Chapter

Renewable Energy in Ukraine-Poland Region: Comparison, Critical Analysis, and Opportunities

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Abstract

Fundamental and applied research on renewable energy is actively supported for the development of world science and maintaining the energy independence and security of different countries. This section analyzes the publications of scientists from two countries—Ukraine and Poland—in the field of "thermoelectricity," "photoelectricity," and "bioenergy" to find regularities in each state and to determine the prospects for joint research. Ukraine and Poland share a common border and have similar climatic conditions and historical heritage, but Poland is a member of the EU, and its legislation in the field of renewable energy complies with the regulations of the European Community. Ukraine is making every effort to develop renewable energy. Comparison of the state of research in these countries is also an example of the analysis of the situation at the borders of EU countries and may answer questions related to sustainable development, the mass transition to renewable energy, and the refusal to use fossil fuels and nuclear power plants. The analysis is based on the results of data published in the international scientific databases Web of Science and Scopus. The most advanced areas of research in each country are identified, analyzed, and aimed at practical application.

Keywords: renewable energy, h-index, thermoelectricity, photovoltaic, bioenergy, Poland, Ukraine

1. Introduction

Increasing global warming, with frequent storms, melting ice, droughts, etc., indicates the fatal impact of fossil fuels on the planet's ecosystem.

Unfortunately, the lack of a proper energy policy among the states, in particular those whose economy is based on carbon fuels, often has detrimental effect on the environment [1]. Reducing the dependence on carbon-containing fuels is an important step in transforming a sustainable energy system, being required by Statements on Paris climate agreement [2], which foresees the complete abandonment of fossil fuels by 2050. For this reason, most states have started to support the development of renewable energy sources at the legislative level and to encourage the transition to their widespread use. For example, Directive 2009/28/EC of the European Parliament of 23 April 2009 obliges Member States to provide a specific share of energy from renewable sources for final gross energy consumption in 2020 [3]. On average, 20% of energy should come from renewable sources. For Poland, this figure is about 15%.

However, the challenge of such EU policy is possible noncompliance of these initiatives by states bordering the EU.

Thus, this section analyzes the renewable energy market in two countries—Poland and Ukraine. These countries have a close mentality, driven by a long shared history. The length of the common border is 535 km. The population of Poland and Ukraine is 38 million and 42 million, respectively, with an area of 312.3 km^2 and 603.6 km^2. The most important factor for qualitative and quantitative analysis of the development of renewable energy sources in these countries is their similar geographical location (climate, common mountain system, geographical zone, etc.).

However, the situation with the development of renewable energy in these countries is different. According to 2017 data, the total amount of renewable energy in Poland was 383,168 TJ [4]. It comes primarily from solid biofuels (67.9%), wind (14.0%), and liquid biofuels (10.0%). In Ukraine, according to the State Agency on Energy Efficiency and Energy Saving of Ukraine, renewable energy sources have produced 7566 TJ of energy in the same period [5]. Such significant differences in the amount of energy produced are related to public policy in this area. For Poland, this policy is unified with relevant EU acts, where support is extended from the largest megaprojects to the smallest solar project in the community, leading to the effective development of future renewable energy [6]. Ukraine has only recently started to actively support green energy. The Polish experience can be very helpful for the development of renewable energy in Ukraine because of the centuries-old mental similarity between the populations of both countries. Therefore, the experience of the transition to renewable energy in Poland and the challenges that they face and overcome are beneficial for Ukraine.

This paper attempts to analyze three promising areas of renewable energy development in Ukraine and Poland, such as *solar photovoltaics*, *thermoelectricity*, and *bioenergy*. These directions are chosen for the following reasons. Both countries are in similar latitudes and have relatively close sunny days. Both countries have similar infrastructures, including scientific ones. Academic institutes and universities in these countries have devoted considerable attention to the development of materials science for energy (possibly energy materials science). Solar photovoltaics is one of the areas where it is possible to test the properties of new materials quickly and bring them into production. And, given the powerful global industry in this direction, it is very easy to compare the results obtained with the industry and to select new objects for research flexibly.

Thermoelectricity in these countries does not have a strong practical application but has powerful world-class scientific results obtained by scientists from the universities of Ukraine and Poland [7, 8]. Therefore, in the future, the production and use of thermoelectric devices in these countries may become the world's foremost.

Bioenergy is a specific feature of these countries. Both countries have well-developed agriculture, the waste of which is a direct source for biofuel or biogas [9].

2. Methodology

Scientific results can be analyzed if they are in the form of a publication. To exclude few influential publications, only peer-reviewed ones were selected for analysis. The scientific literature was searched through academic libraries, Web of Science and Scopus, reviewed in English, and published books related to the topic of this section. Given that Ukraine became an independent state in the early 1990s, it is possible to make a clear identification of publications linked specifically to Ukrainian scientific groups since then.

Thus, the search has been performed since 1991. Thanks to advanced tools of scientometric systems, scientific papers were selected, indicating the affiliation of Poland or Ukraine. The procedure is described in detail in [10].

In applying to this section, there were certain features in the proposed methodology. In particular, the review of sources was performed on the basis of analysis of both the most important or the most cited (sorting by number of citations) and the most recent (sorting by date).

In the second stage, analysis of the type of publications, their financial support, as well as the areas specific to each industry, such as "materials science," "physics," "technology," etc., has been done. At the same time, patterns and relationships between the areas of renewable energy studied in this work and within each direction have been found.

At the last stage, a critical analysis of the most prominent publications and regularities was performed to predict the options for the development of a particular direction and to generate the key results for supporting theoretical development within the direction or certain practical technologies.

3. Analysis of results and discussion

For the convenience of performing analysis of research impact conducted by scientists from Poland and Ukraine, the collected data are summarized in **Table 1**.

Even before the 1990s, the number of publications in particular renewable energy areas was one or tens of publications per year. However, since the early 2000s, there has been a rapid nonlinear increase in the number of publications. Are there certain reasons that could explain the sharp changes in the number of publications? Apparently so. One of them is the Treaty of Amsterdam signed in 1997, which laid down the principle of sustainable development for the EU, the essence of which was to improve the production of renewable energy. Another reason may be the awareness of the scientific community of the instability of the existing energy state, the exhaustion of natural resources, and the need to find alternative sources of fuel to reduce emissions into the environment. Another condition that led to a new step in the development of renewable energy was the "forced policy" of thermal collectors in some states, which obliged people to put heat collectors on their homes. Accordingly, the search for cheaper collectors and photoelectric and hybrid systems has become a new cause for the increasing number of publications in this field.

As for Ukrainian publications, the number of papers is much smaller than the number of publications of the world scientific community. The economic situation in the country has a significant impact on the number of publications.

Below is a summary of information available in the international science databases on the state of research in the three renewable energy fields. These three areas are chosen for a number of reasons. This chapter examines studies conducted in two bordering countries. However, Poland is a member of the EU, complies with the relevant directives adopted by the European Community, and anticipates developing its economy and science in terms of forming a single European research area. Ukraine, however, is a neighbor of the EU and the closest neighbor of Poland with related culture and climatic conditions, but is not a member of the EU. For a long time, scientific research in Ukraine was closed to the world scientific community (until the first decade of the post-USSR),

Ukraine	Comparison	Poland
Solar photovoltaics		
1370	Number of publication	2284
38	h-index	66
• Taras Shevchenko National University of Kyiv • NU "Lviv Polytechnics" • Yuriy Fedkovych Chernivtsi National University • Institute of Physics, National Academy of Sciences in Ukraine • National technical University "Kharkiv Polytechnic Institute"	Leading institutions (five items)	• Politechnika Warszawska • Wroclaw University of Science and Technology • AGH University of Science and Technology • Silesian University of Technology • Lodz University
• Engineering (21.63%) • Physics and astronomy (20.71%) • Materials sciences (19.11%) • Energy (7.98%) • Chemistry (7.64%)	Most presented scientific areas	• Physics and astronomy (29.5%) • Materials sciences (25.57%) • Engineering (16.73%) • Chemistry (6.68%) • Energy (5.6%)
• Ministry of Education and Science of Ukraine • National Academy of Sciences of Ukraine • Science and Technology Center in Ukraine • State Fund for Fundamental Research of Ukraine • European Regional Development Fund	Most finance support	• Narodowe Centrum Nauki • Narodowe Centrum Badan I Rozwoju • European Regional Development Fund • European Commission • Fundacja na rzecz Nauki Polskiej
• RF • Germany • Poland • United States • France	Partner country	• Germany • France • United States • United Kingdom • Ukraine
Thermoelectricity		
901	Number of publication	1145
28	h-index	40
• Institute of Thermoelectricity NAS • Ivan Franko LNU • NU "Lviv Polytechnics" • Yu. Fedjkovych ChNU • NTU "Kharkiv Polytechnic Institute"	Leading institutions (five items)	• AGH University • Włodzimierz Trzebiatowski Institute of Low Temperature and Structure Research PAS • Wrocław Branch of PAS • Politechnika Warszawska • Institute of Molecular Physics PAS
• Engineering (26.6%) • Physics (26.6%) • Materials science (24.5 %) • Energy (4.9%) • Computer sciences (4.5%)	Most presented scientific areas	• Physics (29.1%) • Materials science (27.7 %) • Engineering (21.7%) • Chemistry (6.1%) • Energy (3.9%)
• NAS of Ukraine • MES of Ukraine • SFFR of Ukraine	Most finance support	• NCN • SC of Antarctic Research • KBN
• Poland • United States	Partner country	• Germany • Ukraine

Ukraine	Comparison	Poland
• RF • Germany • Austria		• United States • France • Moldova
Bioenergy (energy from biomass and biofuel)		
71	Number of publication	324
13	h-index	37
• National University of Life and Environmental Sciences of Ukraine • NU "Lviv Polytechnics" • Taras Shevchenko National University of Kyiv • Vasyl Stefanyk Precarpathian National University	Leading institutions (five items)	• Polish Academy of Sciences • Uniwersytet Jagielloński w Krakowie • Uniwersytet Warminsko-Mazurski w Olsztynie • Wrocław University of Science and Technology • Uniwersytet im. Adama Mickiewicza w Poznaniu
• Energy • Agricultural and biological sciences • Environmental science • Biochemistry, genetics, and molecular biology • Engineering	Most presented scientific areas	• Biochemistry, genetics, and molecular biology • Agricultural and biological sciences • Environmental science • Energy
• European Commission • Ministry of Education and Science of Ukraine	Most finance support	• Narodowe Centrum Nauki • Ministry of Higher Education
• Germany • Italy	Partner country	• United States • Germany

Table 1.
Comparative statistic characteristics of the researches of Ukraine and Poland, carried out in the directions "solar photovoltaics," "thermoelectricity," and "bioenergy."

and later for a long time did not integrate into it due to the significant lack of funds caused by the poor economy. However, these two countries are now implementing the desire to develop together and are an example of how a competitive scientific environment can be started at the EU's border.

3.1 Solar photovoltaics

Photoelectricity is one of the most popular types of renewable energy today. The reason for this is a free source—solar radiation, which, by getting on properly prepared semiconductor materials, is converted into direct electric current due to the known phenomenon, photo effect. Interest in photovoltaics arose a long time ago; however, only with the development of silicon technology, it has become widespread in almost all countries of the world. On the other hand, industrial silicon production is a technologically complex, expensive, and environmentally hazardous process. Therefore, the scientific community of the world today is trying to find new, cheaper, and environmentally friendly materials that would significantly reduce the cost of photovoltaic energy produced. These are, first and foremost, thin-film materials of different types of heterostructure, materials with nanoinclusions, etc. Thus, these studies have evolved from the usual design decision toward materials science.

Analyzing publications by the tag "solar photovoltaics" requires careful study. For the entire period (1991–2019), there are 2292 publications of Polish researchers in the Scopus database. However "open access" for research results has only 403 of 2292 publications, being available publicly. By citation number h = 66 is the total number of solar photovoltaic publications in the period of 1991–2019.

However, it should be borne in mind that not all publications are concerned with the production, storage, or conversion of solar energy and only a fraction of the publications are relevant to the search query. The observations were made on the first hundred of the most cited publications and the most recent publications. The most interesting of them were selected for analysis.

The most cited is the paper [11] of h = 2122. It presents a brief overview of well-established multilevel converters strongly oriented to their current state in industrial applications and the review of new converters that have made their way into the industry. In addition, new promising topologies and nontraditional applications powered by multilevel converters were discussed.

One of the most cited papers is [12], discussing specific chemical and physicochemical requirements for organic compounds to be applied in organic or hybrid electronic devices such as photodiodes, light-emitting diodes, photovoltaic cells, etc.

One of the most cited (184 times) and new publications (2019) is [13] which reports a new non-fullerene n-type organic semiconductors that have attracted significant attention as acceptors in organic photovoltaics (OPVs) due to its great potential to realize high-power conversion efficiencies. OPVs made exhibited a high efficiency of 15.7%.

Among other publications, papers related to "organic solar cells," "polymer solar cells," "semiconductor heterojunctions solar cells," "silicon-based solar cells," "dye-sensitized solar cells" (DSSCs), "perovskite photovoltaics," and other materials, due to their high power conversion efficiencies, can be found. These papers describe possible physicochemical processes and phenomena that occur during the preparation of materials, testing of properties and their approbation as metastabilities of electrical properties, photoelectrical parameters, light sensitivity and absorbance, chemical treatment and deposition methods, bands, defects, grain boundaries, exiton binding energies, factors affecting conversion efficiency, etc.

In particular, since 1991 dye-sensitized solar cells (DSSCs) have attracted considerable interest from the scientific and commercial communities due to their promising characteristics as solar light converters. About 8% of the first 200 publications are related to the topic of materials for solar cells.

By the tag "solar photovoltaics," the most cited are also the studies on the properties of TiO2 [14, 15] and ZnO [16, 17] and heterojunctions based on them.

Other highly cited publications are research papers about polymeric materials in photovoltaic device application for polymer solar cells [18] or investigation and modeling of metastabilities in chalcopyrite-based thin-film solar cells, for example, Cu(In,Ga)Se2- [19] or ZnO/CdS/Cu(In,Ga)Se2-based [20] thin-film solar cell.

The newest publications are related to the issues of ecology, economics, etc., in particular the implementation and application of hybrid energy conversion systems in Poland [21, 22]. There have also been publications on non-silicon PV modules [23], studies of weather and climate conditions on the efficiency of solar energy conversion [24], etc.

The results presented in these papers became the basis for the development of the production of renewable energy sources and the effective commercialization of certain scientific results.

The solar photovoltaics sector is one of the fastest growing renewable energy sectors in Poland and in the world. The photovoltaic market in Poland has enormous, but so far highly unused, development potential.

The total installed capacity in photovoltaic sources at the end of 2018 was about 500 MW, and already in May 2019, it exceeded 700 MW. The growth of new PV installations is dynamic. In 2018, Poland finally began to stand out from the other EU countries and with an annual increase of 235 MW was already in the ninth place. Considering current and real investments in progress, in 2019 Poland may be in fourth place in the EU in terms of annual increases in new solar power sources. The authors of the report estimate that in 2019 there will be even 1 GW of new PV installations and the cumulative power of solar installations in Poland at the end of the year will be 1.5 GW.

Solar energy in Ukraine has been actively developing since the end of 2008 with the adoption of a "green" tariff at the legislative level, which made financially attractive investments in industrial grid solar power plants.

According to the State Agency on Energy Efficiency data (http://saee.gov.ua), the theoretically possible potential of solar energy in Ukraine is more than 730 billion kWh per year, and technically possible is only 34.2 billion kWh per year.

The use of solar panels on rooftops by private households by 2050 can reach 40–50%. In addition, the use of solar collectors for water heating will be more cost-effective. These technologies will provide hot water demand in private households for 70–100% during summer and 15% in winter.

For the investigation period, there are 1370 publications in Scopus, which are 922 fewer than in the same period in Poland. Only 114 of 1370 publications are in "open access." By the number of citations, h = 38 is the total number of solar photovoltaic-related publications during this period.

The most cited publication with the participation of Ukrainian researchers [25] with h = 207 is concerned with efficient photocatalytic water splitting.

The paper [26] was one of the fundamental at the time (2000s) in which design and photovoltaic performance of solar cells based on various semiconductor nanorod materials, such as TiO_2, ZnO, CdS, CdSe, CdTe, CuO, and Si, were presented and compared with respective solar cells based on semiconductor nanoparticles; specific of synthesis and application of carbon nanotubes in photovoltaic devices were also reviewed in these papers.

The largest number of publications in Ukraine by the tag "solar photovoltaics" relates to photoelectric materials science, mainly, these are high-tech results aimed at optimizing the parameters of existing materials for photovoltaics, improving methods for their production and research, as well as creating new efficient and low-cost materials for competing with existing ones.

The highly cited are the studies on the properties of CdTe-based heterojunction solar cells. The first works devoted to the study of CdTe properties in Ukraine since its independence appeared in 1997 [27]. The first mention of the concept of quantum efficiency of CdS/CdTe SCs appeared in 2012 [28].

Solar modules based on the developed flexible solar cells ITO/CdS/CdTe/Cu/Au on polyimide films were mentioned in 2009 for the first time [29].

The researches in [30, 31] were mainly focused on CdTe-based compounds. The publications with the tag "solar photovoltaics" on CdTe-containing compounds make up ~12.5% of the first 200 publications by researchers from Ukraine, while the percentage of publications related to silicon and its possible modifications for use in solar power is ~10%. However in recent years, there has been an increase in the number of publications of other scientific groups in this field, which demonstrate the modern competitive achievements [32, 33].

Publications looking at the prospects of using quantum dots (QD) in solar cells are very popular. Their photophysical and electrophysical properties can be varied by different particle size and shape, and QD can provide absorption of solar energy in a much wider spectral range compared to conjugated organic compounds [34].

At the forefront of science are promising techniques for the development of technologies of second-generation PV systems, the efficiency of which is now comparable to that of silicon and the cost and consumption of material are significantly lower [35].

Analyzing recent publications as a whole, we can observe a tendency to the interest in modeling of weather condition influences on properties of photovoltaic installations, methods of its identification [36], modeling of building energy supply based on PV modules [33, 37], microgrid with hybrid renewable energy system, and the concept of energy accumulation from photovoltaic and wind power plants [38].

However, the structure of most publications has the character of fundamental research in semiconductor physics. Semiempirical approaches that combine materials science research, the development of low-dimensional structure fabrication technology, the testing of the obtained parameters to work as a photocell, and point to the prospect of further practical application are the main features of Ukrainian scientists.

3.2 Thermoelectricity

Thermoelectric energy conversion, like photovoltaics, is based on known effects discovered more than a hundred years ago. The principle of thermoelectric power generation devices is very simple: the thermoelectric device (usually a thermoelectric generator or module) is placed so that one side is at higher and the other at lower temperatures. Accordingly, due to the temperature difference, thermoelectric driving force arises, or, in other words, it is possible to record the potential difference or the presence of direct current. Despite such ease of use, thermoelectricity has long been considered inefficient due to its low efficiency. However, when semiconductors were proposed to be used as thermoelectric materials in the mid-twentieth century, it was an important step to start the rapid development of this field. Industrial thermoelectric devices have relatively low efficiency. This is about 4–8%, which is significantly inferior to the efficiency of photovoltaics (up to 28%). However, such small values make it possible to create a whole series of different autonomous energy sources, which are used in medicine, space applications, automotive technology, etc. The undeniable advantage of thermoelectricity is the reliability of the devices, their quietness, and the extremely long service life.

The thermoelectric module is based on a sequence of n- and p-type conductivity materials. It is the quality of these materials that determines the effectiveness of the device. That's why researchers are trying to create new, low-cost, high-efficiency materials. These are nanomaterials, multicomponent compounds, and materials with the inclusion of different phases, etc.

Studies in thermoelectricity are closely related to semiconductor materials science. The most cited papers, with the participation of Polish authors, relate to fundamental studies of the electronic properties of a wide range of semiconductors. These are, in particular, the study of the first principles of resonance states or transport phenomena of carriers [39, 40]; the study of fundamental processes in modern materials, in particular, nanostructures and materials with nanoinclusions [41]; and the engineering of new ones, including multicomponent structures that are promising for practical use in thermoelectric because of their unique properties, environmental friendliness and relatively low cost [42, 43]. However, attention is paid to the study of classical thermoelectric materials, and the obtained results correspond to a high world level. This is, in particular, a study taking into account current approaches, both experimental and theoretical, of compounds of types IV–VI [44] and II–VI [45].

However, the most recent publications refer to the same directions [46, 47]. It is important to note here that the most cited papers by Polish scholars refer to those published mainly in the last 5–10 years. That is, at this time there is a peak of qualitative research, recognized by the scientific community of the world. For the same reason, the latest publications have the authorship of the same scientific teams. These are representatives of well-known scientific centers, such as AGH University (Krakow), two institutions in Wrocław, and Institute of Molecular Physics PAS in Poznan (see **Table 1**). The geography of the research institutions is quite broad and not concentrated in a particular region, which indicates the systematic support of such high-tech research in Poland by the state. In terms of quality, it is worth noting the list of the most popular publications in which scientists from Poland are published. Among the most quoted, the unambiguous leader is *Physical Review*, which testifies to the development of fundamental research. The *Journal of Alloys and Compounds*, the *Journal of Electronic Materials*, and the *Solid State Ionics* are also very popular. Regarding publications that are newest at the time of analysis, they have been published in the *Journal of Alloys and Compounds*, the *Journal of Electronic Materials*, and the *Journal of Applied Physics* (**Table 1**). The impact factors (IF) of each of these journals range from three to seven. That is, the average journals in which Polish scholars are published also belong to the flagship publications.

The most cited papers by researchers from Ukraine concerned with new classes of materials that are in line with global trends—the search for new, environmentally friendly and inexpensive materials. It includes theoretical work concerning the modeling of new classes of multicomponent compounds [48] and modeling of performance with respect to new classes of thermoelectric materials—skutterudite [49], half-Heusler alloys [50], or graphene [51]—as elements of end devices.

However, the study of classical materials is also carried out at a high level. Moreover, in some cases the effects investigated in certain materials for the first time are demonstrated. The publications are devoted to the type II–VI materials (Bi-Sb crystals, Bi2Te3) [52] and IV–VI compounds and studies of thermoelectric parameters oscillations for PbSe [53], new compounds of LATT-PbAgSbTe type [54], or multilayer heterostructures based on them [55].

Moreover, a number of papers published by Ukrainian scientists contribute significantly to the development of the theory of thermoelectric phenomena [56].

A feature of research in thermoelectricity is the inexpensive opportunity to test ready devices. The largest thermoelectricity center in Eastern Europe located in Chernivtsi (Ukraine), namely, the Institute of Thermoelectricity of NAS and MES of Ukraine with ALTEK production company, based of which thermoelectric generators are developed and tested [57], or in Odesa (Thermion Co.) [58]. There are also a large number of citations concerning the cooling systems or the use of thermoelectric measuring devices [59].

Ukrainian researchers usually publish their results in such leading editions as *Applied Physics Letters*, *Acta Materialia*, and *Journal of Alloys and Compounds*. These are journals with an impact factor of 3–7. However, unlike the journals in which Polish scholars usually publish their most cited papers, there is a certain balance between applied results and purely material studies.

An analysis of scientific papers published recently shows that the trend remains to investigate multicomponent bulk and low-dimensional compounds and nanomaterials [54, 60, 61].

But, at the same time, there is a large number and very clearly directed applied research concerning the development of specific thermoelectric devices, in particular for medicine [62] or hybrid power systems that combine different types of renewable energy generation in a single device [63].

Also, the International Thermoelectric Academy has been established on the base of the Institute of Thermoelectricity in Chernivtsi, which unites the efforts of not only Ukrainian scientists but also representatives of practically all known scientific centers of the world engaged in thermoelectricity. The *Journal of Thermoelectricity*, published by them, is one of the most popular journals for Ukrainian scientists in the field of thermoelectricity.

3.3 Biofuel energy

Unlike the two previous areas covered in this section, the development of bioenergy is more specific and needs the presence of certain sectors of the economy in the country. Ukraine and Poland, among other countries, are favorably distinguished by the presence of developed agriculture. Accordingly, the rational disposal of biomass waste from crop and livestock products is very important. At the same time, along with the environmental issue, the issue of renewable electricity generation is partially addressed. In the agricultural regions of both countries, various biogas stations have been actively introduced. Thus, there is a different approach to this area of renewable energy: the realities of the economy require its development to a new, more effective scientific level. And the presence of a common border and similar geographical conditions is a factor that creates the same technological conditions for the development of bioenergy for both countries.

Among all renewable energy resources, one of the most promising and strategically important is the bioenergy resource. The role and importance of bioenergy for the development of the economy have been repeatedly emphasized in the reports of scientists, experts, practitioners, and all those who are in one way or another involved in energy problems.

Bioenergy is closely connected with notions "biomass" and "biofuel." Biomass means organic matter of plant origin and waste materials obtained through natural or artificial transformation that can be used for energy purpose. Biofuel is a renewable energy source derived from plant or animal biomass. Although in many studies the terms biomass" and "biofuel" are used interchangeably, we consider it appropriate to differentiate them. Biomass is a raw material, whereas biofuel is a product of biomass processing.

The analysis of publications shows that bioenergy research is highly relevant in terms of environmental improvement, namely, the study of biocomposites (or biopolymers) as a replacement for plastics [64] and biodiesel production [65]. The most interesting renewable energy sources for the Polish region are agricultural biomass wastes, which are also useful for improving the environment and for medical purpose [66]. However, the most interesting is the production of biogas [67–71], which requires cheap agricultural raw materials. The review [67] is the most important in terms of process technology development for biogas (i) production, (ii) conditioning, (iii) utilization, and (iv) industrial symbiosis. And given the high capacity of biogas plants in Poland, attention has been paid to researching the quality of compost for the production of quality biogas [71–73].

As far as biomass is available as by-product of many industrial and agricultural processes almost everywhere, easy to be obtained, and is a carbon-neutral energy source, biomass represents a growing renewable energy source with high growth potential in the economic analysis of bioenergy in Europe [74–77].

Nowadays, bioenergy is a field of great interest to the scientific community. We can observe growth in the amount of publications, starting from the mid-2000s. The most important reason for that was oil peaking at over $136 a barrel in 2008.

The most cited papers related to biomass and biofuel have been published in the following journals: *Renewable and Sustainable Energy Reviews* (h-index is 193), *Biomass & Bioenergy* (h-Index is 143), *Bioresource Technology* (h-Index is 229), *Renewable Energy* (h-index is 143), and *Energy* (h-index is 146).

Also according to the Scopus database, the most prominent and influential scientists in the sphere of bioenergy have been determined. They are Omer, A.M. from the United Kingdom (122 publications on biomass as renewable energy source); Pari, L. from Italy (103 publications); and Kaltschmitt, M. from Germany (102 publications).

Using the Scopus database, it was determined that h-index of publications related to biomass and biofuel for Poland is 37, and for Ukraine it is 13 (**Table 1**).

A couple of years ago, Poland and Ukraine had the same problems with energy efficiency, being dependent on the old gas transmission infrastructure. The energy systems of two countries are based on large-scale installations for electricity production and distribution. Research in this field, developing renewables, in particular bioenergy resources, are crucial for both countries.

Most of the papers from Polish authors are focused on general prospects of biomass development. Thus, in [78] the largest establishments producing bioethanol and biodiesel have been analyzed. The comparative analysis of different renewable energy resources for rural areas has been done [79].

The influence of energy efficiency in biofuel production on the potential fulfillment of agricultural energy demand has been investigated in [80]. The mathematical model shows the results of exclusion of crops from food production aimed at satisfaction of the energy purposes. Ref. [81] presents a range of products which can be obtained from agricultural production and used for energy purposes. The paper [82] analyzes the potential volume of raw materials that can be obtained from agriculture in Poland for biogas production.

A lot of publications are aimed at technical characteristics of biomass production. Ref. [83] presents results of the study on biomass processing technologies for willow and black locust biomass.

Moreover, according to the forecast in 2020, approximately 80% of the final energy from renewable sources will come from biomass, and almost all of it will be generated from agriculture [84]. The changes in the structure of biomass use are shown. Thus the use of biomass for heating is decreasing, while the share of biomass for electricity and biofuel is getting larger. At the same time, there is a tendency in the publications about the environmental friendliness of bioenergy, in particular, its contribution to reducing the greenhouse effect [85, 86].

A number of papers of Ukrainian scientists are also devoted to general trends in bioenergy production. The analysis of biological resources for biofuel production in Ukraine has been done in [87]. Aspects of transition to agrobioenergy in Ukraine, as well as strategies and recommendations to a variety of stakeholders to facilitate this transition, are suggested in [88, 89].

The positive trends in bioenergy are emphasized in a number of studies. The estimated energy potential of existing biomass waste is about 25 million tons, and the energy potential of biomass which can be grown on unused agricultural lands is about 13 million tons [90]. The paper [91] analyzes the Ukrainian and European Union rapeseed markets being horizontally integrated.

The authors [92] calculated the profit from the biogas installation for poultry farm, and in [93] the main practical steps of establishing a Ukrainian biogas market have been given.

A joint publication [94] summarizes the studies on bioaerosols which were carried out in the years 1972–2009 in the following branches of agricultural industry in the Ukraine and Poland: animal farms, feed facilities, production of biofuel from rape, etc. Another joint publication [95] assesses the potential of biomass, obtained from by-products of crop production and animal breeding, which can be used for energy purposes.

4. Results and discussion

Considering the three selected areas of renewable energy analysis in Ukraine and Poland, it is possible to distinguish certain common features. First of all, the cooperation of Polish and Ukrainian scientists, expressed through a large number of joint publications, is a priority of both countries. Also, scientists from both countries successfully cooperate with their colleagues from Germany and the United States in all the areas of research (**Table 1**). That is, it is not only for photovoltaics and thermoelectricity where it is necessary to synthesize new materials and study their fundamental properties but also for bioenergy, the practical development of which is determined solely by the economic situation in the agricultural sector. It is logical to explain that there are joint studies of both neighboring states and high tech, which possess the most advanced equipment.

Regarding the publications of Polish scientists in recent years, their applied orientation should be noted. In particular, for thermoelectricity these are the problems of creating cooling systems [96, 97], creating different types of thermoelectric elements for sensors [98], and developing classical thermoelectric generators [99]. However, there are several publications concerning hybrid systems, such as the combination of thermoelectricity and photoelectricity [100].

The number of publications on thermoelectricity is comparable in both countries: 1145 submitted by Polish scientists and 901 by Ukrainian. But the h-indexes are different here. It is almost 50% higher for Polish publications (**Figure 1**, blue line). It means that publications of Ukrainian scientists, which are often of a very high scientific level, are still published in less well-known world scientific community journals and, thus, less cited. There is an even greater difference in this regard for the photoelectricity direction. The number of publications of Polish scientists is 2284, while for Ukrainian scientists is 1370. h-indexes for Polish and Ukrainian scientists are 66 and 38, respectively (**Figure 1**, blue line).

There is a difference in the number (324 and 71, for Poland and Ukraine, respectively) and the "impact index" (37 and 13, respectively) of publications in the bioenergy direction.

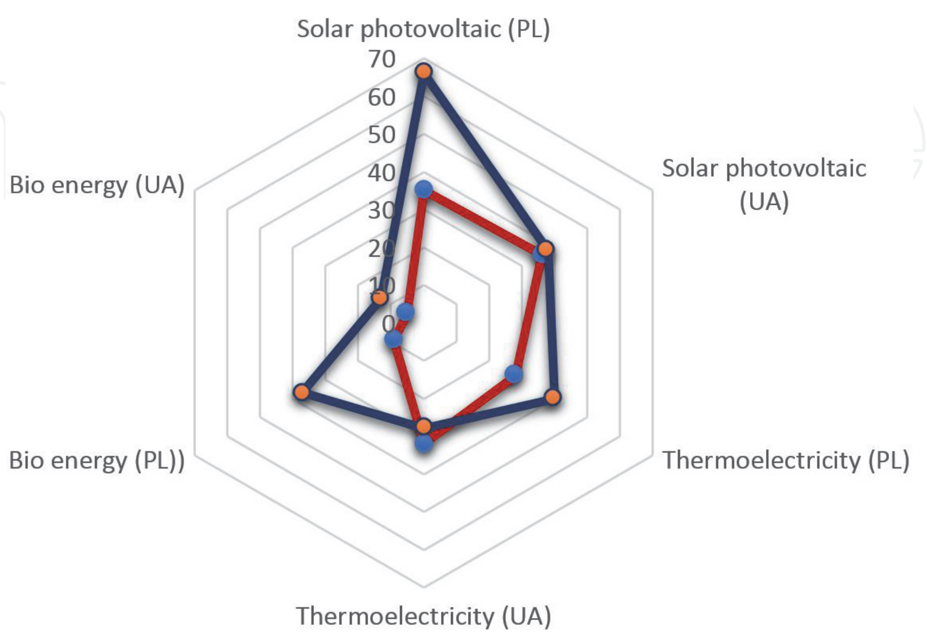

Figure 1.
h-index (blue line) and normalized h-index (red line) for publications of investigation directions for Ukrainian and Poland cases.

Apparently, in all these areas, the number of publications is very different, as well as h-indexes. For more efficient analysis, their normalized dependencies are constructed (**Figure 2**):

$$h_{norm} = h_i/N_i, \quad (1)$$

where h_i is the h-index of publications in the relevant direction and N is the total number of publications in this direction.

As can be clearly seen from **Figure 1** (red line), the normalized values of the h-index of publications of Ukrainian and Polish scientists are practically the same in magnitude for the directions of "photoelectricity" and "thermoelectricity." That is, we can conclude that the quality of scientific publications in high-tech fundamental directions is almost the same for scientists of both countries.

For "bioenergy," the h-index of Polish scientists is significantly higher. This indicates a stimulation of such research at the state level in Poland and too little support from Ukraine at this stage. However, given that publications by Ukrainian scientists have begun to be published in this field in the last few years and through partnerships between scientific institutions of both countries, it is possible to predict an increase in both the quantity and quality of such materials within the next 5 years.

Comparison of highly cited publications of Polish and Ukrainian scientists in the field of thermoelectricity indicates that the emphasis of Polish scientists is on the study of the properties of materials; however, the development of devices has actively begun to develop only in recent years. For Ukraine, a feature is the parallel existence of whole series of works, devoted to thermoelectric materials science and

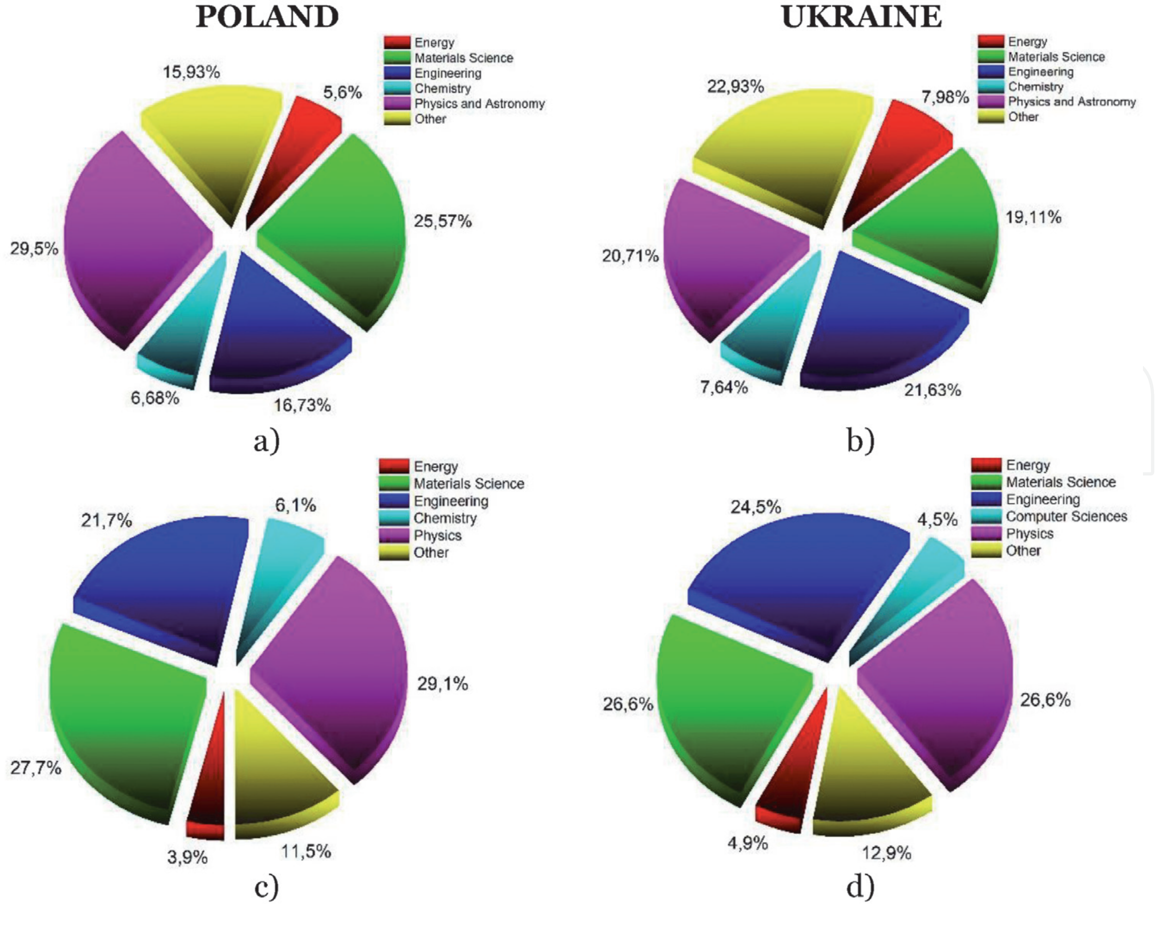

Figure 2.
h-indexes of publications by research areas in solar photovoltaics (a and b) and thermoelectricity (c and d) used (1). Left column for Poland research papers and right column for Ukrainian research papers.

thermoelectric application systems. One of the conclusions following from this analysis is that there has always been a good basis in Ukraine for the industrial production of thermoelectric systems or elements. In Poland, it is only in the initial stages of creation. However, taking into account the quality of research carried out by Polish scientists, the emerging industrial base will be focused on the new, environmentally friendly thermoelectric materials. Today, they are cheaper but have significantly lower values of thermoelectric efficiency. The progress that has been made in recent years gives hope for a breakthrough in this promising direction.

The main scientific directions on the keywords "photoelectricity" and "thermoelectricity," which are technologically similar, are shown in **Figure 2**. For ease of analysis, each direction is indicated by the same color in each figure. It is important to note that under the direction of photoelectricity, Polish scientists' research is mainly focused on fundamental research (physics and materials science), while for Ukraine there is a certain shift of priority to applied research (engineering and physics). With regard to "thermoelectricity," here such a shift is less noticeable, but still it is. In other words, significant and recognized technical solutions are more specific for Ukraine, while more fundamental results are observed in Polish scientists.

For photovoltaics, the situation is similar. In Ukraine it used to be related to photoelectric research for military or space purposes. They often had an applied aspect and were not aimed at publishing scientific achievements. Following the reorientation of the state to peaceful tasks, often representatives of the most famous institutions (Kharkiv, Kyiv) demonstrated a considerable number of publications on technical aspects of the operation of photoelectric systems or design of the lines for their production. But so far collaborative work has emerged, and as a result high-level collaborative publications appear.

Therefore, since 2016 the number of joint Ukrainian-Polish publications has been increasing annually. If we consider separately the number of published papers in Poland and Ukraine by the tag "solar photovoltaics" for 2019, it can be noted that in Poland 158 papers were published, while in Ukraine there are only 64.

5. Conclusions

For the effective development and implementation of renewable energy, different factors must be considered simultaneously. In the short term, the introduction of renewable energy sources is determined by the economic factor and the availability of certain investments in green energy. However, the long-term perspective requires the development of new, environmentally friendly and effective research and the creation of opportunities for their implementation.

Globally, no state can address the issue of renewable green energy on its own. In order to develop international cooperation, a critical analysis of two neighboring countries, Poland and Ukraine, has been made, but, apart from their close geographical location, there are significant differences in economic and legislative systems. Such an analysis is a typical example of the development of cooperation between states at the EU border.

The quality of research can be proved on the basis of quality scientific publications in peer-reviewed journals. The number and impact of such scientific publications indicate the potential of scientific teams, their relevance, and the possibility of implementation.

The normalized h-index indicates that, in the spheres of basic materials science research for energy, this value is practically at the same level, whether or not it is an

EU Member State. The corresponding value of hnorm is 35 and 36, respectively, for studies in Poland and Ukraine in the direction of "photoelectricity" and 28 and 32 in the direction of "thermoelectricity." However, the difference of almost two times (9 and 5, respectively) for the direction of "bioenergy" indicates a much greater progress of Polish scientists in this direction. Such values can be transferred with some accuracy to the other countries at EU borders. That is to say, fundamental research has a high priority almost everywhere, whereas applied research that require sophisticated installations for testing them or expensive simulation software are more effectively implemented in EU countries.

Conflict of interest

The authors declare no conflict of interest.

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