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Investing in Distributed Generation Technologies at Polish University Campuses during the Energy Transition Era

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Abstract: The functioning of universities during the energy transition can be quite a challenge for them. On one hand, it is necessary to pursue a sensible policy of sustainable development based on the growth of their own renewable energy sources and electricity storage facilities. The aim of such measures is to increase self-consumption and ensure partial energy self-reliance while reducing carbon dioxide emissions into the atmosphere. On the other hand, the current geopolitical situation has indicated significant problems in the energy sectors of European Union countries. From the point of view of decision-makers at universities, the main concern should be ensuring the continuity of the operation of such a facility, including ensuring the energy security of the sites under management. Thus, it is necessary to merge these two areas and consider the development of an energy management strategy on university campuses oriented towards the development of distributed generation resources. For this purpose, one of the methods of multi-criteria decision aiding the ELECTRE I was used. As a result of the analyses, an energy management strategy was established for the main campus of the Warsaw University of Technology, which simultaneously ensures energy security and sustainability efforts.

Keywords: distributed generation; smart grids; universities; energy strategy management; multi-criteria decision aiding; energy crisis

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1. Introduction

The current global geopolitical situation has once again triggered a discussion on energy security, both in Europe and the United States [1]. It is estimated that dependence on fossil fuel supplies from Russia over the years has caused significant turmoil in the commodity gas and electricity markets [2,3]. On the other hand, highly developed countries are setting ever more demanding limits on carbon dioxide (CO_2) emissions [4]. There are also doubts about whether meeting climate targets is more important than ensuring energy security, particularly in European Union countries [5–7]. It should be borne in mind that meeting climate targets is often associated with an additional cost, resulting from the purchase of CO_2 emission allowances under the European Emissions Trading Scheme (EU ETS). The unpredictability of prices on the EU ETS influences changes, often rapid, in the electricity market in member countries, especially those whose generation structure is based on fossil fuels, such as coal. Poland is included in such countries [8]. On the other hand, the implementation of climate goals also means the rapid growth of renewable energy sources (RES) [9,10]. In Poland, more than 10 GW of RES generation capacity has been put into operation over the past decade [8–11]. However, it is known that wind and solar power plants are unstable and their generation depends on weather conditions. As a result, researchers have been trying, for several years, to combine generation sources characterized by different generation technologies, thus forming hybrid systems [12]. In general, such sources can therefore be classified as distributed generation resources, i.e., generating units, with electricity storage with a capacity not exceeding several MW [12]. The next step in the development of modern power grids is the setting up of microgrids, i.e., area-small power systems based on distributed generation resources. Their purpose is not only to optimize the technical or economic operation of the facilities [13–15], but a major focus has also been placed on improving energy security by making the facility self-sufficient and achieving a certain degree of autonomy from the power supply from the power grid [16,17]. This is achieved through the use of stable energy sources, such as combined heat and power (CHP) gas turbines or electric energy storage, usually in battery-based form (BESS) [18–20]. Ensuring energy security and independence is also the subject of other considerations in the area of creating microgrids and using distributed generation resources. It enables the normal functioning of humans [21,22], while providing access to basic resources and minimizing the negative environmental effect in the form of CO_2 emissions [23,24]. Such solutions are often used for islands [25–27] or areas with poor accessibility to the electricity grid, where the primary source of power is diesel generators [28].

As state universities are also affected by high prices in the energy market, thus significantly increasing the cost of purchasing electricity, it is necessary to consider whether it is worthwhile to carry out the investment process of building distributed generation resources on university campuses [29,30]. The literature also raises the issue of investing in microgrids at university facilities to improve the reliability of the electricity supply and provide a kind of self-reliance in energy management [31]. Such an action requires the development of a certain research methodology and, consequently, the formation of a strategy for energy management on campuses. This article sets out to find an answer to these problems. However, it is important to remember that any energy management strategy has its limitations. The first consideration is related to ensuring the continuous operation of the university. Thus, the development of an energy management strategy will start with an analysis of the security aspects. Only by ensuring energy security will further considerations, such as economic efficiency and adaptation to climate change, be possible. It is well-known that the public, especially younger citizens, are increasingly being brought up with zero-carbon policies and the efficient use of the Earth's resources. Nevertheless, from the point of view of university authorities, it is important to keep in mind the possibility of the general operation of facilities where students will learn about climate change. Thus, the need to provide energy reliably seems inevitable. This article presents all of the aforementioned aspects, however, the main goal that has been set is to establish an energy management strategy that will ensure the energy security of the facility, and only in the subsequent steps will it be possible to adapt to climate change.

2. Distribution Generation at University Campuses

2.1. State of Art

The subject of developing distributed generation (DG) resources on university campuses is highly popular in the literature. For this reason, the most important issues analyzed by researchers around the world are presented, and then the gap in the knowledge that the authors want to fill is pointed out. The paper [32] presents the possibility of building PV power plants on the buildings of the Politecnica de Madrid. It mainly presents a methodology for assessing the potential of buildings for installing PV power plants and evaluating the economic viability of the selected solutions. In paper [33], the same case was analyzed at the University of Sichuan. This allowed the researchers to verify that the use of PV power plants covered about 40% of energy consumption by its own production. The possibility of building a microgrid on campus was also analyzed. The article [34] presents a strategy for reducing demand so that Selcuk University Medical Faculty buildings can operate in island mode. Staying on the topic of European universities, another issue analyzed was how to reduce emissions while maintaining economic indicators and using multiple energy carriers. Such research was described in a publication [35] for Marche Polytechnic

University in Ancona, Italy. The paper [36] analyzed the possibility of building a combined heat and power (CHP) source and establishing a low-temperature heating network on the Tallinn campus. It was found that integrating this network with the city's district heating network would bring reductions in the carbon dioxide emissions and primary energy consumption. Trigeneration systems were also analyzed from an economic and technical point of view [37]. The authors in [38] point out that the higher education sector in the UK lacks investment and regulation aiming to create smart campuses. They also point out that the case studies that have been conducted do not coincide with the established concepts. The literature also contains cases of analysis of DG infrastructure development on other continents. The publication [39] presents the possibility of establishing a microgrid at the Brazilian University. In publication [30], an assessment of the technical and economic feasibility of such an installation at the University of California in San Diego was presented. The publication [40], on the other hand, used graph theories to plan the construction of distributed energy systems, taking the campus site in Handan City as an example. The authors in [41] presented simulations of the operation of a microgrid concept at Abdelmalek Essaadi University in Morocco. Another article featured deals with the analysis of data on the cost of generating electricity from a gas turbine and a diesel generator at Covenant University in Ota Nigeria [42]. The studies also assessed the carbon footprint at Universitas Pertamina in terms of electricity consumption, transportation and waste generation [43].

2.2. Novelty

Due to the growing demand for electricity and the cost of purchasing electricity in Poland, it is necessary to take measures to introduce an energy management strategy, especially in state-funded units. It should be noted that the articles mentioned in Section 2.1. mostly consider single investment tasks, such as the development of PV installations [32], the creation of microgrids [39] and CO_2 emission reductions [35]; however, a holistic approach to the establishment of a full-scale energy management strategy is missing, especially in Polish conditions. These are quite peculiar as Poland is on the verge of changes in the energy sector. Increasing indicators of not covering the demand for power in the system do not ease the process of modernizing the power infrastructure, as simply attaching RES installations may not have the expected effect. As the authors are proactive in the field of energy transition at the Warsaw University of Technology, it was decided to conduct a study to establish a methodology for creating an energy management strategy based on five areas of focus, the so-called pyramid of energy goals. The task of developing such a pyramid involves addressing the question of what successive stages of the electrification of facilities the decision-maker should carry out, considering the continuity of the company's operations, i.e., the realization of its business activities. Then, knowing the general framework of the problem in the electrification of the decision-maker's facilities, it is necessary to develop a methodology for handling the investment process. Such a methodology is made within the framework of this article. It should be able to solve problems of the multi-criteria assessment of the options. Hence, it is necessary to describe the criteria. This article defines four criteria for the evaluation of options for the electrification of university facilities, which are described in the original method. Then, five decision options were defined, which can be followed by the decision-maker. Each of these options is an attempt to represent real decisions made by university facility managers. Next, a solution to the multi-criteria decision aiding problem was proposed in the author's methodology using the widely known ELECTRE I method. This method is widely used in solving problems from social life [44], the construction sector [45–49], transportation [50] and even energy [51–53], including the development of renewable energy sources [54]. However, a holistic approach to establishing strategies on how to develop a distributed generation infrastructure on university campuses using such a method has not been found in the literature. In addition to the aforementioned methodology, the article also presents simulations for the main campus of Warsaw University of Technology, as a prime example of the application of such a strategy.

3. Methodology for Establishing Energy Management Strategies on Polish University Campuses

3.1. Early Stages

The issue of establishing strategies for energy management and the development of distributed generation technologies on university campuses is complex and requires the design of a holistic approach to the subject. Universities are such complex administrative units, combining many areas from everyday life, that it is necessary to propose a methodology for assessing their ability to achieve energy efficiency improvement goals while promoting sustainable development. It should also not be forgotten that, particularly in Europe, university campuses are located in urban centers [32], which do not facilitate the process of planning for the construction of their own energy sources as they are often facilities under the protection of heritage conservators [55]. Therefore, as a first step, decision-makers should order a detailed audit of the electricity infrastructure for the facilities under consideration. A facility should be understood as a university campus with its own power supply infrastructure with points of connection to the power grid or a single building with an independent connection. Next, the priority modernization measures for the existing power infrastructure should be defined. The next step is to define the project budget and establish a time horizon. At this point, the decision-maker should indicate whether the tasks planned for implementation are to be implemented immediately (the criterion for the fastest effect) or are to be the basis of a long-term strategy. Due to the construction time of individual low-carbon electricity solutions, it is suggested to set a threshold of 1 year, 5 years and more than 5 years. The decision-maker should also decide whether the planned development of distributed generation technologies is intended to strengthen the field of research, teaching or broader administration.

3.2. The Pyramid of Energy Goals

With this knowledge, one should then design development concepts for the facilities selected by the decision-maker. The authors propose that the aforementioned concepts should be based on the so-called pyramid of energy goals. Figure 1 shows this pyramid.

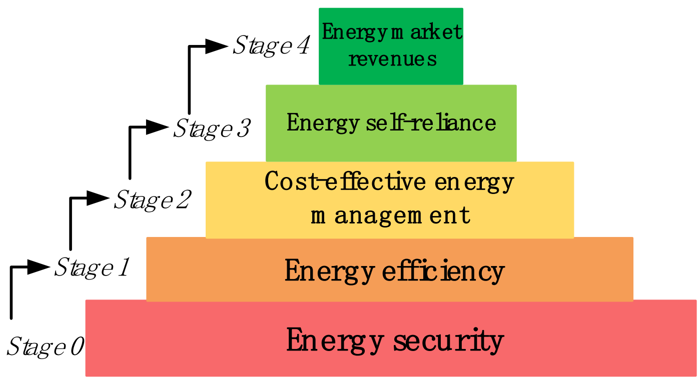


Figure 1. Proposition of the pyramid of energy goals for decision-maker.

The foundation of the pyramid of energy goals is the energy security of the facility—**Stage 0**. It should be emphasized that, according to the authors, without ensuring an adequate level of security in supplying the loads, including the particularly critical loads, there can be no further process of improving the energy efficiency of facilities or investing in modern energy solutions. There is a possibility that the savings from installing, for example, renewable energy sources will be absorbed by the cost of not delivering energy to selected critical loads. At this stage in the development of distributed generation resources on university campuses, decision-makers should take care to install generators that provide power that is safe for the facility. The next step is to plan distributed generation development solutions for energy efficiency—**Stage 1**. Such tasks, in terms of DG development, can include investment in renewable energy sources that do not require significant interference with campus infrastructure, e.g., photovoltaic power plants on rooftops. The capacity of generators should also be expanded to include further loads requiring practically uninterruptible operation. A significant increase in the importance of distributed generation can be seen in the next stage of the development of these technologies on university campuses. We are talking about providing opportunities to optimize the management of electricity from an economic perspective—**Stage 2**. At this stage, the diversification of RES and other technologies, such as electricity storage, should be considered, but there must be an economic viability to the project. It is proposed that RES installations scattered over many buildings will operate in a coordinated manner, forming a virtual power plant—VPP [56]. The penultimate stage in the development of distributed generation technologies on university campuses is investment in energy independence—**Stage 3**. At this stage, the construction of a stable source, not necessarily RES, but with a low carbon footprint, should be considered. In addition, it should be ensured that energy security measures are implemented through the aforementioned source and energy storage facilities, accumulating surpluses from distributed RES installations. Everything should also be managed by a superior control and supervision system. The last stage of the development of distributed generation technology on campuses (**Stage 4**) takes into account the assumptions from Stage 3 and indicates the further development of electricity storage and demand-side reduction activities for consumers. This means that, in addition to maintaining the essential energy functionality of the facility, there are opportunities for additional revenue from the sale of surplus energy and the provision of other services to distribution system operators (flexibility services) or the transmission system operator (ancillary services, demand reduction, capacity mechanisms). It should be emphasized that the possession of demand reduction resources can bring significant profits, especially in cases of an increasing number of hours in which the demand will not be covered by the generation.

3.3. Decision Options

Once in possession of the assumptions regarding the modernization of the electricity infrastructure for the development of distributed generation technologies, it is then necessary to establish possible decision-making options. Decision options refer to a series of actions that will be taken by the decision-maker to determine the strategic objectives. The following describes examples of the options that were defined at the phase of the research work:

- **Option 1:** This refers to the situation in which the university authorities will want to secure the most important facilities, regardless of economic and environmental costs. As mentioned in Section 3.1, energy security is the foundation of the pyramid of energy goals. It should be emphasized once again that without ensuring the stability of the electricity supply, further attempts at modernization are meaningless, as the lost costs due to a power outage can be much greater than the savings from installing on-campus solar power plants.
- **Option 2:** This refers to the situation in which the university authorities will want to promote their policy of conducting electricity management on the basis of sustainable development. This means that the main goal will be to indicate the greatest possible reduction in carbon dioxide emissions into the atmosphere, which should contribute to improving the air quality, particularly in highly urbanized areas.
- **Option 3:** This is a modification of Option 1, however, in securing the needs of university buildings, the lowest possible capital expenditures and operating costs should be taken into account. This option is a kind of optimization of the actions of decision-makers, who must manage public funds in an appropriate manner.
- **Option 4:** This is the option in which decision-makers are determined to upgrade the electricity infrastructure, however, the financial aspect is the most crucial. This means that distributed generation development efforts must be optimized in terms of the capital expenditures incurred, as well as in the operating phase of the operational costs.

- **Option 5:** This is a scenario in which decision-makers do not have a clear position on which way to go with electricity infrastructure modernization based on investments in distributed generation technologies.

3.4. Criteria for Evaluating the Options

With the knowledge of the proposed options for the development of an electricity infrastructure on university campuses, it is also necessary to define the criteria to quantify them. Four criteria were defined based on the analysis conducted on energy management at university facilities.

3.4.1. Criterion 1—Cost of Purchasing and/or Generating Electricity

The first criterion belongs to the group of economic criteria and concerns the cost of purchasing energy from the electricity grid and/or generating energy from the site's own generation sources. First, it is necessary to consider the forecast electricity demand for the facility. Let E_t^{DEM} denote the demand for electricity at a given hour t of the calendar year. However, it is important to keep in mind that the demand must be analyzed over a horizon of several years. Thus, it is necessary to develop a method for forecasting the demand for electricity at a given hour t of the facility under study. For this purpose, the authors establish the coefficient of load adjustment k_t^{DEM}. It was determined as follows:

$$\bigwedge_{t\in T} k_t^{DEM} = \frac{\sum_{yp=1}^{YP} \frac{E_{t,\ yp+1}^{DEM}}{E_{t,yp}^{DEM}}}{YP} \tag{1}$$

where: $E_{t,yp}^{DEM}$—the electricity demand of a given facility at hour t of year yp, expressed in kWh; yp—the year for which the decision-maker has a set of historical energy consumption data; YP—the number of years for which the decision-maker has a set of historical energy consumption data; T—the set of hours in a year, equal to 8760.

Let yf denote the year of analysis of the development of distributed generation technologies, relative to the last year in the YP set, i.e., for which the decision-maker has a set of historical data. Thus, the forecast electricity demand in year yf can be calculated:

$$E_{t,\ yf}^{DEM} = \left(E_{t,ypl}^{DEM} \cdot k_t^{DEM}\right)^{yf-ypl} \tag{2}$$

where: $E_{t,\ yf}^{DEM}$—the electricity demand of a given facility at hour t, in year yf, expressed in kWh; $E_{t,ypl}^{DEM}$—the electricity demand of a given facility at hour t, in year ypl, expressed in kWh; ypl—the most recent year from the YP set for which the decision-maker has a historical data set.

Then, it is necessary to determine for each hour t the volume of electricity that can be produced by sources that belong to distributed generation resources. Thus:

$$TECH_i = \{tech_1,\ tech_2, \ldots, tech_{TC}\} \tag{3}$$

$$\bigwedge_{t\in T} E_{t,\ GR}^{GEN} = \sum_{i=1}^{TC} E_{t,\ i}^{GEN} \tag{4}$$

where: $TECH_i$—the set of distributed generation technologies planned for operation at the decision-maker's facilities; i—the element of the set $TECH_i$; $E_{t,\ GR}^{GEN}$—the volume of electricity planned to be produced in hour t from distributed generation sources, expressed in kWh.

Based on Equations (2) and (4), the estimated volume of electricity to be purchased from the power system can be determined:

$$\bigwedge_{t\in T} E_{t,\ yf}^{GRID} = E_{t,\ yf}^{DEM} - E_{t,\ GR}^{GEN} \tag{5}$$

where: $E^{GRID}_{t,\,yf}$—the volume of electricity expected to be purchased from the electricity system, expressed in kWh.

Being aware of the volume of electricity expected to be purchased from the electricity grid and the volume produced from the site's own sources of distributed generation, the total annual cost of energy purchase and/or generation can be calculated. It is determined from the formula:

$$C^{y}_{GRID+GR} = \sum_{t=1}^{8760} \left(E^{GRID}_{t,\,yf} \cdot c^{GRID}_{un} + \sum_{i=1}^{TC} E^{GEN}_{t,\,i} \cdot c^{i}_{un} \right) \tag{6}$$

where: c^{GRID}_{un}—averaged unit cost of purchasing electricity from the grid, including the electricity trading and distribution fee, expressed in PLN/kWh; c^{i}_{un}—averaged cost of generating electricity at a given distributed generation source, expressed in PLN/kWh; $C^{y}_{GRID+GR}$—annual cost of generating energy at the site's own sources and purchasing energy from the grid, determined for sources operating in the normal operating regime, expressed in PLN.

The foregoing considerations are applied to sources of distributed generation that run in the normal operating regime. That is, they operate year-round and serve the needs of the facility under the control of the decision-maker. However, it is also necessary to consider situations in which certain sources of distributed generation will be activated on an emergency basis, when there are restrictions on the supply of electricity to end users. To determine the duration of the operation of such devices, an indicator from the power system reliability theory—Loss of Load Expectation (LOLE)—was used, which denotes the expected total duration of power deficits over the considered period [57,58]. These technologies include, in particular, diesel generators, energy storage and demand-side response (DSR) measures. Thus, using the (4) Formula, it is possible to determine the cost of generating energy (or reducing it) in a given year:

$$C^{y}_{GR_{SAF}} = \sum_{t=0}^{LOLE_y} \left(\sum_{i=1}^{TC} E^{GEN_{SAF}}_{t,i} \cdot c^{i}_{un} \right) \tag{7}$$

where: $C^{y}_{GR_{SAF}}$—the annual cost of generating energy in the site's own resources of distributed generation, determined for sources, storage and power demand reduction measures operating in the emergency mode, expressed in PLN; $E^{GEN_{SAF}}_{t,i}$—the volume of electricity generated in DG resources aimed at operating in the emergency mode, expressed in kWh.

Thus, the total cost of generating energy in the site's own distributed generation resources or/and purchasing from the electricity grid is:

$$C^{y}_{TOTAL} = C^{y}_{GRID+GR} + C^{y}_{GR_{SAF}} \tag{8}$$

where: C^{y}_{TOTAL}—the total cost of generating energy in the site's own distributed generation resources or/and purchase from the power grid, expressed in PLN.

3.4.2. Criterion 2—Carbon Dioxide Emissions into the Atmosphere

The second criterion analyzed the concerns regarding the environmental impact of the designed distributed generation resources during their operation. The baseline for quantifying this effect will be the calculation of the equivalent of kilograms of carbon dioxide emitted into the atmosphere. Thus, from the set of DG technologies planned to be installed on the site, defined by the set of $TECH_i$, only those technologies should be selected whose CO_2 emission factor is greater than 0. Hence:

$$\bigwedge_{i \in TC} em^{CO_2}_{i} = \begin{cases} 0, & if\ the\ i\text{-}th\ technlogy\ belongs\ to\ RES\ or\ NPP\ or\ BESS \\ > 0, & if\ the\ i\text{-}th\ technlogy\ doesn't\ belong\ to\ RES\ or\ NPP\ or\ BESS \end{cases} \tag{9}$$

where: $em_i^{CO_2}$—the unit carbon dioxide emission factor for the *i*-th distributed generation technology, expressed in kg CO_2/kWh; *NPP*—Nuclear Power Plant; *RES*—renewable energy source; *BESS*—battery energy storage system.

A special case should be determined for the volume of electricity consumed from the power grid. In such a case, the unit carbon dioxide emission factor for the end-user supplied from the electricity grid, which is determined by the competent authorities calculating the emission parameters (in Poland—the National Balancing and Emission Management Center), is used. Let $em_{EndUs}^{CO_2}$ denote this value. There remains the question of including demand reduction measures in the facility's carbon balance. In this case, it is necessary to calculate the product of the planned volume of demand reduction and the factor $em_{EndUs}^{CO_2}$. Thus, the total emissions for the facility are:

$$EM_{TOTAL}^{CO_2} = \sum_{t=1}^{8760} \sum_{i=1}^{TC} E_{t,\,i}^{GEN} \cdot em_i^{CO_2} + E_{t,\,yf}^{GRID} \cdot em_{EndUs}^{CO_2} - E_{t,\,DSR}^{GEN} \cdot em_{EndUs}^{CO_2} \tag{10}$$

where: $EM_{TOTAL}^{CO_2}$—total annual carbon dioxide emissions to the atmosphere using distributed generation resources, expressed in kg CO_2 equivalent; $E_{t,\,DSR}^{GEN}$—demand reduction volume in hour *t*, expressed in kWh.

However, when analyzing the environmental impact of the development of distributed generation, it is important to consider the difference between the option in which we use distributed generation technologies and the one in which all energy would be taken from the grid. Thus:

$$EM_{diff}^{CO_2} = EM_{TOTAL}^{CO_2} - \sum_{t=1}^{8760} E_{t,\,yf}^{DEM} \cdot em_{EndUs}^{CO_2} \tag{11}$$

whereas, if:

$$EM_{diff}^{CO_2} < 0 \tag{12}$$

this is considered a positive environmental effect—reducing carbon dioxide emissions into the atmosphere.

3.4.3. Criterion 3—Enhancing the Energy Security of the Facility

The third criterion analyzed is the determination of the facility's energy security improvement factor. Energy security improvement refers to the ability to cover the annual demand of the most critical loads from its own distributed generation resources. However, in order to determine the priority of supplying the given loads, it is necessary to assign them to the set of all loads located in the decision-maker's facility. Let $\boldsymbol{Z_{load}}$ denote the set of n loads located in such a facility. Each of the loads can then be defined by the vector $\boldsymbol{L_n}$, according to the equation:

$$\boldsymbol{L_n} = \left[ID_n,\ B_n^j,\ P_n, PRIOR_n,\ DSR_n \right] \tag{13}$$

where: ID_n—identification code of the nth load; B_n^j—number of the jth building in which the nth load is located; P_n—rated power of the nth load, expressed in kW; $PRIOR_n$—priority of power supply to the nth load, determined by the decision-maker's expert method; DSR_n—realization of demand-side response by the nth load; whereas if:

$$PRIOR_n = \begin{cases} 1, & when\ priority\ is\ the\ highest \\ 2, & when\ priority\ is\ medium \\ 3, & when\ priority\ is\ the\ lowest \end{cases} \tag{14}$$

$$DSR_n = \begin{cases} 0, & when\ load\ is\ not\ providing\ DSR\ service \\ 1, & when\ load\ might\ provide\ DSR\ service \end{cases} \tag{15}$$

this means that the set of loads $\boldsymbol{Z_{load}}$ looks as follows:

$$\boldsymbol{Z_{load}} = \begin{bmatrix} ID_1 & B_1^j & P_1 & PRIOR_1 & DSR_1 \\ ID_2 & B_2^j & P_2 & PRIOR_2 & DSR_2 \\ ID_n & B_n^{j+1} & P_n & PRIOR_n & DSR_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ ID_{n+k} & B_{n+k}^{j+m} & P_{n+k} & PRIOR_{n+k} & DSR_{n+k} \end{bmatrix} \tag{16}$$

However, taking into account the priority of power supply, the $\boldsymbol{Z_{load}}$ set can be represented as a sum of sets with different values of the $PRIOR_n$ parameter:

$$\boldsymbol{Z_{load}}\boldsymbol{=}\boldsymbol{Z_{load}^{PRIOR1}} \cup \boldsymbol{Z_{load}^{PRIOR2}} \cup \boldsymbol{Z_{load}^{PRIOR3}} \tag{17}$$

where: $\boldsymbol{Z_{load}^{PRIOR1}}$—the set of loads with the highest supply priority, i.e., when $PRIOR_n = 1$; $\boldsymbol{Z_{load}^{PRIOR2}}$—the set of loads with medium supply priority, i.e., when $PRIOR_n = 2$; $\boldsymbol{Z_{load}^{PRIOR3}}$—the set of loads with the lowest supply priority, i.e., when $PRIOR_n = 3$.

From the point of view of the energy security of the facility owned by the decision-maker, the most important thing is to provide supply to loads with the parameter $PRIOR_n = 1$. However, in practice, it is impossible to meter all loads, so it is necessary to estimate the forecast demand for energy and the capacity of sources to guarantee energy security. Let P_{TOT}^{PRIOR1} denote the sum of the rated power of the loads with the highest supply priority. Thus, the following condition should be fulfilled:

$$P_{TOT}^{GEN_{SAF}} \geq P_{TOT}^{PRIOR1} \tag{18}$$

where: $P_{TOT}^{GEN_{SAF}}$—capacity generated by stable distributed generation resources among the set of installed DG technologies at the decision-maker's facility, which can operate without connection to the power system and have a fuel reserve for at least 4 h, expressed in kW.

However, it should be borne in mind that the decision-maker's facilities may be located in a highly urbanized environment, and their size should also be optimized by other parameters such as annual energy consumption and installed capacity utilization rate. Thus, the condition described by equation (18) may not be fulfilled, however, the decision-maker must then select the loads belonging to the set $\boldsymbol{Z_{load}^{PRIOR1}}$ so that the DG resources will cover the demand of the selected loads of category 1. This means that:

$$\begin{cases} P_{TOT}^{GEN_{SAF}} < P_{TOT}^{PRIOR1} \Leftrightarrow \; P'^{PRIOR1}_{TOT} < P_{TOT}^{PRIOR1} \wedge P'^{PRIOR1}_{TOT} = P_{TOT}^{GEN_{SAF}} \\ P_{TOT}^{GEN_{SAF}} \geq P_{TOT}^{PRIOR1} \Leftrightarrow \; P'^{PRIOR1}_{TOT} = P_{TOT}^{PRIOR1} \wedge P'^{PRIOR1}_{TOT} \leq P_{TOT}^{GEN_{SAF}} \end{cases} \tag{19}$$

where: P'^{PRIOR1}_{TOT}—the sum of the rated power of the selected highest-priority loads required for the operation of the decision-maker's facility, expressed in kW.

Next, it is necessary to proceed to the determination of the volume of electricity consumed by priority "1" loads, for which the continuity of the supply must be ensured. For this purpose, the LOLE indicator will be used again, which, in principle, determines the number of hours in which there may be problems with access to electricity. In addition, as already mentioned, it is impossible to meter all loads; therefore, an estimated value of the aforementioned electricity volume has been determined:

$$E_{TOT,yf}^{PRIOR1} = \frac{P'^{PRIOR1}_{TOT}}{P_{TOT}^{PRIOR}} \cdot \frac{\sum_{t=1}^{8760} E_{t,\,yf}^{DEM} \cdot LOLE_{yf}}{8760} \tag{20}$$

where: P_{TOT}^{PRIOR}—the sum of the rated power of all loads belonging to the $\boldsymbol{Z_{load}}$ set, expressed in kW; $LOLE_{yf}$—the value of the LOLE index in the yf-th year, expressed in hours;

$E_{TOT,yf}^{PRIOR1}$—the estimated volume of electricity consumed by priority "1" loads in the yf-th year of analysis.

The next step is to determine the volumes of energy produced by stable distributed generation resources for periods when there may be problems with access to electricity $E_{yf}^{GEN_{SAF}}$. Thus:

$$\bigwedge_{ts \in TC} E_{yf}^{GEN_{SAF}} = \sum_{ts=1}^{TS} P_{ts}^{GEN_{SAF}} \cdot LOLE_{yf} \tag{21}$$

Only at this point can the facility's energy security improvement factor k_{saf} be determined. Its value depends on the amount of electricity produced by distributed generation resources during the year. That is, the capacity condition described by equation (19) is treated as always being fulfilled, even when the most important priority "1" loads must be selected. The aforementioned coefficient is defined by the equation:

$$k_{saf} = \begin{cases} 0,\ jeli\ \ E_{yf}^{GEN_{SAF}} < E_{TOT,yf}^{PRIOR1} \\ 1,\ jeli\ E_{yf}^{GEN_{SAF}} = E_{TOT,yf}^{PRIOR1} \\ \frac{E_{yf}^{GEN_{SAF}}}{E_{TOT,yf}^{PRIOR1}},\ jeli\ E_{yf}^{GEN_{SAF}} > E_{TOT,yf}^{PRIOR1} \end{cases} \tag{22}$$

3.4.4. Criterion 4—Incurred Total Capital Expenditures

The last criterion analyzed is the amount of capital expenditure incurred by the decision-maker. Let $CAPEX_i^{TECH}$ denote the unit capital expenditure planned to be incurred by the decision-maker for the installation of the i-th distributed generation technology, expressed in PLN/kW. Thus:

$$CAPEX_{tech} = \sum_{i=1}^{TC} CAPEX_i^{TECH} \cdot P_i \tag{23}$$

where: P_i—the installed capacity of the i-th distributed generation resource, expressed in kW; $CAPEX_{tech}$—the total capital expenditures for the distributed generation development project, expressed in PLN.

3.4.5. Weighting Coefficients for the Criteria

The next step is to assign weighting coefficients to each criterion in a given option for the development of an energy infrastructure on university campuses. Table 1 shows the proposed weighting factors for the developed options and criteria.

Table 1. Weighting coefficients for the developed criteria and options.

Option | Criterion	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Option 1	0.05	0.05	**0.85**	0.05
Option 2	0.05	**0.8**	0.05	0.1
Option 3	**0.3**	0.1	**0.3**	**0.3**
Option 4	**0.4**	0.05	0.15	**0.4**
Option 5	0.25	0.25	0.25	0.25

Weighting factors were selected according to how the criterion fits into the decision option. The first decision option addresses securing the energy demands of university facilities regardless of economic and environmental costs. According to the pyramid of energy goals shown in Figure 1, it can be concluded that this is the implementation of measures to maintain contingency in the operation of the facility. Accordingly, the highest weight was assigned to criterion 3, i.e., the energy security of the facility, and the other evaluation criteria were distributed proportionally. The second decision option concerns the situation in which the university's authorities focus on the sustainable development of the university's infrastructure; hence, the greatest weight is given to criterion 2, regarding the reduction in carbon dioxide emissions into the atmosphere. Criteria related to the cost of purchasing energy and energy security have the least weight, while the more important criterion is that of incurring the capital expenditure. The third option is a modification of Option 1, but in addition to energy security issues, financial aspects are taken into account. Hence, equal weight is assigned to criteria 1, 3 and 4. Option 4 refers to the situation in which the decision-maker primarily takes into account financial aspects; hence, criteria 1 and 4 have the highest weight. Energy security is taken into account in third place, and the least important are aspects of CO_2 emissions into the atmosphere. The last option (fifth) refers to a situation in which the decision-maker is undecided, i.e., the weighting factors are equal.

It is also necessary to specify how each criterion was evaluated in the given options. Each criterion was graded on a scale of 1–5, where 1 is the worst, 5 the best. Table 2 shows how to sort the individual values calculated in the following criteria, which allow you to assign grades, i.e., determine the best place in the ranking.

Table 2. Sorting order for each criterion.

Criterion	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Sorting order	min → max	max → min	max → min	min → max

3.5. Multi-Criteria Decision-Support Method

Due to the necessity of solving a multi-criteria problem involving the selection of the best option, it was decided to use methods from the ELECTRE (French: Élimination et Choix Traduisant la Realité) family. ELECTRE methods are those that involve selecting the best possible solution, which is achieved by comparing different options of solutions using an index of similarities and differences between solutions. ELECTRE methods are particularly useful in the selection, grading and assignment of problems [59]. ELECTRE methods are often more effective than others because they do not require long running times and the calculations performed are short and relatively simple. ELECTRE is more than just a method that facilitates decisions, it is a method that incorporates a kind of philosophy to help the user make a decision [60]. In the literature, one can find examples of using methods from the ELECTRE family to solve multi-criteria decision-making problems [54,61,62]. The ELECTRE I method was used to analyze the problem posed in this article. In the ELECTRE I method, the goal is to create preference groups. It is assumed that the variant ai, which is placed at a higher level than the variant a_j, is the stronger variant due to its relations with all variants. The algorithm of the ELECTRE I method can be presented in the following five steps [50].

In step one, define a set of decision variants (objects) $\boldsymbol{A}$ to be evaluated, including N elements [50]:

$$\boldsymbol{A} = \left\{a_1, \ldots, a_i, \ldots, a_j, \ldots a_N\right\} \tag{24}$$

where: a— the decision option, i, j— the numbers of decision options.

Step two involves defining a set of evaluation criteria $\boldsymbol{G}$ consisting of K elements [50]:

$$\boldsymbol{G} = \{g_1,\ g_2, \ldots, g_k, \ldots g_K\} \tag{25}$$

where: g_k—evaluation criterion, k—evaluation criterion number.

In step three, the weights of the criteria from the set $\boldsymbol{G}$ and the values of the veto coefficients v_k for each criterion are determined. The value of the weight of each criterion w_k is determined based on the following relations [50]:

$$w_k \geq 0 \wedge w_k \leq 1,\ \ k = 1, \ldots, K \tag{26}$$

whereas:

$$\sum_{k=1}^{K} w_k = 1 \quad (27)$$

or when expressing values in percentages:

$$w_k \geq 0\% \wedge w_k \leq 100\%, \quad k = 1, \ldots, K \quad (28)$$

$$\sum_{k=1}^{K} w_k = 100\% \quad (29)$$

where: w_k— the weight of the k-th criterion.

In step four of the algorithm, a pairwise comparison of the decision alternatives takes place. This action is aimed at verifying the hypothesis of compatibility conditions and the lack of incompatibility. This step of the algorithm can be divided into four sub-steps.

In step 4.1, for each pair of objects (a_i, a_j), a compliance factor is determined based on the following equation [50]:

$$c\left(a_i, a_j\right) = \sum_{k=1}^{K} w_k \varphi_k\left(a_i, a_j\right) \quad (30)$$

where: φ_k—binary relation on the set of options, taking the following value:

$$\varphi_k\left(a_i, a_j\right) = \begin{cases} 1, & g_k(a_i) \geq g_k\left(a_j\right) \\ 0, & g_k(a_i) < g_k\left(a_j\right) \end{cases} \quad (31)$$

where: $g_k(a_i)$—the value of the *i-th* option according to the k-th criterion.

The values of $\varphi_k(a_i, a_j)$ are set in zero-one matrices $\boldsymbol{\Phi_k}$ [50]:

$$\boldsymbol{\Phi_k} = \left[\varphi_k\left(a_i, a_j\right) \in \{0, 1\} : a_i \in A, a_j \in A\right], \quad k = 1, \ldots, K \quad (32)$$

In step 4.2, the compliance condition is checked, which is conducted based on the following relation [50]:

$$c\left(a_i, a_j\right) \geq s \wedge s \in <\ 0.5; 1\ > \quad (33)$$

where: s—the compliance threshold, which divides the set of decision options into individual sets with different levels of dominance.

Step 4.3 concerns the task of constructing a set of concordance pairs (a_i, a_j) of $\boldsymbol{C_s}$ options. They must meet the following condition [50]:

$$\boldsymbol{C_s} = \left[\left(a_i, a_j\right) \in \boldsymbol{AxA} : c\left(a_i, a_j\right) \geq s \wedge s \in <\ 0.5; 1\ >\right] \quad (34)$$

In step 4.4, the construction of a set of incompatibilities takes place. It is built by determining pairs of variants in the incompatibility set for which the veto rule should be applied—a new incompatibility set $\boldsymbol{D_v}$ is created. Thus, it is necessary to separately determine the threshold value v_k (veto threshold) for each criterion in advance. Exceeding this value means that one object dominates over another, given the criterion, in such a significant way that the other criteria cannot change this relationship. The condition of non-incompatibility presents itself as follows [50]:

$$g_k(a_i) + v_k[g_k(a_i)] \geq g_k a_j \quad (35)$$

where: v_k—the value of the veto threshold for the k-th criterion.

The set of incompatibilities $\boldsymbol{D_v}$ is formed from pairs of objects satisfying the opposite condition to the relation (35) and is determined by the formula [50]:

$$\boldsymbol{D_v} = \left\{\left(a_i, a_j\right) \in \boldsymbol{AxA} : \exists g_k(a_i) \in \boldsymbol{G} : g_k(a_i) + v_k[g_k(a_i)] < g_k\left(a_j\right)\right\} \quad (36)$$

The last sub-step (4.5) is to examine the superiority relation. This is conducted based on the formation of the set $\boldsymbol{S}(s, v)$, which is the common part of the set $\boldsymbol{C_s}$ and the complement set $\boldsymbol{D_v}$ in the space $\boldsymbol{AxA}$ [50]:

$$\boldsymbol{S}(s,v) = \boldsymbol{C_s} \cap \overline{\boldsymbol{D_v}} \tag{37}$$

whereas:

$$\overline{\boldsymbol{D_v}} = (\boldsymbol{AxA}) \backslash \boldsymbol{D_v} \tag{38}$$

The fifth step involves the construction of a graph of relationships between the decision options based on the set $\boldsymbol{S}(s, v)$. The vertices of the graph are the decision options, and its arcs indicate the superiority relations previously determined between the options.

3.6. The Formation of the Strategy

The final step in the pursuit of decision-making solutions for the development of energy infrastructure based on distributed generation technologies on university campuses is the formation of energy management strategies and the setting-up of simulation scenarios for a given case. However, due to the individual nature of each case, general assumptions should be made during the implementation of such a measure:

- Analysis of the reliability indicators of the operation of national power systems in the perspective: 1 year, 5 years and more than 5 years;
- Analysis of the country's economic development prospects;
- Analysis of the country's energy policy;
- Integration of the university's strategic goals with the goals of the electricity infrastructure development.

A summary of all the considerations for distributed generation technology development projects can be presented by means of a flowchart. Figure 2 shows a graphical representation of the subsequent steps of the presented methodology.

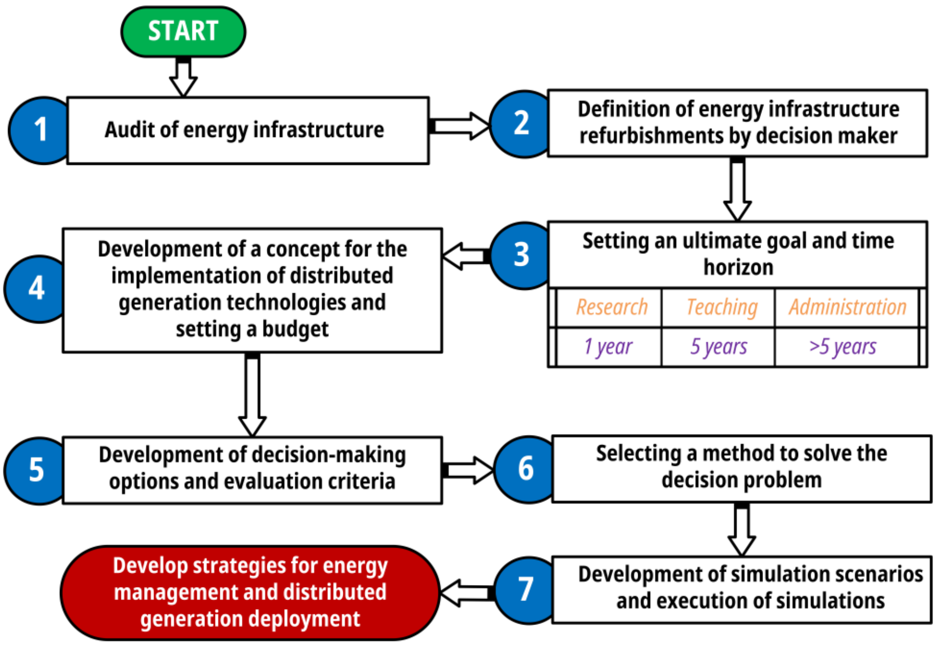
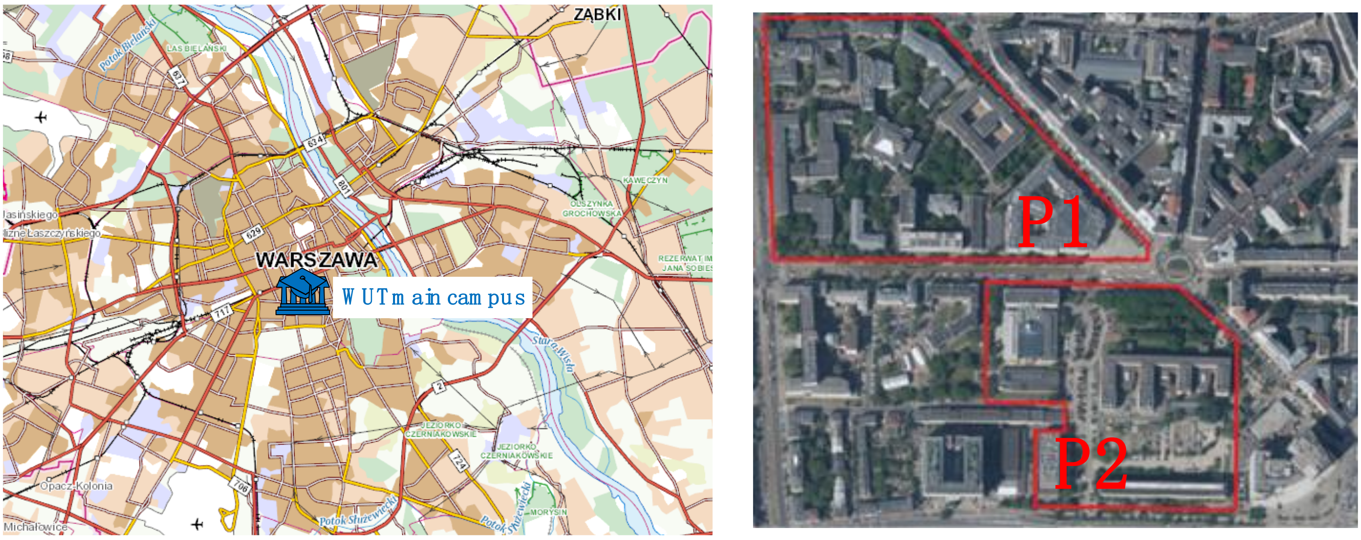


Figure 2. Methodology for forming energy management strategies for university facilities.

4. Case Study—Warsaw University of Technology Main Campus

4.1. General Description

According to the theme of the publication, it is necessary to consider the possibility of developing distributed generation technologies on university campuses in Poland during the energy transition. For this problem, it is necessary to carry out the analysis over a longer time horizon, i.e., 2023–2030, as analysis conducted only in the year of material development may be inaccurate. Therefore, the author's approach to the use of multi-criteria decision-making methods was applied, supplementing the selection of an appropriate option using the ELECTRE I method with the development of energy management strategies on such facilities. Thus, the purpose of this case study is to design development scenarios that will influence decisions made by university authorities and to analyze them. The main campus of the Warsaw University of Technology (WUT), located in the center of Warsaw, was selected as the study object. Figure 3a shows the location of the campus on a map of Warsaw, while Figure 3b shows a satellite photo of the facility. It is worth noting that the campus is split by a street in Warsaw, so it is divided for the purpose of this article into two parts—P1 and P2.



(**a**) (**b**)

Figure 3. Location of the Warsaw University of Technology main campus (**a**) Map of Warsaw; (**b**) Satellite image.

4.2. Current State of the Power Infrastructure on WUT Main Campus

The electric power infrastructure of the WUT main campus is based on a network established in the mid-20th century. The main campus has its own internal power grid that connects all of the buildings by medium voltage, as shown in Figure 4. There are currently several solar power plants on the main campus; however, they are dispersed, not integrated with each other and used mainly for research purposes. In addition, there is one vehicle-charging station installed with two charging points, with a total capacity of 77 kW. Figure 5 shows selected PV installations on the roofs and facades of WUT's main campus buildings. As part of the research work, a preliminary audit of the electricity infrastructure was performed, which identified its weakest points. Due to the research nature of the work, step (2) from the methodology shown in Figure 2 was omitted. Next, the goals and time horizon to be considered were established. The main objective of the power infrastructure upgrades being developed for the development of distributed generation on the WUT main campus is to design modern, low-carbon electricity sources that will:

- Maintain the continuous operation of facilities, including pre-defined critical loads;
- Optimize the economic and energy efficiency of the facility;
- Enable advanced research on the impact of distributed generation on the operation of the WUT campus power grid;
- Expanding student education with real-world applications of renewable energy and electricity storage solutions.

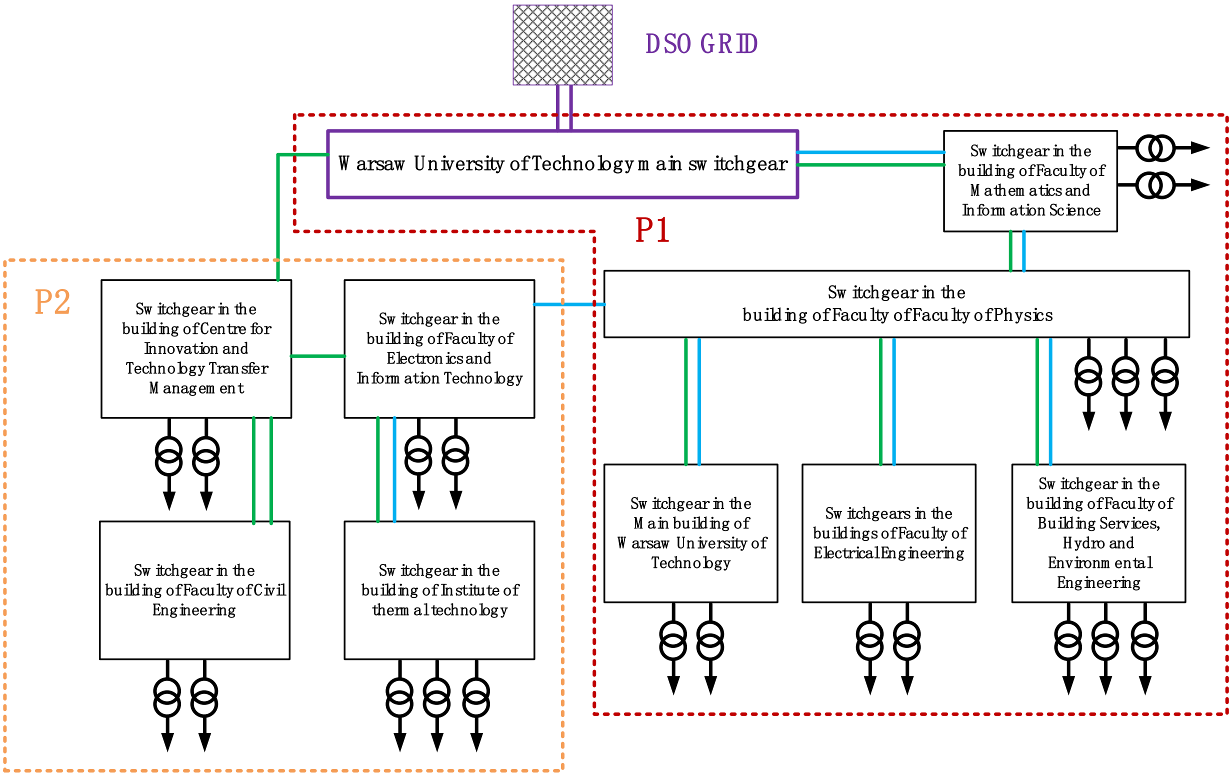


Figure 4. Single line diagram of power infrastructure of WUT main campus.

(**a**) (**b**)

Figure 5. Existing distributed energy sources at the Warsaw University of Technology main campus (**a**) on the building of Faculty of Building Services, Hydro and Environmental Engineering; (**b**) on the building of Faculty of Electrical Engineering.

In terms of the time horizon, an analysis interval of 2023–2030 is indicated. It should be pointed out that, for the aforementioned interval, the LOLE indicator is expected to deteriorate significantly in Poland [63,64]. Table 3 shows the values of the LOLE indicators in 2023–2030. The information was obtained from reports prepared by the Transmission System Operator, but the simulations only used data from the document prepared in 2020 [63]. The volumes of the LOLE indicators, it should be recalled, affect the duration of the operation of sources in emergency mode.

Table 3. Volumes of LOLE factors [63,64].

Year	2023	2024	2025	2026	2027	2028	2029	2030
LOLE (2020 report) [h/a]	0.66	0.24	1.7	2.4	3.93	12.05	33.72	103
LOLE (2022 report) [h/a]	2.45	5.85	22.12	302	230	257	1120	1040

4.3. Developed Concepts of DG Technlogoies on WUT Main Campus

Based on the aforementioned information, five concepts for the development of distributed generation technologies were designed, corresponding to the five stages of development from the pyramid of energy goals, shown in Figure 1.

- **Concept 0—**The basic concept, which assumes the purchase of mobile generators with a capacity of 2 × 250 kW. Preliminary surveys conducted in August 2022 indicated that the capacity of loads with the highest power supply category is about 3 MW. Therefore, when deciding on the implementation of such a concept, decision-makers will make a selection of switchboards to be supplied with generators.
- **Concept 1—**This is an extension of the assumptions of concept 0, with issues related to energy efficiency. Preliminary calculations have been made, which show that the potential in the PV installations on the WUT main campus could be 300 kW. It should be borne in mind that the target capacity of the installation will be possible to calculate after an audit of the roofs for the installation of such sources. In addition, the power of the diesel generator was increased to 1 MW.
- **Concept 2—**In this concept, it was proposed that the potential from the PV installation be divided into two parts. The first, with a capacity of 225 kW, would work for the WUT main campus' needs. The remaining 75 kW would be dedicated to charging a 450 kWh battery electric energy storage, which would support the operation of the electric vehicle charging station (currently installed). In addition, it is planned to install 10 × 3 kW micro wind turbines. This will allow the creation of hybrid systems, the operation of which would be supervised by a control and monitoring system.
- **Concept 3—**This concept is correlated with stage 3 of the pyramid of energy goals and concerns the possibility of ensuring the independent operation of the campus in the event of unplanned interruptions in the energy supply from the power grid. For this purpose, it was necessary to analyze the minimum demand for electricity and power. As a result of the analysis, it turned out that the minimum hourly power demand is about 800 kW, and a stable power source was selected for this power. The choice fell on a combined heat and power (CHP) source that would simultaneously be able to supply heat to the WUT facilities throughout the year. Nevertheless, it should be remembered that for such an investment to be economically justified, it is necessary for the CHP source to operate all year round. In this concept, the generator would be replaced by a battery-based electricity storage with a capacity of 1 MW and a capacity of 4 MWh (backup time of 4 h). In order to charge this storage in a cost-effective manner, it is planned to install parking shelters on the P2 site, which would be equipped with PV installations. The potential is tentatively estimated at 655 kW.
- **Concept 4—**This is an extension of concept 3 with the potential to provide demand-side response (DSR) services to the Transmission System Operator under ancillary services or capacity market. This allows the university to generate additional revenue, as long as formal and legal conditions are met. It is also an increase in the campus' energy security potential, as the selection of the lowest-priority loads will allow for a faster response during an unplanned power system outage.

Figure 6 shows a plan of WUT's main campus with the symbols of each investment within the developed concepts applied. It should be mentioned that these symbols are only indicative of the location of a particular DG technology and are not related to the capacity or location of a particular plant.

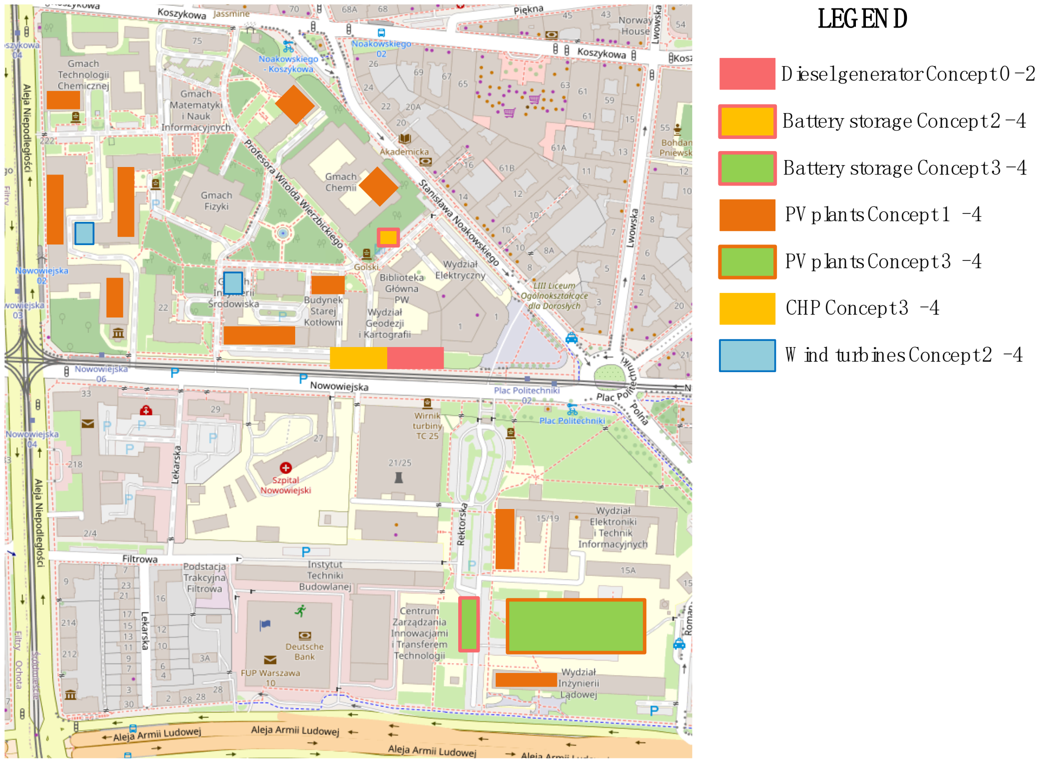


Figure 6. Location of DG within developed concepts at the WUT main campus.

4.4. Results and Discussion

In order to begin the task of finding the best concept for the development of DG technology on the WUT main campus, it was first necessary to acquire data to calculate the projected demand for electricity at a given time of the year. Data from the years 2019–2021 and the first half of 2022 were collected from the local DSO. The average annual energy demand for these years was 13 GWh. Thus, according to Formulas (1) and (2), the values for each hour were calculated. Then, using several simulation software, the operation of the sources included in the concepts presented in Section 4.3 was selected and analyzed, followed by calculations for the remaining criterion values, according to the methodology presented in Section 3. For the purpose of the simulation, a fixed energy purchase price of 575 PLN/MWh was assumed, which is based on the price of the contract obtained by WUT on the day the research work began. A discount rate calculation was omitted to facilitate the simulation. For individual DG resources, the parameters were assumed as in Table 4.

Table 4. Simulation parameters for DG resources–based on [65–68].

Parameter	Distribution Generation Resource			
	PV Plant	**Wind Power Plant**	**Gas CHP**	**Diesel Generator**
Unit cost of generating electricity [PLN/MWh]	185.00	127.00	1288.00	1900.00
Unit CAPEX [PLN/kW]	2989.00	5794.00	3325.00	800.00
The rate of unit CO_2 emissions [kg CO_2/MWh]	0.00	0.00	348.81	675.34

In addition, the parameters calculated for the end user were assumed. The unit emission factor was determined on the basis of the National Center for Balancing and Emission Management (KOBiZE) and was equal to 708 kg CO_2/MWh [69]. It was also necessary to assume a unit CAPEX for the construction of battery electric energy storage, which was equal to 6000 PLN/kW. A significant problem arose in calculating the cost and investment outlay for the DSR measures. Thus, it was assumed that the unit CAPEX for the DSR is equivalent to the average unit CAPEX for the BESS and diesel generator. In terms of the cost of reduction, it was assumed that the cost of running such a service must be no greater than the potential salaries for reduction. Accordingly, the rate quoted by the Transmission System Operator for the implementation of the ancillary service "Intervention Consumption Reduction" was assumed to be equal to 16,100 PLN/MWh [70].

Tables 5–9 show the results of the individual criterion values for the following concepts for the years 2023–2030.

Table 5. Values of the criteria 1–4 in proposed Concept 0.

Concept 0				
Year	**Criterion 1—Cost of Purchasing and/or Generating Electricity [PLN]**	**Criterion 2—Difference in Carbon Dioxide Emissions into the Atmosphere [kg·10^3]**	**Criterion 3—Enhancing the Energy Security of the Facility**	**Criterion 4—Incurred Total Capital Expenditures [PLN]**
2023	9,062,241.07	0.22	0.000	400,000.00
2024	9,897,363.20	0.08	0.000	
2025	10,962,381.72	0.57	0.000	
2026	12,313,280.44	0.81	0.000	
2027	14,031,804.07	1.33	0.000	
2028	16,233,172.87	4.07	0.000	
2029	19,074,244.12	11.39	0.000	
2030	22,793,636.79	34.78	0.000	

Table 6. Values of the criteria 1–4 in proposed Concept 1.

Concept 1				
Year	**Criterion 1–Cost of Purchasing and/or Generating Electricity [PLN]**	**Criterion 2—Difference in Carbon Dioxide Emissions into the Atmosphere [kg·10^3]**	**Criterion 3—Enhancing the Energy Security of the Facility**	**Criterion 4—Incurred Total Capital Expenditures [PLN]**
2023	8,932,318.81	−236.28	1.000	1,696,700.00
2024	9,767,041.95	−236.57	0.000	
2025	10,833,447.47	−235.58	0.000	
2026	12,185,011.19	−235.11	0.000	
2027	13,904,988.32	−234.08	0.000	
2028	16,114,071.12	−228.59	0.000	
2029	18,975,728.87	−213.96	0.000	
2030	22,760,937.54	−167.17	0.000	

Table 7. Values of the criteria 1–4 in proposed Concept 2.

Concept 2				
Year	**Criterion 1—Cost of Purchasing and/or Generating Electricity [PLN]**	**Criterion 2—Difference in Carbon Dioxide Emissions into the Atmosphere [kg·10^3]**	**Criterion 3—Enhancing the Energy Security of the Facility**	**Criterion 4—Incurred Total Capital Expenditures [PLN]**
2023	8,900,218.22	−286.96	1.000	2,320,520.00
2024	9,734,941.35	−287.25	0.000	
2025	10,801,346.88	−286.26	0.000	
2026	12,152,910.59	−285.79	0.000	
2027	13,872,887.73	−284.76	0.000	
2028	16,081,970.52	−279.27	0.000	
2029	18,943,628.28	−264.64	0.000	
2030	22,728,836.94	−217.85	0.000	

Table 8. Values of the criteria 1–4 in proposed Concept 3.

Concept 3				
Year	**Criterion 1—Cost of Purchasing and/or Generating Electricity [PLN]**	**Criterion 2—Difference in Carbon Dioxide Emissions into the Atmosphere [kg·10^3]**	**Criterion 3—Enhancing the Energy Security of the Facility**	**Criterion 4—Incurred Total Capital Expenditures [PLN]**
2023	13,060,685.87	−3045.15	1.798	12,138,315.00
2024	13,895,965.32	−3045.45	1.646	
2025	14,960,436.99	−3044.41	1.486	
2026	16,311,073.51	−3043.92	1.323	
2027	18,029,024.07	−3042.83	1.161	
2028	20,227,351.44	−3037.09	1.004	
2029	23,060,305.97	−3021.74	0.000	
2030	26,753,749.12	−2972.69	0.000	

Based on Tables 5–9, it can be concluded that only concepts 3 and 4 can realistically provide energy security for the facility. It should be noted that any action focused on the installation of low-emission power sources will have a positive effect on the environment, despite the stated increase in energy demand (according to Equation(2)). In addition, according to the expected results, the capital expenditures increase significantly with the degree of technological advancement on campus. The cost of purchasing and generating energy, despite the measures used to increase self-consumption (own sources), increases between 2023 and 2030, regardless of the concept used. In addition, in concepts 3 and 4, the operating CHP source generates additional costs (mainly variable). The LOLE index values (2020 report) from Table 3 were used for the analysis [63].

Table 9. Values of the criteria 1–4 in proposed Concept 4.

Concept 4				
Year	**Criterion 1—Cost of Purchasing and/or Generating Electricity [PLN]**	**Criterion 2—Difference in Carbon Dioxide Emissions into the Atmosphere [kg·10^3]**	**Criterion 3—Enhancing the Energy Security of the Facility**	**Criterion 4—Incurred Total Capital Expenditures [PLN]**
2023	13,072,204.46	−3045.66	2.881	15,823,915.00
2024	13,900,153.90	−3045.63	2.637	
2025	14,990,106.07	−3045.72	2.381	
2026	16,352,959.27	−3045.76	2.120	
2027	18,097,612.00	−3045.85	1.861	
2028	20,437,652.86	−3046.33	1.609	
2029	23,648,800.90	−3047.62	1.371	
2030	28,551,346.32	−3051.74	1.150	

Subsequently, it was decided to analyze potential scenarios for considering the decision options. This means that a decision option was selected for each year of analysis (2023–2030). Ten scenarios were designed, which are described in Table 10.

Table 10. Scenarios considered in the simulations.

Scenario	Description
A	Implementation of decision Option 1 in 2023–2030
B	Implementation of decision Option 2 in 2023–2030
C	Implementation of decision Option 3 in 2023–2030
D	Implementation of decision Option 4 in 2023–2030
E	Implementation of decision Option 5 in 2023–2030
F	Implementation of Option 3 in 2023–2026, and Option 1 in 2027–2030. Such a strategy is based on the need to secure the facility while taking into account economic criteria, nevertheless, as of 2027, the LOLE index exceeds the value assumed by the Polish authorities as safe; hence, the option of securing regardless of cost should be implemented.
G	Implementation of Option 5 in 2023–2026, followed by Option 2 in 2027–2030. The decision-maker in this scenario is undecided about which direction to pursue the development of DG technology on campus. However, starting in 2027, they pursue a policy of sustainable development. This year is also due to the average time for upgrading the energy infrastructure on campus.
H	Implementation of Option 4 in 2023–2026 and Option 3 in 2027–2030. The decision-maker, for the first four years, leads the modernization of the campus energy infrastructure with a focus on cost optimization, but from 2027 onwards, for energy security reasons, the strategy aims to ensure the continuity of the university's operations while maintaining financial optimization.
I	Implementation of Option 2 in 2023–2026 and Option 1 in 2027–2030. The decision-maker wanted to pursue a policy of sustainable development, but the energy security situation forces him to devote all his attention to securing the facility.
J	Implementing Option 2 in 2023–2026, Option 3 in 2027–2029 and Option 1 in 2030. The decision-maker adopts a similar strategy as in Scenario I, but by 2030, tries to secure the facility with financial optimization in mind.

For the implementation of the ELECTRE I method, each concept (0–4) was rated for each criterion, in each variant, on a scale of 1–5, where 1 is the worst, 5 the best. Veto thresholds were then determined. These parameters are shown in Table 11. The weighting factors for each criterion were previously shown in Table 1. The compliance factor for all variants was set at 0.6.

Table 11. Veto thresholds for each criterion in different years of analysis.

Year	**Veto Thresholds**			
	Criterion 1	**Criterion 2**	**Criterion 3**	**Criterion 4**
2023	3	2	2	2
2024	3	2	3	2
2025	3	2	3	2
2026	3	2	3	3
2027	3	2	3	3
2028	3	2	3	3
2029	3	2	4	3
2030	3	2	4	2

After running the algorithms of the ELECTRE I method, the simulation results were obtained. Table 12 shows the selected best concepts in each of the analyzed scenarios. In cases where several variants were equivalent, the best variant was chosen by taking into account the minimization of capital expenditures.

Table 12. The chosen best concepts for DG development on the WUT main campus in years 2023–2030.

Scenario	Best Concept							
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
A	4	4	4	4	4	4	4	4
B	4	4	4	4	4	4	4	4
C	2	2	2	2	2	2	2	2
D	2	2	2	2	2	2	2	2
E	2	2	2	2	2	2	2	2
F	2	2	2	2	4	4	4	4
G	2	2	2	2	4	4	4	4
H	2	2	2	2	2	2	2	2
I	4	4	4	4	4	4	4	4
J	4	4	4	4	2	2	2	4

Based on Table 12, it can be concluded that only two concepts (2 and 4) were selected as the best. Upon further analysis, this is not surprising, as concept 2 already includes a significant share of DG technology, which will increase the facility's self-consumption rate and achieve a positive environmental effect in terms of reducing carbon dioxide emissions into the atmosphere. It also does include plans to invest in its own CHP source and BESS, which have very large capital expenditures. Nevertheless, guided by the goals of energy security, only concept 4 was considered. This is evident even from the calculations shown in Table 9, in which the security coefficients of the facility are the highest. Concept 4 also provides a significant reduction in CO_2 emissions. The results of the concept selection using the ELECTRE I method can be summarized as follows: either the decision-maker invests a large amount of money in the implementation of the energization tasks or he is looking for compromise, implementing only a fracture of the tasks needed to be completed. The last element of the analysis was to determine the "resultant" energy management strategy on the WUT main campus. The number of the best places of a given concept in a given year was taken into account. Table 13 presents the results of this analysis.

Table 13. The resultant energy management strategy on WUT main campus.

	The Resultant Strategy							
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Concept	2	2	2	2	2/4	2/4	2/4	4

Based on Table 13, it can be stated that the resultant energy management strategy on the WUT main campus consists of the development of concept 2 until 2026. In the years 2027–2029, the decision-maker may choose to continue the implementation of concept 2 or decide to implement concept 4, assuming that it will have the appropriate capital expenditures. In 2030, the decision-maker should choose concept 4. Some progress can be observed in the implementation of the tasks related to the development of DG technology, thanks to which it is not necessary to spend large capital expenditures from the very beginning of activities.

5. Conclusions

This paper discusses the issues related to the development of distributed generation resources on university campuses in Poland. The author's methodology for evaluating the options for the development of such an infrastructure depending on the choices of the decision-maker was proposed. One of the most important achievements of this study is the definition of a pyramid of energy goals, which forms the foundation for projects of DG resource development concepts. Importantly, the base of such a pyramid is the decision-maker's assurance of the facility's energy security. Often, in public spaces, people talk about the necessity to improve the energy efficiency of facilities, while forgetting about the importance of reviewing the level of reliability of the electricity supply to the end user. Based on the research conducted, it can be concluded that, contrary to appearances, it is not easy to carry out such an activity. Only in cases of very advanced design concepts has it been possible to obtain surplus energy from stable sources, that is, to provide a reserve of energy security for the campus. Other aspects that will be of interest to decision-makers at universities are the costs of generating and purchasing electricity from the grid. It should be borne in mind that the demand for energy on the WUT campus is increasing from year to year. Adding to this the volatile situation in the Polish energy market, the decision-maker is right to wonder whether investment in its own power generation infrastructure will be a more reliable means of assessing the cost of electricity consumption. Studies have confirmed that the development of RES (solar and wind power plants) will reduce the cost of purchasing electricity, with relatively low operating costs. If it is necessary to install a stable source (CHP gas), the operating costs of working such sources will cause an increase in the overall cost of purchasing and generating power. In the conducted research, the ELECTRE I method was used to select the best concept. This is a basic decision-support method. Subsequent studies may lead to the use of other methods from the ELECTRE family or others based on multi-criteria decision support. In conclusion, the topic of power supply for university campuses is bound to be important in the coming years, especially for state and university authorities. The rising cost of maintaining facilities will certainly prompt them to invest in DG resources.

As part of future work, it is planned to create, among other things, a methodology that will allow the calculation of the cost of non-delivered energy on university campuses. This index will be important as it will represent the real value of capital expenditures that could cover possible gaps in the uninterrupted supply of electricity, especially considering the increasing values of the LOLE index. Subsequent activities will also include the extension of the analyses carried out in this paper to other facilities of the Warsaw University of Technology, which will be carried out within the framework of the STRATEG project, implemented as part of the Initiative for Research University Excellence (IDUB). The result of the entire program of actions related to the analysis of the energy security and efficiency of WUT campuses is expected to be the development of an energy management strategy, considering planned refurbishments, as well as organizational changes in the structure of the university.

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