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COMPREHENSIVE STUDY AND EVALUATION METHOD FOR PHOTOVOLTAIC POWER GENERATION SYSTEMS

Theses of PhD Dissertation

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CONTENT

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1. INTRODUCTION

In recent decades, the demand for electricity has increased significantly, this is due to the automation of technologies on the one hand, and the spread of electronic devices serving the comfort of homes on the other. For the sake of sustainability, there is an increasing effort worldwide to generate electricity needs with the help of renewable energy sources. In terms of electricity production, solar energy occupies an important place in the global energy context. Solar systems have become an increasingly important source of energy in recent decades. In recent years, Hungary's energy policy has clearly focused on increasing the proportion of renewable energy sources, including solar systems.

With the tightening of current regulations on solar PV systems, it will be much more important in the future to regulate and control the entire electricity system. Energy security and reliability will continue to be essential, alongside increasing attention to the integration of solar PV systems into the electricity grid. According to the annual data of the Hungarian Energy and Public Utility Regulatory Office (MEKH) for 2022, the share of renewable sources in electricity generation has reached 21.4 percent, with solar energy accounting for the largest share of 61.8 percent [1]. The success of the domestic support scheme has accelerated solar power plant development to such an extent that the planned 2030 solar capacity was already achieved by the end of 2024. However, increasing energy sovereignty and security of supply have created complications for the balance of the electricity system. The Hungarian electricity system has reached its limits of absorption capacity. Therefore, the focus has now shifted to the modernisation and digitalisation of the electricity system.

The other strategic direction is to focus on using as much of the electricity generated locally as possible, in which case energy storage and batteries play a significant role. Solar PV systems with battery storage will become much more important in the future. Their deployment will reduce the load on the grid, as electricity generated and not used during peak hours can be stored locally, thus reducing the losses due to long-distance transmission. Optimally chosen battery capacity can provide improved efficiency for power systems. In addition, batteries increase household self-consumption and autonomy, thereby also contributing to lower energy costs.

In recent years, the dynamic changes in the legislation on the installation of solar PV systems have made the regulations difficult to follow, which has significantly increased uncertainty and mistrust among those interested in using renewable energy. A solar PV system is a significant investment that can place a heavy burden on a family's budget, so it is important to be able to track the associated costs and obligations in a transparent way.

To design the right solar system, it is essential to consider all aspects. When selecting a solar system, the investment cost and the payback period are usually the parameters that are the focus of the analysis. In many cases, these calculations are carried out using a simplified method, which may give an inaccurate result for the characterisation of the solar system, as it does not take into account the changes that have occurred over the years. In order to fully optimise a solar PV system, it is necessary to look not only at the economic side, but also at the security of energy supply and technology side.

The aim of my work was to develop a decision support system that helps to give a comprehensive picture of the transparency of each solar PV system. On this basis, I have set up a triangle model that helps to analyse each solar PV system from the perspective of three disciplinary approaches. The triangle model implements an optimum search procedure.

The process of finding the optimal system for solar PV systems raises a number of issues that need to be considered from several angles. There are several methods available to size and select a solar PV system, but many factors are not considered that may change the outcome of the selection. Taking all these into account, it is advisable to further investigate each system and to check, compare and interpret each context separately. In order to identify the impact and weight of all important and apparently less important factors in the decision-making process, a comprehensive model is therefore necessary.

The structure of my thesis starts with a literature review, in which I detail the types of solar panels. Then, after a brief description of the operating principle of solar cells, I will present the types of solar systems. After the literature review, I will discuss in detail the design of the pillars used in the triangular model. I will then present the application of the triangular model by examining different solar PV systems.

2. DECISION SUPPORT AND DECISION MAKING METHODS

When choosing solar systems, decision-makers usually base their decisions on economic considerations. Return on investment and long-term cost savings are key factors in the choice process. Decisions are not limited to initial costs, but also take into account sustainability aspects that affect the long-term performance of the systems. In the next chapter, I will describe in more detail the triangle model, which integrates security of energy supply, technology assessment and economic analysis. This model allows decision-makers to gain a more comprehensive picture of the evaluation of solar PV systems, taking into account a careful weighing of costs and benefits.

2.1. General structure of the triangle model

The three pillars of the triangular model are security of energy supply, technological studies and economic analysis (Figure 1). In order to gain a deeper understanding of these pillars, I have introduced three sub-pillars aimed at a thorough analysis of the specific characteristics of the systems. The assessment is based on a five-level scoring system [2], which allows each system to be scored '0', '1', '2', '3' or '4' for each sub-point. The 0-4 scale is simple and easy to understand, which helps to make quick and efficient decisions. A 0 is the worst score and a 4 is the best score, providing an objective assessment. The scale provides a scoring system that allows easy comparison of different options.

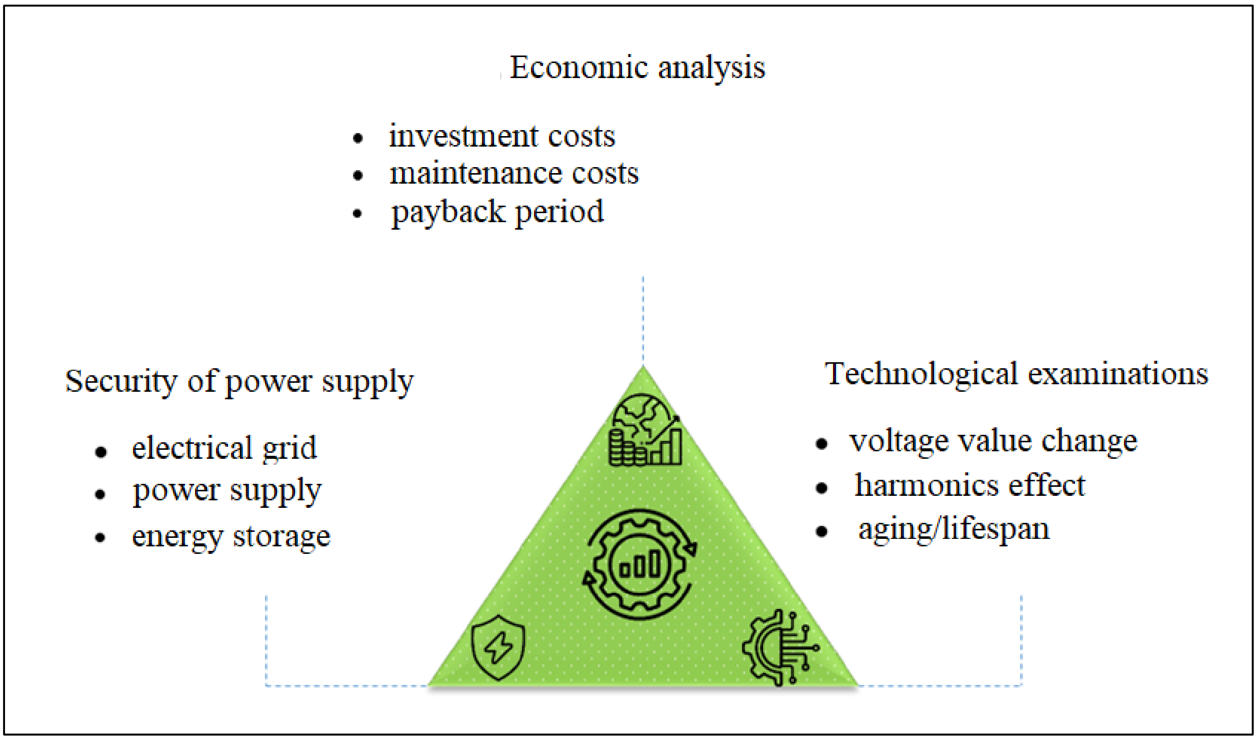


Figure 1. Theoretical structure of the triangle model

This is particularly important because it helps to maintain consistency in the analyses, so that the same principles are applied in all cases. The scale gives enough leeway to detect subtle differences, which helps to identify important differences without over-complicating the system. In the literature to date, I have not found a decision support or decision making method that integrates these pillars simultaneously.

The first pillar is security of energy supply. One of the areas to be examined within this pillar is the electrical grid connection to the solar PV system and other related extensions. The second pillar in this area concerns the loss of power supply. For users, continuity of power supply is not a negligible factor. This point looks at how solar PV systems can diversify energy supply to increase the supply to consumers and, where appropriate, minimise energy losses. The third point under this pillar looks at the energy storage capacity of the system. That is, whether or not the system is capable of storing energy and to what extent.

The second pillar is the technological assessment of solar PV systems. Within this, one of the most important points is the variation of the voltage value. Both a decrease and an increase in this value will have a negative impact on the devices connected to the grid, the solar PV system and the grid itself. The second area under consideration within this pillar is the effect of harmonics, which also has a negative impact on the devices connected to the grid, especially if the harmonics caused by each device also affect each other. The third area is the study of ageing and lifetime.

The third pillar is economic analysis. The installation of solar PV systems has a significant initial cost, but in order to increase the lifetime of these systems, it is also worth paying attention to maintenance. Failure to clean the panels regularly can not only lead to performance degradation, but can also cause permanent damage to the panels in some cases. Taking all this into account, it is worth calculating the payback period for each solar PV system as accurately as possible.

The triangular model takes these areas into account and, based on this, returns a measure of the solar system's characteristics and other user requirements, which helps to make each system comparable. In the following chapters, I provide a thorough explanation of the meaning of each score and the evaluation criteria for each subsection in the detailed analysis. The triangular model is designed to provide a means of objectively comparing and ranking solar PV systems, where a higher overall score clearly indicates a more favourable outcome or a better system.

3. IMPACT OF SOLAR PV ON THE SECURITY OF ENERGY SUPPLY

I will examine the security of energy supply by introducing three further points on solar PV systems. The electricity grid, the energy supply to the consumers and the energy storage capacity of the system [3].

3.1. Electricity network scoring system

I have developed a scoring system based on the condition and distance of the electrical network. The scoring system for the electrical network assessment is shown in Table 1. If the electrical network is suitable to accommodate the solar PV system without any network improvements, it will score the maximum points in the scoring system (4 points). Any necessary interventions will reduce the score depending on the extent of the interventions. The investment cost of the 100 m distance defined in the scoring system (HUF 530 000 for overhead lines and HUF 850 000 for underground cables) is of the same order of magnitude as the specific cost of the solar system.

Table 1. Electricity network scoring system

There is no electrical connection, but there is no need for one in the facility.	0
No electricity connection, the possible connection is more than 100 m from the installation.	1
No connection to the electricity network, the possible connection is less than 100 m from the installation.	2
There is an electrical connection, but upgrading is required (phase number extension, mains and possible extension of protection.	3
There is an electrical connection and no upgrading is required.	4

3.2. Scoring system for energy supply to consumers

Depending on whether consumers require uninterruptible power supply, I have developed a scoring system based on different criteria. Solar PV systems are a good alternative to increase the security of energy supply, as solar PV systems contribute to the diversification of electricity supply, which reduces the exclusive dependence on conventional power generation. The scoring system for the assessment of the energy supply to consumers is presented in Table 2.

Table 2. Scoring system for energy supply to consumers

The electricity supply to the installation is not relevant.	0
There is energy storage, but no grid.	1
There is energy storage, there is grid connection, but in case of grid failure the whole system is shut down.	2
There is energy storage, there is grid connection, but in case of grid failure dedicated consumers can operate.	3
There is energy storage, in the event of a grid failure the whole system can continue to operate.	4

3.3. Scoring system for the energy storage capacity of a solar PV system

Overall, the energy storage capacity of the system is an important part of the electricity supply. In this section, I am not looking at the diversity or the way in which the installation is supplied with energy, but at its extent. There is an important distinction between the following cases. In one case, when a facility's electrical loads can be safely shut down in the event of a power grid outage, a smaller battery capacity is sufficient. The other case is where an outage can still supply electricity to an entire building or dedicated consumers for several hours or, in some cases, a day. In any case, this requires a larger storage capacity. The scoring system for the assessment of the energy storage capacity of the system is presented in Table 3.

Table 3. Scoring system for the energy storage capacity of the system

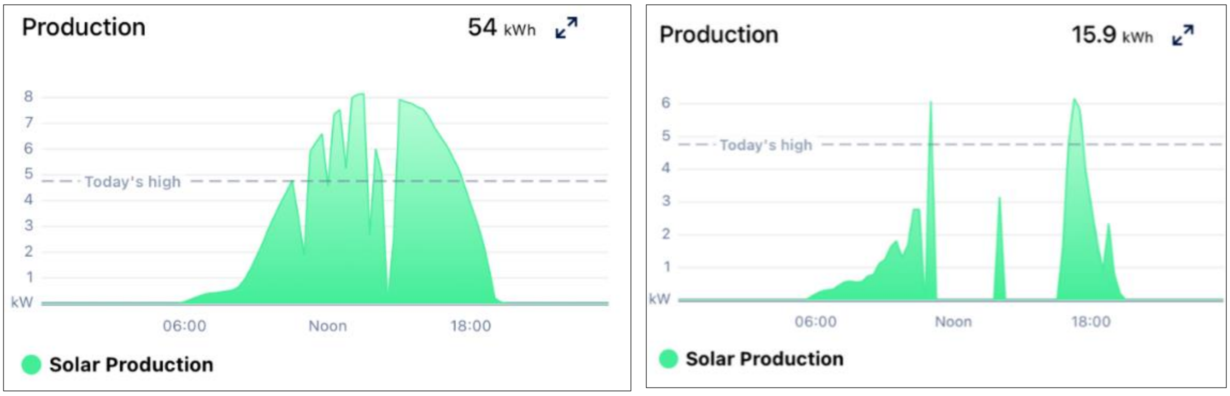
There is no energy storage and it is not necessary.	0
No electricity connection to the grid, but electricity supply can be maintained for 5-10 hours.	1
No grid connection, but electricity supply is maintained for 10-24 hours.	2
There is an electrical grid connection but electricity supply can be maintained for 5-10 hours after the outage.	3
There is a grid connection, but electricity supply can be maintained for 10-24 hours after the outage.	4

4. TECHNOLOGICAL ASSESSMENT OF SOLAR PV SYSTEMS

The first of the three sub-points of the pillar for the technological examination of the triangle model is the change in the voltage value. The second sub-point is harmonic distortion, which is an important power quality issue. The third test point is the aging and service life of the components, as these are decisive for the long-term functionality of solar systems.

4.1. Scoring system related to voltage value change

If the number of solar PV systems on a given section of the grid increases, it can also cause phenomena such that the output voltage of these generating units can increase the grid voltage to such an extent that the inverter operation of some units may be negatively affected. For example, at a time of day when the system should be generating, the inverter will shut down because the grid voltage value falls outside the acceptable (even standard) range.



(a) (b)

Figure 2. (a) Solar PV production under normal operating conditions, (b) loss of production due to voltage rise

This phenomenon is much more pronounced when a solar PV system has no self-consumption at a given time of day, but is in a state of grid-feedback. If the building has self-consumption, be it from any consumer or battery charging, the magnitude of the voltage rise is smaller. The scoring system for the voltage change assessment is given in Table 4. The standard MSZ 447:2019 "Connection to the low voltage public distribution network" allows a voltage variation of +8/-7.5%, so I have taken this as a basis.

Table 4. Scoring system for voltage value variation

Not relevant because there is no network connection.	0
It always causes a voltage rise of over 8% if there is no self-consumption.	1
Always causes a voltage rise but below 8% if there is no self-consumption.	2
If there is no self-consumption in the building, it may cause a voltage increase, but due to the battery capacity connected to the system, it may occur after recharging at a value above 8%.	3
If there is no self-consumption in the building, there is a very small chance (up to 8% max) of voltage rise due to the large battery capacity.	4

4.2. Scoring system for the total harmonic distortion value

There are several methods available to improve the harmonic profile of a solar PV system. One is the use of filters and regulators. These can be passive or active filters or regulators. In addition, the selection and correct adjustment of inverters of the right quality can also help to reduce the harmonics of the system. Proper wiring and earthing will also help to reduce the negative effects of harmonics. Using a battery bank can improve the harmonic profile of the network, depending on the type of inverter. Charging electric cars usually has a negative impact on harmonics, but with fixed battery banks you can improve harmonics depending on the system. The scoring scheme for the total harmonic distortion value is given in Table 5. The THD value cannot be predetermined as it depends on the installation environment. It can be verified by a posteriori measurement. Therefore, the scoring scheme in the table is based on the experience used in the design.

Table 5. Scoring system for the value of Total Harmonic Distortion

Not relevant because there is no network connection	0
Expected to cause high THD (Battery undersized and without filter).	1
Expected to cause moderate THD (Battery oversized and without filter).	2
Expected to cause low THD (Battery undersized and with filter).	3
Expected to cause negligible THD (Battery oversized and filtered).	4

4.3. Life expectancy and ageing

For a solar system, the selection of system components is crucial in terms of lifespan. An inverter, if it is undersized, may spend many operating hours in the upper limit of the working point range during its operation. This can lead to relatively early failure of the inverter. In the case of battery cells, if the sizing basis is not well chosen, it can lead to an early capacity reduction or even destruction of the battery cells. It depends on whether you are under or over sized. If it is undersized, too many charge and discharge cycles will be harmful. If the battery pack is over-sized, continuous "trickle charging" will be dangerous [5, 6, 7, 8, 9]. The scoring system for the aging-related evaluation is contained in Table 6.

Table 6. Scoring system for ageing

Undersized inverter and undersized battery.	0
Undersized battery and optimally sized inverter.	1
Undersized inverter and optimally sized battery.	2
Oversized battery and oversized inverter.	3
Optimally designed system.	4

5. ECONOMIC ANALYSIS OF SOLAR PV SYSTEMS

Solar PV systems, like all investments, have significant costs. The most important and most significant cost is the investment cost, which includes planning, permitting and construction costs. In addition, there are costs for the operation and maintenance of the system, depending on the nature and size of the system. Another important factor is the calculation of the payback period, which is intended to show the extent to which and when the investment will be recovered for the investor from an economic point of view [4, 10, 11].

5.1. Scoring system for investment costs

Each type of solar system has a different design. Depending on the type of system, it will have different requirements from the electricity supplier and different investment costs.

For an island system, there is no authorisation procedure, so the planning and authorisation costs do not apply to this type of system. For an island system, it is the battery installation that adds the significant extra cost compared to a conventional grid-connected solar PV system.

The grid-connected solar PV system will incur the costs of the planning and permitting process listed above. The system is able to feed electricity from unused solar energy back to the grid, which is taken over by the electricity supplier in accordance with the current legal regulations.

Hybrid systems work as a combination of stand-alone and grid-connected systems. Comparing grid-connected and hybrid systems, the hybrid system is also more expensive due to the investment cost of battery cells. Optimal design means design adapted to consumption needs.

Table 7. Scoring system for investment costs

Oversized panels or oversized battery pack	0
Hybrid system with battery farm and panels (with optimum sizing)	1
Island system (with optimal sizing)	2
Hybrid system with panels only (optimum sizing) without battery bank	3
Grid-connected system (with optimal sizing)	4

5.2. Scoring system for maintenance costs

The maintenance and operating costs of solar PV systems are relatively low, but there are some potential costs and cost elements to consider. Regular cleaning of solar panels may be necessary to maintain efficient operation and maximum performance. In addition, for island and hybrid solar PV systems, batteries may require replacement and maintenance costs, especially in the longer term when battery capacity may be reduced. The installation of a solar PV system can increase the value of property insurance. This can also be classified as maintenance and operation costs. If the solar system requires regular monitoring, maintenance or operation costs can be added to the annual budget. This usually applies to larger systems. In addition, if there are administrative tasks related to accounting, this can also add to the annual costs [10]. The scoring system for the assessment of maintenance and operation costs is presented in Table 8.

Table 8. Scoring system for maintenance costs

Annual cleaning, insurance, battery maintenance, system monitoring staff, administrative costs (e.g. accounting)	0
Annual cleaning, insurance, battery maintenance, system monitoring staff	1
Annual cleaning, insurance, battery maintenance	2
Annual cleaning, insurance	3
Annual cleaning	4

5.3. Scoring system related to the elapsed time

The scoring system for the payback period assessment is set out in Table 9. For the payback period calculation, in addition to the score of 0, a negative value has been added to take into account the payback period beyond the lifetime of the solar panel. If the payback period will be longer than 30 years, it will receive -1 point for each additional year in the evaluation. So, for example, 31 years means -1 point, 32 years -2 points, 42 years -12 points in the scoring.

Table 9. Scoring system for payback period

Every year over 30 years means -1 point	-1, -2, -3…-n
Between 26-30 years is the payback period	0
between 21-25 years is the payback period	1
between 16-20 years is the payback period	2
between 11-15 years is the payback period	3
Between 0 and 10 years is the payback period	4

6. INVESTIGATION OF SOLAR SYSTEMS USING THE TRIANGLE MODEL

Using the triangular model, five solar PV systems were investigated. For islanded systems, two different configurations. For grid-connected systems, one configuration operating without a battery installation and two configurations with a battery installation. For the calculations, I used a price of 36 HUF per kWh of electricity. For grid-connected solar PV systems, the ratio of self-consumption to back-generation has a significant impact on the payback period of a solar PV system, as these ratios influence how much electricity needs to be purchased from the grid and how much can be back-charged. In addition, the difference between purchase and feed-in prices is an important factor, as under current regulations the price of feed-in is much lower than the price of grid purchase. Therefore, consumption patterns, in particular efforts to increase self-consumption, have a positive impact on payback periods. In a battery-less 5 kW solar PV system, about 30-40% of the electricity produced by a household can be used directly, as it is only available at the moment of production. If a 5 kWh battery is also installed, the self-consumption can increase to 60-70%, as the energy produced during the day can be used in the evening or at night. And with the installation of a 10 kWh battery, the self-consumption rate can reach 70-80%, significantly reducing the need to buy from the grid [13, 14]. I have based my calculations on the upper bounds of each case. When evaluating real systems, more detailed analyses are needed, as individual consumption patterns alone have a large impact on payback times. To ensure comparability, the analyses should be carried out under uniform boundary conditions.

6.1. Investigation of off-grid solar PV systems

For stand-alone systems, two different configurations were tested. In the first case, a 5 kWp system was fitted with a 5 kWh capacity battery farm. In the second case, I doubled the capacity of the battery farm for the same system to achieve system autonomy. The investment costs of the island systems under study are shown in Table 10 and the return on investment is shown in Table 11. The investment costs for each system element are based on averaging the consumer prices available in December 2023. The island system can operate independently from the electricity grid. Therefore, in the case where the installation is located very far from a potential grid connection point, it provides a suitable solution to supply the building with electricity.

Table 10. Investment costs of the island systems studied

Configuration	Investment items	Comment	Quantity	Unit price (HUF)	Total price (HUF)	Total (HUF)
Offgrid (case 1)	Solar panels	450 Wp/pcs	11	60 000	660 000	2 660 000
	Inverter + Charge Controller	5 kW	1	500 000	500 000	
	Cables, accessories, installation, mounting brackets				600 000	
	Batteries	5 kWh	1	900 000	900 000	
Offgrid (case 2)	Solar panels	450 Wp/pcs	11	60 000	660 000	3 560 000
	Inverter + Charge Controller	5 kW	1	500 000	500 000	
	Cables, accessories, installation, mounting				600 000	
	Batteries	5 kWh	2	900 000	1 800 000	

Table 11. Payback period for the island systems studied

Configuration	Simplified payback	Compaund payback
Offgrid (case 1)	~ 12 years	~ 25 years
Offgrid (case 2)	~ 16 years	~ 31 years

The scoring results of the triangular model for islanded systems are shown in Table 12. Based on this, the first configuration scores 10 points. For the second configuration the overall score was 6. This value is due to the fact that the payback period is very increased due to the investment cost of the batteries (increased to 31 years), this is due to the scoring system not scoring 0 but -1 (in the sense of a payback period of more than 30 years). The battery plant in the second configuration was scaled with double capacity. So, if we want to increase the autonomy of the system by expanding the battery farm, the payback period will increase dramatically. These values can be reduced by including a relevant tender or grant and reducing the investment costs.

Table 12. Scoring results of the triangle model for the tested isolated systems

Category		Offgrid case 1	Offgrid case 2
Security of energy supply	Security of energy supply Electrical network connection and other extensions	0	0
	Energy supply to consumers	0	0
	Energy storage capacity of the system	1	2
	Partial score	1	2
Technological investigations	Voltage change problems	0	0
	Effect of harmonics	0	0
	Lifespan and aging	4	3
	Partial score	4	3
Economic analyses	Investment costs	2	0
	Maintenance and operating costs	2	2
	Payback time	1	-1
	Partial score	5	1
Total score		**10**	**6**

6.2. Examination of a networked system

From the economic side, this type of system received a very good evaluation in all three sub-points, which is understandable from the point of view that apart from the solar panels and the inverter, the system does not contain any other decisive equipment, which would represent a more serious cost compared to other solar systems. However, compared to the offgrid system, the planning and other licensing costs still appear as investment costs. The summary is given in Table 13.

Table 13. The investment costs of the examined grid-connected system

Configuration	Investment items	Comment	Quantity	Unit price (HUF)	Total price (HUF)	Total (HUF)
Ongrid system	Solar panels	450 Wp/db	11	60 000	660 000	2 490 000
	Inverter + Charge Controller	5 kW	1	730 000	730 000	
	Cables, accessories, installation, mounting brackets				1 100 000	

Table 14. The payback time of the investigated networked system

Configuration	Simplified payback	Compaund payback
Ongrid system	~ 11,1 years	~ 25 years

The payback time of the examined grid-connected system is shown in Table 14. It is necessary to note that, based on the compound payback time calculation, the payback time of the system is 25 years. Based on the simplified payback calculation, this value is 11.1 years, which can be said to be quite inaccurate. This can be said for the calculation of all systems, that the simplified return calculation yielded a much smaller value than the complex return calculation.

Table 15. Scoring results of the triangle model for the investigated network-connected system

<table>
<tr><th colspan="2">Category</th><th>Ongrid system</th></tr>
<tr><td rowspan="3">Security of energy supply</td><td>Security of energy supply Electrical network connection and other extensions</td><td>3</td></tr>
<tr><td>Energy supply to consumers</td><td>0</td></tr>
<tr><td>Energy storage capacity of the system</td><td>0</td></tr>
<tr><td colspan="2">Partial score</td><td>3</td></tr>
<tr><td rowspan="3">Technological investigations</td><td>Voltage change problems</td><td>2</td></tr>
<tr><td>Effect of harmonics</td><td>2</td></tr>
<tr><td>Lifespan and aging</td><td>4</td></tr>
<tr><td colspan="2">Partial score</td><td>8</td></tr>
<tr><td rowspan="3">Economic analyses</td><td>Investment costs</td><td>4</td></tr>
<tr><td>Maintenance and operating costs</td><td>3</td></tr>
<tr><td>Payback time</td><td>1</td></tr>
<tr><td colspan="2">Partial score</td><td>8</td></tr>
<tr><td colspan="2">Total score</td><td>19</td></tr>
</table>

From the evaluation of the grid-connected system, it can be seen that in terms of energy supply security, it received a better evaluation than the stand-alone systems, but this system did not achieve a high score in this subsection either. Based on economic analyses, this system proved to be the most economical configuration. Based on the evaluation of the triangle model, this system received 19 points. The summary is given in Table 15.

6.3. Examination of a hybrid solar system

In the case of hybrid systems, I examined two different configurations, similar to the stand-alone systems. In the first case, I connected a battery pack with a capacity of 5 kWh to a 5 kWp system. In the second case, I doubled the capacity of the battery for the same system in order to increase the autonomy of the system, so I tested it with a battery with a capacity of 10 kWh.

Table 16. Investment costs of hybrid systems

Configuration	Investment items	Comment	Quantity	Unit price (HUF)	Total price (HUF)	Total (HUF)
Hibrid (case 1)	Solar panels	450 Wp/db	11	60 000	660 000	3 510 000
	Inverter + Charge Controller	5 kW	1	750 000	750 000	
	Cables, accessories, installation, mounting brackets				1 100 000	
	Batteries	5 kWh	1	1 000 000	1 000 000	
Hibrid (case 2)	Solar panels	450 Wp/db	11	60 000	660 000	4 510 000
	Inverter + Charge Controller	5 kW	1	750 000	750 000	
	Cables, accessories, installation, mounting brackets				1 100 000	
	Batteries	5 kWh	2	1 000 000	2 000 000	

Table 17. Payback time for hybrid systems

Configuration	Simplified payback	Compaund payback
Hibrid (case 1)	~ 15,7 years	~ 29 years
Hibrid (case 2)	~ 20 years	~ 34 years

The investment costs of the tested hybrid solar systems are shown in Table 16, as well as the payback times in Table 17. The compound payback time calculation is 29 years in the first case and 34 years in the second configuration. In this case, I fitted the battery with a double capacity, so the solar system is able to supply the consumers for a longer period of time, due to a possible power outage. However, the payback time of the system is drastically increased, similar to the stand-alone system. These values can be reduced by applying for a grant or grant.

The scoring of the triangle model in the case of hybrid systems is shown in Table 18. Based on this, the first configuration received the highest score, which is 22. However, in the second case, the payback time increased a lot, which increased to 30 years, due to the payback time scoring system, it was not rated 0, but -4, so this hybrid received a total score of solar system received 19 points.

Table 18. Scoring results of the triangle model for the hybrid system under investigation

Category		Hibrid system case1	Hibrid system case 2
Security of energy supply	Security of energy supply Electrical network connection and other extensions	3	3
	Energy supply to consumers	3	3
	Energy storage capacity of the system	3	4
Partial score		9	10
Technological investigations	Voltage change problems	3	3
	Effect of harmonics	3	3
	Lifespan and aging	4	4
Partial score		10	10
Economic analyses	Investment costs	1	1
	Maintenance and operating costs	2	2
	Payback time	0	-4
Partial score		3	-1
Total score		**22**	**19**

6.4. Summary of the investigation of solar systems

6.4.1. Summary of the examined offgrid systems

In the case of stand-alone systems, there is no network connection, which is why several test points are not relevant in the triangle model for these systems. For this reason, it is worthwhile to examine these systems separately and not to compare them with networked systems. Because here the security of the energy supply depends only and exclusively on the solar system. So the facility is much more dependent on itself and cannot cooperate with several other facilities on a network. In the case of the two stand-alone systems, the first configuration received a higher score in the summary, which is 10 points. Although Energy Supply received a lower value in terms of safety, in the case of the second configuration, the payback time increased drastically, so the overall score is 6 points.

6.4.2. Summary of the examined ongrid systems

It is possible to subject the battery-less and the two hybrid systems to a joint analysis, since there will be no irrelevant points in the triangle model due to the network connection, in contrast to the isolated system. In the case of grid-connected systems, it can be observed that the most economical configuration is the one that does not contain a battery, but the energy supply is significantly worse in terms of safety compared to the hybrid solar system. Based on the results, if we examine only the economic side, the hybrid system received a worse evaluation in almost every case, however, if we take into account energy supply security and technological tests, it can be seen that this type of solar system received a higher overall score according to the evaluation of the triangle model . However, it is important to keep the payback period in mind. If the investment and other costs are greatly increased, the payback period increases drastically, which negatively affects sustainability.

7. THESES - NEW SCIENTIFIC RESULTS

T1. **The decision support and assessment method I developed - the so-called triangle model - I determined that in the case of household-sized solar systems, the hybrid system with 5 kWp power and 5 kWh battery capacity achieved a higher overall score compared to the grid-connected system without a battery, so its use is preferable. If we double the capacity of the battery, it will not pay off economically without tender support.**

Background explanation: I developed a decision support evaluation method for the purpose of selecting the optimal solar system that meets consumer needs, which I called the triangle model and I tested its applicability with the help of small household-sized power plants with a power of 5 kWp of various designs. If only the economic aspects are taken into account when choosing the solar system, then the traditional solar system clearly gets the highest value (8 points). If we expand the test with the other two pillars (Energy supply security and Technological tests), in terms of total scores, the 5 kWp hybrid solar system with a 5 kWh capacity battery pack achieves the highest score (22 points). If we choose a 10 kWh battery for the 5 kWp hybrid solar system, the value of the economic analysis is -1 point (due to the payback time) and the total score falls to 19 points.

Own publications related to the T1 thesis: [S1], [S2], [S3], [S5], [S6], [S13]
The related chapters of the dissertation: 3, 4.1.3, 4.2.2, 4.3.2, 5.1.4, 5.2.5, 5.3, 6.1, 6.2, 6.2, 7

T2. **I found that in the case of residential consumers, the optimal battery capacity defined in kWh is between 1 and 3 times the value of a 1 kWp solar system, which can be specified based on individual daily consumption needs (trends).**

Background explanation: Determining the correct battery capacity for hybrid solar systems is a complex task. From the tests carried out, I found that in the case of small power plants for residential use, household-sized, compared to a 1 kWp solar system, the storage capacity of 1 times is not sufficient to meet the consumption needs and to satisfy the storage and retrieval needs. Oversizing from three times the storage capacity upwards is realized in the summer period.

Own publications related to the T2 thesis: [S1], [S6], [S13]
The related chapters of the dissertation: 4.3.1

T3. **I found that local and global power points are formed on the voltage-current and voltage-power characteristic curves for all tested DC faults, with the exception of the rupture fault. With the loss of the number of solar panels, the performance of the system decreases in direct proportion, until the number of failed panels reaches the critical value, which leads to the shutdown of the inverter. The critical value depends on the minimum input voltage value of the inverter.**

Background explanation: In solar systems, certain types of DC-side faults, such as an open fault or any form of short-circuit, can be a fire hazard, these faults (e.g. overshooting) are detected by modern inverters and are immediately switched off, while in the case of non-drastic DC faults, it can be said that they caused production drop problems. The DC-side faults that I examined are open fault, short-circuit fault, ground fault, shielding fault and bypass diode fault. It is clear from the measurements and simulations that the value of the working point on the DC side decreases both in terms of voltage and current, if at least one of the investigated errors occurs.

Own publications related to the T3 thesis: [S7]
The related chapters of the dissertation: 5.1.2

T4. **I found that as the number of errors in the solar cell string increases, the inverter is able to maintain the voltage level required by the network, which is necessary for operation and feeding back to the network, at lower and lower ambient temperatures. As the number of failed/failed panels increases, the inverter's regenerative capacity decreases. After the reduction to the critical panel number, the voltage value required for the operation of the inverter is not available, and therefore it switches to idle state.**

Background explanation: The determination of the optimal number of solar panels connected to the inverter follows from the combination of the nominal power of the inverter in addition to the changes caused by the temperature coefficients. The inverter can be loaded with at least 80% and a maximum of 120% of its nominal power. For the chosen inverter, the minimum number of panels is 16, the nominal is 20, and the maximum is 24. So, if there are 20 panels and 1 falls out, it creates a 25% change on the DC side. That is, the difference between the current and the minimum voltage is reduced by this much. If 2 panels fail, this is already 50%. When 4 panels fail, the voltage drops to the minimum. If the weather warms up, this will further decrease and the inverter will shut down, because it cannot regulate further to ensure that the AC side has the required voltage. All of these are the reasons why nowadays the number of panels is already oversized compared to what is required for the inverter, so only the number of panels between the oversizing and the minimum causes a change.

Own publications related to the T4 thesis: [S4], [S7]
The related chapters of the dissertation: 5.1.3

T5. **I found that with the same level of irradiation, significant differences in the degree of harmonic distortion can occur, especially due to dynamic environmental changes, including cloud migrations, as a result of which the degree of distortion can even exceed the standard limits.**

Background explanation: Inverters produce harmonics during operation. The amount of harmonic production is influenced by environmental influences. In the case of static environmental changes, the intervention of the inverter controls less, thus the harmonic production remains below the standard value, but due to a possible cloud transition, the inverter must be dynamically controlled. Another influencing factor is the ambient temperature and the temperature of the panels. It can be seen from the measurements and simulations that the THD value of the inverter current is affected by different solar radiation levels. While the harmonic distortion value of the measured current ranges between 3-4% in the morning hours, this value rose to 14-16% in the afternoon due to cloud migrations, exceeding the standard limits. In both cases, the irradiation intensity was 350 W/m². These results show that the degree of harmonic distortion is closely related to the environmental factors and the control dynamics of the inverters, even under the same irradiation conditions.

Own publications related to the T5 thesis: [S5], [S13]
The related chapters of the dissertation: 5.2.3., 5.2.4.

T6. **Based on the examinations, I found that the calculation of the payback time has the greatest influencing power within the economic pillar in the triangle model. During the decision-making process, this pillar is of outstanding importance, as it creates the biggest score differences when comparing two different systems. It is essential to use uniform economic calculation methods during the comparison, so that the results are comparable and the decisions remain well-founded.**

Background explanation: The price of electricity has a direct impact on whether an investment pays off economically, while network connection is also a determining factor. If the connection point is located at a greater distance, it significantly increases the costs of the investment, which further affects the payback period of the project. Another important aspect of the economic pillar is whether the investment can be financed from its own resources, or whether it is necessary to use external subsidies or loans. Together, these factors determine whether a project is financially sustainable or not. When comparing different systems, it is essential to use the same economic calculation methods for real comparability. The triangle model takes into account all relevant factors and can handle the zero values that may arise in some cases. If a given factor is not relevant for the given system, the model treats it accordingly, thus ensuring an accurate and balanced analysis.

Own publications related to the T6 thesis: [S1], [S6], [S13]
The related chapters of the dissertation: 6.3, 7.1, 7.2, 7.3, 7.4

8. LIST OF OWN PUBLICATIONS RELATED TO THE RESEARCH AREA

Quality publications related to the dissertation::

[S1] R. Lipták, I. Bodnár, *Optimal sizing of battery storage for photovoltaic systems*, in Proceedings of the 2023 24th International Carpathian Control Conference (ICCC), 2023, pp. 236–241., (**SCOPUS és Web of Science**)

[S2] G. Kozsely, I. Bodnar, D. Matusz-Kalász, R. Lipták, *Determination of Solar Panel's Characteristics by Flash Testing*, 2022 23nd International Carpathian Control Conference (ICCC), pp. 233-238, 2022, (**SCOPUS és Web of Science**)

[S3] I. Bodnár, D. Matusz-Kalász, R.R. Boros, R. Lipták, *Condition Assessment of Solar Modules by Flash Test and Electroluminescence Test*, Coatings, vol. 11, no. 11, 1361, 2021, (**SCOPUS, Q2, IF: 2.881**)

[S4] R. Lipták, I. Bodnár, *Control Problems of Solar Power Plants*, in 22nd International Carpathian Control Conference (ICCC 2021), 2021, pp. 1–5. (**SCOPUS és Web of Science**)

Other publications related to the dissertation::

[S5] R. Lipták, I. Bodnár, *Effects of photovoltaic systems on the behavior of harmonic components in low voltage network*, Analecta Technica Szegedinensia, vol. 2, no. 17, pp. 32–47, 2023.

[S6] R. Lipták, *Comperative analysis of different types of photovoltaic systems from the technical and economic,* in Elektrotechnikai és Elektronikai Szeminárium 2022: konferencia előadások publikációi, 2022, pp. 82–97.

[S7] R. Lipták, I. Bodnár, *Simulation of fault detection in photovoltaic arrays,* Analecta Technica Szegedinensia, vol. 15, no. 2, pp. 31–40, 2021.

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[S12] R. Lipták, I. Bodnár, *Napelemes villamosenergia-termelő rendszerek*, Multidiszciplináris Tudományok: A Miskolci Egyetem Közleménye, vol. 10, no. 4, pp. 434–443, 2020.

[S13] R. Lipták, I. Bodnár, *Analysis of Photovoltaic Systems from Energy Supply Security, Technological and Economic Asp*ects, XXXIX. Kandó Konferencia 2023 Kiadvány kötet , ISBN: 978-963-449-357-0, 2024

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