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Energy Security in the Era of Climate Neutrality

An analysis of alternative scenarios for
ensuring continuity of electricity supply
while minimizing greenhouse gas emissions

Warsaw, December 2020

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A study conducted at the National Centre for Energy Analyses (NCAE) established by the National Centre for Nuclear Research (NCBJ) and PSE Innowacje, commissioned by Polskie Sieci Elektroenergetyczne S.A. (PSE).

Assumptions were prepared at the Office of the Government Plenipotentiary for Strategic Energy Infrastructure (BP), and parametrization was consulted with PSE representatives.

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List of abbreviations

BP	Office of the Government Plenipotentiary for Strategic Energy Infrastructure
COA	Central Optimization Algorithm
CF	Capacity Factor
CSS	Continuous Supply Segment
DSM	Demand Side Management
DSR	Demand Side Response
FOM	Fixed Operation and Maintenance Cost
HR	Heat Rate
LCOE	Levelized Cost of Energy (average discounted production cost of an energy unit in the proposed energy mix)
LOLE	Loss of Load Expectation
NCAE	National Centre for Energy Analyses
NCBJ	National Centre for Nuclear Research
OCGT/CCGT	Open / Combined Cycle Gas Turbine
OECD-NEA	Nuclear Energy Agency
OVN	overnight cost
PSE	Polskie Sieci Elektroenergetyczne

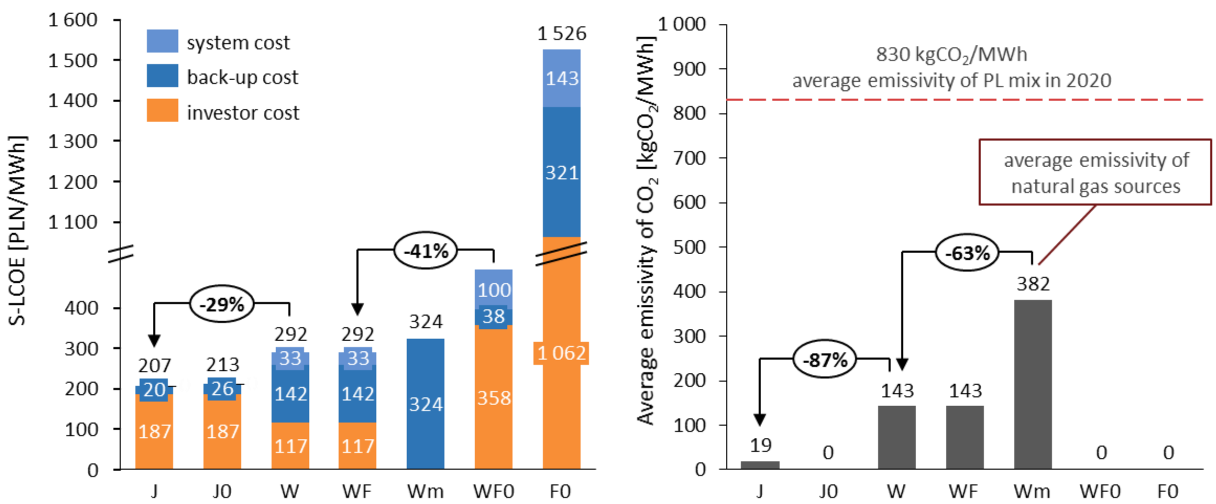
PPS	Polish Power System
PRSP	development plan for satisfying the contemporary and future electricity demand
PV	photovoltaics
RES	Renewable Source of Energy
S-LCOE	System Levelized Cost of Electricity
TLT	Technical Lifetime
TSO	Transmission System Operator
VOLL	Value of Lost Load
VOM	Variable Operation and Maintenance Cost
VRES	Variable Renewable Energy Sources

Executive summary

The idea of the study is to find the optimal strategy that will ensure 6 GW of constantly available capacity for the Polish Power System (PPS) for a period of 60 years. The installed capacity is to guarantee real energy security for final consumers and PPS itself, through continuous electricity supply up to the level of 6 GW at the lowest possible cost, based on the assumption of self-balancing of this part of the power system described in this report as Continuous Supply Segment (CSS). The competitiveness of solutions is also assessed in terms of the volume of CO_2 emission, in order to find a strategy with the highest potential for emission reduction.

In order to achieve the above objectives, four low-emission strategies and three zero-emission strategies have been developed. They differ as to their composition of available zero-emission technologies, renewable energy sources (RES) and nuclear energy as well as technologies that provide necessary backup capacity, represented by natural gas sources and energy storage facilities. An optimization model developed for the study (the optimizer) has enabled a composition of sources with the lowest cost from the final consumer's perspective to be selected from among technologies available under each strategy. The energy mix created this way for each strategy is treated as a constant throughout the 60 years under analysis.

The strategy quality assessment indicators include S-LCOE (System Levelized Cost of Energy). System LCOE is the average discounted production cost of an energy unit in the proposed mix, calculated for the entire strategy implementation period, taking into account the power system costs, i.e. development costs of transmission and distribution networks, and system flexibility costs.



Strategy code	J	J0	W	WF	Wm	WF0	F0
Leading technology	nuclear PP	nuclear PP	onshore & offshore wind	onshore & offshore wind + PV	offshore wind	onshore & offshore wind + PV	photovoltaics (PV)
Back-up technology	natural gas	nuclear PP	natural gas	natural gas + storage	natural gas	storage	storage

Figure 1. System LCOE decomposition (left-hand graph – intersection of the y-axis separating two ranges of values is introduced for better clarity) and emission benchmarks for the respective strategies (right-hand graph)

Key findings of the study

The list below contains the most significant findings from the study conducted, referring to the strategy codes from Table 1, discussed in detail in Chapter 2.

- Nuclear strategies (J, J0) are the most cost-effective, with their system LCOE by 80 PLN/MWh lower than the best RES strategies (W, WF). This translates into savings of approximately PLN 100 billion (discounted value) over a 60-year timespan, as compared to renewable strategies.

- Due to the high capital expenditure, offshore wind has not been built by the optimizer in any of the scenarios analyzed, which likely results from the early development of this technology compared to the rest of considered renewables. In the offshore strategy (Wm), the optimizer, when minimizing the costs, has opted for production of energy solely from the backup sources (CCGT).

- Zero-emission strategies based on RES (F0, WG0) are the most expensive ones despite the fact that the lowest energy storage cost projections have been assumed. This is due to the need to significantly increase the number of renewable installations and storage facilities resulting from periods of low or zero RES energy production.

- System costs together with backup costs represent more than a half of the total costs in the wind strategies (W, WF) and a significant share in the solar strategies. Such a substantial difference in costs justifies a change in criteria for economic assessment of renewable technologies.

- According to the parametrization adopted, network development costs do not occur in the case of dispatchable generating sources as they can largely use the existing power network for construction of new units that replace the decommissioned ones.

- Dispatchable sources do not incur balancing costs, as they have the capability to follow changes in electricity demand.

- Strategies with wind sources (W, WF) supported by gas result in CO_2 emissions that are 7.5 higher than in the case of nuclear energy, if supported by gas (J). This results from their much greater reliance on backup gas capacity.

- Among zero-emission strategies, the lowest total cost is achieved under the J0 strategy, based solely on the nuclear technology. Achieving a zero CO_2 emissions with other strategies under the present and currently expected conditions is very expensive.

1. Introduction

1.1 Reasons for the study

There is a growing public awareness of the consequences of energy acquisition, processing, and use, which largely contributes to a shift in the understanding of economic efficiency in the context of both the energy sector and the globalization. The most resonant topic that prevails in the public debate in recent years is responsibility of the energy sector for its negative impact on climate, environment, and public health. The growing dissent forces policymakers to reduce environmentally harmful externalities through regulatory measures. This leads to the development of new cost categories, which were not attributed previously to electricity generation, and they permanently alter competitiveness of individual generation technologies.

Research commissioned by the European Commission with a view to identify and parametrize the indirect costs caused by the energy sector contributes to gradual tightening of the EU's climate and energy policy. In effect, the EU Green Deal [1] package presented in December 2019 aims at achieving the Community's climate neutrality by 2050. The increasingly ambitious greenhouse gas emission reduction targets set in line with EU policy, and the consequently rising price of the carbon emission allowances, trigger an increase in wholesale electricity prices, thus systematically reducing competitiveness of the Polish economy.

In case of Poland, unfavorable market and regulatory conditions make it impossible for the baseload power plants to cover their costs from an increasingly subsidized energy market. That further impairs financial efficiency of the outdated generation base. This leads to an increase in the number of technical and economic outages of dispatchable units although they are necessary for the stable operation of the power system. According to the latest plan of development of the national transmission system by the PSE, the Polish electricity TSO, PRSP [2], in order to maintain the current power supply reliability standard (LOLE = 3h/year), the Polish power system would need 3-6 GW of new generation capacity until 2030. The following years will require intensive investments in generation sources, both for systemic and economic reasons.

Taking into account the EU's climate neutrality targets and other conditions, Poland is facing the largest and most costly energy transition in history. This great investment campaign can be a driving force for economic development and an opportunity for economic optimization of the energy sector. For optimal development, it is necessary to ensure the security of electricity supply at a minimum cost to the final consumer. To achieve this, policy makers should take into account all costs associated with the development of available low- and zero-emission technologies, in particular the systemic costs that tend to be overlooked in public discourse [3]. This study demonstrates the rationale for taking into account the backup technologies, network development, balancing and flexibility of the PPS as important components of the cost criterion determining the effectiveness of the energy strategies analyzed.

1.2 Ways of maintaining energy security in the times of climate changes

This study assumes that there are entities with a vested interest in the stable operation of the electricity system and the security of electricity supply for households and businesses in fully decarbonized conditions.

Stable operation of the power system is an intrinsic value for the transmission system operator, whose principal goal is such arrangement of relations between different stakeholders that its undisturbed operation is guaranteed. Thus, naturally, each TSO is looking for solutions supporting the variable generation of renewable sources. From the TSO's point of view - as an entity uninterested in the economic viability of particular technologies - the technology providing support for VRES is irrelevant as long as it ensures or supports the required level of security of supply.

Another type of entity interested in stability of decarbonized power system is the public authority, which in Poland is legally responsible for the energy security of the country. Severe interruptions in the supply of electricity would certainly have far-reaching economic and political consequences, as this commodity remains vital for the prosperity of households and the entire economy. At the same time, the government is responsible to the society for ensuring energy security in not only economically justifiable but also cost-optimal manner.

Acknowledging the needs of the secure operation of the system of both entities, it was assumed that in today's and foreseeable future conditions, the main source of ensuring the adequacy of VRES generation (in case of insufficiently favorable weather conditions) will be the following set of technologies: gas generation, energy storage, and nuclear power plants, as dispatchable sources of electricity. Battery warehouses were selected as a verified form of storage, taking into account the lower projected cost of this solution and the higher efficiency of the entire energy transformation chain compared to hydrogen-based solutions. Demand-Side Management (DSM) services, which are good tools to improve the flexibility of the system, could be treated as good solutions complementing the system operation. However, they do not solve the problem of possible mismatch of generation and demand due to prolonged low performance of weather-dependent sources (several or dozen days of no wind and high cloudiness for northern latitudes). Therefore, DSM services were not included in the scope of the study.

1.3 The concept of a Continuous Supply Segment as a remedy for systems with increasing generation uncertainty

The results of the study present a comparison of the economic effectiveness of alternative support options for ensuring the security of electricity supply in low-emission and zero-emission systems. The main assumption of the analysis is the need to ensure continuity of electricity supply to a segment of the power system, here assumed to amount of 6 GW. The tested section of the system must meet the requirement of full availability for 365 days a year, and therefore in all weather conditions, which must take into account the specificity of the power system operation in particular geographic conditions: i.e. windiness, insolation, and ambient temperature. For further discussion, the system's segment under test will be referred to as a **Continuous Supply Segment (CSS)**.

The Segment can be treated as a part of any larger power system, responsible for supporting the base of electricity demand and in no way determining the structure of generation of the rest of the system. The size of CSS is selected to ensure stable operation of the entire system with high variability of generation. The Segment is designed, inter alia, to prevent significant overloading of network nodes and maintain the voltage and frequency stability of the system with dynamic changes on the VRES generation and prosumer energy intake in the remaining part of the decarbonized system. Hence the necessity to adopt the assumption of its full availability, regardless of weather conditions. The applied solution aims to minimize the risk of collapse of the synchronous power system and its breakdown into smaller, unbalanced parts. The materialization of such a risk, most often leading to blackout, may result in enormous economic losses and a significant hazard to the life and health of people living in areas subject to unexpected supply interruptions. Due to the social responsibility of the TSO and public authorities, such a situation is to be avoided by all means, which constitutes an additional motivation to abandon the approach based on incorporating VOLL for the analyzed segment of the power system and to adopt the assumption that the proposed segment would be fully available.

In case of this study, the Continuous Supply Segment was determined at the level of 6 GW, which corresponds approximately to 18-20% of the peak power demand in Poland - PSE estimates approximately 28 GW of demand in 2030, whereas in 2040 – approx. 32 GW is expected[1]. The value of installed capacity in the CSS and its share in the peak power demand depends on the specificity of the system under test, however precise sizing of the block along with mere determination of the method used for this purpose could have been the subject of separate studies. Nevertheless, taking into account the need to ensure the security of supply by TSO, the report suggests the need to maintain a certain amount of available generation operating at the base of the power system. The research problem formulated in this way neither determines the shape and production technologies, nor does it make assumptions as to the energy demand characteristics of the rest of the system (circa 80% in this study). In other words, the postulate of continuous availability of generation, adopted in this study, applies only to a certain part of the power system, carefully defined at the level of 18-20% of the entire domestic consumption.

Of course, the development of energy storage technology, prosumer-based energy communities, and consumer awareness expressed by participation in DSR-type programs may prompt us to rethink the

[1] PSE, Development plan for satisfying the contemporary and future electricity demand for 2021-2030, p. 19-20, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf/8c629859-1420-432f-8437-6b3a714dda9c?safeargs=646f776e6c6f61643d74727565.

idea of "base load" as power generation from dispatchable sources only. The analysis of the availability of power based on available RES technologies shows, however, that it is not possible to meet consumer needs uninterruptedly based on these innovative solutions only. Each time it is necessary to secure a certain type of back-up sources, with e.g. gas or storage. Interestingly, the inclusion of energy storage does not question the concept of base load itself, but only indicates an alternative way of satisfying it (this method was included in the compared strategies). In turn, the potential of DSR - estimated depending on the peak demand in the system - from several hundred megawatts to several gigawatts, is very strongly dependent to timescale in which energy consumption would be withdrawn. The above facts do not make it possible to question the need to guarantee the supply corresponding to a certain critical level of the basic demand needed for the stable operation of the power system.

1.4 Central Optimization Algorithm as a tool for optimizing end-user costs – differences between social and investor's economic accountings

To clarify the nature of the research problem, the Central Optimization Algorithm (COA) concept has been created. In the model-based approach, the COA is an algorithm for finding a solution which is optimal in both technical and economic terms from the point of view of the entire Polish Power System within the set boundary conditions. For the purpose of this study COA was used to find optimal energy mix of a separate fragment of the NPS, corresponding to the characteristics of the postulated Continuous Supply Segment.

The role of the COA is to ensure energy security, defined as the ability to maintain stable continuity of energy supply at a minimum cost to final consumers and with minimum CO_2 emissions. To this end, the COA offers a long-term, economically optimal energy strategy, setting out the directions of the electricity sector's development and thus meeting the cost minimization condition.

In defining the strategy, the algorithm uses a social economic account that differs significantly from the investor cost's account. From the point of view of the social economic account, the overarching objective is to minimize the total costs for the economy due to electricity generation, taking into account all hidden costs incurred by the energy sector. Reduction of the total cost allows the final consumers to better meet their remaining non-electricity needs, which naturally allows for an increase of consumption of other goods and services. Another positive outcome is expected improvement of price competitiveness of the Polish enterprises in the international and domestic markets, which, combined with greater purchasing power potential of consumers, should drive up the domestic economy. On the other hand, the investor cost's account is naturally aimed at maximizing the individual profits of an investor within the given legal regime. Any indirect costs of generating electricity are passed in this case upon other market participants, onto external environment and onto the final consumers, and they are not significant for investors.

In the social account, the Central Optimization Algorithm, while setting out its investment strategy, indirectly acts like a holder of final consumers' capital. It does not hold any physical money for alternative investment projects; it only has the ability to oblige the consumers to bear certain costs. At the same time, due to the high diversity and fragmentation of consumers who benefit from energy consumption, no revenues from the implementation of the strategy are calculated. This finally brings the social economic account to the cost side, which takes into account the direct and indirect costs of electricity generation as well as the depreciation of production units and grid assets, which represents capital expenditure in the energy sector.

In implementing the strategy developed by the COA, final consumers are not responsible for gathering the physical capital necessary to cover capital expenditure during construction period. The responsibility for the generation of capital lays within the energy sector which expects a certain return on investment from final consumers (market). The nuclear sector is specific in the sense that the state is internationally responsible for the nuclear safety, which would justify the state's capital contribution to such investments.

The Central Optimization Algorithm simulates optimal market mechanisms that enable investors to make their investments provided for in the strategy and to receive a reasonable return on invested capital while respecting the environment and other market participants (technical aspects). The indirect costs of energy generation incurred by investors are taken into account in the social account as external costs. The COA minimizes the overall cost of the strategy by taking into account the system, environmental, climate, and macroeconomic costs that the investor does not include in his economic account. For the purposes of this study, external costs are limited to system costs, while the climate constraints were taken into account as the basic predicament of the electricity mixes considered as they were limited only to low- and zero-emitting ones.

By purchasing electricity, the final consumer repays capital expenditure and bears the operating costs of the energy sector that result from the mix as determined by the COA, taking into account all external costs generated by the investor (energy sector). The decision to repay the capital expenditure needed to implement the strategy is taken at the very beginning of the process, and the algorithm computes the capital expenditure for the construction period as accumulated at the beginning of the simulation period. This solution allows comparability of energy technologies to be maintained despite their different lifetimes by applying the equivalent for expenditure for the defined strategy implementation period (e.g. capital expenditure corresponding to the 60-year period of generation from natural gas sources). This solution is viable because of limited impact of discount on the social account, based, with regard to capital expenditure, solely on depreciation costs.

1.5 Subject of the study: Seeking an optimal low- and zero-emission strategy that maintains energy security of the PPS

The aim of the analysis is to discuss the economic effectiveness of various strategies aimed at providing Continuous Supply Segment. It was assumed that the low- and zero-emission strategies for this part of power system are implemented as green-field investments - they are built from scratch without using any existing generation infrastructure. The adopted assumption corresponds to the simplification of the need to replace a significant amount of old, available generation capacity in the existing power system, which is expected to be phased out in a similar period of time. In Poland, this situation corresponds to the expected closure of large energy complexes based on lignite, e.g. the power plant in Bełchatów, systematically operating as the base load due to low variable fuel costs. The length of time for analysis was set to 60 years, considering the greatest technology lifespan available today, but the method used to compare the strategies takes into account the lifespan of all the technologies under scrutiny, without favoring or marginalizing any of them.

More detailed objective set before the Central Optimization Algorithm is to provide the Polish Power System (PPS) with 6 GW of continuously available capacity for a period of 60 years. The capacity to be built is to ensure baseload capacity necessary for stable operation of the power system and to guarantee certainty of power supply to final consumers within the predefined limit of 6 GW.

Taking into account the global trends in the pursuit of climate neutrality, four low-carbon strategies and three zero-emission strategies are considered. Each strategy involves a combination of leading zero-emission technologies, i.e. renewable energy sources or nuclear energy, and technologies that provide the necessary backup capacity, represented here by natural gas sources and energy storage facilities. The composition of a given electricity mix remains unchanged throughout the 60 years covered by the analysis.

As part of the optimization, each strategy must guarantee stable electricity supply with full balancing of this part of the system, i.e. without exportable energy surpluses and similar shortages to cover imports. Therefore, the inability to import and export surplus energy generated by all technologies in Continuous Supply Segment, including RES, was assumed. Adopted assumption is the equivalent of the previously adopted contractual limit of no impact on the remaining part of the power system. From the point of view of the entire power system, high uncertainty in the availability of cross-border connections in the event of energy surpluses or shortages was also assumed. The adopted assumption results from the highly probable saturation of regional markets with energy originating from wind and solar installations. This can occur as a result of adopting further RES targets, which are similar for all the neighboring countries. Advancing trends may therefore lead to electricity surpluses and shortages over the same periods of time occurring across larger regions of the EU, limiting the possibility of import-export "on demand". In long-term perspective, such characteristics disqualify cross-border connections as a support for the proposed CSS. It is obvious, however, that the cross-border interconnections will be properly used in the operation of the rest of the power system, supporting its balancing and stable operation.

For each strategy, the COA optimally selects the energy mix from among available technologies, at the lowest cost from the perspective of final consumers. The strategy quality indicators include S-LCOE (System Levelized Cost of Energy). System LCOE is the average discounted production cost of an energy unit in the proposed mix, calculated for the entire strategy implementation period, taking into account the costs of the power system, i.e. development cost of transmission and distribution networks, as well as development costs of the system flexibility.

1.6 Main assumptions of the study

Optimization of technology choice – each strategy should supply energy at the lowest possible cost and the lowest possible CO_2 emission. The optimization consists in the appropriate choice of leading and backup technologies, so as to minimize the objective function over the 60-year strategy implementation period.

Electricity production – each strategy ensures continuous electricity production of 6 GW × 8760 h/year × 60 years. Production of excess energy (if any) is not taken into account in calculating the system LCOE.

Backup share – if the leading technology of a basket is unable to fully cover the demand, the rest is covered by the backup capacity assigned to the strategy concerned. If a CO_2 emissive backup capacity (natural gas) is used, the cost of carbon prices is included in the total strategy cost.

Technology operation period – all technologies used under a given strategy operate throughout the study period, i.e. for 60 years. The generation structure within the given strategy does not change along the 60-year strategy implementation period and in the case of a shorter technical lifetime of a technology, its repowering takes place; costs reduction – that result from the repowering and technology advances within the generation structure concerned – are reflected.

Construction time – the identical, cumulative time of construction of all sources needed to calculate financing costs during construction (interest before loan principal repayment starts) is set at 8 years. The total capital expenditure – including repowering from entire 60-years strategy implementation period is incurred evenly over 8 years of construction before commercial operation date of first power plant. This simplification has been intended to limit the impact of discount on the economic comparability of long-life technologies with technologies of a shorter lifetime.

Unit capital expenditure – for the purposes of the study, it has been determined in terms of million PLN /(MW×life year), where expenditure depends on the installation lifetime. For example, in order to achieve the objective of ensuring 60 years of continuous energy generation under the wind strategy, three generations of wind sources with a 25-year lifetime will be created, of which only 40% (10/25) of the costs of the 3rd generation will be included in total capital expenditure. The amount of unit expenditure for each successive technology generation decreases in line with the market trends taken into account in the study.

Asset retirement costs – for nuclear power plants: included in the retirement charge of PLN 17.2/MWh (variable cost) as set in the Regulation of the Council of Ministers of 10 October 2012 on the amount of contributions to the NPP retirement fund [4], for other technologies: a 5% increase in OVN costs is assumed in accordance with the OECD-NEA methodology [5].

System costs – in order to reflect the impact of non-dispatchable sources on the power system, the study takes into account the transmission and distribution network development costs and the costs of system flexibility, correlated with RES development. The costs of system flexibility are understood as resulting from the need for power rump up / rump down and the cycle of start-up / shut-down of dispatchable sources. Owing to their high level of capability for dispatching, ability to follow demand and to largely use the existing network infrastructure in the case of substituting old plants, dispatchable technologies (nuclear, natural gas) are characterized by negligible values of system costs (taken as zero in the study) [6-12].

Interest rates – the cost of capital during construction and the cost of capital after commencement of loan repayment, as well as the discount rate is taken to amount 3% and it is identical for all strategies. The low interest rate results from the assumption that lenders providing 100% of capital expenditure in each case can be international financial institutions or the state treasury.

Capital and interests repayment – calculated on the amount of write-off of capital expenditure on fixed assets (and it takes into account the cost of investment financing in the construction period). The total cost of the strategy is spread into 60 equal yearly instalments at the interest rate of 3%.

Economic assumptions – capital expenditure, variable costs, fixed costs, fuel prices and carbon prices are variable over successive years of the analysis in line with the forecasts adopted [13-14].

2. The review of strategies

As part of the study, seven strategies presumed for achievement of the long-term objective of ensuring generating capacity for the Polish Power System were analyzed. A list of competitive solutions under analysis is provided in Table 1. The strategies differ in the type of leading technology and the backup capacity implementation method –these two dimensions are illustrated in Figure 2.

Table 1. Characteristics of the studied strategies for ensuring capacity in the PPS

STRATEGY CODE	AVAILABLE TECHNOLOGIES	INTERPRETATION
W	onshore and offshore wind + gas	mix of wind energy supported by gas installation, in line with EU tendencies
Wm	offshore wind + gas	use of offshore wind farms in the Baltic as zero-emission source supported by gas units
F0	photovoltaics + energy storage	zero-emission strategy providing for the development of prosumer energy, in which energy storage facilities support PV cells
WF	onshore and offshore wind, PV + gas, and energy storage	mix optimization for all available RES and backup technologies (gas technologies and energy storage facilities)
WF0	onshore and offshore wind, PV + energy storage	zero-emission strategy in which wind and photovoltaic energy development is backed by large-scale energy storage facilities
J	nuclear energy + gas	nuclear power plant ensuring high availability and supported by gas installations during outages
J0	only nuclear energy	zero-emission strategy, in which nuclear energy operates as the primary and backup source

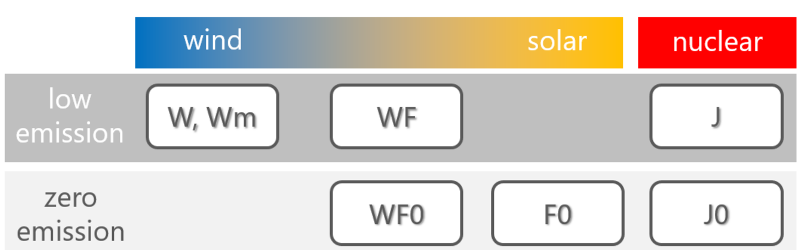


Figure 2. Matrix of strategies analyzed for ensuring generating capacity for the PPS – the strategies are grouped according to leading technology (in columns) and CO_2 emission assumptions (in rows)

2.1 W strategy

2.1.1 Mix results

The results for the strategy are shown in Table 2 and Table 3 below. From among renewable energy sources available to the optimizer, it chooses the construction of onshore wind farms. More than 10 GW assigned to wind installations exceeds the necessary condition of 6 GW capacity in each hour. Yet, taking into account the efficiency of electricity production due to variable wind force (capacity factors), the installation size required is rational. As a backup to wind farms, 6 GW is to be provided in gas-fired units in the CCGT and OCGT technologies, whose capacities proportions are roughly 2:1. The optimizer did not use the option to build offshore wind farms as the onshore had proved to be more cost-effective.

Table 2. Optimum energy mix (technology composition) under W strategy

Optimization result: installed capacity [GW]			
onshore wind	offshore wind	gas (CCGT)	gas (OCGT)
10.17	**0**	**4.03**	**1.97**

Table 3. Discounted costs of implementation of strategy W decomposed into fixed, variable, and system components and broken down into the cost of leading and backup technologies[2]

Measure / strategy	W		
Mix composition	onshore and offshore wind + gas		
	RES	BACK-UP	TOTAL
System LCOE [PLN/MWh]			**291.6**
1. Fixed cost [PLN bn/60 years]	138.4	35.3	**173.7**
- Capital expenditure	96.3	26.8	**123.1**
- Cost of capital	10.7	3.0	**13.7**
- Fixed operating cost	31.4	5.5	**36.9**
2. Variable cost [PLN bn/60 years]	0.0	132.6	**132.6**
- CO_2 emissions	0.0	29.5	**29.5**
- Fuel	0.0	98.4	**98.4**
- Variable operating cost	0.0	4.7	**4.7**
3. System cost [PLN bn/60 years]	38.6	0.0	**38.6**
- Network development	24.3	0.0	**24.3**
- Flexibility development	14.3	0.0	**14.3**
Total cost [PLN bn/60 years]	177.0	167.9	**344.9**

[2] The numerical values in the tables are rounded, which may cause an apparent inaccuracy in summing up cells versus respective columns or rows.

2.1.2 Decomposition of costs

The costs of the leading technology represent only 40% of the total expenditure on strategy implementation. The other parts belong either to the system cost (approx. 10%) or the backup cost (50%). The high level of backup cost is associated with fuel and carbon prices (in aggregate, approx. 40% of total costs) and the value of investment in generation capacity (10% of total costs).

2.1.3 Notes on the solution

The optimization task is a linear programming problem and it covers more than half a million hours and as many decision variables with which generation and technology efficiency costs are associated and evolving over time. For verification, as well as for better understanding of the optimization result, we will use a simplified non-linear model created on the basis of average values of parameters that, in case of full optimization, change over time.

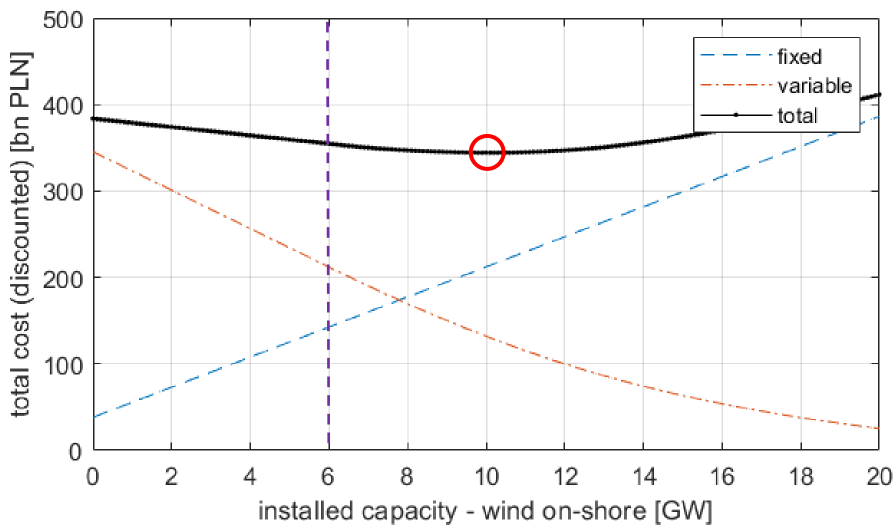


Figure 3. Optimization of implementation costs of W strategy

Figure 3 presents the cost of the strategy implementation in relation to the installed capacity of onshore wind farms, based on the assumption that the backup technology is natural gas, that the analysis period is 60 years long, and the required demand level of 6 GW has been satisfied at any time. The left edge of the graph (0 MW value on the X-axis) represents a lack of renewable technology installed – the energy generation is based at this point on the backup technology only. Along the RES expansion, the fixed and system costs of the strategy W increase (blue straight line), while its variable costs (orange curve) decrease as a result of declining consumption of natural gas in favor of electricity production from the wind farms. The savings amount, represented by decreasing black curve of total costs, diminishes where RES installed capacity exceeds 6 GW and the part of energy produced exceeds the production volume for which gas backup capacity would be responsible. The total cost (**black curve**) is the lowest for the optimal solution, i.e. for approximately 10 GW of installed capacity in wind technologies.

2.2 Wm strategy

2.2.1 Mix results

In this strategy, the optimizer decides that offshore wind is too expensive as compared to natural gas power plants and therefore the optimum solution (Table 4) shows a complete lack of offshore wind farms. As a consequence, in this case, the CCGT units represent both the leading and the backup technology.

Table 4 Optimum energy mix (technology composition) under the Wm strategy

Optimization result: installed capacity [GW]		
offshore wind	gas (CCGT)	gas (OCGT)
0	**6.00**	**0**

Table 5. Discounted costs of implementation of strategy Wm decomposed into fixed, variable, and system components and broken down into the cost of leading and back-up technologies

Measure/strategy		**Wm**	
Mix composition		offshore wind + gas	
	RES	BACK-UP	**TOTAL**
System LCOE [PLN/MWh]			**324.4**
1. Fixed cost [PLN bn/60 years]	0.0	38.3	**38.3**
- Capital expenditure	0.0	29.7	**29.7**
- Cost of capital	0.0	3.3	**3.3**
- Fixed operating cost	0.0	5.2	**5.2**
2. Variable cost [PLN bn/60 years]	0.0	345.4	**345.4**
- CO2 emissions	0.0	77.4	**77.4**
- Fuel	0.0	255.9	**255.9**
- Variable operating cost	0.0	12.1	**12.1**
3. System cost [PLN bn/60 years]	0.0	0.0	**0.0**
- Network development	0.0	0.0	**0.0**
- Flexibility development	0.0	0.0	**0.0**
Total cost [PLN bn/60 years]	0.0	383.7	**383.7**

2.2.2 Decomposition of costs

Almost 90% of the strategy implementation expenditure consists of variable costs, of which ¾ is the cost of natural gas (Table 5). In the total we do not see the costs associated with expansion of the power grid, neither the balancing nor flexibility costs. These costs' components are not assigned to the natural gas units, for which it is assumed that their location and operation mode do not force distribution and transmission network operators to incur additional expenditure.

2.2.3 Notes on the solution

Figure 4 presents the cost of strategy implementation in relation to installed capacity of offshore wind farms, based on the assumption that the backup technology is natural gas. The fixed and system costs increase with RES expansion (blue straight line), and the variable cost decreases due to falling consumption of natural gas (orange curve). An increase in investment costs, resulting from the construction of offshore wind farms, exceeds from the very beginning the savings related to abandoning energy production in gas power plants even with rising carbon prices (from PLN 105/tCO_2 to PLN 210/tCO_2 in 2050). Consequently, the total costs (**black curve**) reaches its lowest value at the extreme left point of the graph – with no offshore wind farms built. Implementation of the mix under one of the strategies with RES as the leading technology by means of the backup technology only is a controversial, although rational result of the COA simulation. The optimization result does not allow for a conclusion to be drawn on the implementation cost of the offshore wind energy in the rest of PPS.

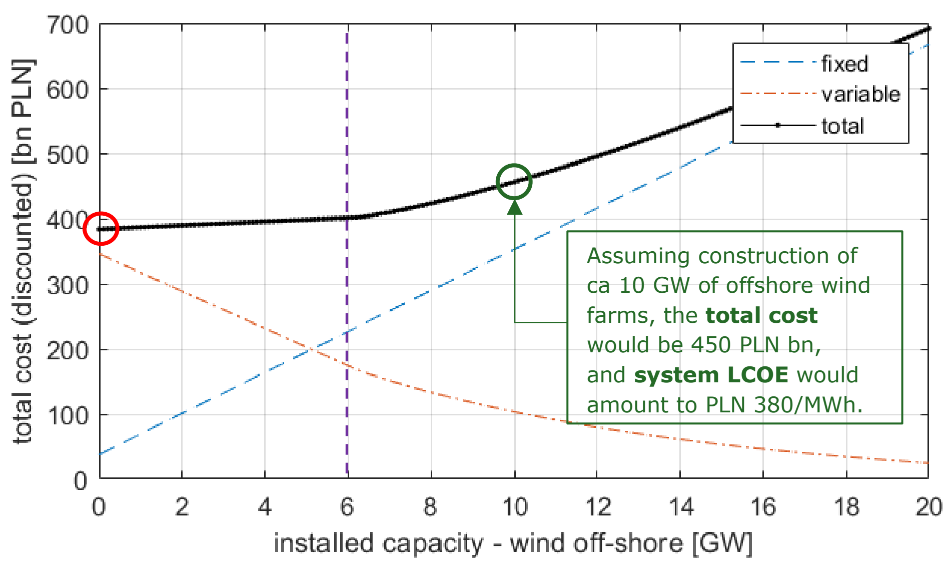


Figure 4. Optimization of Wm strategy implementation costs

Despite lack of wind farms in the optimal solution as simulated by COA, let us make an attempt to estimate the cost of off-shore strategy with a given amount of renewable capacity installed, and based on the same parameters of simulation. For this purpose, an illustrative juxtaposition of total costs vs installed off-shore capacity is used (Fig. 4). It shows that a set RES installed capacity of ca. 10 GW involves total expenditure of approx. PLN 450 billion and system LCOE of PLN 380/MWh. Its backup (CCGT) costs would amount to approx. PLN 140 billion (with approx. PLN 100 billion for variable costs, and PLN 38 billion for fixed costs, as in the case of the backup fixed cost in Table 5). The remaining amount of approx. PLN 310 billion is the cost of investment in RES generation resources, O&M costs and the system cost generated through 60 years of operation.

One of the cost parameters significantly affecting the unviability of offshore wind farm technologies is the CO_2 emission allowances price. In the strategy considered, it accounts for nearly ¼ of the variable costs associated with energy production from CCGT sources. In the analyzed period, depending on the simulated year, emission prices per tonne of carbon dioxide assume a value in the PLN 118-214 range, the average value being approx. PLN 189/tCO_2. The calculations show that offshore wind becomes an attractive technology at the average cost of emission certificates of approx. PLN 270/tCO_2.

The real costs of implementation of the Wm strategy could be higher, if a reserve for the CCGT units is considered. If we assume that each generating unit operates for 95% of time in a year, an optimal set is 20 units of 316.8 MW each, out of which only 19 blocks operate in each moment in time. If we take into consideration thus conceived reserve of one unit, it does not change the total operating costs (fuel, CO_2) of the strategy. It does, however, bring the total fixed costs up by 5%, as it rises the total installed capacity to 6316.8 MW, instead of 6000 MW. As a result, the total discounted costs of implementation of the strategy Wm get higher by PLN 2 billion, which makes ca. 0.5% of its total discounted costs, while it does not influence relative positioning of the strategies analyzed.

2.3 F0 strategy

2.3.1 Mix results

The Central Optimization Algorithm shows the need to install almost 180 GW of PV capacity, and the size of storage that guarantees continuity of electricity supply is set at above 200 GWh (Table 6).

Table 6. Optimum energy mix (technology composition) under F0 strategy

Optimization result: installed capacity [GW]	
photovoltaics [GW]	energy storage [GWh]
178.59	**203.08**

Table 7. Discounted costs of implementation of strategy F0 decomposed into fixed, variable and system components and broken down into the cost of leading and backup technologies

Measure/strategy		**F0**	
Mix composition		photovoltaics + storage	
	RES	BACK-UP	**TOTAL**
System LCOE [PLN/MWh]			1 535.9
1. Fixed cost [PLN bn/60 years]	1 256.2	379.6	**1 635.8**
- Capital expenditure	1 000.6	300.2	**1 300.8**
- Cost of capital	111.6	33.5	**145.1**
- Fixed operating cost	144.1	45.9	**189.9**
2. Variable cost [PLN bn/60 years]	0.0	0.0	**0.0**
- CO2 emissions	0.0	0.0	**0.0**
- Fuel	0.0	0.0	**0.0**
- Variable operating cost	0.0	0.0	**0.0**
3. System cost [PLN bn/60 years]	168.7	0.0	**168.7**
- Network development	147.0	0.0	**147.0**
- Flexibility development	21.7	0.0	**21.7**
Total cost [PLN bn/60 years]	1 424.9	379.6	1 804.5

2.3.2 Decomposition of costs

Very high F0 strategy implementation cost (Table 7) is divided into: investor cost, being a sum of fixed and variable costs of the leading technology (70%), cost of backup – energy storage facilities (approx. 20%) and system cost (approx. 10%).

2.3.3 Notes on the solution

The average level of stored energy needed is shifted in phase with respect to PV generation (Figure 5). The needed storage size becomes apparent every December, when batteries are fully discharged during five successive days (Figure 6).

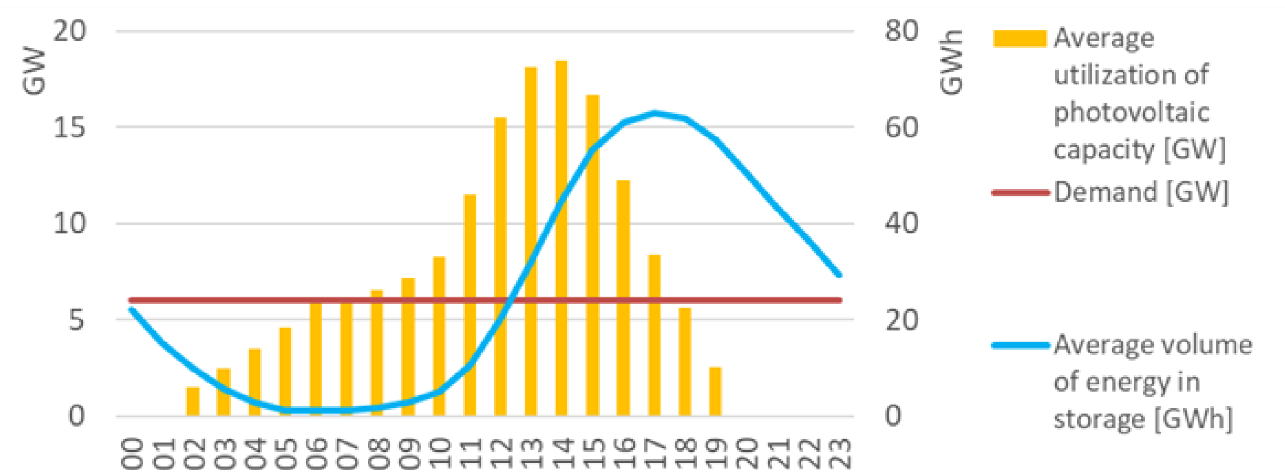


Figure 5. Summary of average utilization of capacity from PV installations against the average level of energy accumulated in storage facility (hour stated for UTC±00:00)

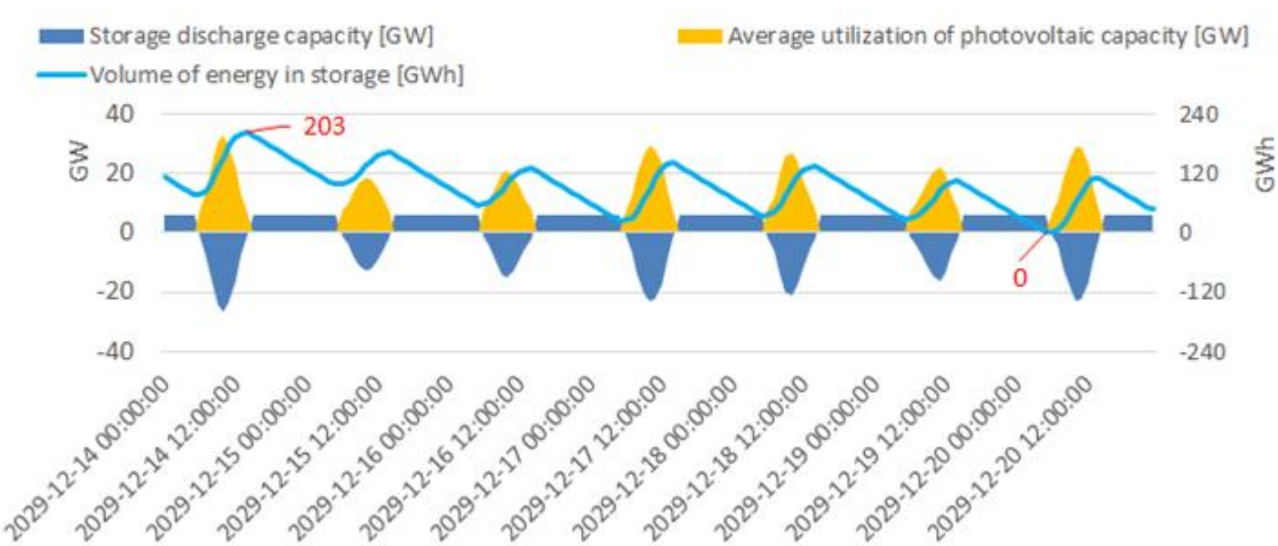


Figure 6. Storage capacity trajectory over time. A 203 GWh storage facility is discharged to zero within a few winter days

Why has the COA chosen such a large installation size? If the F0 strategy assumed only the production of energy corresponding to the volume of 6 MW× 60 years, with no need to ensure the continuity of supply, installation with a capacity of 42 GW in PV cells would be sufficient (given the average annual capacity factor of the PV technology at geographic location of Poland). Total value of such an investment in 60-year analyzed period would be PLN 286 billion. However, having regard to the need to ensure continuous availability of capacity, i.e. implementation of energy storage facilities, and to increase the PV capacity volume for charging the storage, the necessary PV capacity increases more than four times to about 180 GW. Importantly, the volume of energy produced in such configuration exceeds the demand by almost 320% – excess energy is a consequence of the limited demand (assumed at 6 GW in each hour) and finite capacity of energy storage facilities.

Implementation of F0 implies overproduction of energy. Consequently, it is important to analyze the assumption of inability to export electricity or utilize the excess production in another way. Excess energy potentially influences calculation of the system levelized cost of energy (S-LCOE), on the other hand the overproduction coincide with the moments when explicit demand of local consumers has been satisfied. A solution that could be used to rationalize overproduction of energy is power-to-gas technology (which is an extension of the range of electric energy storage methods). Consideration of excess energy in S-LCOE has been discussed in Appendix 4.1.

It is worth to highlight that estimates of S-LCOE with excess energy are in fact placed in the lower boundary of potential costs associated with the implementation of power-to-gas approach. The real costs would be substantially higher due to:

- the need for additional storage installations, which are not considered in an optimal energy mix, as determined for strategy F0,
- lower values of effectiveness of excess energy, as a consequence of taking into account efficiency lost for recovery of stored energy.

2.4 WF strategy

2.4.1 Mix results

The energy mix calculated by COA under the WF strategy is identical with the technology composition chosen for the W strategy (Table 8). The capability to use photovoltaic sources and energy storage facilities (not available for COA under the W strategy) does not affect the final mix composition due to a lower effectiveness of the added technologies.

Table 8. Optimum energy mix (technology composition) under WF strategy

Optimization result: installed capacity [GW]					
onshore wind	offshore wind	PV	gas (CCGT)	gas (OCGT)	storage
10.17	**0**	**0**	**4.03**	**1.97**	**0**

Table 9. Discounted costs of implementation of strategy WF decomposed into fixed, variable and system components and broken down into the cost of leading and backup technologies

Measure/strategy	**WF**		
Mix composition	onshore and offshore wind and photovoltaics		
	RES	BACKUP	**TOTAL**
System LCOE [PLN/MWh]			**291.6**
1. Fixed cost [PLN bn/60 years]	138.4	35.3	**173.7**
- Capital expenditure	96.3	26.8	**123.1**
- Cost of capital	10.7	3.0	**13.7**
- Fixed operating cost	31.4	5.5	**36.9**
2. Variable cost [PLN bn/60 years]	0.0	132.6	**132.6**
- CO2 emissions	0.0	29.5	**29.5**
- Fuel	0.0	98.4	**98.4**
- Variable operating cost	0.0	4.7	**4.7**
3. System cost [PLN bn/60 years]	38.6	0.0	**38.6**
- Network development	24.3	0.0	**24.3**
- Flexibility development	14.3	0.0	**14.3**
Total cost [PLN bn/60 years]	177.0	167.9	**344.9**

2.4.2 Decomposition of costs

Table 9 illustrates the results of cost decomposition for the WF strategy, which are identical with those for the W strategy (Table 3).

2.4.3 Notes on the solution

The three curves presented in the graph below (Figure 7) illustrate discounted total costs for the three RES technologies in relation to the installed capacity volume, based on the assumption of CCGT technology operating as backup. The circles represent optimally cost-effective levels of renewable technologies. The inclusion of photovoltaic sources and energy storage facilities in the optimization has not altered the solution of the W strategy, due to a high cost of PV installations and energy storage facilities. Onshore wind with backup natural gas capacity has come up again as the cheapest RES strategy, because of decreasing capital expenditure and the capacity factor higher than for PV.

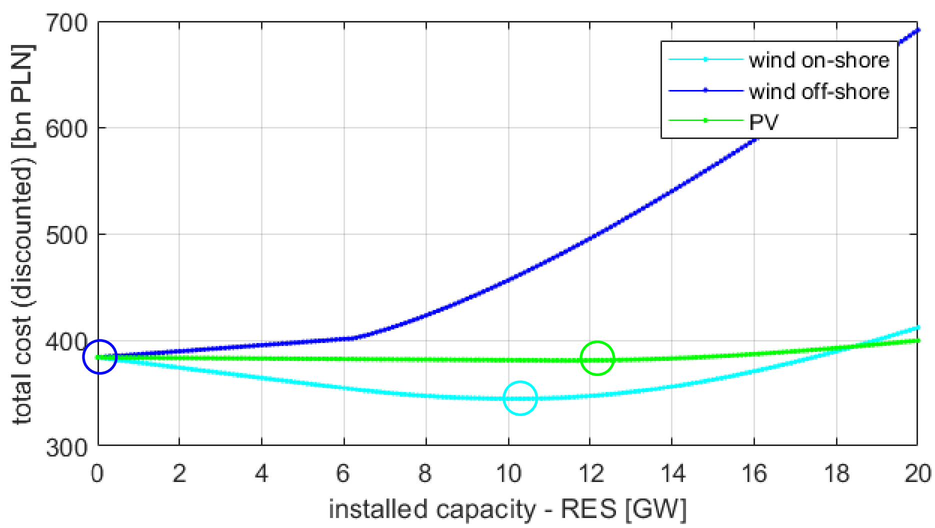


Figure 7. Optimization of the implementation costs of selected renewable technologies. The figure introduces three curves representing total cost, which are analogous to the black lines depicted on Fig. 3-4. Yet, unlike on Fig. 3-4, decomposition of the total cost into fixed and variable components has been omitted.

2.5 WF0 strategy

2.5.1 Mix results

WF0 is a zero CO_2 emissions strategy that offers three renewable technologies and one (zero-emission) backup technology. The optimum choice provides mainly for the use of onshore wind farms (over 31 GW) supported by energy storage facilities with a capacity of 23.9 GWh. The COA has not provided for a share of photovoltaic sources (Table 10).

Table 10. Optimum energy mix (technology composition) under WF0 strategy

Optimization result: installed capacity [GW]			
onshore wind	offshore wind	photovoltaics	storage [GWh]
31.10	**0**	**0**	**23.90**

Table 11. Discounted costs of implementation of strategy WF0 decomposed into fixed, variable and system components and broken down into the cost of leading and backup technologies

Measure/strategy	**WF0**		
Mix composition	onshore and offshore wind and photovoltaics + storage		
	RES	BACKUP	**TOTAL**
System LCOE [PLN/MWh]			**495.3**
1. Fixed cost [PLN bn/60 years]	423.2	44.7	**467.8**
- Capital expenditure	294.4	35.3	**329.7**
- Cost of capital	32.8	3.9	**36.8**
- Fixed operating cost	95.9	5.4	**101.3**
2. Variable cost [PLN bn/60 years]	0.0	0.0	**0.0**
- CO2 emissions	0.0	0.0	**0.0**
- Fuel	0.0	0.0	**0.0**
- Variable operating cost	0.0	0.0	**0.0**
3. System cost [PLN bn/60 years]	118.0	0.0	**118.0**
- Network development	74.3	0.0	**74.3**
- Flexibility development	43.6	0.0	**43.6**
Total cost [PLN bn/60 years]	541.1	44.7	**585.8**

2.5.2 Decomposition of costs

The results of the cost decomposition are shown in Table 11. More than 70% of the total costs is the fixed cost of leading technologies. A large value of installed capacity in renewable sources entails high system costs (20% of the total).

2.5.3 Notes on the solution

In terms of the total cost, the WF0 strategy ranks between the least cost-effective F0 strategy (from which it differs in the option to use onshore wind farms) and the cheapest of the renewable strategies – WF, from which it differs in the lack of the option to use natural gas power plants.

WF0 is one of two strategies that provide for the construction of energy storage facilities, yet the WF0 selected battery capacity differs significantly from the volume proposed under F0. The difference in the size of storage facilities is influenced by the two factors:

1. Capacity factors for renewable technologies differ substantially, with efficiency of the onshore wind farms by 2.5-3 times highest. Meeting only the energy needs at the volume of 6 GW × 60 years would require only 16 GW of installed capacity. Yet, satisfying the demand for continuous capacity availability necessitates double increase in RES installation size. As compared to F0, the strategy WF0 is characterized with higher minimum production levels and lower requirements with regard to the size of energy storage (24 GWh, as compared to 203 GWh).

2. The pattern of capacity availability (resulting from the distribution of capacity factor values) operates to the advantage of wind energy. For photovoltaics, energy production interruptions may reach well over ten hours each, which necessitates storage capacity of at least 200 GWh. Energy production from a set of distributed wind turbines rarely comes down to zero, and more than ten successive windless hours never occurred according to the input data set. For this reason, storage discharge is not of a structural, but of an ad hoc nature, which allows the required storage capacity level to be reduced.

2.6 J strategy

2.6.1 Mix results

Under the J strategy, the leading technology is nuclear energy, which satisfies a large majority of capacity and electricity demand. As a backup technology, CCGT with 1 GW of installed capacity has been recognized as necessary during outages of nuclear units (Table 12).

Table 12. Optimum energy mix (technology composition) under J strategy

Analysis result: installed capacity [GW]		
nuclear energy	gas (CCGT)	gas (OCGT)
6.00	**1.00**	**0**

Table 13. Discounted costs of implementation of strategy J decomposed into fixed, variable and system components and broken down into the cost of leading and backup technologies

Measure/strategy	J		
Mix composition	nuclear energy + gas		
	NPP	BACK-UP	**TOTAL**
System LCOE [PLN/MWh]			207.2
1. Fixed cost [PLN bn/60 years]	162.8	6.4	**169.2**
- Capital expenditure	101.4	5.0	**106.3**
- Cost of capital	11.3	0.6	**11.9**
- Fixed operating cost	50.2	0.9	**51.0**
2. Variable cost [PLN bn/60 years]	58.6	17.3	**75.8**
- CO2 emissions	0.0	3.9	**3.9**
- Fuel	29.7	12.8	**42.5**
- Variable operating cost	28.9	0.6	**29.5**
3. System cost [PLN bn/60 years]	0.0	0.0	**0.0**
- Network development	0.0	0.0	**0.0**
- Flexibility development	0.0	0.0	**0.0**
Total cost [PLN bn/60 years]	221.4	23.7	**245.1**

2.6.2 Decomposition of costs

High investor costs (of the leading technology) represent 65% of the strategy implementation expenditure. The operation of nuclear power plants generates 25% of the total costs of the strategy, while backup represents 10% (Table 13).

2.6.3 Notes on the solution

The analysis provides for the construction of 6 nuclear power units of 1 GW installed capacity each. Each of the units operates for 95% of the year (with 2.5 weeks of unavailability allowance), and unit outages do not overlap. A backup source (natural gas power plants) with a total capacity of 1 GW provides power during the non-availability of nuclear power units, operating at full capacity for 30% of the year (as shown in Figure 8).

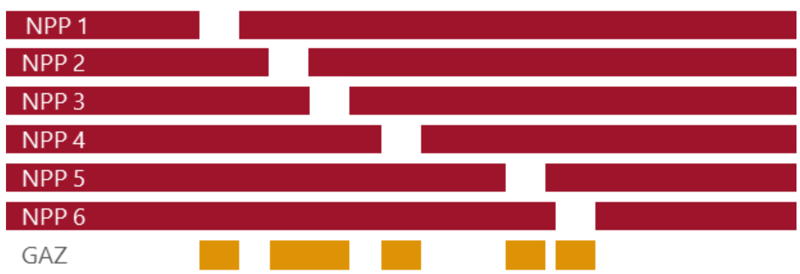


Figure 8. A scheme of non-availability of the nuclear units over time covered by backup operating range (natural gas units)

2.7 J0 strategy

2.7.1 Mix results

The optimization of J0 strategy assumes that 6 GW of installed capacity in nuclear units gets backup in the form of an additional 1 GW supplied by the same technology (Table 14), since nuclear power units satisfy both required continuity of electricity supply and zero CO_2 emissions.

Table 14. Optimum energy mix (technology composition) under J0 strategy

Analysis result: installed capacity [GW]	
nuclear energy (leading technology)	nuclear energy (backup technology)
6.00	**1.00**

Table 15. Discounted costs of implementation of strategy J0 decomposed into fixed, variable and system components and broken down into the cost of leading and backup technologies

Measure/strategy	J0		
Mix composition	nuclear energy		
	NPP	BACK-UP	**TOTAL**
System LCOE [PLN/MWh]			212.8
1. Fixed cost [PLN bn/60 years]	162.8	27.1	**190.0**
- Capital expenditure	101.4	16.9	**118.3**
- Cost of capital	11.3	1.9	**13.2**
- Fixed operating cost	50.2	8.4	**58.5**
2. Variable cost [PLN bn/60 years]	58.6	3.1	**61.7**
- CO2 emissions	0.0	0.0	**0.0**
- Fuel	29.7	1.6	**31.2**
- Variable operating cost	28.9	1.5	**30.4**
3. System cost [PLN bn/60 years]	0.0	0.0	**0.0**
- Network development	0.0	0.0	**0.0**
- Flexibility development	0.0	0.0	**0.0**
Total cost [PLN bn/60 years]	221.4	30.2	**251.7**

2.7.2 Decomposition of costs

The total cost is generated by fixed and variable costs assigned to the leading technology, i.e. nuclear energy (Table 15, cf. Table 13). In order to highlight expenditure on the construction and use of the backup unit, part of the total funding is assigned to the “backup” category. Consequently, the cost of the backup unit represents 14% of the investment, despite the fact that it accounts for 5% of electricity production. This disparity is due to a lower level of production as compared to the leading technology units, with identical investment costs for each of the 7 nuclear units built.

2.7.3 Notes on the solution

The COE provides for the construction of 7 nuclear power units of 1 GW installed capacity each. Each of the 6 leading units operates for 95% of the year (with 2.5 weeks allowed for unavailability), and the unit outages do not overlap. A backup source (also in nuclear technology) with a total capacity of 1 GW provides power during the non-availability of the leading power units, and it operates at full capacity for 30% of the year (as shown in Figure 9).

A possible operation of backup capacity in excess of the time necessary to replace the non-availability of the primary units again raises the problem of use of the excess energy, so clearly visible already in the case of the F0 strategy. As with F0, power-to-gas technologies can be an option.

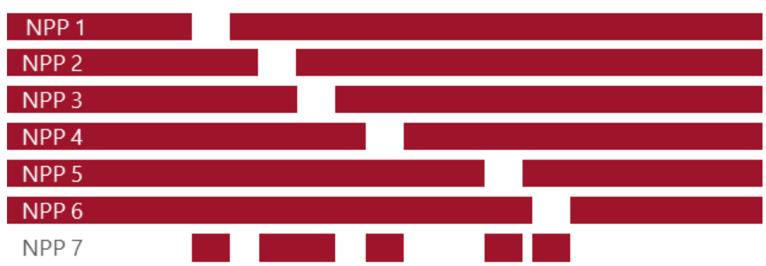


Figure 9. A scheme of non-availability of nuclear units over time and backup operating range. In this case, backup is provided by an additional unit built in the leading technology (nuclear)

3. Summary

The list below and Figure 10 summarize the results obtained in the study.

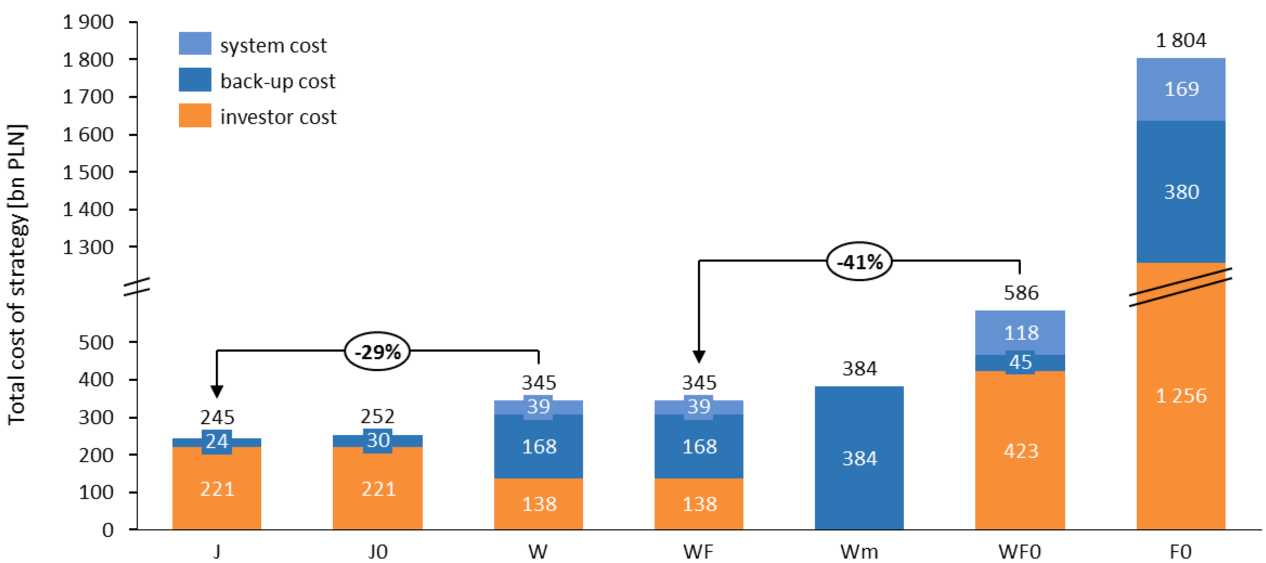
1. The use of nuclear energy appears as the cheapest way to increase energy security through the development of Continuous Supply Segment, also under the option that requires zero CO_2 emissions.

2. The cost analysis of ensuring full availability of capacity shows a lack of economic viability for offshore wind farms as a source of energy securing the operation of the PPS, yet development of this technology in rest of the power system may be determined by other considerations.

3. Onshore wind seems the most cost-effective renewable technology. Offshore wind and photovoltaic investments generate high costs even at a low cost of capital (WACC=3%).

4. For strategies based on non-dispatchable renewable sources the necessity to provide backup capacity proves costly (and comes with CO_2 emissions), as it accounts for up to half of the total costs of energy generation.

5. RES strategies involving zero CO_2 emissions require construction of large storage facilities and generation capacity sufficiently high to ensure storage charging.



Strategy code	J	J0	W	WF	Wm	WF0	F0
Leading technology	nuclear PP	nuclear PP	onshore & offshore wind	onshore & offshore wind + PV	offshore wind	onshore & offshore wind + PV	photovoltaics (PV)
Back-up technology	natural gas	nuclear PP	natural gas	natural gas + storage	natural gas	storage	storage

Figure 10. Summary of the total discounted costs of individual strategies by investor costs, system and backup costs [PLN billion]

The aim of the study was to analyze the economic efficiency of possible scenarios allowing the implementation of the CSS concept without prejudging the shape of the rest of the power system. Therefore, the conclusions presented above should not be translated directly into the rest of the power system, which is unknown in this study. An important aspect of the study is to illustrate the impact of the obligation to fully secure generation from uncontrollable power on the total costs associated with the development of such technologies. Mentioned effect is also visible at the level of the entire PPS through retail market prices increase, in particular with high penetrations of weather-dependent sources in the production of electricity. Available solutions that improve the flexibility of the power system, such as DSM, interconnectivity, energy storages or power-to-gas technologies, allows to increase the security and stability of the system, however they cannot be treated as a substitute to the standard power reserve. What's more, these solutions could generate additional costs related to the management of the system over the needs of the standard reserve. For this reason, part of the conclusions regarding the scale of costs with full reservation of uncontrollable sources can be treated as an illustration of the challenges related to the construction of zero-emission energy systems based 100% on uncontrollable sources.

An interesting supplement to the study would be a market analysis of the profitability of the generation infrastructure built according to each of the strategies. Nevertheless, the research question that is the subject of the study has no ambition to introduce the perspective of a private investor and does not go that far, limiting itself to the analysis of costs (within the limits of a specific security block). Due to the need to ensure neutral conditions for examining the competitiveness of individual strategies, it was intentionally decided to ignore the effect of the electricity market, which would probably lead to mutual "cannibalization" of competing generation technologies. The adopted simplification aims to eliminate all non-cost-based factors that reward or discriminate individual technologies against each other. Therefore, the analysis presented here concentrates on the implementation costs, and intentionally pays no attention to income resulting from generating sales revenues in a competitive environment. This is particularly important in the case of strategic planning of technology development, the implementation of which will cost hundreds of billions of zlotys, and the marginal cost of which, as communicated to the market, comes close to zero.

4. Addenda

4.1 Methodological assumptions and parametrization

The aim of the study is to assess the different strategies for providing stable electricity supply to the Polish Power System (PPS). Several aspects of each strategy chosen are assessed:

- The **total cost**, understood as the total investment for the implementation of the strategy; in particular, with regard to the leading and backup technologies, it includes investment, fuel, CO_2 emission certificate costs, variable and fixed operating costs, and system costs (responsible for the expansion of the transmission and distribution network and ensuring system flexibility).
- The **level of CO_2 emissions** associated with the CCGT and OCGT technology. The emissivity of natural gas technologies per unit of electricity produced (after taking into account the efficiency of the generation units) is given in Table 18.
- **System LCOE** (System Levelized Cost of Energy, S-LCOE), is the average, discounted total cost of production of an energy unit from the specified mix during the period under study, taking into account the power system costs. System LCOE is defined as:

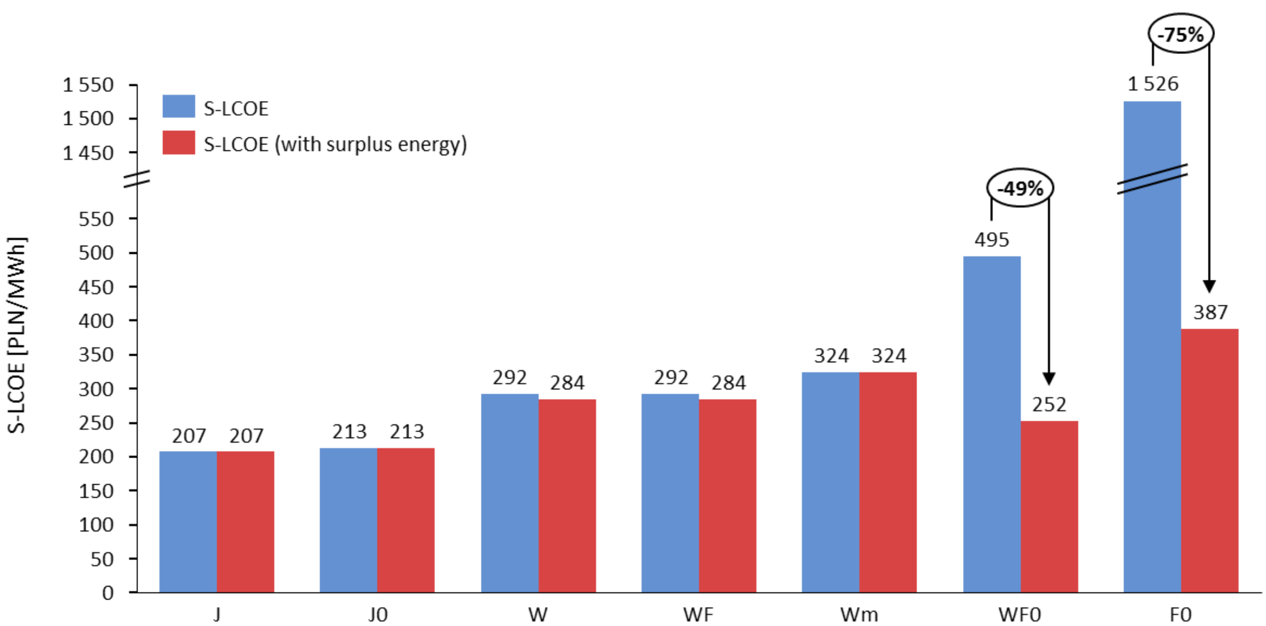
$$\text{System LCOE} = \frac{\sum_{y=9}^{68} \frac{\sum_{t \in TECH} P_t^{ins} \cdot KS_{t,y} + E_{t,y}^{year} \cdot KZ_{t,y}}{(1+r)^y}}{\sum_{y=9}^{68} \frac{\sum_{t \in TECH} E_{t,y}^{year}}{(1+r)^y}},$$

where:

t		–	index representing an element of the set of generation and storage technologies $TECH$
y		–	index representing year of analysis, assuming values from 1 to 68 (the 1 to 8 interval represents the construction period)
r	[-]	–	discount rate
P_t^{ins}	[MW]	–	installed capacity in generating or storage technology t (value independent of time in line with the assumption of technology mix invariability during the period under study)
$KS_{t,y}$	[PLN/MW]	–	total fixed costs assigned to technology t in year y (including system costs)
$E_{t,y}^{year}$	[MWh]	–	volume of energy generated in technology t in year y
$KZ_{t,y}$	[PLN/MWh]	–	sum of variable costs assigned to technology t in year y

S-LCOE has two differences from the classically defined LCOE [15]: it is calculated not for the selected technology, but for a set of technologies (called a strategy) and takes into account the system costs which are an estimate of the PPS's expenditure related to the implementation of the strategy. In addition, according to the assumptions of the study concerning the inability to use surplus energy, energy production in each year y is limited to volume (including all technologies) $\sum_{t \in TECH} E_{t,y}^{year} = 8760\,\text{h} \times 6\,\text{GW}$.

The impact of the above assumptions on the conclusions concerning the average price of electricity can be estimated on the basis of a parallel assessment of the system LCOE with another value, i.e. **S-LCOE with surplus energy** (i.e. taking into account the actual energy production $\sum_{t \in TECH} E_{t,y}^{year}$, which may exceed the set level of demand). The Figure 11 below illustrates the differences between the S-LCOE values of the two system LCOEs. The differences are growing with the higher the S-LCOE value without energy surpluses and they reach as much as 75% for the F0 strategy. In the case of the WF0 strategy, S-LCOE with surplus energy is PLN 252/MWh, which puts the strategy in 3rd place in the cost effectiveness ranking, after the nuclear strategies J and J0.



Strategy code	J	J0	W	WF	Wm	WF0	F0
Leading technology	nuclear PP	nuclear PP	onshore & offshore wind	onshore & offshore wind + PV	offshore wind	onshore & offshore wind + PV	photovoltaics (PV)
Back-up technology	natural gas	nuclear PP	natural gas	natural gas + storage	natural gas	storage	storage

Figure 11. Comparison of values of system LCOE against S-LCOE that takes into account surplus energy, marked in blue and red respectively, for each of the seven analyzed strategies, arranged in ascending order of the system LCOE value (without surpluses)

The key parameters necessary for the calculation of the values of the above measures are the proportions of the energy mix for each of the strategies (P_t^{ins}) which are determined by the Central Optimization Algorithm by solving the linear optimization problem presented in the next part of the report.

4.2 Optimization problem

The objective of optimization is to choose the appropriate energy mix (composition of acceptable technologies) to minimize the total cost when the set limits are met. The objective function is expressed in the following formula:

$$\min_{P_t^{ins}, E_{mag}^{max}, E_{t,h}} \left(\sum_t CKS_t \cdot P_t^{ins} + CKM \cdot E_{mag}^{max} + \sum_{t,h} JKZ_{t,h} \cdot E_{t,h} \right)$$

where:

P_t^{ins}	[MW]	–	installed capacity in generation technology t,
CKS_t	[PLN/MW/60 years]	–	total fixed cost; discounted sum of fixed costs assigned to an installed capacity unit in technology t in the whole analyzed period (including system costs),
$E_{t,h}$	[MWh]	–	energy generated in technology t by hour h,
$JKZ_{t,h}$	[PLN/MWh]	–	unit variable cost; discounted sum of variable costs assigned to technology t in hour h,
E_{mag}^{max}	[MWh]	–	energy storage capacity,
CKM	[PLN/MWh]	–	total storage cost; discounted sum of fixed costs assigned to storage capacity unit in the whole analyzed period.

The technology set t is subject to optimization changes between strategies, as does the presence of the term $CKM \cdot E_{mag}^{max}$ in the equation formula, which occurs only in testing the WF, WF0 and F0 composition. Independent variables in the optimization process are P_t^{ins}, E_{mag}^{max} and $E_{t,h}$, which means that the result of a COA operation is the choice of an energy mix and an electricity production schedule broken down into selected technologies over 525,600 hours covered by the simulation (the study does not provide for leap years).

Limitations on the solution:

- $\forall h\colon \sum_t E_{t,h} = 6000\ \mathrm{MWh}$ – constant demand of 6000 MW in each hour under analysis,
- $\sum_{t \in STER} P_t^{ins} = 6000\ \mathrm{MW}$ – capacity in dispatchable installations ($STER$), i.e. natural gas or nuclear, equal to demand in every hour under analysis,
- $\forall h\ \forall\ t \in STER\colon 0 \leq E_{t,h} < P_t^{ins} \cdot 1\ \mathrm{h}$ – energy generated in a given technology in a time unit is limited by installed capacity,
- $\forall h\ \forall t \in OZE\colon P_t^{ins} \cdot cf_{t,h} \cdot 1\ \mathrm{h} = E_{t,h}$ – energy generated by RES sources depends on *capacity factors* time series,
- $4\ \mathrm{h} \cdot P_{mag}^{ins} = E_{mag}^{max}$ – storage capacity corresponds to 4 hours of operation at maximum discharge capacity,

In addition, the following are necessitated in connection with energy storage:

- limiting the energy level in storage to its size,
- the law of conservation of energy in storage facility,
- identical levels of energy collected in storage facility in the first and last hour of the period under analysis.

Parametrization of the optimization problem requires the determination of costs CKS_t, CKM and $JKZ_{t,h}$.

4.3 Cost parametrization method

4.3.1 Fixed costs of energy generation and storage technology

For the purposes of the study, the concept of time equivalent of unit capital expenditure has been adopted, represented by the PLN million/(MW x life year) index, with expenditure depending on the installation lifetime. This allows for economic comparability of energy technologies with different lifetimes – it is aimed to limit full depreciation of assets to a time equal to the set strategy period.

For example, when a 60-year strategy is created, to achieve the objective of ensuring continuous energy generation for 60 years under the wind strategy, three generations of wind sources with a 25-year lifetime each will be created, of which only 40% (10/25) of the costs of the 3rd generation will be included in total capital expenditure. The amount of capital expenditure for each successive technology generation decreases in line with market trends taken into account in the study (Table 16). Following the construction decision for a particular technology generation, capital expenditure for each successive operation year is summed up until the generation change or end of the strategy implementation period.

In order to calculate the comparable construction costs of a generation fleet, a uniform 8-year construction period has been assumed, in which the total capital expenditure is incurred, necessary to implement the 60-year strategy. The cumulative capital expenditure has been distributed evenly over the 8 years of construction, and the cost of capital of 3% has been assumed for a construction period equal for each technology basket. This simplification has been intended to limit the impact of discount on the economic comparability of long-life technologies with technologies of a shorter lifetime.

Depreciation of all generating assets is calculated on the write-off amount for accumulated capital expenditure on fixed assets, including interest added to the initial value of fixed assets. The investment cost of the technology concerned is spread into 60 equal instalments with an interest rate of 3%.

The annual fixed cost is composed of depreciation of investment plus fixed operational and maintenance costs assigned to a given year of analysis t. In calculating the total fixed cost CKS_t and the total storage cost CKM, the sum of annual fixed costs is subject to a discount rate of 3%, the reference year being 2020.

4.3.2 Unit variable costs

Unit variable costs of energy generation are made up of: fuel costs, costs of CO_2 emissions, and variable operational and maintenance costs. The value $JKZ_{t,h}$ is subject discount at rate of 3%, the reference year being 2020.

4.3.3 Other assumptions and cost/effectiveness assumptions.

4.3.3.1 Methodological assumptions

The list below illustrates the most significant methodological assumptions made for the study:

1. Generating capacity of dispatchable sources reaches the nominal capacity.
2. Outages of renewable and backup sources are not taken into account.
3. The cost of nuclear fuel disposal and the NPP infrastructure are included in fixed costs of the nuclear technology at PLN 17/MWh [16], whereas for other technologies the cost of infrastructure removal is included as a 5% mark-up on overnight capital expenditure (OVN) [17].

4.3.3.2 Summary of main parameters of the model

Table 16, Table 17 and Table 18 indicate main parameters used in the study to build the optimization model.

Table 16. Model parameters for the respective generation technologies. The fields marked (*) represent extreme values of parameters as they change over the 60-year period under analysis. The parameter marked (**) represents the sum of the discounted value of depreciation, fixed O&M costs, system costs, and retirement costs for the technology concerned, incurred over the entire period under analysis, divided by the volume of installed capacity in this technology.

Model parameters – generation technologies

	photovoltaics	wind onshore	wind offshore	gas (OCGT)	gas (CCGT)	nuclear PP	energy storage
Technology lifetime [years]	25	25	25	30	30	60	15
Unit capital expenditure (overnight) [PLN m/MW]	3.29 - 2.42*	5.53 - 4.21*	12.51 - 7.79*	2.17 - 2.02*	3.10 - 2.88*	21.41	1.94 - 1.85* (1 MW for 4 h)
Unit discounted fixed cost [PLN m/MW]**	7.98	17.40	31.42	4.87	6.38	28.08	7.48
Capacity Factor [%]	12.0 - 16.0*	36.6 - 40.0*	46.4 - 52.1*	-		-	-
Efficiency [%]	-	-	-	37.3 - 37.6*	52.2 - 52.3*	32.6	85.0

Table 17. Model parameters – system costs representing yearly transmission and distribution network expansion expenditure and the cost of ensuring PPS flexibility in relation to installed capacity (MW) of non-dispatchable RES. The table shows extreme values of the parameters changing over the 60 years' period under analysis

Model parameters – system costs

Technology	Penetration [%]	**Network development [PLN k/(MWxYEAR)]	Flexibility development [PLN k/(MWxYEAR)]
photovoltaics	20	32.6 - 43.8	4.8 - 6.4
onshore wind	40	102.7 - 112.2	60.3 - 65.8
offshore wind	40	132.2 - 148.5	45.8 - 51.5

Table 18. Model parameters – fuel and CO_2 emission allowance costs. The table shows extreme values for the 60-year period under analysis

Model parameters – fuel and emission cost range [PLN/MWh]

	gas (OCGT)	gas (CCGT)	nuclear PP
uranium	-	-	25 - 27
gas	263 - 323	188 - 233	-
CO2	58.47 - 113.50	41.86 - 81.62	-

4.3.3.3 Data sources

Fuel and CO_2 emissions prices: based on [18]

Contract capital expenditure – Overnight Cost (OVN):

- Renewable technologies – mid projections [19], adjusted for the EU market on the basis of [20],
- Nuclear and CCGT power plants – mid projections [21],
- OCGT peaking power plants and energy storage facilities [22].

Fixed operating (O&M) costs (FOM) and variable operating (O&M) costs (VOM):

- All generation technologies – mid projections [23],
- Energy storage – low projections [24].

Energy generation efficiency – Heat Rate (HR):

- OCGT peaking power plants [25],
- Other generation technologies – mid projections [26].

Capacity Factors (CF):

- Offshore wind – mid projections offshore, TRG3-mid [27].
- Onshore wind [28],
- Photovoltaics (PV) [29],
- Capacity factor time series for renewable technologies:
  Polskie Sieci Elektroenergetyczne, based on the Pan-European Climatic Database (ENTSO-E).

Lifetime of the respective technologies – Technical Lifetime (TLT): adopted on the basis of [30-31].

System costs: based on [32-38].

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