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Review

Exergy and Exergy-Economic Approach to Evaluate Hybrid Renewable Energy Systems in Buildings

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Abstract: Hybrid renewable energy systems (HRES) combine two or more renewable energy systems and are an interesting solution for decentralized renewable energy generation. The exergy and exergo-economic approach have proven to be useful methods to analyze hybrid renewable energy systems. The aim of this paper is to present a review of exergy and exergy-economic approaches to evaluate hybrid renewable energy systems in buildings. In the first part of the paper, the methodology of the exergy and exergo-economic analysis is introduced as well as the main performance indicators. The influence of the reference environment is analyzed, and results show that the selection of the reference environment has a high impact on the results of the exergy analysis. In the last part of the paper, different literature studies based on exergy and exergo-economic analysis applied to the photovoltaic-thermal collectors, fuel-fired micro-cogeneration systems and hybrid renewable energy systems are reviewed. It is shown that the dynamic exergy analysis is the best way to evaluate hybrid renewable energy systems if they are operating under a dynamic environment caused by climatic conditions and/or energy demand.

Keywords: hybrid renewable energy systems; exergy; efficiency; costing method; micro-grid

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1. Introduction

The European Union (EU) has set an ambitious target to reduce energy use by 32.5% by 2030 [1]. One of the promising sectors to apply reduction measures is the building sector, which accounts for 43% of the final energy consumption in the EU [2]. On the other hand, residential buildings account for 26.3% of the final energy consumption in the EU, of which approximately 80% is for space heating and domestic hot water energy end-use, and the rest for electricity use [2,3]. Hybrid renewable energy systems (HRESs) are decentralized energy systems that combine two or more renewable energy systems with or without a conventional energy system and energy storage [4] These systems can be integrated into buildings for local energy production to satisfy heat and electricity demand. The promising hybrid approach for the residential HRESs is to combine fluctuating solar energy production technologies with a controllable fuel-fired micro-cogeneration unit [5]. Romero Rodríguez et al. [6] studied different configurations of hybridizing solar technologies (photovoltaic (PV) panels and solar heat collectors) with an internal combustion engine (ICE)-based micro-cogeneration unit with thermal storage in residential buildings in different Spanish locations. They modelled the systems on the TRNSYS environment and calculated primary energy (PE) consumption, emissions and the life cycle cost. Their results showed the highest PE consumption and emissions reduction with the most advanced configuration. However, this configuration resulted in the highest LCC as well. Kotowicz and Uchman [7] presented a residential HRES that included a natural gas-fired Stirling engine micro-cogeneration unit coupled with PV panels and electrical energy storage in a residential building. They conducted an energetic and economic evaluation of the proposed HRES with different PV and storage capacities, and their model was experimentally validated. Their results presented that the system was able to enable a high-level of self-sufficiency with the available technologies. The Stirling engine-based micro-cogeneration was coupled with solar technologies in [8,9] as well.

Currently, the analysis, optimization, costing and control methods of the HRES and different system components are based on the energy flows and the first law of thermodynamics. The primary energy approach is commonly used to reduce fossil fuels and increase the share of renewable energies to satisfy given energy demand. Finally, the aim is to balance the energy quantities between energy supply and demand. However, the quantity-based approach does not give any information about the quality of the energy source or the quality requirements of the demand side.

Fuel-fired or solar-based micro-cogeneration, or combined heat and power (CHP), systems have been seen as a key technology to reduce primary energy use and CO_2 emissions in the building sector and to be part of the hybrid renewable energy systems. Micro-cogeneration systems have been modelled by several authors in the literature [10–15]. In addition to modelling, the energy and economic performance of these systems have been analyzed. The International Energy Agency published Annex 42 [16], in which the fuel-fired micro-cogeneration systems for residential buildings were studied in terms of model development and experimental testing. Bouvenot et al. [17] developed a dynamic model comprising biomass-fired steam engine-based micro-cogeneration. The model was validated by experimental results and built into the TRNSYS environment. Bouvenot et al. [18] also experimentally investigated a gas-fired Stirling engine micro-cogeneration system, and a simulation model was developed. Uchman et al. [19] studied a gas-fired free-piston Stirling engine coupled with thermal storage and built up a data-driven model. González-Pino et al. [20] investigated a gas-fired Stirling micro-cogeneration system as well. They built up an experimental set-up and modelled the detailed behavior of the unit in terms of start-up and cool-down periods and partial load performance. Martinez et al. [21] investigated the performance of a solar micro-cogeneration system integrated into a residential building. The parabolic trough collectors were used to produce steam for a steam engine prime mover. Brottier and Bennacer [22] experimentally investigated the thermal performance of 28 photovoltaic–thermal panel installations in a residential building environment. Aunón-Hidalgo et al. [23] experimentally studied a residential HRES that included PV panels, solar thermal collectors, a natural gas-fired Stirling engine-based micro-cogeneration unit and thermal and electrical storage. The energy performance and CO_2 emissions of the system were assessed. Their results showed 75.6% coverage of the total energy demand and a reduction in CO_2 emissions of 36.2%.

Herrando et al. [24] evaluated the levelized production cost of generated energy (heat and electricity) from the flat-box PVT collectors installed in residential buildings in three European locations—Athens, London and Zaragoza. The lowest cost was reached in Athens. However, their costing method did not differentiate between heat and electricity, which have different qualities. Mundada et al. [25] calculated the Levelized Cost of Electricity (LCOE) for a hybrid energy system including photovoltaic (PV) panels, battery storage and an internal combustion engine (ICE)-based micro-cogeneration unit. The hybrid system was installed in a residential building, and a case study was presented. Their results showed that the considered hybrid energy system is economically feasible under certain economic conditions. However, the authors did not take into account the heat production of the micro-cogeneration unit but allocated all fuel costs to the electricity production, which increases the LCOE.

The above-mentioned studies addressed the performance and cost analysis of micro-cogeneration systems and hybrid energy systems based on the first law of thermodynamics. However, the second law of thermodynamics is required to complete the energy and cost assessment of these systems. By combining the first and second laws of thermodynamics in the system analysis, the quality of energy can be defined. This combined analysis is called "Exergy analysis". A quantity of energy is seen as pure exergy if it can be transformed into work. However, often only a part of the energy can be considered as exergy. In each energy conversion process, in contrast to energy, exergy is destroyed due to the irreversibility of the process. On the other hand, thermoeconomics are used to combine energy and economics to evaluate the economic viability of the energy systems and define specific costs of the energy products. The conventional energy-economic analysis is a well-established evaluation method, but its weakness is that energy does not tell any information about its value (exergy), and the monetary value should be assigned to the value of a commodity [26]. For example, the same quantities of heat and electricity have different exergy, and we value them differently because they can do different things for us [26]. Due to this, it is more rational to assign the monetary value with quality measure and not quantity measure of energy. The exergo-economic analysis is used to create a relation between the costs and exergy flows of the energy system. To the best of the authors' knowledge, there is no review work focusing on the exergy and exergo-economic analysis of the HRESs based on the micro-cogeneration in the building-related micro-grid. This work intends to fill a research gap in selecting the reference temperature and nature of the analysis, which can be from steady-state to dynamic.

In this work, the exergy analysis is proposed to be used in the evaluation of different domestic HRES components to reveal quality matching between energy supply and demand. For example, the high-quality potential of electricity or wood pellets is lost if these fuels are used directly to cover low-quality space heating demand. Although the energy efficiency could be as high as 98%, the exergy efficiency can drop close to 10%. Additionally, the exergo-economic analysis is proposed as a costing method to define more rationally and sustainably the specific costs of energy products of the HRES in a micro-grid. This is important information when evaluating the economic viability and sustainability of the prosumer's energy self-sufficiency created by the HRES compared to reference systems. The grid-connected prosumer can use the defined specific costs when selling the energy products to the electric or heat grid. The objective of this work is to provide a research contribution by reviewing the literature in which the exergy and exergo-economics analysis has been applied to the micro-cogeneration systems and HRES in the building-related micro-grid.

Since the 1970s, exergy analysis has been commonly and widely applied in industrial power plants to increase the overall efficiency and the output of the plant. The exergy analysis has also found its way to analyze building energy systems, for example, the Annex 49 Final Report [27]. However, in this case, the target can be to increase the efficiency and output of the energy system as well as to reduce the quality of the input energy to still maintain the output, which satisfies the energy requirements of the building, such as thermal comfortability. The other significant difference between the power plant and building energy system is the operational temperature level, which is extremely close to the ambient temperature in the micro-sized systems. This highlights the importance of defining the reference temperature, which is used to calculate exergy.

As the first step, this literature review introduces the formulations and indicators of the exergy and exergo-economic analysis to reveal the irrational use of energy and specific costs of energy products in building-related energy systems. The exergo-economic analysis is proposed to be a method to define the specific cost of the energy product in a decentralized energy system until to micro-scale. Next, the strong and weak points of the exergy approach are discussed and suggestions are presented. Finally, the selected studies are presented that apply the exergy approach to photovoltaic–thermal collectors, fuel-fired micro-cogeneration systems and hybrid renewable energy systems. The common issues of the studies are discussed in the conclusion.

2. Methodology of the Exergy Approach

In this section, the methodology to conduct the exergy and exergo-economic analysis is presented with the main performance indicators found from the literature. The selection of the reference temperature is discussed.

2.1. Thermal Exergy Calculation

Heat can be transferred by convection, radiation and mass flows. When heat is transferred by convection from temperature T to the environment T_0, the thermal power Q is recognized. The exergy of the thermal power Q transferred by convection under steady-state conditions is calculated as follows [28]:

$$Ex = Q\left(1 - \frac{T_0}{T}\right), \tag{1}$$

The term in parentheses defines the quality of the thermal power Q and is called "exergetic temperature factor", "quality factor" or "Carnot factor" [28,29].

For the radiative heat transfer in which a certain body absorbs radiation from air to convert it into available work or exergy, the following definitions occur [28]:

$$Q = \varepsilon\sigma A\left(T^4 - T_0^4\right), \tag{2}$$

$$Ex = Q\left[1 - \frac{4}{3}T_0\frac{(T^3 - T_0^3)}{(T^4 - T_0^4)}\right], \tag{3}$$

In Equation (3), the quality factor exists in parentheses as in Equation (1) but it also takes into account the exergy destruction generated by the absorption of the radiation.

The thermal power Q can also be transferred by a mass flow $\dot{m}$ in temperature T, which is greater than the reference temperature T_0. When taking into account the physical component of exergy, the exergy of the mass flow $\dot{m}$ can be written [28,30]:

$$\begin{aligned} Ex = \dot{m}\,[(h - h_0) - T_0(s - s_0)] &= \dot{m}c_p\left[(T - T_0) - T_0 ln\left(\frac{T}{T_0}\right)\right] \\ &= \dot{m}c_p(T - T_0)\left[1 - \frac{T_0}{(T - T_0)} ln\left(\frac{T}{T_0}\right)\right], \end{aligned} \tag{4}$$

where h and s are the specific enthalpy and entropy, respectively, and the quality factor is in the last square brackets. This quality factor can be applied in the case of varying states of the system [31]. In terms of micro-cogeneration and hybrid renewable energy systems in buildings, the thermal exergy of the mass flow is a highly important parameter because the mass flow is used to transfer heat from the energy conversion system to the building or thermal storage.

The quality factor f_q was defined above using the temperature difference between the system and the reference environment. This factor shows a share of useful work extracted from an energy conversion process that has reached its reference environment. Concerning this, the quality factor can also be defined as a ratio between the available exergy and energy as follows [31]:

$$f_q = \frac{Ex}{En}, \tag{5}$$

2.2. Solar Radiation as Exergy Source

In terms of solar-based micro-cogeneration systems, the exergy of solar irradiation is used as fuel exergy for the system and converted into heat and electricity. According to the common opinion in the literature, solar radiation is not seen as a pure exergy source, but a conversion coefficient, or quality factor, is used to define the exergy of solar irradiation. However, there are several opinions with regards to defining the magnitude of the conversion coefficient. Jeter [32] proposed to use the Carnot Factor as a conversion coefficient as follows:

$$\psi = 1 - \frac{T_0}{T_{sol}}, \tag{6}$$

where T_{sol} is the solar temperature of 5777 K. Using the Carnot Factor approach leads to an assumption of the direct contact between Earth and Sun, and the reversible thermal engine receives all available solar irradiation as an input. However, this approach does not take into account the quality reduction that has taken place when solar radiation is converted into useable heat utilized by the ideal heat engine [28].

According to [33,34], Petela gave a different approach to defining the coefficient. In his study, he compared non-atmospheric solar irradiation to irradiation from an undiluted blackbody. Next, he used the heat equal to solar irradiation absorbed by the blackbody as an input for an ideal piston cylinder with the initial state presented by (V_1, T_1). Petela stated that the maximum work of the irradiation is defined by this piston cylinder when it settles into the reference temperature (dead-state) T_0 [34]. Finally, he presented the following coefficient to calculate the maximum available work from the solar irradiation [34]:

$$\psi = 1 - \frac{4}{3}\frac{T_0}{T_{sol}} + \frac{1}{3}\left(\frac{T_0}{T_{sol}}\right)^4, \tag{7}$$

The exergy of solar irradiation G_{irr} to a receiving surface A is presented as follows:

$$Ex_{sol} = AG_{irr}\psi, \tag{8}$$

Equations (6) and (7) result in the values of 0.948 and 0.931, respectively [32]. In terms of evaluating the available energy of solar irradiation, Pons [35] argued that, in addition to the radiative nature, the direct and diffuse irradiation of solar energy should be considered. Almost the same daily solar insolation can be observed with different direct/diffuse rations depending on the cloud coverage of the sky. This leads to a qualitative difference in the received solar energy input. Pons [35] showed that if the distinction between direct and diffuse radiation is taken into account, the quality factor on a cloudy day is between 0.68 and 0.7, and in clear sky conditions between 0.9 and 0.91. In this way, the varying quality of solar insolation is considered, which is missing from the approaches presented by Equations (6) and (7). Despite the detailed and accurate approach of Pons, the conversion coefficient presented in Equation (7) is used in this thesis to evaluate solar exergy.

2.3. Reference Environment

The amount of the system's energy is independent of its environmental state. However, the reference environment or dead state is always mentioned in the definition of exergy, and the exergy is calculated as a work between the system and its environment or dead state. Due to this, two states are required to be defined when using the exergy analysis. The first state is the actual state of the system, and the second state is the reference state, equilibrium or dead state. Selecting a suitable reference environment was stated as a problem already in the early years of exergy analysis [36]. Once the reference environment is specified, the value of exergy can be fixed depending on the state of the system [30]. Due to this, the exergy value, as a result of the system analysis, is highly sensitive to the defined reference environment and its properties should be defined carefully.

The total exergy of a system includes the following four components with different property associations: chemical exergy associated with the chemical composition, physical exergy associated with the system pressure and temperature, kinetic exergy associated with the velocity of the system and potential exergy associated with the system height [37]. The physical exergy has two components, which are thermal and mechanical exergy. In terms of thermal exergy, the reference environment is described by the temperature. The greater the difference between the state and its environment, the greater the amount of exergy and the useful work.

In terms of micro-cogeneration and hybrid renewable energy systems in buildings, a restricted dead state, defined by Moran and Sciubba [30], can be considered. In this state, only the physical exergy in terms of mechanical and thermal equilibrium is considered and the difference to the environment in the velocity and elevation properties are set to zero [30]. In the restricted dead state, the reference temperature and pressure can be set to be ambient with atmospheric values of T_0 = 25 °C and p_0 = 1 atm, respectively. However, in this thesis, only the thermal exergy component of the physical exergy is used in the analysis. Additionally, the electrical energy flow produced by the energy systems is considered. Electrical work is seen as pure exergy and can be fully converted into useful exergy.

Typically, the reference environment is defined to be the natural surroundings of the system with constant properties of pressure, temperature and chemical composition. When the system reaches the properties of the reference environment, it has reached the dead state, and there is no possibility to extract useful work anymore. Rosen and Dincer [15] presented that the reference temperature T_0 is the main property that has an impact on the results of the exergy analysis. Additionally, they showed that if the temperature difference between the system and environment is large, the amount of exergy is less sensitive to the variation of the reference temperature. However, if the system temperature is close to the reference temperature, which is the case in micro-cogeneration systems and buildings, the values of exergy are highly sensitive to the variation in the reference temperature [38]. Due to this, in terms of low-temperature applications, the reference temperature should be selected carefully to obtain the most realistic and comparable exergy analysis results.

In terms of the micro-cogeneration systems for buildings, the selected reference temperature in the literature is the ambient temperature of the surroundings [39–41]. However, the ambient temperature fluctuates strongly over time, which would result in a dynamic reference temperature. The variable reference temperature has been adopted for the exergy analysis by some authors in the literature. However, Pons et al. [42] studied exergy with fluctuating ambient conditions. They stated that the reference temperature T_0 must be fixed and constant because a variable reference temperature would lead to the thermodynamic contradictions. In the literature, there is no agreement of the value of the constant reference temperature, and some authors adopt values such as 20 °C or 25 °C. However, if the yearly analysis is conducted, the ambient temperature varies strongly in many locations depending on the season of the year. Selecting the reference temperature of 25 °C for a winter month leads to misleading results. Due to this, Fujisawa and Tani [43] adopted the average monthly ambient temperature, and Evola and Marletta [44] selected the monthly minimum ambient temperature to be a constant reference temperature in the exergy analysis of the solar micro-cogeneration system.

In a conclusion, the selection of the reference environment has a high impact on the results of the exergy analysis, and there is still a lack of a common reference environment definition in the scientific community. The common definition would make different exergy analyses comparable and facilitate the standardized use of exergy analysis in energy systems and buildings.

2.4. Exergy Indicators

To assess the energetic and exergetic performance of a hybrid renewable energy system, several indicators are introduced in the literature. When considering a control volume of an energy conversion system, the following energy and exergy balance equations can be written, respectively:

$$\sum E_{fuel} = \sum E_{product} + \sum E_{loss}, \tag{9}$$

$$\sum Ex_{fuel} = \sum Ex_{product} + \sum Ex_{d}, \tag{10}$$

where "*fuel*" indicates energy and exergy inputs to the system and "*product*" indicates energy and exergy outputs, such as thermal and electrical products in terms of micro-cogeneration. According to the first law of thermodynamics, a part of the fuel energy is converted into energy losses, E_{loss}, to the environment. However, according to the second law of thermodynamics, a part of fuel exergy is destroyed, Ex_d, in the energy conversion process. The exergy destruction Ex_d is also called exergy irreversibility of the process.

The energy and exergy efficiency are the main indicators to quantify the effectiveness of converting the fuel energy and exergy into the products and are presented as follows, respectively:

$$\eta = \frac{\sum E_{product}}{\sum E_{fuel}} = 1 - \frac{\sum E_{loss}}{\sum E_{fuel}}, \tag{11}$$

$$\zeta = \frac{\sum Ex_{product}}{\sum Ex_{fuel}} = 1 - \frac{\sum Ex_d}{\sum Ex_{fuel}}, \tag{12}$$

Compared to the energy efficiency η, the exergy efficiency ζ gives a more detailed insight into the performance of the conversion process because it takes into account different values of heat and electricity. Due to this, the exergy analysis is particularly useful in terms of analyzing the cogeneration systems. It also gives a good understanding of how good the thermodynamic rationality of the energy system is [28]. While the exergy efficiency aims to improve the performance by reducing energy quality degradation, the energy efficiency intends to reduce emissions [29]. For many energy systems, the energy losses to the environment are minimized effectively, and the energy efficiency can be high. However, the exergy destruction in the process can still be high and more difficult to reduce than energy losses. The exergy destruction rate is calculated as follows:

$$\Omega = \frac{\sum Ex_d}{\sum Ex_{fuel}}, \tag{13}$$

The exergy destruction rate can be used to identify the system components that cause the majority of the exergy destruction. The exergy irreversibility rate, which causes the exergy consumption, can be calculated based on the exergy efficiency as follows [45]:

$$Ir = (1 - \zeta) Ex_{fuel}, \tag{14}$$

In the case of micro-cogeneration systems, heat and electricity are produced simultaneously from a single fuel source. Due to this, it is useful to evaluate the performance of the cogeneration system by comparing it to the separated production of heat and electricity. The energetic comparison indicator is the Primary Energy Savings (*PES*), which reveals the savings relative to the reference system of the separated production. The *PES* is presented as follows [46]:

$$PES = \left(1 - \frac{1}{\frac{\eta_{el}}{\eta_g} + \frac{\eta_{th}}{\eta_b}}\right) \times 100\%, \tag{15}$$

where η_g and η_b are the electrical and thermal efficiency of power grid and thermal boiler, respectively, and η_{el} and η_{th} are electrical and thermal efficiency of the cogeneration system, respectively.

Alongside the PES indicator, Ertesvåg [45] introduced an exergetic comparison indicator called the Relative Avoided Irreversibility (*RAI*) which also considers the thermodynamic value difference between heat and electricity. The *RAI* is expressed by the irreversibility rate generated in the cogeneration and separated production as follows:

$$RAI = 1 - \frac{Ir_{CHP}}{Ir_g + Ir_b}, \tag{16}$$

2.5. Exergo-Economics

Decades later, after the concept of exergy was introduced, a need to link thermodynamics and costing aspects arose. In 1932, J. H. Keenan proposed a costing method that used exergy to allocate costs properly to different energy products [47]. He studied a cogeneration plant and concluded that exergy, instead of energy, gives the proper measure for the economic value of the produced electricity and steam. J.H. Keenan was followed by

M. Benedict, who presented the use of the exergy costing method in the optimal system design in 1949 [47].

Energy economics is a method that combines energy and economics to define monetary values for different energy commodities, such as fuel, electricity and heat. However, the fact is that energy is a quantity and not of value, and, due to this, there is no relation between the costs and value [26]. However, exergy represents the value of energy and combining economics with exergy is a rational costing method [26].

The term "exergo-economics" was first introduced by Tsatsaronis in 1983 [26]. He wanted to clearly describe a thermo-economic analysis that integrates exergy and economics with exergy costing. Thermo-economics considers any thermodynamic analysis conducted with or next to any economic analysis of the same system, and the analyses do not have to be merged [26]. In this case, the thermodynamic analysis can take into account both the first and/or second law of thermodynamics. Thermo-economics has two separate quantifiers, which are energy/exergy and money. Energy/exergy assesses the technical performance of a system and money assesses the profitability of the energy products [48]. However, in exergo-economics, the exergy-based thermodynamic analysis is integrated with the economic analysis, assigning monetary values for the exergy flows through exergy costing [26].

2.5.1. Principles of Exergo-Economics

The exergo-economics are based on the exergy flows, exergetic and non-exergetic costs. In terms of cogeneration systems, a certain input exergy flow is experienced by the system and generated into two different exergy products, heat and electricity. Additionally, valueless exergy destruction flow occurs due to irreversibility in the conversion process. On the component level, an input flow can be a product of a previous system component, and the product can be an output of the system or input for the next component in the system [49].

In addition to exergy flows, each component has cost flows that can be divided into exergetic and non-exergetic cost flows. The exergetic cost flow depends on the exergy flow entering and leaving the component and refers to the money used to produce a certain exergy flow. The non-exergetic cost does not depend on the magnitude of the exergy flows in the component but refers to the initial investment cost and operation and maintenance cost of the component [49]. Figure 1 shows the exergy, exergetic cost and non-exergetic cost flows of the kth component. The exergy input cost flow is seen as a fuel "F", and the exergy product cost flows are seen as product "P". In terms of cogeneration, Product 1 is electricity, and Product 2 is heat, and the related exergy product costs are $\dot{C}_{P1}$ and $\dot{C}_{P2}$.

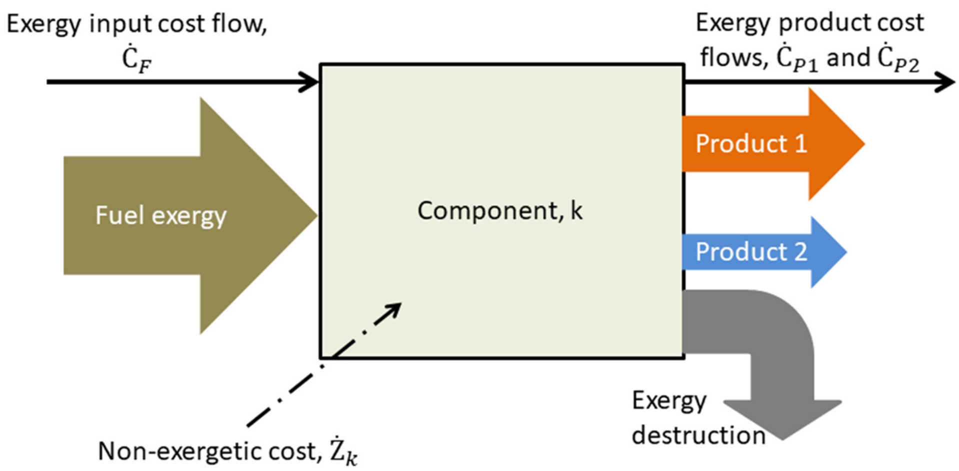

Figure 1. The principle of exergo-economic balance.

In the exergo-economic cost balance of the component, the exergy product cost flows equal to the sum of the component's non-exergetic cost and the exergy input cost. Generally, the costs in the exergo-economic analysis are presented as rates in 1/s or 1/h, and the analysis is conducted in a steady-state with the constant rates of the costs. The non-exergetic cost of the component k is as follows [49]:

$$\dot{Z}_k = \dot{Z}_I + \dot{Z}_{OM}, \tag{17}$$

where $\dot{Z}_I$ is the initial investment costs and $\dot{Z}_{OM}$ is the operation and maintenance cost of the component. Generally, the exergy cost associated with a certain exergy flow is calculated as follows [47]:

$$\dot{C}_i = c_i \dot{Ex}_i, \tag{18}$$

where $\dot{Ex}_i$ is the exergy rate of the considered flow and c_i is the specific cost of the exergy unit in the flow i. The exergy destruction flow defines the irreversible loss of exergy within the component. The monetary value of the destruction flow can be set to zero if the analysis aims to calculate the costs of the final products [47]. In this case, the exergy destruction cost rates $\dot{C}_d$ are directly transferred to the final exergy products, such as heat and electricity in a cogeneration system [47]. Finally, the exergo-economic cost balance for the component k in Figure 1 is presented as follows [47]:

$$\dot{C}_{P1} + \dot{C}_{P2} = \dot{C}_F + \dot{Z}_k - \dot{C}_d, \tag{19}$$

$$c_{P1}\dot{Ex}_{P1} + c_{P2}\dot{Ex}_{P2} = c_F\dot{Ex}_F + \dot{Z}_k, \tag{20}$$

Equation (20) shows that the exergo-economic analysis can be used to calculate the specific monetary value for the final products of the system by considering costly exergy destruction of the fuel exergy and the non-exergetic costs. These specific costs of the final product can be used for pricing and can be recovered by selling the products. On the other hand, these costs can be compared to a reference system and recovered by generating savings by onsite use of the products.

2.5.2. Exergo-Economic Analysis Methods

In cost accounting, the costs should represent value, and exergy shows the real value of energy, which makes it rational to associate the costs with exergy instead of energy [50]. As stated by Tsatsaronis [47], the exergy and exergo-economic analyses can be considered as methods for cost accounting and optimization. Exergo-economics can be used to evaluate multi-product energy systems and their designs, and to optimize the operation and the design of the system or individual component. In the literature, the exergo-economic analysis has been proven to be a rational method for cost accounting and optimization to increase the efficiency of the energy systems. However, there is still an urgent requirement to simplify and standardize the exergo-economic method to be adopted by the engineers and decision-makers, according to Tsatsaronis [47].

The above-discussed fundamentals of exergo-economics have led to different methods to combine exergy and economics. All these methods have the common characteristics of using exergy as a commodity of value, defining the costs and prices of the exergy products of the system, evaluating economic profitability and feasibility and aiming to optimize the operation and design of energy systems by minimizing costs [50]. Rosen [50] reviewed different methods to conduct the exergo-economic analysis. He distinguished the most common methods of loss–cost ratio analysis, EXCEM analysis, exergy cost accounting, and exergy and environmental economics.

The loss-cost ratio analysis recognizes the correlations between exergy destruction and capital costs to improve system design in terms of efficiency or capital costs reduction [51]. The EXCEM analysis was developed by Rosen and Dincer [51] to enhance the process simulator software Aspen Plus by the exergy approach. The analysis is used to assess the process and system and is based on the four quantities, as indicated in the name, which are exergy, cost, energy and mass [51]. The main principle of the EXCEM analysis is that mass and energy flows are conserved, and exergy and cost flows decrease and increase, respectively, or remain constant [51].

The widely used and general methodology of exergy cost accounting is the SPECO analysis proposed by Lazzaretto and Tsatsaronis [52]. The name of the analysis indicates the Specific Exergy Costing, and it is used systematically to determine exergy efficiencies and costs per exergy unit in energy systems [52]. The main principle of the SPECO is to define exergy fuel(s) and product(s) of each system component. Afterwards, the fundamentals from business administration are used to form the cost balances and auxiliary costing equations to calculate the exergy-related costs for each exergy input and output flow of the system components [52].

The SPECO analysis uses the fuel-product (F-P) principle to determine the costs of the exergy flows. In contrast to exergy analysis, the exergy costing based on the F-P principle does not distinguish between costs of high- and low-value products. According to Lazzaretto and Tsatsaronis [52], the P principle concludes that supplying any exergy unit to any product stream happens at the same average cost. This leads to the fact that the P principle is against the principle of high quality and high price, for example, electricity should have a higher price due to the higher energy level than low-grade waste heat. To solve this contradiction, Wang et al. [53] proposed a modified exergo-economic analysis method to allocate the multi-product cost consistently according to the principle of high quality and high price. They considered different energy levels of different exergy products by applying a principle stating the direct proportionality of the specific cost of any flow to its energy level. The energy level of electricity equals 1 and is defined as follows for thermal products [53]:

$$EL = \frac{\Delta Ex}{\Delta H} = 1 - T_0 \frac{\Delta S}{\Delta H}, \tag{21}$$

where T_0, ΔEx, ΔS and ΔH are the reference temperature, exergy, entropy and enthalpy changes, respectively.

The environmental aspects are added to the analysis in exergy and environmental economics. Sciubba [54] proposed a method called Extended Exergy Accounting (EEA), which integrates exergy accounting and thermos-economics with environmental factors. The main benefit of EEA is that it enables a direct quantitative comparison of non-exergetic parameters, such as labor and environmental impact. This is conducted by calculating the exergetic equivalents for non-exergetic parameters.

2.6. From Steady-State to Dynamic Exergy and Exergo-Economic Analysis

The exergy analysis can be conducted as a steady-state, quasi-steady state or dynamic analysis [31]. Compared to high-temperature energy conversion processes, such as centralized thermal power plants, the micro-cogeneration systems operate close to the outdoor conditions. Due to this, the exergy flows in the micro-cogeneration systems are highly sensitive to variations in the conditions of the reference environment, as discussed in Section 3.1. As consequence, the dynamic exergy analysis is required to conduct an accurate performance analysis of the micro-cogeneration systems and a steady-state analysis is recommended to be used only for the first estimations of the system exergy performance [28].

The quasi-steady analysis is a simplification of the dynamic analysis and can be a reasonable solution if conducting the fully dynamic exergy analysis is demanding. The error between the analyzing methods depends on the climate conditions and is expected to be larger for milder conditions [31].

Blanco [31] concluded that when comparing different energy systems, such as solar micro-cogeneration systems, the quasi-steady or dynamic exergy analysis is the best choice to evaluate the performance in terms of minimizing the error in the analysis.

3. Exergy in Hybrid Renewable Energy Systems

3.1. Exergy of Different Technology Types

The different technology types for building energy systems can be evaluated based on their energy performance. However, the exergy performance gives better insight into energy quality degradation in the conversion process by revealing the real thermodynamic performance of the system. Energy efficiency concerns only the quantity aspects related to energy production, neglecting the quality aspect. For this reason, the exergy method, which is based on the second law of thermodynamics, is used to complete the energy assessment of the system.

Depending on the energy conversion technology, different amounts of exergy is destroyed to attain electricity and useful heat. Table 1 shows the energy and exergy efficiencies of different technology types during the conversion process under the same environmental conditions.

Table 1. Energy and exergy efficiency of different energy conversion devices [55,56].

Energy Conversion Device	Energy Efficiency	Exergy Efficiency
Oil furnace	85%	4%
Electric heater	100%	5%
Electric heat pump	300%	15%
Combined heat and power unit	85%	40%
Photovoltaic	15%	16%
Solar thermal	75%	10%
Photovoltaic–thermal	66%	16%

Table 1 reveals that the conventional oil furnace heating system has an energy efficiency of 85%, but the exergy efficiency is only 4% because of high exergy degradation in the conversion process. The oil furnace can burn a thousand-degree flame resulting in hot water at only 60 °C temperature. The heat pump can reach an energy efficiency of 300% because it takes "free" energy from the environment. However, from the exergy point of view, the environment is taken into account, and only the electricity used in the heat pump has quality as an input in the energy conversion process. Table 1 shows that a combined heat and power system has the highest exergy efficiency of 40%. Its energy efficiency is the same as the oil furnace, but the high quality of the electricity production increases the exergy efficiency significantly. Based on the exergy efficiency, the use of cogeneration is highly recommended [55].

Electricity is seen as pure exergy, and the exergy content of heat depends on the temperature difference between heat and the environment or the reference state. Solar radiation has high exergy content and has a quality factor of around 0.93 [56]. Table 1 also presents the energy and exergy efficiencies of solar photovoltaic (PV), solar thermal and photovoltaic–thermal (PVT) technologies.

The energy and exergy efficiency of solar PV is 15% and 16%, respectively. The exergy efficiency is higher because electricity is seen as pure exergy, but solar radiation is not. The energy efficiency of the solar PV is mainly limited due to the physical limitations in the photoelectric conversion and heat losses to the environment are caused by the conversion process. Solar heat generation reaches an energy conversion efficiency of 75%, but the exergy efficiency is only 10% due to the low-temperature level of the generated heat, which is close to the ambient temperature. The solar cogeneration technology can reach an energy efficiency of over 66%, but the exergy efficiency is the same as the solar PV because the temperature of the generated low-grade heat is even closer to the ambient temperature than in the solar thermal technology [56].

However, the electrical efficiency of the PVT should be higher than solar PV because of the cooling effect, which increases the electrical energy and exergy efficiency. This should be considered when comparing solar PV and PVT technologies [57]. Additionally, high-temperature PVT technologies have been developed, and those can reach the same temperature levels as solar thermal [58]. Due to this, the exergy efficiency of solar cogeneration increases significantly.

Torio and Schmidt [27] introduced, in the Annex 49 Final Report, the low exergy approach for buildings and their energy systems. They presented that the most efficient and sustainable way to produce energy is to have a good match between the supply and demand in terms of their quality levels. The high-quality fuel should be used to satisfy high-quality demand and vice versa. Figure 2 presents the energy quality flows in the building environment to match the quality levels of the supply and demand sides.

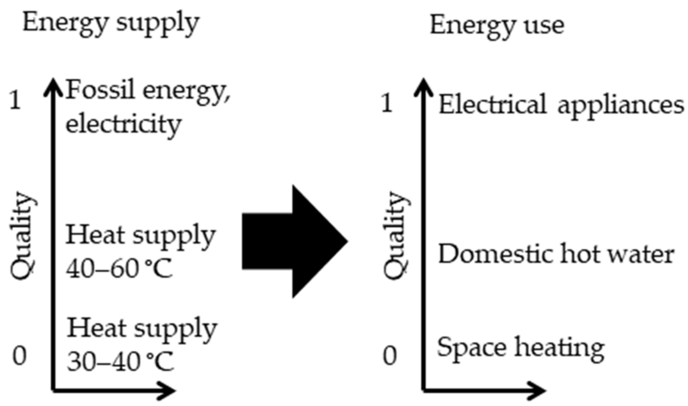

Figure 2. Optimal matching of the supply and demand quality levels in the building environment. Figure is adapted from [3].

The heat demand in buildings has typically low-quality demands, as shown in Figure 2—the domestic hot water required is from 55 °C to 60 °C and the room temperature is maintained at around 20 °C. For these purposes, the low-quality energy sources are ground source, solar and waste heat [27]. As discussed earlier, solar irradiation has a quality factor of 0.93, which is almost as high as natural gas of 1.03. However, the exergy approach does not separate non-renewable and renewable energy sources, which should always be evaluated in addition to the exergy analysis [31]. Due to this, in the case of solar energy, it has to be considered that it is free of charge and CO_2 emissions, which makes it highly sustainable. Generally, the high-quality fuels, such as fossil fuels or biomass, are required to produce electricity (f_q = 1) for household appliances. In this case, biomass fuel is the most sustainable way to produce electricity due to its renewable nature and low CO_2 emissions. However, biomass is a limited renewable source that should be used in highly efficient systems [27]. The external combustion engine-based cogeneration systems are suitable for highly efficient biomass use.

In conclusion, when evaluating the energy technology types for buildings, the usage of the exergy approach is highly recommended. This approach reveals the thermodynamic reality of efficiency and considers the environment where we live. Completing the energy assessment with the exergy approach reveals that the micro-cogeneration systems can have significantly higher exergy efficiency (40%) than the boiler (4%). Additionally, Torio and Schmidt [27] stated that the cogeneration systems should be used for heating instead of the high-energy efficient boilers. Based on the given review of the exergy in the different technology types, the solar and fuel-fired cogeneration systems can have a renewable nature and the highest exergy efficiencies.

3.2. *Exergy and Exergo-Economic Analysis of Photovoltaic–Thermal Collector (PVT)*

The exergy performance of solar-based micro-cogeneration systems is highly dependent on fluctuating environmental conditions, such as solar irradiation and ambient temperature. Due to this, a dynamic analysis is reasonable to analyze the exergy performance of the PVT collectors over a certain time horizon. However, both steady and dynamic analyses exist in the literature with different reference temperature approaches.

Evola and Marletta [44] conducted a dynamic exergy analysis of a PVT collector, exergy-based operation optimization and exergo-economic analysis under the weather conditions of Catania, Italy. The water-cooled collector was a prototype with glazing and an air gap before the PV layer. The analysis was conducted on an annual performance and monthly basis. Due to the annual analysis, the authors selected the approach for selecting the reference temperature according to Pons [42]. In this case, the reference temperature was changed dynamically, and the monthly minimum temperature was used as a reference temperature in their analysis. The authors selected to calculate the exergy of solar radiation according to Equations (7) and (8) presented in Section 2.

The results of Evola and Marletta [44] showed monthly exergy efficiencies of which the thermal varied only from 0.5 °C to 2.5 °C. The low thermal exergy efficiency was caused by the thermal energy production close to the ambient temperature. The authors' results showed a highest overall efficiency of 14.2% with a constant inlet temperature of 20 °C. As a comparison, the highest overall energy efficiency was 70%. The authors concluded that increasing the inlet temperature increased the exergy performance of the PVT, and they optimized the inlet temperature for the system control to maximize the annual exergy yield. However, the optimal temperature did not result in the maximum annual energy yield. Finally, they conducted the exergo-economic costing method for the PVT to identify the cost of the thermal output of the collector according to its exergy generation.

Abdul-Ganiyu et al. [59] used exergy analysis to experimentally analyze the technical and economic performance of the water-based PVT collector in comparison to the PV panel under the weather conditions of Ghana. The authors selected the exergy analysis for a better comparison of two technologies and used the yearly average daily ambient temperature was used as a reference temperature in the analysis. The measured weather and operational data were used as input for the PVT and PV models in TRNSYS simulation software to perform annual dynamic analysis. Finally, the PVT resulted in a lower levelized cost of exergy than the PV system, especially if the battery storage was connected to the system.

Mourshed et al. [60] applied the energy and exergy analysis to the small flat-plate PVT collector presented in Figure 3, which was simultaneously cooled by water and air. They used an experimental set-up of the PVT collector to conduct the analysis. The authors conducted a semi-steady-state analysis for daily operation and used the ambient temperature of the collector as a reference temperature. They resulted in a maximum thermal exergy efficiency of 2.89%, of which 0.64% was covered by air cooling and 2.25% by water cooling. The authors concluded that the overall exergy efficiency of the collector was doubled when using water and air cooling of the collector simultaneously.

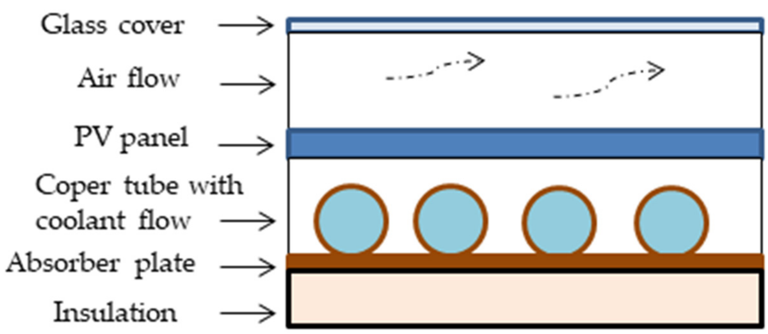

Figure 3. The cross-section of the PVT collector with water and air cooling systems adapted from [37].

Martínez-Gracia et al. [61] presented an exergy assessment of a case study including PVT collectors, a solar-assisted heat pump and seasonal thermal storage. The real installation of the system was realized under the weather conditions of Zaragosa, Spain, to provide electricity, heat and DHW for a social housing building. The dynamic hourly simulations of the system were performed by a model developed into TRNSYS simulation software. In addition to the exergy analysis, the exergy cost analysis was conducted. The authors used the soil temperature around the system as a reference temperature for the exergy analysis, and the analysis was performed on a monthly and yearly basis.

The results of [61] presented the monthly exergy fuel, product and irreversibility associated with different system components. The monthly exergy efficiency of the PVT field varied between 13% in July and 17% in April. The highest thermal exergy production was in May due to cooler ambient temperature than during the highest solar fuel months from June to August. The PVT field had the lowest unit exergy cost of approximately 6 due to irreversibility because of its position at the beginning of the system. The cost of the PVT field was impacted only by its own irreversibility. While the cost of the delivered heat by the seasonal storage and heat pump were approximately 13 and 15, respectively.

3.3. Exergy and Exergo-Economic Analysis of Fuel-Fired Micro-Cogeneration System

The fuel-fired micro-cogeneration, or combined heat and power (CHP), systems have been modelled and analyzed by several authors in the literature. These systems utilize an internal or external combustion engine or fuel cell as a prime mover technology. The International Energy Agency published Annex 42 [16], in which the fuel-fired micro-cogeneration systems for residential buildings were studied in terms of model development and experimental testing. Bouvenot et al. [17] developed a dynamic model using biomass-fired steam engine-based micro-cogeneration. The model was validated by experimental results and built into the TRNSYS environment. Uchman et al. [19] studied a gas-fired free-piston Stirling engine coupled with thermal storage and built up a data-driven model based on the experimental measurements. González-Pino et al. [20] investigated gas-fired Stirling micro-cogeneration as well. They built up an experimental set-up and modelled the detailed behavior of the unit in terms of start-up and cool-down periods and partial load performance.

The above-mentioned studies only considered the performance analysis based on the first law of thermodynamics. However, the second law of thermodynamics is required to complete the energy assessment of the micro-cogeneration systems. Due to the controllable nature of the fuel-fired micro-cogeneration systems, the exergy analysis has been conducted in steady-state conditions without building or environmental-related dynamic behavior.

Gonçalves et al. [62] conducted an energy and exergy analysis on the steady-state experimental data of the internal combustion engine (ICE)-based micro-cogeneration system and compared the performance to a reference system. The experimental data were used to validate a dynamic TRNSYS model of the micro-CHP system to conduct the analysis. They compared the performance of the cogeneration system to a reference system including the electric grid connection for electricity and a gas boiler for heat production. Additionally, 20% renewable energy production was added to the reference system. As comparison indicators, the energy-based *PES* and exergy-based *RAI*, introduced in Section 2.4, were used. The authors selected the reference temperature to be constant at 10 °C to calculate the thermal exergy production of the micro-cogeneration cooling flow.

The results of [62] showed a maximum overall exergy efficiency of 33% at full load operation and with an inlet temperature of 60 °C. At the same operation point, the thermal exergy efficiency was 9% and the electrical 24%. The exergy efficiencies were sensitive to the inlet temperature and the part load ratio. As a comparison result, the micro-cogeneration had a positive *PES* indicator in any case of the reference system efficiency but a negative *RAI* indicator if the electric grid had an efficiency above 44%.

Taie et al. [63] studied the energy and exergy performance of the ICE-based micro-cogeneration system on the device and component level to identify the main areas of inefficiency. The investigated system was the market-available Honda ECOWILL unit with an electrical power of 1 kW. They analyzed the steady-state experimental data. Their results revealed that the largest exergy destruction occurred in heat transfer. The authors used the environmental temperature of 20 °C as a reference temperature. It resulted in an overall exergy efficiency of 30.2%, including an electrical efficiency of 23.1% and thermal exergy efficiency of 7.1% due to the low-grade heat production of the system. As a comparison, the overall energy efficiency was 74.5%. The authors indicated the key areas of the exergy destruction to be combustion and heat transfer from the engine block to the coolant fluid.

Taie and Hagen [64] performed energy and exergy analysis for another market-available ICE-based gas-fired micro-cogeneration system called Marathon Ecopower with 4.5 kW_e nominal electrical power. The analysis was conducted on the system and component level through experimental testing. Results demonstrated an electrical efficiency of 24% and overall efficiency of 94.5%, while the overall exergy efficiency was only 33.7%. However, this was over 3% more than with the Honda ECOWILL system. The largest exergy destruction and energy loss resulted from combustion and unrecovered heat transfer, respectively.

The authors of this review performed a system level energy and exergy analysis of a biomass-fired Stirling engine-powered micro-cogeneration system with an electrical power of 1 kW_e in [65]. This system is a market-available Pellematic Condence_e manufactured by the ÖkoFEN company and was experimentally tested in the INSA Strasbourg ICUBE laboratory. The unit is presented in Figure 4. The analysis was based on the experimental results at full load conditions. The reference temperature was selected to be 10 °C to be close to the mains water. The electrical efficiency was 7%, and the overall energy efficiency was 105% due to the condensing technology. However, the overall exergy efficiency dropped to 14% due to low-grade thermal production at 64 °C. The overall exergy efficiency was increased to 24% if the inlet water temperature was increased. They resulted in the positive *RAI* indicator if the system was connected to the thermal storage when compared to a reference system of separated energy production.

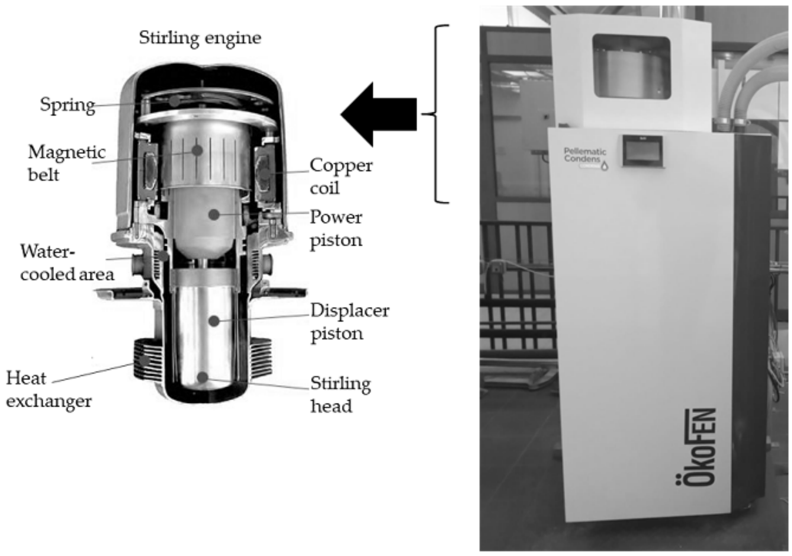

Figure 4. Stirling engine powered Pellematic Condence_e micro-cogeneration system analyzed in and adapted from [65].

Wang et al. [66] performed an exergy assessment for the fuel cell micro-cogeneration systems at the component and system level. They developed and validated a dynamic model of the flame solid oxide fuel cell (SOFC) with 1.1 kW_e nominal power output for a residential application. The system was analyzed under steady-state conditions at the design and part-load point. The reference temperature of 20 °C was selected for the exergy analysis, and in addition to the physical exergy, the chemical exergy was used to calculate the exergy of a gas flow. The results showed an overall energy and exergy efficiency of 93% and 22.5% at the design point, with an electrical efficiency of 15.7%. At the part load point, the exergy efficiency dropped to 17.4%.

Due to the dependence on the constant fuel feed, the steady-state analysis of the fuel-fired micro-cogeneration units using the constant reference temperature in the exergy analysis is more reasonable than in the case of photovoltaic–thermal collectors that are dependent on the fluctuating weather conditions. However, in the annual analysis of the fuel-fired micro-cogeneration system, the monthly varying reference temperature could be more reasonable than the constant value over the year.

Each of these experimentally analyzed fuel-fired micro-cogeneration systems resulted in a higher overall exergy efficiency than the other building heating systems presented in Table 1.

3.4. Exergy and Exergo-Economic Analysis of Hybrid Renewable Energy Systems

The micro-cogeneration systems rarely operate as a single unit but are integrated with the whole building system, including highly dynamic energy demand. The cogeneration systems are typically integrated with thermal and/or electrical storage and can be hybridized with other energy production systems.

Mahian et al. [67] presented a review of exergy analysis in the cogeneration systems with different prime movers. Their results revealed that more exergy-based investigations are recommended on small-scale systems in the residential sector. Additionally, more research should be focused on hybrid cogeneration systems with renewable energy sources. The exergy analysis of a single micro-cogeneration unit can be extended to consider an exergo-economic analysis of a hybrid renewable energy system based on cogeneration.

Wang et al. [68] conducted the exergy and exergo-economic analysis of the hybrid energy system based on the ICE micro-cogeneration system coupled with solar heat collectors (SHC) for combined cooling, heating and power (CCHP) production. In addition to the ICE micro-CHP unit and solar thermal collectors, the system included an absorption heat pump (AHP) and thermal energy storage. The model of the hybrid energy system was built and validated to conduct the steady-state analysis for cooling and heating periods. However, a constant reference temperature of 25 °C was used throughout the analysis. In their exergo-economic analysis based on the SPECO method, the energy levels of the different energy products (electricity, space heating, chilled water and domestic hot water) were taken into account to handle the fact that the higher quality energy product should have a higher unit cost of exergy. The unit cost of the energy products was calculated in the four defined schemes with and without solar energy and CO_2 cost.

The results from [68] for the overall system energy and exergy efficiency were 75.3% and 22.4%, respectively. On the component level, the SCH resulted in the lowest exergy efficiency of 9.7% and the ICE micro-cogeneration unit of 46.9% due to high electricity production capacity. However, the highest exergy destruction was caused by the ICE micro-cogeneration unit followed by the AHP and SHC. The performed exergo-economic analysis resulted in the following unit costs: electricity 0.127 €/kWh, space heating 0.363 €/kWh, cooling 0.562 €/kWh and DHW 4.764 €/kWh.

In [69], Wang et al. presented an exergy and exergo-economic analysis and optimization of the same hybrid energy system as in [68], but the solar heat collectors were replaced by the concentrated PVT collectors to have an impact on the exergy efficiency and the exergo-economic costs. The analysis was conducted in a steady-state to satisfy the energy demand on a hotel building. The reference temperature was selected to be 25 °C. The PV coverage ratio was optimized to reduce specific costs. The overall exergy efficiency of the system was 22.7%, and the PVT collectors resulted in an exergy efficiency of 16.62%, which is a significant improvement compared to the SHC in [68]. Table 2 presents the percentages of exergy destruction caused by each system component. The concentrated PVT collectors caused the highest destruction rate, followed by the ICE micro-cogeneration system.

It is interesting that the authors in [69] performed the exergo-economic analysis based on the SPECO with and without the energy level of the products in Equation (21) and compared the results. The comparison resulted in a 20.3% higher specific cost of electricity if the energy levels were taken into account as well as the lower cost of heat products. This reveals the importance of allocating the costs fairly to the energy products of the system to avoid underestimation of the prices of high-quality products. Integrating the concentrated PVT collectors reduced the exergo-economic cost by 6.4% compared to the SHCs.

Table 2. The exergy destruction caused by each system component [69].

System Component	Energy Efficiency
AHP	26.3%
HX	0.36%
ICE	31.45%
PVT	41.59%
Thermal energy storage	0.30%

Chen et al. [70] presented the exergy and exergo-economic analysis of the solar-driven combined cooling, heating and power system based on the organic Rankine cycle and absorption heat pump for residential energy production. The system included parabolic trough collectors (PTC) for solar heat production and a geothermal energy source. In their analysis, the energy levels of the products were taken into account, and the steady-state analysis was separated into three seasons: heating, cooling and transition. Additionally, the analysis was conducted under conditions of four different climatic regions in China. The reference temperature of the analysis was selected to be the average ambient temperature of each season and was specific for each location. The results for the system were an annual overall exergy efficiency of 9.6% and energy efficiency of 56.5%. The PTCs caused the highest exergy destruction in the system. The specific cost of electricity was the highest during the heating period in each location and lowest in the cooling period, resulting in 0.106 USD/kWh in Beijing. The annual cost of electricity was 0.12 USD/kWh and space heating and cooling was 0.31 USD/kWh and 0.22 USD/kWh, respectively.

The above-mentioned exergo-economic studies considered only steady-state operation conditions. This approach has been used more in large power plant applications where the exergy flows stay constant over a certain period. However, when including solar technologies and highly dynamic residential energy demand profiles in the analyzed system, dynamic system analysis is more recommended than a steady-state.

Calise et al. [71] presented a dynamic exergy and exergo-economic analysis of a renewable polygeneration system that provided heating, cooling, electricity and fresh water for small, isolated communities in Naples, Italy. The system model was built into the TRNSYS simulation environment and combined concentrated PVT collectors, a biomass heater, an absorption chiller and multiple-effect distillation for seawater desalination. They were able to present the exergy flows and efficiencies of each system component on an hourly level. Additionally, they presented the exergo-economic costs of the energy products on weekly and seasonal levels. However, in their SPECO-based analysis, the energy levels of different energy products were not taken into account, and the reference temperature of 25 °C was selected to be constant over a year. As discussed in Section 3.1, the reference temperature has a higher influence on the exergy generation if the system operates close to the ambient conditions. This would lead to a recommendation of using a changing reference temperature.

In [71], the authors' dynamic analysis revealed high fluctuation of the exergo-economic costs of energy products over the year, which cannot be seen from a steady-state analysis. The annual system exergy efficiency was around 10% which was highly sensitive to solar availability. The highest exergy destruction was caused by the concentrated PVT collectors and backup biomass heater. The annual exergo-economic cost of electricity was 0.1748 EUR/kWh, and on the weekly basis, the cost varied from 0.075 EUR/kWh to 1.26 EUR/kWh. The lowest cost was indicated during the weeks from 13 to 45 and the highest during the winter weeks from 1 to 3 and 46 to 52. The annual exergo-economic cost of fresh water, cooling and space heating was 3.457 EUR/kWh_{ex}, 0.9858 €/kWh_{ex} and 0.8057 EUR/kWh_{ex}, respectively.

The authors of this article conducted dynamic exergy and exergo-economic analysis of a novel hybrid renewable energy system based on micro-cogeneration in [9,72]. The analyzed system included market-available components of PVT collectors, a biomass-fired Stirling engine micro-cogeneration system and sensible thermal energy storage. The system model was built into a Matlab/Simulink environment. The analysis was conducted under three different European climates and economic conditions in Tampere, Finland; Strasbourg, France; Barcelona, Spain. The reference building was simulated by IDA ICE software, and the location-specific building construction was considered in defining the U-values of the building envelope. The reference temperature was selected to be the minimum monthly temperature in each location. The results were presented on an annual and monthly basis, and the SPECO method was used in the exergo-economic analysis by taking into account the energy levels of the products.

In this study [9], the annual overall exergy efficiency varied from 13% to 16% depending on the location. The PVT collectors caused the highest exergy destruction during the summer, and the micro-cogeneration unit during the winter. The hybridization reduced costly exergy destruction caused by the micro-cogeneration unit. The annual exergo-economic cost of electricity was 28% lower in Barcelona than in other locations because of the higher share of the PVT production and the lower utilization of the costly micro-CHP unit. Additionally, there were more beneficial economic conditions. The exergo-economic cost of electricity varied from 0.189 EUR/kWh to 0.798 EUR/kWh depending on the month and location, as presented in Figure 5. The lowest cost resulted during the summer months due to good solar availability in each location. The lowest space heating and domestic hot water costs were 0.26 EUR/kWh$_{ex}$ and 0.35 EUR/kWh$_{ex}$, respectively.

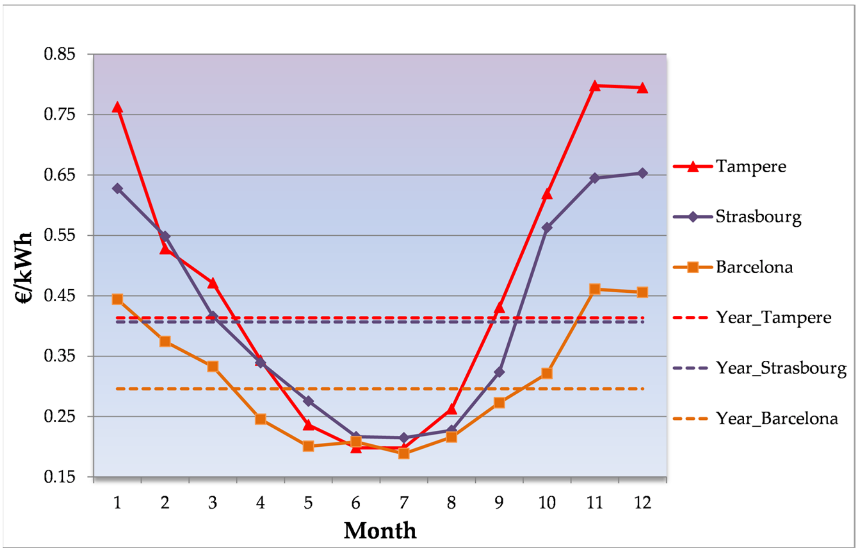

Figure 5. The exergo-economic cost of electricity on monthly and annual basis in different locations adapted from [9].

4. Conclusions

In this paper, a review of exergy and exergo-economic analysis applied to building-related hybrid renewable energy systems was presented. First, the methodology of the exergy and exergo-economic analysis was introduced as well as the main performance indicators. The reference temperature was found to have a high impact on the results, especially on ambient temperatures at which the building energy systems are operating. The lack of a general reference temperature makes the comparison of the different results difficult.

The review revealed that the dynamic exergy analysis is the best way to evaluate hybrid renewable energy systems if they are operating under a dynamic environment caused by weather conditions and/or energy demand. The review also revealed that typical building energy system technologies, such as the electric heater and heat pump, have lower exergy performance than energy performance. The highest exergy efficiency was reached with the cogeneration system. However, the matching of the supply and demand quality levels in the building environment suggested using renewable and low-quality fuels, such as geothermal heat, solar and waste heat. In terms of exergy, combustion-based energy production should be avoided in the buildings to have a reasonable matching of the quality levels. High-quality fuels, such as fossil fuels or biomass, should be used only to generate electricity if possible. The exergy analysis is a highly recommended tool to improve and optimize hybrid renewable energy systems.

Finally, several studies in the literature using exergy and exergo-economic analysis applied to the photovoltaic–thermal collectors, fuel-fired micro-cogeneration systems and hybrid renewable energy systems were reviewed. The review showed variety in selecting the reference temperature and using the steady-state or dynamic analysis approach. However, the common result between the studies was to have significantly higher energy than exergy efficiency of the energy system. The average ambient temperature was the most used reference temperature, which is reasonable if the system's behavior depends on the ambient conditions, such as the PVT and heating demand of a building. This reveals the reality that the quality of thermal energy is not the same in each location and time of the year. The dynamic exergo-economic analysis of different hybrid renewable energy systems revealed the similar dynamic behavior of the exergo-economic costs of the energy products, which was impossible to indicate from the steady-state analysis. This result emphasizes the importance of using the dynamic approach in the exergo-economic analysis as well if the system is depending on the dynamic environment. The results showed that exergo-economics is a reasonable costing method for the decentralized HRES with cogeneration for the micro-grid prosumers.

For future work, the commonly accepted exergy approach with the reference environment should be established to ensure the implementation of the exergy analysis in the energy-related strategies and modelling of communities and countries, as has been realized in Switzerland by Codina et al. [73]. Additionally, the exergo-economic analysis should be applied more as a costing method when evaluating the prices of the prosumers' energy products fed to the thermal or electrical grid, as proposed in [74].

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