Controllable Renewable Energies: An Alternative to Nuclear Power

Cost Comparisons for Poland, Slovakia, Czech Republic and Hungary

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1. BACKGROUND: DEMAND FOR CONTROLLABLE POWER PLANTS

The need for controllable power generation in Europe will grow sharply in the next decade. As a result of the decommissioning of coal-fired and nuclear power plants, partly for political reasons and partly due to their age, European power markets will need new technologies for electricity generation. These must also meet the power system's growing requirements for flexibility.

Although photovoltaic (PV) and wind energy systems currently have very low power generation costs, their power production is not controllable and their contribution to supply security is negligible. Their integration into power grids raises flexibility requirements for other grid users. The willingness to invest in controllable fossil-fuelled (coal or gas) power plants is diminished both by the desire for energy independence and concern about climate change. Nuclear power plants are generally ascribed high availability and predictable revisions. Even if this assessment is currently changing because of the unavailability of French nuclear power plants (NPPs) in the winter of 2016/2017, in principle NPPs are technically suitable for providing supply security with a low level of dependency on energy from abroad and a low climate impact. For this reason, nuclear power plant projects are being planned or are already under construction in France, Poland, Slovakia, Czech Republic, and Hungary; this study will examine them in detail. These new nuclear power plants bear very high financial and ecological risks.

This raises the question of technical and economic alternatives. A controllable renewable energy (CRE) power plant comprising photovoltaic (PV) and wind energy systems for the low-cost use of primary energy, and electrolysers[1] with gas-fired power plants for controllability and thus supply security, is a solution that is technically conceivable. This alternative to nuclear power provides a high degree of energy self-sufficiency and has a low environmental impact. But is it also economical?

To answer this question, this study will compare the costs of power production in NPP projects that are planned or under construction in the Visegrad countries with the costs of a cost-optimised CRE power plant providing at least the same volume of electricity and degree of supply security.

[1] The basic operation of electrolysers and the CRE power plant is shown in detail on page 5.

2. ELECTRICITY GENERATION COSTS OF NUCLEAR POWER PLANT PROJECTS

The average cost of electricity produced in a nuclear power plant (NPP) is largely unknown. In principle, the costs are made up of those costs incurred in the construction of a new NPP[2] and the costs of operation and maintenance.[3] The latter are divided into a fixed cost component and a variable component which accrues with every MWh of power generated during operations. But the figures in relevant literature and publicly accessible sources of information on current NPP projects vary greatly and do not paint a uniform picture. Some of this is due to necessary technological differentiation, but it is also due to the fact that costs and risks in operations and dismantling are assessed very differently by each country.

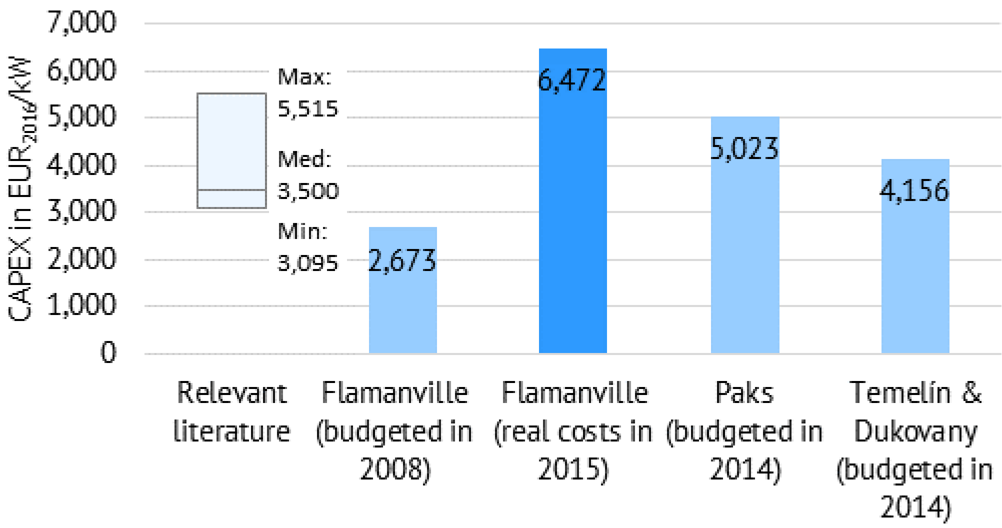

Figure 1: Comparison of the CAPEX in the relevant literature for nuclear power plants with currently budgeted and actual figures for new European NPP construction projects

Six studies were evaluated as a reflection of energy industry research.[4] These studies gave a median figure of EUR 3,500/kW for the CAPEX (such figures are referred to hereafter as “figures in the relevant literature”), with a range between EUR 3,095/kW and EUR 5,515/kW. These figures tend to be lower than the planned or projected costs given for current European NPP

[2] Capital expenditure (CAPEX)

[3] For operating expenditures (OPEX), only internal costs are taken into account. Costs incurred during dismantling or as a risk premium during operations are often not fully included and their magnitude is not sufficiently known. Since the state often bears a share of these costs and risks, they are considered external costs and are not taken into account.

[4] (Connect Energy Economics, 2015) (Department of Energy & Climate Change, 2013) (European Climate Foundation, 2016) (European Climate Foundation, 2010) (U.S. Energy Information Administration, 2013)

projects. Costs for Temelin 3 and Dukovany 5 in the Czech Republic are EUR 4,156/kW; for Paks II[5] in Hungary, the cost is EUR 5,023/kW; and for Flamanville 3 in northern France, costs are EUR 6,472/kW. The absolute value of the CAPEX underlines the dimension of investments and these fluctuations. For Flamanville 3, the CAPEX has risen from a planned EUR 4 billion (2008 EUR value) to EUR 10.5 billion (2015 EUR value).[6] According to figures found in the relevant literature, the costs for an NPP with an installed net capacity of 1,630 megawatts would be up to EUR 8.99 billion. (Unless otherwise noted, all monetary figures in this paragraph are 2016 EUR values.)

Based on a service life of 50 years, with a weighted average cost of capital (WACC)[7] of 6.89%[8] and 6,500[9] full hours of use, the cost of capital is between EUR 38.30/MWh and EUR 70.90/MWh. The capital costs for nuclear power plants can be significantly higher, depending on the allocation of risks; with a WACC of 10%, the range increases to between EUR 54.30/MWh and EUR 100.40/MWh. The cost of capital thus accounts for a major share of the total costs.

According to data provided by the relevant literature, fixed operating and maintenance costs are between EUR 62/kW and EUR 118/kW per year (both 2016 EUR values). For an NPP like Flamanville 3, with a capacity of 1,630 megawatts, the annual fixed operating and maintenance costs according to data in the relevant literature lie between EUR 101 million and EUR 192 million (2016 EUR values). Added to this, as variable operating costs, are the short-term marginal costs, for which Energy Brainpool assumes an average cost of EUR 7/MWh. At 6,500 full hours of use, these annual variable costs for Flamanville 3, our sample power plant, total EUR 74 million.

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[5] Here reactor blocks 5 and 6 are meant.

[6] Adjusted for inflation, this corresponds to an increase from EUR 4.36 billion to EUR 10.55 billion (2016 EUR values).

[7] WACCs (real) depict weighted interest rates which are calculated using interest rates for loan capital, interest rates for equity depending on the expected return, and the rate of inflation. With the help of WACCs, long-term investments with future cash flows are converted into annual values, making them comparable.

[8] Real mixed interest rate for investments in power plants (9% nominal interest, 2% inflation).

[9] In 2016, France's nuclear power plants had 6,800 full hours of use.

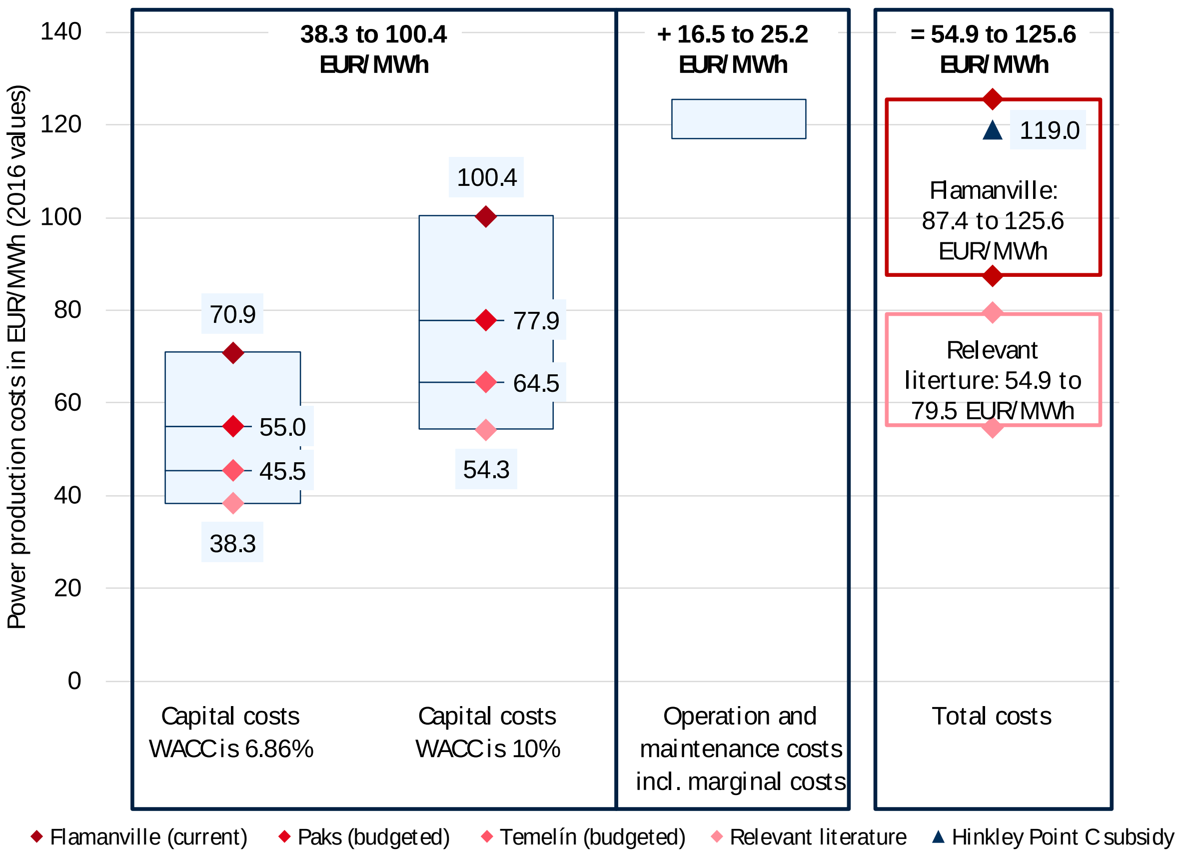

Figure 2: The range of cost components for nuclear power plants (NPPs) in current European NPP projects, derived from the relevant literature

Total costs are the sum of these cost components. Figure 2 shows that the range between figures provided by the relevant literature (minimum) and the CAPEX for Flamanville 3 (maximum) for 6,500 full hours of use is between EUR 54.90/MWh and EUR 125.70/MWh (both 2016 EUR values). A comparison with the EUR 119/MWh (2016 value) in financial support for the Hinkley Point C NPP in the UK tends to confirm the upper limit of this wide range. A minimum price of USD 123.50/MWh (nominal value) has also been reported for the Turkish NPP project Akkuyu, but the wording of the contract for this project makes a direct comparison difficult. Only budgeted figures for the Temelin/Dukovany and Paks NPP projects are available so far and final total costs will depend on the uncertain future cost development of these projects. Compared to the costs for Flamanville 3, expected figures are 29% to 56% higher. The subsidy rate for Hinkley Point C is also well above the level of budgeted figures—which are within the range of the usual figures found in the relevant literature. However, there is no real reason why nuclear power projects in Hungary or the Czech Republic could be realised at significantly lower costs than in other European countries.

3. ALTERNATIVE: A CONTROLLABLE RENEWABLE ENERGY POWER PLANT

As an alternative to nuclear power, a concept is presented here for a renewable power plant which supplies electricity that is controllable and makes at least the same contribution to supply security. This chapter describes how such a CRE power plant functions. The economic evaluation needed for the comparison with nuclear power will be provided for each Visegrad country in the following chapter.

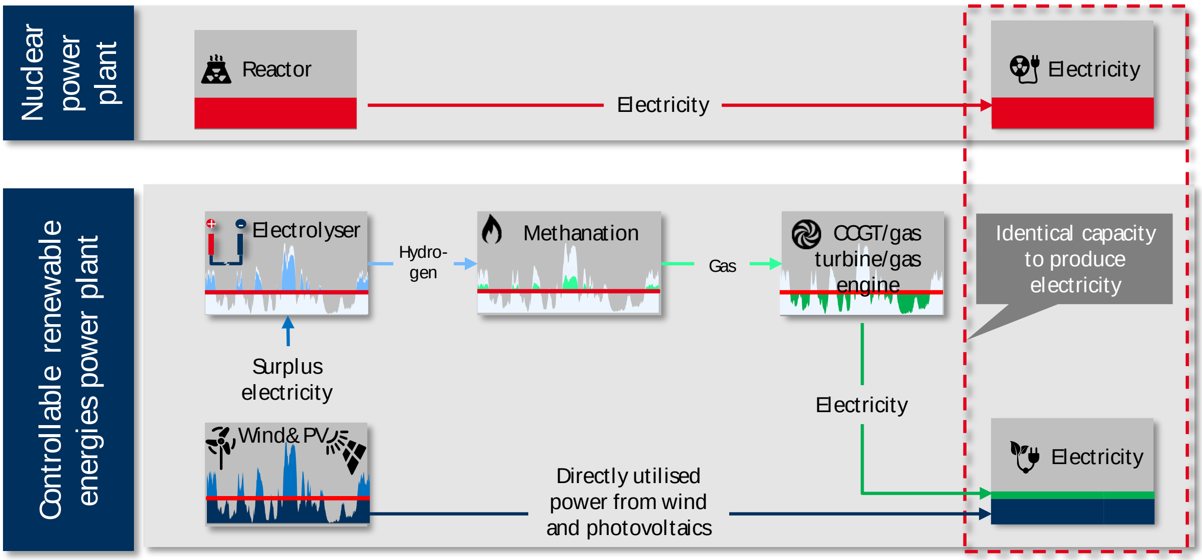

Figure 3: The concept of the controllable renewable energies power plant

Intermittent renewable energies can only partially meet the demand for power at times when they actually produce electricity. Strong solar radiation and high wind speeds generate surpluses, while at other times, the demand for electricity cannot be fully met—and in some few situations renewables feed practically no power into the grid. Alone, they cannot reliably cover immediate electricity needs. If the (surplus) electricity not immediately utilised is used for electrolysis, water is chemically separated into oxygen and hydrogen. Hydrogen is then enriched with carbon dioxide. This causes a reaction which produces methane and is referred to as methanation.[10] In this way, renewable energy is converted into gas. Methane, and to a certain extent hydrogen, can be fed into the gas grid and stored in gas storage facilities. Various gas power plant technologies[11] can utilise methane, and to a certain extent hydrogen, to generate

[10] This last step in the process of methanation is optional if a hydrogen infrastructure is in place, making it possible to transport and store hydrogen.

[11] These include combined cycle gas turbines, gas turbines (partial use of hydrogen possible) and gas-fuelled engines (direct use of hydrogen possible).

power when it is needed and guarantee controllability of the system. In this study, a controllable power plant system using renewable energies will be referred to as a CRE power plant, the workings of which are shown above in Figure 3.

To identify what constitutes an optimised CRE power plant, we need to dimension its individual components as best we can. This is influenced by each country's potential in wind and solar energy, investment conditions, and technical parameters. Figure 4 shows the options for dimensioning and their correlations based on the hourly residual load that occurs over a period of one year. In this example, the CRE power plant is expected to meet a constant demand for one gigawatt of power.

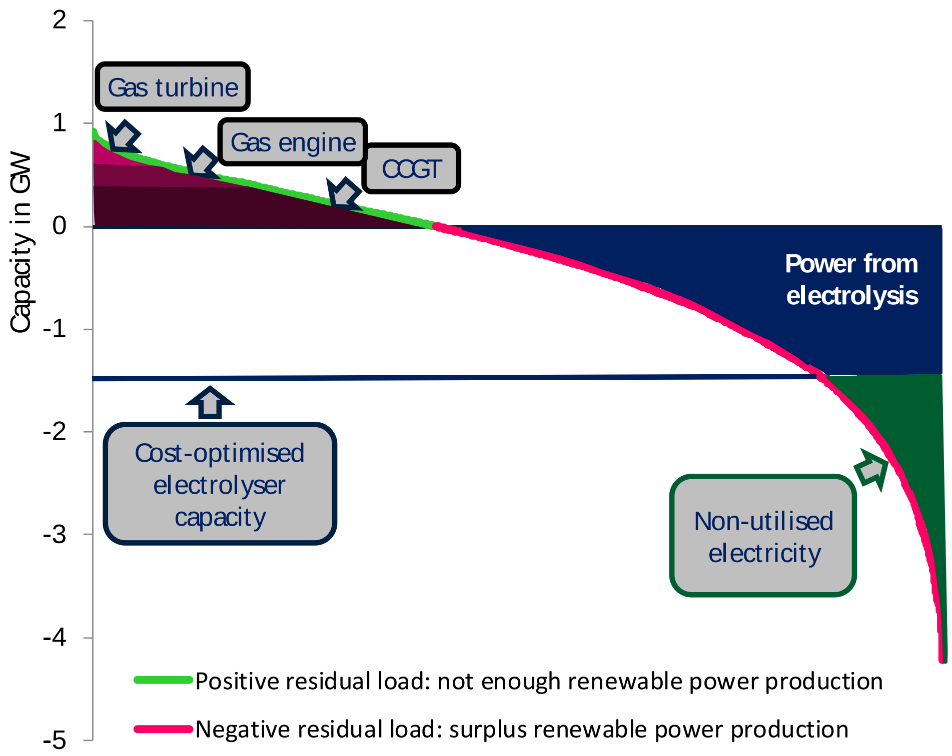

Figure 4: The hourly residual load of base load power demand when supplied by intermittent renewable energies and visualisation of options for dimensioning CRE power plant components

The system costs of a CRE power plant consist of the following two cost components, which are minimised in joint optimisation.

Firstly, minimal power production costs are determined in EUR/MWh of the intermittent renewable energies. This is done by optimising the ratio of installed PV and wind capacity, taking into account the national hourly wind and solar potential in the 2012 meteorological year and the respective technology costs. The result of this optimisation is the output required from intermittent renewable energies, their economically optimised ratio, and the costs of producing electricity from intermittent renewable energies—this as the first part of a CRE power plant.

Secondly, the additional costs of controllability are determined in EUR/MWh. This occurs by varying the optimal electrolyser capacity in MW and by determining a cost-optimised composition of the gas power plant's output. When residual load is positive (meaning not enough power is being generated from intermittent energy sources), then gas power plants must produce electricity. Three technologies are available for power production: gas turbines, gas engines, and combined cycle gas turbines (CCGT). Figure 4 shows their cost-optimised shares[12] in the conversion of electrolysis gas into electricity. A surplus of electricity from intermittent renewable sources results in a negative residual load. This means that demand is being met and surplus electricity can be converted into gas that can be stored. In a cost-optimised system, a certain portion of this surplus would not be utilised (green area in Figure 4) because the additional electrolysers required for this would be underutilised and therefore not economical.[13] Taking into account the efficiency factors for electrolysers and gas power plants, it is crucial for optimisation that PV and solar facilities produce enough usable surplus electricity (blue area) over the year.

The costs of the individual components of a CRE power plant consist of the relevant capital costs of the initial investment (CAPEX) and the operations and maintenance costs (OPEX). This study assumes a European average figure for the CAPEX and OPEX within a given power production technology, but uses country-specific WACC and full hours of use for the intermittent renewable energy facilities. The numerical data is provided in the tables in the Appendix. Due to the single market and the flow of information, cost differences between European countries are based on the cost of capital and not on the actual cost of capital goods.[14] The cost of capital

[12] A peak residual load occurs during very few hours, for which inexpensive, but less effective gas turbines are suitable. Demand for electricity at residual load periods that occur a bit more frequently can be met with somewhat more expensive, but more efficient gas engines. As hydrogen gas engines, these could make energy-intensive methanation redundant. This is an effect that has not been taken into account in this study, but which would probably increase the overall efficiency of a CRE power plant. Combined cycle gas power plants are even more efficient, but also more cost-intensive, and only make sense for a greater number of operating hours. The optimal costs of these three gas power plants was determined using the CAPEX, OPEX and their degree of efficiency.(Linkenheil, et al., 2017, p. 24).

[13] The electricity is not used for purposes of economic optimisation. It is possible to use this electricity with other flexibility options such as load transfer or storage.

[14] Costs of capital are defined as the interest on loans. The relevant literature refers to weighted costs of capital as WACC.

is driven by the financing structure between the project developers and the investors.

Furthermore, the expected returns and risk premiums of those involved also play a role.

4. ALTERNATIVES TO NUCLEAR POWER IN THE VISEGRAD COUNTRIES

There are nuclear power plant projects being planned or constructed in all four Visegrad countries—Poland, Slovakia, Czech Republic and Hungary. The total net capacity of these projects amounts to 15.6 GW. These projects are described below. The sections that follow describe and compare economically optimised CRE power plants for each country as an alternative.

4.1. NUCLEAR POWER PLANT PROJECTS IN PLANNING

The background to these projects is that older coal-fuelled plants and nuclear power plant (NPP) reactors will reach the end of their technical service lives and need to be replaced to ensure power generation capacity. The planning and construction of new NPPs is supposed to guarantee supply security without jeopardising energy independence. Poland plays a special role among the Visegrad countries because no NPPs have gone into operation there so far.[15]

NPP projects in these countries are all in the planning phase, each in a different stage of progress. Initial figures for the construction budgets of the new power plants at the Paks site in Hungary and the Temelin/Dukovany site in the Czech Republic have been made public, while in Poland agreement must still be reached on a suitable location. The current status of the planning phase in each country is summarised below on the basis of publicly available information from the World Nuclear Association.[16] Information for Poland was supplemented with details from a project report by the Polish energy utility PGE.[17]

4.1.1. HUNGARY

Since the mid-1980s, four reactors with a total net capacity of about 1,800 MW have been in operation at the Paks site. Their scheduled shutdown would be in the mid-2020s, at the end of their 40 years of service life. To prevent a shortfall in power supply, two new reactors with a total net capacity of 2,400 MW are supposed to be built on the same site. According to planning, investment costs are predicted to total around EUR 12 billion. The reactors are scheduled to start generating electricity in 2026. According to the World Nuclear Association, there is a

[15] The construction of four reactors at the Zarnowiec site was discontinued in 1990 due to protests.

[16] (World Nuclear Association, 2018)

[17] (PGE, 2016) Polska Grupa Energetyczna is a Polish energy utility that announced plans in 2009 to build two nuclear power plants in Poland.

Russian financing proposal for 80 percent of the investment costs. The Hungarian parliament agreed to the terms of financing in February 2017. The Russian state-owned company Rosatom expects to begin construction in 2020.

4.1.2. POLAND

Polish energy policy envisages having a fixed share of nuclear power in the energy mix by 2050. At the same time, the share of coal in overall production is supposed to be decreased to reduce CO^2 emissions. There are definite plans for a site with a total net capacity of 3,000 MW which should go online in 2029. The preliminary development phase is supposed to be completed by the end of 2018 and construction is expected to start in 2023. The model type and financing model are to be defined in a call for tender. According to its own project report, PGE will receive a 70-percent stake in the NPP. A state subsidy is also being discussed that would be similar in form to the contract for difference (CFD)[18] designed for the British Hinkley Point C nuclear power plant. PGE's project report states that more than 70 percent of the residents of Choczewo are supportive, although they live only 20 kilometres away from the Zarnowiec NPP project abandoned in 1990 due to protests. Another NPP in the eastern part of the country, also with a net capacity of 3,000 MW, is supposed to generate power from 2035. Three locations for this power plant are currently being discussed.

4.1.3. CZECH REPUBLIC

So far there are two sites with a total net capacity of just over 3,600 MW. The four reactors at Dukovany went online around 1986 and are supposed to be shut down in mid-2020. The two reactors at Temelin have been operating since the beginning of 2000 and could generate electricity until at least 2040, assuming they live out their expected 40 years of service. The construction of two new reactors, each with a net capacity of 1,200 MW, is planned at each of the two existing sites. Costs are estimated to be about EUR 5 billion per reactor, meaning that today the total figure for investment costs is EUR 20 billion. A definite date already exists for the start of Dukovany 5's construction; Dukovany 5 and Dukovany 6 (no construction date yet) are meant to replace the four old reactors. According to plans, the other reactors are expected to go online between 2035 and 2040. A state subsidy in the form of a CFD is also being

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[18] A contract for difference protects the contract holder against fluctuations in price. Should the stock market price fall below the agreed CFD, the contractor reimburses the difference. Should the stock market price go above the agreed CFD price, the contract holder pays the difference. This creates a stable revenue stream, which gives the project developer planning security.

discussed in the Czech Republic, guaranteeing a power purchase price between 60 EUR/MWh and 90 EUR/MWh. But there is currently no consensus on the exact subsidy conditions due to diverging interests between the government and the project developers.

4.1.4. SLOVAKIA

Slovakia currently has two reactors at each of its Bohunice and Mochovce sites, with a total net capacity of just over 1,600 MW. The Bohunice NPP began operating in the mid-1980s. It will reach the end of its technical service life in 2025 and is supposed to be replaced by one new reactor with a net capacity of 1,200 MW. Mochovce did not begin operating until 1999. Mochovce 3 and 4 are already under construction and are expected to go online at the end of 2018 and the end of 2019 respectively; together they will have a net capacity of almost 900 MW. Another nuclear power plant is planned for construction in Kecerovce—also with a net capacity of 1,200 MW. The start of construction and the commissioning date are unknown so far.

The figure below shows the present planning status of NPP projects in these four countries; the size of the circles indicates their planned net capacity.

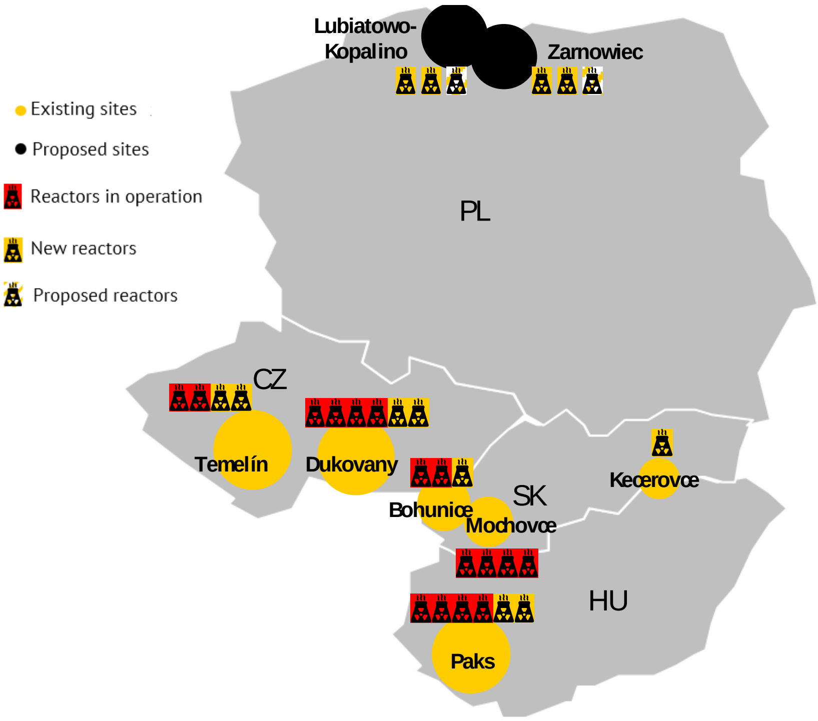

Figure 5: Status of nuclear power plant projects in the Visegrad countries[19]

4.1.5. SUMMARY OF THE TECHNICAL PARAMETERS OF THE NUCLEAR POWER PLANT PROJECTS

Table 1 summarises technical parameters for further research and for comparison with a CRE power plant according to country. Only those power plant projects which are not already under construction have been taken into account so that Mochovce 3 and 4 in Slovakia have not been included.

[19] The reactor blocks at Mochovce, already advanced in construction, are categorized as operational.

Table 1: Summary of technical parameters for planned nuclear power projects in each country

Country	Installed capacity in MW	Full hours of use per year	First power production	Power production costs in EUR/MWh (2016 EUR values)		
				Budgeted/ relevant literature values	Flamman-ville	Hinkley Point C subsidy
HU	2,400	7,240	2027	55 to 80	87 to 126	119
SK	2,400	6,900	2027			
PL	6,000	7,240	2035			
CZ	4,800	6,470	2035			

Power production can be estimated using past records of full hours of use. Since this is not possible for Poland, we have used Hungarian figures, assuming there would be a rather high number of full hours of use.

4.2. THE ALTERNATIVE CONTROLLABLE RENEWABLE ENERGY POWER PLANT

The electricity generated by NNP projects in Visegrad countries could also be produced by a CRE power plant while still delivering the same degree of supply security, as described in detail in Chapter 3. In the following, the dimensioning and the costs of an economically optimised CRE power plant meant to replace the function of the NPPs will be described for each country. Optimisation takes place by varying the installed capacity of onshore wind power plants, PV facilities and electrolysers. The capacity of the proposed gas power plants is not an optimisation parameter; it is set to the same capacity as the NPPs. The amount of solar and wind power utilised makes it possible to operate these gas power plants exclusively with electrolysis gas from renewable energies throughout the entire year. The addition of individual components to the CRE power plant can be carried out successively and thus with a high degree of planning flexibility. To compare costs, the study used the first expected year of power generation from the proposed nuclear power plants as the year of the CRE power plant's commissioning.

In the process of dimensioning, additional synergies can be taken advantage of if the individual components of the CRE power plant are coordinated not only at the national level, but also optimised across all Visegrad countries. Assuming that all four Visegrad countries use the electrolysis gas[20]—which can be accomplished by transporting the gas through the European gas network[21] —another cooperation scenario has been calculated (subsequently referred to as V4). Trade in electrolysis gas can link favourable sites for wind, for example in Poland, with favourable solar sites in Slovakia, for example, without causing the supply security of each country's electricity system to be directly dependent on each other. In the interests of an optimal economic solution, this would allow one country's surpluses to be used by other countries—moreover, gas trading would bring economic benefits to both countries. In this second scenario, we continue to assume that the EU guarantees[22] for investments in renewable energies currently under discussion will be introduced. This would standardise the assumed WACCs at 5.4%, effectively lowering the costs of the intermittent renewable energies.

Table 2: Cost-optimised dimensioning of the CRE power plants in Visegrad countries
*) Due to very limited experience with wind power in Slovakia, actual wind potential has not been sufficiently studied and a very low level of potential has been assumed in these calculations.

	Intermittent electricity				Controllability			
Country Year	Required output from renewables	Share of wind	Share of PV	Power production costs of intermittent renewables	Gas power plant capacity	Electro-lyser capacity	Additional costs of controll-ability	Total costs
	MW	%	%	EUR/MWh	MW	MW_{el}	EUR/MWh	EUR/MWh
HU 2027	12,118	74	26	72.56	2,400	2,866	56.11	128.67
SK 2027	19,019	59	41	89.74	2,400	3,699	77.49	167.23*
CZ 2035	24,167	72	28	74.06	4,800	6,201	45.01	119.08
PL 2035	30,872	79	21	69.83	6,000	8,470	41.90	111.73
V4 2027	85,678	77	23	67.09	15,600	16,808	53.08	120.17
V4 2035	84,233	71	29	60.36	15,600	21,534	39.66	100.02

[20] In principle, it is desirable for these countries to exchange electricity in addition to transporting gas, as that would significantly lower overall costs. However, in view of limited cross-border capacities and the minimal number of plans to expand capacities for electricity exchange within the Visegrad countries, such a trade network is not currently foreseeable.

[21] Gas volumes fed into and delivered from the European gas network are compared on the balance sheet. A system analysis which includes the need for investments into the gas network is not part of this study.

[22] See (Temperton, et al., 2018)

The results of the optimisation have been summarised in Table 2. The CRE power plant components of primary intermittent electricity generation and the plant's controllability are listed separately. The costs of a CRE power plant system in the Visegrad countries, assuming that these countries exchange gas among themselves, would amount to EUR 120/MWh (2016 EUR value) on average in 2027. The cost degression of electrolysers and renewable energies by 2035 would reduce these costs by another EUR 20/MWh. The four national scenarios are each more expensive than the corresponding V4 scenario for the year in question. A direct comparison is however limited by the fact that in the Visegrad cooperation scenario, a lower and uniform cost of capital was assumed than in the national scenarios.

The electricity generation costs of NPPs are shown in Table 1. Detailed costs cannot yet be determined for each individual country, as discussed in Chapter 2. The costs of electricity generation in current European NPP projects have been valued at EUR 87/MWh to EUR 126/MWh (2016 EUR values) (Flamanville) and at EUR 119/MWh (2016 EUR value) (subsidy rate for Hinkley Point C). The electricity generation costs of CRE power plants in the national scenarios tend to be even lower when compared to the reference year of 2035 in the V4 scenario.

4.2.1. DIMENSIONING AND COSTS

A differentiated view of dimensioning and the costs of intermittent renewable power production on one hand, and the components for controllability on the other, are key when addressing the cost of the electricity generation of a CRE power plant. The following chapter is therefore divided into two parts and analyses the factors that influence each of these cost components. The factors taken into account are the full hours of use, the PV feed-in profile,[23] the wind feed-in profile,[24] and the costs of intermittent renewable energies[25] and electrolysers.[26]

Dimensioning and costs of generating electricity using intermittent renewable energies

Looking at the optimised shares of power generated by wind and PVs in Table 2, we notice that the optimised wind share is mostly between 70% and 80%. The only exception is Slovakia—the reason being the low number of documented full hours of use of wind, amounting to only 1,334

[23] (Pfenninger & Staffell, 2016)

[24] (Pfenninger & Staffell, 2016)

[25] Energy Brainpool (2018. *Meta-Analysis of 24 Studies with 135 Data Sets on the Costs of PV, Onshore Wind and Offshore Wind Power*. Figures are provided in the Appendix.

[26] (Energy Brainpool, 2018). Figures are provided in the Appendix.

hours.[27] In contrast, the average number of full hours of use in Hungary, Poland and the Czech Republic is 2,093. This means that in Slovakia, the PV share tends to be higher. This also means that in Slovakia, the cost of generating electricity from intermittent renewable energies is higher at just under EUR 90/MWh, which is EUR 24/MWh more than the average cost in the other three countries.

In Poland, on the other hand, the optimised share of wind power is relatively high since the number of full hours of use of onshore wind power is nearly twice that of PVs. This is due to Poland's natural wind potential, exemplified by a number of favourable sites on the Baltic Sea. This natural potential for a specific kind of renewable energy partly explains the low intermittent renewable energy costs. The 2012 meteorological year was chosen to represent an average weather year and used as the basis of calculations so that annual variations in weather effects, solar radiation and wind speeds did not distort results. The year 2012 portrays average wind and solar supply compared to the past 30 years. In the optimisation, the specific costs in EUR/MW per year of both intermittent technologies and their full hours of use determine the share of power generated by onshore wind and PVs by minimising electricity generation costs in EUR/MWh.

In addition to this natural potential, however, the national financing environment, which depends on the regulatory framework, is also decisive for the optimised mix of wind and PV power. This financing, contained in the cost of capital, is taken into account by project developers in optimising the mix.

Table 5: Assumptions for the economic calculation of intermittent renewable energy facilities (*Meta-Analysis of 24 Studies with 135 Data Sets on the Costs of PV, Onshore Wind and Offshore Wind Power*)

in the Appendix provides an overview of the cost of capital assumed in this study. The cost of capital makes it possible to determine the specific costs for onshore wind and photovoltaics in EUR/MW per year for each country. In Hungary and Slovakia, the annual costs for the installation of one megawatt of onshore wind capacity are about 30% higher than for photovoltaics, and in the Czech Republic and Poland they are 50% higher. These figures also depend on the year we look at, as renewable technologies are subject to progressive cost

[27] The data available for modelling the amount of Slovakia's wind power feed-in and calculating the real potential of wind power is currently limited. The challenge faced in the modelling process is that until 2015, only two larger turbines with a total capacity of 3 MW had been installed and calibrating the model based on historical data would be very imprecise.

degression. For each country, this year corresponds to the year in which the new NPP project is expected to first generate electricity (see Table 1).

Some modelling results in Table 2 precisely show the influence of this financing environment and cost degression. If in Poland, for example, an NPP scheduled to go into operation in 2035 is replaced by a CRE power plant, the cost degression will have already progressed further than if it were to go online in 2027, when Paks II in Hungary, for example, is scheduled to start generating electricity. The total costs are proportionately lower. A second example is the share of PV in the V4 scenario set in 2035. This share is six percentage points higher than it would have been in 2027, although the calculation is based on the same feed-in profiles. According to Energy Brainpool's meta-analysis, the future cost degression of photovoltaics will be greater than that assumed for onshore wind, making PV less expensive relative to onshore wind over time.

Dimensioning and costs of controllability

The installed capacity of electrolysers has to be high enough to provide exactly the same amount of electrolysis gas as required by gas power plants to generate electricity. How high the additional ensuing costs are depends on the load profile and the corresponding balancing effect of wind and PV power. In the national scenarios, these costs range between EUR 40/MWh and EUR 77/MWh. The V4 cooperation scenario set in 2035 has the lowest costs for controllability. In Slovakia however, the additional cost of EUR 77/MWh for controllability is very high. Added to that, the costs of intermittent renewable energies are already high in Slovakia due to the very low number of full hours of use assumed for wind power. In a direct comparison with the results for Hungary, this additional cost occurs despite both countries having identical gas power plant capacity. The difference of just 350 hours (see Table 1) between the NPPs' full hours of use is also a minor parameter with little influence. Of more importance is the fact that the electrolyser capacity needed in Slovakia is about 800 MW higher than in Hungary, due to the weaker balancing effect of onshore wind and PV. The consequence is that there is less direct use of electricity and lower utilisation of the electrolysers. As a result, Slovakia has a particularly high economic incentive to import from the other Visegrad countries the electrolysis gas it needs for its own gas power plants. This is also shown in the detailed overview of the results of the two V4 scenarios in

Table 6 in the Appendix. Installed electrolysis capacity in Slovakia is much lower, and this scenario provides for the possibility of importing around 10 TWh of electrolysis gas from other Visegrad countries.

Another important determining factor is the expected cost degression for electrolysers. This becomes apparent when we look at and compare both V4 scenarios. The optimised installed capacity of the electrolysers in 2035 is 4.7 GW or 28% higher than in 2027. This increase results from the cost degression of the electrolysers (see

Table 4: Assumptions used for the economic calculation of electrolysers and gas power plants

in the Appendix). In 2035, more inexpensive electrolysers could be installed in the optimised system, as they will have by then become economically viable even with fewer full hours of use. In 2027, the electrolysers in optimised operation will still have to achieve a higher number of full hours of use. This higher electrolyser capacity will also make it possible to use more of the surplus from electricity generation in the CRE power plant system.

4.2.2. THE INFLUENCE OF IMPROVEMENTS IN FINANCING CONDITIONS

A decisive parameter for the power production costs of intermittent renewable energies is the financing environment of capital-intensive investments in renewable energy facilities. Comparing the assessment of these costs, they seem to be significantly lower in Slovakia than in the other Visegrad countries (see

Table 5: Assumptions for the economic calculation of intermittent renewable energy facilities (*Meta-Analysis of 24 Studies with 135 Data Sets on the Costs of PV, Onshore Wind and Offshore Wind Power*)

). EU guarantees could improve financing conditions here too.[28] What effect would a reduction in WACC have on CRE power plants in these countries?

To answer this question, the WACC was set at 5.4% for all countries, as previously assumed only for Slovakia. This figure could be achieved through guaranteed subsidies for intermittent renewable energies or by removing bureaucratic and legal planning hurdles. As a result, investors would pass on lower risk premiums when granting loans to project developers.

This new optimisation of production costs for CRE power plants in the three countries results in costs ranging from EUR 97/MWh to EUR 111/MWh, and to a certain extent they are significantly

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[28] See (Brueckmann, 2018).

lower than the subsidy rate of EUR 119/MWh for the Hinkley Point C nuclear power plant. Table 3 shows the change in the dimensioning and costs of CRE power plants optimised in this way as compared to the previous optimisation.

Table 3: Improvements in CRE power plants shown as differences to the baseline scenario

	Intermittent electricity				Controllability			
Country	Required renewable capacity	Share of wind	Share of PV	Power production costs of intermittent renewables	Gas power plant capacity	Electro-lyser capacity	Additional costs of controll-ability	Total costs
	MW	%	%	EUR/MWh	MW	MW_{el}	EUR/MWh	EUR/MWh
HU	265.01	-2	2	-12.16	identical	-252.74	-5.51	-17.67
CZ	389.36	-2	2	-11.71	identical	-470.83	-4.13	-15.84
PL	570.44	-3	3	-10.68	identical	-600.42	-4.01	-14.69

One obvious effect of improved financing conditions is that more capacity in intermittent renewable energies is built up overall in each country. The cost- optimised ratio in the CRE power plant is shifted to more renewable power generation with fewer electrolysers. Additionally, the lower cost of capital increases the optimal share of photovoltaics (PV) relative to onshore wind, shifting this proportion slightly in favour of PV.

Improved financing conditions have the effect of reducing renewable electricity generation costs by EUR 11.50/MWh on average. At the same time, the additional costs attributed to controllability also decrease by about EUR 4.50/MWh on average. This is due to the reduced installed capacity of electrolysers. Compared to the baseline scenario, the installed capacity of electrolysers decreases on average by 8% in all countries. The electrolysers that are built attain more full hours of use, on average about 7% more. However, the share of electricity not used directly or utilised by electrolysers increases.

In summary, it can be said that the more favourable financing conditions we assume here reduce the cost of electricity generated by a CRE power plant by EUR 15 to EUR 18 per MWh. The costs of intermittent renewable power production decline, as do the costs that make the system controllable. The leverage that financing costs have on investments in intermittent renewable energies has an even greater effect on the entire CRE power plant.

4.3. CRITERIA FOR GOVERNMENTAL DECISION-MAKING

In addition to the economic criteria considered in this study, the parameters listed below also play a role in governmental decision-making.

CRITERIA	NUCLEAR POWER PLANT	CRE POWER PLANT
Security of supply	High availability of power; predictable revisions; cluster risk due to centralised structure; higher energy independence than natural gas power plants.	Energy independent; high availability of gas power plants; decentralised structure; increased need for grid modification; assumes system services such as control power; cold-start capability; fossil fuel backup for natural gas imports; few electrolysers have been tested on an industrial scale so far.
Must-run load and flexibility	Flexibility only up to minimum load; higher must-run base load hampers the integration of intermittent renewable energies; load change increases costs.	Hardly any or no must-run load depending on the choice of technology; intermittent renewables can reduce output only; some surplus electricity is switched off; flexibility in meeting demand gains in value.
Value creation	Import of power plant components and fuel elements, with domestic processing a possibility; high demand for expertise, meaning a skilled domestic workforce is provided training over decades.	Domestic synthetic gas production and storage; possibility of manufacturing some components domestically; import of components for gas power plants; decentralised structure benefits rural areas; optional decentralised waste heat recovery.
Implications for gas infrastructure	Utilisation of existing gas network may be low in future if nuclear power plants are built.	High utilisation, and expansion may be needed; if hydrogen is used directly in engines/fuel cells, there is increased demand for a hydrogen infrastructure.
Scalability/ modularity	Low scalability.	Possible to successively expand and adapt dimensions to meet demand.
Environmental impact	Operations have low emissions; risk of nuclear contamination (regionally and	Operations are nearly climate-neutral; greater land use; gas power plants emit

	internationally); no safe final storage site for radioactive waste exists.	nitrogen oxide.

5. CONCLUSION AND PROSPECTS

In the coming decade, Europe will see demand for controllable, climate-neutral power plants that do not compromise European and national energy independence. The Visegrad countries are therefore planning to build nuclear power plants (NPPs) with a total net capacity of 15.6 GW, which roughly corresponds to the NPP capacity that Germany has been shutting down since 2011 and will continue to do until 2022. According to plans that are still not clear, France by 2030 could replace about six aging nuclear power plants, due for shutdown, with NPP projects that have a capacity of 10 GW; this would be in addition to current construction of the Flamanville 3 nuclear power plant. New NPPs are also being built in the UK and in Turkey.

Based on the costs of electricity generation in nuclear power plants, an economic calculation shows that budgeted figures and figures found in relevant literature, ranging from EUR 55/MWh to EUR 89/MWh (in 2016 EUR values), have often been significantly exceeded in recently planned NPP projects. In Flamanville, high cost increases are expected to raise the cost of power production to between EUR 87/MWh and EUR 126/MWh (2016 EUR values), and Hinkley Point C in the UK is receiving financial support amounting to EUR 119/MWh (2016 EUR value). Other costs not yet taken into account are accrued when radiation is released and when radioactive waste from NPPs is stored. It is difficult to quantify the extent of additional financial risks and the long-term additional costs due to environmental impacts.

One alternative to this situation is a controllable renewable energy power plant system that generates electricity from intermittent renewable sources as well as operates, to ensure controllability, electrolysers and gas power plants (with methanation as a between-step in this process). With comparable costs, this kind of system produces electricity with the same consistent security of supply, high energy independence, and minimal effect on the climate. Even considering today's expensive financial environment for renewable energies and even without joint optimisation within the Visegrad countries, the costs of this alternative are comparable. In Poland, they amount to about EUR 112/MWh, in the Czech Republic to EUR 119/MWh, and in Hungary to EUR 129/MWh. The potential in Slovakia however is still uncertain because of limited experience there with wind power; initial analyses indicate costs would be as high as EUR 167/MWh due to poor wind conditions.

Average power production costs for such a power plant system would be significantly lower if surplus electricity across the Visegrad countries were converted to electrolysis gas and distributed via the European gas network to these countries as needed. In this case, and assuming that standardised financing costs decline to a certain extent in these countries, costs would decrease to EUR 120/MWh by 2027 and to EUR 100/MWh (both EUR figures in 2016 values) by 2035.

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7. APPENDIX

Table 4: Assumptions used for the economic calculation of electrolysers (Energy Brainpool, 2018) and gas power plants (Linkenheil, et al., 2017)

Electrolysers					
First power produc-tion	CAPEX	OPEX	Age	WACC	Specific costs
Year	EUR/ kW	% of CAPEX	Years	%	EUR/ MW/year
2025	750	3.5	15	6.86	107,869
2030	500	3.0	15	6.86	69,413
2035	400	2.5	19	6.86	48,296

Power production			
Techno-logy	Specific costs	Rate of efficiency	Price of fuel
	EUR/ MW/year	%	EUR/ MWh
Gas turbines	47,000	41	40
Gas engines	59,000	49	40
CCGT	85,000	59	40

Table 5: Assumptions for the economic calculation of intermittent renewable energy facilities (*Meta-Analysis of 24 Studies with 135 Data Sets on the Costs of PV, Onshore Wind and Offshore Wind Power*)

		Onshore wind			PV				Specific costs	
Country	First power produc-tion	CAPEX	OPEX	Age	CAPEX	OPEX	Age	WACC	Wind	PV
	Year	EUR/ kW	% of CAPEX	Year	EUR/ kW	% of CAPEX	Years	%	EUR/ MW/year	
HU	2027	1,162	3.15	21	1,068	1.96	26	8.25	154,238	121,897
SK	2027	1,162	3.15	21	1,068	1.96	26	5.30	128,982	97,542
CZ	2035	1,078	3.15	21	828	1.96	26	8.00	141,005	92,825
PL	2035	1,078	3.15	21	828	1.96	26	8.00	141,005	92,825

Table 6: Detailed results for the V4 scenarios in Table 2. If "balance gas" is positive, electrolysis gas is imported over the year.

First year of power gener-ation	Country	Intermittent electricity			Controllability	
		Required output from renewables	Share of wind	Share of PV	Electrolyser capacity	Balance gas
		MW	%	%	MW_{el}	GWh_{th}
Vise-grad 2027	HU	14,599	74	26	3,696	-3,750
	SK	10,163	62	38	789	10,414
	CZ	24,511	76	24	4,324	591
	PL	36,406	83	17	7,999	-7,255
Vise-grad 2035	HU	14,884	70	30	4,848	-4,773
	SK	10,082	53	47	1,425	10,396
	CZ	24,126	70	30	5,531	659
	PL	35,141	78	22	9,730	-6,281

8. ABOUT ENERGY BRAINPOOL

Energy Brainpool GmbH & Co. KG provides independent expertise on energy markets with a focus on market design, price development and trading in Germany and Europe. Tobias Federico founded the company in 2003 with one of the first spot price forecasts in the market. Today Energy Brainpool's range of products includes the fundamental modelling of electricity prices using Power2Sim software, diverse analyses, forecasts and research-based studies. Energy Brainpool provides advice on strategic and operating issues and since 2008 has been offering advanced training programmes for experts in the field. The company combines knowledge and competence on business models, digitalisation, and the management of trade, procurement and risk, boasting many years of practical experience in controllable and intermittent energy production.

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