Cleaner technologies for sustainable development

Mikulčić, Hrvoje; Baleta, Jakov; Klemeš, Jiří Jaromír

Cleaner Engineering and Technology 7 (2022) 100445

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Cleaner technologies for sustainable development

Hrvoje Mikulčić[a,b,*], Jakov Baleta[c], Jiří Jaromír Klemeš[d]

[a] MOE Key Laboratory of Thermo-Fluid Science and Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China
[b] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000, Zagreb, Croatia
[c] Faculty of Metallurgy, University of Zagreb, Aleja narodnih heroja 3, 44000, Sisak, Croatia
[d] Sustainable Process Integration Laboratory - SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69, Brno, Czech Republic

A B S T R A C T

Anthropogenic influence on global warming is now undeniably proven scientific fact. Ever-increasing efforts directed towards cleaner technologies are needed given the fact that COVID-19 caused disturbances in global supply chains, and a record increase in natural gas prices led to coal power production revitalization, nuclear renaissance and overall hampering of the energy transition. Cleaner technologies are becoming increasingly important on our path towards sustainable development. Present work builds on contributions from this special issue dedicated to the four Sustainable Development of Energy, Water and Environment Systems Conferences held in 2020 by emphasizing the role of cleaner technologies and detecting research trends. By dissecting recent examples of cleaner technologies in environmental systems, water systems and industrial processes, circular economy principles are obeyed through the application of cleaner technologies, where the material and energy loops are closed through cross-sectoral integration. Digitalization and advanced control concepts are expected to accelerate that integration under the smart paradigm. As technology for decarbonization is maturing and becoming increasingly compatible with the market, the focus is placed more on the social dimension of sustainability.

1. Introduction

The latest contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change undeniably proved an anthropogenic influence on global warming (IPCC, 2021). After a short decrease in global CO_2 emissions during the year 2020 caused by the COVID-19 pandemic (Le Quéré et al., 2020) through reduced industrial activity and lower energy consumption, they have rebounded to the pre-pandemic levels during the last year. The fact that abruptly increased electricity demand consequently caused an increase in coal produced electricity for 43% (Jones et al., 2021) also raises additional concerns. It should be noted that this increase was mainly achieved by existing coal generation capacities and not by the installation of new ones. Even when the economic perspective only is taken into account, it is not really necessary to rely on fossil fuel sources anymore since renewables are now within commercial grasp. The majority of newly installed renewable power generation capacities (62%) in 2020 had lower costs than the cheapest new fossil fuel alternative (IRENA, 2021). Average battery pack prices for stationary storage and electric vehicles decreased 89% from 2010 (Henze, 2021), and it is expected that it will fall below 100 $/kWh within the next few years.

Tackling the COVID-19 pandemic imposed an additional environmental burden through the disposal of personal protective equipment and population vaccination (Klemeš et al., 2020). Zhao et al. (2022) proposed a waste personal protective equipment processing system based on energy recovery as well as the onsite production of basic chemicals and renewable fuels. The capacity, location and number of such processing facilities were determined by the optimisation method. Since the COVID-19 vaccination campaign is expected to continue due to a still small share of the vaccinated population and new virus strains, sustainable practices to vaccination management (Klemeš et al., 2021) should be implemented due to its environmental, energy and economic impact (Jiang et al., 2021). It has been shown that the waste to the energy industry is highly immune to pandemic shocks (Kordel and Wolniak, 2021), and taking into account the need for supply security, and it has never been more important to minimize production waste and use the waste from one process as an input to other. Also, distributed energy sources are especially appealing today since they have the potential to secure energy independence, especially in light of increased fossil fuel prices and disrupted supply chains (Hoang et al., 2021). An interdisciplinary approach and coordinating global actions, backed by suitable green recovery policies, could transform COVID-19 threats into great opportunities for the world's sustainability.

As it is becoming clearly evident that Paris Agreement targets are not

* Corresponding author. Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000, Zagreb, Croatia
E-mail addresses: hrvoje.mikulcic@fsb.hr (H. Mikulčić), jiri.klemes@vutbr.cz (J.J. Klemeš).

https://doi.org/10.1016/j.clet.2022.100445
Received 17 January 2022; Received in revised form 13 February 2022; Accepted 13 February 2022
Available online 16 February 2022

going to be reached by current measures, the EU has set more ambitious goals of reducing greenhouse gas emissions by at least 55% by 2030 when compared to 1990 amounts (European Commission, 2019). In order to achieve those targets tightening of the EU emissions trading system directives should take place, and it is expected that set goals can be achieved even without nuclear energy renaissance and still expensive carbon capture and storage technology (Pietzcker et al., 2021). To stop "carbon leakage" caused by ambitious European climate goals last year European Commission adopted a Carbon Border Adjustment Mechanism (CBAM) targeting sectors of metallurgy, cement, electricity and fertilizer (European Commission, 2021). It is expected to start from 2023 when importers of selected products should declare embedded emissions in their products and reach their full implementation in the year 2026, where all the imported products will have to be justified by the CBAM certificates. Such practice should not only prevent "carbon emissions leakage" but also influence non-EU industries to embrace greener production practices. The demand for energy from the buildings' sector is covered with the Renovation Wave Strategy (European Commission, 2020a), which aims to double the buildings' renovation rates in the following ten years focusing on the reduction of energy poverty, emissions decarbonization of cooling and heating, and renovation of public buildings. There are some sectors and industrial processes that are hard to emissions decarbonise, such as air, maritime and heavy-duty transport, as well as some carbon-emissions-intensive industrial processes. Hydrogen, ideally produced from renewable energy sources, can replace fossil fuels in those sectors. The European Hydrogen Strategy aims to reach 1 Mt of renewable hydrogen produced by the year 2024, reaching a tenfold increase from 2025 to 2030 (European Commission, 2020b). Green hydrogen will also serve as energy storage, coping with the renewable energy sources intermittency. Revised renewable energy directive (RED II) requires 14% of renewable energy inland transport, which is, besides renewable electricity, also possible with advanced biofuels and biogas, whose share should amount to at least 3.5% in 2030 (European Comission, 2018). Bioliquids defined as fuels for other energy purposes than transport within RED II directive have a potential to expand range of application of renewable energy (Seljak et al., 2020).

IEA's roadmap for the global energy sector (IEA, 2021) identified more than 400 milestones for reaching close to net-zero CO_2 emissions by the year 2050. The most important measures include immediate termination of investments in new fossil fuel supply projects, no additional investments in new coal power plants without CO_2 abatement measures and phasing out of internal combustion engines in new passenger cars by 2035. Through systematic global decarbonisation efforts of the energy sector, it will be possible to decrease emissions per unit of energy which will, together with an increase in energy efficiency, lead to the decoupling of economic growth from CO_2 emissions. It seems like a challenging task, but there are already reported 21 countries accomplishing this ambitious goal (Aden, 2016), which can be used as the learning example for the rest of the world by generalising their measures.

Based on the exposed matter, it can be seen that additional challenges are placed on our joint path towards sustainable civilization development, requiring more joint effort and integration by smart technologies. Environmental management serves as one of the pillars of sustainable development (Mikulčić et al., 2017), and cleaner technologies should provide tools for global system transition. It can also be seen in Fig. 1 that the topic "cleaner technology" is achieving a significant increase of penetration in research work within the last three years, propelled by the importance of circular economy principles.

Only through a multidisciplinary approach combining research and technological efforts from a wide variety of scientific fields it is possible to achieve integration of sectors, processes, and energy flows (Krajačić et al., 2018). It is the intention of this work to discuss the current status of cleaner technologies in the area of energy, water and environmental systems by building upon the contributions from this special issue dedicated to the four Sustainable Development of Energy, Water and Environment Systems Conferences held in 2020. The work is organized in three sections summarizing recent examples of cleaner technology in environmental systems, water systems and industrial processes.

2. Cleaner technologies in environmental systems

The latest study of the International Maritime Organisation estimated that the share of emissions from the shipping sector has increased from 2.76% in 2008 to 2.89% in 2018 (International Maritime Organization, 2021). Near-shore ship emissions lower air quality in the coastline areas, so appropriate measures should be implemented. Usually, ship emissions during the voyage are estimated employing either a top-down approach or a bottom-up approach. Recently, Topic et al. (2021) proposed a new method as a hybrid between mentioned methods. It analyses available ship track density data and average information about the voyage to supply ship activity for emission calculation. Compared to traditional approaches, this new method is efficient, cost-effective and precise, especially in the case of increased calculation

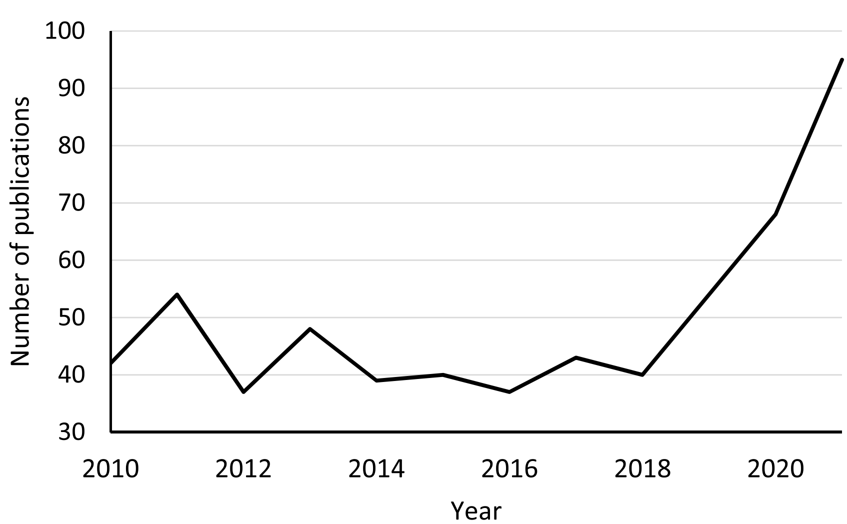

Fig. 1. Number of publications in Scopus (keywords: cleaner, technology) (Scopus, 2022).

sample size. Chen et al. (2019) assessed different control measures, namely cleaner fuels, installation or retrofit of exhaust gases cleaning system, installation or retrofit of a selective catalytic reduction system and application of shore-side generated electricity coupled with weather forecast and chemistry model on the air quality of Pearl River Delta. Liquified Natural Gas was proven to be the most effective method for air quality improvement, followed by retrofit of selective catalytic reduction system, with shore-side electricity as a supplement. Barsi et al. (2020) designed and optimised a mini combined heat and power cycle for ship utilities. The proposed system resulted in an electrical efficiency of 28.2% and cogeneration efficiency of 75%. Dynamic simulation of cruise-ship envelopes with related energy systems, including customized weather data, was conducted in the work of Barone et al. (2020). Special emphasis was placed on the optimisation of waste heat recovery, encompassing low- medium- and high-temperature waste heat. The optimisation procedure yielded a reduction in fuel consumption, pollutant emissions and operating costs with short paybacks time, lower than five years for analysed case studies. Among the many measures to reduce GHG emissions from maritime transport, application of low roughness antifouling coatings has been just recently analysed, and results are encouraging this easily implementable procedure with the return of investment measure of analysed cases ranging between 1.5 and 3 years (Farkas et al., 2021).

The cement industry represents one of the main global CO_2 emitters, and improvement of cement production process equipment is imperative (Mikulčić et al., 2015) since there is no indication that more sustainable material will replace it on a global scale in the forthcoming time. Cement cyclones have a significant influence on the calcination process by providing a certain degree of limestone degradation. Mikulčić et al. (2014) performed a numerical analysis of highly swirled multiphase flow within cement cyclones and demonstrated its validity as a valuable tool for real industrial cyclones analysis. Flying ash from combustion in industrial facilities is not necessarily an environmental burden, but after it is separated from the exhaust gases, it can be used as a feedstock in production processes, very often in concrete production, or in agriculture. Maes et al. (2021) analysed emerging Dusty Cloud Separator (DCS) technology using ex-ante LCA. The analysis considered change expected by extrapolating the current technology level to the industrial scale, changes in current practice, as well as changes in the electricity mix. The environmental benefit was almost completely determined by the amount of ultra-fine ash collected and used as a cement substitute for ultra-high-performance concrete. Ash and slag generated during the biomass firing in power plants are side products which could be further utilised depending on their composition. Wang et al. (2020) characterised fly ash and slag from four different biomass powerplants by studying the ratio between ash and slag, unburned carbon content, their leaching components and composition with respect to major and trace elements. Slag was shown to be more appropriate for direct soil improvement, whereas fly ash could be used in fertilizer production by leaching. Ocłoń et al. (2021) utilised fluidized boiler fly-ash to form the geopolymer matrix as a thermal backfill for underground power cable instead of typical mixtures of cement and sand. Not only was industrial waste turned into a valuable product, but also it is possible to have savings in cable design because of a higher value of thermal conductivity. Premur et al. (2016) analysed the possibility of incorporating material from waste printed circuit boards as a filler in a concrete mixture. Although was shown a significant decrease in compressible strength, up to 5% could be used as a container for arsenic and cadmium, achieving relatively satisfactory strength. Kovac et al. (2016) employed thermodilametric, thermogravimetric, differential thermal analysis, differential scanning calorimetry and flash method to study fly ash addition to the ceramic body. The addition of fly ash did not show to affect the thermal properties of heated samples, but the contraction was three times larger in the samples with flying ash. Mikulčić et al. (2016) assessed mitigation measures for reducing CO_2 emissions in cement manufacturing by emergy and ecological footprint analysis. Emergy retained a similar level during case studies, but a combination of alternative fuels with increased efficiency of kiln process lowered the environmental impact of the cement manufacturing. Muneron et al. (2021) compared the environmental performance of ceramic bricks and concrete blocks employing life cycle assessment. Ecosystem quality, human health and natural resources were included categories, and ceramic bricks topped concrete blocks in all categories.

The development of cities with regard to low carbon emissions could be economically appealing, but there is a need for a coordinated multilevel and intersectoral approach of the governmental bodies (Gouldson et al., 2016). The building sector is one of the most intensive energy consumers, and renovation of existing buildings is an important step in reducing greenhouse gas emissions. Pombo et al. (2016) proposed the method for residential buildings retrofitting by combining Life Cycle Assessment and Life Cycle Cost and then using Pareto optimisation to choose from available strategies. In the case study of Madrid, results have indicated that current renovation strategies should have been aided with a low additional investment of 8% to achieve 43% of environmental savings and 45% of financial savings. Smart metering devices in district heating systems provide information for big data analysis used for demand side management, optimisation of district heating operation strategies and improving energy efficiency by custom-tailored measures. Gianniou et al. (2018) conducted a clustering-based analysis of smart meters data in the district heating system of Aarhus City in Denmark. They concluded that most of the consumers could be approximated by relatively constant load profiles and that energy-intensive customers tend to have more stable consumption. The work conducted by Gesteira et al. (2021) filled the gap in knowledge about residential sector demand by providing generic patterns for the energy demand of characteristic family houses in the Mediterranean region. The usefulness of the study is seen as it can be utilised as a tool for better demand-side management strategies for designers and policymakers. Najjar et al. (2019) developed a mathematical framework for sustainable residential building decisions by combining Life Cycle Assessment, Building Information Modelling and mathematical optimisation programming. With that tool, it is possible to select building components that reduce energy consumption, life cycle energy use and cost while simultaneously preserving minimal impact on the environment. Since it is obvious that climate change will not be stopped but can be only made less intrusive by our current and future actions, a question emerges how can it be its consequences alleviated. Ayikoe Tettey and Gustavsson (2020) tried to offer part of the answer by exploring the influence of climate change through the cooling demand variations and the risk of overheating of a typical residential building in Sweden. Building envelope measures successfully reduced heating energy consumption but resulted in the rise of cooling demand which was tackled by the implementation of the best available technique appliances and lighting. Heat loss of the building in contact with the ground is strongly affected by water table depth due to the high thermal conductivity of water. It is therefore important to have information about water table depth in the urban areas, so that appropriate legislation can be applied in areas with shallow water table depth. James et al. (2021) established that there is large uncertainty of water table depth data in Australia, which has a profound impact on urban areas. Almost half of the observed urban zone was shown that have water table depths less than 5 m, meaning there would be 24–54% higher heat losses compared to the cases without a water table.

Biomass is the most abundant renewable energy source, although it should be noted that renewability is only met if, during the lifetime, biomass absorbs CO_2, which is released through combustion. It also contains high amounts of alkali metals that can cause ash deposits on heat transfer surfaces, as well as bed agglomeration. Those problems could be partially solved by cofiring biomass with sludge. Deng et al. (2020) examined cofiring of wheat straw with sewage and petrochemical sludge in terms of characterizing ash fusion behaviour and mineral matter transformation. The addition of petrochemical sludge and sewage sludge to wheat straw generally increased ash fusion temperatures, influencing thus ash deposit formation and agglomeration. The best anti-sintering behaviour was achieved with petrochemical sludge, but generally speaking, it could also be modified by sludge share in the mixture. Manić et al. (2021) demonstrated a novel method for assessing biomass self-ignition risk based on the dynamic thermal analysis, which defines the thermogravimetry index of spontaneous ignition. It enables relatively quick categorization of different biomass types, which can be further used for the design of appropriate fire and explosion hazard safety measures. Moço et al. (2018) studied ash deposit formation of pulverized grape pomace in the drop tube furnace. Collected ash samples were analysed by electron microscope with an electron microscope equipped with an energy dispersive X-ray detector. Results indicated that the studied fuel was not suitable for industrial combustion systems due to the high inclination for slagging and fouling formation. Since the mechanical preparation of biomass for pulverized combustion is costly, the work of Branco and Costa (2017) dealt with the effect of particle size on burnout and PM emissions during agricultural residues combustion. There was a significant influence on the burnout values, but PM emissions were rather similar in investigated cases. Yin (2020) presented an overview of biomass preparation methods for suspension firing. If the cofiring share of biomass raises up to 100%, advanced pre-treatment via anticorrosion additives and extra thermal pre-treatment is necessary, which is too costly when the present energy market is considered. Deng et al. (2018) studied catalytic properties of potassium salts during the oxy-fuel combustion of biomass as a technology for achieving CO_2 negative emission. Results indicated that potassium salts promote devolatilization and accelerate char-oxidation with stronger catalysis in CO_2 than in the N_2 atmosphere. Pehlivan et al. (2017) analysed the effects of pyrolysis temperature, and heating rate on the properties of pyrolysis produced biochar from the cherry pulp. The maximum achieved yield was 31.25%, and cherry pulp was proven as a promising candidate for char and future biodiesel production. Brigagão et al. (2019) investigated corncob energy conversion pathways by combustion, gasification and fast pyrolysis. Although fast pyrolysis had higher energy recovery, the economic analysis revealed gasification technology as the most profitable one, followed by the combustion route. Cerinski et al. (2020) applied nonlinear autoregressive networks with exogenous inputs (NARX) for modelling dynamics of biomass gasification in the fixed bed downdraft gasifier. It was concluded that NARX could be used for the online prediction of syngas composition in gasification with lower data recording frequency. In that case, the training dataset should be expanded to retain the prediction accuracy.

Energy recovery of waste is the preferred option compared to landfill disposal, and it can be performed by gasification, combustion or pyrolysis, all those direction routes being vividly researched. Iordanidis et al. (2018) investigated combustion properties of different types of municipal solid waste, sewage sludge, and agri-residues with lignite in a 30-50-70 wt% ratio by performing calorific value determination, thermogravimetry and proximate analysis. Organic blends and sewage sludge had the worst combustibility, and sunflower shells proved to be the most reactive. Stančin et al. (2021) co-pyrolysed polystyrene with biomass sawdust to enhance bio-oil properties as a promising way for the integration of waste management and the power production sector. Share of 25% of polystyrene in the fuel mix doubled the yield of bio-oil, reduced the yields of PAH's and promoted the yield of aromatic hydrocarbons. Wang et al. (2018) investigated the influence of temperature and volatile residence time on soot formation during polyurethane pyrolysis. Results demonstrated that the initialisation of soot formation needs high temperature and long volatile residence time. A chemical pathway was introduced that explains the development of soot precursor particles.

Biomass represents the most stable form of renewable energy and can be processed in biorefineries in valuable chemicals and fuels. Alternative approaches to conversion of bio-based and waste-based feedstock are intensively investigated alongside classic conversion techniques, such as presented in the previous paragraph. Bio-oil as the pyrolysis product has some undesirable properties to be used as a fuel substitute, one of them being stability. Yiin et al. (2016) investigated acetone, ethyl acetate and ethanol as solvents for the stabilization of the bio-oil from empty fruit bunch. Ethanol was the most effective one, inhibiting phase separation in addition to lowering the viscosity and reducing the water content of the bio-oil. Plum seeds as biomass waste are a valuable source of antioxidants. Savic and Savic Gajic (2021) optimised the antioxidants extraction process by using Box-Behnken design varying extraction time, ethanol concentration, liquid-to-solid ratio and extraction temperature. Under optimal conditions, 1.5 mg/g of the amygdalin was obtained. In the earlier study, ultrasound-assisted extraction of antioxidants from Black Locust Flower by means of the central composite design was presented (Savic Gajic et al., 2019). Extraction time had the largest impact, followed by the extraction temperature and solvent concentration. Recently, the antioxidants from black locust flowers were used to enforce the oxidative stability of plum seed oil as the by-product of the food industry (Savic Gajic et al., 2021). The performed kinetic study yielded optimal process parameters, and oil prepared in such a manner was used for the development of moisturizing cream. Singh et al. (2017) studied the influence of phosphoric acid dosage, bleaching earth dosage and reaction time onto the peroxide value of the crude rubber seed oil with the aim of its refinement by using the Response Surface Methodology. The most influencing factor was bleaching earth dosage, and authors were able to achieve a peroxide value of 0.1 milliequivalents/gram. Extraction of free fatty acids from feedstock is an important step in biodiesel production, which should be preferably from waste feedstocks to follow principles of a circular economy. Petračić et al. (2021) examined the deacidification of three different waste biodiesel feedstocks with deep eutectic solvents. Extraction efficiency was positively correlated with solvent PH values and negatively correlated with polarities and molar volume.

An interdisciplinary approach and cross-sectional action are imperative if a society is going to tackle the growing threat of climate change. Such a large scale sustainable concept was suggested by Franchina et al. (2021), who made an attempt to connect circular thinking with green supply chains under the umbrella of smart cities by exploiting the benefits of digital technologies. On the example of solid waste management, it was demonstrated that new technologies could act as a catalyser for sustainability on a larger scale, such as that of the city. Most of the world population resides in the urban region, and the continuation of this trend is expected. It is obvious that city sustainability will play a vital role if we are to achieve the global sustainability of our civilization. As the urban population grows, it is important to implement sustainable decisions in smart city design and planning. Beccali et al. (2017) proposed an experimental public lighting system incorporating Wi-Fi, video surveillance, car parking and environmental monitoring. It was reported 81.25% of energy savings compared to the old system before the upgrade. Hammad et al. (2019) developed a mathematical framework for land-use, zoning and infrastructure decisions in smart cities. The size of the transport network mostly influenced the computational time, and it was demonstrated that cost could increase up to 52% when carbon emissions are given top priority by decision-makers. The circular economy paradigm in waste management is an emerging concept, and although there are readily available solutions, one should be aware that increased system cost can lead to social acceptance challenges regardless of the benefits provided in general. Tomić and Schneider (2018) investigated the possibility to use the energy from waste to power the whole waste management system. The results of a case study on the city of Zagreb showed that energy recovery of treated waste can make up for up to 60% of energy needs in 2020 and 50% in 2030. Tomić and Schneider (2020) employed Life Cycle Assessment based framework to investigate the socio-economic effects of waste management strategy. It was shown that the lowest system costs are achieved in the case of combined material and energy recovery, where final disposal is outsourced. Uncertainty of the cost of such service was the main problem in reliable planning. Contrary to the established mechanical recycling technology of plastic waste, chemical recycling offers a route to transform it into monomers, thereby recovering the material's original properties. Using microwave heating offers swift heating and faster reaction rates. Frisa-Rubio et al. (2021) designed a microwave reactor for the depolymerization of polyamide-6, polyamide-6,6 and polyurethane. A sensitivity study with respect to frequency, number of electromagnetic waves emitting ports and their arrangement revealed that a combination of microwave frequencies leads to the improvement of electromagnetic field homogenization, minimizing unwanted hotspots. The suboptimal treatment process has been identified as the main cause of the low recycling amount of lightweight packaging plastics. Feil et al. (2019) tackled the mentioned problem by adopting volume-flow dependent control of the conveyor for loading of the mechanical part of mechanical-biological waste treatment plant together with an optical warning system for loading personnel. Global supply chains have been shown to be sensitive to large scale disruptions such as recent pandemics, so their strengthening is a necessity in order to increase system resilience. Sellitto and de Almeida (2019) investigated the position of waste sorting plants in local supply chains and determined the following roles: supply locally present industries with raw materials and energy, environment protection through decreased load on landfills and social support through local job generation. Hoehn et al. (2021) explored the socially challenging path of degrowth approach to the circular economy of food production and waste management sector with the aim of reaching targets set by the Paris Agreement. The goal was circular bioeconomy, interpreted as the necessary level of degrowth from which circular production/consumption model in food production is possible. Results indicated that reduction of meat, seafood and wish consumption is the most useful direction for achieving a degrowth level of 58.9% in 2040 for the case study of Spain.

3. Cleaner technologies in water systems

Growing world population and climate change further underline the water scarcity problem, and groundwater represents its potential source. It should be taken into account that high fluoride levels in groundwater represent a health risk for the population, so extraction of fluoride is often mandatory. Since water scarcity is pronounced in rural areas of third world countries, there is a necessity for affordable technological solutions for fluoride removal from groundwater. Scheverin et al. (2021) investigated the effect of the surface modification of magnetic zeolites nanocomposites by aluminium and calcium cations incorporation on fluoride removal. Newly developed material was shown to be an efficient fluoride adsorbent in laboratory conditions, with slightly decreased performance in the case of actual groundwater. Singh et al. (2020) employed a different strategy by using hybrid anion exchange resin-impregnated by zirconium. Fluoride removal decreased with an increase in pH value and bicarbonate concentration. The process was improved by lowering the pH value of the water sample and regeneration of saturated resin with NaOH and NaCl solution. Piwowar and Dzikuć (2021) analysed the influence of the emissions from the agricultural sector in Poland on water pollution. Significant water quality deterioration was observed because of an increase in agriculture chemicalisation. Institutional support and supervision regarding water pollution from the agricultural sector were identified as necessary to steer it towards environmental sustainability. Czarny et al. (2017) developed a dynamic rainwater harvesting system model with an energy management strategy employing collection, storage, PV modules and batteries. The developed model was used for the simulation of operation in Cambodia and was able to cover annual water demand, but with a critically low recovery ratio, which left potential for further optimisation. Sahin et al. (2018) investigated water budget adjusting according to scarcity against water restrictions. It was demonstrated that suitable pricing models are more effective and acceptable measures than water restrictions, with the additional benefit of sustaining the long term sustainability of water resources. Karimov et al. (2018) introduced the additional concept of water savings in regions with insufficient resources. They showed that water scarcity could be bypassed by a change in cropping patterns, which can further enhance social gains. Change of alfalfa wither winter wheat followed by green gram yielded water savings of 114–163 Mm^3/y in the case study of Fergana Valley. Naspolini et al. (2020) investigated which economic effects mostly influence the Brazilian water demand. The most important identified sectors were agriculture, livestock, forestry and fishing, as well as energy and natural gas supply. Analysis showed how the economic activities are influenced by public water policies, enabling future improvements regarding regulation and possible economic incentives.

4. Cleaner technology in industrial processes

Industrial furnaces represent intensive CO_2 emission sources from industry (Ritchie and Roser, 2020) and their improvement through simulation optimisation of working parameters is a relatively simple way to achieve significant energy savings and consequently emission reduction. Cradle to gate LCA of aluminium extrusion process comparing different heating process technologies and electricity mix of four European countries was conducted by Royo et al. (2018). It was determined that direct current induction should be fully applied in countries with low CO_2 equivalent emission factors, and heating systems should be retrofitted in countries with a high share of carbon emissions sources in the electricity mix. Wang et al. (2017) performed a numerical simulation of slab reheating furnaces in order to investigate the optimum arrangement of the side burners. Side burner rearrangement achieved 9% higher heating efficiency. Juric et al. (2020) compared the discrete transfer radiative method and discrete ordinate method on the geometry of industrial furnaces. Both modelling approaches compared satisfactorily with experimental results, with the discrete ordinate method being more accurate but also more computationally intensive. Mikulčić et al. (2021) performed a simulation of ammonia/methane/air mixture combustion in the experimental burner as one of the aspects in continuing effort for decarbonization of the energy sector. Of analysed three chemical kinetics models, neither one was able to reproduce CO emissions, while O_2 was excessively consumed, giving rise to a conclusion that further work on the carbon chemistry within ammonia burning conditions is needed. Jurić et al. (2021) compared extended coherent flame model and flamelet generated manifold approach on the combustion inside compression ignition engine. Both modelling approaches captured the experimental trend of nitric oxide emissions, whereas the flamelet generated manifold approach had reduced calculation time reduced by approximately one half. Nitrogen oxides represent one of the most harmful combustion products, and their accurate numerical modelling can help optimise combustion devices. Bešenić et al. (2018) implemented chemical mechanisms of nitrogen oxides formation during solid fuel combustion in the finite volume method based on computational fluid dynamics software. The model was able to reproduce temperature, burnout and nitrogen oxides' levels with good accuracy allowing simulation of real industrial applications. Heat exchange network (HEN) retrofitting is usually aimed at energy savings while minimizing the associated cost. The performance of heat exchangers deteriorates with age, so more realistic conditions should be taken into account. HEN retrofit model that takes into account long-term investment and maintenance planning was developed in the work of Chin et al. (2020). Results yielded 14% of higher net present value compared to previous solutions under the planning horizon of 20 years.

Arguillarena et al. (2021) conducted an assessment of the carbon emissions footprint of the hot-dip galvanisation process by including direct emissions, emissions from electricity production and indirect emissions coming from upstream and downstream processes. Steel and primary zinc production were identified as the main contributors to the carbon footprint. Zinc recovery from spent pickling baths could reduce the environmental impact of the upstream processes. As batteries are becoming increasingly used energy storage and with the rise of electric vehicles, considering limited lithium resources, recycling of wasted lithium batteries is becoming an important topic. In the recent review of lithium-ion batteries treatment by Mossali et al. (2020), pyrometallurgy was identified as the most used technique at an industrial scale for metal recovery but possessed environmental threat due to intensive energy needs and large emissions. It is also not able to extract lithium. Contrary, hydrometallurgy is complex, dependent on the cathode chemistry, so it is not yet ready for sustainable industrial scale. Salim et al. (2020) utilised a participatory System Thinking approach to study end-of-life management of residential photovoltaic panels and battery energy storage. It was pointed out that effective end of life management should include landfill limitations, product stewardship schemes and industrial incentives for promoting recovery activities. Ebin et al. (2019) applied a laboratory-scale pyrolysis method to recover zinc from household battery waste by means of carbothermic reduction. More specifically, the effect of carbon concentration on the Zn recovery was studied, and 99% of recovery was reached by using a reducing agent-containing 11 wt% C at 950 °C process temperature. Bezsonov et al. (2019) proposed a neural network model for the continuous carbon steel pickling process which decreased steam consumption by 8% and acid consumption by 26% whilst retaining process quality and efficiency.

5. Conclusion

By building upon the scientific contributions of the SDEWES conference series held in 2020, the present work identified the main research directions and cleaner technology trends for sustainable development. The main topic of waste minimization on the principles of circular economy emerged from the overview in the section Cleaner Technologies in Environmental Systems, together with a plethora of research on standard and alternative methods of waste conversion. Cleaner technology in water systems is mostly concentrated on the water sector in rural areas since they are affected by water scarcity, emissions from the agricultural sector and its activities. Groundwater treatment, the importance of public policies and the influence of cropping patterns were underlined with examples of each activity. Cleaner technology in industrial processes demonstrated that by employing advanced mathematical models, improvement through optimisation of operating parameters is a relatively simple way to achieve significant energy savings and consequently emission reduction. With an increase in the penetration of renewable energy sources, a shortage in the supply of rare earth metals is expected, together with problems of used batteries and photovoltaic panels recycling. It is evident that more and more waste from different industrial processes is increasingly used as a valuable input feedstock for other processes. Such practice should not necessarily result in increased overall production costs, especially if the whole lifetime of the product is considered and external cost of traditional industries are accounted for. Digitalization and advanced control concepts based on big data acquisition and processing are tools for the integration of various sectors under the *smart* paradigm. As technological advancement pushed renewable energy sources and decarbonization in the sphere of economically viable, the focus is gradually shifting towards the social and interest sphere. Time is of the essence while additional complexities in the global sustainability problem are introduced with ongoing pandemics and disrupted supply chains. Detected increase of cleaner technologies in scientific publications is expected only to grow in the future. It is the idea of this work to be used by researchers as one of the inputs for steering their research directions guided by presented trends, but also to serve as a source of information to the general public.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This contribution has been supported by the project Sustainable Process Integration Laboratory – SPIL, funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, the Operational Programme Research, Development and Education of the Czech Ministry of Education, Youth and Sports by EU European Structural and Investment Funds, Operational Programme Research, Development and Education.

References

Aden, N., 2016. The Roads to Decoupling: 21 Countries Are Reducing Carbon Emissions While Growing GDP. https://www.wri.org/insights/roads-decoupling-21-countries-are-reducing-carbon-emissions-while-growing-gdp. (Accessed 3 January 2022).

Arguillarena, A., Margallo, M., Urtiaga, A., 2021. Carbon footprint of the hot-dip galvanisation process using a life cycle assessment approach. Clean. Eng. Technol. 2, 100041. https://doi.org/10.1016/j.clet.2021.100041.

Ayikoe Tettey, U.Y., Gustavsson, L., 2020. Energy savings and overheating risk of deep energy renovation of a multi-storey residential building in a cold climate under climate change. Energy 202, 117578. https://doi.org/10.1016/j.energy.2020.117578.

Barone, G., Buonomano, A., Forzano, C., Palombo, A., Vicidomini, M., 2020. Sustainable energy design of cruise ships through dynamic simulations: multi-objective optimization for waste heat recovery. Energy Convers. Manag. 221, 113166. https://doi.org/10.1016/j.enconman.2020.113166.

Barsi, D., Costa, C., Satta, F., Zunino, P., Busi, A., Ghio, R., Raffaeli, C., Sabattini, A., 2020. Design of a mini combined heat and power cycle for naval applications. J. Sustain. Dev. Energy, Water Environ. Syst. 8, 281–292. https://doi.org/10.13044/j.sdewes.d7.0309.

Beccali, M., Lo Brano, V., Bonomolo, M., Cicero, P., Corvisieri, G., Caruso, M., Gamberale, F., 2017. A multifunctional public lighting infrastructure, design and experimental test. J. Sustain. Dev. Energy, Water Environ. Syst. 5, 608–625. https://doi.org/10.13044/j.sdewes.d5.0164.

Bešenić, T., Mikulčić, H., Vujanović, M., Duić, N., 2018. Numerical modelling of emissions of nitrogen oxides in solid fuel combustion. J. Environ. Manag. 215, 177–184. https://doi.org/10.1016/j.jenvman.2018.03.014.

Bezsonov, O., Ilyunin, O., Kaldybaeva, B., Selyakov, O., Perevertaylenko, O., Khusanov, A., Rudenko, O., Udovenko, S., Shamraev, A., Zorenko, V., 2019. Resource and energy saving neural network-based control approach for continuous carbon steel pickling process. J. Sustain. Dev. Energy, Water Environ. Syst. 7, 275–292. https://doi.org/10.13044/j.sdewes.d6.0249.

Branco, V., Costa, M., 2017. Effect of particle size on the burnout and emissions of particulate matter from the combustion of pulverized agricultural residues in a drop tube furnace. Energy Convers. Manag. 149, 774–780. https://doi.org/10.1016/j.enconman.2017.03.012.

Brigagão, G.V., de Queiroz Fernandes Araújo, O., de Medeiros, J.L., Mikulcic, H., Duic, N., 2019. A techno-economic analysis of thermochemical pathways for corncob-to-energy: fast pyrolysis to bio-oil, gasification to methanol and combustion to electricity. Fuel Process. Technol. 193, 102–113. https://doi.org/10.1016/j.fuproc.2019.05.011.

Cerinski, D., Baleta, J., Mikulčić, H., Mikulandrić, R., Wang, J., 2020. Dynamic modelling of the biomass gasification process in a fixed bed reactor by using the artificial neural network. Clean. Eng. Technol. 1, 100029. https://doi.org/10.1016/j.clet.2020.100029.

Chen, D., Zhang, Y., Lang, J., Zhou, Ying, Li, Y., Guo, X., Wang, W., Liu, B., 2019. Evaluation of different control measures in 2014 to mitigate the impact of ship emissions on air quality in the Pearl River Delta, China. Atmósfera 216, 116911. https://doi.org/10.1016/j.atmosenv.2019.116911. Environ.

Chin, H.H., Wang, B., Varbanov, P.S., Klemeš, J.J., Zeng, M., Wang, Q.-W., 2020. Long-term investment and maintenance planning for heat exchanger network retrofit. Appl. Energy 279, 115713. https://doi.org/10.1016/j.apenergy.2020.115713.

Czarny, J., Präbst, A., Spinnler, M., Biek, K., Sattelmayer, T., 2017. Development and simulation of decentralised water and energy supply concepts - case study of rainwater harvesting at the Angkor Centre for Conservation of Biodiversity in Cambodia. J. Sustain. Dev. Energy, Water Environ. Syst. 5, 626–644. https://doi.org/10.13044/j.sdewes.d5.0171.

Deng, S., Wang, X., Zhang, J., Liu, Z., Mikulčić, H., Vujanović, M., Tan, H., Duić, N., 2018. A kinetic study on the catalysis of KCl, K_2SO4, and K_2CO_3 during oxy-biomass combustion. J. Environ. Manag. 218, 50–58. https://doi.org/10.1016/j.jenvman.2018.04.057.

Deng, S., Tan, H., Wang, X., Lu, X., Xiong, X., 2020. Ash fusion characteristics and mineral matter transformations during sewage sludge/petrochemical sludge cofiring with wheat straw. J. Clean. Prod. 260, 121103. https://doi.org/10.1016/j.jclepro.2020.121103.

Ebin, B., Petranikova, M., Steenari, B.-M., Ekberg, C., 2019. Recovery of industrial valuable metals from household battery waste. Waste Manag. Res. 37, 168–175. https://doi.org/10.1177/0734242X18815966.

European Comission, 2018. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources. Brussels, Belgium.

European Commission, 2019. The European Green Deal. Brussels, Belgium.

European Commission, 2020a. A Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, Improving Lives. Brussels, Belgium.

European Commission, 2020b. A Hydrogen Strategy for a Climate-Neutral Europe. Brussels, Belgium.

European Commission, 2021. Directorate-General for Taxation and Customs Union, Carbon Border: Adjustment Mechanism. Publications Office, Brussels, Belgium. https://doi.org/10.2778/584899.

Farkas, A., Degiuli, N., Martić, I., Vujanović, M., 2021. Greenhouse gas emissions reduction potential by using antifouling coatings in a maritime transport industry. J. Clean. Prod. 295, 126428. https://doi.org/10.1016/j.jclepro.2021.126428.

Feil, A., Coskun, E., Bosling, M., Kaufeld, S., Pretz, T., 2019. Improvement of the recycling of plastics in lightweight packaging treatment plants by a process control concept. Waste Manag. Res. 37, 120–126. https://doi.org/10.1177/0734242X19826372.

Franchina, L., Calabrese, A., Inzerilli, G., Scatto, E., Brutti, G., de los Ángeles Bonanni, M. V., 2021. Thinking green: the role of smart technologies in transforming cities' waste and supply Chain's flow. Clean. Eng. Technol. 2, 100077. https://doi.org/10.1016/j.clet.2021.100077.

Frisa-Rubio, A., González-Niño, C., Royo, P., García-Polanco, N., Martínez-Hernández, D., Royo-Pascual, L., Fiesser, S., Žagar, E., García-Armingol, T., 2021. Chemical recycling of plastics assisted by microwave multi-frequency heating. Clean. Eng. Technol. 5, 100297. https://doi.org/10.1016/j.clet.2021.100297.

Gesteira, L.G., Uche, J., De Oliveira Rodrigues, L.K., 2021. Residential sector energy demand estimation for a single-family dwelling: dynamic simulation and energy analysis. J. Sustain. Dev. Energy, Water Environ. Syst. 9 https://doi.org/10.13044/j.sdewes.d8.0358.

Gianniou, P., Liu, X., Heller, A., Nielsen, P.S., Rode, C., 2018. Clustering-based analysis for residential district heating data. Energy Convers. Manag. 165, 840–850. https://doi.org/10.1016/j.enconman.2018.03.015.

Gouldson, A., Colenbrander, S., Sudmant, A., Papargyropoulou, E., Kerr, N., McAnulla, F., Hall, S., 2016. Cities and climate change mitigation: economic opportunities and governance challenges in Asia. Cities 54, 11–19. https://doi.org/10.1016/j.cities.2015.10.010.

Hammad, A.W.A., Akbarnezhad, A., Haddad, A., Vazquez, E.G., 2019. Sustainable zoning, land-use allocation and facility location optimisation in smart cities. Energies 12. https://doi.org/10.3390/en12071318.

Henze, V., 2021. Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite [WWW Document]. BloombergNEF. URL. https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/#_ftn1. (Accessed 15 January 2022). accessed.

Hoang, A.T., Nižetić, S., Olcer, A.I., Ong, H.C., Chen, W.-H., Chong, C.T., Thomas, S., Bandh, S.A., Nguyen, X.P., 2021. Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: opportunities, challenges, and policy implications. Energy Pol. 154, 112322. https://doi.org/10.1016/j.enpol.2021.112322.

Hoehn, D., Laso, J., Margallo, M., Ruiz-Salmón, I., Amo-Setién, F.J., Abajas-Bustillo, R., Sarabia, C., Quiñones, A., Vázquez-Rowe, I., Bala, A., Batlle-Bayer, L., Fullana-i-Palmer, P., Aldaco, R., 2021. Introducing a degrowth approach to the circular economy policies of food production, and food loss and waste management: towards a circular bioeconomy. Sustainability 13. https://doi.org/10.3390/su13063379.

IEA, 2021. Net Zero by 2050. Paris, France.

International Maritime Organization, 2021. Fourth IMO Greenhouse Gas Study 2020 Executive Summary. IMO (London, the UK).

Iordanidis, A., Asvesta, A., Vasileiadou, A., 2018. Combustion behaviour of different types of solid wastes and their blends with lignite. Therm. Sci. 22, 1077–1088. https://doi.org/10.2298/TSCI170704219I.

IPCC, 2021. Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In press.

IRENA, 2021. Renewable Power Generation Costs in 2020. International Renewable Energy Agency, Abu Dhabi.

James, M., Ren, Z., Peterson, T.J., Chen, D., 2021. Water table depth data for use in modelling residential building ground-coupled heat transfer. Clean. Eng. Technol. 3, 100096. https://doi.org/10.1016/j.clet.2021.100096.

Jiang, P., Klemeš, J.J., Fan, Y. Van, Fu, X., Tan, R.R., You, S., Foley, A.M., 2021. Energy, environmental, economic and social equity (4E) pressures of COVID-19 vaccination mismanagement: a global perspective. Energy 235, 121315. https://doi.org/10.1016/j.energy.2021.121315.

Jones, D., Fulghum, N., Tunbridge, P., 2021. Global Electricity Review 6-month update: H1-2021 [WWW Document]. 'Building back badly' Glob. power Sect. Emiss. soar. URL. https://ember-climate.org/project/global-electricity-review-h1-2021/#. (Accessed 27 October 2022). accessed.

Juric, F., Vujanovic, M., Zivic, M., Holik, M., Wang, X., Duic, N., 2020. Assessment of radiative heat transfer impact on a temperature distribution inside a real industrial swirled furnace. Therm. Sci. https://doi.org/10.2298/TSCI200407285J, 285–285.

Jurić, F., Stipić, M., Samec, N., Hriberšek, M., Honus, S., Vujanović, M., 2021. Numerical investigation of multiphase reactive processes using flamelet generated manifold approach and extended coherent flame combustion model. Energy Convers. Manag. 240, 114261. https://doi.org/10.1016/j.enconman.2021.114261.

Karimov, A.K., Hanjra, M.A., Šimůnek, J., Abdurakhmannov, B., 2018. Can a change in cropping patterns produce water savings and social gains: a case study from the Fergana Valley, Central Asia. J. Hydrol. Hydromechanics 66, 189–201. https://doi.org/10.1515/johh-2017-0054.

Klemeš, J.J., Fan, Y.V., Tan, R.R., Jiang, P., 2020. Minimising the Present and Future Plastic Waste, Energy and Environmental Footprints Related to COVID-19. Renewable and Sustainable Energy Reviews, p. 127, 109883.

Klemeš, J.J., Jiang, P., Fan, Y.V., Bokhari, A., Wang, X.C., 2021. COVID-19 pandemics Stage II – energy and environmental impacts of vaccination. Renew. Sustain. Energy Rev. 150, 111400. https://doi.org/10.1016/j.rser.2021.111400.

Kordel, P., Wolniak, R., 2021. Technology entrepreneurship and the performance of enterprises in the conditions of covid-19 pandemic: the fuzzy set analysis of waste to energy enterprises in Poland. Energies 14, 3891. https://doi.org/10.3390/en14133891.

Kovac, J., Trnik, A., Medved, I., Stubna, I., Vozar, L., 2016. Influence of fly ash added to a ceramic body on its thermophysical properties. Therm. Sci. 20, 603–612. https://doi.org/10.2298/TSCI130911077K.

Krajačić, G., Vujanović, M., Duić, N., Kılkış, Ş., Rosen, M.A., Ahmad Al-Nimr, M., 2018. Integrated approach for sustainable development of energy, water and environment systems. Energy Convers. Manag. 159, 398–412. https://doi.org/10.1016/j.enconman.2017.12.016.

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Change 10, 647–653. https://doi.org/10.1038/s41558-020-0797-x.

Maes, B., Buyle, M., Audenaert, A., Craeye, B., 2021. Enhanced fly ash use in concrete: ex-ante LCA on an emerging electro-mass separation technology. Clean. Eng. Technol. 2, 100076. https://doi.org/10.1016/j.clet.2021.100076.

Manić, N., Janković, B., Stojiljković, D., Radojević, M., Somoza, B.C., Medić, L., 2021. Self-ignition potential assessment for different biomass feedstocks based on the dynamic thermal analysis. Clean. Eng. Technol. 2, 100040. https://doi.org/10.1016/j.clet.2020.100040.

Mikulčić, H., Vujanović, M., Ashhab, M.S., Duić, N., 2014. Large eddy simulation of a two-phase reacting swirl flow inside a cement cyclone. Energy 75, 89–96. https://doi.org/10.1016/j.energy.2014.04.064.

Mikulčić, H., Vujanović, M., Duić, N., 2015. Improving the sustainability of cement production by using numerical simulation of limestone thermal degradation and pulverized coal combustion in a cement calciner. J. Clean. Prod. 88, 262–271. https://doi.org/10.1016/j.jclepro.2014.04.011.

Mikulčić, H., Cabezas, H., Vujanović, M., Duić, N., 2016. Environmental assessment of different cement manufacturing processes based on Emergy and Ecological Footprint analysis. J. Clean. Prod. 130, 213–221. https://doi.org/10.1016/j.jclepro.2016.01.087.

Mikulčić, H., Duić, N., Dewil, R., 2017. Environmental management as a pillar for sustainable development. J. Environ. Manag. 203, 867–871. https://doi.org/10.1016/j.jenvman.2017.09.040.

Mikulčić, H., Baleta, J., Wang, X., Wang, J., Qi, F., Wang, F., 2021. Numerical simulation of ammonia/methane/air combustion using reduced chemical kinetics models. Int. J. Hydrogen Energy 1–16. https://doi.org/10.1016/j.ijhydene.2021.01.109.

Mossali, E., Picone, N., Gentilini, L., Rodrìguez, O., Pérez, J.M., Colledani, M., 2020. Lithium-ion batteries towards circular economy: a literature review of opportunities and issues of recycling treatments. J. Environ. Manag. 264, 110500. https://doi.org/10.1016/j.jenvman.2020.110500.

Moço, A., Costa, M., Casaca, C., 2018. Ash deposit formation during the combustion of pulverized grape pomace in a drop tube furnace. Energy Convers. Manag. 169, 383–389. https://doi.org/10.1016/j.enconman.2018.05.080.

Muneron, L.M., Hammad, A.W., Najjar, M.K., Haddad, A., Vazquez, E.G., 2021. Comparison of the environmental performance of ceramic brick and concrete blocks in the vertical seals' subsystem in residential buildings using life cycle assessment. Clean. Eng. Technol. 5, 100243. https://doi.org/10.1016/j.clet.2021.100243.

Najjar, M., Figueiredo, K., Hammad, A.W.A., Haddad, A., 2019. Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings. Appl. Energy 250, 1366–1382. https://doi.org/10.1016/j.apenergy.2019.05.101.

Naspolini, G.F., Ciasca, B.S., La Rovere, E.L., Pereira Jr., A.O., 2020. Brazilian Environmental-Economic Accounting for Water: a structural decomposition analysis. J. Environ. Manag. 265, 110508. https://doi.org/10.1016/j.jenvman.2020.110508.

Ocłoń, P., Cisek, P., Matysiak, M., 2021. Analysis of an application possibility of geopolymer materials as thermal backfill for underground power cable system. Clean Technol. Environ. Policy 23, 869–878. https://doi.org/10.1007/s10098-020-01942-8.

Pehlivan, E., Özbay, N., Yargıç, A.S., Şahin, R.Z., 2017. Production and characterization of chars from cherry pulp via pyrolysis. J. Environ. Manag. 203, 1017–1025. https://doi.org/10.1016/j.jenvman.2017.05.002.

Petračić, A., Sander, A., Vuković, J.P., 2021. Deep eutectic solvents for deacidification of waste biodiesel feedstocks: an experimental study. Biomass Convers. Biorefinery. https://doi.org/10.1007/s13399-021-01511-z.

Pietzcker, R.C., Osorio, S., Rodrigues, R., 2021. Tightening EU ETS targets in line with the European Green Deal: impacts on the decarbonization of the EU power sector. Appl. Energy 293, 116914. https://doi.org/10.1016/j.apenergy.2021.116914.

Piwowar, A., Dzikuć, M., Dzikuć, M., 2021. Water management in Poland in terms of reducing the emissions from agricultural sources – current status and challenges. Clean. Eng. Technol. 2, 100082. https://doi.org/10.1016/j.clet.2021.100082.

Pombo, O., Allacker, K., Rivela, B., Neila, J., 2016. Sustainability assessment of energy saving measures: a multi-criteria approach for residential buildings retrofitting—a case study of the Spanish housing stock. Energy Build. 116, 384–394. https://doi.org/10.1016/j.enbuild.2016.01.019.

Premur, V., Vučinić, A., Vujević, D., Bedeković, G., 2016. The possibility for environmental friendly recycling of printed circuit boards. J. Sustain. Dev. Energy, Water Environ. Syst. 4, 14–22. https://doi.org/10.13044/j.sdewes.2016.04.0002.

Ritchie, H., Roser, M., 2020. CO_2 and Greenhouse Gas Emissions [WWW Document]. Our World Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions. (Accessed 12 January 2022). accessed.

Royo, P., Ferreira, V.J., López-Sabirón, A.M., García-Armingol, T., Ferreira, G., 2018. Retrofitting strategies for improving the energy and environmental efficiency in industrial furnaces: a case study in the aluminium sector. Renew. Sustain. Energy Rev. 82, 1813–1822. https://doi.org/10.1016/j.rser.2017.06.113.

Sahin, O., Bertone, E., Beal, C., Stewart, R.A., 2018. Evaluating a novel tiered scarcity adjusted water budget and pricing structure using a holistic systems modelling approach. J. Environ. Manag. 215, 79–90. https://doi.org/10.1016/j.jenvman.2018.03.037.

Salim, H.K., Stewart, R.A., Sahin, O., Dudley, M., 2020. Systems approach to end-of-life management of residential photovoltaic panels and battery energy storage system in Australia. Renew. Sustain. Energy Rev. 134, 110176. https://doi.org/10.1016/j.rser.2020.110176.

Savic, I.M., Savic Gajic, I.M., 2021. Optimization study on extraction of antioxidants from plum seeds (Prunus domestica L.). Optim. Eng. 22, 141–158. https://doi.org/10.1007/s11081-020-09565-0.

Savic Gajic, I., Savic, I., Boskov, I., Žerajić, S., Markovic, I., Gajic, D., 2019. Optimization of ultrasound-assisted extraction of phenolic compounds from black locust (robiniae pseudoacaciae) flowers and comparison with conventional methods. Antioxidants 8, 248. https://doi.org/10.3390/antiox8080248.

Savic Gajic, I.M., Boskov, I.A., Savic, I.M., 2021. Black locust flowers as a natural source of antioxidants: sustainable production of high-quality oil from plum by-product and its incorporation in the moisturizing cream. Clean. Eng. Technol. 3, 100135. https://doi.org/10.1016/j.clet.2021.100135.

Scheverin, V.N., Russo, A.V., Horst, M.F., Jacobo, S., Lassalle, V.L., 2021. Design of magnetic nanotechnological devices for the removal of fluoride from groundwater. Clean. Eng. Technol. 3, 100097. https://doi.org/10.1016/j.clet.2021.100097.

Scopus, 2022. SCOPUS Database, Advanced Search [WWW Document]. URL. https://www.scopus.com/search/form.uri?display=basic&clear=t&origin=searchauthorlookup&txGid=daa3cceb6bc106a96b49db8de4ea0ad0. (Accessed 15 January 2022). accessed.

Seljak, T., Buffi, M., Valera-Medina, A., Chong, C.T., Chiaramonti, D., Katrašnik, T., 2020. Bioliquids and their use in power generation – a technology review. Renew. Sustain. Energy Rev. 129, 109930. https://doi.org/10.1016/j.rser.2020.109930.

Sellitto, M.A., de Almeida, F.A., 2019. Analysis of the contribution of waste sorting plants to the reverse processes of supply chains. Waste Manag. Res. 37, 127–134. https://doi.org/10.1177/0734242X18815968.

Singh, H.K.G., Yusup, S., Abdullah, B., Cheah, K.W., Azmee, F.N., Lam, H.L., 2017. Refining of crude rubber seed oil as a feedstock for biofuel production. J. Environ. Manag. 203, 1011–1016. https://doi.org/10.1016/j.jenvman.2017.04.021.

Singh, S., German, M., Chaudhari, S., Sengupta, A.K., 2020. Fluoride removal from groundwater using zirconium impregnated anion exchange resin. J. Environ. Manag. 263, 110415. https://doi.org/10.1016/j.jenvman.2020.110415.

Stančin, H., Šafář, M., Růžičková, J., Mikulčić, H., Raclavská, H., Wang, X., Duić, N., 2021. Co-pyrolysis and synergistic effect analysis of biomass sawdust and polystyrene mixtures for production of high-quality bio-oils. Process Saf. Environ. Protect. 145, 1–11. https://doi.org/10.1016/j.psep.2020.07.023.

Tomić, T., Schneider, D.R., 2018. The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach. Renew. Sustain. Energy Rev. 98, 268–287. https://doi.org/10.1016/j.rser.2018.09.029.

Tomić, T., Schneider, D.R., 2020. Circular economy in waste management – socio-economic effect of changes in waste management system structure. J. Environ. Manag. 267, 110564. https://doi.org/10.1016/j.jenvman.2020.110564.

Topic, T., Murphy, A.J., Pazouki, K., Norman, R., 2021. Assessment of ship emissions in coastal waters using spatial projections of ship tracks, ship voyage and engine specification data. Clean. Eng. Technol. 2, 100089. https://doi.org/10.1016/j.clet.2021.100089.

Wang, J., Liu, Y., Sunden, B., Yang, R., Baleta, J., Vujanović, M., 2017. Analysis of slab heating characteristics in a reheating furnace. Energy Convers. Manag. https://doi.org/10.1016/j.enconman.2017.04.005.

Wang, X., Jin, Q., Zhang, J., Li, Y., Li, S., Mikulčić, H., Vujanović, M., Tan, H., Duić, N., 2018. Soot formation during polyurethane (PU) plastic pyrolysis: the effects of temperature and volatile residence time. Energy Convers. Manag. 164, 353–362. https://doi.org/10.1016/j.enconman.2018.02.082.

Wang, X., Zhu, Y., Hu, Z., Zhang, L., Yang, S., Ruan, R., Bai, S., Tan, H., 2020. Characteristics of ash and slag from four biomass-fired power plants: ash/slag ratio, unburned carbon, leaching of major and trace elements. Energy Convers. Manag. 214, 112897. https://doi.org/10.1016/j.enconman.2020.112897.

Yiin, C.L., Yusup, S., Mohamed, M., Udomsap, P., Yoosuk, B., Sukkasi, S., 2016. Stabilization of empty fruit bunch derived bio-oil using solvents. J. Sustain. Dev. Energy, Water Environ. Syst. 4, 38–47. https://doi.org/10.13044/j.sdewes.2016.04.0004.

Yin, C., 2020. Development in biomass preparation for suspension firing towards higher biomass shares and better boiler performance and fuel rangeability. Energy 196, 117129. https://doi.org/10.1016/j.energy.2020.117129.

Zhao, X., Klemeš, J.J., You, F., 2022. Energy and environmental sustainability of waste personal protective equipment (PPE) treatment under COVID-19. Renew. Sustain. Energy Rev. 153, 111786. https://doi.org/10.1016/j.rser.2021.111786.