

Article

Research on the Possibilities of Expanding the Photovoltaic Installation in the Microgrid Structure of Kielce University of Technology Using Digital Twin Technology

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Abstract: Global challenges related to sustainable development are increasingly focusing on the use of digital twin technology as a universal tool for optimizing and monitoring renewable energy installations. This article discusses digital twin technology as a support for sustainable development based on the analysis of microgrid structures. Digital twins allow the creation of virtual models of physical systems. This capability facilitated the accurate replication of the microgrid model at Kielce University of Technology using ETAP (Electrical Transient Analyzer Program) software (version 22.5). The operational parameters of the microgrid structure were analyzed for the examined power range of the photovoltaic installation to determine the possibilities of expanding the existing installation. The impact of the photovoltaic installation's power on the operational parameters of the microgrid structure was visualized, and final conclusions were formulated. Moreover, the integration of digital twin technology into renewable energy systems not only enhances operational efficiency but also plays a pivotal role in advancing sustainability objectives. Through real-time monitoring and predictive maintenance, digital twin technology facilitates the optimization of energy production and distribution, thereby reducing waste and contributing to the overall sustainability of energy systems. This technology enables the simulation of various scenarios, such as fluctuations in energy demand or the integration of new renewable sources, which can inform more sustainable decision-making processes. In the context of microgrids, digital twin technology ensures that energy production is closely aligned with consumption patterns, minimizing energy losses and enhancing grid resilience. Furthermore, digital twin technology supports the sustainable expansion of renewable installations by providing detailed insights into potential environmental impacts and the long-term sustainability of various energy configurations. As the demand for clean energy continues to grow, digital twin technology will be indispensable in achieving a balance between energy needs and environmental stewardship, ensuring that the expansion of renewable energy sources contributes positively to global sustainability objectives.

Keywords: digital twin; microgrid; sustainable development; sustainable technology; energy sustainability; photovoltaic installation; operational parameters



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1. Introduction

The development of industry, transportation, and communication methods contributes to the continuous increase in the demand for electrical energy. The study and comparison of the transitional performance of electrical power systems became essential in the era of growing interest in integrating renewable energy sources (RESs) into the grid. In 2021, the global installed capacity from renewable sources reached 3064 GWh, with a growth

dynamic of 9.1%, where 88% of renewable energy was derived from wind and solar power [1,2].

RESs are progressively being integrated into the global electrical power grid, offering an alternative to fossil fuels. This integration impacts the stability of electrical power systems. In article [3], the microgrid is presented as a resource with significant potential that can enhance the dispersion of energy resources and the decentralization of energy systems.

ETAP software is a tool used for the analysis of various transitional states within electrical power systems, including the state that is reached after the connection of a microgrid. Typically, it operates with simulation modules in offline mode, but it also allows for the utilization of data for advanced monitoring or real-time simulation, optimization, and intelligent load shedding (1). ETAP has been designed with the capability to accommodate both alternating current (AC) and direct current (DC) networks, offering users the flexibility to work with either type of network through the use of multiple interface views. The software is capable of performing a number of analyses, including load flow, fault, harmonic, optimal power flow, DC load flow, and protection coordination analysis. A comparative analysis of PowerApps and ETAP in power flow studies has yielded results that are almost identical, thereby confirming the reliability of these programs [4]. A review of the literature indicates the necessity to choose an appropriate analytical platform for testing, managing, and monitoring microgrids integrated into electrical power systems. The ETAP environment enables the modeling of energy networks, which can support the industry in designing and planning the expansion and transformation of traditional networks into smart grids.

ETAP conducts load flow analysis using the Newton–Raphson method. The operation scheme of this method is presented in [3].

Digital twin technology offers significant advancements in the pursuit of energy sustainability by enabling more efficient and informed management of renewable energy systems. Beyond simply optimizing operational efficiency, digital twin technology allows the in-depth analysis and simulation of energy systems, which is critical for integrating renewable energy sources, like wind and solar, into existing grids. This capability is particularly important for ensuring the stability and reliability of energy systems as they evolve to meet the growing demand for clean energy. By accurately modeling the behavior of microgrids and larger energy networks, digital twin technology helps identify potential inefficiencies and areas for improvement in real time, allowing for initiative-taking measures that reduce energy waste and enhance system resilience [1,4].

Furthermore, the adoption of digital twin technology supports long-term energy sustainability by facilitating the strategic planning and expansion of renewable energy installations. Through predictive modeling and scenario analysis, digital twin technology provides valuable insights into the environmental impacts and sustainability of different energy configurations, aiding in the decision-making process for future energy infrastructure developments [2,3]. As the energy sector continues to shift toward renewable sources, digital twin technology will play an essential role in aligning energy production with sustainability goals, contributing to a more resilient and environmentally conscious energy future.

2. Digital Twin Technology—Support of Sustainable Development

The development and increasing utilization of digital twin (DT) technology are gaining significant importance as a supportive element for sustainable development. A “digital twin” can be defined as a virtual model that replicates a process, object, or system as accurately as possible, operating in real time. DT technology enables the analysis, monitoring, and optimization of selected processes without the need to update the actual object. Digital twin technology impacts sustainable development in multiple ways, encompassing process and resource management and their optimization, as well as monitoring and improving energy efficiency. In urban management, the use of DT technology allows for better management of natural resources, such as water and energy, thereby limiting their irrational use. Creating a model of a given system enables the identification of areas where resource

losses can be reduced, thereby improving savings, including financial ones. By integrating DT technology with modern IoT (Internet of Things) sensors, cities could precisely track resource consumption and optimize their distribution, moving closer to the concept of a smart city [5–7].

Continuing the analysis of sustainable urban development, it can be noted that the use of digital twin technology allows not only for resource management but also for managing urban infrastructure in the contexts of traffic flow and the optimization of power grid operations. Through the capability to simulate various scenarios, it is possible, for example, to predict how urban infrastructure will behave in the event of extreme weather phenomena or unexpected traffic signal failures. Managing the city's energy network potentially contributes to increasing the share of renewable energy sources by predicting the behavior of the entire system, thereby reducing CO₂ emissions [6,7].

Referring to examples of DT technology applications in the manufacturing sector, it can be observed that it supports sustainable development through the optimization of production processes, which, in turn, reduces energy and material consumption. Simulations that enable the identification and elimination of bottlenecks in production processes using digital twin technology are examples. As a result, manufacturing plants show increased energy efficiency and waste reduction. Combining DT technology with the Industry 4.0 concept enables the creation of more integrated and sustainable supply chains, which is crucial for reducing the carbon footprint and protecting the environment [8,9].

Digital Twin Technology and Renewable Energy Sources

The use of DT technology in conjunction with RESs can significantly enhance and modernize energy management approaches in the energy sector. Digital twin technology enables the modeling and monitoring of the status of photovoltaic installations, wind farms, and biomass facilities. Incorporating energy storage systems into a modeled energy infrastructure offers an innovative approach to the challenges associated with energy management, especially in the context of the diverse functions these storage systems can perform [10,11]. The efficient management of production and distribution significantly improves the optimization of installed systems, enhancing their efficiency and improving supply stability [12,13].

The implementation of digital twin technology in the renewable energy sector enables the simulation of weather conditions for a given location, which directly impacts the production of electrical energy. This facilitates more effective optimization of the management of produced energy, as well as forecasting potential failures and planning maintenance, which reduces the risk of downtimes and minimizes operational costs. Having an actual model of a given renewable energy installation allows for monitoring its performance, thereby enabling more rapid identification of operational problems that arise during exploitation [13,14].

Therefore, the role of digital twin technology is crucial for achieving sustainable development. Its application allows for the effective management of resources and processes, leading to the optimization of their operations. This optimization contributes to the creation of more sustainable and resilient urban and industrial systems. The continuous development of digital twin technology establishes an environment where its role becomes increasingly significant in promoting sustainable development and resilience across various sectors.

3. Construction of the Microgrid at Kielce University of Technology

A microgrid can be defined as a network comprising distributed power plants, consumers, and energy storage devices. These networks typically operate parallel to the electrical power grid and can switch to island mode during emergency situations [15]. Island mode operation may require balancing generation and load. In such cases, it is prudent to reduce the load of non-critical consumers when generation is insufficient.

At Kielce University of Technology, a microgrid solution has been implemented. The system includes a photovoltaic installation (50 kW on the roof and 500 kW installed on

carports), which serves as the primary source of renewable energy. The wind installation, consisting of six vertical wind turbines, has a capacity of 23.2 kW. The microgrid also includes an energy storage system with a capacity of 500 kW and 400 kWh. A gas engine and generator serve as emergency power sources. The system is complemented by electric vehicle charging stations. An integral component of the microgrid is the controlled loads, which include all consumers located at the campus of Kielce University of Technology [16]. Structure of the solution introduced at Kielce University of Technology is shown in Figure 1.

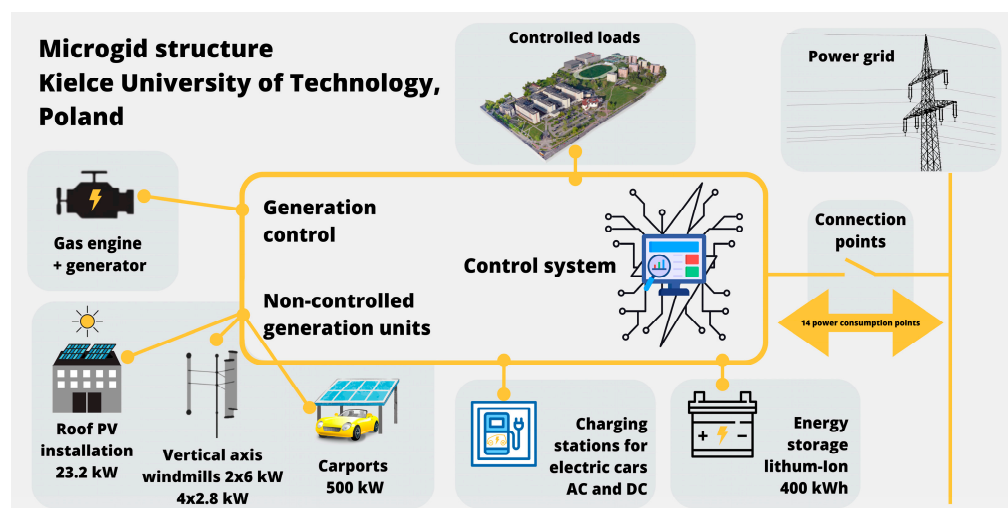


Figure 1. Microgrid structure of Kielce University of Technology. Source: Author's own elaboration.

4. Methodology and Research Tools

4.1. ETAP Software

ETAP is an advanced tool for modeling, analyzing, automating, and optimizing electrical networks. Developed by Schneider Electric (Rueil-Malmaison, France), it is designed as a versatile engineering tool that enables the creation of digital twin technology models of electrical networks in industrial facilities. It allows for the real-time monitoring of electrical systems, facilitating complete understanding and optimization of their operations. Load flow analysis is possible if the network is equipped with a swing bus. Using this software, accurate digital representations of physical electrical networks, known as digital twin technology, can be created [17]. These models allow for the simulation, analysis, and optimization of operations without the risk of interfering with actual systems, supporting the concept of sustainable development. This primarily enables the anticipation of problems and the planning of maintenance in advance, knowing how the network will behave before any changes are implemented [18].

The ETAP software, which was employed in this study, offers a number of key functionalities, as follows:

- The software enables the accurate modeling of power systems. ETAP enables comprehensive dynamic simulations, facilitating an examination of system behavior under diverse operational circumstances, which is crucial for assessing the influence of prospective infrastructure alterations [19];
- Reliability assessment: By simulating a variety of operational scenarios, the software assists in the identification of potential failure points and planning of preventive measures to enhance system stability;
- Energy consumption analysis: The digital twin technology model created within ETAP provides a framework for the evaluation of energy usage patterns, thereby supporting strategies for energy optimization and system efficiency improvements;
- Safety and compliance evaluation: ETAP enables comprehensive safety analyses, ensuring compliance with industry standards and improving the overall safety performance of the power system;

- Infrastructure expansion planning: ETAP supports the planning of infrastructure expansions, including the integration of renewable energy sources, by modeling and assessing the potential impacts before actual implementation.

4.2. Power Regulation Capacity Analysis

Investing in RESs should always be preceded by thorough expertise on the impact of connecting a photovoltaic (PV) installation to the electrical network of a facility. Solar energy is a key element in the energy transformation of enterprises, reducing carbon dioxide emissions and other air pollutants. However, introducing a new PV installation into an existing facility's infrastructure can pose many technical challenges. Often, the existing network may not be adapted to accept new loads in the form of a photovoltaic installation, which can lead to issues with maintaining the stability and reliability of the existing electrical system. In such cases, where the decision to invest in RESs is to be conscious and responsible, one of the most important steps to take is to perform an analysis of the power regulation capacity [20].

The analysis of power regulation capacity determines the extent to which the electrical network of a given facility can process and distribute the power generated by a new photovoltaic installation while maintaining stable operational conditions. The purpose of this analysis is to determine whether and how the connected photovoltaic installation will affect the network in terms of production management and electrical energy consumption. Given the high variability of production for installations utilizing solar energy, this analysis is crucial and should be conducted to assess the impact of RESs on the quality of electrical energy in the network [21,22].

Thanks to the precision of this analysis, it is possible to quickly identify problems related to the integration of a new photovoltaic installation with the existing distribution network, which will allow for the implementation of corrective actions to ensure effective energy production management. In this way, the risk of system destabilization is reduced, thereby enhancing the optimal use of locally produced energy from renewable sources. The power regulation capacity analysis allows for maintaining long-term energy sustainability, ensuring the security of investments in renewable energy sources [23].

4.3. Power Factor and Connection of a New Source to the Network

Connecting a micro-installation or small installation to a low-voltage distribution network can cause changes to significant network parameters. The decision to connect a micro-installation or small installation to the electrical power network requires the assessment of many parameters that reflect the impact of energy sources on network operating conditions. It is crucial to verify whether the operation of the considered source will exceed permissible levels of energy quality indicators or overload elements of the network system. To assess connection capabilities, it is necessary to examine network conditions at the planned connection point of the micro-installation or small installation and obtain data regarding generation units [24].

One of the basic parameters of the source that is part of the micro-installation or small installation is the power factor $\cos\varphi$, with a specified characteristic of $\cos\varphi_{ind}$ or $\cos\varphi_{poj}$. Differentiating the nature of the power factor helps to establish various operating states of the installation. During the generation of active power, reactive power of an inductive nature may be produced; thus, the power factor is inductive ($\cos\varphi_{ind}$). Conversely, if reactive power of a capacitive nature is produced during the generation of active power, the power factor is capacitive ($\cos\varphi_{cap}$). The distribution system operator ($\cos\varphi = \cos\varphi_{desired}$) sets the value of the power factor. It is also permissible to operate with a variable power factor with a characteristic of the power factor $\cos\varphi(P)$ specified by the operator.

4.4. Model Assumptions and Conducted Research

The objective of the conducted research was to verify the rationale for expanding the existing photovoltaic installation of 500 kWp located at the campus of Kielce University of

Technology and examine how the microgrid electrical system would behave after connecting additional photovoltaic installations of 100 kWp unit power. The research started from the existing installation (500 kWp) and increased its power by 100 kWp, ending at 1000 kWp. The expansion of the system was constrained to 1000 kWp due to the spatial limitations encountered at the Kielce University of Technology campus. The available area for photovoltaic installations was insufficient to accommodate further capacity increases, thereby establishing a physical boundary that defined the maximum achievable power output within the scope of the project. The behavior of the system was examined using power regulation capacity analysis for the electrical network of the campus (microgrid PŚk).

The diagram presented (Figure 2) illustrates the systematic approach undertaken in this research project, detailing each critical phase from the initial analysis to the final reporting stage. The methodology follows a structured workflow that ensures thorough consideration of both technical and environmental factors, thus contributing to the accurate assessment and feasibility of the photovoltaic system expansion. Each step in the process is designed to build upon the previous one, creating a comprehensive framework for analyzing and validating the proposed investment.

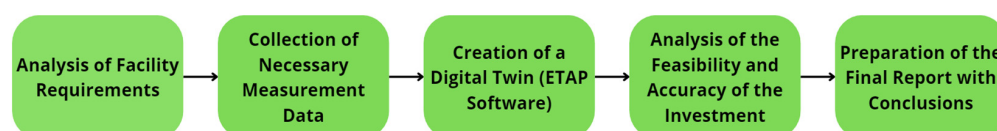


Figure 2. Diagram illustrating the overall research process. Source: Author's own elaboration.

Presented below is a detailed explanation of each step in the process:

1. **Analysis of Facility Requirements:** The initial stage of the study entails a comprehensive evaluation of the facility's energy requirements and operational constraints. This entails the identification of the power demand patterns, peak usage times, and the presence of any existing energy management systems. The objective of this study was to ascertain the feasibility of enhancing the PV capacity while adhering to the spatial constraints of the Kielce University of Technology campus;
2. **Collection of Necessary Measurement Data:** The accurate and reliable collection of data is of paramount importance for the effective simulation and modeling of the proposed system. This phase is dedicated to the gathering of all relevant information, including solar irradiance levels, historical energy consumption data, and technical specifications of the existing photovoltaic (PV) installation. These measurements provide the foundational data necessary for the creation of a digital twin of the microgrid system.
3. **Creation of a Digital Twin (ETAP Software):** The ETAP software is employed to develop a digital twin of the facility's microgrid. This entails the creation of a virtual model that replicates the physical components of the energy system, thereby facilitating real-time simulations and performance analysis. The digital twin technology is indispensable for accurately modeling the behavior of the expanded PV installation under diverse operating conditions, thus enabling a precise evaluation of potential outcomes;
4. **Analysis of the Feasibility and Accuracy of the Investment:** Once the digital twin is operational, the subsequent step is to analyze the feasibility and accuracy of the proposed photovoltaic (PV) expansion. Computer simulations are conducted to evaluate the performance of the system when scaled up to 1000 kWp, taking into account both the technical limitations and physical constraints (e.g., space availability on campus);
5. **Preparation of the Final Report with Conclusions:** The final phase comprises the synthesis of the findings from all preceding steps into a comprehensive report. This includes detailed conclusions on the technical viability.

This methodical approach guarantees that each pivotal element is subjected to comprehensive assessment, thereby establishing a solid basis for the determination of the optimal

course of action regarding the expansion of the photovoltaic system at the Kielce University of Technology campus.

To perform the research as accurately as possible without making changes in the real network, the ETAP software was used to create a digital twin of the PŚk microgrid. Below is a block diagram (Figure 3) reflecting the current state of the campus microgrid at Kielce University of Technology, while a detailed schematic from the design phase is included as an attachment in the Supplementary Materials section at the end of this article.

Block diagram reflecting the microgrid model of the Kielce University of Technology

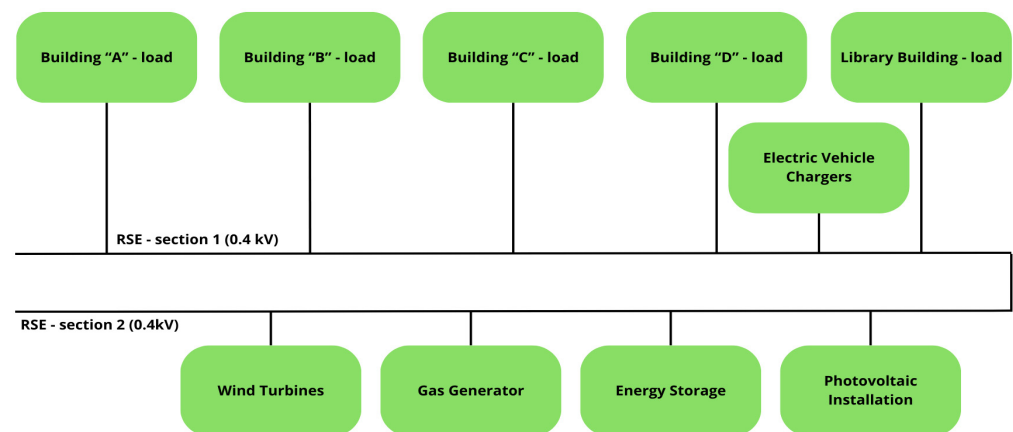


Figure 3. Block diagram reflecting the microgrid model of Kielce University of Technology. Source: Author's own elaboration.

The components of the studied photovoltaic installation include:

- Photovoltaic panels: JaSolar (Beijing, China) JAM60S10-340/MR (1470 units);
- Inverters: Huawei (Shenzhen, China) SUN2000-60KTL-M0 (2 units), Huawei (Shenzhen, China) SUN2000-100KTL-M1 (4 units).

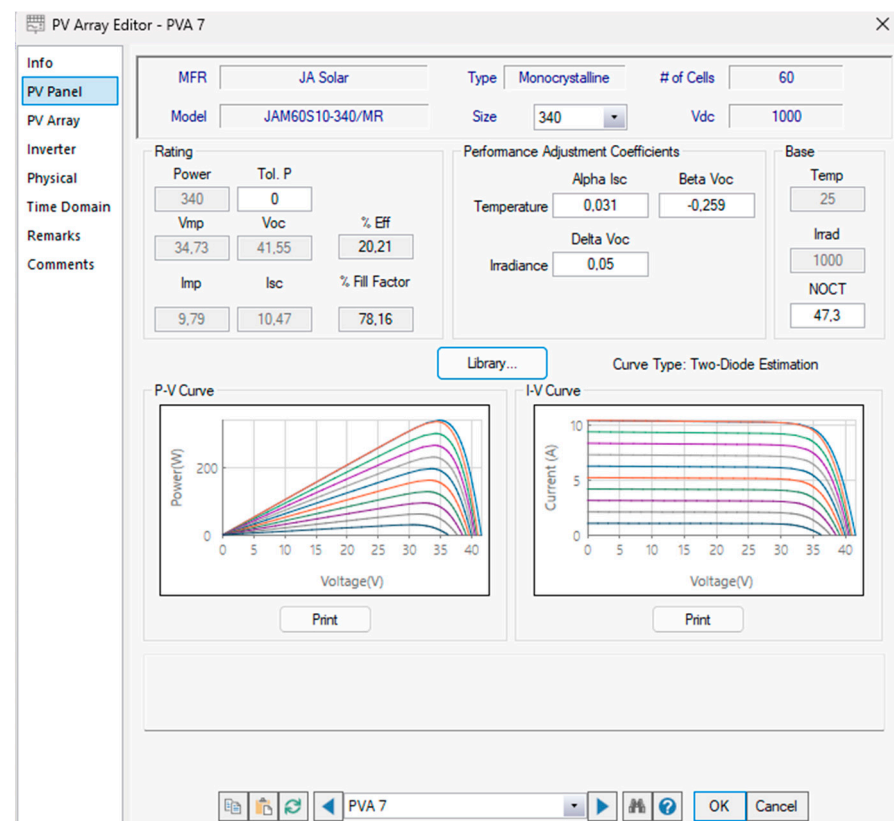
Detailed parameters of the photovoltaic panels (Table 1) and settings in ETAP software (Figure 4) are presented below:

Table 1. Detailed parameters of the photovoltaic panels used in the model. Source: Author's own elaboration.

Parameter	Specification
Model	JAM60S10–340/MR
Nominal Power	340 W
Module Efficiency	20.7%
Cell Type	Monocrystalline
Number of Cells	120 (half-cells)
Dimensions (height/width/thickness)	1689 × 996 × 35 mm
Weight	18.7 kg
Maximum System Voltage	1500 V
Maximum Overcurrent Protection	20 A
Junction Box	IP68, with bypass diodes
Cable Cross-section	4 mm ²
Load Capacity	5400 Pa

Table 1. *Cont.*

Parameter	Specification
Temperature Coefficient of Pmax	−0.35%/°C
Temperature Coefficient of Voc	−0.27%/°C
Temperature Coefficient of Isc	0.048%/°C
Operating Temperature Range	−40 °C to +85 °C
Warranty	12-year product warranty. 25-year performance warranty.
Connector Type	Compatible with MC4

**Figure 4.** ETAP software—settings of the photovoltaic modules used. Source: Author’s own elaboration.

Detailed parameters of the smart string inverters (Table 2) and settings in ETAP software (Figure 5) are presented below:

Table 2. Detailed parameters of the inverters used in the model. Source: Author’s own elaboration.

Parameter	Specification	Specification
Model	SUN2000–60KTL-M0	SUN2000–100KTL-M1
Maximum Input Voltage	1100 V	1100 V
Maximum Current per MPPT	22 A	20 A
Maximum Short Circuit Current per MPPT	30 A	40 A
Starting Voltage	200 V	200 V

Table 2. Cont.

Parameter	Specification	Specification
MPPT Operating Voltage Range	200 V–1000 V	200 V–1000 V
Rated Input Voltage	720 V/480 V, 600 V/400 V	720 V/480 V AC, 600 V/400 V AC, 570 V/380 V AC
Maximum Number of Inputs	12	20
Number of MPP Trackers	6	10
Rated Active AC Power	60 kW	100 kW
Maximum Apparent AC Power	66 kVA	110 kVA
Maximum Active AC Power ($\cos \varphi = 1$)	66 kW	110 kW
Rated Output Voltage	480 V, 3W+PE: 220 V/380 V, 230 V/400 V, 3W+N+PE	480 V/400 V/380 V, 3W+(N)+PE
Rated Output Current	For 480 V–72.7 A and for 400 V–86.7 A	For 480 V–120.3 A, for 400 V–144.4 A and for 380 V–152.0 A
Rated AC Grid Frequency	50 Hz/60 Hz	50 Hz/60 Hz
Maximum Output Current	For 480 V–79.4 A, for 400 V–95.3 A	For 480 V–133.4 A, for 400 V–160.4 A and for 380 V–168.8 A
Adjustable Power Factor	0.8 leading to 0.8 lagging	0.8 leading to 0.8 lagging
Maximum Total Harmonic Distortion	<3%	<3%

To expand the installation by each additional 100 kWp (up to 1 MW), replication of the Huawei SUN2000-100KTL-M1 inverter with connected photovoltaic modules was used. In every used inverter the IT parameter was set as the Earthing Type, which in this case meant isolation terre.

In order to perform the power regulation capacity analysis, specific loads for consumers belonging to the PŚk microgrid were assumed. The research was conducted on a typical day of campus activity, which was 8 May 2024 at 12:30 PM. The analysis is based on these data because this is the time of the week when the campus has the highest number of students attending classes simultaneously, and the photovoltaic installation produces the most power during the midday hours. Consequently, this is the moment when the network may potentially be most burdened by consumption while experiencing maximum energy production.

To conduct the selected analysis, in addition to changing the power of the PV installation (from 500 to 1000 kWp), the power factor ($\cos \varphi$) of the inverter was varied to examine how the network would behave under different operating scenarios of the inverters. For these devices, values were set at -0.9 , -0.8 , 0.8 , 0.9 , and 1 . Consequently, the following tests were conducted, for which results were obtained:

The power factor, $\cos \varphi$, of the network determines the utilization of electrical energy (active power) by the receiving elements relative to the supplied energy (apparent power). When this factor is less than 1 (standard up to a value of 0.85), a situation arises where energy is drawn but not utilized (reactive power). This can lead to many potentially dangerous phenomena, such as the overheating of wires, which is particularly alarming for large industrial plants. The higher the power factor, the better the utilization of electrical energy by the devices to which power is delivered. The power factor thus determines energy efficiency; a low value indicates less efficient use of energy. Reducing the power

factor can affect the level of surcharges and discounts for the power factor, imposed on industrial electricity consumers [25].

The screenshot shows the 'Inverter Editor - Inv16' window in ETAP software. The 'Rating' tab is active. The DC Rating section includes fields for kW (111.1), V (1000), Vmax (110%), Vmin (20%), and FLA (111.1). The Efficiency section has a table for %Load (100, 75, 50, 25) and %Eff. (90, 90, 90, 90), along with Imax (105%). The AC Rating section includes kVA (100), kV (0.4), FLA (144.3), Normal Operating Voltage (Vmin 90%, Vmax 110%), and %PF (100). The AC Grounding section shows Earthing Type set to 'IT - Individual' and 'Distributed Neutral' checked.

Figure 5. ETAP software—settings for the utilized inverter SUN2000-100KTL-M1. Source: Author’s own elaboration.

Therefore, verifying this factor is crucial before commencing work on investments in large photovoltaic installations that may significantly impact the destabilization of network operations or create hazardous conditions.

5. Research Results

Based on the data (Table 3) obtained from the power regulation capacity analysis, graphs were prepared, as shown below. Figure 6 illustrates the change in the behavior of the $\cos\phi$ of the PŚk campus energy network depending on the control of the $\cos\phi$ values on the inverters.

Table 3. Results of the studies for the expanded installation. Source: Author’s own elaboration.

	PV500	PV 600	PV700	PV800	PV900	PV1000
cos phi inverter	cos phi grid					
1	0.992	0.993	0.994	0.987	0.995	0.996
−0.9	0.847	0.848	0.849	0.848	0.847	0.846
0.9	0.905	0.904	0.903	0.903	0.902	0.902
−0.8	0.736	0.734	0.732	0.728	0.724	0.720
0.8	0.803	0.800	0.797	0.795	0.793	0.791

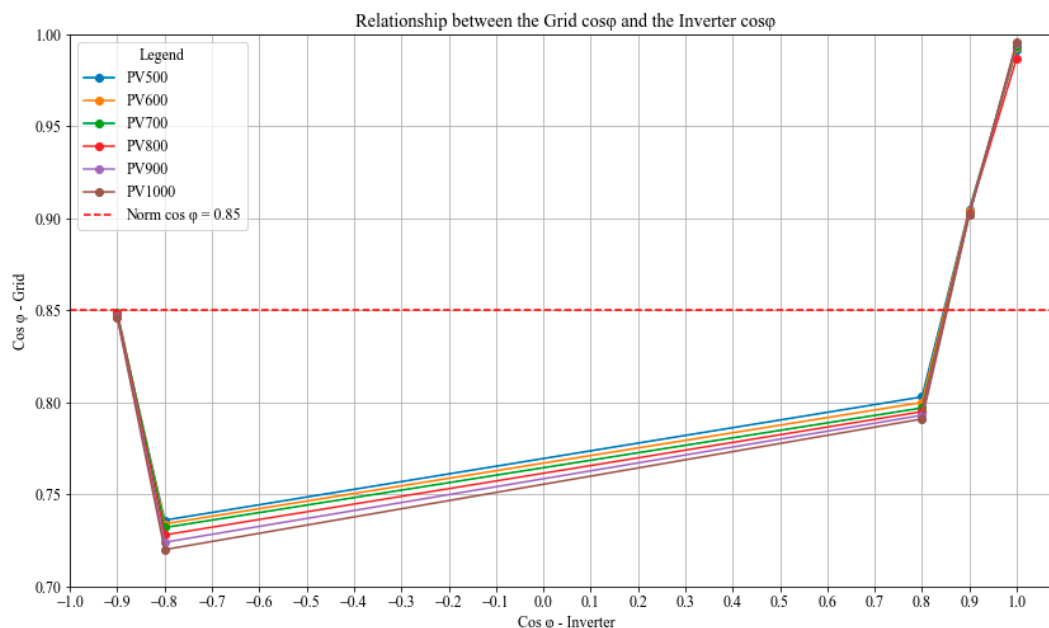


Figure 6. Relationship between the grid $\cos\phi$ and the inverter $\cos\phi$. Source: Author's own elaboration.

Analyzing the results obtained (Figure 6), it can be observed that for each of the tested cases of PV installation power, only three points of network $\cos\phi$ values meet the standard; these are for the inverter $\cos\phi$ settings of -0.9 , 0.9 , and 1 . In cases where inverters are set to $\cos\phi$ values of -0.8 and 0.8 , a drastic drop below the norm is visible, indicating destabilization of the receiving network, which could potentially pose a threat to network operation.

The results of the power regulation capacity analysis indicate the significant impact of the expansion of the photovoltaic installation on the stability of the microgrid's operation. From the conducted simulations, it emerges that for an increase in the power of the PV installation to 1000 kWp, only by setting the power factor $\cos\phi$ to -0.9 , 0.9 , and 1 can the network be maintained within the norms. A drop in the power factor below the norm when setting $\cos\phi$ to -0.8 and 0.8 indicates potential threats of network destabilization, which can lead to overloads and improper functioning of the receiving devices. These results suggest that further expansion of the photovoltaic installation should be preceded by a detailed analysis of the impact on network stability, including potential corrective actions, such as reactive power compensation or the installation of additional energy storage systems.

The results of the conducted studies are consistent with the existing literature, which highlights the need for the precise adjustment of PV installation parameters to the characteristics of the receiving network. Research by Rekioua [22] on the integration of large PV installations in distribution networks also points to the necessity of monitoring the power factor and the possibility of introducing corrective actions. Similar conclusions were formulated in the work by Al-Shetwi et al. [23], where the importance of dynamic analysis when connecting new renewable energy sources was emphasized. In the context of the analyzed PŠk microgrid, the research results confirm these findings, simultaneously highlighting the importance of specific local conditions, such as the characteristics of consumers and load profiles.

The analysis of the power regulation capacity and its impact on microgrid stability, as shown in Figure 6, underscores the critical importance of aligning photovoltaic system expansions with sustainability principles. Ensuring the stability of the microgrid while increasing the installed PV capacity is essential for maintaining a reliable and resilient energy supply. The findings that only specific power factor settings (-0.9 , 0.9 , and 1) keep the network within acceptable operational norms highlight the necessity of precise control and monitoring systems, which are fundamental to sustainable energy management.

From a sustainability perspective, the destabilization risks identified when the power factor deviates from these optimal settings emphasize the need for careful planning and integration of renewable energy sources. Overlooking these risks could lead to inefficiencies, increased wear on infrastructure, and potential outages, which contradict the principles of sustainable development. The results advocate incorporating advanced energy management systems, such as reactive power compensation or the integration of energy storage solutions, to mitigate potential destabilization and ensure that the transition to renewable energy does not compromise grid stability.

These considerations are pivotal as the global energy sector shifts toward greater reliance on renewable sources. Sustainable technology must not only focus on generating clean energy but also on ensuring that the infrastructure supporting the transition is resilient, efficient, and capable of adapting to fluctuations in power generation and consumption. Therefore, the insights gained from the study reinforce the importance of sustainable practices in the design, expansion, and operation of microgrids, ensuring that renewable energy integration is both environmentally responsible and technically sound.

6. Discussion

Analyzing the impact of photovoltaic installations on the operation of microgrids reveals several benefits, including:

- The optimization of system performance: Analysis allows for the optimization of microgrid parameters depending on the installed capacity of the photovoltaic installation. This enables the achievement of maximum efficiency and the reduction of energy losses;
- Increased reliability: Understanding the impact of the photovoltaic installation on the microgrid facilitates the identification of potential problems and their correction, contributing to increased reliability and stability of the system;
- Support for investment decisions: Based on the results of an analysis, better investment decisions related to the expansion or modernization of microgrids can be made;
- Improved energy management: Analysis provides a better understanding of how the power of the photovoltaic installation influences the energy balance of the microgrid, enabling more efficient energy management.

The conducted research demonstrates the impact of expanding an existing photovoltaic installation on network operating conditions. As the designated power of the photovoltaic installation connected to the studied facility increases, the power factor of the network decreases. It remains advisable to maintain the $\cos\varphi$ setting of the inverters at -0.9 , 0.9 , and 1 .

Lowering the power factor carries implications for the enterprise, including the need to use cables with larger cross-sections to ensure appropriate long-term load capacity and the installation of generating and processing devices with higher-rated power. This may necessitate the use of apparatus with higher-rated currents and permissible fault currents, which involves incurring increased investment costs.

Digital twin technology plays a significant role in sustainable development, contributing to the optimal management of electrical energy. It can support improvements in energy efficiency. For facilities interested in integrating RESs with existing infrastructure, digital twin technology enables the identification of potential threats and pinpointing of vulnerabilities in planned ventures.

The application of digital twin technology in the study of the microgrid at Kielce University of Technology fits into the broader context of global efforts for sustainable development. Digital twin technology is becoming a key tool in managing complex energy systems worldwide. In the context of climate change and increasing demand for renewable energy, DT technology can play a significant role in optimizing resource consumption and enhancing energy efficiency, which is essential for achieving the sustainable development goals of RESs. Further research into the use of digital twin technology across diverse sectors has the potential to significantly enhance the sustainability, resilience, and efficiency of urban and industrial systems on a global scale. In particular, extending this model to

encompass additional renewable energy sources, such as wind or geothermal energy, could offer invaluable insights into the development of hybrid microgrid systems. Furthermore, applying this model to diverse institutions or urban campuses with differing infrastructure and geographical constraints would assist in evaluating its adaptability and scalability, thereby facilitating broader implementation and the creation of bespoke energy solutions for specific contexts. Such studies could encourage interdisciplinary collaboration and drive innovations in energy management and digital twin technology.

The findings and technological applications discussed underscore the fundamental role of sustainable technology in the transition toward a more resilient and environmentally friendly energy infrastructure. By enabling precise control and optimization of energy resources, digital twin technology improves operational efficiency and ensures that the expansion of renewable energy sources is conducted in a manner that aligns with sustainability goals. The ability of digital twin technology to provide real-time data and predictive analytics facilitates more informed decision-making, reducing the risk of network instability and minimizing the environmental impact of energy production. This approach aligns with the principles of sustainable development, which advocate for the responsible and efficient use of resources to meet present energy needs without compromising the ability of future generations to meet their own.

Moreover, the integration of digital twin technology in energy systems allows for continuous monitoring and adaptation to changing environmental conditions, which is crucial in the face of climate change. By supporting the development of smart grids and other advanced energy management systems, digital twin technology contributes to a more sustainable energy landscape where renewable sources can be maximized while ensuring grid reliability and efficiency. This technology not only supports the immediate operational needs of microgrids but also fosters long-term sustainability by enabling the scalable and adaptive integration of renewable energy sources, thereby contributing to the global effort to mitigate the impacts of climate change and promote sustainable energy practices.

Supplementary Materials: The following supporting information can be downloaded at: https://drive.google.com/file/d/14gCAb76Fo4RyC0aegh13v6nNNuGDW0lj/view?usp=drive_link (accessed on 15 October 2024). Figure S1: Digital twin of the microgrid structure at Kielce University of Technology.

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