EXTENDED ABSTRACT OF THE PHD THESIS

Thermo-Ecological Cost assessment for renewable energy systems

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Scientific Discipline: Environmental Engineering, Mining and Energy

Introduction

The purpose of this extended abstract is to provide a concise presentation of the most important content contained in the thesis. The summary includes the following elements:

- scope,
- objectives and theses of the thesis,
- description of the research subject,
- main results and conclusions,
- references to the main publications,
- summary of the author's original contribution.

The PhD thesis was written in English. It was based on a collection of published articles that were thematically related.

Scope

The thesis entitled *Thermo-Ecological Cost Assessment for Renewable Energy Systems* consists of five chapters. Below, the descriptions and scope of each part of the thesis are presented.

Chapter 1 introduces the topic of the thesis by presenting the background, motivation, and theoretical framework. It begins with a discussion of the global energy demand and the increasing importance of renewable energy sources (RES). The chapter then introduces the thermo-ecological cost (TEC) methodology, outlining its definition, balance equations, and practical applications. Energy demand profiles for electricity, heat, and cooling, which serve as the basis for further technical and environmental analysis, are also presented. Finally, the chapter describes the main components of the microgrid, including the photovoltaic (PV) module, solar collector, photovoltaic-thermal (PV/T) module, wind turbine, heat pump, adsorption chiller, and energy storage system.

Chapter 2 presents the first stage of the research conducted within the framework of the thesis. It is based on the article *Thermo-ecological analysis - The comparison of collector and PV to PV/T system*, which constitutes Appendix 1 of the thesis. The chapter outlines the methodology for determining the thermo-ecological cost (TEC) for a PV/T system—a topic previously unexplored in the literature. The study demonstrates the application of the thermo-ecological methodology to evaluate hybrid PV/T technology and compares it with conventional PV systems and solar collectors. Methods for allocating fuel between heat and electricity production are also discussed. Furthermore, the chapter assesses energy efficiency and highlights the environmental benefits of implementing PV/T. These results form the basis for the further integration of the PV/T system into the microgrid model analysed in the subsequent chapters.

Chapter 3 is based on the article *Thermo-ecological analysis of the power system based on renewable energy sources integrated with energy storage system*, which constitutes Appendix 2 of the thesis, and summarizes the second stage of the research. The chapter focuses on the analysis of different configurations of renewable energy sources within a microgrid. The system's performance was evaluated under specific climatic conditions, taking into account the implementation of an energy storage system. The thermo-ecological cost (TEC) indicator was employed for these analyses. Homogeneous and mixed configurations were compared, identifying optimal arrangements in terms of system resilience and environmental performance. The results highlight the benefits of combining complementary energy sources and incorporating energy storage.

Chapter 4 is based on the article *Thermo-ecological assessment of microgrid supported with renewable energy* (Appendix 3). In this chapter, the scope of the analysis of a renewable energy-based multi-generation microgrid is extended to include not only electricity but also usable heat and cooling. Two analytical tools were employed: thermo-economic analysis (TEA), which combines exergy efficiency and cost considerations, and the thermo-ecological cost (TEC), which reflects the environmental burden associated with resource use. The chapter includes an analysis of exergy flows and the variability of system operation on both daily and seasonal timescales. The results demonstrate that TEC more accurately reflects the sustainable nature of multi-generation microgrids (in terms of resource optimization, emission reduction, and system resilience) than TEA.

Chapter 5 presents a summary of the results and conclusions. The role of the thermo-ecological cost (TEC) as a coherent tool for evaluating various renewable energy technologies and microgrid configurations is emphasized. The chapter highlights the advantages of hybrid systems and the importance of seasonal complementarity. It also demonstrates the benefits of energy storage for the resilience and sustainable development of energy systems.

The doctoral dissertation also includes: the list of references cited in the thesis (Bibliography), the abstract in English (Abstract), and the abstract in Polish (Streszczenie).

Objectives and Theses

The main objective of this doctoral thesis was to develop and apply the Thermo-Ecological Cost (TEC) methodology for the assessment of energy systems based on renewable energy sources. To achieve this primary objective, the following specific objectives were defined:

- Determination of the TEC value for a photovoltaic-thermal (PV/T) system. These data were not previously available in the literature, and their determination was crucial for the continuation of further research on the microgrid in which the PV/T system was planned.
- Development of a method for allocating the thermo-ecological cost in hybrid systems such as PV/T.
- Comparison of solar technologies (PV, solar collector, PV/T) in terms of their thermo-ecological cost and consumption of non-renewable resources.
- Simulation and analysis of a microgrid based on multiple renewable energy sources integrated with an energy storage system.
- Determination of TEC values for a microgrid producing electricity, heat, and cooling.
- Identification of optimal energy mix configurations for the microgrid that minimize the thermo-ecological cost and maximize independence from the external grid.
- Indication of the environmental and resource-related benefits resulting from the integration of various renewable energy sources and energy storage technologies.

Description of the research subject

The subject of the research was a microgrid based on renewable energy sources (RES). The system incorporated the following technologies:

- wind turbines,
- solar technologies, i.e., photovoltaic (PV) panels, hybrid photovoltaic-thermal (PV/T) modules, and solar collectors,
- cogeneration engine (CHP engine) powered by biogas produced in the biogas plant,
- heat pumps (ground-source and air-source),
- an energy storage system (electrolyser, hydrogen storage, and fuel cells).

The analysed microgrid is a trigeneration system, encompassing sources of electricity, heat, and cooling. Energy storage was implemented to enable the longest possible autonomous operation of the system, while the diversity of energy sources aims to reduce dependence on a single weather variable. The operational scheme of the analysed microgrid is shown in Figure 1.

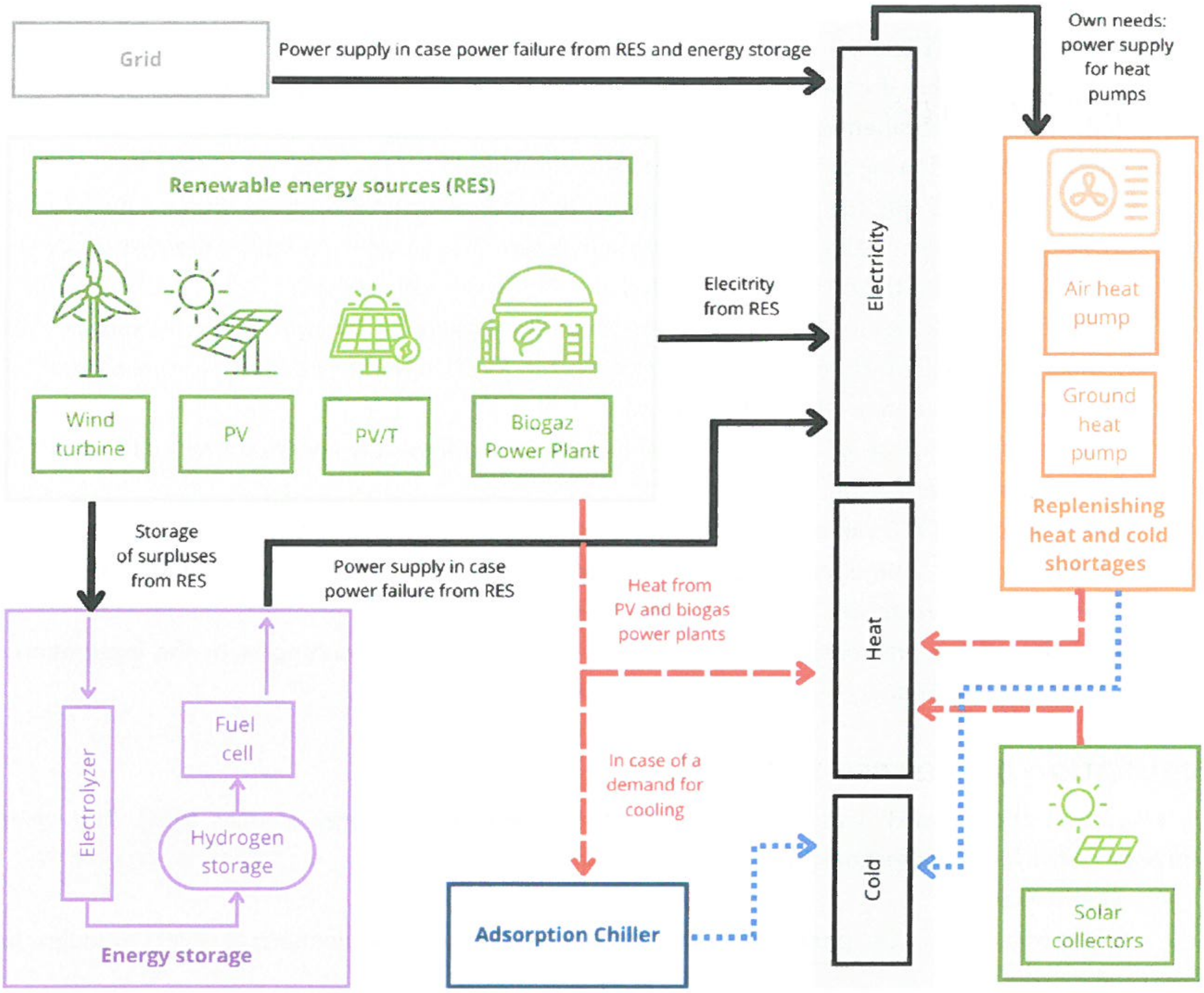

Figure 1. Operational scheme of the microgrid

In the microgrid, electricity is generated by the wind turbine, photovoltaic (PV) panels, PV/T modules, and a biogas-fuelled cogeneration unit (biogas plant). Electricity from renewable energy sources (RES) is primarily used to meet the current demand of end-users. Any surplus electricity generated by RES is directed to the energy storage system, which consists of an electrolyser, hydrogen storage, and a fuel cell. When renewable energy sources do not meet the current demand of the microgrid, electricity is drawn from the storage system. If this is insufficient and the current consumption exceeds the combined production from RES and available storage, electricity is drawn from the external grid.

Heat is also produced within the system. It originates from the PV/T system and the biogas plant. The system additionally includes solar collectors, which provide domestic hot water, primarily during the summer months. Heat from the PV/T system and the biogas plant can also be used for cooling purposes through the application of adsorption chillers.

In cases where the amount of heat generated within the system does not meet the current demand, heat pumps (air-source and ground-source) are utilized. Their implementation allows for the compensation of both heat and cooling deficits. The operation of individual system components was simulated based on actual weather conditions characteristic of Katowice, Poland. Figure 2 presents the exergy flows in the analysed system.

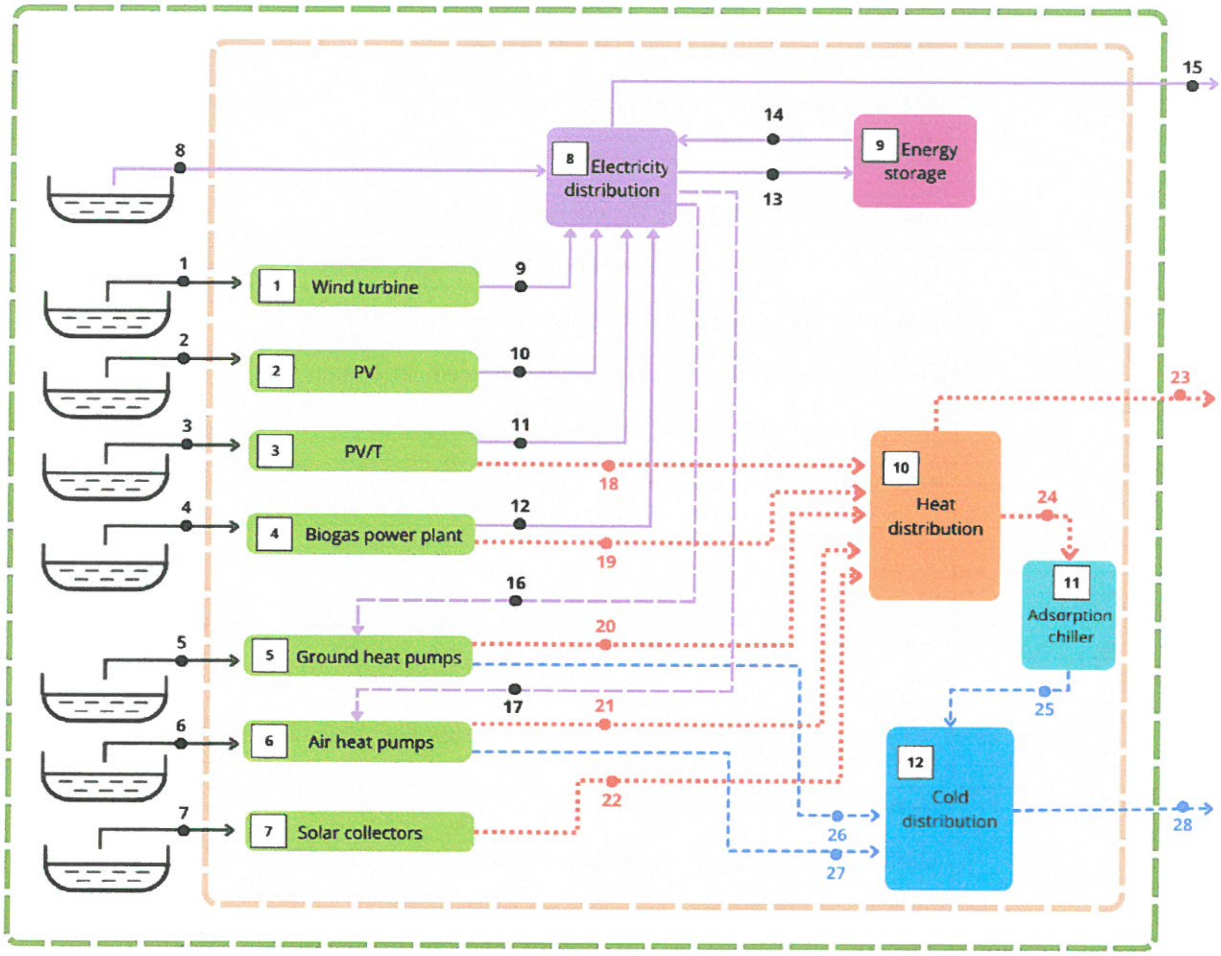

Figure 2. Exergy flows in the analysed system

Flows 1–8 represent the exergy supplied from outside the system, including wind energy, solar radiation for PV panels and PV/T modules, chemical exergy for biogas production in the cogeneration unit (CHP engine), ground and air heat for the heat pumps, solar radiation for the collectors, and electricity from the external grid in case of a deficit. These flows are directed to the corresponding components of the microgrid. The notation and description of all exergy flows are presented in Table 1.

Table 1. Symbols and description of exergy flows in the analysed system

Flow	Description
$\dot{B}_1$	wind energy used for generation in the wind turbine
$\dot{B}_2$	solar radiation flow used for electricity production by PV panels
$\dot{B}_3$	solar radiation flow used for electricity production by the hybrid PV/T module,
$\dot{B}_4$	chemical energy used to generate biogas and subsequently heat and electricity in the CHP engine
$\dot{B}_5$	ground heat used in the ground-source heat pump
$\dot{B}_6$	atmospheric air heat used in the air-source heat pump
$\dot{B}_7$	solar radiation flow used for heat production by the collector
$\dot{B}_8$	electrical energy flow from the external grid (supplied to the system in case of shortage
$\dot{B}_9$	electrical energy generated by the wind turbine,

Flow	Description
$\dot{B}_{10}$	electrical energy generated by the PV system
$\dot{B}_{11}$	electrical energy generated by the PV/T system
$\dot{B}_{12}$	electrical energy generated by the biogas-powered CHP
$\dot{B}_{13}$	electrical energy supplying the energy storage system,
$\dot{B}_{14}$	electrical energy generated by the energy storage system.
$\dot{B}_{15}$	electrical energy supplied to end consumers
$\dot{B}_{16}$	electrical energy supplying the ground-source heat pump
$\dot{B}_{17}$	electrical energy supplying the air-source heat pump
$\dot{B}_{18}$	heat from the PV/T module
$\dot{B}_{19}$	heat from the biogas-powered CHP engine
$\dot{B}_{20}$	heat from the ground-source heat pump
$\dot{B}_{21}$	heat from the air-source heat pump
$\dot{B}_{22}$	heat from the solar collectors
$\dot{B}_{23}$	heat is directed to end users
$\dot{B}_{24}$	heat is directed to adsorption chiller
$\dot{B}_{25}$	useful cooling from the adsorption chiller,
$\dot{B}_{26}$	useful cooling from the ground-source heat pump
$\dot{B}_{27}$	useful cooling from the air-source heat pump

In the analysed system, each component corresponds to specific fuel and product flows. This allows for a detailed analysis of exergy flows and the identification of energy loss points and potential optimization opportunities. The outgoing flows from individual components are subsequently directed to the electricity, heat, or cooling distribution systems. All relationships between the flows are presented in Table 2.

Table 2. Fuel and product equations for the system components

No.	Component	Fuel	Product
1	Wind turbine	$F_1 = \dot{B}_1$	$P_1 = \dot{B}_9$
2	PV	$F_2 = \dot{B}_2$	$P_2 = \dot{B}_{10}$
3	PV/T	$F_3 = \dot{B}_3$	$P_1 = \dot{B}_{11} + \dot{B}_{18}$
4	Biogas plant with CHP engine	$F_4 = \dot{B}_4$	$P_3 = \dot{B}_{12} + \dot{B}_{19}$
5	Ground-source heat pump	$F_5 = \dot{B}_5 + \dot{B}_{16}$	$P_5 = \dot{B}_{20} + \dot{B}_{26}$
6	Air-source heat pump	$F_6 = \dot{B}_6 + \dot{B}_{17}$	$P_6 = \dot{B}_{21} + \dot{B}_{37}$
7	Solar collector	$F_7 = \dot{B}_7$	$P_7 = \dot{B}_{32}$

No.	Component	Fuel	Product
8	Electrical energy distribution	$F_8 = \dot{B}_8 + \dot{B}_9 + \dot{B}_{10} + \dot{B}_{11} + \dot{B}_{12} + \dot{B}_{14}$	$P_8 = \dot{B}_{13} + \dot{B}_{15} + \dot{B}_{16} + \dot{B}_{17}$
9	Energy storage	$F_9 = \dot{B}_{13}$	$P_9 = \dot{B}_{14}$
10	Heat distribution	$F_{10} = \dot{B}_{18} + \dot{B}_{19} + \dot{B}_{20} + \dot{B}_{21} + \dot{B}_{22}$	$P_{10} = \dot{B}_{23} + \dot{B}_{24}$
11	Adsorption chiller	$F_{11} = \dot{B}_{25}$	$P_{11} = \dot{B}_{21}$
12	Cooling distribution	$F_{12} = \dot{B}_{25} + \dot{B}_{26} + \dot{B}_{27}$	$P_{12} = \dot{B}_{28}$

For the system analysis, the thermo-ecological cost (TEC) was selected as the primary assessment tool. TEC corresponds to the cumulative consumption of non-renewable exergy required to produce a given product. The TEC analysis also accounts for the exergy required to compensate for environmental damages resulting from the emission of harmful substances (waste). Figure 3 illustrates the concept of the thermo-ecological cost (TEC) balance.

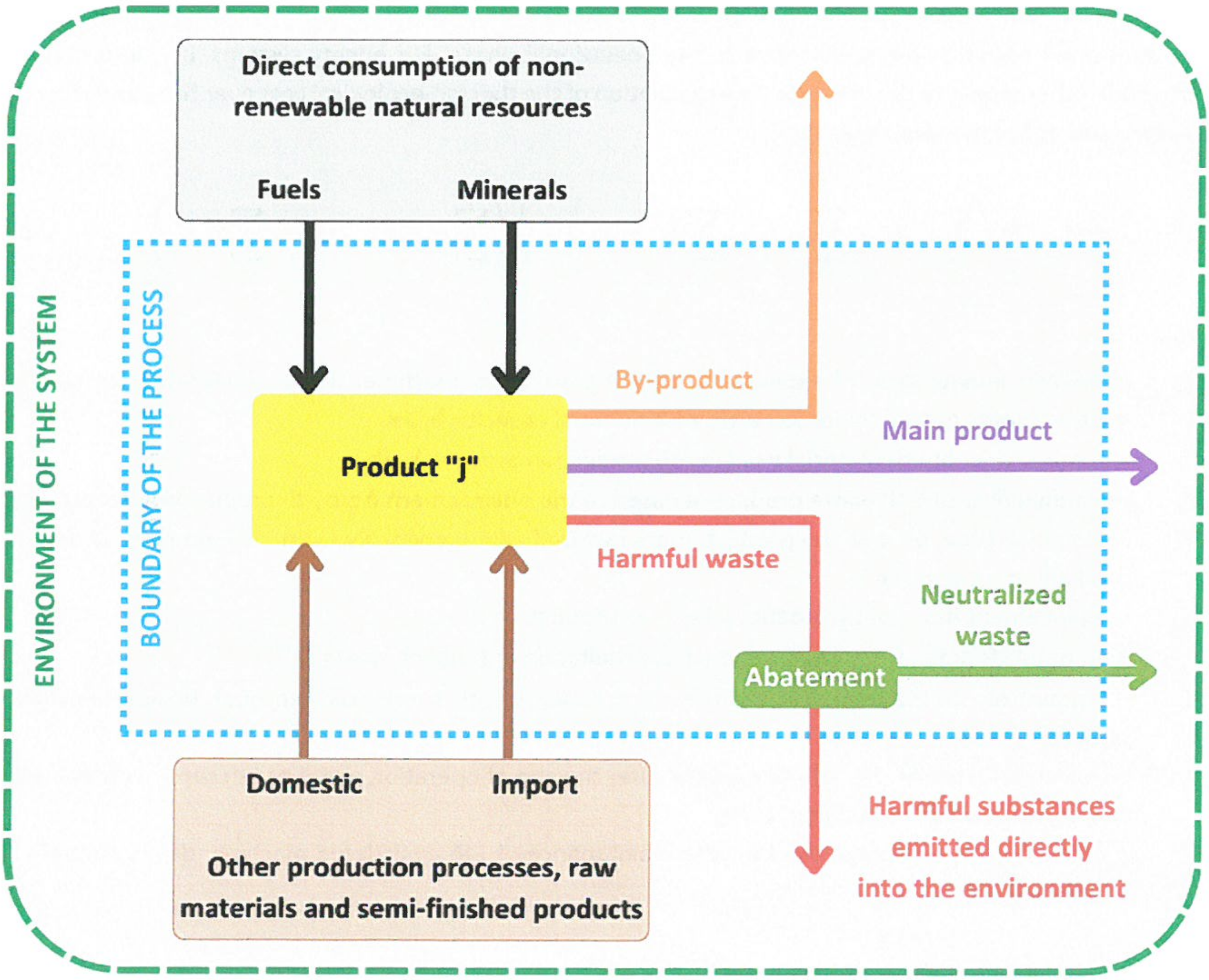

Figure 3. Schematic representation of the TEC balance equation

The specific Thermo-Ecological cost can therefore be defined as the sum of the three terms in equation (1). The first term of the equation refers to the non-renewable exergy of natural resources directly consumed in the process b_{sj}. The second term accounts for the thermo-ecological cost of harmful substances ζ_k generated during the process. Both of these elements contribute to an increase in the TEC value. The third term, associated with by-products i f_{ij} can reduce the operational TEC indicator ρ_i or increase it when the consumption of the i-th material per unit of the j-th main product is significant.

$$\rho_j = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k - \sum_i (f_{ij} - a_{ij})\rho_i \tag{1}$$

Where:

b_{sj} – exergy of s-th non-renewable natural resource immediately consumed in the process under consideration per unit of j-th product, MJ/kg,

ζ_k – Thermo-Ecological cost of k-th harmful substance, MJ/kg,

p_{kj} – amount of k-th harmful substance from j-th process, kg,

f_{ij} – coefficient of by-production of i-th product per unit of j-th main product, e.g. in kg/kg or kg/MJ,

a_{ij} – coefficient of consumption of i-th material per unit of j-th main product, e.g. in kg/kg or kg/MJ,

ρ_i – specific Thermo-Ecological cost of i-th product, e.g. in MJ/kg.

The presented equation primarily refers to the operational phase. For energy systems, it is also essential to include other stages of the life cycle. The calculation of the thermo-ecological cost over the entire life cycle is expressed as follows (equation 2).

$$\rho_j^{LCA} = \theta_n \left(\sum_i \dot{G}_i \rho_i + \sum_k \dot{P}_k \zeta_k - \sum_u \dot{G}_u \, \rho_j s_{ju} \right) + \frac{1}{\tau_j} \left(\sum_l G_l \rho_l \,(1 - u_l) + \sum_r G_r \rho_r \right) \tag{2}$$

Where:

θ_n – average annual time of exploitation of j-th considered machine, device, installation or building, in other words annual operation time with nominal capacity, h/year,

$\dot{G}_i$ – nominal flow of i-th material used in j-th production process, kg/h,

$\dot{P}_k$ – nominal flow of k-th waste product released to the environment from j-th production process, kg/h,

$\dot{G}_u$ – nominal flow of u-th by-product manufactured simultaneously with j-th product within the production process, kg/h,

s_{ju} – replacement index of by-product u by main product,

τ_j – nominal lifetime of j-th machine, device, installation or building, years,

G_l – amount of i-th material used for the construction of j-th considered machine, device, installation or building, kg,

u_l – expected recovery rates of i-th material after the end of operation phase of j-th considered machine, device, installation or building, kg/kg,

G_r – amount of r-th material used for the maintenance of j-th considered machine, device, installation or building, kg.

Main results

This chapter presents the main results of the conducted research, divided into specific stages. In the first part, solar systems were analysed. A literature review revealed a research gap concerning the lack of thermo-ecological cost (TEC) values for photovoltaic/thermal (PV/T) systems. The PV/T module is a hybrid device that simultaneously produces electricity and heat from solar radiation. As part of the study, a comparison was also made with other solar technologies: a photovoltaic (PV) module and a solar collector. The simulation results indicated that the annual energy production from the PV/T module amounts to 267.07 kWh, which is approximately 1.5 times higher than the yield from the PV system. Figure 4 presents the monthly electricity production from the PV/T and PV systems.

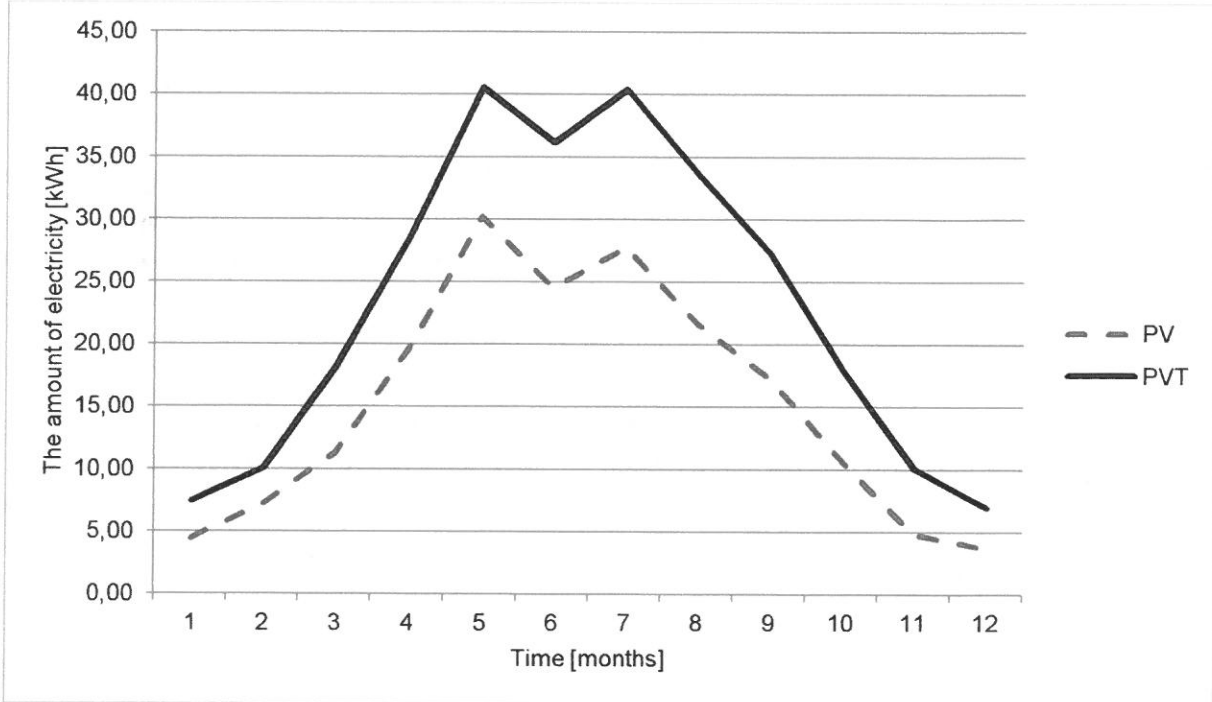

Figure 4. Electricity from PV/T and PV by months

When analysing heat generation, it was observed that in this case the solar collector achieved a higher yield than the PV/T module. The solar collector produced 2191.49 kWh of heat annually, while the PV/T system generated 540.84 kWh.

Subsequently, the thermo-ecological cost (TEC) for the PV/T model was calculated. The analysis included the exergy of materials used both for the construction of the collector and for the additional equipment. The calculations also accounted for the operational lifetime of the installation as well as the potential recovery of materials after decommissioning. The obtained TEC value for the PV/T system was 0.253 [MJ/MJ].

Due to cogeneration — the simultaneous production of electricity and heat by the PV/T module — the computational algorithm also considered the allocation of thermo-ecological costs. Two approaches to fuel allocation between heat and electricity production were proposed:

- The first approach was based on the exergetic cost, defined as the total exergy consumption associated with the generation of a useful product. Based on the specific TEC of the PV/T system,

it was possible to determine what portion of solar energy was assigned to heat and electricity production, respectively.
- The second approach employed the thermo-ecological cost (TEC) method, using proportional TEC indicators for conventional (substitute) technologies.

Table 3 presents the results of the calculations. The thermo-ecological cost of electricity in the PV/T system equals 0.153 (first allocation) or 0.193 (second allocation), which is lower than for a conventional PV system (0.26) and significantly lower than for coal-based systems — for coal-fired power plants, the corresponding value is 4.39.

Table 3. Thermo-Ecological Cost (TEC) Analysis of the PV/T System.

TEC [MJ/MJ]	First Allocation	First Allocation
Thermo-ecological cost of electricity	0.153	0.193
Thermo-ecological cost of useful heat	0.100	0.060

In the subsequent part of the study, representative days for the four seasons—spring, summer, autumn, and winter—were analysed. The aim was to observe seasonal variations in the TEC values for the PV/T system and to examine how the proposed thermo-ecological cost allocation methods respond to different levels of electricity and heat production. It was observed that, in the second allocation approach, TEC values exhibited greater stability and were closer to the annual average than in the first allocation.

In the second phase of the research, various renewable energy mixes were simulated and analysed. The objective was to determine the optimal configuration of cooperating renewable energy sources within the microgrid. The analysis also incorporated an energy storage system, evaluating its integration potential under different renewable mix scenarios. The performance of each renewable source and the storage system was assessed based on hourly data.

An example of the results is presented below. Figure 5 illustrates a summer day characterized by high renewable energy generation. During periods of partial mismatch between energy demand and renewable energy supply (e.g., in the morning or afternoon), the deficit was compensated by the energy storage system. These results were obtained for a scenario including four simultaneously operating renewable sources: a 4.0 MW wind turbine, 4.0 MW PV/T, 4.0 MW PV, and a 3.0 MW biogas unit.

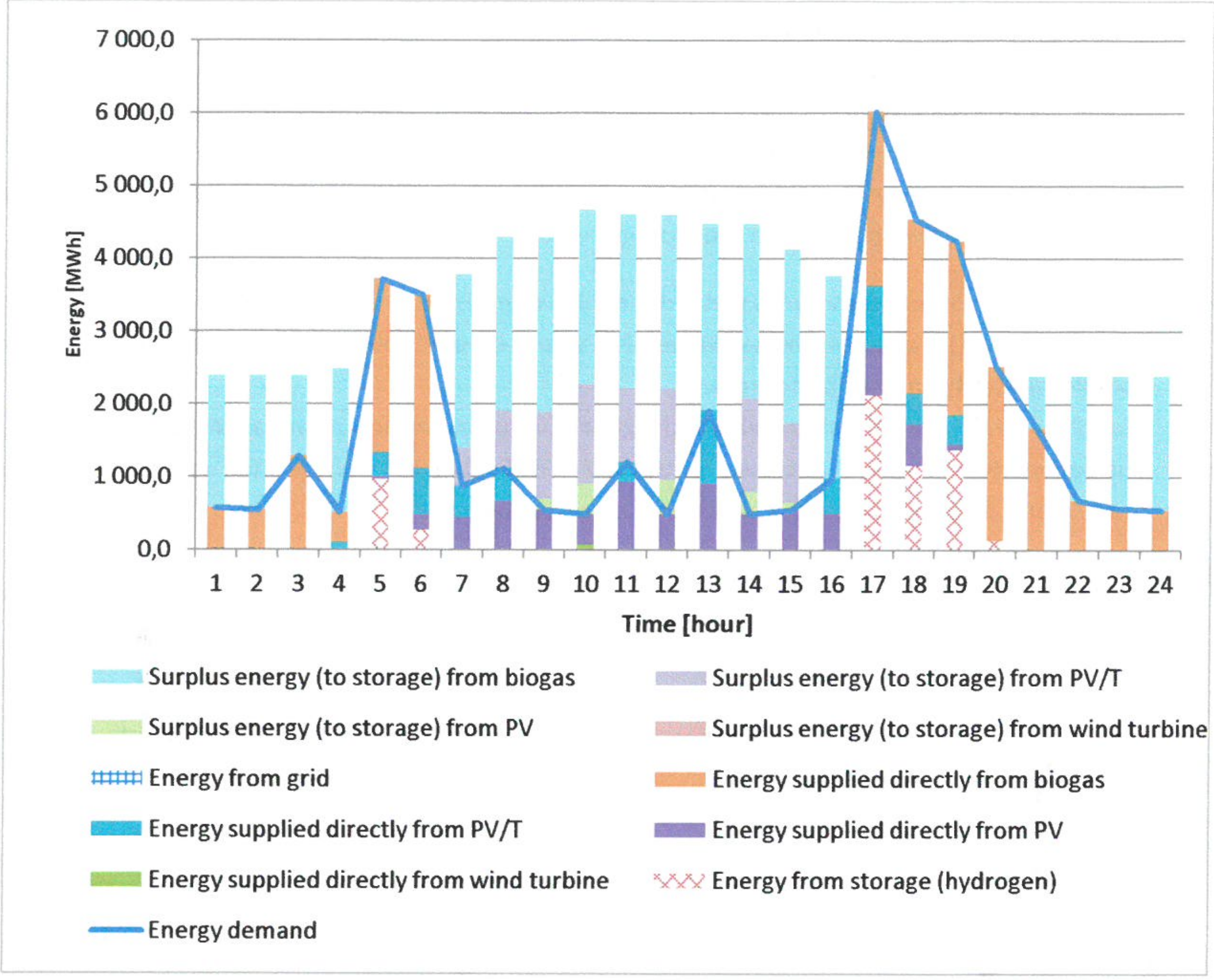

Figure 5. Hourly consumption and generation for a summer day with high renewable generation.

The analysis included various configurations of renewable energy source (RES) mixes. In the first step, a microgrid based on a single type of RES was analysed, followed by combinations of two, three, or four types of sources. The nominal capacity of each system was 15 MW for all analyses.

For single-source RES systems, characteristic features of each energy source were observed. This information was then used to construct more complex mixes. In two-source mixes (e.g., PV/T + wind or biogas + PV/T), an improvement in seasonal complementarity was observed. The PV/T + biogas system was able to meet demand almost throughout the year, with minimal reliance on the external grid. Adding a third source further improved system performance. Three-source systems (e.g., PV + PV/T + biogas or PV/T + wind + biogas) demonstrated even greater resilience, although deficits still occurred during winter when storage capacity was insufficient. The best results were achieved in the four-source configuration. The system comprising PV, PV/T, a wind turbine, and biogas provided the most favourable outcome. Grid supply was only necessary at the beginning and end of the winter season.

For a more in-depth analysis, the thermo-ecological cost (TEC) was applied. A system based solely on PV panels exhibited the lowest TEC values in summer, reflecting high renewable energy production and efficient use of energy storage. A similar seasonal pattern was observed for PV/T, but with an even lower TEC in summer due to the higher system efficiency. In the wind-based system, TEC values remained relatively high throughout the year, with a local minimum in March when wind conditions were most favourable. In contrast, the biogas system achieved the lowest annual TEC, as it provided the most stable energy supply conditions.

In the second stage, two-source systems were analysed, and the following results were obtained:

- The "PV/T + wind" configuration exhibited relatively high TEC values due to frequent reliance on the external grid, improving only during summer peaks in PV/T production.
- In the "PV/T + biogas" mix, TEC gradually decreased with an increasing share of RES and more effective use of the energy storage system.
- The "wind + biogas" system achieved the lowest TEC values in summer and maintained favourable performance in autumn thanks to the storage system.

The analysis of three cooperating sources yielded the following results:

- The "wind + PV/T + biogas" mix maintained TEC values below 1 for most of the year, indicating strong complementarity among the sources.
- The "PV + PV/T + wind" system exhibited higher TEC due to continuous reliance on the external grid.
- The best performance was obtained for the "PV + PV/T + biogas" mix, with TEC values below 1 for 11 months and dropping below 0.2 between May and November.

The final stage involved a four-source renewable energy mix, which is presented in Figure 6.

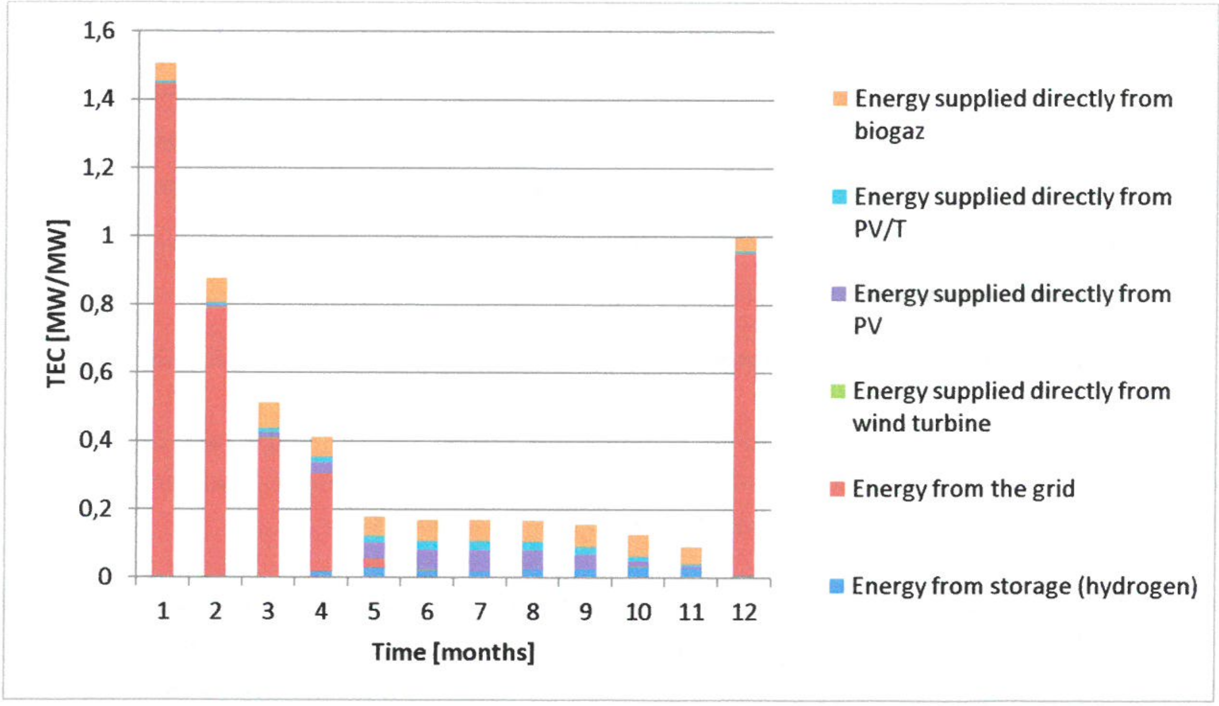

Figure 6. Thermo-Ecological Cost (TEC) – energy production based on four renewable energy sources (4.0 MW wind turbine, 4.0 MW PV/T, 4.0 MW PV, and 3.0 MW biogas).

The configuration based on four types of RES (PV, PV/T, wind, and biogas) exhibited consistently low TEC values throughout the year. Only in January did TEC exceed 1.5, reflecting significant energy imports from the external grid during low RES production and insufficient stored hydrogen. In December, TEC increased close to 1 due to depletion of the storage system and the lack of excess energy to replenish the hydrogen reserves.

Further studies included an analysis of 28 exergy flows. Among these, eight flows represent inputs to the system, while three correspond to the output flows of electricity, heat, and cooling supplied to end-users. The flows were described in the "Description of the Research Subject" section of this extended abstract.

The conducted analysis allowed for the representation of the system status in terms of exergy flow values for each hour of the year. Table 4 presents a sample dataset for a representative hour (April 3, 8:00 AM). The table illustrates how exergy flows are managed at this specific time, reflecting both production and consumption within the microgrid. These results are important for understanding the balance between renewable energy generation, storage, and the fulfilment of demand.

Table 4. Exergy flows.

Name	Fuel	Product	Exergetic efficiency	System irreversibility	Exergetic cost	Thermo-ecological cost (TEC)
Skrót	**F**	**P**	**η_B**	**I**	**k***	**(TEC)**
Unit	kW	kW	-	kW	-	-
			Electricity			
PV	13 233.2	1 621.5	0.1	11 611.8	8.2	0.3
PV/T	13 233.2	2 082.7	0.2	11 150.6	6.4	0.2
Wind turbine	36 087.6	10 465.4	0.3	25 622.2	3.4	0.1
Biogas CHP plant	1 459.1	830.6	0.6	628.5	1.8	0.7
Gird (Polish grid energy mix)	0.0	0.0	-	-	-	-
Energy Storage (from ES)	0.0	0.0	-	-	-	-
Energy Storage (into ES)	9 328.1	7 531.5	0.8	1 796.6	1.2	0.1
			Heat			
PV/T	0.0	0.0	-	-	-	-
Solar collector	1 320.0	209.2	0.2	1 110.9	6.3	0.6
Biogas CHP plant	505.3	305.5	0.6	199.8	1.7	0.3
Air heat pump	2 559.6	486.9	0.2	2 072.7	5.3	4.0
Ground heat pump	1 424.4	445.4	0.3	979.0	3.2	2.4
			Cold			
Adsorption Chiller	0.0	0.0	-	-	-	-
Air heat pump	0.0	0.0	-	-	-	-
Ground heat pump	0.0	0.0	-	-	-	-

Representative hours throughout the year were selected for the analysis. The selection considered the following factors:

- Seasonal variations in energy production – differences in electricity, heat, and cooling generation depending on the time of year.
- Daily fluctuations in production – variability in, for example, solar irradiance and wind speed throughout the day.
- Seasonal differences in energy demand – changes in electricity, heat, and cooling requirements depending on the month and time of day.
- Balance between production and consumption – the possibility to observe energy surpluses or deficits within the system.

One of the analysed cases was April 3 at 8:00 AM. At this time of year, the main source of electricity was the wind turbine. The system generated a surplus of electricity, which was directed to the energy storage system. Heat production was primarily provided by the biogas-fuelled cogeneration unit. Heat deficits were compensated by the output of heat pumps and solar collectors. During this period, there was no cooling demand, so no useful cooling flows were recorded. Figure 7 shows the exergy values for the analysed hour, while Figure 8 presents the exergy flows entering and leaving the system. It can be observed that, at this time of year, the system was storing energy: the total incoming exergy significantly exceeded the outgoing flows, resulting in energy storage.

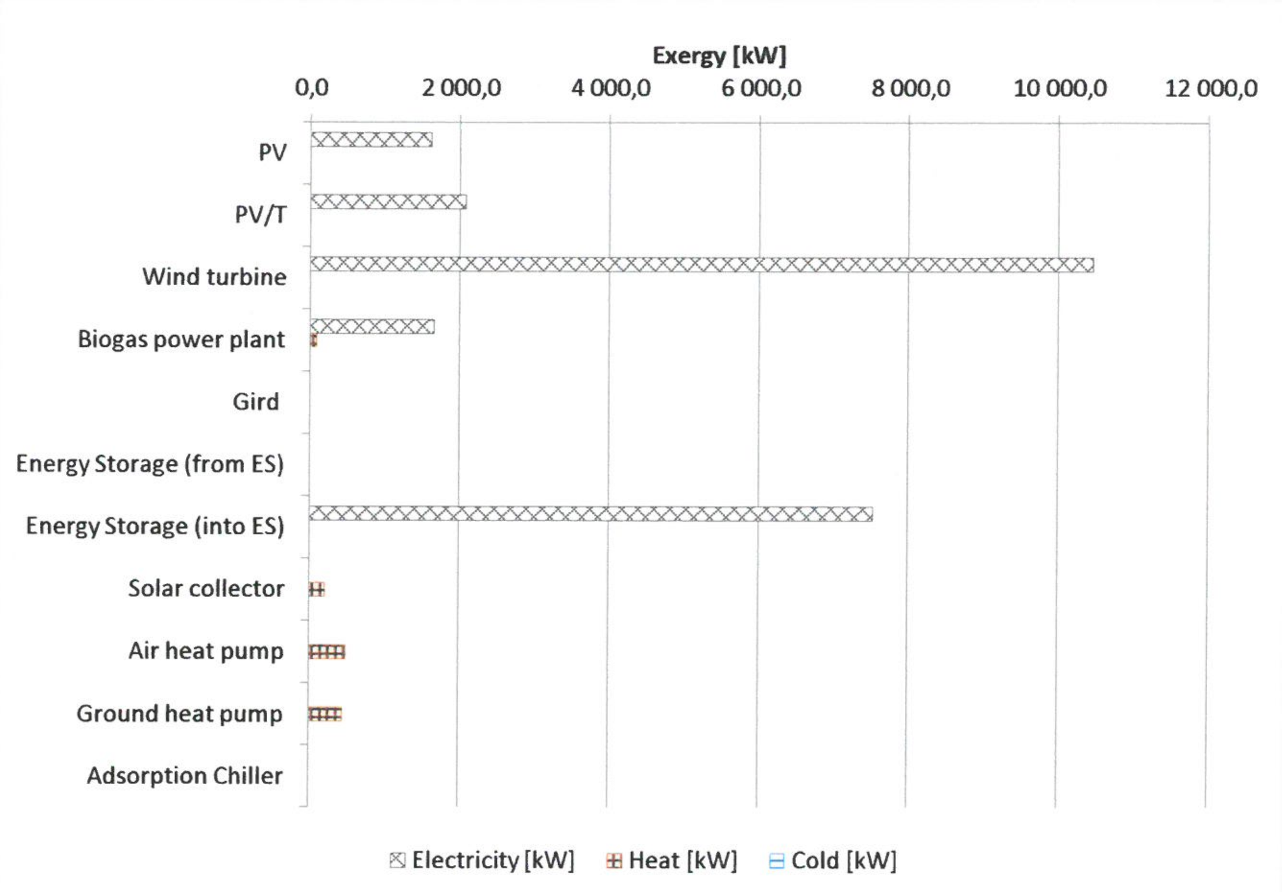

Figure 7. Exergy values for April 3 at 8:00 AM

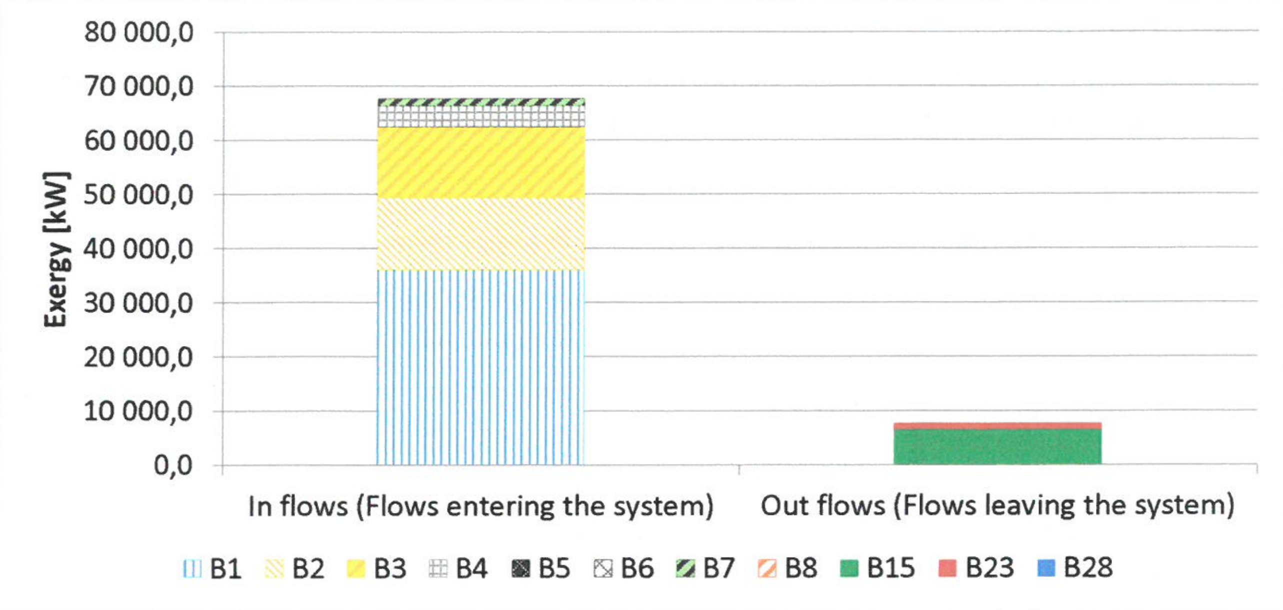

Figure 8. Exergy flows entering and leaving the system on April 3 at 8:00 AM

Among other representative cases, selected days (hours) during the remaining seasons—summer, autumn, and winter—can be briefly described:

- July 28, 2:00 PM (summer, high solar irradiance):
    - The main sources of electricity were the PV and PV/T systems, supported by the biogas-fuelled cogeneration unit.
    - Heat was supplied by PV/T, solar collectors, and the biogas-fuelled cogeneration unit.
    - Heat surpluses were directed to the adsorption chiller, enabling cooling production.
    - Additional cooling demand was met by heat pumps.
- October 6, 3:00 PM (autumn):
    - Electricity generated by PV, PV/T, the biogas-fuelled cogeneration unit, and the energy storage system was insufficient to meet demand, requiring supplementary electricity from the external grid.
    - Heat was supplied by PV/T, the biogas cogeneration unit, solar collectors, and heat pumps.
    - There was no cooling demand.
- December 15, 10:00 PM (winter, night):
    - No generation from wind or solar sources (PV, PV/T, collectors) occurred.
    - Electricity was primarily supplied by the biogas-fuelled cogeneration unit, supplemented by the energy storage system and the external grid.
    - Heat was provided by the cogeneration unit in combination with heat pumps.
    - There was no cooling demand.

Main conclusions

This section of the summary presents the conclusions derived from the conducted research and analyses described in the thesis. The following points provide a concise overview of the main findings:

- The conducted analyses demonstrated that TEC analysis is a comprehensive tool for assessing the environmental costs associated with the operation of energy systems.
- A significant result of this research is the calculation of TEC for the PV/T system (previously absent in the literature), including the allocation of thermo-ecological costs to electricity and heat production.
- The TEC analysis showed that electricity and heat produced by the PV/T system have TEC coefficients below 1, meaning that the exergy of the resources used to produce the product is lower than the exergy content of the product itself.
- Hybrid systems, such as PV/T, generate lower environmental costs compared to conventional photovoltaic systems (PV) and solar collectors.
- Due to the continued use of non-renewable resources in the final product (e.g., materials used in energy system components), no currently known energy production technology can achieve a zero TEC coefficient.
- When comparing different energy systems (renewable and conventional), global TEC analysis provides a reliable method to evaluate and compare systems, clearly indicating the impact of processes on the depletion of non-renewable resources.
- Even when comparing similar energy systems (e.g., PV and PV/T), TEC is a more appropriate analytical tool, as it accounts for the effect of renewable energy sources on non-renewable resources and more accurately reflects the system's environmental impact. Traditional efficiency metrics only assess the process itself without situating it in the broader environmental context.
- Traditional thermo-economic analysis (TEA) has limited applicability in hybrid systems. TEA results may misleadingly suggest maximizing the use of external resources without considering their origin or minimizing energy conversion within the system. In contrast, TEC provides a clear assessment of the resources supplied to the system.
- TEC analysis offered guidance for designing energy mixes that minimize environmental impact and resource depletion, showing which mix provides the best conditions for microgrid stability while using resources efficiently.
- Observations highlight the potential of TEC as a valuable tool for evaluating and optimizing energy systems, contributing to analytical approaches that consider the broader environmental context (Earth).
- TEC-based data allow the placement of analysed systems within a planetary context, highlighting their impact on global environmental issues such as climate change, resource depletion, dependency on imported materials, and environmental degradation. Such challenges require comprehensive, planetary-scale analyses, which TEC provides.
- The obtained data can inform public policies on the efficient use of resources, renewable energy deployment, and energy storage systems.
- The research sheds new light on the design of sustainable microgrids, offering guidance for creating flexible systems that accommodate daily and seasonal variations in renewable sources.

- A limitation of this study is its focus on a limited geographical area. Applying TEC to one location allowed capturing specific local conditions. Future research should extend analyses to other regions and perform comparative TEC studies, enhancing understanding of regional differences and identifying the most sustainable solutions.
- Future studies should consider climate change impacts on microgrids, enabling evaluation of TEC benefits under changing climatic conditions. This would provide valuable insights for adaptive planning and resilient energy infrastructure design.
- Further research could focus on approaches to minimize TEC values. While achieving a zero thermo-ecological cost is unrealistic due to reliance on non-renewable resources and environmental costs, exploring the most sustainable options and energy mixes remains crucial.
- Analyses could be expanded to optimize integration and energy storage technologies. Promising directions include sustainable production of energy components and efficient recovery and recycling processes.
- Future research could also include social aspects of the energy transition, such as societal acceptance of new technologies, the impact of energy investments on local communities, and energy transition equity. Including these factors would enhance the assessment of effectiveness and sustainability of implemented solutions.

References to main publications

The thesis consists of three thematically focused articles listed below. Full texts of these articles have been included as appendices to the doctoral thesis (Appendices 1–3). Within the main body of the thesis, the articles are referenced using Roman numerals (I–III):

I. Agnieszka Szostok, Wojciech Stanek, *Thermo-ecological analysis - The comparison of collector and PV to PV/T system*, Renewable Energy, Volume 200, 2022, Pages 10-23, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2022.09.070.

II. Agnieszka Szostok, Wojciech Stanek, *Thermo-ecological analysis of the power system based on renewable energy sources integrated with energy storage system*, Renewable Energy, Volume 216, 2023, 119035, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2023.119035.

III. Wojciech Stanek, Agnieszka Szostok, *Thermo-ecological assessment of microgrid supported with renewable energy, Energy*, Volume 314, 2025, 134256, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2024.134256.

Summary of the author's original contribution

The following points highlight the elements that constitute the author's independent and original contribution to the development of research on thermo-ecological analysis. This contribution encompasses all stages of the research work, from the formulation of the problem, through the execution of the study, to the interpretation of results and publication of findings. The author's contribution specifically includes:

- Formulating the research problem and hypotheses, and defining the scope and directions of the analysis.
- Conducting a comprehensive literature review and identifying research gaps.
- Developing the concept of individual studies and proposing appropriate methodologies, including the selection of analytical tools (e.g., TEC analysis, TEA, component characteristics) and evaluation criteria.
- Independently designing the microgrid, performing simulations, and analysing various energy mix configurations.
- Assessing and interpreting results after each simulation, providing critical evaluation of outcomes, and proposing directions for further research.
- Determining the thermo-ecological cost (TEC) for the PV/T system, a value previously unavailable in the literature.
- Proposing TEC allocation methods in hybrid systems, both for a single energy system (PV/T) and for a multigenerational microgrid integrating multiple renewable energy sources.
- Developing the application of the thermo-ecological cost for multigenerational microgrids to enhance their sustainability and reduce the consumption of non-renewable resources.
- Actively participating in the preparation of publications derived from the research, as indicated in previous points.
- Drawing final conclusions and formulating the theses of the doctoral dissertation.

In summary, the PhD thesis represents the author's original and independent contribution to the advancement of research on thermo-ecological analysis. It covers the development of the conceptual framework, execution of the research, and interpretation of results. Furthermore, the research findings have been regularly published, contributing to the growth of knowledge in the field of Thermo-Ecological Cost analysis and providing a foundation for further studies in this area.