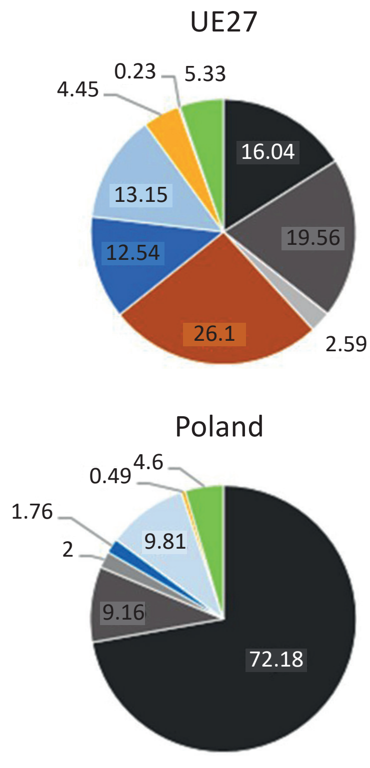

Fig. 1
Share of different sources in electricity generation in 2019, in the EU (excluding Bulgaria, Cyprus, and Malta) and in Poland (according to IEA, https://www.iea.org/reports/monthly-electricity-statistics)

Variability in electricity demand

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

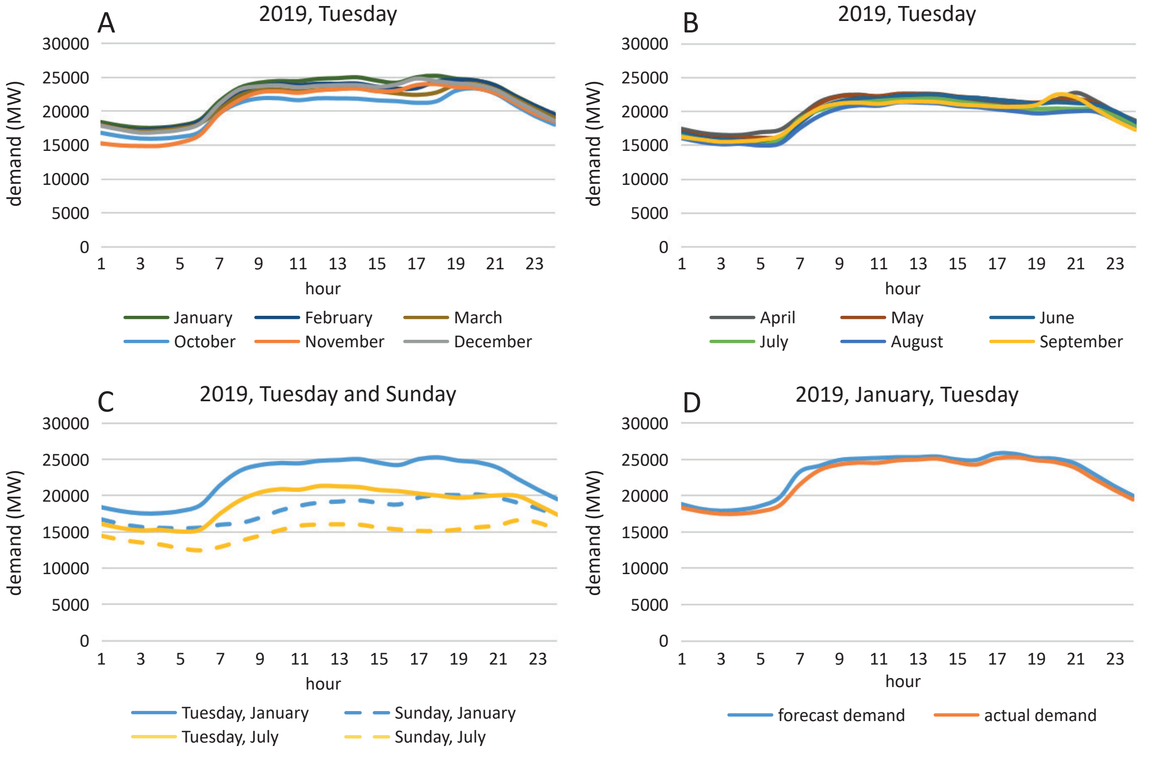

Fig. 2
Diurnal variability of electricity demand in Poland from January to March and from October to December (A); from April to September (B); differences between a weekday (Tuesday) and a weekend day (Sunday) (C); difference between forecast and actual demand on Tuesday, 15 January 2019 (for other 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 CO_2 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 CO_2. 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 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.

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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.

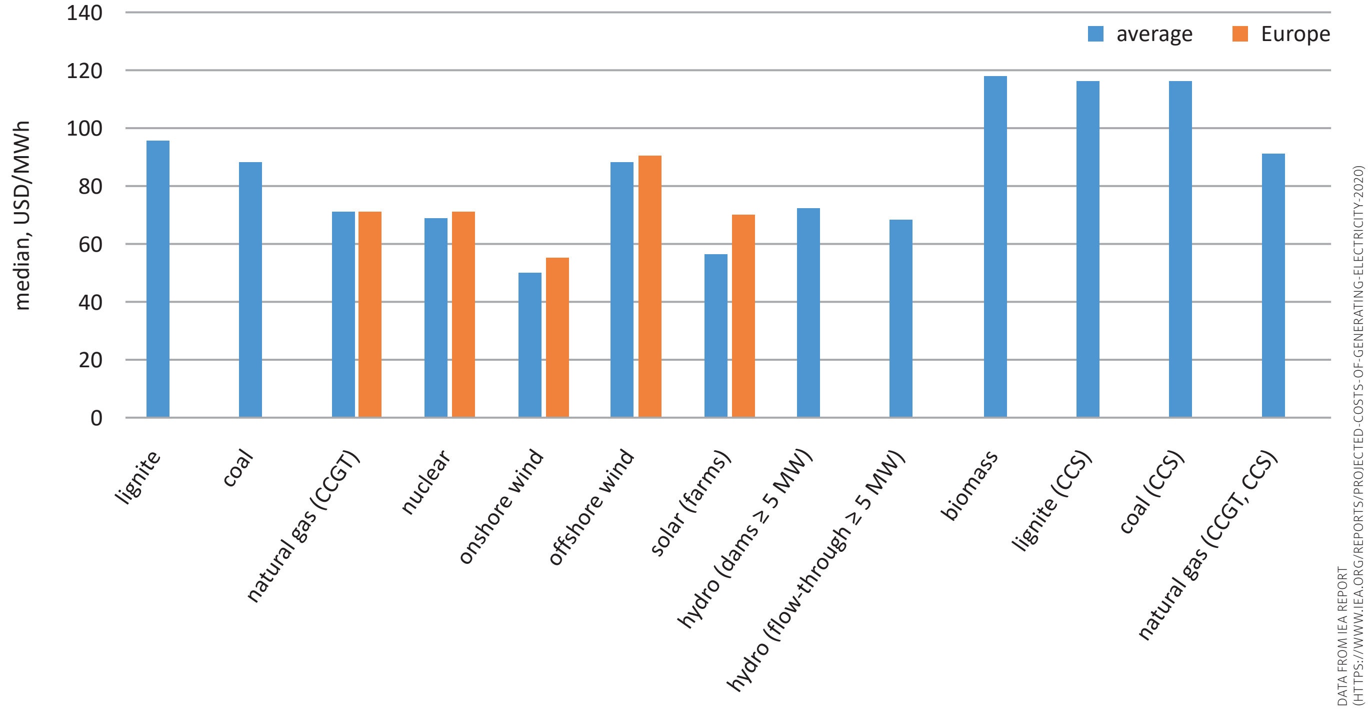
What if DSR isn't enough? Then we may end up having different levels of power-supply limitation, a situation familiar to the older generation in Poland. Consumers will be cut off in a predetermined order. However, unless major outages occur, this is thankfully still only a hypothetical possibility.

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



DATA FROM IEA REPORT (HTTPS://WWW.IEA.ORG/REPORTS/PROJECTED-COSTS-OF-GENERATING-ELECTRICITY-2020)

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 CO_2 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-ofgenerating-electricity-2020.

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