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Review

Review of Hot Topics in the Sustainable Development of Energy, Water, and Environment Systems Conference in 2022

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Abstract: The current applications in the energy sector are based largely on fossil fuels which release greenhouse gas emissions to the atmosphere. To face the issue of global warming, the energy sector has to transfer to and develop sustainable energy solutions that do not release carbon emissions. This is one of the primary motivators for the SDEWES conference as well as for this review, and previous ones, examining the most recent works based on sustainable and green energy production in such fields. The 17th Conference on the Sustainable Development of Energy, Water, and Environment Systems (SDEWES) was held on 6–10 November 2022 in Paphos, Cyprus. The SDEWES conference aims at solving complex and ongoing concerns that approach a long-term perspective and supporting innovative solutions and continuous monitoring and evaluation. This review paper aims at collecting the main presented papers focused on the following hot topics: low-carbon technologies based on renewable and clean-energy systems, including mainly biomass, solar, and wind energy applications; energy storage systems; hydrogen-based systems; energy-saving strategies in buildings; and the adoption of smart management strategies using renewable energy systems. These topics are investigated in order to propose solutions to address the issues of climate change, water scarcity, and energy saving. From the analyzed works, we note that some key issues for sustainable development remain to be further addressed: such as novel and advanced energy storage systems, green hydrogen production, novel low-temperature district heating and cooling networks, novel solar technologies for the simultaneous production of power and high temperature heat, solar desalination for hydrogen production systems, and agrivoltaic systems for the production of power and food.

Keywords: sustainable development of energy; low-carbon and renewable energy technologies; energy saving in buildings; smart management

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Citation: Chu, W.; Vicidomini, M.; Calise, F.; Duić, N.; Østergaard, P.A.; Wang, Q.; da Graça Carvalho, M. Review of Hot Topics in the Sustainable Development of Energy, Water, and Environment Systems Conference in 2022. *Energies* **2023**, *16*, 7897. https://doi.org/10.3390/en16237897

Academic Editor: Antonio Zuorro

Received: 17 October 2023
Revised: 16 November 2023
Accepted: 17 November 2023
Published: 4 December 2023

1. Introduction

Energy is a fundamental prerequisite for modern living; however, current sources are based largely on fossil fuels, thus releasing carbon, which had taken eons to store, into the atmosphere over a relatively short time period [1,2]. Therefore, the oil and gas industries, which play a dominant role in terms of greenhouse gas emissions, have to transfer to and develop sustainable energy solutions [3].

In this context, there is an eminent need to shift to energy sources that do not release carbon and a real need to enhance the holistic understanding of the nexus between energy and sustainable development [4]. This is one of the primary motivators for the SDEWES conference as well as for this review, and the previous ones [1,2], examining the latest work in the energy field.

The SDEWES conference is a well-known international event that focuses on the integration of sustainable development principles into energy, water, and environmental systems [5]. It brings together researchers, professionals, policymakers, and industry experts to exchange knowledge, present research findings, and discuss innovative solutions. Special attention was dedicated in the 5th SEE SDEWES Conference Vlore, 3rd LA SDEWES Conference Sao Paulo, and 17th SDEWES Conference Paphos on the following hot topics: (i) waste and carbon capture systems based on clean-energy technologies [6], (ii) renewable energy systems, including mainly biomass, solar, and wind energy applications; (iii) energy storage systems [7]; (iv) hydrogen-based systems; (v) energy saving strategies in buildings; and (vi) the adoption of smart management strategies using renewable energy systems.

According to the above-reported list, this review paper aims to summarize the contribution of the main works in the framework of these selected hot topics. However, the included works also address issues related to the use of (i) thermal power plants using advanced cycles; (ii) district heating in smart energy systems (which are based on the integration of heat produced by renewable energy systems, cogeneration units and industrial waste/excess heat, waste-to-energy and CHP [8], and power-to-heat and heat pumps [9]); (iii) advanced sustainable energy conversion systems (electrolysis, fuel cells, thermoelectric, thermionic, organic, ORC, and waste/excess heat recycling); (iv) low-temperature renewable heat systems (waste/excess heat, solar thermal, geothermal, and heat pumps); (v) modeling for pollution avoidance and energy efficiency (CFD models, air pollution spreading, water pollution spreading, heat and mass transfer modeling, and combustion modeling); and (vi) economic assessments for energy systems [10] and thermal engineering projects [11].

The SDEWES conference served as a gathering for 496 professionals, including scientists, researchers, and experts, specializing in sustainable development. Attendees hailed from 52 countries across six continents. Of these participants, 349 were present at the physical venue, while 147 joined virtually. The conference featured a comprehensive program consisting of 337 oral presentations distributed among 34 regular sessions and 14 special sessions. Distinguished experts in their fields delivered four plenary lectures and engaged in two-panel discussions, contributing to the richness of the event.

This review has been organized into the following sections: Section 2 explains the background issues which make it necessary to obtain the economic and sustainable development of energy production; Section 3 is about waste and carbon capture, where the technologies and system layouts that are necessary to shift from conventional fossil energy power systems to renewable generation systems are summarized; Section 4 through Section 6 are based on renewable energy technologies, namely, biomass energy applications (Section 4), solar energy applications (Section 5), and wind energy applications (Section 6); Sections 7 and 8 are pivotal for the management of the fluctuations of renewable energy production; they describe the importance of the adoption of energy storage technologies, namely, energy storage systems (Section 7) and hydrogen-based systems (Section 8); Section 9 discusses energy saving in buildings, considering that the reduction in the energy consumption of this sector is crucial to obtain the sustainable development of energy production; and finally, Section 10 covers renewables with smart management, focusing on the integration of machine learning techniques to optimize performance, boost efficiency, and refine the decision-making processes of renewable energy systems.

2. Contents: The Issues behind the Sustainable Development of Energy Systems

The concern of how sustainable growth in the economy can be achieved without a negative impact on the environment has become a major issue in the world today due to climate change [12]. Concerns about climate change, emission reduction, and environmental sustainability have become crucial in accomplishing long-term development goals [13]. Growing populations, increased urbanization, improved living standards, technological advancements in manufacturing, and increased economic competitiveness all contribute to an increased demand for energy [14]. These issues require a holistic and multidisciplinary approach involving governments, industries, academia, and civil society. Collaboration, innovation, and a commitment to sustainable development principles are also crucial for creating a resilient and low-carbon energy future [15]. Thus, it is essential to meet present energy needs without compromising the ability of future generations to meet their own needs. Some key issues and considerations related to the sustainable development of energy systems include greenhouse gas emissions, renewable energy transition, energy efficiency, infrastructure and investment, policy, technology innovation, energy security, etc. [16].

To face these issues, several energy technologies, methods, and approaches have been studied in the literature to obtain the economic and sustainable development of energy production. This paper aims to summarize the research papers investigating the methods of obtaining the sustainable development of energy production. Therefore, the detected hot topics relate to the sustainable development of energy, water, and environmental systems utilizing low-carbon technologies based on renewable and clean-energy systems (including mainly biomass, solar, and wind energy applications), energy storage systems, hydrogen-based systems, energy saving strategies in buildings, and the adoption of smart management strategies using renewable energy systems. For each hot topic, a comprehensive description of the papers focusing on the topic has been reported, as seen in the following sections.

3. Waste and Carbon Capture

The development of low-carbon technologies is crucial for mitigating climate change and transitioning to a more sustainable energy future. Some new research lines, such as carbon capture, utilization, and storage (CCUS), sustainable transportation, a circular economy for materials, etc., can contribute to advancing low-carbon technologies [17].

The advancement of low-carbon combustion technologies, the shift from conventional fossil energy power systems to renewable generation systems, and the adoption of waste-to-energy processes are imperative for the decarbonization of numerous countries striving to attain their net-zero carbon emission goals [18], e.g., New Zealand set the goal to achieve zero emissions by 2050 [19].

In this framework, the following papers summarize several options for innovative technologies.

Ilea et al. [20] presented absorption and stripping systems designed for carbon capture. They put forward an innovative decentralized control system that incorporates optimized setpoints, with the ultimate goal of enhancing the efficiency of carbon dioxide capture. The approach involved implementing a cascade configuration along with additional control loops, all aimed at elevating both the carbon capture performance and the overall energy efficiency of the plant. Their research revealed that the energy performance index observed a 3% reduction, while the absorption rate experienced a 1% increase when compared to the reference cases. This suggests that the proposed approach could be instrumental in achieving improved energy efficiency and enhanced carbon capture performance within such systems.

Zhang et al. [21] proposed a novel coal gangue disposal technology that could reach 300,000 tons/year. The results of this study showed that the average removal rate for combustible components might reach 88.47%, indicating great advantages and stability compared with normal calorific value coal gangue. Wong et al. [22] presented a study of Malaysian companies to understand their perceptions towards a net-zero carbon future. Results indicated that, by implementing advanced technologies coupled with nature-based solutions, the employees as well as the company had the capabilities and showed a positive attitude toward using their financial resources to transition Malaysia into a carbon-neutral nation.

Energy recovery from the combustion of municipal solid wastes is the most important part of protecting the Earth's ecology [23]. Waste-to-energy uses trash as fuel for power generation. It was noticed that the development of waste-to-energy recovery technologies might contribute to emission and pollutant reduction [24]. Furthermore, wastes are also capable of replacing low-quality fossil fuels in heating and power plants. Common technologies for the combustion of municipal solid wastes include mass burn facilities, modular systems, and waste-derived fuel systems.

Putna et al. [25] proposed a methodology to assess the efficiency of a waste-to-energy plant on the air pollution load after integrating it into existing district heating systems, with one of the case studies involved using real-world data. It was shown that the emission load could be significantly reduced by up to 83%.

De Greef et al. [26] authored a comprehensive review paper delving into the behavior of inorganic compounds within waste-to-energy combustion processes. Their review adopted a multidisciplinary perspective, taking into account both the waste-to-energy and biocircular economy approaches. This investigation was particularly pertinent due to the recent tightening of emission limits, as well as the goals of enhancing energy efficiency and recovering materials from the process. Their paper addressed a wide array of topics related to waste-to-energy combustion plants, focusing on the inorganic compounds commonly found in thermally treated waste, such as chlorine (Cl), sulfur (S), phosphorus (P), and various metallic elements. A noteworthy aspect of their study is the integrated and multidisciplinary viewpoint used to discuss these topics. One of their main aims was also to pinpoint specific areas that warrant further investigation; this included developing better control mechanisms for inorganic compounds in industrial waste-to-energy combustion processes. Additionally, the authors suggested the removal of unsuitable materials and substances to facilitate reuse or recycling. To achieve these goals, the authors advocated for the expansion of artificial intelligence (AI) control systems that are tailored to combustion processes. This expansion could be accomplished by creating predictive numerical models and conducting experimental research. Such AI-driven approaches would aid in better understanding and managing the behavior of inorganic compounds typically encountered in waste furnaces.

4. Biomass Energy Applications

To achieve reductions in CO_2 emissions, there has been a growing focus on radical measures such as exploring solutions for the enhancement of waste biomass utilization [27]. Simultaneously, biomass wastes often encompass substantial energy resources that can be converted into fuels [28]. Basically, biomass can be converted into fuels through various processes. Some new research lines and areas of focus, including thermal conversion, biochemical conversion, and chemical conversion [29], can contribute to biomass energy application.

Martins et al. [30] developed the technology to produce microalgae by using secondary brewery wastewater. Compared to the existing biomass-based upgrade strategies of microalgae, the use of wastewater becomes extremely promising due to the co-production of biofuel by oligosaccharides and protein.

Jerzak et al. [31] used fiberboard, brewery spent grains, and soybean meal for the pyrolysis process in a fixed-bed reactor at a temperature of 773 K. The results showed a stronger correlation between a more endothermic pyrolysis process and the heating value of the pyrolysis gas, as well as improved biomass pyrolysis when measuring a higher K_2O/CaO ratio in the ash. It was also found that 4–10% of the higher heating value of the raw materials was lost during the conversion process.

Ibrahim et al. [32] put forward a progressive and eco-friendly approach for altering the structure of wool, aiming to attain remarkable and lasting antibacterial effects as well as UV-blocking capabilities. The modified wool was intended for crafting multifunctional textile items, which find utility in a broad spectrum of sustainable protective textiles. The outcome of their research demonstrated that the efficacy of both the modification and functionalization processes was greatly influenced by the choice of enzyme and active material employed. Furthermore, the team's investigations revealed that the enzymatically synthesized keratinolytic proteases have the potential to be conveniently employed in eliminating protein-based stains, such as those arising from blood and eggs. It is worth noting that technologies related to converting wastewater into biogas production have also captured the interest of researchers, presenting an attractive avenue for exploration. By combining these innovative strategies, Ibrahim and colleagues contributed to the development of textiles that not only exhibit enhanced functional attributes but are also aligned with principles of environmental sustainability.

Ferreira et al. [33] introduced a novel technique for estimating the expansion of a liquid fluidized bed, utilizing a force balance concept on the bed and drag correlations. Through their research, they found that the drag correlation approach yielded notably more dependable outcomes, displaying an average coefficient of determination of 0.92. Comparing their results with findings from other sources in the literature substantiated the robustness and scalability of their method. The proposed method's potential for estimating the expansion of a liquid fluidized bed has significant implications. It promises a simpler and safer application of this technology, particularly in areas like wastewater treatment and biogas production. This advancement not only contributes to the optimization of these processes but also extends their reach and usability in practical applications.

Merzic et al. [34] reported that the largest power utility in Bosnia and Herzegovina plans to introduce short rotation coppice type willow as the dedicated energy crop in former areas of coal mines. Their results showed that the willow produces a much higher yield in comparison to Mischantus.

Molina-Besch [35] investigated the life cycle analysis (LCA) of bioplastics. It was found that the energy properties and bio-based behavior of bioplastics are extremely interesting. They revealed that since the end-of-life stage of bioplastics differs from fossil-based materials, the use-phase of bioplastics is often overlooked in LCA.

Baldelli et al. [36] conducted a comprehensive study that aimed to assess the effects of photovoltaic (PV) systems, thermal energy storage, and power supply arrangements on the efficiency of an integrated bio–thermo–chemical upgrading process for wet residual biomass. Their investigation introduced an inventive integration of anaerobic digestion with thermochemical conversion processes, with a specific focus on employing a membrane reactor for the production of high-purity hydrogen from wet residual biomass. The performance of this integrated plant was thoroughly analyzed across various scenarios, each with the goal of minimizing grid energy consumption. The researchers employed a Simulink/Simscape model to assess parameters such as hydrogen production, primary energy requirements, conversion efficiency, and CO_2 emissions. The plant architecture aimed to produce hydrogen and included several units: anaerobic digestion (AD), pyrolysis (Py), oil reforming (P-Ref), and syngas reforming (Ref). The process begins with the AD unit, fueled by biomass, generating biogas and a solid residue. The solid residue goes through a dryer and then a pyrolyzer, which rapidly heats it to 500 °C in a fast pyrolysis process. This yields three products: char, used for heat generation; bio-oil, used for bio-based fuel production; and pyro-syngas, which is fed into a reformer. A palladium-catalyzed membrane is employed to separate high-purity hydrogen from the remaining syngas. PV panels provide continuous power to sustain the plant's operations, with excess power managed through the power grid. To lessen grid reliance, thermal energy storage (TES) converts surplus PV power into heat, fulfilling the plant's thermal energy requirements. The study evaluated three distinct scenarios: a reference scenario using only grid power, a renewable energy scenario with power supplied by both the grid and a PV field, and a similar scenario incorporating TES to support plant operations by using stored heat energy from the PV surplus. In conclusion, Baldelli and colleagues' research introduced a sophisticated approach to maximizing the efficiency of a bio–thermo–chemical process for wet residual biomass by integrating renewable energy sources, thermal energy storage, and advanced processing units. This innovative method not only showcases improved energy efficiency and environmental benefits but also paves the way for more sustainable waste-to-energy systems.

5. Solar Energy Applications

Solar energy holds diverse applications spanning various sectors and stands as a vital resource in the shift toward a sustainable energy landscape. Emerging research avenues encompass solar photovoltaic (PV) power generation [37], solar water heating [38], solar air conditioning [39], off-grid power systems [40], solar desalination, and more. These can collectively contribute to the progression of solar energy utilization.

Italos et al. [41] investigated the performance of an active solar energy system in a residential apartment building. By applying the proposed active solar system with a double skin façade, the energy consumption of the building was comprehensively reduced by 83.5%, which is a cost-efficient solution for buildings in the south-eastern Mediterranean area. Marletta et al. [42] studied the performance of a thermally driven solar-assisted cooling system. It was highlighted that the primary energy demand and CO_2 emissions could be reduced by over 75% when compared to the conventional electric-driven chiller. However, after raising the collecting surfaces, the delivered rate of thermal energy became non-negligible, showing similar behavior to the coefficient of performance (COP). Solar energy is also used for generating power, cooling, heating, and desalinized water. Moosazadeh et al. [43] conducted a study focused on an integrated system that combines multiple energy conversion technologies. This integrated system comprises several components, including the Kalina cycle (KC), organic Rankine cycle (ORC), ammonia–water refrigeration, pressure retarded osmosis (PRO), and forward osmosis (FO). The research explored the performance, efficiency, and potential benefits of this intricate combination of energy conversion processes. Each of these technologies plays a role in optimizing energy utilization and conversion across various applications and contexts. The integration of these diverse technologies can potentially lead to the enhanced overall efficiency and resource utilization of energy-related systems. Their results showed that the sustainability index of the proposed system reached 0.73, showing much greater efficiency than that of power generation systems with fossil fuels.

Panagopoulos et al. [44] analyzed an innovative concentrating solar thermal system that used a micro-mirror array on the receiver for solar energy concentration. The system was simulated in COMSOL software, showing 683 to 729 kWh of annual energy generation with temperatures ranging from 115 to 225 °C. Zheng et al. [45] presented an energy and exergy analysis of a direct absorption solar collector which could absorb and convert solar energy directly into heat energy without an intermediate fluid or heat transfer medium. The photothermal conversion was evaluated under various magnetic fields. It was noted that the application of ferrofluid and magnetic fields may enhance solar energy efficiency, showing a relevant effect of direct absorption in solar collectors.

Grommes et al. [46] undertook a study investigating the advantageous influence of the albedo (reflectivity) of red soil on the annual yield of bifacial PV systems in western Africa. To achieve this goal, they developed a comprehensive bifacial PV simulation model that combined an optical view factor matrix with power output simulation techniques. The simulation model accounted for various factors that impact energy efficiency, particularly ground-reflected irradiance on the rear side of the panels which is contingent on the albedo of the ground surface. The performance of the bifacial PV module was calculated using the one-diode model, utilizing simulated radiance data for both the front and rear sides of the module. Radiation reaching these sides was determined using a hybrid Perez model for irradiance reflection and diffuse light calculation, alongside a 2D view factor model for radiance distribution. To validate their simulation model, the researchers conducted specific measurements in three different locations in Ghana (Kuwasi, Accra, and Akwatia). Notably, the red soil in two of these locations exhibited higher albedo values compared to the majority of natural ground surfaces, contributing positively to the annual yield of bifacial PV panels. The average albedo values ranged from 0.175 to 0.335, with the calculated average albedo of red soil in Ghana being approximately 0.260 ± 0.025. The research determined that while no direct correlation could be established between albedo and geological properties, the presence of red soil had a favorable impact on the energy yield of bifacial PV systems. For instance, in northern Ghana, a bifacial PV system with 19.8% efficient modules could achieve an annual energy yield of 509 kWh/m^2 and a bifacial gain of up to 18.3% compared to monofacial PV panels. The study's findings are transferable to regions with similar red soil composition and offer insights into optimizing the performance of bifacial PV systems in areas characterized by these specific geological conditions.

Mannino et al. [47] conducted a study focused on developing degradation forecast models for PV modules in both onshore and offshore floating systems. This investigation is particularly relevant as floating PV panels can be deployed on lakes and dams, providing a solution to land use challenges for other purposes. Their main objective was to assess how the marine environment influences the degradation patterns of PV modules, crucial for designing modules with extended lifespans. The study aimed to evaluate the impact of the marine environment on the reliability and durability of PV systems, considering the unique stressors present in such conditions. To achieve this, meteorological data from offshore locations were utilized to analyze the effect of the marine environment on degradation trends. Specifically, two Mediterranean locations with the same latitude but differing longitudes were compared over the course of a year. Unexpectedly, the outcomes from the model indicated a lower degradation rate in the offshore environment (0.95% power decay) compared to the mainland (3% power decay). However, these results were deemed unrealistic due to discrepancies between the model's calibration conditions and the analyzed study environment. The higher power decay observed in the onshore case was attributed to the need to revise the model. The study highlighted that the empirical coefficients of the model must be recalculated based on the actual installation environment. Furthermore, the model's estimation of degradation in the offshore case did not account for several environmental factors characteristic of marine settings. The study stressed the necessity of a more comprehensive model that considers the detrimental effects caused by wind, as well as other environmental factors such as waves and sea salinity. In conclusion, Mannino and colleagues' work underscores the significance of developing accurate degradation forecast models for PV modules in floating systems, both onshore and offshore. It emphasizes the importance of adapting models to the specific installation environment and accounting for all relevant environmental variables to ensure realistic and reliable predictions of module degradation.

Calise et al. [28] developed a comprehensive study involving a dynamic simulation model and thermoeconomic analysis for an innovative hybrid solar system designed to produce biomethane from the organic fraction of municipal solid waste. The system integrates various technologies to achieve its goals, and the researchers conducted thorough modeling and analysis to evaluate its feasibility and benefits. The production of biogas was modeled in a plug flow reactor using MATLAB® software [48]. This model was used to predict the temperature within the reactor, enabling the study of how temperature impacts the growth and decay of the primary microbial species involved in the process. The anaerobic digestion model proposed is a coupling of thermal and biological models, designed to simultaneously simulate both the thermal heating and biological reactions taking place in the reactor. The anaerobic digestion model was then integrated into a dynamic simulation model developed within the TRNSYS environment. This allowed for a comprehensive yearly dynamic simulation of the reactor as well as renewable technologies to provide the necessary heat and power for the plant. Specifically, the heat required to maintain the reactor temperature was generated by an evacuated tube solar thermal collector array spanning approximately 200 m^2. Meanwhile, the power demands for the biomethane upgrading unit were met by a 400 m^2 photovoltaic (PV) array. The upgrading unit employed a selective membrane system to remove CO_2 from the biogas mixture, enhancing its quality. Excess power generated by the system was stored in a lithium-ion battery setup. The overall plant was also connected to the grid to manage power exchanges.

The system aimed to treat a waste flow of 626 kg/h, yielding approximately 850 tons/year of biomethane. This arrangement notably decreased the reliance on natural gas and grid power compared to a reference system without renewable energy integration. The economic analysis factored in the capital costs of components as well as the incentives granted for biomethane injection into the gas grid or supply to gas stations. The results indicated that, while the model provides valuable insights into biogas production variations, an optimization process is essential to determine the optimal sizing of solar collectors and the PV field. The evacuated tube collector met 35% of the heat demand, while over 50% of the power demand was addressed by the PV array. However, to achieve grid independence, the PV capacity coupled with the battery system needs expansion. The payback period was also reduced from 7.5 years to around 5 years with the inclusion of public incentives. In conclusion, Calise and team's study showcases the potential of a hybrid solar system for biomethane production from municipal solid waste. It emphasizes the significance of both technical modeling and economic analysis in designing sustainable energy systems.

6. Wind Energy Applications

Wind energy and solar energy are the two renewable energy sources that have gained the highest attention for their role in the energy transition [49]. It is well known that wind energy is usually largely available in coastal and open areas, where it can be converted into electricity using wind turbines [50]. Wind energy is a significant and growing source of renewable power. Some new research lines and areas of focus include offshore wind farms, hybrid energy systems, remote monitoring and maintenance, microgrids and decentralized energy, etc., that can contribute to advancing wind energy applications. Conversely, wind turbines typically exhibit a higher capacity factor in comparison to solar PV systems [51]. Presently, the levelized cost of electricity associated with wind energy tends to be lower than that of solar energy, showcasing favorable economic viability [52]. Nonetheless, wind turbines could exert a more pronounced environmental impact, particularly on bird and bat populations, in contrast to PV systems.

Lamagna et al. [53] investigated an offshore wind turbine coupled with a reversible solid oxide cell (rSOC) and evaluated the mutual benefits considering local energy management. It was found that a 120 kWe rSOC system could be coupled to a 2.3 MW wind turbine, providing electricity during wind shortages or maintenance. Majidi et al. [54] designed software involving the maximum likelihood, the WAsP, and the least squares algorithms in order to figure out the best offshore wind layouts for farm installation. Two scenarios of offshore wind farm layouts were analyzed in the Northwest Persian Gulf, indicating excellent potential for offshore wind energy generation.

Rusu et al. [55] estimated the wind climate during the 21st century in the area of the Black Sea basin. Results showed that the average wind power was improved by about 10–20% in the western part, which was regarded as the most energetic and most appropriate region for wind energy harvesting. Meanwhile, the basin showed quite similar features compared to the Atlantic Ocean region. Ulazia et al. [56] investigated the long-term collocated wind–wave energy trend in Canary Island. Data from 1981 to 2020 were used to estimate the wind–wave energy feasibility index, which showed an increment of 5% per decade.

Polykarpou et al. [57] introduced an innovative data-driven tool, based on non-linear optimization techniques, for the purpose of siting offshore wind farms. This user-friendly tool is designed to handle complex, non-linear relationships and heterogeneous factors without relying on oversimplified assumptions. The approach effectively navigated through the potentially complex cost function landscape, considering a range of technical variables pertinent to selecting the optimal locations for offshore energy production facilities. The researchers applied this data-driven tool in the central Aegean Sea, a region characterized by high offshore wind energy potential. The objective function integrated various heterogeneous criteria including water depth, wind speed, constraints linked to activities, like shipping routes, and technical limitations such as proximity to shore, distance from ports, and compatibility with electrical grid infrastructure. To tackle the optimization problem, the team developed an algorithm based on sequential Monte Carlo methods. The results generated by the tool were presented in the form of rectangular areas, each measuring one square km. These areas were color-coded to represent their suitability for offshore wind farm development. Dark green regions indicated highly recommended areas, while lighter green areas were moderately favorable, and almost white areas denoted the least suitable locations. The study also highlighted the importance of energy storage for enhancing the viability of offshore wind projects. Given the intermittent nature of wind power production, energy storage solutions become crucial to ensure a stable power supply that can match varying demands. The researchers suggested hydrogen as a promising energy storage medium due to its higher energy density compared to batteries. Hydrogen could act as an energy carrier, helping to minimize transmission losses and reduce the installation costs of electrical transmission systems. In conclusion, Polykarpou and colleagues' work presents a sophisticated and data-driven approach to optimizing the siting of offshore wind farms. The incorporation of complex technical factors and constraints, as well as the consideration of energy storage solutions, contributes to making the offshore wind energy sector more efficient, reliable, and economically viable.

7. Energy Storage Systems

It is worth highlighting that the operational versatility of sustainable energy power plants can be augmented through the integration of energy storage systems [58]. Thermal energy storage mechanisms can play a pivotal role in elevating energy efficiency, amplifying the utilization of renewable energy resources, and curbing overall energy consumption and expenditures [59]. These storage solutions find applications across diverse sectors, encompassing power generation, industrial processes, building systems, and transportation avenues [60]. Some new research lines and areas of focus include thermal energy storage via phase change materials (PCMs) [61], compressed-air [62], chemical materials, etc., in solar [63] and wind [64] energy systems that can yield great contributions.

Wen et al. [65] proposed an integrated power generation system with a liquid air energy storage apparatus that could store the off-peak electricity in liquid air. Lamrani et al. [66] numerically studied the use of shell-and-tube thermal energy storage devices in low-temperature applications. By reducing the heat transfer fluid from −4 °C to −7 °C, the charging time could be reduced by 37%. Increasing the tube number and using water/ice as a cold storage medium obtained better performance compared to commercial PCMs such as RT2-HC and RT4-HC. Liu et al. [67] proposed a two-level optimization model by combining system simulation and plant optimization. In the case of a 1 GW integrated plant combining wind, solar, and battery storage, the economic benefits of energy storage exhibited a proportional relationship with the overall capacity. However, the rate of growth is mitigated as the capacity increases. The income cannot fulfill the requirements of economic development when the incomes of capacity mechanisms and auxiliary services are not involved.

Nuclear energy has been a topic of both promise and controversy in the context of sustainable development. It offers potential benefits in terms of low carbon emissions and a consistent energy supply, but it also presents challenges related to safety, waste management, and proliferation risks [68].

Aunedi et al. [69] introduced a modeling approach aimed at minimizing both the investment and operational costs within a decarbonized energy system. The study centered on a specific case involving a 1610 MW nuclear power plant. The research sought to optimize the integration of various energy sources and storage technologies to enhance the system's efficiency and economic performance. The outcome of the study revealed significant benefits from the application of a 4.5 GWh thermal storage capacity, coupled with a discharging time of 2.2 h. For a system dominated by wind energy, the net system benefits per unit of flexible nuclear generation were in the range of 29–33 GBP per year. In a solar-dominated system, the benefits ranged between 19 and 20 million GBP per year.

These findings suggest that by strategically incorporating energy storage and managing the operation of the nuclear power plant, substantial economic gains can be achieved within a decarbonized energy system.

Geothermal energy holds significant promise as a sustainable and renewable energy source that can contribute to both environmental protection and socioeconomic development. It harnesses heat from the Earth's interior to generate electricity and provide heating or cooling for various applications [70]. Shumiye et al. [71] adopted energy storage with boiling and reverse osmosis water purification combined with solar and geothermal energy to generate electricity at nighttime. The exergy efficiency could reach 49.25%. Battery storage helps in stabilizing electrical grids by providing fast response times and helping to manage fluctuations in electricity supply and demand [72]. Meanwhile, a battery storage system has the benefits of peak shaving and load shifting and provides backup power during grid outages or emergencies, ensuring a reliable power supply for critical loads [73]. Manso-Burgos et al. [74] evaluated a battery energy storage system with different capacities by comparing the demands of residential and commercial loads. The results depicted that a locally optimized energy community can simultaneously fulfill the environmental, economic, and self-consumption goals. Minica et al. [75] evaluated the advantages of energy storage and flexible cooling loads. It was also revealed that the system's operating costs rose by over 19% when reserve limitations were applied. On the other hand, when flexible assets were permitted in the energy storage market, significantly higher incomes could be achieved, indicating that the reserve capacities provided by energy storage and demand response display an important impact.

Yesilyurt and Yavasoglu [76] introduced a comprehensive model for vanadium redox flow batteries (VRFBs), a type of energy storage system that holds significant promise due to its design flexibility, potential for indefinite lifetime, cost-effective manufacturing on a large scale, and recyclability of its electrolytes. The proposed model is centered around a 1 kW/1 kWh VRFB system and was developed within the MATLAB Simulink environment. The model is capable of capturing both the steady-state and dynamic characteristics of VRFBs. It takes into account various specific features of the flow battery, including the shunt current, charge transfer resistance, ion diffusion, and energy consumption associated with circulation pumps. Notably, the model also addresses the aging effect, specifically porous electrode aging, which pertains to the degradation of the carbon-based porous electrodes used in VRFBs over time. This aging can impact the battery's performance, efficiency, and overall lifespan. The key novelty of this work is the creation of an extensive equivalent circuit model for VRFB batteries, enabling integration into the dynamic simulation environments frequently used for renewable energy technologies, such as TRNSYS. The equivalent circuit model establishes a relationship between the external behavior of the battery during operation and its internal state, offering insights into its performance and health. The researchers validated the model's accuracy by comparing simulation results from the equivalent circuit battery model with actual datasets, demonstrating a model accuracy of 3%. This modeling approach contributes to a better understanding of VRFB behavior, aiding in the optimization and implementation of these energy storage systems within dynamic renewable energy scenarios.

Bielka et al. [77] investigated the technologies of carbon dioxide capture and storage to reduce anthropogenic carbon dioxide emissions into the atmosphere. The main investigated processes were separation and dehydration. Both processes were compared by selecting a suitable method of CO_2 separation and compression. In particular, the authors considered CO_2 capture from the emission source and its final compression for transport in a liquid state. Therefore, the key features of the suitable geological storage were also investigated as well as the CO_2 transport to the storage. For gas dehydration, the absorption using liquid glycols was used due to the low plant cost of this technology. Triethylene glycol was also employed as a liquid due to its higher sorptive and recoverable properties. In order to reduce the cost of the triethylene glycol plant, multistage compression with cooling before the gas dehydration was employed. The pressure of gas supplied to the dehydration unit was assumed equal to 45 bar, the mass flow rate of TEG was selected as 0.5 kg/s, the H_2O out of the TEG unit was 26.6 ppm, and the cooling gas temperature after each compression stage was assumed equal to 20 °C. The use of more compressors was able to reduce the gas temperature downstream through successive compression stages by decreasing the energy required by the entire plant and the amount of heat that must be collected during the gas stream cooling process. Assuming that the geological storage site is located 30 km from the capture place and the carbon dioxide amount captured after the post-combustion is 2.449 million tons/year, the simulations performed by BR&E ProMax software (developed by Bryan Research and Engineering Inc.) obtained the following results: the minimum power demand required to compress the gas and reduce the plant's operating costs were 7047 kW, 15,990 kW, and 24,471 kW, for 25%, 60%, and 100% plant load, respectively, when adopting a maximum post-compression gas temperature of 95 °C for each cycle. The optimal number of compression stages for the efficiency of the system was five. From an economic viewpoint, the authors needed to transport the carbon dioxide in the liquid state even if a slightly higher density than in the supercritical state was obtained. Concerning the key features of geological storage, the authors considered storages suitable when they had appropriate values for permeability, porosity, and potential reservoir capacity; the presence of impermeable cover rocks in order to prevent carbon dioxide from migrating to higher layers, aquifers which do not contain potable water for human use purposes; and a reservoir located more than 800 m below the ground surface due to conditions of high pressure and temperature to store carbon dioxide.

8. Hydrogen-Based Systems

Hydrogen-based systems hold promise as a versatile and low-carbon energy carrier. Some new research lines and areas of focus include green hydrogen production, hydrogen storage and transportation, hydrogen infrastructure development, hydrogen fuel cells, etc., that can contribute to advancing hydrogen-based systems. Note that hydrogen is considered one of the cleanest and most energy-intensive alternatives with respect to fossil fuels [78]. Dincer et al. [79] presented the framework for developing hydrogen technologies, establishing necessary infrastructures, and selecting suitable resources to achieve a more resilient and sustainable hydrogen energy system. Their results indicated that nuclear energy can be considered the most suitable source for hydrogen production, with a global warming potential (GWP) value as low as 0.027.

Henry et al. [80] presented a techno-economic analysis for green hydrogen production from wind energy. Results showed that the price of hydrogen from wind can be reduced to 4.85 GBP/kg, which is comparable with the price of natural gas. However, the price of hydrogen is basically due to the high capital costs of the related equipment. Hydrogen produced by steam methane reforming accounts for 60.0% of the global hydrogen demand. Wu et al. [81] numerically studied a packed bed reactor integrated with diverging tubes to improve hydrogen generation efficiency. It was noted that the overall heat transfer coefficient rose by 9% after applying a packed bed with an inclined orientation while the hydrogen production increased by 34%. Jin et al. [82] reported that renewables are inadequate at satisfying the electricity demand due to their variable and intermittent features. They proposed an energy storage system via a fuel cell and hydrogen in a 220 kW small-scale hydropower plant. Results showed good round-trip efficiency; however, considerable economic investments were the main concern because of the high energy-to-power ratio. Adisorn et al. [83] provided a perspective for hydrogen production by using wastewater in arid countries such as Jordan. Two expert workshops were carried out and various routes for hydrogen production in water-scarce contexts were discussed. Khani et al. [84] developed catalytic gasification technology to generate hydrogen gas in which spinel-type oxide-supported Ni catalysts were applied. The gas yielded 32.2 vol% of hydrogen with low CO_2 and zero CH_4, providing a new prospect for economical hydrogen generation.

9. Energy Saving in Buildings

Efficiency gains in building energy consumption constitute a pivotal dimension in realizing energy transition objectives [85]. Buildings constitute a substantial portion of the total primary energy demand [86]. Within this context, the adoption of energy-saving strategies [87] can yield profound effects on greenhouse gas emissions and operational energy expenditures.

Reducing buildings' GHG emissions is also crucial to achieve the sustainable development goal [88]. Ligardo-Herrera et al. [89] developed an innovative open access planning tool that can assess the energy consumption of house units, buildings, and districts. Thus, end-users could estimate energy savings by changing their energy habits, equipment, and sources. Users could also identify how much carbon dioxide emissions could be reduced by using renewable sources, by smart tools encouraging users to reach the net-zero-energy target.

Montagud-Montalvá et al. [90] focused on the waste heat recovery from a data center located on the Vera campus with a yearly demand of 1,661,020 kWh. By introducing a 300 kW polyvalent heat pump, more than 254,106 kWh/year thermal energy saving and 64,035 kg/year CO_2 emission reduction could be achieved on the Vera campus. Piselli et al. [91] evaluated the role of seasonal thermal energy storage units for residential buildings. Their results showed that the possible EU scenarios depend on a plurality of factors, namely, cultural context, demographic features [92] and residential heating practices. It should be mentioned that the impact of technology unbalance might compromise the achievement of equitable energy transition. Dall-Orsoletta et al. [93] identified the achievements of electric vehicles associated with some potential issues related to battery development, components composition, and recycling use. The high upfront costs and investment in charging infrastructure might limit development during the operational stage in poor and rural communities. Ming et al. [94] developed thermotropic materials that might limit indoor solar radiation transmission. As a result, the thermotropic materials could adjust the dynamic regulation of solar energy and achieve energy-saving for building indoor environments.

Schindler et al. [95] conducted a study that focused on the optimized operation of district heating networks in two distinct case studies situated in the Burgenland towns of Oberwart and Neusiedl am See. Their approach revolved around the integration of electricity and heat sectors through power-to-heat systems. The investigation included the integration of a biomass plant and/or a gas boiler into district heating systems, as well as the incorporation of wind energy. Specifically, the research explored the integration of two types of heat pumps, both air-to-water and water-to-water, fueled by the electricity generated from wind turbines. The optimization process, aimed at minimizing costs, was carried out using a mixed-integer linear programming (MILP) model. Each system component was represented as a separate block in the model, and their interactions were incorporated through additional constraints, ensuring energy conservation between the components. The study also delved into the economic implications of changes in gas and electricity prices for district heating systems, considering the substantial variations between 2022 and 2019–2020. The layouts of the investigated systems are depicted in the Ref. [95]. In the first district heating network (DHN1), a biomass plant fed the system through heat storage, while a power-to-heat unit in the form of a boiler was integrated to consume electricity from the local grid. The authors suggested replacing the boiler with a heat pump, emphasizing its potential to produce a greater amount of heat with the same power input. Additionally, they proposed installing a cost-efficient power-to-heat plant with a nearby PV plant to optimize electricity production. In the second district heating network (DHN2), a biomass plant and a gas boiler supplied the system through storage. Here, wind energy, generated by a 30 MW peak power wind source, powered two air-to-water and two water-to-water heat pumps. The study revealed that a substantial portion of heat production could be fulfilled by heat pumps during summer operation, offering a more environmentally friendly solution with biomass and CO_2 savings. The authors recommended integrating a

PV plant to produce electricity mainly during summer, thereby replacing gas-powered heat production. In summary, Schindler and colleagues' research offers insights into optimized district heating network operations, exploring various configurations and renewable energy integrations to enhance efficiency and sustainability.

Díaz-Ramírez et al. [96] conducted an environmental evaluation of the Hellisheidi geothermal power plant using exergy allocation factors. The geothermal plant, a combined heat and power double-flash facility located around 30 km east of Reykjavik, Iceland's capital, has an installed capacity of 303.3 MW of electricity and 133 MW of heat. The plant draws energy from geothermal fluid extracted from deep wells through a network of 36 km of pipes. The geothermal fluid is then directed to high-pressure separators, where it is separated into steam and brine. The study employed a life-cycle assessment approach with an exergy allocation factor, utilizing a functional unit of 1 kWh of electricity and 1 kWh of hot water for district heating in Reykjavik's capital area. The life-cycle stages considered encompassed the construction, operation (including maintenance and abatement operations), and well closure of the geothermal plant. To ensure accuracy, the study utilized an updated life-cycle analysis database and assessed the results using the ReCiPe method. The outcomes, obtained through exergy allocations, indicated that the majority of the environmental impact should be attributed to electricity production, aligning with expectations. Notably, the construction stage emerged as the primary contributor to the overall environmental burden for 16 of the 18 indicators assessed. This stage accounted for around 70–80% and 60–70% of the impact on heat and power production, respectively. This was primarily due to mechanical equipment, geothermal wells, and the power plant building. The mechanical equipment played a significant role in the indicators related to eutrophication and ecotoxicity, contributing around 30–40%. Geothermal wells were the most influential in categories concerning global warming and resource scarcity. The heating station building was responsible for the highest environmental burden, making up around 60% of the total impact. In both power and heat production, the consumption of materials like steel and concrete had the most substantial environmental impact. The turbine generator and heat exchanger for district water heating were the key factors affecting the environmental performance of power and heat production, respectively. Enhancements in equipment construction were suggested as a means to reduce the environmental burden of the Hellisheidi geothermal power plant. In terms of specific indicators such as global warming potential (GWP, kg CO_2 eq.) and water consumption (WCP, m^3), the operation and maintenance stage had the most pronounced impact, accounting for over 90% of the impact for both electricity and heat production. This was due to greenhouse gas emissions and water consumption during plant operation. The inclusion of abatement units had a positive effect in minimizing CO_2 emissions. The end-of-life stage exhibited the lowest impact across all indicators examined.

10. Renewables with Smart Management

The integration of machine learning techniques holds the potential to optimize performance, boost efficiency, and refine decision-making processes in renewable energy systems [97]. Machine learning, a subset of AI, centers on crafting algorithms and models that empower computers to learn from data and enhance their performance iteratively. This involves crafting systems that can autonomously learn and improve based on experience, without explicit programming for a particular task. Machine learning algorithms are tailored to discern patterns, correlations, and insights within data, enabling them to make forecasts, classifications, or choices using new, previously unseen data. This technology has witnessed application across diverse domains, spanning image and speech recognition, recommendation systems, autonomous vehicles, and numerous others [98].

Lovorka et al. [99] developed a mathematical model based on simulation modeling for environmental protection which can successfully contribute to environmental pollution prevention without any unnecessary risk. Heracleous et al. [100] proposed assessment scenarios that can meet the energy demands for educational buildings by using Integrated

Environmental Solutions and life cycle costing analysis. As a result, a framework was developed to support the decision-making for climate change resilience. Parlak [101] reviewed various smart technologies used in gas pipelines and steel oil fields and developed a smart application for in-line inspection.

Ulrich et al. [102] introduced an optimization algorithm capable of incorporating increased loads into distribution grid infrastructure by leveraging data from smart meters and/or smart meter gateways. This algorithm involved the creation and application of a mathematical programming formulation. Its primary function was to ascertain the most efficient charging schedule for all electric vehicles linked to the distribution grid. This schedule was devised with consideration of various criteria to prevent breaching physical grid limitations and ensure equitable charging for all electric vehicles while simultaneously enhancing the grid operation. Furthermore, the system's scalability and fail-safe operation were considered by decentralizing all the components. The outcomes of this study highlighted that the developed optimization algorithm facilitated higher transformer loads compared to a conventional P(U) control approach. Notably, this was achieved without causing grid overload, a problem observed in scenarios where optimization or P(U) control was absent.

Thiran et al. [103] introduced the concept of the typical days clustering technique for optimizing energy system models. This technique involves representing a full-year time series with a reduced number of characteristic days, leading to more efficient computations. However, the authors identified a gap in the literature regarding the impact of this technique on the results of energy system optimization models, particularly in the context of multi-regional whole energy systems. To address this gap, the researchers developed an energy system model using EnergyScope Multi-Cells. This model was designed to simulate the operation of interconnected regions within a larger energy system. The study focused on nine diverse cases, each involving different numbers of typical days, various types of days, and differing quantities of regions. To assess the trade-offs between model accuracy and computational cost, the authors introduced a bottom-up a posteriori metric termed the "design error". This metric provided insights into the deviations between the results obtained using the full-year time series and the ones achieved through the typical days clustering technique. The study found that by employing 10 representative days, the computational time could be significantly reduced, ranging from 8.6 to 23.8 times, depending on the specific case. This reduction in computational burden was achieved while maintaining a design error below 17%. Notably, in all studied scenarios, the time series error proved to be a reliable predictor of the design error. In essence, Thiran and co-authors' research highlights the advantages of using the typical days clustering technique in energy system optimization models, particularly in multi-regional contexts. This technique offers a practical means of achieving computational efficiency without significantly compromising model accuracy, contributing to the optimization of complex energy systems.

Yavasoglu et al. [104] presented the in-line inspection technique via robotic system inspection sensors in natural gas distribution pipelines. The robot could detect the pipeline with lower attenuation frequency and improved the communication factor over 500 times. Tzima et al. [105] presented a study showcasing the application of machine learning methods to monitor the built environment of historic clusters in Cypriot towns, specifically Limassol and Nicosia. The aim was to enhance an online Heritage-Building Information Modeling (HBIM) platform for remote urban monitoring. The research project utilized a computational technique based on machine learning to handle the substantial amount of data involved. The online platform incorporated 3D models of the examined building clusters, enabling the observation of transformations in the built environment caused by natural phenomena or human activities. The machine learning approach facilitated the analysis of these changes and the identification of potential risks. The processing workflow for this project was executed using the SNAP environment, a tool commonly employed for Earth Observation analysis. The study yielded valuable insights into urban landscape changes and dynamics, particularly highlighting trends in town expansion. Notably, the research also detected the land changes that occurred in Nicosia between 2016 and 2022. The digital tool developed in this research has significant implications for urban planning and management. By providing accurate and up-to-date monitoring capabilities, the tool offers a foundation for crafting more effective strategies for city authorities and other stakeholders. This enhanced monitoring can help define policies and incentives that contribute to the sustainable management and development of historic clusters within cities like Limassol and Nicosia.

11. Conclusions

In this paper, the main research works presented at the SDEWES conference series are reported. As the review clearly shows, there are numerous energy technologies, methods, and approaches to obtain the economic and sustainable development of energy production. This is crucial in order to reach the energy and emission reduction targets for future decarbonization. In the present paper, the works on the topics are summarized as (i) low-carbon technologies based on renewable and clean-energy systems (including mainly biomass, solar, and wind energy applications); (ii) energy storage systems; (iii) hydrogen-based systems; (iv) energy saving strategies in buildings; and (v) the adoption of smart management strategies using renewable energy systems.

The collected papers provide insight into topics related to thermal power plants by using advanced cycles, district heating in smart energy systems, advanced sustainable energy conversion systems including electrolysis, fuel cells, thermoelectric, thermionic, organic, ORC, waste/excess heat recycling, low-temperature renewable heat systems (waste/excess heat, solar thermal, geothermal, and heat pumps), modeling for pollution avoidance and energy efficiency (CFD models, air pollution spreading, water pollution spreading, heat and mass transfer modeling, and combustion modeling), and economic assessments for energy systems and thermal engineering projects.

In this framework, the reviewed papers are motivating for readers focusing on the sustainable development of energy and water sectors and their integration. In fact, the sustainable development of energy, water, and environment systems (SDEWES) is crucial for achieving long-term environmental, social, and economic goals. It involves the integration and optimization of energy generation, water management, and environmental protection to ensure a harmonious and sustainable relationship between these interconnected systems. Additionally, it is a complex and ongoing process that requires a long-term perspective, innovative solutions, and continuous monitoring and evaluation. It is essential for addressing global challenges such as climate change, water scarcity, and environmental degradation while promoting social well-being and economic prosperity.

However, we should note that some key issues for problems related to climate change, water scarcity, and energy saving in regard to sustainable development remain to be further addressed in the coming future works, e.g., (i) novel and advanced energy storage systems; (ii) green hydrogen production; (iii) novel low-temperature district heating and cooling networks; (iv) novel solar technologies for the simultaneous production of power and high-temperature heat; (v) solar desalination for hydrogen production systems; and (vi) agrivoltaic systems for the production of power and food.

In this framework, in the coming future, new policies and market instruments will have key roles in promoting sustainable energy development. Hence, a comprehensive evaluation and investigation involving political exploration, technology analysis, and economic study, should be undertaken. Therefore, this paper will be useful for providing useful recommendations for future addresses on the research. It is evident that future SDEWES conferences will continue to serve as platforms for promoting the concept of sustainable development in various critical areas including energy, water, food, transport, and the environment. These conferences will likely provide a space for advanced research discussions and presentations that encompass technical, economic, and social aspects. The SDEWES community is anticipated to closely follow these developments and engage in the discussions and activities. For those interested in staying updated and participating in the

SDEWES conference series, it is recommended to check out the International Centre for Sustainable Development of Energy, Water, and Environment Systems' (SDEWES Centre) website. This platform should offer further information on upcoming conferences, activities, and resources related to the fields of the sustainable development of energy, water, and environmental systems.

Author Contributions: W.C. and M.V. prepared the initial draft. The manuscript was corrected and reviewed by F.C., N.D., P.A.Ø., Q.W. and M.d.G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The guest editors sincerely appreciate the authors who submitted their high-quality manuscripts to this special issue. We also thank all the reviewers who spent time and gave their highly valuable comments and thank the managing editors of Energies for their great effort and excellent support.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AI	Artificial intelligence
CCUS	Carbon capture, utilization, and storage
CFD	Computational fluid dynamic
CHP	Combined heat and power
COP	Coefficient of performance
GHG	Greenhouse gas
LCA	Life cycle analysis
ORC	Organic Rankine cycle
PCM	Phase change material
PV	Photovoltaic
SDEWES	Sustainable development of energy, water, and environment systems
TES	Thermal energy storage

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