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The Polish Practice of Probabilistic Approach in Power System Development Planning

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Abstract: Power systems can be analyzed using either a deterministic or a probabilistic approach. The deterministic analysis centers on studying the quantities and indicators that characterize the operating states of the power system under strictly defined conditions. However, the long-term horizon of planning analyses, the changes of marketing mechanisms, the development of renewable electricity sources, the leaving from large-scale generation, the growth of smart technology and the increase in consumer awareness make the development of transmission networks a non-deterministic problem. In this article, we propose a planning procedure that takes the probabilistic elements into account. This procedure was developed to take into account the high variability of power flows caused by the generation of renewable sources and international exchange. Such conditions of the power system operation forced a departure from deterministic planning. The new probabilistic approach uses the existing tools and experience gained during subsequent development projects. As part of the probabilistic approach, simulations were carried out using the Latin Hypercube Sampling and Two Point Estimation Method algorithms. These methods effectively reduce the computation time and, at the same time, give satisfactory results. The verification was carried out on a test grid model developed in accordance with the technical standards used in the Polish Power System. Effects were assessed using a deterministic and probabilistic approach. This analysis confirmed the practical possibility of using the probabilistic approach in planning the development of transmission network in Poland. When using a probabilistic approach to predict power flow, the criteria of technical acceptability for a given development variant and the manner in which the strategy is determined are of particular importance.

Keywords: power system; development planning; probabilistic power flow

1. Introduction

1.1. Transmission Expansion Planning

Transmission expansion planning (TEP) is a process that leads to the determination of a time-task schedule for implementing activities in the network [1]. Thus, the transmission network should be characterized by an appropriate structure and parameters that account for the commercial transactions and energy transmission requirements that exist due to the producer-consumer relationship. This process is carried out in an environment that considers both the supply and demand sides, as well as the economic and socio-political conditions. Controlling technical and environmental changes should enable forecasts of situations that may impact the network's operation to be developed, which can be combined with simulations to determine appropriate modernization and investment measures. The prediction and verification of such solutions is possible only after carrying out a series of technical and economic analyses.

By conducting studies that account for both the economic and technical issues (criteria) under established environmental conditions, the network's condition to be assessed. These conditions can be defined unequivocally (i.e., deterministically), or they can be assigned a

certain probability of occurrence, which is known as the probabilistic approach. The probabilistic approach is of particular importance in the conditions of operation of renewable sources. Additional challenges are posed by the process of expanding energy markets and the existence of variable power flows between countries. In this situation, the probabilistic approach allows for better modeling of the situation in the power system and then the assessment of fulfillment with the technical requirements for the power grid.

1.2. Organization of the Research Problem

Transmission expansion planning processes based on a probabilistic approach require identifying the applicability and requirements for analysis of the power system. This issue is presented in Section 2. This chapter introduces the distinction between the character and application of the deterministic and probabilistic approaches in system analyzes. By limiting the subject of research to the applications of the probabilistic approach in network analyzes, Section 3 highlights the issues that can be included in the TEP process using probabilistic models. The highlighted issues in many cases find their implementation proposed by various researchers. Section 4 briefly presents a literature review of available methods and approaches used in the problems of power grid development. These methods became the inspiration for the formulation of the TEP process implemented in the Polish Power System (PPS). Hence, Section 5 presents the development of methods for modeling and organizing the TEP process. This chapter has been divided into the period until the introduction of the energy market and after the introduction of the energy market, when the PRiMSP model was created.

The further development of the power system, including renewable energy sources, common energy market, distributed energy resources and customer elasticity, required further proposals to reorganize the TEP process. These challenges contributed to another proposal to model the TEP process using a probabilistic approach. Such a research problem is described in Section 6. The description presents the assumptions and methodology of the probabilistic approach for PPS. Section 7 presents case study for the transmission grid model. This example showed the effectiveness of introducing the probabilistic approach in the field of planning transmission investments, taking into account technical standards. Section 8 contains a discussion of the results obtained and an assessment of the effects of extending the TEP process, which is a contribution to the current practice of development planning in Poland.

2. Probabilistic Analysis vs. Deterministic Analysis

Two approaches are known for the analysis of power system operation: deterministic and probabilistic [2,3]. The deterministic analysis is based on calculating network parameters under strictly defined conditions [2,4]. These conditions are shaped by the operation requirements, available information on the system, strategic assumptions and expert knowledge. Therefore, each information has a discrete value and represents an event. Due to a lack of conviction to include each event in the analysis, variants are introduced so that the impact of changing a given parameter has on the result can be examined. This constitutes a specific set of data, often different in subsequent analysis cycles, which is used to recognize changes in the result for given conditions [4].

The probabilistic approach uses random variables instead of determined values [3,5]. In this case, the calculations are performed for values whose occurrence has a specific nature, based on the event, with an assigned probability. This nature can be analyzed in the timeline (e.g., event frequency), or quantitatively by measuring the incurred loss as a function of the scale or number of events. For either approach, a probabilistic description is used to represent the data in the analysis, thus, it is necessary to know the probability distribution or the type of probability distribution function with specific characteristic parameters. Then, the state of the system can be described with a probabilistic model, which can, in turn, lead to complications in the mathematical description. An alternative method is the simulation approach, in which successive implementations (i.e., randomly

selected data values) are used in the computational process. In this case, it is necessary to obtain a sufficient number of results, which can then be evaluated to allow for statistical hypotheses to be tested and verified. A statistically significant number of results, especially when considering multivariate distributions, is on the order of thousands of samples, which may require a significant amount of time to perform calculations. Therefore, it is an area of application to study solutions that optimize the calculation time at the expense of the quality of the obtained results.

When justifying the probabilistic approach, it should be noted that a long list of issues can be distinguished in regards to the system's operation, the nature of which is random (probabilistic). The scale of issues is also related to the time function, so it refers to both current (operational) problems and future (planning) problems. Below, a short description based on a literature review of selected problems related to these issues is provided [6–8].

2.1. Operational Planning Issues

The timescales of operational planning issues range from seconds to days and consider things such as the selection of sources and the amount of energy they can produce to meet the customers' needs. It has long been considered that the ability of existing sources to meet demand is a stochastic problem. If sources are not available as expected, the load may not be perfectly predicted. To protect against these uncertainties the operating plan includes a power reserve in the system.

Systems with a high share of generation in solar and wind sources also require the use of reserves. However, in these systems, setting the correct level of reserves requires a more involved probabilistic approach, as these technologies use unpredictable natural phenomena. This, in turn, requires generators have an associated probability representing their availability, which indicates whether production from a given renewable energy source (RES) will be available and at what level of production.

2.2. Generation Development Issues

Capacity planning problems focus on adding new generation resources to the system, not on evaluating the functionality of existing ones. New sources can be included in the system to balance increased demand for power to ensure reliability standards are met, or to compensate for the withdrawal of existing sources. Planning new generation capacities is undoubtedly a stochastic problem, due to the occurrence of errors in forecasting demand, assessing the dates of decommissioning existing generators, and the introduction of new types of technologies.

When planning the development of production resources for conventional technologies, the dynamics of load changes in short (e.g., hourly) time intervals, as well as in-between them, is often overlooked, assuming that the work is externally controlled as needed. In the case of renewable sources, these rules are not met which introduces an additional random thread in the analysis of development sources.

2.3. Network Development Issues

The problem of network development planning has a horizon measured in decades. Since transmission lines are used as long-term assets, such an investment should be resistant to changes in the energy system over a period of 50 years. On this timescale, important factors like the demand curve, the level and technologies of energy production, their locations and many other factors change dramatically. These values affect the assessment of the network, but precisely predicting this value so far out is not possible.

Large numbers of renewable sources increase the uncertainty of the generation location. Contrary to conventional sources, which theoretically can be located freely throughout the system, RES have location limitations. From an economic point of view, these locations are associated with the greatest vulnerability of natural energy resources and additionally are distant from consumers. Furthermore, the development of renewable energy sources depends heavily on the policy being pursued. The pace of construction of these systems

is incomparably faster than the construction of transmission systems; therefore, in the absence of a coordinated, centralized development strategy it is necessary to predict the location of new sources. Moreover, the operation of these sources can significantly change the use of the existing and planned network infrastructure and must be accounted for as well.

Hence, the development of sources in network development planning is usually treated as an external variable (i.e., not included in the development analysis task). For such situations, future network structures are optimized.

3. The Use of the Probabilistic Approach in Network Analyses

Probabilistic analyses scope in calculations related to the operating of the power system is very wide and includes the following areas:

- Generation adequacy;
- Network operation planning;
- Operational forecasting (demand and supply);
- Network reliability,
- Other, where assessing the risk of exceeding the set criteria is done.

Within these areas, detailed issues [6,9] can be distinguished in the following topics:

- Generation adequacy analysis—the stage of a copper plate to balance the system (without the network), verification of indicators, mainly loss of load probability (LOLP) or loss of load expectation (LOLE);
- Probabilistic power flow—replaces the scope of deterministic analyses when modeling load changes according to probability distributions in the event horizon;
- Analysis of emergency states—as an alternative to the deterministic *N-x* criterion by assessing the probability of an event instead;
- Analysis of the working conditions of distributed sources—model generation levels in non-centrally planned sources;
- Forecasting the demand and energy prices—use statistical information;
- Selection of generating units—take into account the random nature of reporting the readiness and availability of the source;
- Reliability analysis—map the risk of damage to an element of the electrical system or the impact of external conditions on the continuity of the system;
- Load capacity analysis—assess the correlation between environmental conditions and demand forcing;
- Maintenance works—predict the availability of network systems in the segment based on previously scheduled maintenance;
- Modeling of unpredictable generation (e.g., wind and photovoltaics)—use statistical information on the supply of primary energy and predict the expected level of supply;
- Modeling of generation in water sources—account for the random nature of changes in atmospheric conditions and subsequent changes in the state of flows in the hydrological system and cascade systems.

For the development planning task, the deterministic approach may not account for all of the important parameters that influence the quality of the power system operation in the future, including its safety and reliability. The deterministic approach in this setting often represents the traditional "worst-case" planning. However, the deterministic approach to planning often does not include the low probability of this case, which significantly affects the economics of the procedure. Thus, deterministic planning does not allow for the calculation of measures in the assessment of system reliability. Conversely, techniques that effectively help to map uncertainty in the planning process have been implemented as part of a probabilistic development planning approach. The probabilistic approach aims to illustrate failures and, consequently, reduce the risk of system failure. Then, the effects resulting from system failure can be assessed and accounted for in the planning process.

The probabilistic approach to system development planning includes methods to quantify the risks associated with different options.

4. Network Development Planning—Methods and Approaches

It is estimated that due to the uncertainty of future development conditions, the application of deterministic criteria may lead to overinvestment in transmission capacity. The current investment outlays in a few years may appear in the category of stranded costs. Probabilistic criteria make it possible to avoid such a case and they can be applied with limited financial resources. However, a question always arises about the justified level of investment expenditure. In some countries, this level is defined by the willingness of consumers to pay increased electricity bills, while in other countries the total cost of operating the electricity system is minimized or the socio-economic effects are maximized. Therefore, it is not without reason that the current global trend is to maximize the use of the existing transmission capacity. Hence, security-constrained optimal power flow (SCOPF) has been widely used in the planning process, as well as the introduction to the set of considered development variants of the elements of modernization or systems for monitoring and controlling the operation of the system [10].

This review of the methods of planning the development of transmission networks in the world clearly demonstrates the motivations to use elements of the probabilistic approach [6]. The probabilistic approach focuses primarily on the issue of grid infrastructure availability and on determining the amount of electricity produced from renewable sources, mainly wind farms and photovoltaic sources. Additionally, in practically all projects financed by the European Union, elements of probabilistic methods are proposed [11–15].

A survey of current planning methods reveals an apparently common trend of combining the deterministic and probabilistic approaches. Often, the probabilistic approach is part of detailed analysis that complements the deterministic analysis. For example, by performing probabilistic analyses within deterministic scenarios of development conditions, which are defined as a rational combination of the forecast of power demand, the development of the generation sector and the anticipated cross-border exchange. Another example is N-1 deterministic criteria operating in parallel, and probabilistic criteria defined using the value of the customer reliability (VCR) of electricity supply [16]. At the other extreme, there are deterministic methods without elements of probability, methods using elements of game theory, or integrated planning. An interesting example in this respect is that of France and Great Britain working together on a probabilistic method and software, the implementation of which only took place in France.

Another critical element of the transmission grid development planning process is the issue of electricity market reflection and market behavior. In this regard, examples of sequential computation can be found in which the computation sequences involve performing market analyses with a simplified network representation, followed by a network computation with a simplified market representation. An alternative approach is to assume the long-term behavior of entities within the market, which means the energy is purchased from the cheapest sources, thereby leading to the application of the SCOPF-type task.

In the probabilistic approach, simulation methods, especially Monte Carlo, are primarily used because they are relatively simple to implement and are considered the most accurate. Cases of using other methods, such as the two-point estimation method (2PEM), have also been identified [17,18].

A critical element in the process of planning the development of the transmission network is the calculation time, which applies to both the deterministic and probabilistic approach. In a deterministic approach, for example, there are no limits to the number of scenarios of development conditions considered during the planning process. In some countries it is a relatively small number (e.g., three), while in others several dozen are analyzed. In either case, a question arises as to how the probability of their occurrence should be determined. In the case of probabilistic (i.e., simulation) methods, the number of

simulations are usually on the order of tens of thousands. Hence, the computation time becomes a critical factor, especially if simulation methods are used to consider different development scenarios. Therefore, an attempt is made to shorten the computation time using several methods, including:

- Simplification of the model (clustering, equivalents, direct current flows);
- Using specialized tools to optimize calculations;
- Division of the computational process into sub-processes implemented on separate computers;
- Limiting the scope of application of simulation methods.

Due to the conditions presented above, there is no commercially available universal tool for performing probabilistic analyses of the TEP. The reason for this is the lack of a universal (i.e., standardized) probabilistic planning methodology. When probabilistic methods are applied, the scope is individualized and adapted to local conditions, including, among others: the structure of the manufacturing sector, the level of energy market development, the method of financing the transmission network expansion, and the rules regulating the energy sector. Examples of EU projects also indicated problems associated with unifying the methods of planning transmission network development and the need to develop software dedicated to a given method each time.

A review of methods leads to the conclusion that, in general, the process of planning the development of a transmission network is carried out in a continuous loop (Figure 1). First, forecasts of future development conditions are prepared to consider factors such as technical, economic, adequacy, sufficiency, risk, and sensitivity. The results of the analyses are the basis for modernization and investment decisions that result in the implementation of specific projects, which subject to verification in the next planning loop.
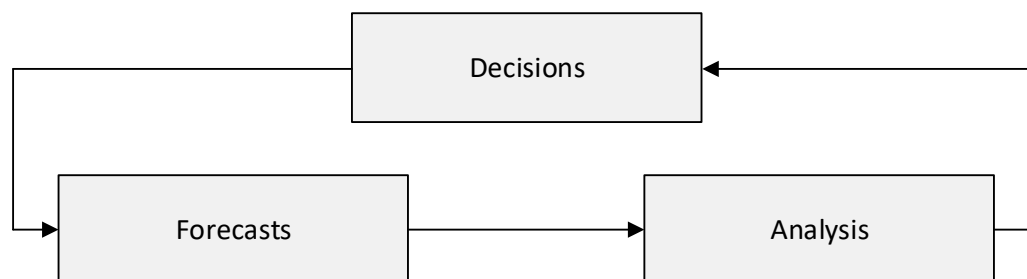
Figure 1. A general planning loop of the planning process for the TEP.

5. An Approach to TEP Process in Poland

5.1. The Period before Energy Market Introduce

In the late 1970s and 1980s, research on optimization methods of TEP, including probabilistic ones, was conducted in Poland. This work covered a wide spectrum of issues [19–21], including:

- Optimization in the manufacturing sector—for which the problem of optimization in nondeterministic conditions was formulated, and elements of game theory were proposed to solve the optimization problem;
- Optimization in system development planning (e.g., generation and transmission)—in which methods of mathematical programming and the basics of economic calculations were shown;
- Optimization of the grid asset exploitation area, where random processes occurring at the interface between humans and nature are presented, as well as decision-making processes under conditions of uncertainty and uncertainty. The issues considered the process of post-failure renovation in distribution networks, assessment of: network losses, power supply unreliability, voltages at consumer interfaces, voltage distortions, short-circuit conditions, current carrying capacity of overhead lines, as well as the need

to coordinate the normative requirements incurred by switching from a deterministic to a probabilistic approach;

- Probabilistic power flow [22], which did not transform directly to practical applications in the polish process of planning the development of transmission network, but constituted the beginning of research in this field in the world [23].

In 1990, the national guidelines for programming the development of the transmission network were published. Their goal was to objectify and standardize the requirements concerning the reliability and quality of the transmission network operation, shorten the development process by providing recommendations and arrangements that narrow the set of solutions under consideration, and standardize the scope of conceptual studies. The guidelines introduced three types of studies: perspective study, concept of development and development program, differing in timescale and update frequency. At that time, the generation, transmission and distribution subsectors were managed under state ownership, thus the guidelines covered both the generation and transmission sectors while the distribution network was covered by separate guidelines. The PPS has been defined as 750, 400 and 220 kV voltage levels. The guidelines were deterministic and defined, inter alia, emergency states (N-1 or N-2), which had to be investigated for receiving stations or power plant connection points. At the beginning of the 1990s, the first computer application in Poland for TEP, named ROZWOJ, was developed. It included the concept of a development option and variant and the concept of a development strategy was defined based on an economic criterion. The objective function of the ROZWOJ application was minimize discounted investment outlays, fixed and variable operating costs, costs of decommissioning network assets, and costs of undelivered energy. A dynamic programming algorithm was used to solve the optimization problem. In this case, the analysis considered 750, 400, 220 and 110 kV closed-circuit networks (the 110 kV network is owned by distribution companies).

Between 1994–1998, the integrated planning methodology was implemented in Poland. This approach consisted of including a joint planning process for the generation and transmission sub-sectors (then separated by organization and ownership), as well as a set of demand management options. In the last version of the plan, developed according to the integrated approach from 1998 (the so-called ZPR-2+), three generation scenarios were considered: coal, export and nuclear. The transmission network was included in the calculations in a simplified way, in the form of eleven areas and connections between them. The connections between the areas were the so-called network bottlenecks, i.e., lines with insufficient bandwidth. The Integrated Planning Model (IPM) program developed by the American company ICF (Washington, DC, USA) was used for the calculations. To select the optimal network development strategy, a criterion function that considered the sum of discounted capital expenditure, network losses costs and costs of undelivered energy was used.

5.2. The PRiMSP Model

In 1997 Energy Act [24] was introduced in Poland, then new elements have started to appear that have not yet been taken into account when planning the development of the transmission grid, such as the issue of the right of way [25] or the development of wind generation [26]. The problem of the right of way may influence on investment outlays and, additionally, may significantly affect the investment's date of completion. On the other hand, wind generation resulted in unspecified directions of power flows in the system. Therefore, both elements necessitated that the best possible use of the existing transmission capacity in the process of planning the development of the transmission network.

In the year 2000, research was conducted on the use of probabilistic methods in the field of power system reliability. The description of analytical methods using Markov chains and processes, as well as the description of simulation methods that can be used in reliability calculations can be found in [27]. There, the method of assessing the value of electricity for the recipient was characterized using an approach analogous to the methods

used in other countries, for example, Australia. However, these methods have not yet been applied to the process of planning the development of transmission network in Poland.

After 2000, work on the Planning for Development and Modernization of the Transmission Network (named PRiMSP) platform was started in Poland in cooperation with the American company Christensen Associates [28]. The diagram of the development planning process implemented on the PRiMSP platform is presented in Figure 2. It proposed to conduct analyses under the development conditions scenarios, which created rational combinations of the following sub-scenarios: power demand, generation and intersystem exchange. Next, technical analyses were performed, in which the generating units were selected and market load distribution calculations were carried out. The selection of the optimal strategy was based on specific economic criteria. They were used to create the following three-step procedure, which took into account probabilistic elements:

- The first step is the selection of the optimal strategy based on a single scenario of development conditions. The primary economic criterion is analogous to the one described in the ROZWOJ application (minimum discounted costs); a dynamic programming algorithm was also used on the PRiMSP platform to solve the optimization task;
- The second economic criterion is the selection of the optimal strategy from approaches defined in the development scenarios. The simultaneous evaluation of following criteria was proposed: expected value of cost, Hurwitz, and mini-maximum loss (regret);
- The third criterion was to be applied when the second step indicated different suboptimal strategies. In essence, it boiled down to the evaluation of individual criteria by various stakeholder groups and assessment of the significance of the opinions of the stakeholder groups. In this regard, the use of the Analytical Hierarchy Process (AHP) method was proposed.

Figure 2 does not explicitly indicate the use of the probabilistic approach, but it was, in fact, implemented on the PRiMSP platform [28]. As part of the development, random states were determined that allowed for different individual scenarios. In order to limit the number of random states being analyzed, the Latin Hypercube Sampling (LHS) method [29] was used for their simulation. The subjects that could be considered are: power demand, availability of network infrastructure (node and branch), generator availability, wind speed, prices of particular types of fuel and intersystem exchange (i.e., power). The program made the results of the direct current (DC) flow calculations available in the form of the mean value and standard deviation. The results included, among other things, nodal voltages, branch flows, power losses, nodal marginal prices, generation cost, undelivered electricity and its cost, grid and producer surpluses, and customer payments calculated on the basis of nodal marginal (i.e., short-term) prices. Moreover, for each random state, it was possible to obtain random values of individual input data.

Two flow programs were implemented on the PRiMSP platform—direct current and alternating current. The constant-current power flow was used to perform calculations for individual random states, which, by assumption, could be relatively large. On the other hand, the alternating current flow was used for two elements: determining the "reserved" transmission capacity for reactive power flow, and for the verification of the final proposal for the expansion of the power system. It was a methodically acceptable solution that is still valid today.

The methodological solutions used on the PRiMSP platform were, in terms of methodology, similar to those of the French ASSESS program and, in some respects, the proposed solutions were more advanced.

The PRiMSP platform allowed for the market identification of transmission constraints, which is important for the TEP process. These limitations are the direct cause of forced generation and the cause of power losses in the meshed network. They can also cause market losses in international trade due to failure to meet the conditions of electricity exchange. The location of the constraints allows for an unambiguous indication and valuation of overloaded branches (lines and transformers). On the PRiMSP platform,

the valuation of constraints was performed on the basis of short-term marginal costs. In addition to the elements of optimization as part of development planning, the PRiMSP platform was built with the use of various programs for network calculations. On the platform, there were programs for calculations: power flow, short-circuit, system stability and reliability. Thus, the PRiMSP platform could be useful not only in development analyses, but also for the preparation of network operation systems, selection of generation sources, reliability assessment, or the above-mentioned power flow calculations.

The lack of further investigation into the transmission system operation and further development of the PRiMSP platform resulted in a return to the scenario-based deterministic approach in planning the development of transmission network. However, research works aimed at using the marginal prices for planning the development of the transmission network, initiated by the PRiMSP platform, were not abandoned. For example, in this work [30] it was proposed to use marginal prices, both short- and long-term, to evaluate various technologies generations, their impact on the operation of the power grid, security of electricity supply and environmental impacts. The issue of short-term and long-term price equilibrium that resulted from choosing the optimal state of economic equilibrium was discussed. In some of the calculations, a probabilistic approach using Monte Carlo sampling was applied.
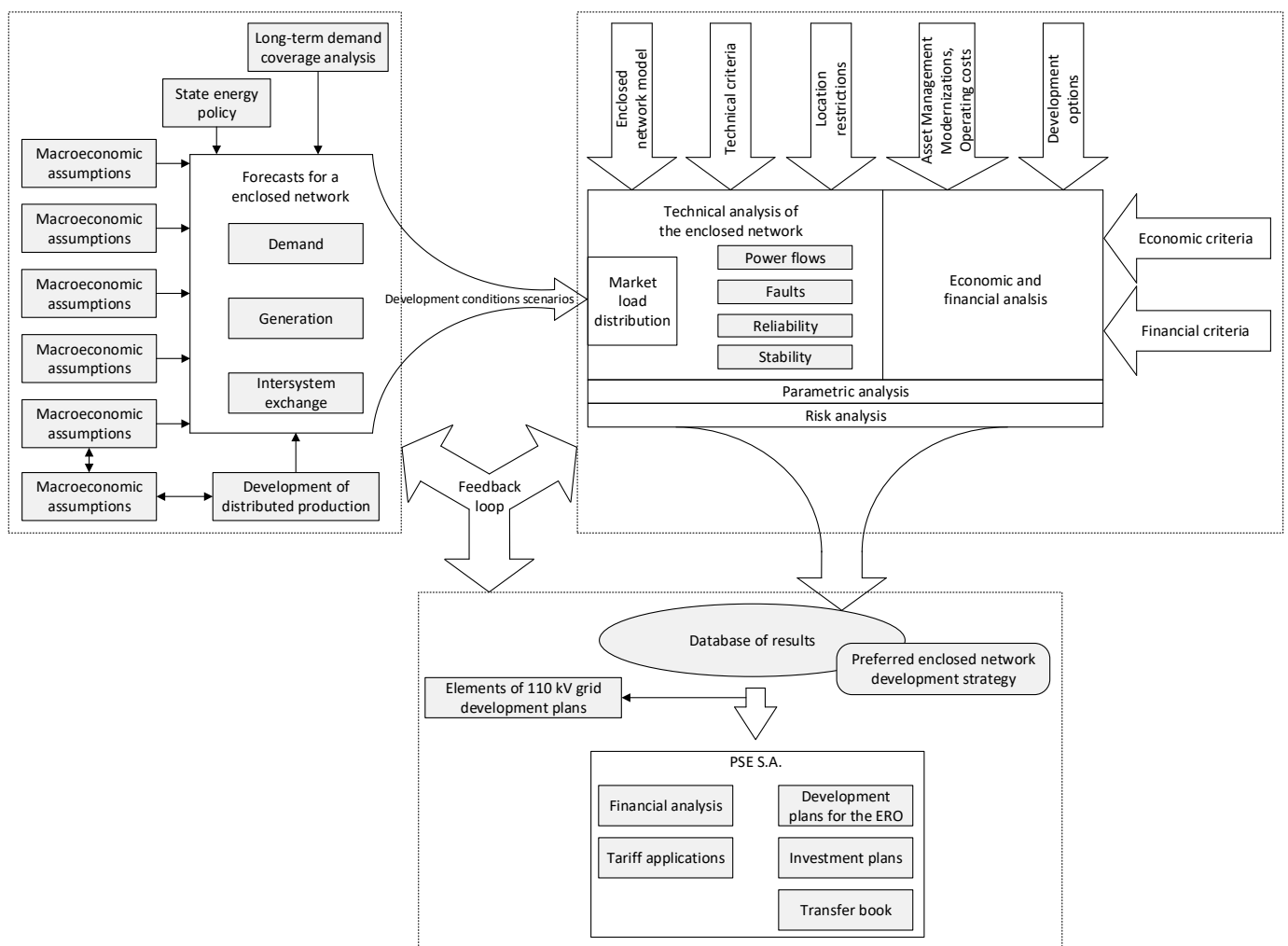

Figure 2. Diagram of the transmission grid development planning process implemented on the PRiMSP platform.

6. Methodology of Probabilistic Approach to TEP Process in Poland

Legal requirements in Poland [24] do not specify the development planning method, so it can be both deterministic and probabilistic, but they define the organizational framework. In this respect, it is required that a development plan in a 10 year horizon is prepared with a 3 year update. It also indicates that the Network Development Plan (NDP) is taken into account with an international scope, as well as spatial development plans and concepts. The Energy Act [24] also indicates the content of the NDP, in particular: the scope of energy supply, projects in the field of modernization, expansion or construction of the network and plans for new generation sources, projects in the field of modernization, expansion or construction of connections with the systems of other countries, the proposed method of financing investments, expected cost to implement the plans, and the schedule of investment implementation (i.e., development strategy). The duties of TSO in Poland also include a forecast of the security of electricity supply for a period no less than 15 years.

Further regulations governing the preparation of a development plan are included in the Polish Grid Code [31]. The provisions are organizational regulations, but do not define the methodology of development calculations. On the other hand, the organization of the development plan development by TSO and the methodology of its preparation are specified in the internal procedures. The description shows that it is a deterministic methodology which accounts for the scenario approach and elements of market analyses. Both traditional power flow programs, programs allowing for optimal power flow and market analyses are used, for example, the PLEXOS program, also used by EirGrid, ENTSO-E, and in Australia. Further development of the methods used for planning the development of transmission network in Poland is focused on accounting for the elements of probability. The emerging concept is presented below.

6.1. Assumptions

6.1.1. Analytical Areas

Achieving the goals of the development plan requires linking two analytical areas: technical and economic (market). Planning in the technical dimension covers the area of analyses, the primary purpose of which is to examine the needs for the TEP to fulfill the technical criteria set before it. Planning in the economic (market) dimension includes analyses of technically feasible solutions (verified network models) which determine the manner and means of implementing the development of the transmission network. The result of the analyses will be the best choice of technically acceptable and economically justified solutions.

6.1.2. Data

Due to the lengthy timescale of the TEP, the data used in the process is not clearly defined. For this reason, three types of data are assumed:

- Determined—with a specific value determined for the period being analyzed;
- Uncertain—with a specific value, but the probability of occurrence is not specified;
- Random—with a specific value and a given probability of its occurrence.

Inclusion in TEP of these data types requires the use of appropriate computational algorithms and tools. Data is determined for each state of the system. Random data is the result of either a time series analysis or a random sampling. Random data is determined for each state of the system and, in the case of time series analysis, it can be specified for a cluster. The uncertain data is determined based on the scenarios considered. For a given scenario, the term Development Conditions Scenario is used, which accounts for all information on energy demand and electricity power, electricity generation and cross-border exchange, prepared on the basis of forecasts of economic development.

6.1.3. Data Sources

From the point of view of available input data, there are two paths for obtaining the information, from a database or from expert knowledge. For databases, random value

distributions are built in the form of a variability profile (stochastic form) or a frequency distribution (probability density). Determined values can also be establish according to the database. In the case of an incomplete database, forecasts of a given size or expert knowledge are used for the technical and economic analyses. As a result, the following form is obtained, depending on the type of data: deterministic, stochastic, probability distribution, scenario. Table 1 summarizes the data groups with the assignment of its type. In selected data groups (RES generation, demand), the profile and size level have been distinguished. The profile determines the variation of data over time (in individual states of the PPS operation), while the value is determined based on the forecast data level.

Table 1. List of input data used in the TEP study with the assignment of the type.

Value	Data Source	Type
Branch parameters	Database	Deterministic
Node parameters	Database	Deterministic
Grid topology [1]	Database	Deterministic
Contingency analysis (*N-k*)	Expert knowledge	Deterministic
Generation profile in wind sources	Database	Stochastic
Generation level in wind sources	Expert knowledge	Deterministic
Generation profile in PV sources	Database	Stochastic
Generation level in PV sources	Expert knowledge	Deterministic
Generation level in hydroelectric power plants	Database	Stochastic
Power demand profile	Database	Stochastic
Power demand level	Expert knowledge	Deterministic
The availability of conventional sources	Database	Probability distribution
New sources [2]	Expert knowledge	Scenario
New grid elements [3]	Expert knowledge	Deterministic
Intersystem exchange	Database	Stochastic
Economic data [4]	Database	Scenario

[1] State in the first year of the analysis; [2] Installed power, location; [3] Determined changes including branches and nodes; [4] Fuel prices, discount rate, emission costs.

6.1.4. Analytical Elements of the TEP Process

The TEP process is carried out hierarchically in three basic steps: sufficiency analysis, technical and economic (market) analyses, technical analyses. The purpose of these activities is to formulate a development strategy, i.e., a schedule for the implementation of tangible investments in the network area. The first step verifies the availability of generation sources and is necessary for further calculations. The second step determines the network candidates and the schedule of their introduction, accounting for the network needs (branch loads under normal and *N*-1 conditions). In the third step, the obtained schedule is verified by considering additional technical requirements. Step three may recommend supplementing the list of network candidates that will be re-marketed in step two. Therefore, it forces a feedback, and the whole process is, therefore, iterative. The TEP process is coordinated by a planner and requires approval of subsequent steps and stages.

6.1.5. Adequacy Analysis

In this step, the optimal power and energy balance in the NPS is determined using stochastic and deterministic data in defined scenarios. The result of this balance is the schedule of the supply-side development needs in the analysis horizon. The balance sheet includes the capacity and production technologies in the subsequent years following the analysis horizon. The sufficiency analysis is conducted in a system without network constraints, which does not consider the network topology.

6.1.6. Technical and Economic Analyses

The basis of the analyses in this step is the optimization of load distribution between generating units as part of the Direct Current Optimal Power Flow (DCOPF) task. The results of the analyses are the powers generated by the available conventional sources in individual states, taking into account the selected technical flow conditions. In addition,

indicators are obtained as a result of these analyses based on whether it is possible to determine the degree of adjustment of the system to the transmission tasks. These indicators include:

- Nodal Price;
- Shadow Price;
- Energy not Served.

The technical and economic analyses are carried out using the nodal model of the network with the proposed candidates under normal and *N*-1 conditions.

6.1.7. Technical Analysis

In this step, the analyses are carried out for selected, representative system states using programs to assess branch loads, short-circuit currents and grid stability margins. The computational scope of the verification process for the examined states include:

- Flow analyses (assessment of branch loads by taking into account the AC power flow method and verification of voltage levels in the transmission network nodes);
- Short-circuit analyses (evaluation of the existing apparatus parameters),
- System stability analysis for small and large disturbances and voltage stability analysis (evaluation of the system operating safety margins).

The results of the technical analyses are used to verify the proposed grid system development schedule and, as a result, to adjust the PPS parameters in terms of the obtained indicators to the requirements specified in the Polish Grid Code [31].

6.2. The Proposed TEP Implementation Procedure

Based on the adopted assumptions, an analytical path was prepared for the calculations carried out, with emphasis placed on the implementation stages. The three steps of the TEP process are marked on this path [32]. Figure 3 presents a proposal for the implementing the calculation process. As part of the technical and economic and technical analyses, this process was carried out using the network model, while the technical and economic analyses are based on the equivalent model for the 110 kV distribution network and interconnections.

The approach considers stochastic and random elements in the area of adequacy analysis, as well as the technical and economic analyses.

In Figure 3 four columns of information have been distinguished which indicate the analytical step being implemented, the assigned stage of calculations, the scope of basic data used and the expected results. It should be noted that the computation process is parallelized in terms of data processing and in series in terms of determining the list of network investments. In this process, the results from a given stage of analysis provide data for the next stage. Implementation of the process requires expert supervision and evaluation of the results at each stage. This can lead to repeated steps or another iteration over several steps.

Two forms of the system model are included in the analytical path of the TEP process:

- Model without branch restrictions, the so-called copper plate model (balance), in which all sources and loads are connected at a common potential;
- Network node model, which includes information about the network topology, impedance and resistance parameters, as well as branch limits.

The network node model is created based on the current network model, the so-called normal system. The balance model is a simplification of the nodal model.

Based on the adopted assumptions, an analytical path for the calculations was prepared. The approach presented in Figure 3 accounts for both stochastic and random elements in the analytical process at the stage of searching for optimal solutions, which, in this case, lead to the development of a grid investment schedule. The presented process of PPS development considers introductory elements (adequacy analysis) and crowning

elements (technical analysis). The new elements added to the TEP process, taking into account the probabilistic approach is presented in Figure 4.
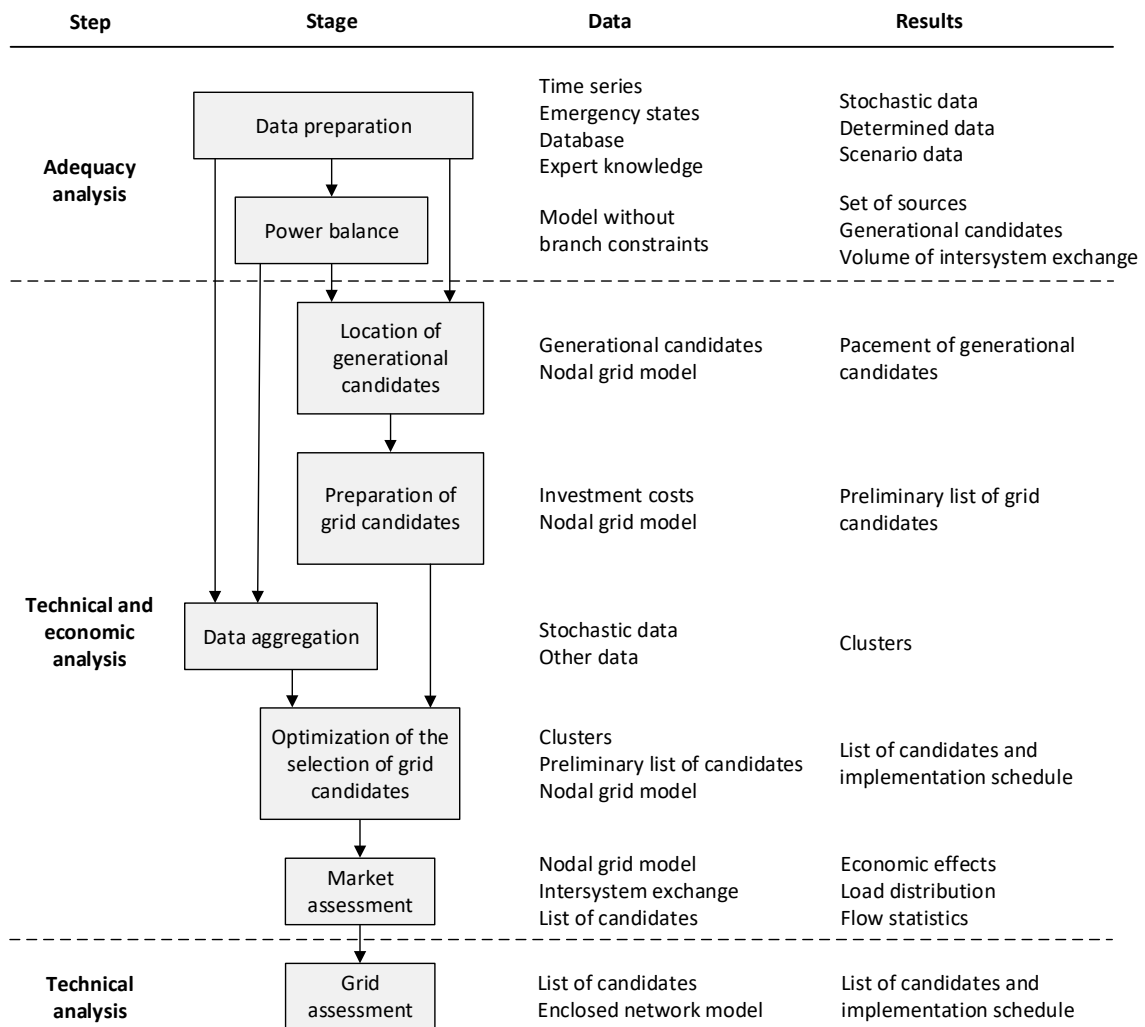
Step	Stage	Data	Results
Adequacy analysis	Data preparation	Time series Emergency states Database Expert knowledge	Stochastic data Determined data Scenario data
	Power balance	Model without branch constraints	Set of sources Generational candidates Volume of intersystem exchange
	Location of generational candidates	Generational candidates Nodal grid model	Pacement of generational candidates
	Preparation of grid candidates	Investment costs Nodal grid model	Preliminary list of grid candidates
Technical and economic analysis	Data aggregation	Stochastic data Other data	Clusters
	Optimization of the selection of grid candidates	Clusters Preliminary list of candidates Nodal grid model	List of candidates and implementation schedule
	Market assessment	Nodal grid model Intersystem exchange List of candidates	Economic effects Load distribution Flow statistics
Technical analysis	Grid assessment	List of candidates Enclosed network model	List of candidates and implementation schedule

Figure 3. The cycle of successive stages of the TEP development.

Step / Stage		Random / uncertain element	The added value for the TEP process
Sufficiency analysisData preparation	Data preparation	The level of demand	Variation of forecast in scenarios
		Demand profile	Use of time series
		Generation levels of renewable sources	Differentiation of power installed in scenarios
		Generation profiles of renewable sources	Use of time series
		The availability of conventional sources	Use of statistical data of failures
		The accessibility of new generation units	Introduction of development scenarios
	Power balances	Generated power and energy	Stochastic nature of balancing based on historical data
		Intersystem exchange	Optimization of intersystem exchange
Technical and economic analyzes	Location of generation candidates	Lack	Distribution of candidates according to expert or market knowledge
	Preparation of grid candidates	The availability of conventional sources	Use statistical data of failures Reduce the risk of missed investments
	Data aggregation	Lack	Reduction of computational costs by introducing clusters that group data from time series
	Optimizing the selection of grid candidates	Stochastic elements of balance in clusters	Use of time series Modeling future market conditions
		The availability of conventional sources	Use statistical data of failures
		Calculations in emergency conditions	Assessment of the amount of expected undelivered energy
	Market assessment	Stochastic and random elements of balance in clusters	Optimizing the date of introducing a candidate and assessing systemic effects
		Branch loads	Branch load distributions and their parameters
		Loads of generating units	Distribution of loads of generating units and their parameters
Technical analyzes		Lack	Verify the admissibility of solutions under the loads of generating units determined as part of technical and economic analyses

Figure 4. Elements added to the TEP process, taking into account the probabilistic approach.

7. Case Study

7.1. Test Network

Pointing to the usefulness of the probabilistic approach in the assessment of future development plans and, in particular, considering the public interest, including savings resulting from avoided or undersized investments, a short calculation example was presented. The purpose of the example is to assess the effects of implementing the TEP process in a probabilistic versus deterministic approach.

The calculations were made on the test network model in a system without extension (zero variant) and for the proposed eleven development variants. The calculations were performed using the deterministic method and two probabilistic methods—simulation and two-point estimation (2PEM) modified with *N*-1 states according to the author's proposal. In the simulation method, the random states of the test model were determined using the LHS algorithm. In all cases, the optimal strategy for the development of the transmission network was determined using the criterion, defined as the minimum of discounted investment outlays.

In this example, a fragment of the PPS network was considered with 39 nodes, in which five nodes are 220 kV voltage and 34 nodes 110 kV voltage. The fragment of the network analyzed here included 50 branches, comprised of six 220 kV lines, six 220 kV/110 kV transformers and 38 110 kV lines. The scheme of the test network is shown in Figure 5. The calculations were made in a 15-year horizon, accounting for a forecast of 2.5% increase in demand.
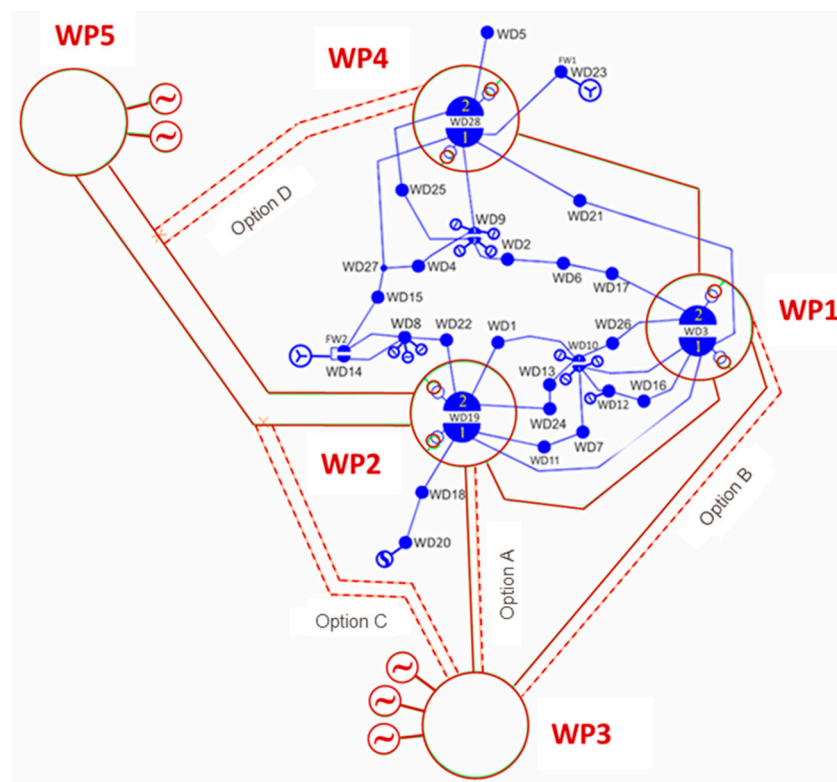
Figure 5. The two-voltage test network adopted for the calculation in the example.

7.2. Calculation Procedure

As part of the deterministic method, power flows were determined using extreme operating conditions of the network. The calculations were performed for the complete system and for the emergency systems, in which the *N*-1 contingency analyses were introduced.

As part of the probabilistic approach, the approximation method and the simulation method were used to calculate the power flow. The 2PEM method with the 2*m* + 1 diagram modified with *N*-1 states was adopted as the approximation method. In the simulation method, the LHS algorithm was used to generate random states.

The 2PEM calculation algorithm starts with loading the input data. According to the method, the first power flow is performed for the values of all nodal variables at the level of their expected value. Subsequent power flows are performed after changing the demand for power or wind generation individually in each node. This step of calculations in the test network means performing 75 power flows (75 independent variables resulting from two values of power demand in each of 35 nodes, two values of power generation

for two wind farms and a system with all variables assuming the value equal to the expected value). These data were read as supplementary data from MS Excel. Their determination required the calculation of two concentration points for each variable in accordance with the idea of the 2PEM method. Then the network system is modified by switching off one branch and the power flow calculations are repeated according to the previous principle. With 50 elements included in the *N*-1 states, this gives a total of 3825 power flows for one development variant in a given year (full system plus emergency states, 51 × 75 in total). Therefore, the calculation of the 2PEM method for the analyzed development variants (Table 2) in one year required the calculation of 45,900 power flows (12 variants × 3825 flows).

Table 2. List of test network development variants and investment costs, in EUR million.

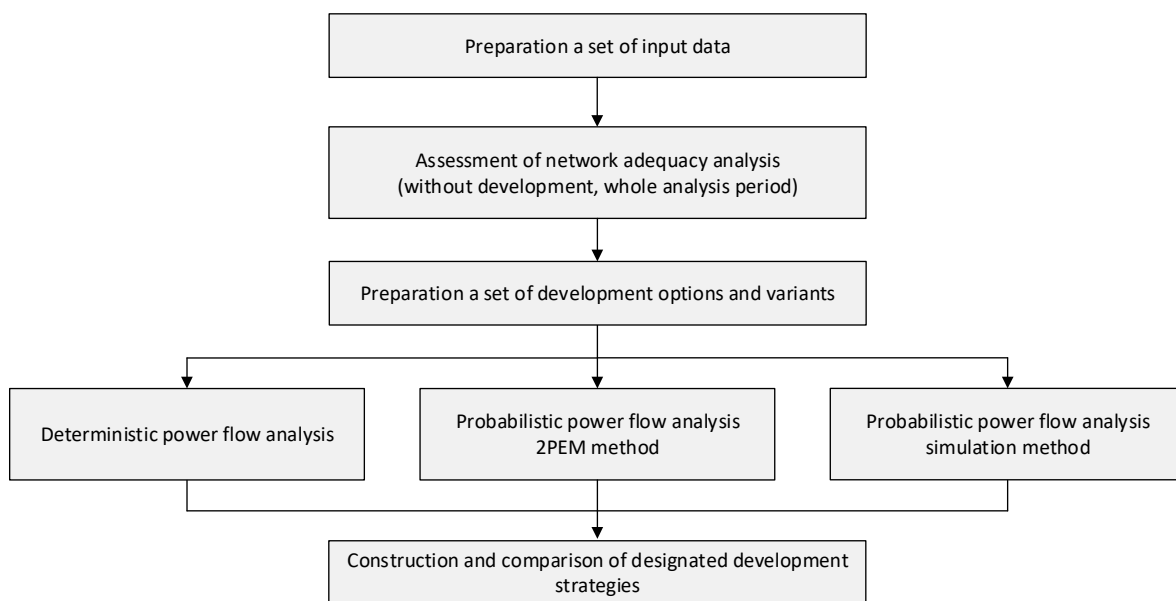| Development Options	Development Variants											
	V0	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11
A	-	x	-	-	-	x	x	-	-	-	x	-
B	-	-	x	-	-	x	-	x	x	-	x	x
C	-	-	-	x	-	-	-	-	x	x	-	x
D	-	-	-	-	x	-	x	x	-	x	x	x
Investment cost	0	400	936	440	120	1336	520	1056	1376	560	1336	1496

The LHS algorithm was used for the calculations using the simulation method. The idea of this method is a determined division of the probability distribution into an assumed number of equally probable intervals (partitions). Then individual intervals are randomly selected and values in the selected interval are randomly generated. For a given interval, this operation is repeated several times, resulting in a batch. After reading the input data, simulation calculations are performed for all variables subject to drawing for the assumed number of partitions and batches. For each random state (in the example their number was 250), the generating units were selected and the DC OPF was calculated. After performing the calculations for all random states, the obtained results were described using the expected value and standard deviation.

The general algorithm of calculations illustrating the development planning process is shown in Figure 6. According to the algorithm, the input data set was developed first. For this set, the network adequacy analysis was performed. The obtained results were the basis for the development of a set of options and variants of development. The development variants were analyzed according to the deterministic approach and two probabilistic methods.

According to the algorithm presented on Figure 6 the analysis of the test network was started with the variant without development (V0). The identified transmission limitations allowed for the formulation of several development options. The designated development options (with the designations as in Figure 5) include:

Option A   Second direct connection between nodes WP2 and WP3.
Option B   Second direct connection between nodes WP1 and WP3.
Option C   Double line from node WP3 to the line between nodes WP2 and WP5.
Option D   Double line from node WP4 to the line between nodes WP2 and WP5.

These options were further analyzed together and its combination let to create 11 development variants in accordance with Table 2.

```
┌─────────────────────────────────────────┐
│        Preparation a set of input data   │
└─────────────────────────────────────────┘
                    │
                    ▼
┌─────────────────────────────────────────┐
│   Assessment of network adequacy analysis│
│  (without development, whole analysis    │
│             period)                      │
└─────────────────────────────────────────┘
                    │
                    ▼
┌─────────────────────────────────────────┐
│ Preparation a set of development options │
│              and variants                │
└─────────────────────────────────────────┘
```

| Deterministic power flow analysis | Probabilistic power flow analysis 2PEM method | Probabilistic power flow analysis simulation method |

```
┌─────────────────────────────────────────┐
│ Construction and comparison of designated│
│        development strategies            │
└─────────────────────────────────────────┘
```

Figure 6. General development planning process algorithm for a test network.

8. Results and Discussion

Based on the results obtained for each method, individual development variants were classified as acceptable or unacceptable in individual years of the analysis period. The collective results of qualifying the development variants are presented in Figure 7, where the numbers of the variants allowed for the development strategy are given. The development strategy is understood as the schedule for installation of development variants to be implemented in individual years of the planning horizon.

In the deterministic method, the optimal development strategy is to implement variants V6 and V10 in the 5th and 15th year and its cost is EUR 648.8 million. In the analytical method, the optimal development strategy consists of implementing the V4 and V6 variants in the 10th and 15th years, respectively, and its cost is EUR 181.6 million. The optimal strategy obtained in the simulation method is the implementation of the V4 variant in year 10 at a cost of EUR 55.6 million.

Based on these results, it can be concluded that in the cases analyzed here the probabilistic approach development strategies yielded lower costs compared to the deterministic method. This, in turn, means lower social costs and an increase in the transparency of solutions thanks to the appropriate selection of data and their use.

It should be noted that in the test network the deterministic *N*-1 criterion is more important because there are more exceedances than in the case of probabilistic methods. The results of these methods are dominated by random states without shutdowns of the network infrastructure, and the shutdowns that do occur do not create difficult network operating conditions. Thus, we conclude that the deterministic case imposes a higher planning standard due to the inclusion of states with a low probability of occurrence used to model the behavior. On the other hand, however, the random states in the simulation methods involved switching off a few or a dozen network elements, which may produce more difficult network operating conditions than those obtained as a result of applying the deterministic *N*-1 criterion. The practice resulting from the probabilistic approach and its results in the form of power flows may significantly affect the formulated plans for network development [33].
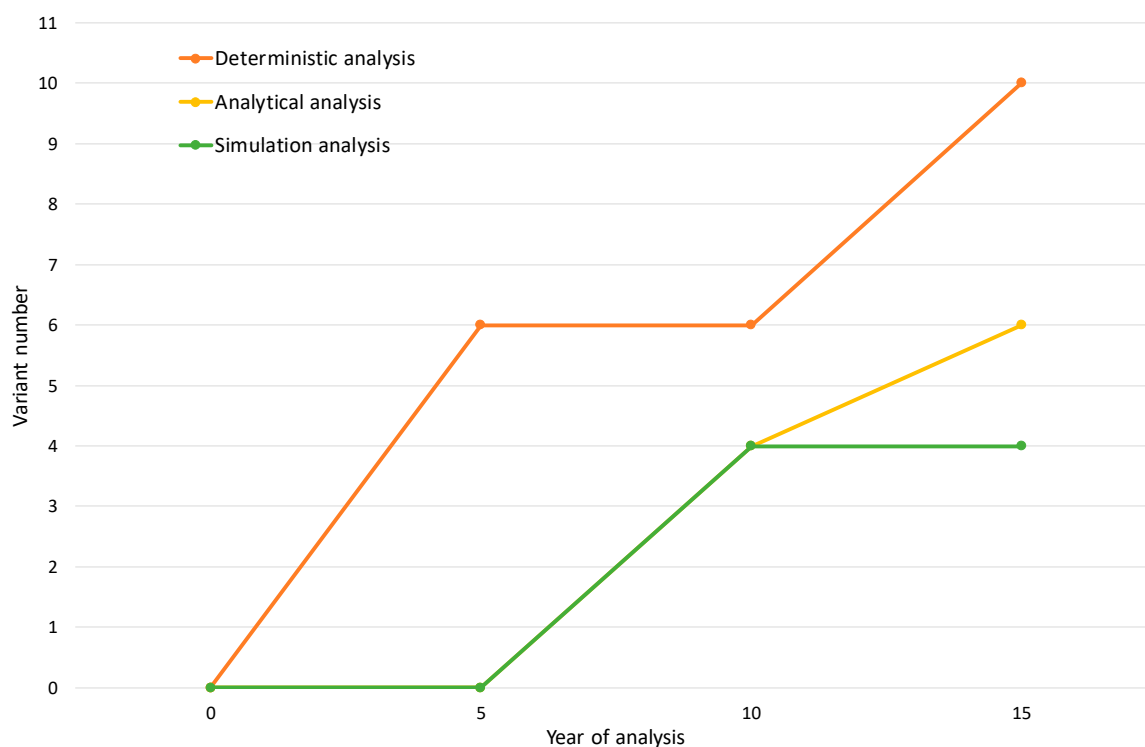
Figure 7. Transmission network development strategies obtained in the model study process.

Based on the analyzes, the following conclusions can be formulated.

- The practical possibility of using probabilistic methods in the TEP process was found. It is possible to use both the simulation method and the approximation method 2PEM. The implementation of simulation method is easier from the point of view of available and currently used IT tools.

- The use of probabilistic power flow requires the creation of new criteria, e.g., technical, economic and decision-making factors taken into account in the process of planning the development of the transmission network. The parameters of the probability distributions appear in place of the determined values obtained so far. In the simulation method, it would be possible to investigate the types of these distributions, in the 2PEM approximation method, simplifying assumptions must be made in this regard.

- When using probabilistic power flow, the criteria of technical acceptability of a given development variant (option) as well as the criteria for evaluating the permissible variants and determining the strategy are of particular importance. In the case of technical criteria, an appropriate percentile can be adopted, e.g., 95th percentile node voltage and branch loads as a valid criterion. A separate issue is the choice of a development strategy, when the probabilistic planning process is carried out within development scenarios.

- An important element of the development planning process is the construction of options, and based on them, variants of network development. It is difficult to expect automation in this respect, due to the maintenance of a rational size of the computational task. Additionally, the simulated operating states of the system in the probabilistic approach created less stringent requirements for the formulation of development options. For this reason, the use of deterministic analysis of *N*-1 states to identify network areas requiring reinforcement seems to be rational. It would be a combination of a deterministic and a probabilistic approach.

- All the considered methods allowed for the formulation of a test network development strategy. In the deterministic method, a development strategy was obtained with the largest investment expenditure compared to probabilistic methods. Probably the

randomly obtained test network states were not critical for the development of this network.

The approach to planning the development of the transmission network presented in this article, both used in the world and now developed in Poland, allows for the formulation of a general comparison in the discussion. A comparison of the deterministic and probabilistic approaches to transmission grid development planning is presented in Table 3, taking into account the selected criteria.

Table 3. Comparison the issues of probabilistic and deterministic approaches.

Criteria	Deterministic Approach	Probabilistic Approach
Degree of network development	There is a danger of reinvention. The network is prepared based on the occurrence of the worst conditions that may occur, regardless of their probability. By definition, the method does not take into account the increase in nondeterministic development conditions.	The development of the transmission network is related to the probability of future development conditions. The determination of some probability values requires the use of heuristic methods. The method fully accounts for the increase in the share of nondeterministic development conditions, and is, by definition, scalable in this respect.
Scope of knowledge	Well-established among national planners and decision makers, an intuitive methodical approach.	A new methodical approach. Interpretation of the results based on the concepts of statistics that are not widely used among planners and decision makers.
Considered criteria	The dominant role of technical criteria, although unambiguous and objective, but defined for determined conditions. Possibility to implement economic criteria.	Equal principles of applying technical and economic criteria. Possibility to use hybrid criteria.
Technical constraints	Defined technical constraints, including: • Permissible voltage levels; • Branch current capacity; • Short-circuit capacity; • The stability reserve.	Necessary definition of guidelines for the adoption of threshold values as part of the technical criteria. The development of the guidelines should be preceded by method calibration analyses performed on the full model of the 110 kV transmission network.
Dataset size	Relatively small sets of results, easy to evaluate and interpret.	Huge databases. Necessity to use tools such as "data mining". Complicated and multi-threaded deductive process.
Calculation time	Possibility to carry out analyses on a single personal computer. Short waiting time for calculation results.	Requires the use of super computers or multi-machine systems via LAN / WAN. Unknown waiting time for results—no national experience in this area
Availability of computational tools	Availability of commercial software tools.	There are commercial software tools, however, they are usually individualized tools prepared for the needs of a specific transmission system operator, taking into account local market conditions.

9. Conclusions

Increasing the effectiveness of the grid development, including the transparency of the actions taken, the TSO developed a consultation process for the proposed actions in which all PPS users participate in this process. Additionally, it is proposed to account for the uncertainty in the planning process, which is implemented as part of the probabilistic approach to planning the development of the Polish Power System. In this respect, elements related to the generation adequacy assessment and the branch loads and, as a result, the investment needs of the transmission network are considered. This develops the traditional deterministic approach based on characteristic states used so far, and allows for important factors influencing the future quality of the power system operation to be taken into account, including its safety and reliability. In addition, it protects the requirements of system users by limiting the level of over-investment costs (stranded cost), thus, increasing the credibility and usefulness of planning procedures developed by TSO.

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