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Renewable Energy Deployment as a Pathway to Sustainability and the Sustainable Development Goals (SDGs): A Review

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Abstract

The energy transition from fossil fuels to renewable energy is underway to achieve a sustainable society based on carbon neutrality. However, there is an ongoing debate about how the implementation of such energy technologies will affect sustainability (social, economic, and environmental aspects). This review outlines research trends on the effects of renewable energy deployment on sustainability from the perspectives of income inequality, energy inequality, human capital, energy education, gender, health, and community, focusing on high-profile papers for the period 2014-2024. Renewable energy and income inequality are negatively related, and promoting renewable energy innovation through R&D subsidies is expected to decarbonize and alleviate poverty. Human capital promotes decarbonization through the diffusion and consumption of renewable energy, but in some cases, the effects are not apparent. However, energy education can be effective in addressing human capital shortages in the renewable energy sector. Gender inequality and energy inequality are closely linked, with women with poor energy access suffering health problems due to smoke pollution from cooking. Women's participation in society will encourage the spread of renewable energy and improve health standards. Local communities with voluntary citizen participation, rather than state initiative, are expected to be the actors that encourage decarbonization through renewable energy.

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1. Introduction

The climate change problem has worsened through the climate crisis to the era of global boiling. To prevent further worsening of global warming, an energy transition toward net-zero emissions by 2050 is needed. Renewable energy (RE) is expected to contribute to the reduction of greenhouse gases. Based on the status of RE use and the development of energy utilization technologies, RE has the potential to supply far more than the current energy demand in the future [1]. Chu et al. [2] pointed out the importance of sustainable energy and then discussed the importance of clean energy generation, transmission, and distribution, the storage of electrical and chemical energy, energy efficiency, and better energy management systems. As shown in Table 1, this progress in basic science has led to vigorous research on multigeneration systems in RE. Wen et al. [3] concluded that the hydrogen-based system is superior to the ammonia-based system. However, it is also pointed out that the ammonia-based system is more efficient in terms of the difficulty of hydrogen storage and the underdeveloped distribution infrastructure [4]. The debate still continues as to whether hydrogen or

Table 1. Recent survey papers on multigeneration systems.

Authors	Systems/Analysis	Technology/Results
Østergaard et al. [5]	Technology for extraction from energy sources Verification of their availability Integration of RE sources	Wind and wave power resources, wind technology, geothermal energy, solar heating, cooling and electricity and salinity gradient technologies
Hassan et al. [6]	Incorporating an adsorption chiller into different configurations of combined cooling, heating, and power systems	Improved efficiency of power-generating systems through the effective use of low-temperature waste heat
Mancarella [7]	Various models and evaluation methods for multigeneration systems	-
Fuentes-Cortés et al. [8]	A multi-objective mixed-integer nonlinear programming problem Trade-off among total annual costs, greenhouse gas emissions, and water consumptions	Optima operation policy
Wen et al. [3]	Technical and economic evaluation of hydrogen and ammonia in multigeneration systems	Hydrogen type system: The cumulative cash position is 83.43 MUSD / The payback period is 14 years Ammonia type system: The cumulative cash position and payback period are 12.78 MUSD / 22 years
Tukenmez et al. [9]	Hydrogen and ammonia production from solar and biomass power generation	The power output of the designed integrated plant is 20 MW and efficiency of 58.76% with 0.0855 kg/s hydrogen and 0.3336 kg/s ammonia
Lykas et al. [10]	Solar power with hydrogen production	Classification of solar collectors, photovoltaics, and hybrid solar devices according to hydrogen production method The most efficient systems are Solar towers, Parabolic Trough Collector, and Concentrated Photovoltaic Thermal Collector

ammonia is the superior alternative fuel toward carbon neutrality.

If two-thirds of the world's energy needs are met by RE supplies, synergies between RE technologies and energy efficiency are important to keep the average surface temperature rise below 2°C through greenhouse gas emission reductions, and it is estimated that the growth of solar and wind power will be high [11]. The new geothermal energy-based multigeneration system with fresh water, drying air, hot water, hydrogen, and ammonia is also compared in terms of its efficiency through system analysis [12]. Sayed et al. [13] outline the environmental impacts of wind, hydro, biomass, and geothermal RE systems and state that the potential for negative environmental impacts of such energy must also be considered. Examples include noise and bird mortality in wind power, polluted water discharge in geothermal power, habitat loss and biodiversity reduction due to energy crop cultivation in biomass power, and water pollution and biodiversity in hydro power. Not only RE generation technologies, but also their distribution systems must shift from traditional hierarchical systems to new, more decentralized systems such as peer-to-peer sharing for connected communities, in order to realize a zero-emission society [14]. Policies, regulations, and innovation are needed to accelerate the growth of RE [11] and to transform the centralized energy supply system into a decentralized, community-based system [15].

Sustainability can be viewed from three aspects: social, economic, and environmental. What effect do RE-related technologies and systems have on this sustainability? Not only the development of technologies and systems, but also understanding their actual quantitative effects would be beneficial for building a sustainable energy system. The social, economic, and environmental impacts of RE technologies can also be linked to poverty and inequality, education, gender, health, and the local community, and their interrelationships are depicted in Figure 1. Therefore, in this review paper, the Sustainable Development Goals (SDGs) are treated as a broad, theme-referential term. This review outlines existing studies for the period 2014-2024 and characterizes the effects of RE technologies on sustainability. This review aims to provide a rapid overview of recent developments in this field. However, the process from developing new environmental technologies to their societal implementation typically takes several years to a decade, depending on the technology's type, complexity and so on. Therefore, a narrative and descriptive review style focusing on prior research from 2014 to 2024 is adopted. To focus on influential research recognized in academia and valued in society, the target prior studies are identified primarily through academic papers with over 100 citations, relying on the Google Scholar search engine.

As explained based on Table 1, these surveys are technical surveys concerning RE technologies and RE systems, outlining research trends in advanced

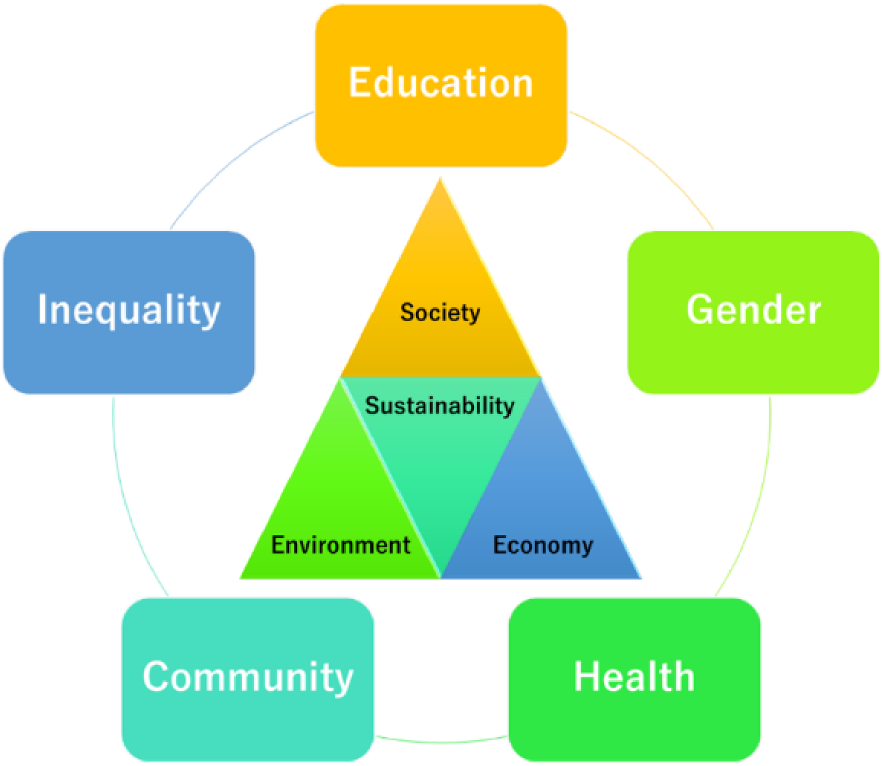

Figure 1. Interrelationship between sustainability and RE.

environmental technologies. Even if these technologies are introduced, the potential for unforeseen adverse impacts on society remains. Therefore, socioeconomic analysis is necessary to understand how RE technologies affect the various elements listed in Figure 1. Various empirical analyses have been conducted on this important research topic, accumulating scientific knowledge. Unfortunately, from the perspective of the SDGs, no review was found that comprehensively addressed income inequality, energy inequality, human capital, energy education, gender, health, and community. All review papers were published some time ago and focused on individual topics. Therefore, this review offers a certain degree of novelty in that it provides an overview of the impacts of RE on the socio-economy from a more integrated perspective.

2. The Relationship between RE, Income Inequality, and Energy Poverty

2.1. Energy Inequality and Income Inequality

There is diversity in the distribution of RE: according to Fu et al. [16], more and more countries and regions are being integrated into international energy networks, and their trading volumes are growing every year. Its main trading entities are Europe, the United States, China, and other Asian countries. Among them, the main traders of solar energy are Europe, the United States, and China, whereas hydro energy trading is smaller and more diversified. With regard to the volume of trading of these energy sources, the existence of inequality, as seen by the Gini coefficient, is confirmed, and the volume of trading is also biased toward certain countries.

A club convergence algorithm classifies 78 countries into five clubs from 2000 to 2018, the RE gap between clubs is widening while the gap within clubs is narrowing [17]. In 35 Organization for Economic Co-operation and Development (OECD) countries from 1990 to 2019, structural transformation of the economy leads to a narrowing of the RE productivity gap, and technological innovation elicits its gap-narrowing effect [18]. As pointed out by Gielen et al. [11], the promotion of innovation in RE reduces the RE gap between countries. At this time, domestic income inequality is also likely to be reduced. This is because many empirical studies show a negative relationship between RE and income inequality. The impact of RE on inequality and the environment is presented in Table 2.

In India and China, income inequality reduces RE consumption and carbon dioxide emissions [19–22]. Per capita income reduces inequality indirectly through increased RE consumption [19]. Fiscal decentralization increases energy demand, but if this demand increases RE consumption, it indirectly reduces inequality [21]. Although RE innovation reduces carbon emissions, when income inequality is lower than a threshold, the decarbonizing effect of this innovation becomes

Table 2. The effect of RE on inequality and the environment.

Authors	Methods	Period	Country/Area	Impact of RE on inequality (Opposite)	Impact of RE on environment (Opposite)	Others
Sharma & Rajpurohit [19]	NARDL	1980-2016	India	RE consumption (−)	CO_2 (−)	Income per capita / Human capital → RE consumption (+)
Bai et al. [20]	Panel FE/TM	2000-2015	China	Decarbonization effect of RE innovation (−)	CO_2 (−) via RE innovation	
Shahbaz et al. [21]	SOR UR / Bootstrapping ARDL bounds test / ADF / VD and IR	1980-2018	China	RE consumption (−)	-	Fiscal decentralization → RE demand (+)
Dong et al. [22]	SYS-GMM / CIPS / CADF	2004-2017	China	RE efficiency → income inequality (−)	-	-
Khan et al. [23]	OLS, FE, difference GMM, SYS-GMM / SUR	2002-2019	Belt and Road countries	RE consumption. (−)	CO_2 (−)	Economic growth → RE consumption (−)
Xu et al. [24]	ARDL / PMG	2000-2021	29 Asian countries (16 high Gini / 13 low Gini)	-	Sustainability index (+) in low Gini index	Green finance → Sustainability index (+)
Masron & Subramaniam [25]	GMM	2001-2014	50 developing countries (Full / Sub samples)	RE mitigates inequality via worsen environment	Sub: Worsen environment → income inequality	RE minimizes worsen environment
Muhammad et al. [26]	AMG / DH causality	1990-2015	23 OECD countries	RE consumption (+)	RE consumption (−)	RE consumption → Economic growth (+)
Uzar [27]	ARDL-PMG	2000-2015	43 developed /developing countries	Income inequality → RE(−)	CO_2 → RE(+)	Corruption → RE(+) Economic growth → no effect on RE
Rather & Mahalik [28]	AMG / CSDH, UR WC / PCSE	1990-2020	58 developed /developing countries	Income inequality → RE generation (−)	-	Innovation → RE generation (+)

Note: NARDL – Nonlinear Autoregressive Distributed Lag; FE – Fixed Effects; TM – Threshold Model; ARDL – Autoregressive Distributed Lag; ADF – Augmented Dickey–Fuller; OLS – Ordinary Least Squares; UR – Unit Root; SYS-GMM – System Generalized Method of Moments; CIPS – Pesaran Cross-Sectionally Augmented IPS; CADF – Cross-Sectionally Augmented Dickey–Fuller; SUR – Seemingly Unrelated Regression; VD – Variance Decomposition; IR – Impulse Response; PMG – Pooled Mean Group; AMG – Augmented Mean Group; DH – Dumitrescu–Hurlin; CSDH – Cross-Sectional Dependence and Heterogeneity; WC – Westerlund Cointegration; PCSE – Panel-Corrected Standard Errors.

insignificant [20]. There is heterogeneity in the magnitude of the effect of energy efficiency improvements on income inequality mitigation [22]; Dong et al. [22] suggest that energy policies for innovation are beneficial not only for decarbonization but also for poverty alleviation.

Not only within one country, but also in the Asian region, RE reduces income inequality and improves environmental quality [23–25]. Heterogeneity in these effects is observed. In countries with low Gini coefficients, RE has positive short-term effects [24]. When the sample is classified into several income groups, the deterioration of environmental quality increases income inequality [25]. However, for OECD countries, RE increases income inequality and increases carbon emissions [26]. In Belt and Road countries, economic growth can increase income inequality because it reduces RE consumption [23]. In OECD countries, when economies grow due to RE consumption, inequality also increases [26]. In general, economic growth contributes to income inequality. Thus, the effect of RE on inequality may indirectly depend on economic growth.

Table 3. The effect on energy inequality.

Authors	Methods	Period	Country/Area	Impact on energy inequality	Results
Meka'a et al. [29]	FGLS and DK	2000-2020	11 SSA countries	Green innovation → Inequality (−)	-
Simionescu et al. [30]	Panel DOLS, MG, and MMQ	2003-2021	27 EU	Unemployment rate → Inequality (+)	Patent of RE project / RE consumption per capita → Utility (+)
Meybodi & Owjimehr [31]	GMM / 2SLS	2001-2020	High-income, upper-middle-income, lower-middle-income countries	Urbanization → Inequality (+) Income / Financial development / Uncertainty of climate change → Inequality (−)	RE consumption → intra-regional inequality in high-income and upper-middle-income countries(−) / inter-regional inequality (+)
Banerjee et al. [32]	Panel FE / FE-2SLS / ETRM	1990-2017	50 developing countries (Asia, Africa, Latin America, Europe)	Inequality → Education (−) / Health (−)	-
Zhao et al. [33]	Dynamic panel for estimation	2000-2014	64 countries (Asia, Africa, Europe, America, Latin America)	RE industry / RE efficiency → Inequality (−)	-

Note: FGLS – Feasible Generalized Least Squares; DK – Driscoll–Kraay; DOLS – Dynamic Ordinary Least Squares; MG – Mean Group; MMQ – Method of Moments Quantile; 2SLS – Two-Stage Least Squares; FE – Fixed Effects; ETRM – Endogenous Threshold Regression Model; SSA – Sub-Saharan Africa; EU – European Union.

When both developed and developing countries are included, the reduction in income inequality will increase RE, while carbon dioxide emissions and corruption will also increase RE [27]. Increased income would increase demand for RE through eco-friendly consumers, while carbon dioxide emissions would encourage the power sector to adopt RE. Reducing income inequality increases RE generation and stimulates the power generation-promoting effects of innovation [28]; Adom et al. [34] confirm the positive effects of RE on income, education, and life expectancy and the negative effects on poverty and income inequality; Wirawan & Gultom [35] find that the RE-based village-grids (RVGs) program is effective in reducing poverty. In outlining the relationship between RE and poverty alleviation, Cheng et al. [36] identify energy access, ecosystem systems, and RE performance in rural households as future challenges. There may be regional differences and hidden channels regarding the interrelationships among RE, inequality, and carbon dioxide that need further examination.

2.2. Energy Inequality

Energy inequality refers to the disparities in energy consumption and access found in a given country or region; the World Health Organization (WHO) estimates that energy poverty causes 1.3million deaths per annum in developing countries due to inadequate indoor cooking stoves and the use of biomass fuels. Mukhtar et al. [37] note that energy poverty in sub-Saharan countries requires strategic funding to build a central RE grid system, as all countries have less than 100% access to electricity. There is a need for strategic financial support to build a central RE grid system. Energy poverty may be related to the positive effects of green finance and fiscal decentralization on RE [21, 24]. The causes of energy poverty in Palestine are inadequate grid systems and a lack of electricity access, due to high energy dependence on Israel [38]. Excessive energy dependence can induce geopolitical risks through political and socioeconomic conflicts in the energy sector. In Guatemala, a trade-off relationship between energy poverty alleviation and RE targets has also been noted [39]. Energy infrastructure can alleviate energy poverty. Identifying factors affecting energy poverty would be effective in achieving equitable energy consumption distribution and energy access.

Energy poverty has a negative impact on income, education, and life expectancy, while its poverty has a positive impact on income inequality [34]. However, while there is a significant relationship between environment, energy, health, and growth in the Brazil, Russia, India, China, South Africa (BRIC) countries from 1975 to 2013, the relationship is different in each country, confirming regional differences [40]. 28 Western countries from 2004 to 2018 also show that energy poverty is highest in Scandinavian countries, low in Bulgaria, and the Balkans have the highest [41]. In this analysis, the factors that have a significant impact on energy poverty are, in turn, energy prices, unemployment rates, and the percentage of people at risk of energy poverty; Muhammad et al. [42] also find that unemployment rates increase energy poverty, while per capita income mitigates energy poverty. In this study, in 27 European Union (EU) countries from 2005 to 2018, RE will contribute to reducing energy poverty as the transition to RE increases.

Table 4. The effect of education on the environment via RE.

Authors	Methods	Period	Country/Area	Impact of human capital on environment / RE	Results
Khan et al. [43]	Westerlund and Edgerton's panel cointegration and AMG	1995-2017	G7 countries	Human capital → Non-RE consumption (−) / RE consumption (+)	Financial development → Non-RE consumption (+) / RE consumption (−)
Hao et al. [44]	SG panel data method; CS-ARDL	1991-2017	G7 countries	Human capital → CO_2 (−)	RE → CO_2 (−)
Zafar et al. [45]	SG methodological approach	1990-2015	27 OECD countries	Human capital → CO_2 (−)	RE → Environment (+) / Economic Growth (+)
Khan et al. [46]	UR, CSD, panel CE, GC, TSLS, two-step GMM	2008-2018	64 Belt and Road countries	Human capital → CO_2 (−)	RE / Technology transfer → CO_2 (−)
Zhao et al. [47]	AMG and CS-ARDL	1990-2020	Jordan, Croatia, Ecuador, Georgia, El Salvador, Honduras, Indonesia, Pakistan, Morocco, Paraguay, Sri Lanka	Human capital → RE consumption (+) / Non-Re consumption (−)	Innovation → RE consumption (+) / Non-Re consumption (−)
Wang et al. [48]	SG econometric tests, GMM and FMOLS	1990-2018	208 countries	Human capital over turning point of EKC → CO_2 (−)	RE under turning point of EKC → CO_2 (−)

Note: AMG – Augmented Mean Group; SG – Second-generation; CSARDL – Cross-Sectionally Augmented Autoregressive Distributed Lag; OECD – Organization for Economic Co-operation and Development; UR – Unit Root; CSD – Cross-Sectional Dependence Tests; CE – Cointegration Estimation; GC – Granger Causality; 3SLS – Three-Stage Least Squares; GMM – Generalized Method of Moments; FMOLS – Fully Modified Ordinary Least Squares; EKC – Environmental Kuznets Curve.

In addition, during the initial transition phase, higher electricity prices from RE increase energy poverty; Li et al. [49] find that without consistent long-term energy poverty alleviation in 14 developed and developing countries, social welfare would deteriorate substantially. Table 3 presents the effects on energy inequality.

RE innovation contributes to the reduction of energy inequality [29, 30]. Hence, research and development (R&D) subsidies for RE would be effective in its reduction. Energy access has a significant impact on the economic development of developing countries, and the reduction of energy poverty improves their health standards [32]. The annual investment of $3.5 billion needed to build energy access is less than the amount of subsidies given to fossil fuels [50]. In EU countries, subsidy policies have been successful. Hence, under inter-regional heterogeneity, the development of RE industries alleviates energy poverty, and poverty reduction through RE is confirmed in European countries [33]. In high-income, upper-middle-income, and lower-middle-income countries, financial development and income reduce intra- and inter-regional energy gaps [31]. Poverty alleviation and financial development are also effective policies to promote RE innovation. This innovation promotion leads to decarbonization through energy poverty alleviation [51].

Corporate social responsibility contributes to the alleviation of energy poverty [52]. This environmental management is justified in terms of environmental justice of RE technologies [53]. Location, infrastructure, and household characteristics are identified as factors that increase the risk of energy poverty in Japan [54]. Without implementing subsidy policies that take these factors into account, energy poverty is unlikely to be alleviated. However, with appropriate institutional reforms, alleviation is possible [55]. Subsidies for the introduction of RE in households are confirmed to be effective in reducing energy poverty [56, 57]. A concerted effort by citizens, businesses, and government is important for poverty alleviation.

3. Education and RE

3.1. Impact of Human Capital on Carbon Dioxide

In general, education contributes to reducing income inequality. If this education leads to an increase in RE and a decrease in carbon emissions, poverty alleviation and decarbonization could be compatible. Table 4 shows that over other time periods, human capital accumulation contributes to increased RE in addition to decarbonization in many countries and regions [43–48]. Higher educational attainment promotes innovation. Hence, innovation expands RE when human capital is taken into account [47]. Decarbonization effects are also

Table 5. The indirect / no effect of education on the environment.

Authors	Methods	Period	Country/Area	Impact of human capital on environment / RE	Results
Zhou & Li [58]	SG UR and cointegration tests / PMG method	1990-2015	69 countries	Human capital determines the non-monotone effect of trade openness	-
Pata & Caglar [59]	Augmented ARDL approach	1980-2016	China	Human capital → CO_2 (−) / No effect on RE	No EKC
Sarkodie et al. [60]	NN, SIMPLS, U test, ARDL, PWFOA	1961-2016	China	RE → CO_2 (−) Human capital enhances the decarbonization effect of RE	EKC
Jena et al. [61]	Panel ARDL	1980-2016	China, India, Japan	Human capital / RE → Sustainability (+)	China: EKC India / Japan: U-shape relationship
Samour et al. [62]	ARDL and NARDL	1990-2018	BRICs countries	Human capital / RE → Sustainability (+)	-
Wang et al. [63]	DSUCR / DH	1990-2016	Next-11	No effect of human capital on RE	Financial development → RE (+)
Nathaniel et al. [64]	CD / CADF) / CCEMG / PMG	1992-2016	BRICs countries	No effect of human capital on environmental quality	RE → Ecological footprint (−)

Note: SG – Second Generation; UR – Unit Root; PMG – Pooled Mean Group; ARDL – Autoregressive Distributed Lag; NARDL – Nonlinear Autoregressive Distributed Lag; DSUR – Dynamic Seemingly Unrelated Cointegrating Regression; NN – Neural Network; PWFOA – Prais–Winsten First-Order Autoregressive; DH – Dumitrescu–Hurlin Causality; CADF – Cross-Sectionally Augmented Dickey–Fuller; CCEMG – Common Correlated Effects Mean Group; BRICS – Brazil, Russia, India, China, and South Africa; Next Eleven (N-11) – Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, Turkey, South Korea, and Vietnam; EKC – Environmental Kuznets Curve.

confirmed for technology transfers from other countries [46]. RE penetration leads to economic growth [45]. An environmental Kuznets curve (EKC) is identified for human capital and carbon emissions, with a tipping point at US$ 19,203. This tipping point determines the decarbonizing effect of human capital and RE [48]. In other words, the decarbonizing effect of human capital is identified in economies past the tipping point, while the decarbonizing effect of RE is before the tipping point. Education can contribute significantly to inequality and decarbonization. However, its contribution may depend on the stage of development of the economy.

Human capital complements the positive effect of trade liberalization on RE [58]. Although the effect of RE on the ecological footprint is ambiguous, human capital contributes to decarbonization and sustainability [59–62]. However, according to Wang et al. [63] and Nathaniel et al. [64], human capital does not confirm decarbonization and sustainability in the Next-11 countries, where future economic development is expected. Instead, financial development and RE will contribute to them. These countries may not have the infrastructure and capital in place to take advantage of productive workers. At this point, measures other than education should be implemented. Table 5 presents the indirect or no effect of education on the environment.

3.2. The Potential of RE Education

RE education is an effective way to promote RE, decarbonization, and poverty alleviation through the accumulation of human capital. However, its educational programs suffer from a lack of a structured curriculum, and even willing teachers suffer from a lack of funding for equipment [65]. The mismatch between the educational curriculum and industry needs makes the job placement of program graduates unclear, causing a shortage of human resources in the energy sector and hindering the development of RE markets [65, 66]. In several empirical studies, the failure of RE to contribute to decarbonization may be due to a marked shortage of human resources in developing countries. Training for teachers and the introduction of online education to stimulate interest in the RE sector, and the creation of new interdisciplinary programs on RE that address the needs of industry, will help to address the human resource shortage [66–68]. In doing so, attention should be paid to the human aspect of individual values, attitudes, and behaviors in order to increase the efficiency of energy education [69]. Kacan [70] proposes the establishment of an Alternative Energy Sources Technology Program in the Department of Electricity and Energy to raise the awareness level for renewable energy sources. Quantitative analysis of the impact of these initiatives on RE and carbon emissions would be desirable.

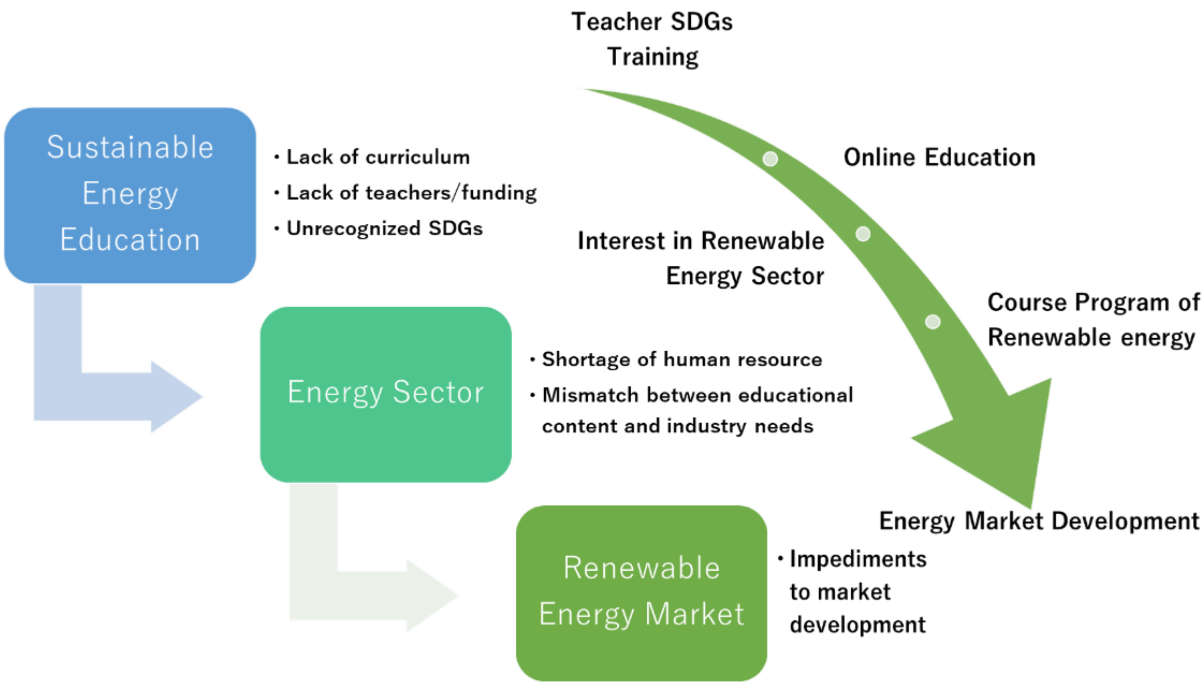

Figure 2. Issues and improvements of RE Education [65–68].

Figure 2 summarizes the process by which RE education contributes to the development of the energy market. Sustainable RE has the potential to contribute to the development of the RE market by supplying talent to the energy sector. However, several challenges requiring resolution have been identified at each stage. These challenges could potentially be addressed through SDGs education for teachers, online education, and the development of a systematic RE curriculum.

4. Role of Gender in RE Systems

4.1. Gender Relationships with RE

The existence of gender disparities in energy use is widely recognized. Feenstra & Özerol [71] have identified energy justice (distributive, recognitional, and procedural justice) and ending policy discourses (women empowerment, gender mainstreaming, and social inclusion) and attempts to conceptualize gender inequality in energy issues. Existing studies emphasize labor supply effects on energy access, but the role of gender-sensitive firms is less analyzed because of the low level of activity of women in energy-intensive sectors [72]. Moreover, most of the previous studies remain experimental and quasi-experimental approaches, and a detailed analysis of the role of gender in the Productive Use of Electricity is an issue for the future.

According to Baruah [73], women in low-income households in India who earn their living from the RE sector are unable to obtain sufficient employment or energy access in the sector due to inadequate levels of purchasing power and low social status. In a field study in a Chinese community, Ding et al. [74] report that RE improves energy intensity and affects women's labor intensity, health status, and cost of living, as well as men's cooking tasks. The introduction of RE (e.g., solar cookstoves and biomass stoves) reduces women's time spent collecting firewood. The use of biogas reduces women's cooking time by 50%, 91% of women use the income from energy savings to buy clothes and cosmetics, and 3% of women enjoy family vacations. The use of RE reduces indoor smoke pollution and prevents disease among women. A field study in an un-electrified village in Tibet found similar results [75]. However, a slight increase in women's work hours points to the existence of gender equality through religious beliefs and industrial structure. In a German study, cultural, social, and political factors influence individual participation in RE systems involving citizens [76]. Table 6 presents the relationship between gender and renewable energy.

4.2. Decarbonization through Women's Empowerment

Women's participation in society plays an important role in the transition to sustainable RE systems. With regard to the impact of the diffusion of low-carbon technologies on gender equality, it is difficult to improve gender equality through RE projects alone unless structural changes occur in the social and cultural as well as the economic dimension [77]. According to Pearl-Martinez & Stephens [78], while gender diversity in the energy

Table 6. Relationship between gender and RE.

Authors	Country	Research topic	Results
Baruah [73]	India	Challenges and constraints faced by women in low-income ecologies who earn their living from the RE sector	Low levels of employment and access for women in the energy sector via inadequate purchasing power and low social status
Ding et al. [74]	China	Impact of RE on gender relations in local communities in western China	RE improves energy intensity and affects women's labor intensity, health status, and cost of living Introduction of RE through solar cookers, biomass stoves, etc., will reduce women's time spent collecting firewood Use of clean energy can reduce indoor smoke pollution and prevent disease in women
Ding et al. [75]	Tibet in Chiha	Investigating the relationship between gender and energy use in rural Tibet	Increased RE has increased household energy consumption and efficiency, while disease rates have decreased Women's empowerment in household energy management has improved and cultural change has occurred
Fraune [76]	Germany	Investigating the impact of cultural, social, and political factors on citizen participation schemes in renewable electricity production	Cultural, social, and political factors, as well as individual preferences and investment attitudes, influence personal participation in RE systems involving citizens

industry encourages innovation, less attention has been given to promoting diversity in the workplace. In China, education spending, female employers, and RE have reduced carbon emissions [79]. However, the direction of future management of carbon-intensive energy regimes and gender equality in energy use varies from country to country in policy [80]. How can women's participation in society be potentially linked to macro-level decarbonization?

Compared to carbon-intensive energy industries, RE industries tend to employ more women workers; Allison et al. [81], in an interview study in the energy industry, noted that women workers who are concerned about the environment have received a good education and are engaged in various energy sectors. Nonprofit organizations on global warming have a potential role in critiquing the energy inequalities of the giant energy industry system and in promoting the creation of decentralized RE regimes in communities and the spread of energy justice in the energy sector. Women's leadership within this organization would facilitate the transition to a RE system and spread energy justice [82]. However, in Portugal, there were no statistically significant gender differences in the impact of knowledge, attitude, and willingness to pay for RE on its use [83].

Women's leadership in politics and management is seen to encourage the spread of RE. In Africa, which has many un-electrified areas, many women spend most of their time securing energy, such as firewood, and suffer health hazards from indoor smoke pollution; Opoku et al. [84] found that increasing the number of female legislators in Africa increased energy access and energy efficiency. In addition, good political governance stimulates the slight effect of increasing the number of female legislators on RE consumption. In an analysis of 11,677 United States (US) companies, two or more female directors increase corporate RE consumption, and their consumption and gender diversity on boards improve corporate financial performance [85]. Reducing energy poverty has a significant impact on gender inequality in education, as well as improving gender inequality in health by increasing employment opportunities and the number of women in the workforce [86]. Whether in developed or developing countries, more women's participation in social positions and responsibilities will increase the diffusion of RE. As a practical activity, the Economic Community of West African States (ECOWAS) has high expectations for the Gender Mainstreaming in Energy Access initiative [87]. Table 7 presents the relationship among gender, health, renewable energy, and the environment.

4.3. Health Impacts of RE

The social advancement of women in Africa can also lead to improved health in order to promote RE because lower energy inequality leads to higher education and health [32]. Replacing kerosene lighting in homes with electric lighting reduces the number of deaths from smoke pollution at higher rates, and replacing lighting with RE reduces carbon dioxide emissions [88]. RE not only improves income, education, and life expectancy, but also reduces poverty and income inequality [34]. Carbon dioxide emissions cause air pollution through the combustion of fossil fuels, which worsens the health of the surrounding population. Hence, in Pakistan, carbon dioxide increases health expenditures, whereas RE reduces carbon dioxide and health expenditures [89]. The environmental improvement effects of RE and health expenditure are also found in the US [90]. In addition to the Anzus-Benelux countries (Australia, New Zealand, the

Table 7. Relationship among gender, health, RE, and environment.

Authors	**Country (year)**	**Research topic**	**Results**
Gender			
Zaman et al. [79]	China (1991-2015)	Time series analysis	Education spending, female employment, and RE are negatively related to carbon emissions
Lieu et al. [80]	Canada, Spain, Kenya	Gender perspectives on the energy transition process through the Alternative Pathways framework	Identify on-stream pathways, off-stream pathways, and transformative pathways in relation to gender equality opportunities and carbon-intensive industries
Allison et al. [81]	US / Canada	Where are women within the energy sector? Do nature concerns and climate change concerns affect women's education and careers?	Women tend to be environmentally concerned, well educated, and engaged in a variety of tasks in the energy sector
Allen et al. [82]	US	Does women's leadership in nonprofit organizations impact the transition to RE systems?	Women's leadership encourages transition to RE systems and spreads energy equity
Martins Gonçalves & Viegas [83]	Portugal	Impact of knowledge, attitude, and willingness to pay for RE on RE use	No statistically significant gender differences in the impact
Opoku et al. [84]	36 African countries (2000-2015)	Impact of women parliamentarians on electricity access, RE consumption, and energy intensity and efficiency	Increasing the number of female legislators increases energy access and energy efficiency Positive effects on RE consumption are marginally significant Good governance moderates these effects
Atif et al. [85]	US (2008-2016)	Impact of women managers' participation on boards of directors on corporate RE	Significant positive effect of two or more female directors on firms' RE consumption Positive effect of RE consumption and board gender diversity on firms' financial performance
Nguyen & Su [86]	51 Developing countries (2002-2017)	Impact of energy poverty reduction on gender inequality, also considering health and education	Reduction of energy poverty increases employment opportunities and the number of women in the workforce Its reduction improves gender inequality seen in terms of health
Health			
Ortega et al. [88]	East Africa (2015)	Residents in East Africa were subjected to Quantified ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, and lower respiratory tract infection-related morbidity and mortality attributable to fine particulate matter (PM2.5) exposure	Percentage of households replacing kerosene-type lighting with electricity → Number of deaths averted 33%→6218 people / 66%→10092 people / 100%→12723 people Complete replacement of kerosene-based lighting in homes with renewable electricity → Black carbon emissions reduction in 2015: 4.4 Gg/year / 3957CO_2eq Gg
Ullah et al. [89]	Pakistan (1998-2017)	Relationship between trade, RE, carbon dioxide, and health expenditure	CO_2 → Health expenditure (+) / RE → CO_2 (−) / Health expenditure (−)
Pata [90]	US, Japan (1980-2016)	Impact of RE and health expenditure on load capacity (biocapacity / ecological footprint)	US：RE / Health expenditure → Environmental quality (+), Japan：RE → Environmental quality (+) Non-significant
Somoye et al. [91]	Nigeria (1965-2019)	Impact of fuel energy and RE on lifespan	Fuel energy / RE → Lifespan (+): long run / short run
Rahman & Alam [92]	Anzus-Benelux countries (1996-2019)	Impact of RE growth and urbanization on lifespan	RE growth / Urbanization → Lifespan (+)
Alola & Kirikkaleli [93]	US (1999-2008)	Relationship among CO_2, RE, immigrants, and health expenditure	Significant feedback causality between CO_2 and RE consumption Positive correlation between the variables in the short run

US, Belgium, the Netherlands, and Luxembourg), RE has been found in Nigeria to improve life expectancy by improve life expectancy [91, 92]. Feedback causality between carbon dioxide and RE consumption is also confirmed [93]. Medical institutions in areas with low electrification rates are unable to provide adequate medical care due to a lack of electricity, which is detrimental to the health of the local population. Therefore, the introduction of self-sufficient RE in such areas will enable smooth medical care and logistics, and enhance the health of the local population [94–96].

5. Local Community and Decentralized RE System

5.1. The Importance of Local Communities in Decarbonization

Local communities play a major role in the diffusion of RE, and autonomous community societies in the provinces were the driving force behind the rapid adoption of RE in Spain in the 2000s, which accounted for 11.6% of major energy consumption [97]. Integrated community energy systems were developed to support their spread, with local government, communities, energy suppliers, and system operators as sustainability actors [15]. Tools to analyze the relationship between energy poverty and RE communities have been developed and applied [98]. According to Kalkbrenner & Roosen [99], in German local RE systems, community identity, social norms, trust, and environmental concerns influence residents' willingness to participate, and participation is more likely in rural areas than in cities. Changes in social norms and trust alter community identity. In rural Indonesia, the RE-based village-grids program has contributed to poverty reduction [34].

However, there are a number of issues that need to be resolved for this system to be successful, and Brummer [100] analyzes the characteristics of community energy and outlines its benefits and barriers to adoption by comparing the U.K., Germany, and the US: a complex regulatory regime hinders the spread of community energy and has hindered its widespread adoption. However, the system's perceived reduction in energy poverty and its perceived sustainable lifestyle have led to its widespread adoption. The barriers in Germany, where there are many RE companies, are tied to the problems of the companies. These are financial issues, such as initial costs related to power generation and distribution facilities. Despite this, the system has become more widespread because of the perceived economic ripple effects that RE education can have on a variety of stakeholders. Because US policymakers are oriented toward large-scale electricity production, a barrier is that local RE systems are not recognized as a policy goal or instrument. To break down this barrier, it is necessary to make it known that the systems are effective as a means of empowering communities, not just for financial benefits [101].

5.2. Political Governance and Decentralized Voluntary Energy Systems

The proactive players in establishing local RE systems are local residents, not the government. In fact, in un-electrified villages in India, residents who are dissatisfied with kerosene electric lights and fuel costs do not trust local power companies regarding electricity supply and expect government leadership [102]. However, according to Cloke et al. [103], local community energy planning in the Global South, implemented in a top-down technical framework by the government, is not very effective in solving energy poverty and improving livelihoods in the region. Large-scale solar land acquisition projects in Charanka and Gujarat, India, have resulted in the enclosure and land acquisition of common land through extra-legal mechanisms, leaving more residents facing a livelihood crisis and accelerating community vulnerability [104]. Political corruption is severe in many developing countries. In such situations, there is a risk that stakeholders on decarbonization will use climate action as a pretext to increase their profits by taking away livelihood assets from vulnerable members of society. In OECD countries from 1990-2019, social and economic conflicts over the energy transition have also been a major factor in the RE productivity gap [33, 51].

To mitigate such conflicts, it is necessary to foster public approval for the substitution of fossil fuels for RE. Since willingness to pay for RE correlates with education and understanding of RE, it is important to have green energy consumers who will encourage its adoption [105]. This proactive consumer will come from the self-governing activities of residents in the community; according to Burke & Stephens [106], decentralized energy sources and technologies will lead to energy decentralization through decentralized political powerLocal cooperation is important for energy transformation and decentralization, while the lack of residents' initiative and women's participation hinders its spread [107].

Energy poverty can be alleviated if the quality of governance in government and communities improves [42]. Electrification through RE in rural areas promotes poverty reduction, but intermediary mechanisms through small-scale industries play an important role [35]. Hanke et al. [108] studied 71 European RE

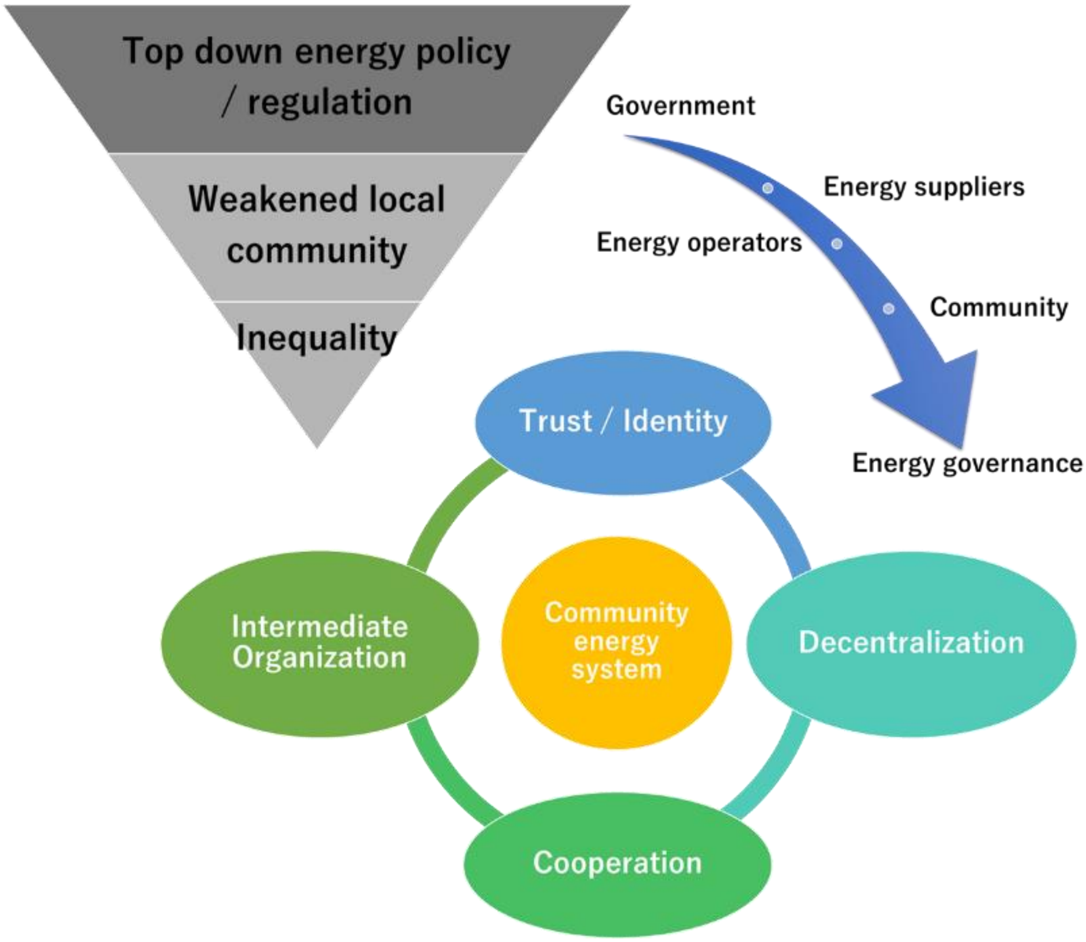

Figure 3. Relationship between RE and local community [97-111].

communities from the perspective of distributive, recognitional, and procedural energy justice, and found that these communities are strengthening their social role through the promotion of voluntary participation and the improvement of energy efficiency by voluntary households. In the creation of a decentralized energy system in the Northern Netherlands, the creation of committed local organizations with a shared vision is the starting point, and communication not only with residents but also with local environmental organizations and regulatory authorities determines its efficiency [109]. In doing so, various issues must also be addressed, such as continuity of safeguards, team leadership, and membership solidarity. Ruggiero et al. [110], through interviews in Scotland (24), Germany (6), Finland (5), N. Ireland (2), Sweden (2), Ireland (1), and Norway (1), analyze the interrelationships between community stakeholders and community RE regimes. The analysis shows that stakeholders influence this energy regime within and between communities, and that key stakeholders (intermediary organizations/local influencers) can be either project supporters or opponents, depending on their interests in the energy plan. In Peru, RE electrification projects have reduced indoor air pollution from wax candles, improved communication through television and radio, and promoted communication participation [111].

Figure 3 illustrates how top-down energy management systems for RE weaken the role of local communities in RE and lead to inequality. Here, transferring the management authority from the government to energy suppliers and operators, and then from these entities to local communities, enhances local energy governance. This is because trust and cooperation regarding RE, along with decentralization through intermediary organizations, contribute to building community-based energy systems.

6. Conclusion

In order to achieve carbon neutrality by 2050, there are high expectations for the introduction of RE. However, debate continues regarding the impact of their introduction on sustainability, which consists of social, economic, and environmental factors. This review outlines the research trends from 2014 to 2024, focusing on papers with the highest number of citations, from the perspectives of income inequality, energy inequality, poverty alleviation, human capital, energy education, gender, health, and community. RE and income inequality/energy inequality are negatively related. Hence, policies that encourage innovation in RE, such as R&D subsidies, are likely to contribute to improving inequality. Human capital accumulation contributes to decarbonization through RE consumption, but some studies question its effectiveness. Gender inequality and energy inequality are closely linked, and women's health suffers greatly. Women's social inclusion is expected to be a driving force for the diffusion of RE. Voluntary community initiatives are attracting attention in the development of sustainable energy regimes.

This review has highlighted several future research topics. The effects of RE on income/energy inequality and the effects of education on RE have been relatively well analyzed. However, empirical analysis of how RE education impacts greenhouse gas emissions and economic development remains limited, necessitating further quantitative research. The relationship between gender and RE appears to be relatively well-studied at first glance. However, given the multifaceted nature of gender, its impact on socioeconomic outcomes is expected to operate through various channels. While this multifaceted nature has spurred diverse empirical research on gender and RE, it also likely hinders the accumulation of research within specific, narrower topics. Alongside discovering new channels in this relationship, future research is also needed to enhance the robustness of known channels through accumulating studies. The relationship between RE and local communities is primarily explored through case studies and institutional analysis, with insufficient quantitative results based on empirical analysis. How should these relationships be verified? What data should be collected? What estimation models should be used? Pioneering research to explore these topics remains a future challenge.

This review summarizes how RE contributes to sustainability through income inequality, energy inequality, poverty alleviation, human capital, energy education, gender, health, and community, thereby contributing to the presentation of such review themes. Particularly, by adopting a narrative descriptive review method, it became possible to detail the interrelationships within each element. On the other hand, the selection of references based on the authors' experience and track record means subjective biases, such as sample bias, remain. The inclusion or exclusion of papers is ambiguous, and the sample size and selection process are not rigorous. A more objective literature collection is necessary, employing stricter review methods such as systematic reviews and bibliometric reviews, and following the PRISMA approach. Such an approach would enable a more accurate and detailed capture of research trends concerning the key survey themes analyzed in this review.

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