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Review

Recent Advances in Low-Carbon and Sustainable, Efficient Technology: Strategies and Applications

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Abstract: The COVID-19 pandemic has had a significant impact on the supply chains of traditional fossil fuels. According to a report by the International Energy Agency (IEA) from 2020, oil-refining activity fell by more than the IEA had anticipated. It was also assumed that the demand in 2021 would likely be 2.6 million bpd below the 2019 levels. However, renewable markets have shown strong resilience during the crisis. It was determined that renewables are on track to meet 80% of the growth in electricity demand over the next 10 years and that sustainable energy will act as the primary source of electricity production instead of coal. On the other hand, the report also emphasized that measures for reducing environmental pollution and CO_2 emissions are still insufficient and that significant current investments should be further expanded. The Sustainable Development of Energy, Water and Environment Systems (SDEWES) conference series is dedicated to the advancement and dissemination of knowledge on methods, policies and technologies for improving the sustainability of development by decoupling growth from the use of natural resources. The 15th SDEWES conference was held online from 1–5 September 2020; more than 300 reports with 7 special sections were organized on the virtual conference platform. This paper presents the major achievements of the recommended papers in the Special Issue of *Energies*. Additionally, related studies connected to the above papers published in the SDEWES series are also introduced, including the four main research fields of energy saving and emission reduction, renewable energy applications, the development of district heating systems, and the economic assessment of sustainable energy.

Keywords: energy saving; emission reduction; renewable energy; district heating and cooling; economic assessment

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1. Introduction

People all over the word are highly vulnerable to the COVID-19 pandemic, which causes millions of deaths globally, especially those living in developing countries. However, several countries are facing severe financial burdens, meaning that additional support will be necessary in the near future [1]. It is predicted that the pandemic will extend the schedule of sustainable development goals beyond 2030.

Based on the Word Energy Investment Report by the International Energy Agency (IEA) [2], global energy investment is expected to rebound this year and increase by 10%, reaching 530 million USD. Renewable energy is estimated to attract 70% of global energy investment in 2021. However, these positive developments will still not alleviate the increase in carbon dioxide emissions due to the rapid economic slowdown created by the pandemic. In the IEA report, global CO_2 emissions are expected to grow by 1.5 billion tons in 2021. Hence, the development and application of novel technologies such as carbon capture and storage (CCS) are capable of improving ecological health as well as attaining commercial success [3]. It is also pointed out that favorable policies and regulations play a v crucial role in maintaining the long-term confidence of investors in renewables [4].

According to the 2030 climate and energy framework of the European Union (EU), emissions should be cut with a binding target of at least 40% before 2030 in comparison to its 1990s level [5]. One of the approaches discussed is to increase the share of renewable energy production to at least 32%, and the other is to improve energy efficiency by at least by 32.5% [6]. Denmark has an official strategy for its CO_2 neutrality target before 2025. It also proposed a project named "100% renewable Copenhagen", which is due for completion by 2050 [7]. The energy use in inland Norway has become almost 100% renewable, with only the local resource potential in its two counties used [8]. New York City in the United States [9] wants to reduce carbon emissions by 80% by 2050. Over 150 cities have adopted clean energy targets in the US, including six cities that have already reached this target [10]. Note that the growth of emissions in developed countries is moderate [11]. By contrast, their exported emissions have become a big concern. Australian exported emissions through coal are double those of its domestic emissions, according to a recent analysis [12]. The United States have rejoined the Paris agreement and renewed their commitment to tackling the global climate issue. However, the cheap strategy for shell gas and other fossil fuels results in an investment distortion, which might adversely hinder sustainability development [13]. For developing countries, the emerging demand market for sustainable energy has grown by almost 70%. China has demonstrated commendable renewable growth, which is consistent with its goal of carbon neutrality by 2060.

The 15th conference on the *Sustainable Development of Energy, Water and Environment Systems* (SDEWES) was held online due to the influence of COVID-19. A visual platform was established that provided a more convenient, favorable and efficient method of communication. The papers presented in the present review paper are mainly cited from articles that were presented at the SDEWES 2020 conference, as well as in past SDEWES conferences. In total, 14 out of the 300 presented papers were selected for publication in this Special Issue of *Energies*.

SDEWES has maintained high publishing standards in special issues and cooperates with journals such as *Applied Energy* [14], *Energy* [15], *Energy Conversion & Management* [16], *Journal of Cleaner Production* [17], *Journal of Environmental Management* [18], *RSER* [19], *International Journal of Hydrogen Energy* [20], *Thermal Science* [21], *Sustainability* [22], etc. In 2017, *Energies* and SDEWES started a long-term cooperation which generated a considerable international influence for both the journal and the conference. The relationship will be continued with greater success [23].

The papers in the present Special Issue can be categorized into four main research fields, including energy saving and emission reduction (four papers), renewable energy applications (one paper), the development of district heating systems (four papers), and the economic assessment of sustainable energy (five papers). These papers, published in the *Energies* SI, are all reviewed in Section 3. Meanwhile, based on recent advances in strategies for and applications of low-carbon and sustainable, efficient technology, papers presented in prior SDEWES conferences and recommended to the journal's SI are also reviewed in Section 2. The present paper aims at presenting the novelties introduced by the papers included in this special issue, in the research fields mentioned above. In order to better show the findings of these papers and the related advancement in knowledge, a literature review was performed in the corresponding area, paying special attention to the works presented at past SDEWES conferences. In particular, Section 2 shows a detailed analysis of the papers presented at previous SDEWES series conferences, regarding the topics related to energy saving, emission reduction, renewable energy applications and district heating systems. The reported analysis clearly shows that the special issue presents important points of advancement with respect to the findings available in the literature.

Readers can identify their research interests in a much clearer way according to the presented classification. The fields include numerous and different alternatives through which to produce energy in a low-carbon and sustainable manner, which is pivotal to achieving the energy transition. This paper is intended to present an overview of the papers available in this area, paying special attention to the works presented during past SDEWES conferences. The contributions summarized in this manuscript are useful for researchers and engineers working in the field of energy production and energy saving by means of recent and advanced low-carbon and sustainable technologies. Therefore, the presented review is not only focused on the description of the papers presented at the SDEWES 2020 Conference and at the prior SDEWES conferences, but also on the description of all the different energy alternatives, classified in four main fields, for sustainable energy management and production.

2. Background

In this section, about 150 papers belonging to the prior SDEWES conferences and to the current literature regarding the different approaches to reaching a low-carbon and sustainable-energy society are reported. Among all the papers, four main fields were identified:

(i) energy saving and emission reduction;
(ii) applications of renewable energy;
(iii) the development of district heating systems;
(iv) the economic assessment of sustainable energy.

Each investigated paper was placed into its corresponding field in order to present, through a clear classification, all the employed methods, developed layouts, used tools and main results of these studies. The authors state that the adopted classification is useful for researchers and engineers working in the field of energy production and energy saving to address in their future studies within the framework of recent and advanced low-carbon and sustainable technologies.

2.1. Energy Saving and Emission Reduction

Currently, the major source of energy is still fossil energy, and its consumption produces a substantial amount of carbon dioxide, leading to concerns over climate warming due to the greenhouse effect [24]. Economic development with low-carbon, sustainable, and efficient strategies has become a general consensus among human beings [25]. The measures implemented include improvements in the efficiency of existing energy sources [26], limitations on high-energy-consumption industries [27], energy management in buildings and waste-product recovery [28]. In this section, recent studies related to energy-saving and emission-reduction methodologies for fossil fuel combustion, the transportation sector, heating ventilation and air-conditioning and high-accuracy prediction models are reviewed.

Fossil fuel combustion is regarded as the highest pollutant source. NO_x, SO_x and CO_2 are regarded as the main harmful gases produced in pressurized oxy-combustion [29]. Promoting fuel saving, improving energy efficiency and replacing conventional fuel consumption with renewable-energy technologies are regarded as general strategies for mitigating pollution emissions and climate change [30]. Tan et al. [31] proposed an improved recovery system that can reuse waste heat in 1000-megawatt coal-fired power plants with the implementation of two plastic heat exchangers made with fluorine plastic. The results showed that the water saving, coal saving and net present value (NPV) of this system could reach up to 95 t/h, 4.11 g/kWh and 102,739,000 RMB with investment payback within 4 years, demonstrating the profitability of mitigating the environmental problems caused by flue gas. Zadravec et al. [32] introduced the flue gas extraction with an effective air-staging strategy for sensible heat recovery. A wood-pellet boiler was installed into a laboratory-sized heating system, while the operating conditions, including the airflow rate, temperatures and combustion ash inside the chamber, were measured. The supplied primary-to-secondary-air ratio was reduced by 54.7%, with a 39.8% reduction in the oxygen concentration in the flue gases and a 31.6% reduction in sensible heat loss. At the same time, emissions such as NOx and CO were reduced by 14.4% and 93.9%, respectively. Costa et al. [33] developed the genetic algorithm to simultaneously optimize the NOx and CO contents of a syngas-powered engine in a power plant. The authors considered that it is possible to achieve high efficiency and low emissions from biomass gasification processes by managing the operating variables, such as the air-to-fuel ratio, exhaust gas recirculation, spark timing, etc., with automatically intelligent (AI) control. The simulated data showed that the proposed managing method indicated a reduction of up to 50% in the NOx and CO pollutants, with nearly zero deterioration in the power output. Loy-Benitez et al. [34] developed a smart multi-objective decision-making approach to combining conventional power systems with renewable energy sources, including solar energy, wind turbines, lithium-bromide absorption chillers, solid-oxide fuel cells (SOFCs), proton-exchange membrane electrolyzers, etc. Results showed that an exergy efficiency improvement by at least 34% can be obtained when introducing a combination of 70% solar- and 30% wind-energy contributions, yielding the highest competitiveness and lowest budget.

The transportation sector also makes a substantial contribution to air pollution in current society. Cipek et al. [35] investigated a battery–electric system combined with a traditional diesel–electric locomotive by equipping a battery energy storage device. It was proven that the fuel cost savings can reach 22~30%, achieving a remarkable reduction in the emission of exhaust gases. They also established a quasi-static model to evaluate the profitability of the system. The results showed that the savings on fossil fuels could not cover the investment of a brand-new battery. Hence, the strategy would become more attractive only if the cost of batteries were to decrease to an acceptable level. On the other hand, for achieving the target of high efficiency and low emissions (HELE), CO_2 capture, utilization and storage technologies [36] also show significant importance across the fossil fuel combustion system [37]. CO_2 can be captured through liquid solvent extraction [38] or by using non-chemical methods such as pressure swing adsorption, temperature swing adsorption and electric adsorption [39]. Another method to decrease CO_2 emissions is to combine power plants with the operation of subcritical or supercritical CO_2 boilers, which can raise the comprehensive efficiency with higher stream pressure. Sunaryo et al. [40] noted that the reduction in CO_2 emissions is 20.9 tons when increasing the supercritical pressure to 240 bar. According to the IEA report in 2019, the energy industry strives to operate with the highest possible energy efficiency, and the IEA works with policy makers and stakeholders to scale up action on energy efficiency to mitigate CO_2 emissions.

In the last few years, a remarkable increase in overall energy demand was obtained in several countries. This global growth in energy consumption is mainly due to the increased adoption of new heating ventilation and air-conditioning (HVAC) systems in the building sector [41]. The main reason for this high growth is the high comfort levels of building occupants [42]. The building sector is responsible for more than 35% of greenhouse gas emissions and accounts for about 40% of the overall end-use of energy in OECD countries [43,44]. Taking into account residential buildings, the energy consumption required for space cooling/heating, appliances, lighting, and domestic hot water (DHW), an average annual consumption per unit floor area of about 180 kWh/m^2 was estimated [45]. From the developed literature search, the energy needed for space heating and cooling accounts for about 50–70% of the total energy consumption [46–48]. The key factors in significant energy consumption are frequently appliances [49], lighting [50], high dynamic thermal transmittance and HVAC systems. In this framework, for achieving the target of the EU climate protection strategy [51], it is clear that the high energy consumption of buildings offers significant potential for reducing carbon emissions. It was reported that over 1/3 of primary energy waste is generated by the nonindustrial building sector [52]. Adopting better building insulation strategies and more efficient HVAC technologies can dramatically reduce the primary energy demand of buildings [53]. The net energy demands of buildings can be significantly reduced when applying appropriate seasonal and daily operating schedules [54]. Simoes et al. [55] studied the energy performance of a solar wall system used for residential buildings in a Mediterranean climate. It was indicated that as much as 20% of the heating demand can be effectively saved without affecting the cooling season. Meanwhile, savings in cooling demand of more than 35% could be reached through the inclusion of night ventilation. Figaj and Zoladek [56] also analyzed a novel solar heating and cooling system for residential applications. Solar energy was collected to thermally drive chillers for both heating and cooling purposes. Computational fluid dynamics (CFD) software was applied to simulate the system. The ambient conditions in Warszawa and Lisbon were considered. The results showed that the primary energy-saving ratio could reach 54.2~66.6% for Warsaw, and 44.3~50.2% for Lisbon. The payback period for configuration investment was about 18.1 years when considering the combination of flat plate collectors and absorption chillers, while the payback period was 27.2 years when combining photovoltaic–thermal collectors with adsorption chillers. Frank et al. [57] proposed an innovative management system by thermally connecting domestic appliances for heating and ventilation. A heat pump was regarded as the central heating and cooling unit. The total energy consumption could reach 35 kWh/year, while the COP of the heat pump was raised from 3.3 to 3.5. Furthermore, a low-GWP refrigerant was applied, and offered further improvement. A static analysis showed that the system's contribution to energy reduction could reach 202 kWh after achieving a COP of 4.4.

A reliable, high-accuracy prediction model is crucial to visualize the effects of uncertainties and diversity in order to achieve optimal objective benchmarks and evaluate them reliably [58]. Prataviera et al. [59] presented an open-source instrument for city-scale buildings and urban energy systems. The electrical analogy was applied to model the thermal behavior of building clusters through resistance–capacitance networks. A broader city district consisting of more than 500 buildings in Padua was studied for benchmarking. In the winter season, the buildings' energy needs ranged from 50 to 125 kWh/(m^2y) according to each building's age, results that were consistent with the provided records. With the development and mature application of AI technology, the prediction model was improved with much higher accuracy, efficiency and reliability for dynamic management. Pinto et al. [60] investigated the energy-management strategy of single buildings at building cluster level. An energy management controller based on Deep Reinforcement Learning (DRL) was adopted for optimizing the energy consumption and coordinating the behavior of the clusters. The DRL strategy was compared with manual management systems in a four-building combination equipped with different energy systems. The results showed that the reduction in operational costs may reach, on average, a decrease in peak demand of about 4–12%. Furthermore, the average daily peak and peak-to-average ratio could be reduced by 10 and 6%, respectively, showing the great benefits of a coordinated approach. Tien et al. [61] also introduced DRL control strategies that can provide real-time monitoring of the amount of time that windows are left open and, subsequently, adjust the air-conditioning system to minimize energy wastage and maintain indoor environment quality, as well as thermal comfort. The strategy was capable of identifying windows' status with an average accuracy of 97.29%, indicating its potential to help building managers to prevent unnecessary heating or cooling demand. Nam et al. [62] developed an energy-efficient management system for underground ventilation based on AI-iterative dynamic programming technology. The energy efficiency could be improved by almost 8.68% after maintaining the subway's indoor air quality, equaling a decrease of 96 t/y of CO_2. In other words, the proactive optimal ventilation system presented a decrease in operating expenditure of more than 4217 USD each year. Ferrara et al. [63] presented a machine-learning technology based on residual neural networks to minimize the primary consumption of non-renewable energy resources. The method showed good prediction accuracy, with a prediction error of 3%, and an energy performance improvement of 47% was reached after identifying the optimized design solutions. Moreover, approaches based on DRL algorithms could enhance search efficiency in the design of optimal solutions. Pietrapertosa et al. [64] launched the Schools4energy initiative, based on the "learning by doing" logic, for raising awareness of energy saving in public buildings among young generations. It was interesting that a pronounced decrease of 4% in natural gas consumption and a slight increase in electricity consumption, of about 0.5%, were observed. Thus, the enthusiastic participation of the young generations illustrated great potential of steadily changing of social attitudes.

2.2. Renewable Energy Applications

Production and living processes based on fossil fuels are causing crucial environmental and social problems [65]. The Earth exhibits substantial changes in its ozone layer, air environment and water resources, along with rising temperatures. Therefore, more it is imperative to apply more sustainable resources to mitigating these destructive processes [66]. Renewable energy resources, such as wind [67], solar [68], biomass [69] and geothermal energy [70], as well as other sources [71], can provide an economic and ecological alternative to fossil fuels to satisfy the increasingly global energy demand. Meanwhile, the control of decarbonization also requires the utilization of new technologies and energy sources [72]. In this section, the applications and advanced development of thermal storage systems for photovoltaic (PV) panels, wind energy, biomass and hydropower, as well as their hybrids, are reviewed.

Among the aforementioned systems, the implementation of solar thermal collectors is expected to rapidly grow [73]. As reported by the International Energy Agency, the gross area of solar systems has reached 686 million m^2 in 2018, which is expected to rise by 191% by 2030 and 745% by 2050, reaching 2000 million m^2 and 5800 million m^2, respectively [74]. Anurag et al. [75] discussed the possibility of incorporating solar PV farms into 13,000 US airports. It was summarized that major challenges such as physical penetration, radar interference and reflectivity and glare should be overcome for safe deployment. Usually, the application of typical solar PV systems in airports was approached based on the availability of over 570 acres of land, indicating that more than 39,000% of the total annual electricity power could be generated considering the demand of existing airports. Song et al. [76] estimated the installation of building rooftops with solar PV systems and simulated the monthly and annual solar radiation. A building featuring flat, hipped, shed, gabled and mansard rooftops was developed; the operating parameters of the PV modules were applied based on the building features in the local district in Beijing, China. It was noted that the number of rooftops eligible for PV systems in the local district was 743, with an installation area of 678,805 m^2. In the study area, the annual electricity potential of the PV panels could reach 63.78 GWh/year, showing the remarkable potential of solar PV panels. Stevovic et al. [77] developed a multi-objective model to investigate solar capacity integrated with non-renewable sources considering circular-economy principles. The objectives, including electricity-production maximization, electricity-cost minimization and greenhouse-gas-emission minimization, were formulated in the model based on the genetic algorithm (GA). It was noted that the highest costs were obtained when zero solar power plants were installed. The lowest production costs and emissions were reached with a solar capacity of 100 MW and the capacity ranged between 50 and 100 MW, respectively, in accordance with the EU Energy Policy 2050 and its goal of reducing emissions. The developed model could provide decision makers with a reasonable way to suggest adequate solutions, promote better policies and develop appropriate strategies.

An optimized absorber makes it possible to achieve a potential increase in PV conversion efficiency. Oclon et al. [78] proposed the model of a U-tube radiator with water–glycol mixture fluid. It was found that the utilization of the cooling system with twelve tubes in six segments showed the highest performance when the electrical power output was 280 W. Subsequently, the novel cooling system was able to increase the gross efficiency of PV solar installations by up to 6.5%. Stanek et al. [79] proposed a hybrid design of a photovoltaic (PV) absorber in terms of cooling as well as heat generation, which can satisfy 74.7% of thermal energy demand. When installing the PV panels with heat pumps, the hybrid system was showen to be competitive with electric heaters in terms of investment. However, it was also mentioned that the proposed system showed little competitiveness with systems based on PV panels and compressed-heat pumps in certain climatic conditions due to the very low level of direct radiation. Moldovan et al. [80] investigated a triangular solar thermal collector with colored absorbers through CFD simulation. The results showed that the mass flow rate and the water-layer thickness indicated a strong impact on the thermal transfer of the absorber, thus further affecting the thermal collector's efficiency. With the increase in the water-mass flow rate, the efficiency of the absorber was maximally improved by 6.9%. However, the relative gains increased to 11.8% after decreasing the layer thickness from 0.02 to 0.005 m.

Wind energy is usually regarded as a cost-effective and environmentally friendly energy resource. Wind turbines can convert kinetic energy into electricity without any combustion, which leads to a reduction in environmental pollution by CO_2, SOx and NOx [81]. With the development of machining technology and equipment, the cost and initial investment of wind turbines has significantly reduced [82], which has attracted more attention from stockholders and policy support for air-pollution reduction. The application of wind turbines plays a crucial role for countries who are heavily dependent on fossil-fuel imports. Nezhad et al. [83] analyzed energy potential by collecting a dataset on the mean wind speed for the previous 40 years across a medium range of the zone surrounding Samothraki island, in the Mediterranean Sea. The offshore wind (OW) energy potential per location and the trend in the OW speed variation were simultaneously analyzed. It was noted that the southwest region of Samothraki Island indicated the pronounced benefits of OW farm installation. A new methodology for estimating the OW speed was also proposed, which was regarded as the crucial criterion when exploiting new OW farms [84]. Sentinel-1 images and Geographic Information System (GIS) software were comprehensively applied to analyze the wind speed dataset and distribution in the Baltic Sea, at locations 11 km and 40 km away from the Lillgrund OW farm. Using a mean monthly dataset spanning 40 years, the difference reached 0.26 m/s and 0.92 m/s, respectively, between the value measured by satellite and the estimated value. Meanwhile, it was found that the recorded error proportionally rose along with the distance increasing from the center of the pixel. Pustina et al. [85] reported a fully coupled hydro-mechanical model to control offshore wind turbines floating in waves. A controller was optimized and applied to analyze the fluctuations, power and structural loads of a 5-megawatt wind turbine to improve its stability. The benefits of implementing actuated control and hydrodynamic viscous terms were both assessed. It was noted that the proposed model demonstrated great effectiveness in alleviating the generated power fluctuations as well as the vibratory loads. Heydari et al. [86] deployed a composite three-stage model based on DRL methodology to accurately forecast wind power output considering the chaotic features of wind speed. After the cosine algorithm (SCA) and long short-term memory (LSTM) network were applied for simulating wind behavior, the proposed hybrid model showed higher accuracy for both ten-minute- and one-hour-interval predictions when compared with ten existing models.

Biomass energy is also an attractive alternative to dispense with fossil fuel dependence, thereby mitigating the greenhouse effect. It is also an effective strategy for waste management [87]. Biomass energy is available in several forms, such as agricultural and energy crops, municipal wastes, wood wastes and their waste products, which are applied for direct combustion and co-combustion with fossil fuels [88]. Pudelko et al. [64] investigated the reuse potential of biochar derived from waste combustion to construct biodegradable and non-fossil bio-composites. The addition of wood and sewage sludge led to higher water rigidity and absorption. The generated composites could be also applied to the manufacture of agricultural accessories, such as holders and clips, for supporting growing plants. Ozgen et al. [89] reviewed the recent studies dealing with the topic of emissions from biomass combustion used for heat generation. They pointed out that some contradictions exist in small-scale domestic appliances. The environmental benefits of renewable bio-energy sources would be compromised in terms of the damage to air quality caused by the generation of substances such as particulate matter and nitrogen oxides. It was estimated that the average emission factor reached 63–72 mg/MJ when implementing woody biomass for heat generation. They suggested that studies on the reduction in the nitrogen oxide in nitrogen-rich biofuels is a critical concern because few alternative biofuels are eligible. On the other hand, biomass production, which can be regarded as a destination for organic wastes, is applied in the power-to-gas process to generate renewable fuels, such as hydrogen and methane [90]. Cavaignac et al. [91] investigated the techno-economic analysis of biogas upgrading processes by removing acid gases from biogas products. Diglycolamine and methyldiethanolamine with diethanolamine were tested as the recipe. It was indicated that the upgrading route based on diglycolamine can clean up to 99% of the CO_2 from biogas, thereby generating a methane-based product with 91% methane. A life cycle assessment (LCA) was also applied to estimate the benefits. It was noted that a 95% reduction in CO_2-equivalent emissions can be achieved with this upgraded form of biomethane production. Integration by using the power-to-gas system and other sustainable energy systems, such as wind and PV panels, may result in further improvements [92]. Eggermann et al. [93] also investigated the LCA of power-to-gas systems. The residual CO_2 from biogas production is applied for methanol synthesis via wind-based electrolysis, whereas hydrogen is obtained. The operating data of a typical plant located in Germany were assessed with nine scenarios to model an uncertainty analysis. It was noted that all of the scenarios showed significant improvements when compared to traditional methanol production from fossil-based approaches. The economic implications of the fossil alternatives were also attractive. Bedoic et al. [94] studied the power-to-gas concept based on food-waste biogas plants, aiming to produce renewable methane. Their mathematical model was developed and corrected by estimating the electricity capacity in an existing 1-megawatt biogas power plant. With the objective of minimizing total costs, the biogas plant, which featured the installation of 18 MWe of wind, 9 MWe of PV and an additional 16-gigawatt grid import could produce 36 GWh of renewable methane, indicating a pronounced reduction in production costs of 60%.

Hydropower energy is the oldest and most common type of renewable source of electricity available and one of the major renewable energy sources used around the globe, accounting for 70% of all the renewable energy measures undertaken since 2016. It originates in water flows from lakes and mountains and it is produced through the transformation of kinetic energy to mechanical energy in hydroelectric power plants [95]. Global hydropower capacity is expected to increase by 17% between 2021 and 2030—led by China (which is expected to remainin the largest hydropower market through 2030, accounting for 40% of global expansion), India, Turkey and Ethiopia [96]. Hydropower can be considered a reliable energy resource with high flexibility and consistency, which can meet both the requirements of base-load electricity and unexpected demands [97]. Although electricity production is only one of the many purposes of reservoirs, hydropower with storage facility provides flexibility for the integration of intermittent renewables into the power system [98]. However, due to the uneven spatiotemporal distribution of water resources in the catchment, the potential risks of insufficient water supply are also considered. For example, a recent work focused on joint distribution and conditional expectation models to analyze the nexus of water supply, hydropower and environment variables, thereby evaluating multiple risks in water-resource systems [99]. In this work, it was highlighted that for frequencies of hydropower generation higher than 90%, both the expected values of water supply sufficiency and water use sustainability significantly decrease, creating possible risks of water supply inadequacy and environmental damage upstream of dams. Another work focused on the modeling of the future power generation mix of different countries, characterized by huge untapped hydro resources in the framework of zero-emission scenarios with 100% electricity coming from hydro and renewable sources. According to the results, the considered scenarios will substitute coal power plants and therefore reduce the dependency on imported fuels or electricity, strengthening national energy security [100].

For both the energy sector and energy transition processes, more intensive efforts are being directed toward emission decarbonization [17]. Along with the development of power generation with renewable-energy resources, efficient energy-storage systems are crucial for improving the fluctuation of the sector in order for it to operate under more stable conditions [101]. Advanced energy storage systems can store energy during trough periods and then release energy when peaks occur, which helps to alleviate load-demand fluctuation. Various energy storage techniques were investigated, such as battery, thermal energy and fuel cells, chemical and electromagnetic storage, etc. [102]. Grabo et al. [103] proposed a numerical model to describe the charging and discharging during thermal energy storage processes. The model was validated against experimental data with measured flow rates between 216 kg/h to 1000 kg/h. A promising capsule design was proposed, showing a storage capacity that was more than 20% higher compared to other shapes. The optimized design was able to provide a thermal output of approximately 4 kW with phase change materials (PCMs); consequently, the energy density rose by 12.6 kWh/m^3, which is equivalent to a 24.5% improvement. Khor et al. [104] studied various granular materials as PCMs for thermal energy storage in packed-bed systems. The results indicated that the alumina particle provides the highest thermal energy storage due to its characteristics of high heat capacity and high density, while micro-encapsulated n-decane particles provide the greatest overall performance in terms of cycle efficiency for packed-bed systems. Meanwhile, electric batteries, which are also major energy-storage approaches, can shift the demand peak during busy times of the day. However, batteries always possess a high weight per unit of stored energy. Thus, fuel cells with the application of hydrogen energy are regarded as alternative options for effective energy storage [105]. Culcasi et al. [106] investigated the use of an acid/base flow battery to store electrical energy via electrodialytic reversible techniques. The results showed that nearly 25~35% of the round-trip efficiency was lost, mainly due to parasitic currents, which limit power conversion with scaled-up stacks. The operating conditions and corresponding configurations should be optimized to tackle this issue, in order to increase the battery's round-trip efficiency. Photocatalytic water-to-hydrogen technology can convert and store solar energy in an eco-friendly manner and shows significant importance, which is why it is regarded as one of the most effective ways to alleviate the current energy crisis and environmental contamination. Liu et al. [107] studied the optical behavior of a $Mn_{0.2}Cd_{0.8}S/CoTiO_3$ photocatalytic system. With a feasible description of the photocatalytic hydrogen evolution mechanism, it was proven that the proposed composite could prominently reduce the overpotential in hydrogen evolution reactions. By contrast, hybrid energy storage systems can be arranged with various layouts with respect to the applied energy source and the scale of photocatalytic systems [108]. The adoption of hybrid and novel renewable systems on a small scale is relatively scarce [109]. Ideally, to achieve a high-efficiency, no-waste energy system, energy produced by turbines, PV, biomass and wind is expected to be systematically managed and integrated with a bidirectional connection to thermal and electric grids. Meanwhile, the grid allows automatically electrical energy storage to be produced in excess and makes it possible to recover it when it is needed by consumers [110]. The integration of variable renewable energy sources into thermal and electric grids and studies on grid flexibility are becoming key topics and, accordingly, many technical problems have been solved [111].

2.3. Development of District Heating System

As mentioned above, the primary energy consumption in the building sector is regarded a crucial issue for low-carbon development [112]. The application of district heating and cooling (DHC) technologies is acknowledged as a promising solution to the supply of temperature conditioning in buildings [113], which can effectively save energy and reduce emissions. For decarbonized and sustainable development, DHC is an attractive solution with the application of low-quality heat resources, both from renewable sources (such as solar PV panels [114], geothermal energy [115], wind [116], biomass [117] and hydropower [118]) and industrially generated waste heat [119]. The evaluation of reliable energy sources for different DHC sectors is quite a challenge, since it is difficult to describe the actual energy profiles in specific districts [120]. In this section, low-temperature heat recovery, sustainable energy resources and thermal energy storage systems and hybrid heat-pump systems and their economic performances are reviewed.

Large amounts of low-temperature heat are directly emitted to the ambient environment in some industry sectors, causing thermal energy waste and energy efficiency decline [121]. Doracic et al. [122] studied the environmental and economic benefits of recovering the waste heat of a district heating system and simulated the utilization potential via QGIS software. They utilized the levelized cost method to evaluate the transport distance from the heat supplies to the customers, the pipe costs and the heat prices of district heating systems in the city of Ozalj. The authors noted that the maximum transport distance from the source side to the demand side was below 23.11 km when assuming 40 GWh of available excess heat supply, along with the lowest price and pipe cost of 1 EUR/MWh and 200 EUR/m, respectively. Meanwhile, the minimum feasible distance was 2.7 km when assuming 10 GWh of available excess heat supply. The pipe cost and total price might increase up to 4 EUR/MWh and 800 EUR/m, respectively. Moser et al. [123] investigated the possibility of recovering industrial waste heat to improve overall system efficiency and simultaneously reduce district heating network costs. They developed the Heat Merit Order Tool for companies to precisely predict the waste heat amount and evaluate profit on investment. For a case study, an investment of approximately 10 million EUR was suggested, with a margin benefit of 2.5 million EUR per year. A payback period within about four years could be achieved, considering the district heating operator and district heating industry. Espoo has a plan to replace coal with renewable fuels, heat pumps and low-temperature waste heat in its district heating system by 2025, aiming to reduce the production costs and CO_2 emissions. Hiltunen and Syri [124] proved the possibility of utilizing data-center waste heat for abandoning coal and natural gas in DH systems. They found that heat production from carbon-neutral sources of 85% could be achieved. As a result, the average production cost would be reduced from 34.89 EUR/MWh to 33.34 EUR/MWh, with almost 40 $ktCO_2$ of annual CO_2 emissions. Meanwhile, liquid cooling systems are more strongly recommended in a DC due to the higher temperature of waste heat. Barone et al. [125] developed a dynamic simulation tool that is able to evaluate the environmental and techno-economic performance of DHC systems. The long-term operating conditions were considered as the evaluation criteria, including the weather, the selling price of the heat for consumers, the national electricity price and the total heating and cooling demand and load. For minimizing the system payback, the suggested number of users was 5×10^3, with a network pumping length of 2.7 km. As a result, the primary energy could be reduced by about 11.0 GWh/y, along with a reduction in the emission of carbon dioxide of 16.1 $ktCO_2$/y.

Sustainable energy resources, including geothermal, solar and biomass energy, were integrated into DHC systems for both energy saving and emission reduction [126]. Carotenuto et al. [115] studied a low-temperature DHC system with the application of renewable energy sources and developed a dynamic model for analyzing its energy-economic characteristics. The one-year simulation was performed at Monterusciello in Southern Italy. It was suggested that solar and geothermal energy can only satisfy the thermal demand of consumers in wintertime, while the application of auxiliary biomass boilers is mandatory to match the cooling demand during summer activation. The yearly energy consumption considering the solar collector efficiency could be reduced by over 40%. Rosato et al. [127] used the dynamic simulation software TRNSYS to explore the performance of a centralized hybrid renewable DHC in Naples, in southern Italy. A thermal energy storage system with a seasonal borehole type integrated with solar-energy resources was adopted in the district heating system and compared with the use of conventional heating resources. The maximum savings on primary energy, CO_2 emissions and operating costs reached 11.3%, 1.7% and 26.4%, respectively, during the full-year operation in the simulation case. Bozhikaliev et al. [128] investigated the environmental assessment of a district heating system in Macedonia dedicated to sustainable biomass energy. Compared to fossil-fuel-based direct heating systems (DHS), the biomass-based system showed attractive benefits in both energy saving and emission reduction in the heating of public buildings. Ostergaard et al. [129] presented the transition efficiency of a district heating system integrating biomass energy sources appropriately. EnergyPLAN software was applied to illustrate the integrating fluctuation of the renewables and the overall system costs. The results showed that the feasibility of energy transition was uncertain, which indicated that it is not cost-efficient to inves in heat storage for the overcapacity flexibility of heat pumps. Aste et al. [130] proposed a district thermal plant with the application of a low-temperature wood biomass source. The plant could provide an urban district with almost fully renewable multi-energy systems, integrating solar PV energy and groundwater heat pumps (GWHPs). It was shown that GWHPs coupled with PV panels can provide sufficient thermal energy in the summertime, showing a 43% saving on electricity consumption. Dorotic et al. [131] analyzed the impact of a wind production increase in a local DHC system. A historical bidding-market dataset was applied to determine the power-market prices. When assuming a power -sector emission factor reaching historical levels, the aid of wind energy allowed a higher capacity, with an additional 33 TWh of thermal production through heat pumps each year. However, when reducing the assumed emission factor to zero, the thermal storage capacity might rise, along with greater wind-energy penetration.

The hybrid heat pump system is still regarded as the priority solution for electricity saving. Askeland et al. [132] used EnergyPLAN to analyze the effect of converting electric heating to flexible district heating, thereby providing hydropower resources to Europe. The results showed that district heating might alleviate the peak-demand load of hydropower facilities at all hours over the course of the year, thus releasing some capacity for potential export. However, when domestic electricity demand is reduced, the shift to district heating might increase the risk of export to drain reservoirs. Pieper et al. [133] reported the influence on the seasonal coefficient of performance (SCOP) of a DHC system when introducing seawater, groundwater, air and a combination of the three as energy sources. The results showed that the optimum proportions of DHC capacity with groundwater, seawater and air heat pumps were 63%, 14% and 23%, respectively. Meanwhile, the combination of heat sources showed a greater SCOP, which were improved by 3% to 11% compared to the individual heat sources.

In order to achieve a lower electricity price, the DHC sector has great potential when implementing thermal-energy-storage (TES) technologies [121]. Quabeh et al. [134] integrated a TES system into district cooling for shaving the cooling peak demand. It was found that more than 30% of the peak-demand load was shaved for as long as 10 h, resulting in the elimination of about 30% of the initial plant capacity. In addition, the implementation of TES achieved a total energy-consumption saving of about 3%, with a corresponding reduction in CO_2 emissions. Dorotic et al. [135] developed an hourly estimated DHC model based on multi-objective optimization, which was able to define supply capacities, including the TES size, as well as the operating conditions for a whole year. The application of the model was tested in Velika Gorica, where its yearly heating and cooling demands were mapped. When evaluated at the same level of yearly CO_2 emissions, the DHC system combined with TES led to reduced investment requirements. Bohm et al. [136] studied thermochemical storage (TCS) based on hydration materials, which are particularly suitable due to their cheap vapor transport and supply costs. For all the investigated cases, the costs of heat production by thermochemical storage were significantly higher compared to other DHS. For the case of industrial-waste heat, the cost of TCS heat production was about 100 EUR per MWh. However, the heat-transfer distance exerted a dominant influence on the potential utilization of TCS materials. The possibility of TCS application became low due to the relatively high material prices. Aunedi et al. [137] proposed a framework to identify the most cost-efficient solution for district-heating supply. A sensitivity analysis was applied to demonstrate the influence of renewable penetration, heat production assets, electricity price volatility, local grid constraints and emission-target changes. It was demonstrated that the lowest cost of the TES capacity targeting could rise by 41~134%. However, compared to the combination of heat and power and centralized heat pumps, whose price was constant, the TES capacity with 50–66% was suggested considering the electricity prices' volatility.

Moreover, the economic aspects should be also addressed for heat savings considering national strategic heat plans. Djorup et al. [138] investigated a fourth-generation DHS for improving the conditions for heat savings and supporting lower supply temperatures. They suggested the application of a fully variable heat tariff scheme with financial incentives for achieving heat savings, while also promoting the development of DHS away from vulnerability to economic and capital market fluctuations. Pavicevic et al. [139] presented an optimization model to evaluate new and existing DHS by considering the equipment commitment, operational parameters, technology costs, energy consumption system efficiency, greenhouse gas emissions and building refurbishment. In total, nine scenarios were developed and the case of a city, Zagreb, was investigated. Scenario 3, incorporating a heat pump and TES without refurbishment, showed the lowest heat prices, of 58.53 EUR/MWh, showing a lowest price of 10.14% in the reference scenario. Subsequently, the CO_2 emissions were also reduced by 54.07%. By contrast, Scenario 5, with a deep-level refurbishment, could reduce CO_2 emissions by 79.26%, although this might result in an increase in the heat price of 0.38%.

2.4. Economic Assessment of Sustainable Energy

As mentioned above, the emission of greenhouse gases and the crisis of fossil energy resources poses new challenges to the whole of human society. Economic development is strongly related to the levels of total energy consumption, as well as environmental emissions. Therefore, renewable energy systems with improved energy efficiency, which are designed in order to achieve sustainable economic and financial development, are gradually arising [140]. The European Union is one of the leading organizations in this transition and aims to achieve a sustainable economy, products and markets [141]. Several national-level policies and strategies have been announced that aim shift away from the utilization of fossil fuels and towards sustainable resources [142]. Studies focused on the economic assessment of policy support [143], electricity market demand [144], the application of hybrid systems and energy storage investment [145] are reviewed, with the aim of evaluating their effects on economic predictions [146]. In this section, the influences of official policies, the electricity market and stakeholders' investment in hybrid sustainable-energy systems are reviewed.

The development of sustainable energy requires the support of positive policies as traction power for reliable and affordable investment in sustainable markets. Vellini et al. [147] performed a comparative assessment of various alternatives to economic-burden-associated strategies, aiming at a direct reduction in CO_2 emissions by 2030 in Italy. The influence of electricity generation on CO_2 production and related mitigation costs was evaluated, which could suggest suitable policies for Italian decision makers to achieve the strongest environmental performance with limited economic decline. The proposed scenarios revealed that high mitigation costs were needed for natural-gas and solar sources. It was also proven that energy efficiency is crucial for both renewable and non-renewable electricity sources and appropriate shares are necessary to achieve the highest environmental objectives in a cost-effective manner. Lekavicius et al. [148] studied the complex impact investment subsidies for households that installed renewable energy systems in residential buildings. Comprehensive factors were considered, including the applied technologies, costs, household income, eventual target, support intensity, design restrictions, etc. The results showed that the policy benefits households with higher incomes. Meanwhile, the subsidies fail to alleviate energy poverty due to the low capacity for investment among the poorest households, although the policy was regarded as efficient from the viewpoint of decision makers. Rong et al. [149] established an indicator system that can quantitatively analyze the economic and environmental benefits of proposed policies in regions of China suffering from environmental deterioration. Five scenarios and eight indicators were applied to simulate 5-year planting patterns and fallow intensities under different hydrological conditions. The authors noted that the influence of policy on the water environment shows higher sensitivity to hydrological conditions in comparison with those of air-environmental and economic features. It was suggested that the accurate place and area selection of farmland significantly helps to increase the input/output ratio of policy, and that changes in planting patterns should be comprehensively considered. Lu et al. [150] revealed the threats to water environments concealed in economic development and proposed a two-staged method to describe the replenishment of water ecosystems. A total of 12 threat indexes were designed, aiming to point out the critical defects during economic development and elicit sustainable initiatives from decision-makers. In their case study of the Beijing-Tianjin-Hebei district of China, the most remarkable threats were the oversized population and the production inefficiency of industrial sectors, which exceeded reasonable levels by 70%.

Electricity prices usually play a significant role for market participants, whose aim is to maximize economic efficiency [151]. The economic objective of countries is to pursue enough energy to meet demand; therefore, the empirical relationship between electricity consumption and gross domestic product (GDP) is helpful for designing long-term energy strategies [152]. Moser et al. [153] performed a study regarding the federal regulatory framework in German cities, concerning the tenant electricity promotion scheme. The authors stated that the growing electricity consumption in these cities is essentially due to the government's promotion of e-mobility, electric-car purchases, electrical heat supply and heat pumps. In addition, they highlighted that the major barrier to scaling up the tenant electricity model is the strong separation between electricity producers and consumers. Simultaneously, the population was principally passive when it came to changing electricity providers, although the installation of rooftop PV generation in urban areas is strongly expounded. Kolin et al. [154] developed the IKoMet methodology for predicting the relationship between the growth of electricity and that of the economy. A new logarithmic growth ratio reflecting both energy and GDP was proposed by introducing dynamic indicators instead of constant indicators in long-term energy analysis. Examples in Italy and Switzerland were used for examination, and the IKoMet model was proven to be a reliable tool for strategic predictions. Mimica et al. [155] proposed a response model considering the price differentials of the day-ahead electricity market in the island archipelago. All the relevant grid constraints implemented in the distributed medium-voltage grid system were also considered. With the application of the response model, a pronounced incentive of 23% for the day-ahead market was achieved, and the demand response value was lower than the breakpoint incentive. Meanwhile, the highest savings reached up to over 260 USD for the scenario with the greatest flexibility. In this regard, the application of the proposed demand-response model would benefit all stakeholders. Heydari et al. [156] proposed a mixed-data forecasting model by introducing the gravitational search algorithm and the generalized regression neural network. Two reliable electricity markets in Pennsylvania and Maryland, in the US, were examined. The results indicated that the proposed model showed higher precision and stability compared to other forecasting models. Thus, accurate prediction was shown to be of great benefit to future decisions by energy-system operators. Schellenberg et al. [157] compared two optimization algorithms to obtain the optimal schedules for renewable energy systems, which could simultaneously provide consumers with operational cost reductions as well as offering benefits to grid operators. The strategies of genetic algorithm (GA) and particle swarm optimization (PSO) were both introduced, yielding differences in prediction precision, running time and stability. It was noted that GA with binary variables performed with 5~15 times higher efficiency than the optimization with the continuous variable curve. Moreover, the PSO indicated a more effective operation plan than GA due to its lower price signals, smaller error, shorter running time and higher stability.

Currently, hybrid energy systems show significant benefits in the determination of minimum electricity targets when the heat demand and the electricity demand can be accurately estimated. Wang et al. [150] performed a heat-and-electricity pinch analysis to assess how much heat should be recovered from hybrid systems. They developed a heat-to-power composite curve to visualize the total energy as well as the individual heat and electricity requirements during working time period. It was noted that the proposed curve might help decision makers to achieve the minimum required heat in an energy system with high speed and good precession. Furthermore, the seasonal regulation of electricity prices should be comprehensively considered along with the demand fluctuation, indicating peak and trough prices. Jimenez-Navarro et al. [158] utilized the Dispa-SET power system model to evaluate the coupling potential of heat and electricity consumption in terms of efficiency, costs and CO_2 emissions. The existing thermal power plants were assessed after combining heat and electricity suppliers. The results showed that the conversion of thermal function into power plants resulted in a pronounced increase in efficiency and a corresponding reduction in both operating costs and CO_2 emissions. However, a large investment was required for the deployment of the thermal networks, with the aim of leveraging their full potential. Flexibility could be further improved when coupling with thermal-storage systems. The initial investment would rapidly increase within a certain range. Liu et al. [159] proposed the multi-dimensional objective-oriented clustering (MOC) method for planning sustainable energy investment with various options for new forms of energy investment. The data of an actual residential community load profile were analyzed under both energy-consumption-only tariffs and coupled-energy-demand tariffs. The use of data from typical days rather than from whole years could significantly reduce the computation time, by 95%, with almost negligible differences of less than 2.8%. The MOC method could produce a time-efficient and accurate evaluation of the financial impact of renewable-energy investments, providing an innovative reference for stakeholders. Rosso-Ceron et al. [160] introduced a fuzzy multi-objective decision model for integrating hybrid sustainable energy systems through the consideration of economic and emission objectives. The proposed model was examined in Puerto, which is a county in southern Colombia. It was estimated that the most sustainable composite is the comprehensive utilization of 47.7% biogas, 31.2% diesel, 7.9% solar PV panels and hydro energy for the remainder. For 0.42 million kg of CO_2 emissions, the cost of the optimized hybrid system was equivalent to 0.57 million USD.

Khosravi et al. [161] carried out an economic analysis of a novel hybrid energy system based on solar and biomass resources in a desalination unit with a capacity of 100 MWe, in Brazil. A solar thermal collector was applied to reduce the annual consumption of fossil fuels. Due to the increasing boiler and relative system efficiency, the proposed hybrid system demonstrated a minimum energy cost of 7.9% per unit kWh, with a slightly higher capital investment cost. Note that the economic feasibility was highly determined by the plant's scale, the output prices and feedstock-specific output quantities. Tschulkow et al. [65] proposed an integrated techno-economic assessment model that can directly predict the economic benefits of biomass-based sustainable energy in laboratory studies. Waste wood was proven to be the most profitable feedstock, providing profitable investment and resilience to economic shocks when adopting a lower capacity at 80 kt/year. Fan et al. [162] developed an integrated-analysis methodology for solid-waste recycling. The proposed approach was able to minimize the demand of energy consumption through a waste thermal drying process, thereby providing a low-cost solution. Considering waste's moisture content, as well as its supply, demand and recovery capacities, solid waste has become a major concern; corresponding solutions include waste matching and the allocation of destinations for waste. The results indicated that an integrated design could recover heat from the solid waste in urban cluster buildings by up to 20%. For industrial solid waste in unmanageable amounts, of 2 t/d, 960 kW of hot utility could be saved with the utilization of recovering heat. As discussed in above, energy storage on the supply side is the greatest challenge. Hydrogen storage is regarded as a potential solution for the future power-to-gas energy transition. Bhandari and Shah [163] analyzed the prospect of hydrogen utilization and its economic development in Germany. They proposed a theoretical assessment model to analyze the hydrogen production chain from solar energy sources. It was concluded that the approach to hydrogen production using grid-connected PV panels shows high market-competitiveness compared to fossil-fuel-based production processes.

Meanwhile, the process pathway for hydrogen production with grid-connected solar PV systems coupled to alkaline electrolyzers could achieve the cheapest investment costs. However, the levelized cost of off-grid systems was expensive regardless of the hydrogen production pathway used. Nastasi et al. [164] proposed a techno-economic analysis for a building complex equipped with solar PV arrays. Energy storage facilities with battery installation and hydrogen production were considered to assess suitable solutions from an economic perspective, considering the cost variations from 2020 to 2040, as projected by official reports. The results showed that the cost–benefit ratio was highly penalized by excess electricity consumption, revenue reduction and weak connections to the distributed power grid. Baldinelli et al. [165] analyzed the market potential of hydrogen-based solid oxide fuel cells (SOFCs) using micro biogas plants in the agriculture sector. An economic assessment of SOFCs was presented for power modules ranging from 10 kWe to 35 kWe on small livestock farms. The average levelized cost of electricity was capable to declining from 0.387 to 0.115 EUR/kWh when using electricity produced from livestock waste. However, the economic investigation also revealed that the share of the total cost associated with SOFCs still limits their feasibility in small distributed plants. Heat exchangers are widely used in chemical process industries for reducing energy consumption. However, the age and performance of heat exchangers might affect a system's efficiency significantly, resulting in operational investment in replacements. Chin et al. [166] proposed an innovative retrofit algorithm for integrating heat exchanger lifetime and reliability predictions and visualizing their benefits. Consequently, the algorithm might suggest a decision as to whether to maintain the heat exchanger, upgrade the heat exchanger, or replace it with a similar device, considering the maximum economic benefits of the operating system. Two realistic cases were validated to elucidate the application, and utility savings with 51% and 74% were obtained, respectively, by introducing the proposed retrofit algorithm, yielding a net present value of at least 14% compared to conventional retrofit solutions. For understanding the end-of-life (EoL) management of battery energy-storage systems for residential solar PV panels in Australia, Salim et al. [167] described various stakeholder profits due to engagement in the modeling process. It was noted that the rapid growth of solar energy and battery storage systems will lead to a crisis of electronic waste. Valuable and hazardous materials that are disposed of in landfill, stockpiled or illegally dumped will exert an adverse environmental impact if no effective EoL management system is built for residential PV panels. A life cycle assessment (LCA) should be applied to determine whether processes are sustainable and economically beneficial [168]. Lotric et al. [169] presented the results of a LCA for manufacturing in comparison to the EoL phase for fuel-cell and hydrogen technologies. They noted an incredible crisis in the environmental ecology when c precious metal materials were not recycled. It was also found that the environmental impact of manufacturing processes can be substantially reduced by recycling the materials used in these processes and replacing some of the raw materials. Another example is the case of pyrolysis. Hydrocarbon materials with various molecular weights can be obtained after thermally breaking polymer chains, such as oil, naphtha, waxes, etc. Larrain et al. [170] investigated economic performance during the pyrolysis processing of mixed polyolefin waste with respective closed-loop and open-loop schemes. With appropriate assumptions, the open-loop recycling displayed greater economic benefits compared to the closed-loop process, showing a probability of observing positive results in the future of about 98%. Considering the oil-price projections, the probability of closed-loop recycling was only around 57%. It was less than 8% compared to the closed-loop scheme.

3. Research Topics Represented in This Special Issue

A total of 14 papers from the 15th SDEWES conference were selected for this special issue. The main ideas and conclusions of these papers are briefly reviewed in the following subsections.

3.1. Energy Saving and Emission Reduction

Thema and Vondung [171] presented a paper as an extended version of their previous work published after the 2020 SDEWES conference (Cologne, Germany), in order to provide a link for energy-poverty indicators to macroeconomic models to allow the integration of these indicators in future policy-impact assessments. Firstly, in this paper, a short discussion about existing energy poverty modeling approaches is reported. Next, a systematic in-depth sensitivity analysis of the two indicators, namely the High Share of Energy Expenses/Income (HS) indicator and the Low Absolute Energy Expenditure (LA) indicator, is presented. In particular, the HS indicator defines the percentage of households whose share of (equivalized) energy expenditure in (equivalized) disposable income is over twice the national median share of energy in income. The LA indicator is defined as the percentage of households whose absolute (equivalized) energy expenditure is below half the national median (equivalized) energy expenditure. For the calculation of these indicators, the Household Budget Survey (HBS), i.e., the currently available pan-European database, including the necessary micro data on income and energy expenditure, was used. For the sensitivity analysis, a set of scenarios for income and energy expenditure changes were defined. In particular, they evaluated the effect of an increase/decrease in these indicators after a change in income or energy expenditure, which largely depends on the specific country-wise income and energy expenditure distribution between households on a micro-level. For example, they considered a rise or decrease in prices or energy-relevant activity levels, due to the increase in heated floor space per capita or energy efficiency measures. In fact, in plausible scenarios, it is expected that building owners may invest in the energy efficiency of buildings with a related decrease in energy consumption, as well as the adoption of more efficient technologies to decrease electricity consumption. The results obtained in this paper can be useful for their effects on the future policies on energy costs and income distributions, such as policies lowering the costs of energy-intensive households, e.g., through energy efficiency measures. The main positive effect on both indicators is obtained if a holistic energy-poverty policy program is implemented. This combines a redistribution of income, lowering high energy costs and a sustainable minimum level of consumption. From the presented analysis, the authors conclude that a closer national analysis and the complementation of the proposed indicators in national cases is needed.

Bagasi et al. [172] presented a review work on the mashrabiya, describing its functions, history, design, structure and typology, mainly in hot weather zones. Mashrabiya is a natural forced ventilation device, frequently used in the traditional architecture of Arab countries. An example of this device in presented in Figure 1. Here, a wooden frame covers the window opening of a building façade and, while decorating the building façade, it provides privacy and allows air and daylight to penetrate inside. The work also presents the testing of the mashrabiya's performance and its influence on the indoor thermal environment by means of a suitable case study. To this end, a residential building in a hot climate was selected. The authors also assess the effect of thermal mass and evaluate the effectiveness of the mashrabiya in achieving thermal comfort. During the experimental investigations, in the summer of 2018, from 4 August to 1 September, the air temperature, relative humidity, air velocity and globe temperature of two similar rooms in a selected historic building, the Baeshen House, were measured. The building, which features abundant mashrabiyas, is located in the Makkah Region, specifically in Old Jeddah, Saudi Arabia. Figure 2 shows the selected building. In the paper, the data regarding the used equipment, the accuracy and the resolution are reported.

The study demonstrated that the mashrabiya can minimize the cooling load. In particular, it was shown that during the daylight hours, the mashrabiya opening allowed more airflow into the room and reduced the indoor temperature by up to 2.4 °C compared to the closed mashrabiya. A significant factor that prevents high variability in indoor-air temperatures is the building envelope. In fact, considering the investigated building envelope, i.e., 60–80-cm-thick load-bearing walls containing limestone, coral, marine and coral reef, the air temperatures of the investigated rooms ranged between 2.1 °C and 4.2 °C.

Conversely, the outdoor temperature recorded a fluctuation between 9.4 °C and 16 °C. The authors state that the evaluation of the thermal comfort was limited to the assessment of the environmental factors without taking into account the personal factors. This mainly occurred because during the tests, it was difficult to involve users under the considered spatial and climatic conditions.

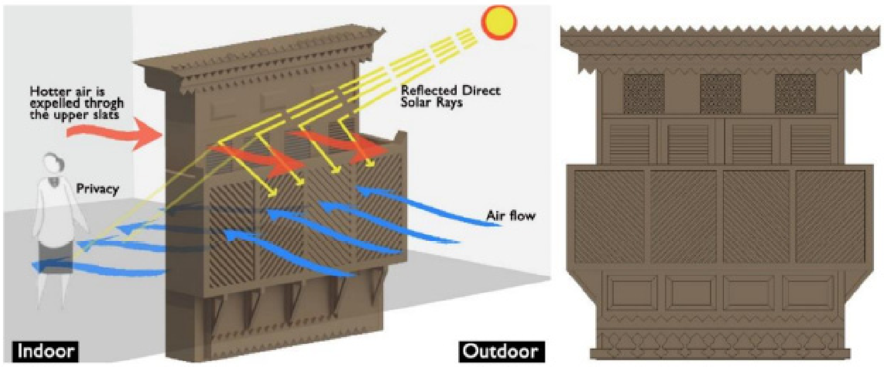

Figure 1. Example of mashrabiya demonstrating its principal functions [173].

Figure 2. Case-study building.

Ren et al. [174] presented a lumped parameter model for the estimation of the health of fuel cells. The aim of their work was to extend the lifetime of a fuel cell, in order to promote and commercialize fuel-cell vehicles. To address this issue, the authors extended a proton-exchange membrane fuel cell (PEMFC) lumped parameter model and integrated novel algorithms required for the assessment of the fuel cell's health in range-extended fuel-cell cars. The unscented Kalman filter algorithm was used to assess the ohmic internal resistance. To validate their model, the authors also performed experimental tests. In particular, their fuel-cell test system (Figure 3) mainly consisted of the following subsystems: a fuel-cell battery, agas supply, a humidification unit, an auxiliary heat dissipation unit, an energy-management unit and data acquisition and control units. The rated power of the fuel cell was 30 kW.

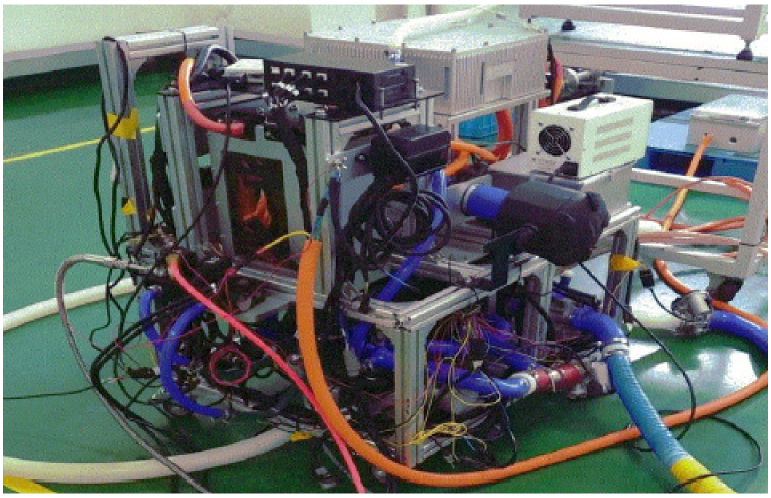

Figure 3. Equipment used in the analysis of the fuel cell's health state.

Using the model, it was found that during the operation, the resistance of the fuel cell gradually increased. In particular, in response to sharp changes in working conditions, the ohmic internal resistance also sharply changes. Therefore, during the use of the fuel cell, repeated stopping and starting phases should be avoided to extend the durability of the fuel cell. Finally, through the comparison between the simulation and experimental results, the authors also proved the accuracy and feasibility of the presented algorithm, with an error of about 2%. The presented model can be useful for predicting fuel-cell stack life and optimizing the operating parameters and control strategies of fuel-cell vehicles, in order to extend battery life and promote fuel-cell-vehicle commercialization.

In the framework of the methods used to abate the SO_2 released by fuel combustion, De Blasio et al. [175] presented a detailed analytical solution of solid particles dissolving in multiphase chemical-reaction systems. Solid–liquid dissolution is a central technique in many industrial applications, such as process engineering, pharmaceutics and pollution control. In this paper, the authors used the particles' shape factor, depending on the surface area, volume and characteristic length of the particle, in an accurate mathematical model, which was tested by comparing the results with the experimental data from several mild acidic-dissolution assays of sedimentary and metamorphic limestone. The authors highlight that the particle shape and surface area are crucial to the dissolution rate in multiphase chemical reactions. The developed model can be used to move our understanding to a more quantitative and predictive level, which is needed for reducing the risk of scale-up and for the design of the next generation of reactors and processes. The error range between the model results and the dozens of experimental analyses is 0.92 ± 0.06.

3.2. Renewable Energy Application

Moser et al. [153] performed a study regarding the federal regulatory framework in German cities, concerning the tenant electricity promotion scheme, in order to identify the barriers to and drivers of the diffusion of this new scheme. According to this model, the tenants are the building's inhabitants, who are supplied with solar power produced on site. In this paper, the transition from centralized to decentralized electricity generation is analyzed regarding both the supply and the self-consumption of power from PV panels. In the case of the tenant model, in fact, landlords installing PV fields on their roofs can self-consume the energy produced or sell it to their tenants. From their analysis, it was found that the rising electricity consumption in cities is due to sector coupling and urbanization, the consideration of climate change and the increasing importance of climate protection, all of which point to improving conditions and increasing demand for tenant electricity in the future. When the economic aspects are taken into account, the cost-effectiveness of tenant models is strongly linked to the regulatory framework, which features high administrative and technical costs. The tenant electricity scheme can make a significant contribution mainly in cities with a growing demand for electricity, reducing the need for grid expansion. The authors state that a crucial driver of the growing electricity consumption in cities is the federal government's promotion of e-mobility, the purchase of electric cars, the electrical heat supply and heat pumps. In addition, they highlight that the federal regulatory framework and institutional actors represent major barriers against scaling up the tenant electricity model due to its interest in the strong separation between electricity producers and consumers. At the same time, the population is principally passive when it comes to changing electricity providers, although the expansion of rooftop PV generation in urban areas is increasing significantly.

3.3. Development of District Heating System

Kudela et al. [176] presented a powerful approach to reducing the complexity of the modern control strategies used to manage the modern fourth- and fifth-generation DHC supply systems. This approach is useful for the development of fast predictive models considering the typically long-lasting thermal effects of the accumulated components included in these new supply systems without computationally expensive solutions. A unit of straight buried pipes in a typical district-heating network was used as an example. The approach presented was predominantly based on OpenModelica, Python and FEniCS software. It was noted that the developed model showed better converge with reasonable solutions and performed 5×10^4 times faster compared to equivalent methods, while preserving the same order accuracy.

Calixto et al. [177] presented the modeling of a district heating network with decentralized heat pumps. The novelty of their analysis resides in the use of decentralized heat pumps with a configuration that is considerably different from those used in traditional networks. The network featured an extra extension, of about 2 km, with a tree structure. The heat sources of the network were based on aquifer wells at 15 °C and industrial-waste heat at 25 °C. In Figure 4, the coefficient of performance (COP) function is represented, and it is possible to observe how the approximate model estimates a higher COP than the detailed model. This is mainly due to the higher temperature assumed on the evaporator side. In fact, for the network-side temperature, the approximate model uses a constant temperature given by the weighted average of the source temperatures, while the detailed model uses the temperature derived from the propagation of the time-dependent source temperatures along the pipes. In addition, for the user-side temperature, the approximate model uses an average climatic curve, while the detailed model uses the actual climatic curves of single users.

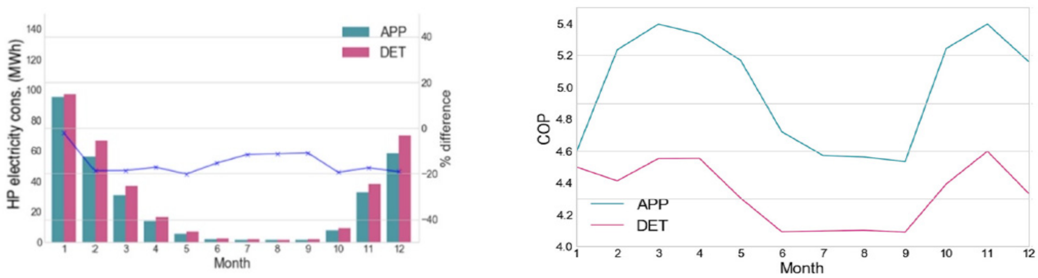

Figure 4. Electric consumption (**left**) and coefficient of performance (**right**) of HPs [177].

However, the detailed model requires about 30 min to solve the considered network for a full year with hourly time steps, while the approximate model is nearly instantaneous.

Calise et al. [178] presented a technoeconomic comparison regarding various energy-efficiency options (solar-energy technologies, improvements in building envelopes, etc.) in Naples (Italy) and Fayoum (Egypt) with dynamic estimation models in a TRNSYS environment. The paper proposed an innovative system including a district heating network for hot water production and a space-heating strategy. The district heating network is shown in Figure 5. The proposed solutions were compared to a reference scenario, where the demand for hot water and space heating can be satisfied by natural gas boilers. Meanwhile, the cooling-energy demand was satisfied by vapor-compression heat pumps, and the electricity demand was met by the national grid. In particular, the primary energy saving, simple payback time and reduced CO_2 emissions for Fayoum were 66.7%, 23 years and 66.8%, respectively. The high simple pay-back was mainly related to the lower electricity and natural gas prices in Fayoum. These results suggest that this solution is quite promising for reducing the consumption of primary energy and the environmental impact of residential districts located in the Mediterranean region.

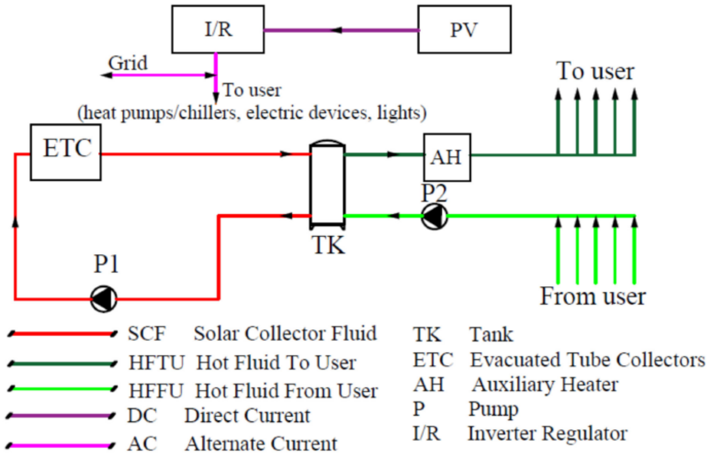

Figure 5. A hybrid district heating network [178].

For the considered weather zones and for the different energy-efficiency measures, pay-back periods, primary energy savings and reduced CO_2 emissions were evaluated. The proposed solutions were compared to a reference scenario, where the hot water and space-heating demand were satisfied by conventional natural gas boilers, the cooling-energy demand was met by conventional air-to-air vapor-compression heat pumps and the electric energy demand was satisfied by the national grid. The results of the best solutions for Naples and Fayoum, including the use of PV panels to generate electric energy and ETCs to obtain thermal energy, are reported in Table 1. The differences summarized in the table were mainly due to the higher solar radiation in Fayoum with respect to Naples.

Table 1. Energy saving and payback in Naples and Fayoum.

Weather Zone	Primary Energy Saving (%)	Simple Pay-Back (Year)	CO_2 Avoided Emissions
Naples	58.2	5	56.8
Fayoum	66.7	23	66.8

Caat et al. [179] presented a work with the aim of demonstrating the utilization of a rooftop greenhouse solar collector with a solar alternative combined with a centralized DHS. The considered rooftop greenhouse could collect large amounts of thermal energy in wintertime and provide dwellings with a high-quality energy source. In particular, a residential city block in the center of Amsterdam, the Helmersbuurt-Oost neighborhood, consisting of 4–6 story buildings with mixed commercial and residential functions, was considered. Considering that Amsterdam has set stringent reduction targets for carbon emissions, i.e., 55% by 2030 and 95% by 2050, the analysis considers as the key performance indicator the total carbon equivalent emissions (CO_2e). A case study with an accurate evaluation model and comprehensive calculations showed that the natural-gas demand of one tenement building with 47 households can be covered by solar thermal energy gathered from a rooftop area of 851 m^2. On the other hand, hydropower resources are abundant in Norway.

3.4. Economic Assessment for Sustainable Energy

Goricanec et al. [180] used Aspen Plus software for exploring low-temperature heat recovery from hot-water boilers. They evaluated the series and parallel connections between the heat pumps and the water-heating system. A commercial boiler with 7435 kW was tested with commercially available heat pumps with an output power of 500 kW, 1.4 MW, 4.5 MW and 9.8 MW, respectively. Ammonia (R717) was applied as the refrigerant fluid. The results showed that the average COP can reach 5.51. These calculations were obtained on the basis that the return water was heated from 50 °C to 70 °C. Meanwhile, considering the economic assumptions related to the heat production, energy prices and economic data reported in the paper, the cumulative discounted cash flows are reported in the following Figure 6. The paybacks on investment are less than 3 and 4 years for electricity prices of 39.62 EUR/MWh and 92.2 EUR/MWh, respectively.

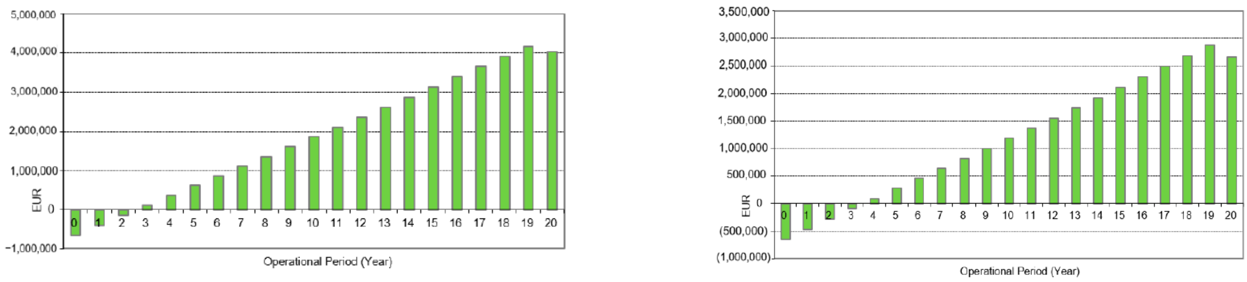

Figure 6. Cumulative discounted cash flow at electricity prices of 92.2 EUR/MWh (**left**) and 39.62 EUR/MWh (**right**).

Meurur and Kern [181] presented a work focused on sustainable aviation fuels (SAF) as an option to significantly reduce emissions in the aviation sector. Figure 7 illustrates the proposed scheme of a power-to-liquid process based on Python, which aims to model the Fischer–Tropsch reactor for open-source simulations. It was noted that the product selectivity showed a strong relation to the reactor temperature. The H_2/CO usage ratio was impacted by some crucial parameters, such as the downstream processes of product separation and product hydrocracking. It was found that the reactor temperature not only affected the reactor activity, but also exerted a significant influence on the chain of the syncrude production, indicating that the conversion rate rose under elevated temperatures. On the other hand, the effect of the reactor pressure on the reaction activity and product selectivity was negligible.

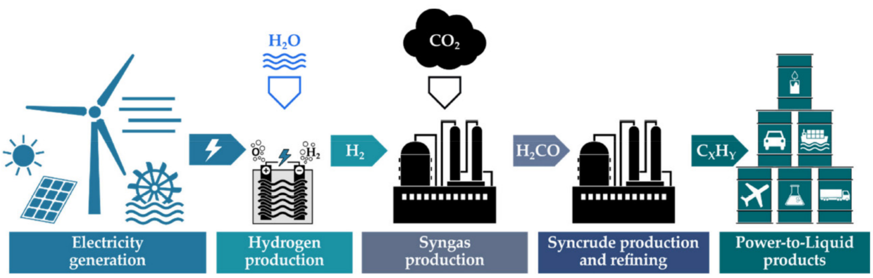

Figure 7. Generic scheme of a power-to-liquid process [181].

Kerosene production based on electrical energy, using the Fischer–Tropsch reaction, was selected due to its simple process structure and low refining effort. Hydrocracking was selected as the technique with which to obtain the syngas. The effects of the main operation parameters on the product selectivity and reactor activity were evaluated. It was shown that the product selectivity was highly determined by the reactor temperature, a crucial parameter in the downstream processes of product separation and hydrocracking and in upstream processes due to its influence on the H_2/CO usage ratio. The reactor temperature not only played a major role regarding the chain-length distribution of the syncrude, but also significantly affected the reactor's activity, leading to increased conversion rates at elevated temperatures. The influence of the reactor pressure on the product selectivity and reaction activity was negligible.

Solis et al. [182] presented an integrated algal biorefinery in the framework of the sustainable bioeconomy, considering resource recirculation. This was obtained by waste minimization and the production of various high-value bioproducts, such as biodiesel, glycerol, biochar and fertilizer. The topic of biofuel production is very important considering that biofuels are a considerable and viable alternative to harmful fossil fuels. The LCA methodology was implemented to properly analyze all the environmental impacts. The algal biorefinery process flow is represented in Figure 8. The process-unit efficiencies and the demand fluctuations were also considered. The results confirm that lower process unit efficiencies lead to a decrease in profit and impact due to low product outputs. Similarly, low profit and environmental impact are obtained in cases of reduced demand due to low biodiesel production. The authors conclude that the LCA in the study currently requires further investigation of the breakdown of the environmental impacts in each process.

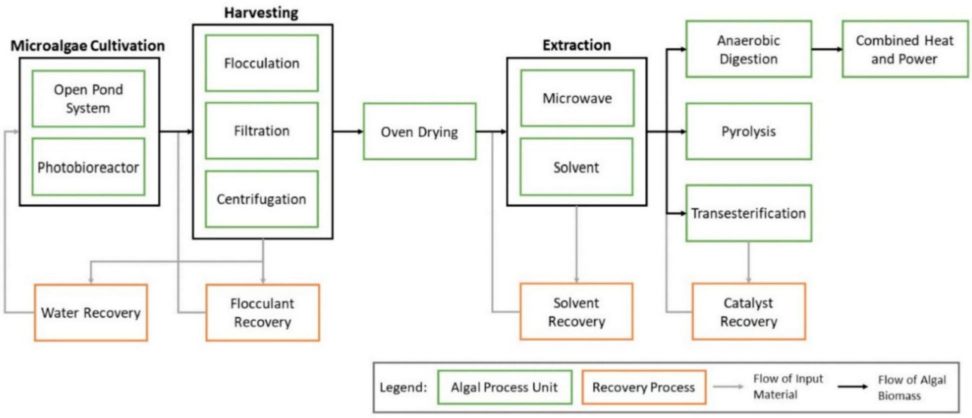

Figure 8. Algal biorefinery process flow [182].

Adisorn et al. [183] presented a more realistic cost–benefit analysis for business sectors. With respect to the general cost–benefit analysis, the relation between the investment costs and the energy-cost savings over the entire life span was considered. The evaluation was approached based on the costs incurred during the life span and those of efficiency services. Three real-world cases were analyzed, by replacing an older motor (4-pole, 30 kW, efficiency class EFF3, efficiency of 85%) named M1 (for an efficient motor of class IE3), with M2 (compressed-air station with 1000 MWh of energy consumption per year) and M3 (water refrigerant for free cooling). For all the cases, the present values are considerably higher than the costs of the considered energy measures. It was noted that M1 exhibited a higher cost–benefit ratio compared to M3, suggesting that investment in all measures is cost-effective when the additional costs of transactions and energy-efficiency services are considered. It was evident that, for applications of compressed air (M2) and free cooling (M3), the cost–benefit ratio is positive, although the performance of these applications is of but lower value than that of motors (M1). These result encourage the development of further projects based on energy-efficiency technologies in order to address the key barriers to their diffusion. Gerbelová et al. [184] presented an analytical investigation on strategies for supporting coal regions through their renewable-energy transition in Slovakia. A value-chain analysis (VCA) was used to assess the economic impact. As shown in Figure 9, four segments were defined for the basic coal industry VCA, including the acquisition of the production factors for input, coal extraction and processing factors for mining, product transportation and trade for transport and final consumption in the end-market. The results confirmed that a net positive cost–benefit ratio for all the developed scenarios can be achieved when replacing existing coal power plants. Due to the expensive capital cost of the installation of the new geothermal system, this scenario shows the lowest net present value. However, the new geothermal power plant presented the highest CO_2 emissions, which were 34% less than those of the existing coal power plant in Slovakia. In addition, the development of deep geothermal technologies can further encourage economic activity and attract investment for geological exploration services as well as knowledge popularization for local residents.

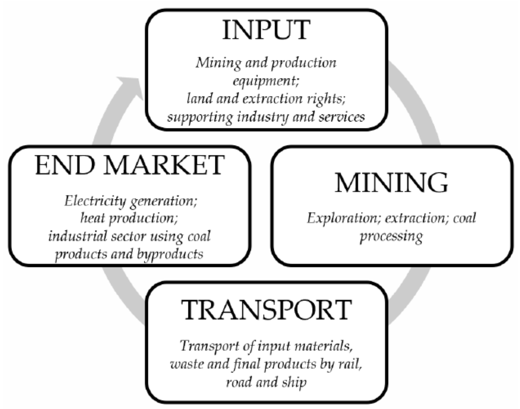

Figure 9. Representative diagram of the coal value chain.

4. Conclusions

This Special Issue of *Energies*, dedicated to the 15th Sustainable Development of Energy, Water and Environment Systems conference, held in 2020 in Cologne, Germany, provides an insight into topics related to recent advances in low-carbon, sustainable and efficient technologies. A total of 14 papers out of 300 presented articles, featuring some of the most distinguished experts in the relevant fields, were selected for publication in this Special Issue of *Energies*. The guest editors of this Special Issue believe that the selected papers presented recent advances in four main fields (energy saving and emission reduction, the applications of renewable energy, the development of district heating systems and the economic assessment of sustainable energy) that will be of interest to the readers of *Energies*.

The studies reviewed in this paper evidently prove that low-carbon, sustainable and efficient technologies are essential to reaching the targets of sustainable and decarbonized development. In this framework, efficiency actions aimed at decreasing energy consumption, the applications of hybrid energy systems and the execution of sustainable policies should be adopted to promote energy saving and emission reduction. In this context, the use of modern control strategies to manage novel fourth- and fifth-generation DHC supply systems is extremely significant for future energy scenarios. Moreover, energy-storage systems are increasingly important for renewable energy applications as well as in DHS. In fact, the papers published in this Special Issue also demonstrated that the energy saving by buildings has a crucial impact on the alleviation of fossil-fuel consumption and greenhouse gas emissions. To this end, renewable sources play a central role due to their wide availability, which is supported by increasingly profitable projects. The application of sustainable aviation fuels could be an option to significantly reduce emissions, as well as the minimization of the environmental impact of the production of biofuels. Finally, the support of positive policies for reliable and affordable investment in sustainable markets plays an important role in the development of sustainable energy. Long-term energy strategies with appropriate economic objectives should be designed country level to balance electricity consumption and GDP.

Future SDEWES conferences will further focus on the fields of the sustainable development of energy, transport, water, food and environment systems, their integration, their technical, environmental, economic and social perspectives, etc. Information on upcoming events and other activities related to SDEWES conferences can be found on the website of the International Centre for Sustainable Development of Energy, Water and Environment Systems (SDEWES Centre).

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