

Review

# Multi-Criteria Decision-Making (MCDM) for the Assessment of Renewable Energy Technologies in a Household: A Review

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**Abstract:** Different power generation technologies have different advantages and disadvantages. However, if compared to traditional energy sources, renewable energy sources provide a possibility to solve the climate change and economic decarbonization issues that are so relevant today. Therefore, the analysis and evaluation of renewable energy technologies has been receiving increasing attention in the politics of different countries and the scientific literature. The household sector consumes almost one third of all energy produced, thus studies on the evaluation of renewable energy production technologies in households are very important. This article reviews the scientific literature that have used multiple-criteria decision-making (MCDM) methods as a key tool to evaluate renewable energy technologies in households. The findings of the conducted research are categorized according to the objectives pursued and the criteria on which the evaluation was based are discussed. The article also provides an overview and in-depth analysis of MCDM methods and distinguishes the main advantages and disadvantages of using them to evaluate technologies in households.

**Keywords:** renewable energy technologies; multi-criteria decision-making; MCDM; household; technologies assessment; RES

## 1. Introduction

The fast development and deployment of efficient renewable energy technologies in different regions of the world has taken place in recent years. Currently, many technologies with high efficiency and reduced cost are available [1]. However, despite already existing achievements in the development of renewable energy sources (RESs) and technology efficiency, it is very important to accelerate RES deployment in all regions of the world and seek to generate energy from RESs. The household sector is the third-largest consumer of energy in the world, with an energy demand of 27% of the total produces. Although greenhouse gas (GHG) emissions from households tend to decline in many regions of the world [2], households still account for 30%–40% of total GHG emissions [3]. According to the findings of the research conducted by Ahlering et al. [4], 93% of direct emissions from the residential sector are due to fuel combustion, i.e., in transport and heating. Therefore, more sustainable use of energy, and in particular, the introduction of renewable energy technologies in households can be one of the key instruments for combating climate change [5]. However, despite technologies becoming cheaper in recent years, the price is still one of the main factors hindering investments [6]. The transition of households to a new power generation system is determined by many factors. These factors differ depending on the economic situation, access to sources, public awareness, state promotion policies, etc. of a particular region. Energy sources used in households can be divided into the following two main

groups: fossil fuels, which include natural gas, oil, and coal; and renewable energy technologies, which include both conventional biomass and modern sources, such as solar, wind, and geothermal energy.

Usually, there are many contradictory aspects when experts want to determine which renewable energy production system could be the most suitable for a household. For example, cost-effectiveness does not always mean convenience or the most environmentally friendly technology, whereas cheap and reliable power supply does not always directly correlate with installation costs and payback. Multi-criteria decision-making (MCDM) methods provide a possibility to evaluate these and other conflicting factors [7] and to decide which alternative is the most suitable according to different criteria. This is the main advantage when comparing with other possibilities regarding making a decision. It is precisely for this reason that it is a very suitable tool to determine which energy production technology is the most suitable for households. There are many different approaches of MCDM, as well as many different criteria that can be used as the basis for the evaluation of technologies. Therefore, the purpose of this article is to review the scientific literature that has used MCDM methods as a key tool to evaluate renewable energy technologies in households, highlighting advantages and disadvantages of MCDM methods, and analyzing the criteria on which the evaluation was based. We reviewed 271 scientific studies, grouped evaluation indicators, distinguished advantages and disadvantages of MCDM methods, and made suggestions for future research design. Such a comprehensive analysis of research using MCDM methods for the evaluation of renewable energy technologies in households allows us to see the potential of each method. Grouped evaluation indicators will make the design of future studies easier, while the distinguished advantages and disadvantages of MCDM methods will help to establish which method is the most suitable for the assessment of technologies in households. The second part of the article provides an overview of the main renewable energy technologies in households. The third part of the article presents a comprehensive analysis of research using MCDM techniques for technology evaluation. The findings of the conducted research are categorized according to the objective pursued, and the criteria on which the evaluation was based are also distinguished and discussed in this part of the article. The fourth part of the article presents an overview and in-depth analysis of MCDM methods, as well as distinguishing the main advantages and disadvantages of using them toward evaluating technologies in households.

## 2. Renewable Energy Technologies in Households

From a household perspective, the use of renewable energy technologies offers a considerable number of benefits, i.e., it improves living conditions by using energy more productively, contributes to sustainable spatial planning and architecture, helps to protect the quality of the environment, and distributes energy in a balanced way and thus gives financial autonomy [8–11]. Solar photovoltaic (PV) and solar thermal, micro wind, heat pumps, and small-scale biomass heating technologies can be distinguished as the main renewable energy technologies in households [12].

### 2.1. Solar Photovoltaic (PV) and Solar Thermal Technology

Solar power could meet the total annual global energy demand, with an average of 1.6 MWh/m<sup>2</sup> of solar power per year [13], yet the annual solar radiation varies widely across the world. Solar power can be used to produce heat and electricity. Solar radiation is converted into thermal energy in solar collectors, and electricity is obtained directly from sunlight using photovoltaic cells. Thermal energy can be used for both water heating and indoor heating. Solar power plants operate autonomously or when connected to the grid. In the first case, the electricity produced is stored in accumulators, which ensure the supply of electricity in the event of demand. There is no need for a battery if the electrical equipment is connected to the power grid, and the electricity produced can be used for one's own consumption and the unused electricity can be supplied to the grid. Solar power is inexhaustible, abundant, and technological achievements in photovoltaics (PV) in the last decade have significantly increased the efficiency of solar energy production [14] and reduced installation costs [13]. In both solar PV and solar thermal technology, solar collectors in households are usually mounted on the rooftops

or in other convenient locations to collect as much sunlight as possible. By absorbing solar energy, the solar thermal system can heat or cool the water. Solar thermal systems differ from solar PV technology as they do not generate electricity.

### *2.2. Micro Wind Technology*

Wind power is based on mature technologies and political incentives in many parts of the world. Increased efficiency and capacity of batteries increase the use of this type of energy [14,15]. Micro wind technology involves a much smaller device than is conventionally used for wind power generation, making it suitable for the production of energy for households. The following two types of wind turbines can be installed: vertical-axis or horizontal-axis wind turbines. The majority of households install wind turbines on the rooftop or a pole to produce wind power, and the efficiency of the technology depends on the size of the turbine and the windiness at that time of year in that area. This technology converts wind into electricity, which could be used for both indoor heating and water heating. Electricity generation is largely based on the rotation speed of the wind turbine; therefore, some geographical areas are more (or less) suitable for electricity generation than others. Wind turbines may also be affected by potential obstructions that are nearby to the wind turbines, such as trees or buildings, which stop or deflect the wind and prevent the turbines from operating at full capacity. In contrast to solar power, this technology emits noise (depending on the make and size of the turbine itself); therefore, if the turbine is on the rooftop of the house, it may be one of the drawbacks for some households.

### *2.3. Heat Pumps Technology*

A heat pump is a device that can supply heating, cooling, and hot water for residential, commercial, and industrial use. Any heat pump equipment can provide heating and cooling at the same time. Depending on the function a device performs, it is called a heat pump, an air-conditioning unit, or a cooling/refrigeration machine [16]. Most of the energy produced is obtained from the environment: heat pumps can use renewable energy from the air, water, or ground. Air source heat pumps use outdoor, indoor, or exhaust air as a source of energy. Ground source (or geothermal) heat pumps use energy from the ground that is generated through a closed-loop horizontal or vertical collector. The energy obtained from the ground is transferred to brine or water and transferred to a heat pump. Water source heat pumps work the same way as ground source (or geothermal) heat pumps. The only difference is that they use the water directly instead of using a closed-loop heat exchanger. Water heat pumps can be connected to rivers, lakes, sewage, cooling water, etc. [17]. There may also be a hybrid heat pump system. Typical combinations are as follows: air source heat pumps and a small gas boiler, heat pump and solar thermal collector [17,18], heat pump and biomass boiler, and heat pump and direct electric back up [16]. The efficiency of heat pump systems depends on the efficiency of the unit itself and the thermal energy needs of the building in which it is used. Specifically, in the case of a private household, the energy demand of a building largely depends on its energy quality and the climatic zone in which it is located [19].

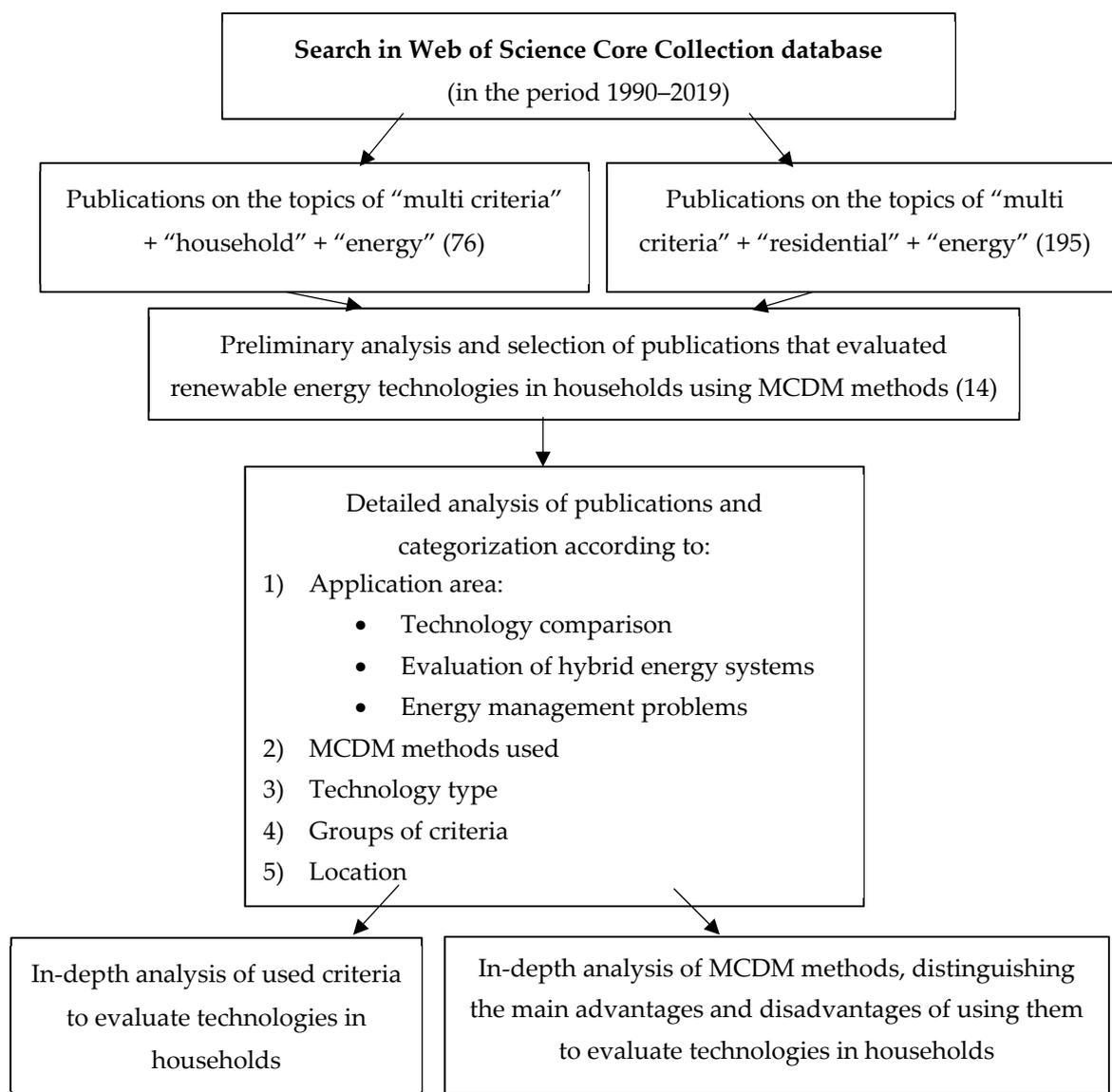
### *2.4. Small-Scale Biomass Heating Technology (Biomass Boilers and Pellet Stoves)*

Small-scale biomass heating systems are usually installed in private households. Wood and by-products of the wood industry are the raw materials used for heat production with this technology. Firewood, wood chips, and wood pellets are most commonly used to heat a private household. Firewood is the oldest and most commonly used form of biomass. The popularity of wood chips has been growing rapidly lately due to the possibility of using them in automatic biomass heating systems. Choosing such a system offers more advantages for people who want to save time and seek comfort compared with traditional wood, i.e., firewood. Wood chips are made from wood waste, other wood products, or are directly made from logs. Wood pellets are the most convenient and sustainable choice compared to the aforementioned alternatives. This fuel is made from sawdust and wood chips and pressed under high pressure without glue or other chemical additives. Wood pellets are high in

energy, easy to transport and store, and are suitable fuel for small, fully automated heating systems. The newest biomass boilers are distinguished for their efficiency and low carbon monoxide (CO) emissions. The efficiency of new biomass boilers increased from about 55% to more than 90%, while the average CO emissions decreased from 15,000 mg/m<sup>3</sup> to less than 50 mg/m<sup>3</sup> [20].

### 3. Literature Review

In order to review the scientific literature, the publications on different topic combinations stored in the Web of Science database were analyzed. A total of 76 scientific studies were reviewed on the topics of “multi criteria” + “household” + “energy,” of which, the assessment of renewable energy technologies in household was carried out in only 9. A total of 195 scientific studies were review on the topics of “multi criteria” + “residential” + “energy,” of which, the assessment of renewable energy technologies in household was carried out in only 5. A diagram of the literature searches and analysis process is given in Figure 1 below.



**Figure 1.** The procedure used for the literature review analysis.

### *3.1. Assessment of Renewable Energy Technologies in Households*

The use of MCDM methods to solve energy sector issues is gaining popularity and becoming one of the main tools, where the use of MCDM methods to evaluate different power generation technologies is one of the highest compared to other methods. A review and analysis of publications that have used MCDM methods to solve energy sustainability issues are presented by Siksnyte et al. [21]. Although it is recognized that the use of renewable energy technologies by households could make a major contribution to the development of a more sustainable energy system and to the decarbonization of each country's economy, the scientific literature does not focus on energy technologies in households. Only in the last 2 years has there been more active publications of research, suggesting that the popularity of such studies will increase significantly in the future. Classification of the reviewed studies is provided in Table 1.

**Table 1.** Classification of reviewed studies on multi-criteria decision-making (MCDM).

Application Areas	Methods Used	Technology Type	Groups of Criteria	Locations	Years of Publications
<ul style="list-style-type: none"> <li>• Technology comparison</li> <li>• Evaluation of hybrid energy systems</li> <li>• Energy management problems</li> </ul>	<ul style="list-style-type: none"> <li>• Criteria importance through intercriteria correlation (CRITIC) [22]</li> <li>• Technique for order of preference by similarity to the ideal solution (TOPSIS) [23]</li> <li>• Analytical hierarchy process (AHP) [24]</li> <li>• Evaluation based on distance from average solution (EDAS) [25]</li> <li>• Weighted aggregated sum product assessment (WASPAS) [26]</li> <li>• Preference ranking organization method for enriching evaluation (PROMETHEE) [27]</li> <li>• Weighted sum method (WSM) [28]</li> <li>• Data envelopment analysis (DEA) [29]</li> </ul>	<ul style="list-style-type: none"> <li>• Solar thermal</li> <li>• Solar panel</li> <li>• Biomass boilers</li> <li>• Micro wind installations</li> <li>• Heat pumps</li> <li>• Gasoline generator</li> <li>• Battery bank</li> <li>• Gas engine</li> <li>• Fuel cell</li> <li>• Air conditioner</li> <li>• Gas boiler</li> <li>• Electric boiler</li> <li>• Utility grid</li> </ul>	<ul style="list-style-type: none"> <li>• Economic</li> <li>• Social</li> <li>• Technological</li> <li>• Environmental</li> <li>• Institutional</li> <li>• Thermodynamic</li> <li>• Acidification</li> <li>• Energetic</li> <li>• Usability</li> <li>• Energetic</li> <li>• Comfort</li> <li>• Functionality</li> <li>• Cost</li> <li>• Benefit</li> </ul>	<ul style="list-style-type: none"> <li>• Lagos state, Nigeria</li> <li>• Pakistan</li> <li>• Ward, Yenagoa, Port Harcourt, Uyo and Calabar, Benin city, Nigeria</li> <li>• Lithuania</li> <li>• Peru</li> <li>• City Novi Sad, Serbia</li> <li>• Narvijoki, Finland</li> <li>• Ontario, Canada</li> <li>• Finland</li> <li>• Denmark</li> <li>• Lithuania</li> <li>• Beijing, China</li> <li>• Kitakyushu, Japan</li> </ul>	<ul style="list-style-type: none"> <li>• 2009 (1)</li> <li>• 2012 (1)</li> <li>• 2014 (1)</li> <li>• 2015 (1)</li> <li>• 2016 (1)</li> <li>• 2017 (1)</li> <li>• 2018 (3)</li> <li>• 2019 (5)</li> </ul>

The assessment of renewable energy technologies in households using MCDM methods are performed for different purposes. The articles can be grouped in three main categories according to their objectives as follows:

1. Technology comparison (comparison of individual technologies).
2. Evaluation of hybrid energy systems (including renewables mix and renewables and non-renewables mix).
3. Energy management problems (such as the assessment of support instruments and political decisions).

For the first group, namely technology comparison, the articles are summarized in Table 2.

**Table 2.** Technology comparison category.

Aim of the Study	MCDM Method	Case Study Location	Technologies	Main Contribution of the Study	Source
The development and validation of an MCDM tool for the assessment of the optimal energy technology.	AHP, PROMETHEE	Kitakyushu, Japan	Utility grid; photovoltaic; wind turbine; batter, gas engine, fuel cell; air conditioner; gas boiler; electric boiler	An integrated evaluation methodology for the assessment of the optimal energy technology was developed by combining linear programming and two MCDM methods. The results of the evaluation show, that renewable energy systems are not competitive.	[30]
The assessment of six household-level heating technologies.	Piecemeal WSM	Finland	Light fuel oil boilers; conventional, current, and future batch-wise combustion; pellet chip stoves; wood chip stoves; gasification technology with pellets chips; gasification technology with wood chips	None of the alternatives was the best in all impact categories.	[31]
The presentation of a new integrated assessment model of building energy supply system (ESSINTEGRA), which provides a rational solution of the energy supply for an energy-efficient house.	WASPAS	Lithuania	Wood boiler, pellet boiler, condensing gas boiler, air–water heat pump, ground–water heat pump, solar collectors, photovoltaic modules	The proposed assessment model can be used to explore a larger number of alternatives, which comprise different renewable energy technologies and their combinations.	[32]

Table 2. Cont.

Aim of the Study	MCDM Method	Case Study Location	Technologies	Main Contribution of the Study	Source
The assessment of three household-level heating technologies.	TOPSIS	Denmark	Solar heating, heat pumps and wood pellet boilers	Solar heating was the best alternative for individual heating, heat pumps was the second-best alternative, wood pellet boiler was the least attractive.	[33]
The establishment of multi-criteria framework for assessment of the public and private impacts associated with the use of renewable energy generation technologies in household sector.	TOPSIS, EDAS, WASPAS	Lithuania	Solar thermal, solar panel, biomass boilers, micro wind installations	The biomass boiler and solar thermal system were the most preferable micro energy generation technologies for use in Lithuania.	[34]
The evaluation and prioritization of the renewable energy technologies in order to fulfill the demand of electricity in the household sector of Pakistan.	AHP	Pakistan	Solar, wind, biomass, geothermal, ocean, hydro energy	Solar energy is the best renewable technology alternative for Pakistan to solve electricity the scarcity problem in the household sector.	[35]
The creation of a methodology for the selection of the most sustainable energy alternative for electricity generation in a residential building.	Fuzzy AHP, Fuzzy PROMETHEE	-	Solar, wind, biomass, geothermal, hydro energy	The proposed integrated MCDM method makes the process easier for the selection of the best renewable energy alternatives. The method was effective at handling uncertain data.	[36]

The article of Ren et al. [30] provides a methodology that helps to evaluate which energy production technology is the most optimal for a household. The authors used linear programming, as well as analytical hierarchy process (AHP) and preference ranking organization method for enriching evaluation (PROMETHEE) multi-criteria methods. The proposed methodology was tested for one Japanese household. The study revealed that renewable energy technologies were not competitive with traditional technologies in the years under research. However, it should be noted that the authors only included four criteria (two economic, one environmental, one energy) in their methodology, which is very low compared to other studies of this type.

Ekholm et al. [31] evaluated six different household-level heating technologies. The authors assessed the health, climate, and acidification impacts using the weighted sum method (WSM) for each impact area separately. The study revealed that none of the technologies was the best in all three impact areas. However, the authors did not take full advantage of the MCDM methods and did not attempt to evaluate which technology would be best when compared to others. Similarly, the criteria identified by the authors in this study related only to pollution without considering the economic or technological aspects, which are very important to the households for the development of various technologies.

The research conducted was for a specific region; therefore, which technology was the best in this region for households could be evaluated if economic and technological aspects were integrated.

The study of Dziugaite-Tumeniene et al. [32] presented an integrated assessment model of a building's energy supply system (ESSINTEGRA), which helps to select the most rational energy supply solution for households. The authors evaluated seven different renewable technologies that could be used to meet the needs of the households depending on the characteristics of the building. The WASPAS method was used to determine energy alternatives. The evaluation model proposed by the authors can also be used to explore more alternatives consisting of different renewable energy technologies and their combinations. The study revealed that biomass and solar power technologies were among the most studied alternatives to reduce the impact on the environment and have the potential to significantly increase the use of renewable energy.

The study of Yang et al. [33] identified which of the available alternatives was the most suitable for the implementation of the Danish energy strategy by 2035. One of the goals of this strategy was to replace all oil boilers with heating systems based on renewable technologies. The authors applied the technique for order of preference by similarity to the ideal solution (TOPSIS) method as a primary tool to prioritize the alternatives. According to the criteria chosen, solar heating was the most suitable alternative for private households, while heat pumps were in the second place and wood pellet boilers were in last place.

Zhang et al. [34] sought to develop a multi-criteria assessment system that would help to evaluate the impact of public and private sectors regarding the use of renewable energy technologies in households. The authors adapted the developed system for the evaluation of renewable technologies in Lithuanian households. The use of three MCDM methods (TOPSIS, evaluation based on distance from average solution (EDAS), and weighted aggregated sum product assessment (WASPAS)) showed that biomass boiler and solar thermal technologies were the most suitable.

Saleem and Ulfat [35] evaluated renewable energy technologies using the AHP method and prioritized the technologies that could help to meet electricity demand in the household sector in Pakistan. Solar power was found to be the best renewable energy option for Pakistan in order to solve the problem related to a lack of electricity in the household sector. The second-best-ranked alternative was wind power, the third was biomass, the fourth was hydro, and the last were ocean and geothermal energy.

Seddiki and Bennadji [36] proposed an integrated methodology, i.e., a new fuzzy integrated Delphi-AHP-PROMETHEE method that helps to select the best renewable energy alternative for electricity generation. The proposed methodology includes a process of matching expert interviews and responses, selecting evaluation criteria, and the integration of multi-criteria analysis methods.

The second group of articles, involving evaluation of hybrid energy systems, are summarized in Table 3.

**Table 3.** Evaluation of hybrid energy systems category.

Aim of the Study	MCDM Method	Case Study Location	Technologies	Main Contribution of the Study	Source
The creation of a decision-making methodology for combined cooling, heating, and power (CCHP) systems driven by different energy sources.	Fuzzy AHP	Beijing, China	Traditional CCHP system driven by gas engine, fuel cell CCHP system, biomass CCHP system, CCHP system based on a gas-steam combined cycle, separation production system	The proposed methodology quantifies uncertainty information and qualitative assessment. The best option from the view of selected criteria was a CCHP system based on a gas-steam combined cycle.	[37]

Table 3. Cont.

Aim of the Study	MCDM Method	Case Study Location	Technologies	Main Contribution of the Study	Source
The development of a methodology to assess the sustainability of energy systems.	WSM	Ontario, Canada	Hydrogen-based storage with solar panels, wind-biomass energy system	The results show that the renewable hybrid energy system was affordable for households in southern Ontario. The developed methodology could be useful as a decision analysis tool for policy and decision-makers to evaluate energy system sustainability.	[38]
An assessment of five renewable energy options in order to find the most sustainable energy system combination.	AHP	Narvijoki, Finland	A non-biomass renewable energy of wind power and hydro power, hydropower combined with solar electricity, a small-scale combined heat and power (CHP) plant with solar electricity	A non-biomass renewable energy option of wind power and hydro power had less of a negative impact than other scenarios.	[39]
The selection of a hybrid renewable energy system for households in six locations in the south-south geopolitical zone of Nigeria in order to solve the rural electrification problem.	TOPSIS	Ward, Yenagoa, Port Harcourt, Uyo and Calabar, Benin-city, Nigeria	Photovoltaic modules, wind, battery, diesel generator	The best hybrid renewable energy system for the three locations (Benin-city, Yenagoa, Port Harcourt) was the diesel generator–photovoltaic modules–wind–battery energy system; for the other locations (Warri, Uyo, Calabar) the best alternative was the photovoltaic modules-wind-battery system.	[40]
The selection of a hybrid renewable energy system for a low-income household.	CRITIC, TOPSIS	Lagos state, Nigeria	Photovoltaic modules, wind, battery, gasoline generator	The most suitable hybrid renewable energy system for a low-income household was the photovoltaic modules-gasoline generator-battery system.	[41]

Jing et al. [37] proposed a model for the assessment of a combined cooling, heating, and power (CCHP) system that helps to evaluate energy production systems from a technical, economic, social, and environmental point of view. The authors also tested the methodology in the case of one residential building in the capital of China, and five alternatives of CCHP were investigated. The authors integrated the fuzzy AHP method in the methodology proposed by them.

Hacatoglu et al. [38] sought to develop a methodology that would help policy makers and other decision-makers to evaluate the sustainability of energy systems. The authors proposed the use of the simplest MCDM method, i.e., WSM, and to apply thermodynamic, economic, and environmental factors for the sustainability evaluation [42]. On the basis of the proposed methodology, the sustainability of hydrogen-based storage with a solar–PV–wind–biomass energy system was evaluated for 50 households in Ontario, Canada. The study revealed that the proposed hybrid energy system based on renewable sources was suitable to meet the needs of these households according to different criteria.

Vaisanen et al. [39], using AHP and life cycle assessment (LCA) methods, sought to determine the most sustainable energy production scenario for a small Norwegian region. The authors investigated the following three technological options for power generation: combined wind and hydropower, hydro and solar energy, and a small-scale CHP plant with solar electricity. The study revealed that combined wind and hydro power was the most sustainable way to supply energy for households in the study area.

Diemuodeke et al. [40], using TOPSIS and Hybrid Optimization of Multiple Electric Renewables (HOMER) software, identified the best hybrid alternatives for renewable energy production in six different regions of Nigeria, which currently have one of the world’s largest electricity deficits for households, especially in rural areas. The authors modelled alternatives by combining photovoltaic modules, wind, battery, and diesel generator power generation systems. The study revealed that a diesel generator–photovoltaic module–wind–battery system would be the most suitable for three regions, while the other three regions would benefit most from a photovoltaic module–wind–battery system.

Babatunde et al. [41] applied criteria importance through intercriteria correlation (CRITIC) and TOPSIS methods, as well as HOMER software, in their study in order to design the most suitable hybrid renewable energy system for low-income households in one of the Nigeria’s regions. The research focused on the modelling of photovoltaic module, wind, battery, and gasoline generator power generation systems and revealed that a photovoltaic module–gasoline generator–battery system was the most suitable according to different criteria.

Articles that solve energy management problems are summarized in Table 4.

**Table 4.** Energy management problems category.

Aim of the Study	Method	Case Study Location	Technologies	Main Contribution of the Study	Source
The development and validation of an MCDM tool for the assessment of household biogas digester programs in rural areas of Latin America.	DEA	Peru	Biogas digester	The methodology for the assessment of household biogas digester programs in rural areas was developed and validated. The methodology created consists of three decision levels, the most important criteria are related to socio-economic aspects, proper digester operation, and digester reliability and durability.	[43]

Table 4. Cont.

Aim of the Study	Method	Case Study Location	Technologies	Main Contribution of the Study	Source
An assessment of support instruments for heating in the household sector and seeking to increase renewable energy sources in meeting energy needs.	PROMETHEE	City Novi Sad, Serbia	Natural gas radiators, natural gas floor heating, electricity, Systems based on wood pellets, systems based on agro pellets, systems based on heat pumps	Investors gave priority to the criteria relating to investment and operational costs.	[44]

Ferrer-Marti et al. [43] created and tested a methodology that was used to evaluate household biogas digester programs in Latin America. The methodology developed by the authors covers the following three levels of decision-making: community, digester model, and digester design selection, and integrates the DEA-compromise programming approach. It is also worth noting that the most important criteria at all levels of decision-making are related to social and economic aspects, as well as the proper operation of the stove and its reliability and durability. The DEA method was introduced by Charnes in 1979 [29]. The method has been developed to evaluate efficiency and is based on mathematical programming [45]. DEA measures the efficiencies of a homogeneous set of decision-making units based on their multiple inputs and outputs [46,47]. The tool is a valuable approach and is used alternatively from or in addition to MCDM. For this reason, Ferrer-Marti et al.’s [43] publication was included in this review.

Vasic [44] evaluated six alternatives to domestic heating using the PROMETHEE method. The study revealed that in order to increase the use of renewable energy sources for heating households in Serbia, special attention should be paid to financial support mechanisms since financial aspects are the most important for those who invest in power generation systems.

3.2. Criteria for Assessment in MCDM models

In this section, a literature review of the criteria for the assessment of renewable energy technologies in household using MCDM methods is discussed. The four most commonly used criteria were economic, social, technological, and environmental. One of the essential indicators for the assessment of renewable energy technologies in households is the economic criterion. It was determined that investment cost, operative and maintenance cost, return on investment, and total net present cost were the most commonly involved criteria used in the assessment of different technologies. All used economic criteria are summarized in Table 5.

Table 5. The overview of economic criteria.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
Total net present cost	+	+		[32,40,41]
Operating cost, maintenance costs, annual costs of year, and running cost	+	+	+	[30,32,33,35,36,41, 43,44]
Cost of energy		+		[40,41]

Table 5. Cont.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
Return on investment, internal rate of return, and payback period	+	+		[33,36,41]
Production capacity	+			[35]
Initial capital cost, initial investment cost, and investment cost	+	+	+	[30,32,33,35,36,40,43,44]
Cost of fuel		+		[40]
Economic development			+	[44]
Affordability		+		[39]
Job creation		+		[39]
Commercial viability		+		[38]
Resource availability		+		[38]
Net present value	+			[36]
Reduced energy bill	+			[33]
Subsidy	+			[33]
Discount rate for year	+			[32]
Residual value of technology	+			[32]

As summarized in Table 6, the most commonly used social criteria were sociocultural awareness, public acceptance, and impact on climate and health. Furthermore, the convenience of the technology also plays a very important role.

Table 6. The overview of social criteria.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
Affordability and ability to pay		+	+	[41,43]
Sociocultural awareness		+	+	[40,41,43]
Sum of climate and health impacts of emissions, footprint, and land area used	+	+		[31,35,37]
Degree of acceptance from society, public acceptance, and social acceptability	+	+		[35,36,39]
Jobs created	+			[35]
Standard of living			+	[43]
Number of potential beneficiaries			+	[43]

Table 6. Cont.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
Health improvement and health		+	+	[39,43]
Access to alternative fuels			+	[43]
Local resources		+		[39]
Inconvenience of the system and maintenance convenience	+	+		[36,37]
Advanced performance		+		[37]
Safeguards		+		[37]

Based on the literature review, the most commonly used technological criteria were renewable fractions, equipment performance time, and reliability. Technological criteria are summarized in Table 7.

Table 7. The overview of technological criteria.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
Total energy production and equipment output power capacity	+	+		[35,41]
Renewable fraction, natural resources availability, and renewability		+		[39–41]
Capacity shortage, adequacy (share of the new energy production, overall energy production), and unmet load		+		[39–41]
Excess electricity		+		[41]
Ease of installation		+		[40,41]
Equipment performance time, life cycle assessment, and lifespan	+	+	+	[35,40,43]
Effective equipment performance of efficiency, efficiency, and high performance	+			[33,35,36]
Technology readiness and commercial maturity of the technology		+	+	[37,40,44]
Presence of skilled laborers in the community			+	[43]

Table 7. Cont.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
Material availability, water needed, and surface requirement	+		+	[36,43]
Ease of daily and maintenance tasks, comfort in the use of the system, and easy to use	+		+	[33,43,44]
Energy return on investment		+		[39]
Reliability and few reparations	+	+		[33,36,39]
Compatibility (grid electricity need)		+		[39]
Primary energy consumption ratio		+		[37]
Exergy efficiency		+		[37]
Regulation property and control property		+		[37]

Environmental criteria are summarized in Table 8. In order to assess the environmental impact of different technologies the most commonly used were GHG intensity and environmental impact criteria. CO<sub>2</sub> emissions, CO<sub>2</sub> and SO<sub>2</sub> emissions, GHG intensity, and GHG emissions were involved in 80% of studies when comparing different renewable energy technologies in household.

Table 8. The overview of environmental criteria.

Criteria	Technology Comparison Category	Evaluation of Hybrid Energy Systems Category	Energy Management Problems Category	Source
CO <sub>2</sub> emissions, CO <sub>2</sub> and SO <sub>2</sub> emissions, GHG intensity, and GHG emissions	+	+	+	[30–33,35–41, 44]
Natural resources availability		+		[41]
Impact on ecological system, Environmental impact, global environmental impact, and life-cycle environmental impact	+	+	+	[35,36,38–40, 43]
Renewable fraction and use of renewable energy	+	+		[33,40]
Agricultural land availability and land area		+	+	[39,43]
Biodiversity		+		[39]
Noise		+		[37]

Zhang et al. [34] chose completely different criteria for their evaluation methodology. The authors divided the criteria into the following two categories: cost criteria and benefit criteria. In addition to economic, social, technical, and environmental criteria, Vaisanen et al. [39] also included institutional

criteria, which are as follows: compatibility with the Renewable Energy Directive, consistency with fiscal policy, and consistency with the public affairs of a country. In addition to economic and environmental criteria, Hacatoglu et al. [38] included thermodynamic criteria for the evaluation of hybrid renewable energy systems. Yet, the criteria of this group can also be named as technical ones since they include energy efficiency, energy efficiency, and size factors. In addition to social and environmental criteria, Ekholm et al. [31] included a group of acidification criteria for the evaluation of heating technologies. In addition to the main groups of four criteria, Seddiki and Bennadji [36] also distinguished the groups of energetic and usability criteria; however, the criteria contained therein could complement the most popular four criteria groups, i.e., energy production and ease of use can be classified as technical and disponibility in the social criteria group. Dziugaite-Tumeniene et al. [32] distinguished between energy, ecological, economic, convenience, and functionality criteria. The authors presented the assessment model that is oriented toward the user of energy; therefore, there is a special emphasis on the evaluation of convenience and functionality criteria. As can be seen from the analysis that was carried out, although some of the criteria used by the authors for the evaluation were subdivided into different groups (some are separated, others are combined), all of these criteria can be grouped into the main four groups discussed above.

#### 4. MCDM Models

Although there are many MCDM methods, some of them are more commonly used in certain studies. A detailed analysis of methods used to solve different issues in the sustainable energy sector was carried out in the study by Siksnelyte et al. [21]. This section discusses MCDM methods that are used to evaluate renewable technologies in the household sector.

The WSM was introduced by Zadeh [28]. The method linearly aggregates all the individual objective functions into one objective by using a weight vector. Popularity of the WSM came from its simple form and ease of use [48]. Although the method is very primitive, it could be an independent method or a component of other methods [49]. It could be used for managing simple, single-dimension problems.

The AHP method was proposed by Saaty et al. [24]. The method analyses MCDM questions according to a pairwise comparison scale. The problem is shaped as a hierarchical structure, which consists of three levels that include aim, criteria, and alternatives. The aim is located at the top level of the hierarchical structure, criteria are in the middle level, the alternatives are at the bottom level. The AHP method does not include sophisticated mathematics calculations and allows one to focus on each criterion; therefore, it is one of the most suitable MCDM methods for solving energy sector problems [50], including the comparison of different renewable energy technologies in households. However, it should be noted that the problem-solving process is quite complicated when more than one decision-maker is involved.

The TOPSIS method was introduced by Hwang and Yoon [23] and is based on the concept that the best solution is that which is closest to the ideal solution [51]. The TOPSIS approach calculates a distance to the positive ideal solution and the distance from the negative ideal solution. The highest closeness value alternative is selected as the best alternative. It is assumed that each attribute has an increasing or decreasing utility.

The CRITIC method was proposed by Diakoulaki et al. in 1995 [22]. CRITIC is an objective weighting approach but there is no need for decision-maker interventions like other weighting methods. The basis of the CRITIC is the intensity of the contrast in the structure of the decision-making question [52]. The method is mostly used to determine the weight of attributes. In the calculation process, it is not necessary to establish the independence of attributes and the qualitative attributes are converted into quantitative attributes.

The EDAS method was introduced by Keshavarz Ghorabae et al. in 2015 [25]. The method is one of the newest and is very practical in conditions with contradictory attributes. The method is characterized as a high efficiency method and involves quite simple calculations. Furthermore,

EDAS is popular in various fuzzy cases [53]. The best solution is chosen by calculating the distance of each alternative from the optimal value. In the calculations, the attributes are independent and all qualitative attributes are converted into quantitative attributes [54].

The WASPAS method was introduced by Zavadskas et al. in 2012 [26]. The method is one of the newest methods of MCDM and is increasingly used. This method is a combination of WSM and the weighted product model (WPM) and is useful for the complete ranking of alternatives. This method determines the relative importance of each criterion and then evaluates and prioritizes alternatives. By combining WSM and WPM methods, WASPAS seeks to reach the highest accuracy [52]. In the calculations, the attributes are independent and all qualitative attributes are converted into quantitative attributes.

The PROMETHEE method was introduced by Brans et al. in 1986 [27]. The method is recognized as an efficient method. There are a few versions of the PROMETHEE method. The success of PROMETHEE methods comes from their mathematical features and their usefulness in solving uncertain and fuzzy information problems. In the calculation process, it is not necessary to establish the independence of attributes and the qualitative attributes are converted into quantitative attributes [51].

Table 9 provides the advantages and disadvantages of MCDM methods that have been used to evaluate renewable technologies in the household sector.

**Table 9.** Advantages and disadvantages of MCDM methods.

Method	Advantages	Disadvantages	Source
WSM	<ul style="list-style-type: none"> <li>• Very simple computation process</li> <li>• Suitable for managing single-dimension problems</li> </ul>	<ul style="list-style-type: none"> <li>• There is no possibility to integrate multiple preferences</li> <li>• Evaluates only one dimension</li> </ul>	[48,49,55,56]
AHP	<ul style="list-style-type: none"> <li>• Can be easily applied to solve different problems</li> <li>• The computation process is quite simple compared with other methods</li> <li>• Results are obtained quite quickly compared to other methods</li> <li>• The method has a comprehensible logic</li> <li>• The method is based on a hierarchical structure; therefore, it has a better focus on each criterion used in the calculations</li> </ul>	<ul style="list-style-type: none"> <li>• Interdependence between alternatives and objectives can lead an inaccurate/wrong result</li> <li>• Additional analysis is required to verify the results</li> <li>• The more decision-makers that are involved, the more complex the assigning weights are</li> <li>• Requires data collected based on experience</li> </ul>	[21,50,57–60]
TOPSIS	<ul style="list-style-type: none"> <li>• Works with a fundamental ranking</li> <li>• The method completely uses allocated information</li> <li>• The information need not be independent</li> <li>• The method has a rational and comprehensible logic, and the concept is in a quite simple mathematical form</li> <li>• The computation process is quite simple compared with other methods</li> <li>• Results are obtained quite quickly compared to other methods</li> </ul>	<ul style="list-style-type: none"> <li>• In principle, the method works based on Euclidean distance and negative and positive values do not influence calculations</li> <li>• A strong deviation of one indicator from the ideal solution strongly influences the results</li> <li>• The method is suitable when the indicators of alternatives do not vary very strongly</li> </ul>	[21,51,61,62]

Table 9. Cont.

Method	Advantages	Disadvantages	Source
CRITIC	<ul style="list-style-type: none"> <li>• One of the most objective methods, where there is no need for decision-makers intervention</li> <li>• The method involves basic statistical operations</li> <li>• The method has simple calculations</li> </ul>	<ul style="list-style-type: none"> <li>• Does not express the relative importance of achieving decision-makers' goals</li> <li>• The method shows only some properties of the initial data</li> <li>• The method does not consider the type of criteria</li> </ul>	[22,52,54]
EDAS	<ul style="list-style-type: none"> <li>• Very practical method in conditions with contradictory attributes</li> <li>• The method characterized as a highly efficient method</li> <li>• Calculations are quite simple</li> <li>• Popular when used for various fuzzy cases</li> </ul>	<ul style="list-style-type: none"> <li>• The method is limited by its hypothesis that the evaluation criteria are compensatory</li> <li>• The method has the same disadvantages as the TOPSIS method; rank reversals not stable</li> </ul>	[53,54]
WASPAS	<ul style="list-style-type: none"> <li>• The method has shorter calculation stages</li> <li>• The method weights the beneficial and non-beneficial criteria in the problem separately</li> <li>• The method is useful for the complete ranking of alternatives</li> <li>• Seeks to reach the highest accuracy</li> </ul>	<ul style="list-style-type: none"> <li>• The method takes into consideration only minimum (for non-beneficial attributes) and maximum (for beneficial attributes) values, and does not consider all the performance values</li> </ul>	[21,52,54,63]
PROMETHEE	<ul style="list-style-type: none"> <li>• The method is especially useful when there are alternatives that are difficult to harmonize</li> <li>• The method works with qualitative and quantitative information</li> <li>• Uncertain and fuzzy information can be incorporated into calculations</li> </ul>	<ul style="list-style-type: none"> <li>• The computation process is quite long compared with other methods</li> <li>• Calculations are very complicated; therefore, the method is only suitable for experts</li> </ul>	[21,54,60,64–66]

## 5. Conclusions

Different power generation technologies have different advantages and disadvantages. However, if compared to traditional energy sources, renewable energy sources provide a possibility to solve climate change and economic decarbonization issues, which are very relevant today. Therefore, the analysis and evaluation of renewable energy technologies has been receiving increasing attention in the politics of different countries and in the scientific literature. The household sector consumes almost one third of all energy produced, thus studies on the evaluation of renewable energy production technologies in households are very important. Since the goals of evaluation from different perspectives (economic, social, environmental, and technological) can be contradictory, the use of MCDM methods in this type of evaluation allows for a comprehensive evaluation of technologies and is one of the best ways to compare them.

The assessment of renewable energy technologies in households using MCDM methods is undertaken for different purposes. According to the aims of the articles, they could be categorized into three main groups: technology comparison articles, evaluation of hybrid energy systems articles, and articles that solve energy management problems.

Grouped evaluation indicators will make the design of future studies easier. Although some of the criteria used by the authors for the evaluation of different renewable energy technologies in household were subdivided into different groups, by their nature, all used criteria can be

grouped into four main groups: economic, social, technological, and environmental. For assessment, renewable energy technologies in households, the four most commonly used criteria were economic, social, technological, and environmental. Investment cost, total net present cost, and operative and maintenance cost were the most commonly used economic criteria. The most commonly used social criteria were sociocultural awareness and public acceptance. The most commonly used technological criteria were renewable fraction, equipment performance time, and reliability. In order to assess the environmental impact of different technologies, the most commonly used were the GHG intensity (80% of studies) and environmental impact (30% of studies) criteria.

The conducted comprehensive analysis of research using MCDM methods for the evaluation of renewable energy technologies in households allows one to see the potential of each method by highlighting the advantages and disadvantages of MCDM methods, which can be used to evaluate which method is the most suitable for the assessment of technologies in households in concrete research, depending on information (qualitative or quantitative), fuzzy cases, qualifications of experts, etc. The WSM method could be used for managing simple, single-dimension problems. Usually, there are many contradictory aspects when seeking to determine which renewable energy production system could be the most suitable for a household. Therefore, the WSM method is not recommended for this type of research. The AHP method does not include sophisticated mathematics calculations and allows one to focus on each criterion; therefore, it is suitable for solving energy sector problems. However, it should be noted that interdependence between alternatives and objectives can lead to inaccurate results and additional analysis is recommended to verify the results. TOPSIS is one of the most popular MCDM methods used for solving energy sector issues. The method has a rational and comprehensible logic, the concept is in a quite simple mathematical form, the computation process is straightforward, and results are obtained quickly. However, the method is only suitable when indicators of alternatives do not vary strongly because a strong deviation of one indicator from the ideal solution strongly influences the final results. CRITIC is one of the most objective methods since there is no need for decision-maker interventions; therefore, it eliminates the subjective point of view of the decision-maker. The EDAS method is a high efficiency method, involves quite simple calculations, and is very useful in various fuzzy cases. However, EDAS is limited by its hypothesis that the evaluation criteria are compensatory. The WASPAS method is one of the newest methods of MCDM and is increasingly used because of its high accuracy and short calculation stages. The method is useful for the complete ranking of alternatives; however, it only takes into consideration minimum and maximum values. The success of the PROMETHEE method comes from its mathematical features and usefulness in solving uncertain and fuzzy information problems. The method is one of the most suitable for the assessment of renewable energy technologies in households; however, PROMETHEE is only suitable for experts because the computation process is very long and complicated.

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