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Editorial

Special Issue "Thermochemical Conversion Processes for Solid Fuels and Renewable Energies"

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Abstract: The world society ratifies international measures to reach a flexible and low-carbon energy economy, attenuating climate change and its devastating environmental consequences. The main contribution of this Special Issue is related to thermochemical conversion technologies of solid fuels (e.g., biomass, refuse-derived fuel, and sewage sludge), in particular via combustion and gasification. Here, the recent activities on operational flexibility of co-combustion of biomass and lignite, carbon capture methods, solar-driven air-conditioning systems, integrated solar combined cycle power plants, and advanced gasification systems, such as the sorption-enhanced gasification and the chemical looping gasification, are shown.

Keywords: thermochemical conversion technologies; combustion; carbon capture and storage/utilization; gasification; solar-driven air-conditioning; integrated solar combined cycle; energy and exergy analyses; thermodynamic modeling; dynamic process simulation

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1. Introduction

Human beings find themselves at the beginning of the 21st century in a contradictory situation in which, on the one hand, significant growth in global demand for energy is expected while, on the other hand, human activities have posed a dangerous rise in the global average temperature by approximately 1.0 ± 0.2 °C above pre-industrial levels. Global warming is likely to reach 1.5 °C in the period between 2030 and 2050 if the consumption of fossil fuels continues to increase at the current rate [1]. It is generally accepted that a great share of greenhouse gas emissions is anthropogenic and originated from utilizing fossil fuels, with contributions coming from manufactured materials (e.g., concrete), deforestation, and agriculture (including livestock). Societies around the world actively support measures towards a flexible and low-carbon energy economy to attenuate climate change and its devastating environmental consequences. These measures include process improvement, new thermochemical conversion technologies, such as gasification or combustion of alternative energy sources, such as biomass [2,3], implementation of carbon capture and storage/utilization technologies [4,5], and promotion of renewable energy sources for power generation and district heating or cooling [6,7], as briefly described below:

- Process improvement of thermal power plants, cement, and metallurgical industries represents an effective method to reduce greenhouse gas emissions. A variety of measures could be considered here, such as an increase in process efficiency and flexibility, and enhancement of operation mode concerning the load change times and the rate of shutdown/start-up procedure [8], as well as process retrofitting with modern flue gas cleaning devices for particulate matter, nitrogen oxides (NO_x), sulfur oxides (SO_x) and carbon dioxide (CO_2).
- The carbon capture and storage/utilization (CCS/U) technologies may offer a rapid response to the global challenge by significantly reducing CO_2 emission from major emitters (e.g., power and cement plants). Depending on the oxidation of fossil fuels and the manner of CO_2 capture, it is distinguished between three CO_2 capture

methods, namely, oxy-fuel, pre-combustion, and post-combustion [9]. In the oxy-fuel process, fossil fuel is combusted using pure oxygen with circulated flue gas to obtain lower adiabatic combustion temperature. The generated flue gas consists of carbon dioxide, where the steam can be easily separated by a condensation process. The main drawback is separating oxygen from air using an air separation unit that is energy-intensive [10]. The chemical-looping process is considered an energy-efficient oxy-fuel method [11,12]. Solid particles of metal oxide are applied as oxygen carriers and these particles circulate between two coupled fluidized beds, namely, air, and fuel reactor. In the pre-combustion method, the solid fuel is gasified using steam and oxygen as a gasification agent (usually at higher-pressure levels in a fluidized bed system or an entrained-flow gasifier). The produced gas consists essentially of hydrogen, carbon monoxide, carbon dioxide, and trace gases. Using a gas-cleaning unit, the carbon dioxide and the trace gases can be separated and the producer gas can be converted into value-added chemicals or combusted in a combined-cycle power plant (integrated gasification combined cycle (IGCC)) [13]. The post-combustion approach has the advantage that existing processes can be retrofitted with CO_2 capture. Two technologies can be used, namely, the chemical scrubbing of flue gas or the carbonate-looping process. The latter uses limestone as a solid sorbent, circulating between interconnected fluidized bed reactors (carbonator and calciner) [14].
- The increased use of renewable energy sources (e.g., biomass, wind power, and photovoltaics) contributes to a decrease in CO_2 emissions in the power generation sector. Through the substitution of fossil fuels by using alternative energy sources such as refuse-derived fuel (RDF), solid recovered fuel (SRF), tire-derived fuel (TDF), and sewage sludge, a considerable reduction in emissions can be further achieved [15]. The electrification of heating and transport sectors offers also a great opportunity for achieving zero emissions. However, variable renewable energy sources can lead to a seemingly paradox situation of negative electricity prices at times of high renewable electricity output and/or low demand, as well as peak electricity prices at times of low renewable electricity output and/or high demand. To maintain the security of supply, there are several potential solutions such as the expansion of high-voltage transmission infrastructure, the use of flexible power plants with CCS/U technologies, and the implementation of large-scale energy storage [16]. The solutions differ in their potential impact, technological maturity, and economic viability so that according to the opinion of authors, the future electricity system will contain all of these concepts to varying degrees with the possible integration of value-adding processes beyond electricity such as the power-to-fuel technology. The carbon-neutral fuels (e.g., hydrogen, methane, gasoline, diesel fuel, or ammonia) can be generated from renewable energy sources by the electrolysis of water to make hydrogen that hydrogenates carbon dioxide or nitrogen captured from thermal power plants or air.

According to the above background and in support of the development of thermochemical conversion processes for solid fuels and renewable energies, this Special Issue contains nominated contributions to:

- Gasification and combustion of alternative fuels (e.g., biomass, refuse-derived fuel, solid recovered fuel, tire-derived fuel, sewage sludge, and low-rank coal);
- Technological combinations of conversion processes based on renewable sources (power-to-fuel);
- Carbon capture and storage/utilization CCS/U technologies (carbon capture-to-fuel);
- Renewable energy for heating and cooling purposes to reduce peak demand, including energy storage systems to mitigate grid imbalances;
- Thermodynamic studies, computational fluid dynamics (CFD), and process simulation of the above-mentioned issues.

The Editors are pleased to bring the best and recent advancements in this field of research to the scientific community in this compact, peer-reviewed Special Issue. Manuscripts that included the latest research progress in terms of development and optimization of conversion processes and concepts, especially for intermittent renewable energy sources, with thermodynamic analysis, CFD and process simulation of these systems were submitted and reviewed by recognized and expert reviewers. In the Special Issue, manuscripts of high quality and that made an explicit contribution to the technical and scientific knowledge were accepted, highlighting the main developments and the new findings. Accordingly, 10 papers were accepted and published in this Special Issue. All articles can be accessed freely online.

2. Special Issue Findings

In the following, a summary of the accepted papers with their most relevant contributions is illustrated.

- The first paper, accepted in this Special Issue, authored by Gallucci, K.; Taglieri, L.; Papa, A.A.; Di Lauro, F.; Ahmad, Z.; Gallifuoco A. from the University of L'Aquila, Italy. In this study, the authors investigated the CO_2 sorption capacity of hydrochar for the upgrading of biogas to bio-methane [17]. The hydrochar was prepared based on a waste product (silver fir sawdust) available in Central Europe and Abies species available worldwide. Experiments were performed using a 316-stainless steel batch reactor at different temperatures and residence times. The hydrochar, obtained hydrothermal carbonization, was activated with potassium hydroxide impregnation and subsequent thermal treatment. The morphology and porosity of the hydrochar, characterized through Brunauer–Emmett–Teller, Barrett–Joyner–Halenda (BET–BJH), and scanning electron microscopy (SEM) analyses, were first evaluated and the sorbent capacity was then compared with traditional sorbents. The authors claimed that the developed hydrochar conceivably offers a new, feasible, and promising option for CO_2 capture using low cost and environmentally friendly materials.
- The authors of the second paper (Heinze, C.; Langner, E.; May, J.; Epple, B.) from the Technical University of Darmstadt, Germany, introduced a new char gasification model that represents all conditions in a fluidized bed gasifier [18]. For abundantly available low-rank coal, the conversion in fluidized bed gasifiers is a feasible technology to produce valuable chemicals or electricity while also offering the option of carbon capture. In this study, the non-isothermal thermogravimetric method was applied to gasify the char of Rhenish lignite at atmospheric pressure by using steam and carbon dioxide as a gasification medium. Two reaction models, namely, Arrhenius and Langmuir–Hinshelwood, as well as four conversion models (volumetric model, grain model, random pore model, and Johnson model), were fitted and evaluated with the measurement data. For both steam and carbon dioxide gasification, the authors stated that the Langmuir–Hinshelwood reaction model together with the Johnson conversion model is the most suitable method to describe the char conversion of the used Rhenish lignite, showing a coefficient of determination 98% and 95%, respectively.
- The third paper, authored by Almoslh, A.; Alobaid, F.; Heinze, C.; Epple, B. from the Technical University of Darmstadt, Germany, compared two mathematical models, namely, the rate-based model and the equilibrium-stage model, when both are applied to simulate the tar absorption process from syngas using soybean oil as a solvent in a research lab-scale test rig [19]. Experimental data at different operation points, published by Bhoi [20], were used to validate the developed models. The authors claimed that the rate-based model has higher accuracy than the equilibrium model. However, a minor deviation between the rate-based model and the experimental data was reported, which increases by increasing the bed height. An analysis study of the tar absorption process was also performed, revealing the influence of height-packed bed, temperature, and flow rate of the soybean oil on tar removal efficiency.
- The fourth paper, accepted in this Special Issue, authored by Savuto, E.; May, J.; Di Carlo, A.; Gallucci, K.; Di Giuliano, A.; Rapagnà, S. from University of Teramo, Italy. In this study, steam gasification experiments for lignite in a bench-scale fluidized-bed gasifier were carried out to evaluate the quality of the gas produced at different oper-

ating conditions [21]. Olivine was used as bed material and the steam/fuel ratio was maintained at approximately 0.65. The influence of temperature and air injections in the freeboard was evaluated in terms of the conversion efficiencies, gas composition, and tar produced. Furthermore, the obtained ashes during the gasification tests were analyzed with X-ray Diffraction (XRD) and Scanning Electron Microscope/Energy-dispersive X-ray Spectroscopy (SEM/EDS) analysis, and an affinity between calcium and sulfur was reported. The authors stated that the increase in the operating temperature leads to an improvement of the gas quality and a lower amount of tar produced. The experiments with air injections in the freeboard did not result in the desired effect on tar reduction. Compared to other tests performed with biomass at similar operating conditions, the amount of tar produced was, however, lower.

- The main contribution of the fifth paper is related to a solar-driven air-conditioning system utilizing absorption technology. In this study, the authors Al-Falahi, A.; Alobaid, F.; Epple, B. from the Technical University of Darmstadt, Germany, proposed a solar driven-absorption cooling system as an alternative technology to the conventional air conditioning of a house under hot and dry climate in Baghdad, Iraq [22]. The effect of different parameters on the solar cooling performance was evaluated. The results show that the weather conditions have a crucial influence on the performance of the solar absorption air-conditioning system, with the peak loads during the summer months. The highest performance was achieved in August with an average coefficient of performance (COP) of 0.52 and a solar fraction of 59.4%. The authors claimed that this study provides a roadmap for engineers, showing that all of the operating and design variables should be considered when developing a solar-driven air-conditioning system under the Iraq climate.
- The sixth paper included in this Special Issue dealt with an important topic that is now under research investigation as an effective gasification technology. By avoiding the use of the costly air separation unit, chemical looping gasification (CLG, see Figure 1) is a novel gasification method, allowing for the production of a nitrogen-free high calorific synthesis gas from solid hydrocarbon feedstocks (e.g., biomass and refuse-derived fuel). An equilibrium process model for an autothermal chemical looping gasification process of biomass was developed by Dieringer, P.; Marx, F.; Alobaid, F.; Ströhle, J.; Epple, B. at the Technical University of Darmstadt, Germany [23]. The results show that pursuing continuous CLG operation leads to challenges in terms of the oxygen carrier (OC) circulation, which is responsible for both, oxygen and heat transport between the air and fuel reactor. According to the authors, the CLG faces an essential dilemma. Here, higher OC circulation rates are necessary to fulfill the process heat balance (i.e., retain constant temperatures in the fuel reactor), whereas significantly lower circulation rates are required in terms of the necessary oxygen transport. Therefore, two strategies to achieve the autothermal CLG behavior through a de-coupling of oxygen and heat transport were suggested and evaluated. The findings of this study encourage deeper numerical modeling of the chemical looping gasification of biomass, as only through the deployment of elaborate models considering hydrodynamics and reaction kinetics can in-depth inferences regarding the process efficiency be offered.
- The authors of the seventh paper, published by Almoslh, A.; Alobaid, F.; Heinze, C.; Epple, B., presented a combined experimental/numerical study on CO_2 absorption [24]. Here, the effect of pressure on the gas/liquid interfacial area was investigated experimentally in the pressure range of 2 to 3 bar using an absorber tray column test rig, erected at the author's institute. Furthermore, a rate-based model was generated based on the design data of the real test rig. A simulated waste gas, consisting of 30% carbon dioxide and 70% air, and distilled water as an absorbent were used in this work. Two gas flow rates were applied. The results predicted by the rate-based model agrees very well with the experimental data. At a higher inlet gas flow rate, the gas/liquid interfacial area was significantly decreased. A pressure increase leads to a

decrease in the gas/liquid interfacial area and thus decreases the absorption rate of carbon dioxide.

- The eighth paper resulted from the collaboration of two universities (Technical University of Darmstadt, Germany) and (Military Technical College, Egypt). The paper, authored by Temraz, A.; Rashad, A.; Elweteedy, A.; Alobaid, F.; Epple, B. investigated the performance of an existing 135 MW integrated solar combined cycle (ISCC) power plant in Kureimat, Egypt [25]. The existing ISCC power plant that consists of a solar field and a solar steam generator integrated into a combined cycle power plant (CCPP) was thermodynamically studied under Kureimat climatic conditions using the concept of energy and exergy analyses. The overall thermal efficiency, the exergetic efficiency, and the exergy destruction of each component in the power plant were calculated at different ambient temperatures (5, 20, and 35 °C) and different solar heat inputs (0, 50, 75 MW). The results show that the solar field has the lowest exergetic efficiency, followed by the condenser. Furthermore, it was found that the thermal efficiency and the exergetic efficiency of the ISCC and the CCPP (when no solar field heat input is supplied) decrease with increasing the ambient temperature.
- The authors (Peters, J.; Alobaid, F.; Epple, B.) from the Technical University of Darmstadt, Germany presented a combined experimental/numerical study on circulating fluidized bed boilers (CFBs) [26]. The ninth paper of this Special Issue contributes to close the knowledge gap for the operational flexibility of CFB. Corresponding to industrial standards, a long-term campaign on Polish lignite combustion during transient operation has been performed at a 1 MW_{th} scale (see Figure 2). A load following sequence for fluctuating electricity generation/demand was reproduced experimentally by four load changes from 60% to 100% load and vice versa. Based on the design data obtained from the test facility, a core-annulus dynamic process simulation model was developed. The core-annulus model was tuned with experimental data of a steady-state test point and validated with the load cycling tests. The simulation results reproduce the key characteristics of CFB combustion with good accuracy. Further numerical results can also be found in [27]. Detailed measurement data were provided during the load change for the most important parameter in the system, such as the pressure and temperature profiles along the riser, the flue gas concentrations, and the solid compositions at different locations of the test facility.
- The last paper of this Special Issue was published by Beirow, M.; Parvez, A.M.; Schmid, M.; Scheffknecht, G. A., from the University of Stuttgart, Germany. In this work, a novel sorption enhanced gasification (SEG) in a dual fluidized bed gasification system was presented [28]. The SEG system is considered a promising and flexible method for the tailored syngas production to be used in chemical manufacturing or power generation (see Figure 3). A simulation model was developed, describing the hydrodynamics in a bubbling fluidized bed gasifier and the kinetics of gasification reactions and CO_2 capture (defined by the number of carbonation/calcination cycles and the make-up of fresh limestone). Experimental data of a 200 kW pilot plant were applied to model validation. The authors claimed that the developed model can successfully predict the performance of the pilot plant at different operation conditions. With the help of the validated model, different operational parameters such as gasification temperature, steam-to-carbon ratio, solid inventory, and fuel mass flow were investigated. The parametric study shows a larger dependence on the limestone make-up, especially for gasification temperatures below 650 °C. The obtained results were summarized in a reactor performance diagram, showing the syngas power depending on the fuel feeding rate and the gasification temperature.

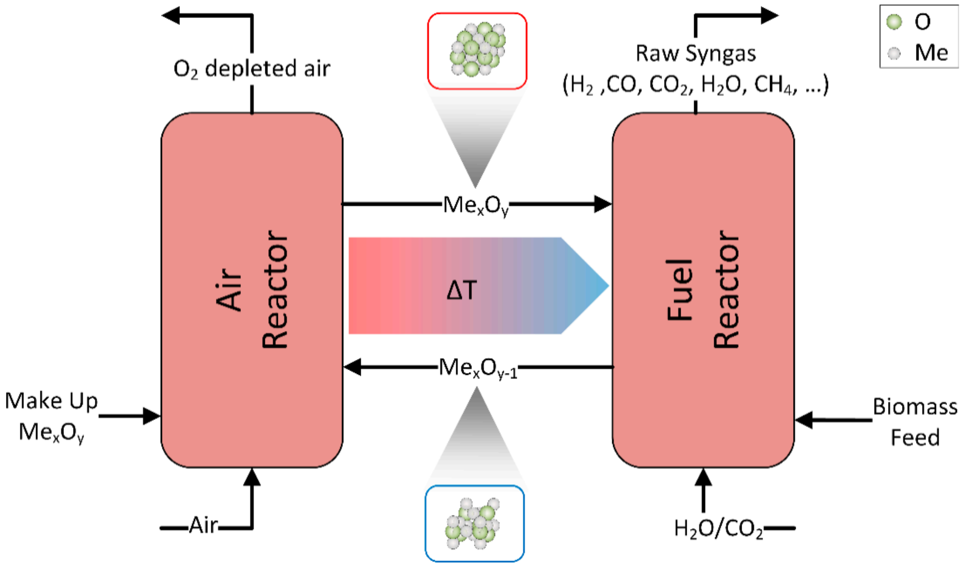

Figure 1. Schematic of the chemical looping gasification process.

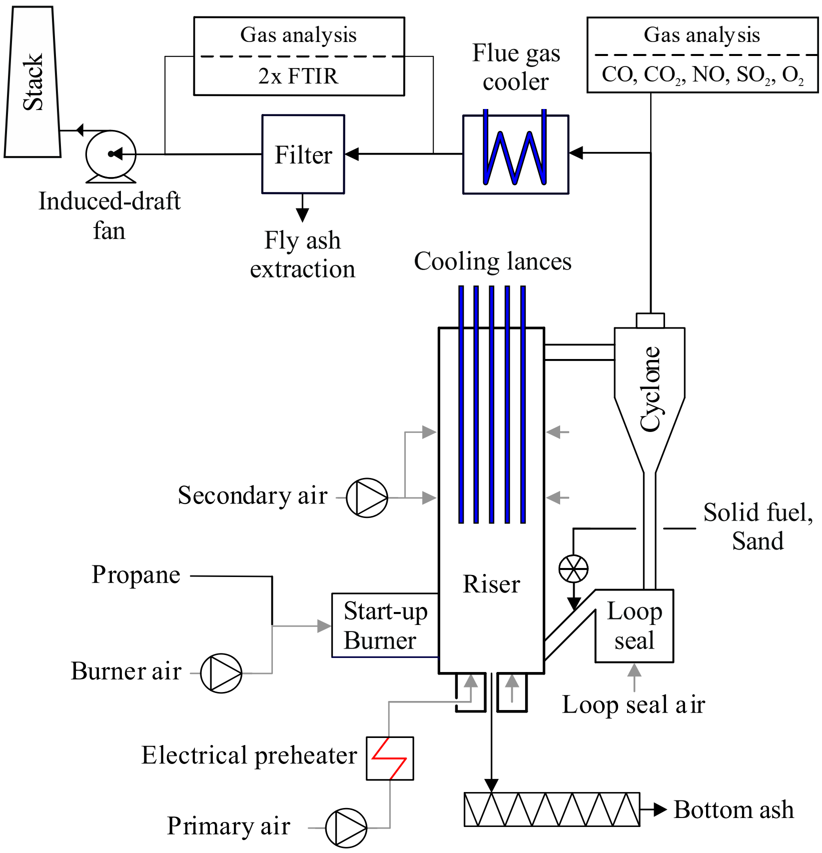

Figure 2. Simplified flow diagram of the 1 MW_{th} pilot plant at the Technical University of Darmstadt.

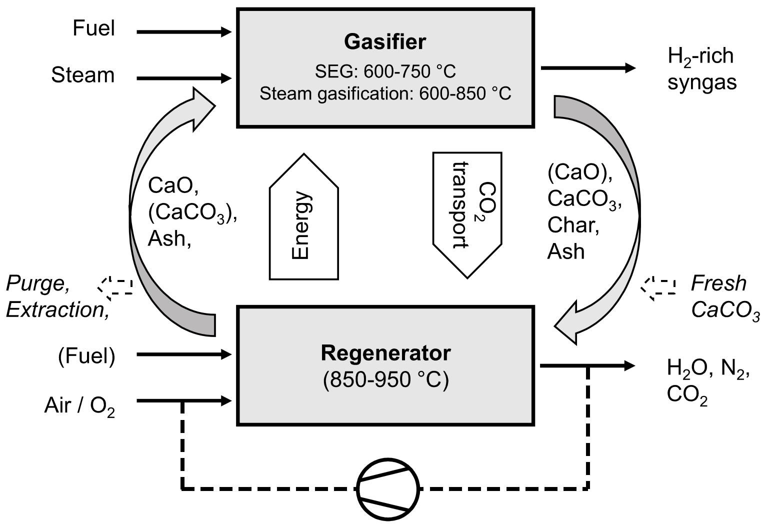

Figure 3. Schematic diagram of sorption enhanced gasification (SEG) process (up to 750 °C) and extended steam gasification mode (up to 850 °C); option of oxy-fuel operation.

3. Conclusions

The editors of this Special Issue are pleased to bring the recent advancements in thermochemical conversion processes for solid fuels and renewable energies to the scientific community. In this Editorial, the majority of published papers (in total four studies) was related to the gasification of low-rank solid fuels (e.g., biomass and lignite), subjected at the early stage of development to a single fluidized bed gasifier and recently to dual fluidized bed gasification systems, such as the sorption enhanced gasification and the chemical looping gasification. Three published papers focused on the evaluation of recent absorption and adsorption technologies for carbon capture. Two published papers were related to the most abundant renewable energy source available "Solar Energy". The solar energy in the first manuscript was used to operate a solar driven-absorption cooling system, while in the second manuscript it was converted into electrical power in an integrated solar combined cycle. The last paper discussed the operational flexibility of a circulating fluidized bed boiler, subjected to a typical operation during fluctuating electricity generation by renewables.

We hope the information collected in this Special Issue, involving new results on thermochemical conversion technologies, will benefit the readers of *Applied Sciences*. All papers were published online, free of cost or access barriers. We also look forward to more submissions to the second volume of this Special Issue "Thermochemical Conversion Processes for Solid Fuels and Renewable Energies: Volume II"—in particular, studies of high-quality, excellence, and clarity that can make a difference in this field of research.

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