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Process assessment, integration and optimisation: The path towards cleaner production

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ABSTRACT

This contribution starts from the broad perspective of the global material cycles, analysing the main resource and pollution issues world-wide from the viewpoint of the disturbances to these cycles caused by human activities. The issues are analysed in the light of the currently developing COVID-19 pandemic with the resulting behavioural and business pattern changes. It has been revealed in the analysis of previous reviews that there is a need for a more comprehensive analysis of the resource and environmental impact contributions by industrial and urban processes, as well as product supply chains. The review discusses the recent key developments in the areas of Process Integration and Optimisation, the assessment and reduction of process environmental impacts, waste management and integration, green technologies. That is accompanied by a review of the papers in the current Virtual Special Issue of the Journal of Cleaner Production which is dedicated to the extended articles developed on the basis of the papers presented at the 22nd Conference on Process Integration for Energy Saving and Pollution Reduction. The follow-up analysis reveals significant advances in the efficiency and emission cleaning effects of key processes, as well as water/wastewater management and energy storage. The further analysis of the developments identifies several key areas for further research and development – including increases of the safety and robustness of supply networks for products and services, increase of the resources use efficiency of core production and resource conversion processes, as well as the emphasis on improved product and process design for minimising product wastage.

1. Introduction

The spread of the COVID-19 disease has led to an abrupt change of the daily life and work patterns of the majority of people worldwide. In the second half of September 2020, the number of infected persons is rising to 30 M, and the number of deaths to 1 M. This has obviously considerable impacts on the global economy as well as the individual states. However, crucial is the development of the situation post-pandemic.

Absolutely crucial issues during the pandemics and post-pandemic are the plastics consumption and the handling of plastic waste. The recent analysis (Klemeš et al., 2020a) revealed a sharp and significant shift in the waste generation patterns – such as the decrease in the overall MSW by about 30% and increase of medical waste nearly 4-fold. They suggested that the risks can be averted by bearing several key points in mind as:

(i) The societal disruption created by the COVID-19 pandemic can lead to significant and persistent economic restructuring. This situation presents a rare chance to shift product systems towards a more sustainable trajectory.
(ii) It is necessary to use indicators such as Plastic Footprint and Plastic Waste Footprint for aiding decision-makers and in public engagement. They are useful to clearly communicate the threat and extend of the environmental burdens in numerical form to non-specialists.
(iii) The plans for plastic use and its waste management have to be continuously developed and adjusted, also making provisions for extreme situations. To work towards a safer and greener planet, every single step considering the complexity

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of various issues becomes an imperative goal of humankind. Future work should be directed by post-pandemic development and extend the concepts discussed in this contribution subject to country-specific conditions that may occur.

A similar observation has been published in (You et al., 2020). They mentioned up to a 5-fold increase in the medical waste generation for various locations and a significant increase in waste mismanagement, giving an example with UK rural communities. The overload of waste management systems causes them to resort to the unsustainable practices of landfilling and incineration at the expense of reduced recycling. Fan et al. (2020a) presented an updated work discussing waste management during the pandemic period. Variable trends in the municipal solid waste generation were found in different cities/countries of Singapore, Shanghai (a city in China) and Brno (a city in the Czech Republic). During the pandemic period of January–June 2020, the MSW in Shanghai decreased by 23% but increased by 3% and 1% in Singapore and Brno. Pandemics initiate necessary changes and improvements, as solving the problem of such magnitude requires reducing the waste generation by redeigning the business practices, business processes, supply chains and also public attitude (Jiang et al., 2021). That trend has been accompanied by a sharp dip (up to 17%) of the global Greenhouse Gas (GHG) emissions, due to the reduced overall activity (Plumer and Popovich, 2020). The cited news item, however, clearly shows that this temporary reduction was quickly compensated with the reopening of many countries during May–June 2020. Such statistics are obtained from public operator associations data – e.g. (ENTSO-E, 2020) and from data aggregators such as (ElectricityMap, 2020). There has been a need for a post-pandemic analysis of energy consumption and related emissions (Klemeš et al., 2020b).

However, the COVID-19 pandemics also intensified the research and innovations which can bring a step change caused by six waves of "Positive Distraction" (Klemeš et al., 2020a). This is expected to bring and promote a strong novel base in a cluster of innovative technologies. There has been a spread out of remote meetings and learning, massive home office use, the growing popularity of e-shopping, raise in e-socialising, related to this intensifying the data transmissions as 5G and 6G, considering urban and rural area sanitary reforms, remote and robotic health monitoring and even treatment, related preference to shortening the commuting, intelligent traffic control, strengthening to favour self-driving autonomous vehicles, advanced digital manufacturing challenging remote and distance production operating, remote construction, building and remote drilling, automated waste management collection and treatment, and also applications of novel ways for deliveries as, e.g. drone. Each of them is having some pros and cons related to energy consumption. Are the beneficial features able to offset its own energy consumption and the rebound effects of increasing demand?

The importance of the (natural) global material cycles for maintaining sustainability has been noted already by Krotscheck and Narodoslawsky (1996), who have analysed the reasons for the requirement that these cycles are not disrupted. The main logic of the requirement lies in realising that any materials are taken from the environment, and waste streams are released to the environment too. An illustrative example is given with the use of an aquifer, where its simultaneous depletion and contamination would soon render it unusable. The importance of understanding the global material cycles can be seen from the persisting works referring to them for deriving insights on resource management and pollution reduction. The examples include the book chapter analysing the evolution of the society-nature interaction (Bruckmeier, 2019).

The further development of the evaluation of the environmental impact is related to the concept of the footprints (Čuček et al., 2012a) – such as GHG, Water. Nitrogen. Each of the footprint measures the degree of disturbance of the natural global cycles, as discussed next. The global material cycles have been classified (Schaub and Turek, 2016) into several categories:

- **Carbon Cycle.** This is characterised by the major reservoirs for carbon compounds and the flows connecting them. From the reservoirs (atmosphere, terrestrial and marine – surface oceans and deep water), the atmosphere is characterised as the smallest one on the mass basis, which explains its vulnerability to the release of sizeable amounts of CO_2 and other GHG.
- **Oxygen Cycle.** The analysis points out that sediments contain about 30 times more oxygen than the atmosphere. The book also points out the close link between the Carbon and the Oxygen Cycles.
- **Water Cycle.** This features a more complex pattern due to the phenomena of flow, evaporation, condensation, freezing, melting, and mixing with other substances. The vast majority of the Earth's water content is in the oceans, and only a small fraction is in circulation over the landmasses. The main concerns are related to water pollution and melting of global ice reservoirs.
- **Nitrogen Cycle.** This is described as the intake of N_2, its conversion into bound forms, the metabolism through live matter and the subsequent denitrification producing molecular N_2 again. The main reservoirs in this cycle are again the atmosphere, the ocean and the land, where the atmosphere contains (3.87×10^9 Gt) more than 99% of the total terrestrial nitrogen. The land part contains a very small amount (3.4×10^5 Gt) – four orders of magnitude smaller than the atmosphere.
- **Sulphur and Phosphorus Cycles.** Sulphur compounds are also critical for natural processes. For sulphur, the bottlenecks are the land and the atmosphere, which have capacities nearly 10^6 times lower than the sum of the oceanic and sediment storages. With the phosphorus, the land is sizeable storage, but the strive for increased phosphorus-based fertilisers creates pollution effects.
- **Chlorine Cycle.** Chlorine compounds also circulate through the main terrestrial reservoirs of land, sediments, ocean and atmosphere, where the salts are best studied as having importance for biological variety and ecosystems.

The interaction of these global material cycles (Schaub and Turek, 2016) include the photosynthesis and respiration processes that bind the Carbon and Oxygen Cycles. A link to the Sulphur Cycle is traced in the final stages of the bacterial decay of biomass. A typical example of an inter-cycle trade-off is the one between GHG and Nitrogen footprints in the production and use of biofuels (Čuček et al., 2012b).

1.1. Issues caused by the disruptions of the natural cycles

From the summaries of the Global Material Cycles (Schaub and Turek, 2016), it becomes clear that the storage parts, that form the bottlenecks of each cycle, also become the most vulnerable to disruption and dysfunction. These give rise to the GHG effect in the atmosphere (bound to the carbon cycle), the water scarcity issues related to the availability of clean and potable water, acid rain issues, terrestrial pollution of urban areas by nitrogen and phosphorus-containing organic compounds and runoff fertilisers.

More broadly, the issues, caused by the intensive exploitation of the natural resources and the pollution flows caused by human activities, can be classified by the types of capital concerned (Stahel, 2019). The most important categories are:

- Natural capital concerned issues – environmental pollution, climate, water pollution
- Human capital concerned issues – health issues caused by the pollution of air, water and soil
- Economic capital concerned issues – costs incurred by increasing extreme events, water pollution and scarcity, air pollution

It has been shown in (Stahel, 2019) that the various types of assets (capital) are strongly mutually dependent and form positive feedback loops. Deterioration or improvement of any of the categories induces changes in the same direction in the others. Quantified confirmations of this can be found in work on the evaluation of the nexus between environmental sustainability, the human capital and the use of renewable energy (Sarkodie et al., 2020) and in the study of the economic development dependence on natural capital exploitation (Hou et al., 2019).

1.1.1. GHG emissions issues

Ritchie and Roser (2017) have compiled a comprehensive analysis of GHG emissions worldwide. While the nominal date of the article is May 2017, this is an interactive online document which is periodically updated. The last update was in December 2019. The published results are fully reusable under the Creative Commons BY 4.0 licence (Creative Commons, 2020a). The data sources used in the compilation include:

- Le Quéré et al. (2018) – a quantitative assessment of the GHG emissions as of 2018 and the related (Global Carbon Atlas, 2020) – one of the publications of the Global Carbon Project (GCP, 2020), showing the geographical distribution on the World map
- Archived information from the Carbon Dioxide Information Analysis Center (Cushman et al., 2003)

That interactive article (Ritchie and Roser, 2017) analyses various aspects of the GHG emissions – including the main contributors, the likelihood to limit the Global Warming within 2 °C, the per-capita emission contributions, cumulative contributions, makes a link to a treatment of the mitigation costs. A snapshot of the GHG emissions trend chart is shown in Fig. 1. Besides the total increase, it is also possible to trace the main contributors to the current emissions and the growth. The alarming trends are the growing emissions coming from China, the United States and to some extent, India. However, the European Union contribution, after some contraction, has stabilised and does not drop for the last few years of the sample, which is also a source of significant concern.

Another observation can be made in terms of the geographical partitioning of the GHG emissions (Fig. 2) as of 2019. It clearly shows the major share of Asia, North America and Europe to the absolute amounts. However, the per-capita analysis (Fig. 3) shows the GHG intensity of the energy use by various countries. Fig. 3a (EDGAR, 2020) shows the 20 most GHG-intensive countries, which includes oil exporters from the Middle East and the rest of Asia, plus some highly-developed countries. Fig. 3b shows the longer-term trend for selected countries, which are significant emitters. It can be seen that from this selection, the clear leaders in emitting (at the point of emission) GHG are the United States, followed by Japan, China (about half f the US intensity), the United Kingdom, India.

Accounting for GHG emissions per product or service consumption, against local generation, is another type of analysis that is considered fairer on the international level. This can be seen in the slicing of the GHG emissions by production and consumption (Fig. 4) for some of the largest GHG emitters. Besides the clarification of who is responsible for the generated GHG emissions, the consumption-based plots and data series are important for the decision-makers in the relevant countries to plan their demand-side management policies, if the GHG emissions should be further curbed. From the given examples, it is clear that for the United States and the European Union, the consumption-based emissions are significantly higher than the production-based. The trends for the major players are slightly upward, indicating the need to seek solutions that would overturn them.

The production-based evaluation has been recently criticised, putting forward the consumption-based evaluation. As has been pointed out in (Yang et al., 2020), the involvement of the Asia-Pacific countries in the virtual footprints in international trade has been in the range 50–71% by the year 2015, while the domestic consumption driving these footprints has been significantly lower. The plots in Fig. 4 (updated up to 2018 for the production-based

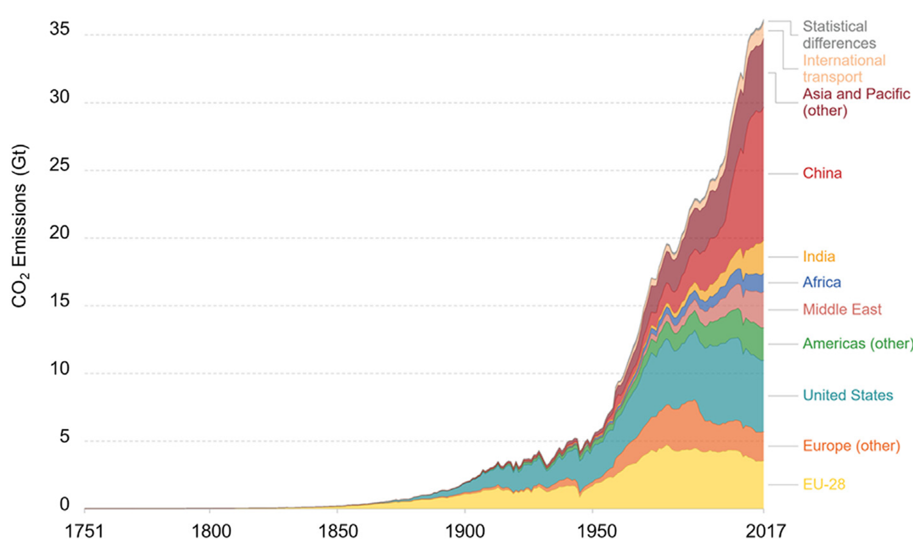


Fig. 1. Trends of the Annual CO_2 emissions by world regions after (Ritchie and Roser, 2017). Source: Carbon Dioxide Information Analysis Centre (CDIAC), Global Carbon Project (GCP). Note: The difference between the global estimate and the sum of national total is labelled "Statistical differences", modified from (Ritchie and Roser, 2017), under the terms of the CC BY 4.0, (Creative Commons, 2020a).

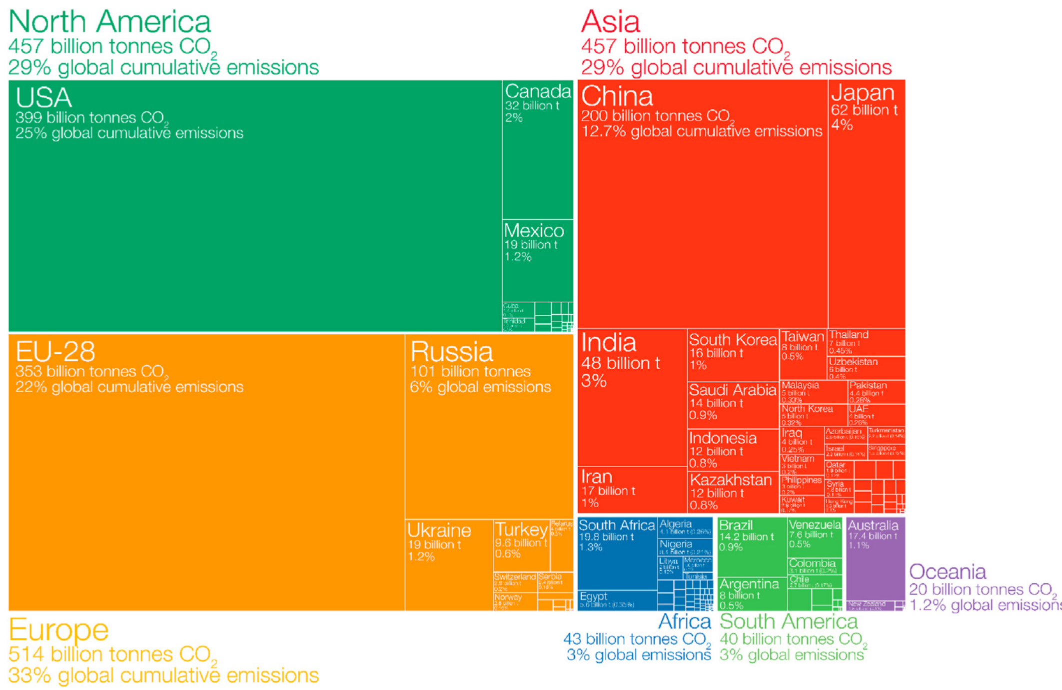


Fig. 2. Treemap of the GHG emissions by World regions (Ritchie and Roser, 2017). Data source: Global Carbon Project (GCP). Shown are national production-based emissions in 2017. Production-based emissions measure CO_2 produced domestically from fossil fuel combustion and cement and do not adjust for emissions embedded in trade (i.e. consumption-based. Figures for the 28 countries in the EU have been grouped as the EU-28 since international targets and negotiations are typically set as a collaborative target between EU countries. Values may not sum to 100% due to rounding). Billion tonnes = 10^9 t. Modified from (Ritchie and Roser, 2017), under the terms of the CC BY 4.0, (Creative Commons, 2020a).

accounting) and a study on the virtual carbon emissions and water flows (Liu et al., 2015) corroborate this, pinning the difference at approximately 20%. It can also be noticed that the EU-28 and the United States feature the opposite proportion with the consumption-based virtual footprints exceeding notably the production-based values.

Since the climate is a vast and complex system, it is difficult to observe and describe. New theories are formulated – such as the one of the "biotic pump" (Pearce, 2020), suggesting that forests play a significant role in the global air mass movements. The theory is currently controversial and is subject to heated debates. However, the existence of the debates and their intensity come to testify the high level of complexity of the problem.

The main impacts of the GHG emissions, discussed in the literature (Bouwer, 2019), is on the climate. This concerns mainly the instability of the climatic phenomena – increased precipitation in some regions, reduced precipitation in others, the increased severity of extreme weather such as hurricanes. As can be seen from the analysis, this is still a subject to debate for some of the impacts and with high confidence for the overall temperature increase.

The impacts of the GHG emissions on crop productivity have been estimated for Canada (Jiang et al., 2020). The results indicate a positive feedback link of the warming and GHG emissions from agricultural activities and the related natural phenomena. The projections of the crop productivities are mixed due to the differing crop life cycles. The article gives examples with the likely increases of soybean productivity by 31%, but also the likely reduction of corn productivity by 7% compared with current (2019–2020) levels.

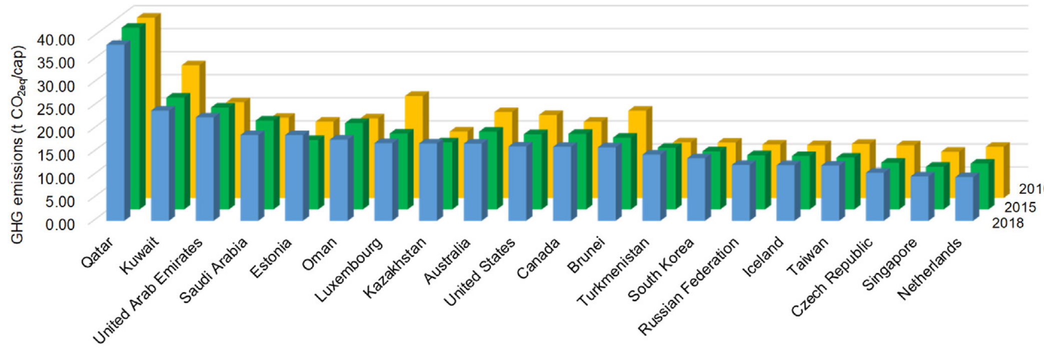
A related analysis focused on livestock has been published by Rojas-Downing et al. (2017). It investigates the cyclic mutual impacts of livestock production and climate change, also finding a positive feedback link. The main contributors to the GHG effects from livestock production are attributed to feed preparation (nearly 50%) and to the deforestation effects (around 9%). While climate change effects on water availability and other factors for livestock production have been identified as important, reliable quantifications are not discussed in the paper.

A recent work (Ren et al., 2020) investigated the variation of Soil Organic Carbon (SOC) in croplands, for the global cropland area, for the period 1901–2010. The study identified two factors to be the main contributors to the organic carbon content in soils – cropland management using fertilisers and irrigation on the one hand and climate change on the other. The authors estimated that the soil management effect (an increase of SOC by 125%) outweighs the climate change effect (decrease of SOC by 3.2%) by order of magnitude. The authors suggest that improved soil management can enable further carbon sequestration, contributing to atmospheric CO_2 reduction.

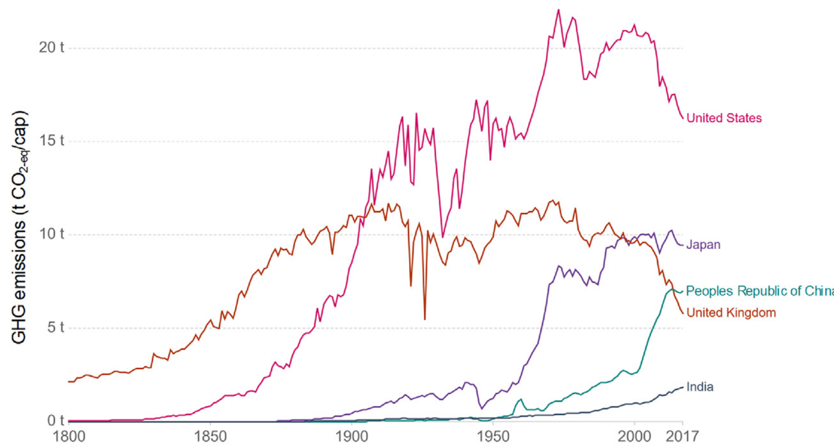
1.1.2. Nitrogen pollution and Nitrogen Footprint

Bound Nitrogen pollution has become very pervasive, as recent scientific results on measurement (Boyle, 2017) have indicated. That perspective article summarises the results of measurements in various media with historical and recent material compositions – such as arctic ice and corals, illustrating the increase in the overall pollution level. The pervasiveness of the impacts has led to the definition of the Nitrogen Footprint concept (Leach et al., 2012) and this has grown into an established tool evaluation of the disturbance effects to the Nitrogen Cycle (Xu et al., 2020).

Schaub and Turek (2016) demonstrated that the rate of artificial nitrogen fixation is comparable with that of biological nitrogen fixation—this doubling of the fixation rate results in pollution mainly of the terrestrial areas with nitrogen compounds. The main effects of the use of reactive nitrogen can be classified as beneficial and detrimental (Leach et al., 2012). To the beneficial effects belong



(a) The 20 selected CO_2-intensive (production-based) countries per capita (EDGAR, 2020)



(b) Annual per-capita GHG emission trends (production-based) of selected countries (Ritchie and Roser, 2017). Source-based on CDIAC, GCP, Gapminder&UN, modified from (Ritchie and Roser, 2017), under the terms of the CC BY 4.0, (Creative Commons, 2020a).

Fig. 3. Per-capita GHG emissions.

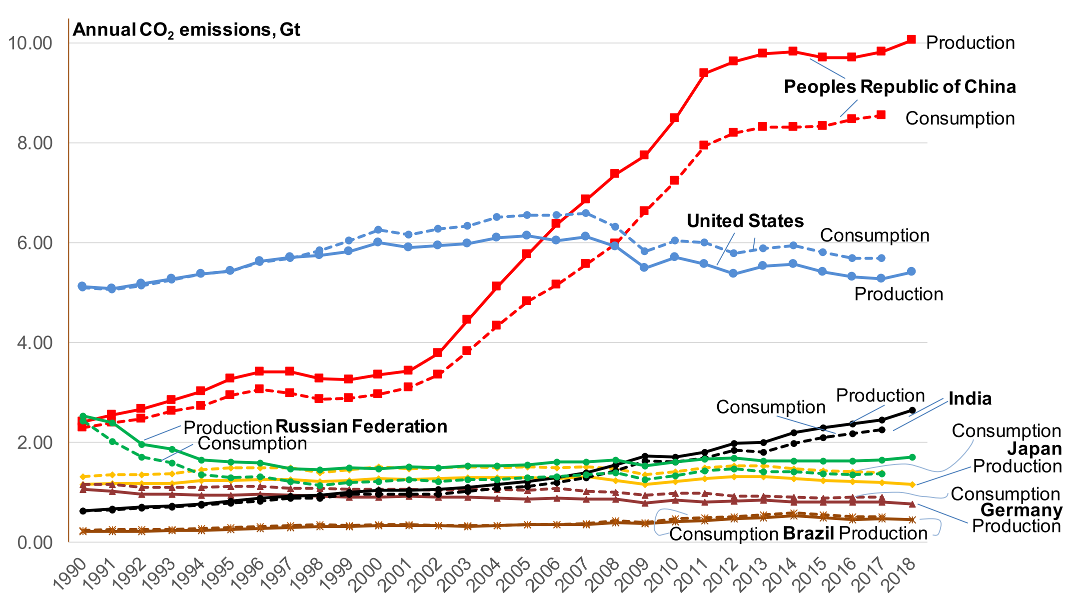


Fig. 4. Trends of the consumption- and production-based CO_2 emissions. Plotted based on data from the Global Carbon Project (Le Quéré et al., 2018) and Our World in Data (Ritchie and Roser, 2017), under the terms of the CC BY 4.0, (Creative Commons, 2020a), data source.

the ability to produce more food for feeding the World population. The detrimental effects are also significant, and they are more complicated to trace. Generally, the problems caused by nitrogen pollution can be grouped into.

- Atmospheric – smog, acid rain, ozone depletion, Greenhouse Gas Effect (Leach et al., 2012)
- Ecosystem – forest dieback, coastal 'dead zones', biodiversity loss (Leach et al., 2012)
- Aquatic – acidification and eutrophication (Erisman et al., 2013)
- Health issues – including respiratory problems directly caused by NO_x, NH_3 suffocation issues, increased susceptibility to infectious diseases (Erisman et al., 2013)

Gao et al. (2020) investigated the spatial-temporal dynamics of the Nitrogen Use Efficiency in the Chinese country-wide food supply chains for the 28-y period from 1990 to 2017, and covered virtual nitrogen as part of the evaluation. The study detected a significant increase (up to 92%) in the nitrogen input to the food supply chains for that period.

Statistical information, available from the European Environmental Agency (EEA, 2020) shows a continued and stable trend for reduction of the NO_x emissions within the European Union (EU-28) – see Fig. 5. The trend record starts from 12.253 Mt for the year 2005 and ends with 7.272 Mt for 2018 – slightly more than 40% reduction for the period. The reductions are approximately proportional among the contributing sectors. That positive development can be traced to the effects on natural ecosystems. On the example of four Norwegian sampling areas, the various forms of nitrogen pollution have been investigated (Kaste et al., 2020) – nitrate, ammonia and organic nitrogen. The overall leaching of nitrogen compounds to the surface water has been found to decrease on the order of approximately 30% for the period from 1990 to 2015, which is in line with the nitrogen deposition trends. These results come to show that the ecosystems in Southern Norway are still away from the normal functioning without nitrogen leaching and that further reduction of the deposition is necessary.

The breakdown of the NO_x pollution by countries world-wide is not easy to track, due to the lack of consistent data. The most recent consistent information found is from 2017 data, by the OECD (2020). They are tracking the NO_x emissions by organisation members. Note that the Russian Federation and the Peoples' Republic of China are not OECD members. On the basis of nominal emissions (Fig. 6a), the major contributors are Australia, Canada, Turkey, the United States and Japan. On a per-capita basis (Fig. 6b), these are Australia, Canada, Estonia, Iceland, Turkey. It can be seen that in both representations, Australia, Canada and Turkey are among the major emitters, which indicates that they should be in the focus of the efforts of NO_x reduction.

It is also important to pay attention to the possible interactions between the rate of deposition of reactive nitrogen and the rate of CO_2 sequestration in natural sinks. Gu et al. (2018) have investigated the issue statistically, at the level of economies and raise the point that reduction of nitrogen pollution may counteract the availability of CO_2 sinks and their efficiency. This can be explained by the direct link (Reay et al., 2008) between reactive nitrogen deposition and bound nitrogen in terrestrial and aquatic plants, which determines their capacity to absorb CO_2.

In addition to NO_x pollution, anthropogenic sulphur oxides (SO_x) emitted to the global sulphur cycle have been causing various critical environmental issues – contributing to climate change and aquatic acidification. Except for direct emissions and damages, the acid precipitation (acid rain, especially) also causes a lot of damage to agricultural crops, plants as well as buildings and constructions (Britannica, 2020). The industrial sector has been the major source of SO_x emissions, and studies found that end-of-pipe treatment combined with energy-saving and shifting to cleaner energy are the key factors (Hang et al., 2019) to mitigate the SO_x emissions and reduce negative environmental impacts.

Empirical evidence has been produced of the influence of nitrogen pollution on the coral reefs in the oceans (Donovan et al., 2020). This is a very strong indication that pollution types are interacting and are very likely to amplify each other's effects. The authors conclude that mitigation of nitrogen pollution may improve the resilience of corals to the effects of climate change.

The outlined problems are subject to treatment by governmental policies, as discussed in (Kirschke et al., 2019). The study has analysed the case of Germany and concluded that there had been little coherence between the various policy instruments, which leads to little or no improvement of the nitrogen pollution of surface or groundwater bodies. For the improvement of the water quality, the authors recommend a closer integration of the policies on water and agriculture, combine with better use of economic instruments.

1.1.3. Water scarcity and pollution

Global water use (withdrawal) increased six times in the past 100 y as a result of a growing population, economic development, as well as shifting consumption patterns (UNESCO, 2017). According to (Worldometer, 2020), water resources withdrawal per capita increased from 0.67 Mm^3 to 3.98 Mm^3 from 1901 to 2014.

Water scarcity and water pollution are the major issues affecting ecosystems and human society around the globe. The developing climate changes have exacerbated these issues by affecting the availability, quality, as well as the quantity of water resources. The World Resources Institute evaluated the baseline water stress by countries at a global scale (Fig. 7). The baseline water stress is defined as the share of the total water withdrawals in the total renewable surface and groundwater availability for the considered area (Hofste et al., 2019). The WRI Aqueduct Water Risk Atlas identified that 44 countries in the world face high water stress. This was estimated as more than 40% of the available water is withdrawn every year (Hofste et al., 2019). Seventeen countries are

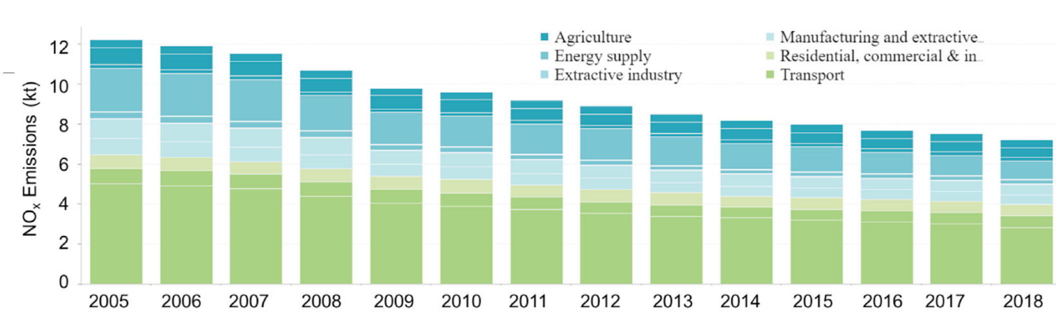
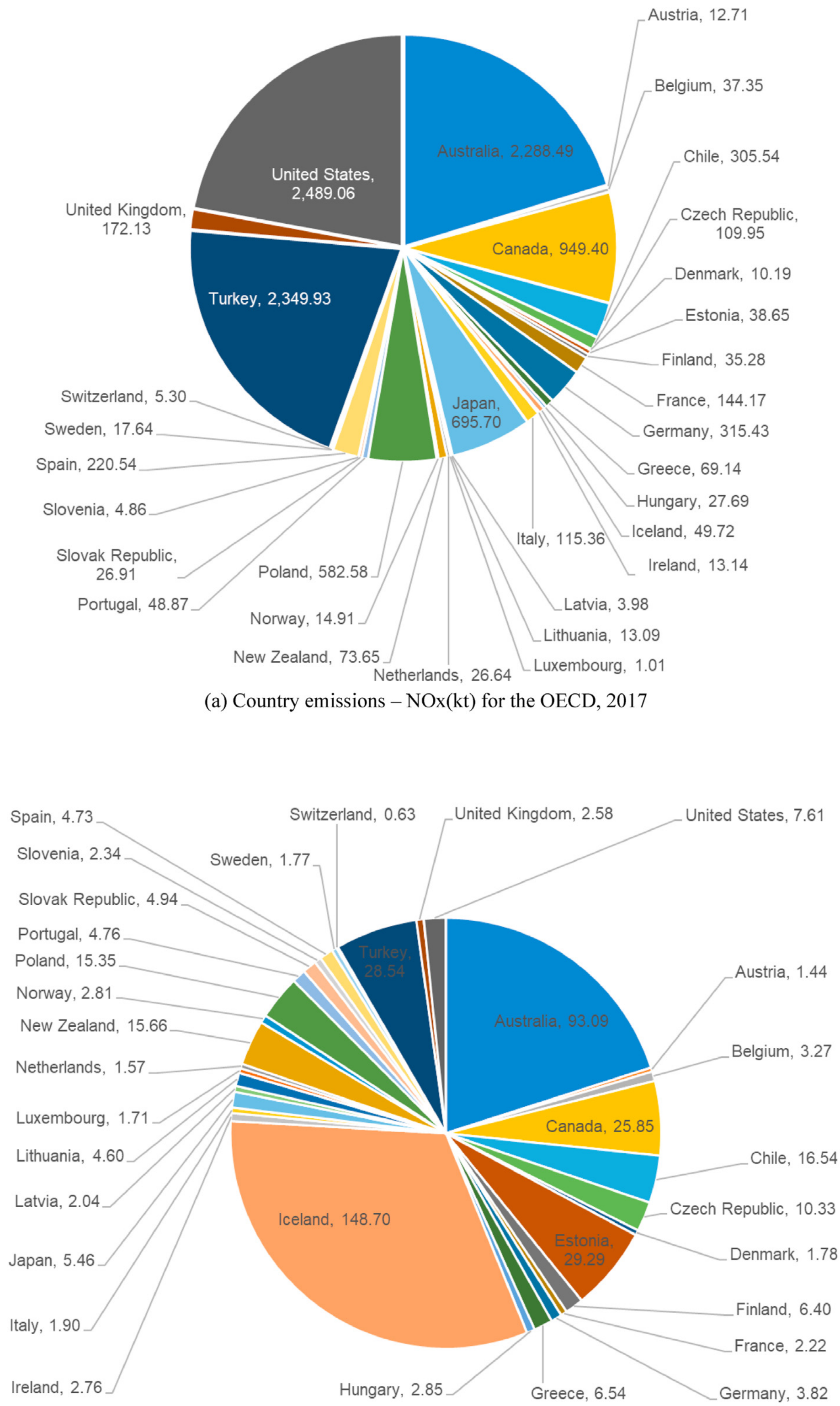


Fig. 5. NO_x Emissions for the EU-28, during 2005–2018, adapted from (EEA, 2020), based on the terms of the Creative Commons – Attribution 2.5 Denmark – CC BY 2.5 DK licence (Creative Commons, 2020c).



(a) Country emissions – NOx(kt) for the OECD, 2017

(b) Per-capita NOx emissions (kg/capita) for the OECD, 2017

Fig. 6. NOx emissions of OECD counties for the year 2017, plotted from datapublished in (OECD, 2020).

reported as having "extremely high" water stress, where the amount of the total water withdrawal exceeds 80% of the availability.

Besides the water scarcity caused by a lack of water quantity, water pollution caused un-usability of water often occurs in rural areas or areas has limited resources to clean the water. Water quality has a significant impact on the usability of the water. Once contaminated, it is almost impossible to remove the contaminants

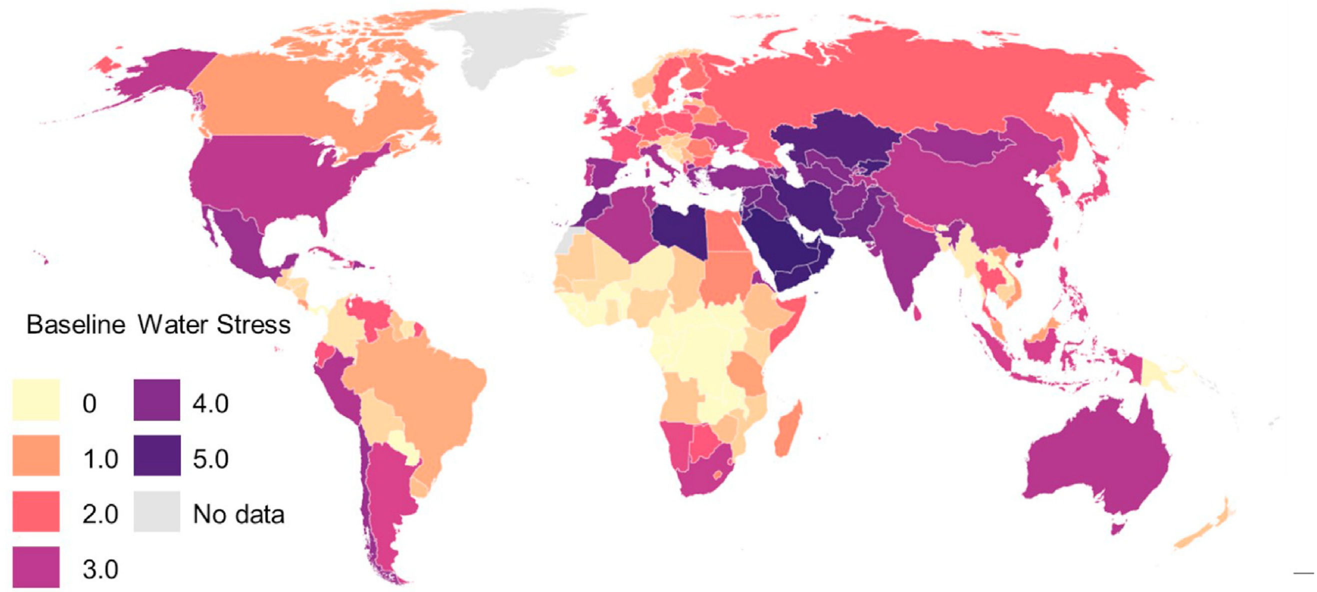


Fig. 7. Baseline water stress by countries in 2019. Generated based on the data provided by Hofste et al. (2019).

and is usually costly to treat the water to be usable. Although wastewater treatment technologies have been improving and widely implemented, there are still 80% of global wastewater running untreated (UNESCO, 2017), containing the pollutions from human activities. Among the 20% treated water, only 2% is reused in Europe, leaving 98% of the treated water discharged into the natural water bodies (Jeffrey, 2018). There is still remarkable potential to improve water use and wastewater reuse efficiency.

Another issue that often occurred in the urban area is the flash flooding and landslides due to the sudden increase of precipitation and inefficient urban water infrastructures. For example, the storm-caused flooding in February in the UK has resulted in floods affected over 82,000 inhabitants, and the total cost of repairing homes and business is expected to be more than 403 M€ (ECIU, 2020). Severe flash floods also occurred in France and Italy and caused dramatic damages (FloodList News, 2020).

Overall, water issues have become more complex due to the increasing consumption, shifting of consumption patterns, generation of more complex pollutants, as well as climate change. Water scarcity, water pollution, and water-related disasters (e.g. flooding, storm, and landslides, etc.) have posed threats to human lives and economic developments. The determination, assessment as well as the management of water use and water reuse is of remarkable significance in both scientific research and practical applications.

1.1.4. Solid waste including plastic waste issues

Solid waste is generated by many sources – including industry, residential and commercial complexes. The sources provide the basis of the main classification – industrial waste and Municipal Solid Waste. Fractions of those waste flows are acutely dangerous to the environment and human health, and they are classified as hazardous.

Waste management is a key activity for keeping the environment clean and the quality of life high. It bears significant potential for GHG emission saving – estimated to up to 75% for the EU (Fan et al., 2020b). The main challenges in waste management, once waste generated, are related to the Waste Hierarchy (Cole et al., 2019), which has been extended to the Circular Economy Hierarchy (Klemeš et al., 2020c), and can be grouped into:

- **Waste separation** – to enable distinct handling of reusable and recoverable materials, and the materials for energy valorisation, from the handling of the fraction that has to be neutralised and landfilled. While the benefits of separation at source have been widely accepted and quantified (Pham Phu et al., 2019), the implementation of this practice is not as wide, to provide the necessary effects, and even has been a discussion whether to make the separation at source mandatory (Hou et al., 2020).
- **Material recovery and recycling** – to achieve several effects, including reduction of materials passed to the next stages, as well as indirect saving of energy, water, other resources and footprints by virtue of substituting products and materials that usually take virgin resources. Such substitution has been preliminarily estimated to provide substantial benefits in terms of footprint reduction – see the example of rare-earth materials recycling (Beylot et al., 2020). A search in Google Scholar on the keywords ≪ “waste recycling”, "product substitution", “footprint reduction” ≫, as of 30/08/2020 (Google Scholar, 2020), produces many studies on product substitutions, but there is an apparent lack of quantitative studies that would relate the rate of recycling quantitatively to the reduction of footprints, energy expenditure and the economic performance.
- **Waste-to-Energy** – intended to provide the final reduction of the waste material flows that are passed to landfill and simultaneously to recover as much energy as possible. A recent review of the studies dedicated to Life-Cycle Assessment of Waste-to-Energy (Mayer et al., 2019) presents the overall picture, observing that at most half of the found studies provided a Life Cycle Assessment of the proposed solutions. From some of the recent sources, a study on the Malaysian Waste-to-Energy potential (Choong et al., 2019) indicates that more than 90% of the GHG emissions can be reduced by Waste-to-Energy, while a study accounting for the emissions from Waste-to-Energy itself (Varbanov et al., 2018), estimates the GHG saving potential of this type of solutions to up to 10–11%. This disparity of estimates calls for a more thorough study and unification of the evaluation context.

- **Landfill** – the remaining waste materials need to be safely disposed of, ensuring that no leaching and other emissions take place (Prasad and Shih, 2016).
- **Logistics** – this is the activity bringing all the discussed stages together by enabling the transportation of the material flows through the supply chain. The logistics are linked to the spatial challenge. Varbanov et al. (2018) have shown that the size of the waste collection area is related to both the efficiency of the central processing facilities and to the footprints from fuel use for the transportation, defining a trade-off.

A notable fraction of the solid waste generated worldwide comes in the form of plastics – up to 10–15% of the total waste generation (Fan et al., 2020a). That study has investigated the trends of waste generation, revealing the correlation between reduced business activity and increased supply chains activity related to residential deliveries. It has to be noted that the COVID-19 situation, still developing at the end of August 2020, has brought up new challenges in dealing with packaging waste (Renner, 2020), much of which comprises plastics.

Much of the plastic waste materials are not bio-degradable or have serious issues if biodegraded (Zheng et al., 2005). As a consequence, they build up in the environment. The most well-known manifestation of this build-up is the Great Pacific Garbage Patch (National Geographic Society, 2019). However, fine plastic particles are very pervasive worldwide, reaching even United States Natural Parks (Stokstad, 2020). Klemeš et al. (2020d) proposed the concept of Plastic Waste Footprint for representing the environmental footprint of plastic pollution, on a Life-Cycle basis. A thorough overview of the issues can be found in the recent book (Letcher, 2020). The main issues so far are:

- The sufficiently accurate estimation of the amount of plastic waste accumulated in the environment and its spatial distribution. Currently, estimates can be found of the plastic production by years and the spatial distribution of the production – Fig. 8 (Klemeš et al., 2020c) and a publicly available summary (Ritchie and Roser, 2018) provides sections on paths and quantities of ocean pollution by plastics, plastics production, the structure of plastic waste disposal, mismanaged plastic waste – either littered or inadequately disposed of.
- The low recycling rate of plastic materials – according to a National Geographic News report (2018), less than 10% of the produced plastics is recycled.
- Identification of the fate of plastic materials and plastic waste (Geyer et al., 2017) – the identification for oceans has been performed (Cantwell, 2020) with varying accuracy and success, but the fate on land and inland water bodies is not yet well covered – as can be seen from a Canadian governmental report (Government of Canada, 2020).

1.2. Previous related reviews

One of the first systematic reviews of environmental footprints and tools for evaluating them has been written by Čuček et al. (2012a). This is a comprehensive summary of the definitions and tools, also extended to the analysis of the single footprints as metrics and their combinations. A follow-up review, building on that one, has been given by Guillén-Gosálbez et al. (2019). That study presents the sustainability problem solving from the viewpoint of Process Systems Engineering (PSE). They emphasise the strengths of PSE in terms of the systematic model solutions, available optimisation methods and the ways of applying the Life Cycle Assessment framework using PSE tools. One of the tools, standing out in the review, is the Pareto-plot, allowing to visualise the trade-off of the system performance between two optimisation criteria.

Currently, the policies are still mainly focused on GHG Footprint reduction. One example in implementing the data collection for policy implementation and adjustment is the summary by Utility Dive (2020a). The need for centralised registries of GHG emissions by utility companies is discussed. Examples of such registries are given with the Edison Electric Institute and the US-EPA. The article reasons that, having a single place online with the GHG emission data, helps in interacting with customers more efficiently and enables decision-making where to target system improvements.

The economic and policy perspectives are also important in tackling pollution problems. In the policy domain, the reduction of resource demands and footprints while preserving and even increasing economic prosperity is denoted by the term "decoupling" (Vadén et al., 2020). That review has analysed 179 literature sources on decoupling, categorising the claimed research results according to the reported types of decoupling. The study has found sufficient evidence of geographically-limited decoupling between Footprints (GHG, Land, Water) and GDP. The authors also report the lack of evidence of global-scope decoupling with sufficient pace. This is a good example of a "detection" study, where the problems or the parameters of the current situation are identified. In order to be useful, such detection has to be followed by setting targets for actions that would bring about the desired decoupling.

The relationship has been reviewed (Sarkodie and Strezov, 2019) between foreign direct investments, economic development and energy consumption on the GHG emissions of the major emitters among the developing countries – China, India, Iran, Indonesia and South Africa, for the period 1982 to 2016. The authors have reported results and provided reasoning for further foreign investment and technology transfer, to enable those countries achieving the sustainable development goals with regard to GHG emissions.

Setting sustainable development goals as the departure point, Hong et al. (2016) have analysed the implementation principles and the main modelling approaches that would the design of sustainable

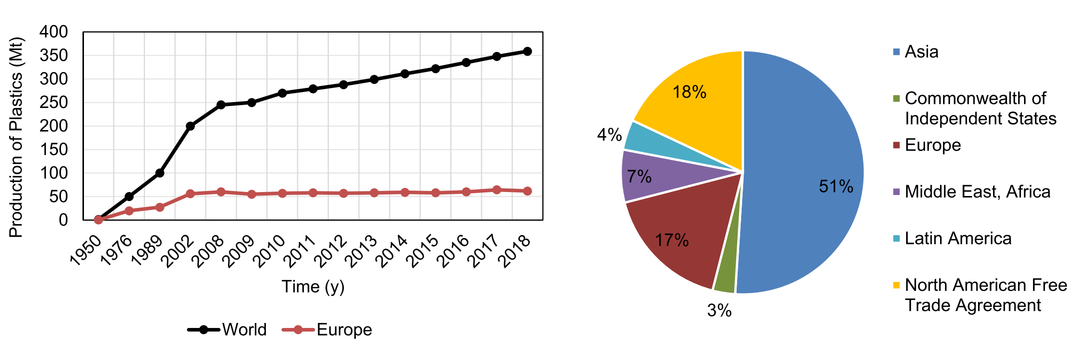


Fig. 8. Plastic production in time and its world distribution (Klemeš et al., 2020c).

biomass-based supply chains. They have identified as prospective several business model components – lean/agile elements, supply chain resilience, and compliance with the sustainability goals (referred to as Green Supply Chain). They have further provided a review of the modelling approaches – highlighting Mathematical Programming, Heuristic Approach, Hybrid Approach, and P-graph.

The role of biorefineries for the implementation of Circular Economy has been reviewed by Ubando et al. (2020). The focus of the analysis was on biorefineries producing fuels from biomass feedstocks. The authors mapped the keyword links by their usage in the analysed publications. They have further classified the identified studies by type of analysis, type of processed feedstock and used technologies. The study concludes that it is necessary to increase the role of biorefineries in utilising waste biomass as a priority over composting and energy products alone, also emphasising the social aspects of job creation and job security.

Some of the tools for optimising the processes involved in supply chains and other societal systems belong to the Process Systems Engineering (PSE) field. This prompted a review (Avraamidou et al., 2020) of the problems related to the Circular Economy implementations and how the PSE tools can help to solve them. From the challenges posed by the problems, the authors have considered the multitude of the possible processing pathways, the chain of stakeholders (an alternative term to denote production-based and consumption-based emission and impact assessments), the presence of multiple scales in the considered problems and the need for reflecting them in the models. From the overviewed tools, the recommendations have been mainly related to those featuring Mathematical Programming models.

Three key characteristics of process design and optimisation have been the foundation of Process Integration. One is the realisation that the efficient integration of process streams and processes brings simultaneous savings on resource intake and emissions to the environment. The second is the developed principle of obtaining performance targets before design and using these targets in the process optimisation as either hard goals to be achieved, or as system performance bounds that cannot be exceeded. The third characteristic is the exploitation of the targets and inherent process constraints – mainly bottlenecks termed Pinch Points, for problem decomposition and simplification, obtaining more efficiently the solutions to complex problems. The development of the Pinch-based methods for Process Integration and Intensification, that improve the process performance in terms of emissions and economy, has been reviewed recently by Klemeš et al. (2018). This review has demonstrated the first steps in the right direction – using the Process Integration philosophy and thinking for devising integrated solutions to the sustainability challenges, confining its considerations mainly to the industrial production applications and supply chains.

1.3. The need for the current review and its goals

The analysis of the problem basis and the summary of the previous related reviews shows that there have been considerations of the environmental footprints as possible indicators to track (Čuček et al., 2012a), as well as their potential application in PSE investigations (Guillén-Gosálbez et al., 2019) aimed at sustainability assessment or improvement. It has become apparent that analyses of industrial process improvements and of partial sets of the necessary measures have been analysed – as in the case of the policies for GHG emission data repositories (Utility Dive, 2020a), or the policy discussion on the topic of “decoupling” (Vadén et al., 2020).

There have been further reviews on the relationship between investments and GHG emissions of the economies (Sarkodie and Strezov, 2019), biomass supply chains (Hong et al., 2016), the role of biorefineries in implementing Circular Economy measures (Ubando et al., 2020), PSE challenges and opportunities (Avraamidou et al., 2020). The latter can be related to the PSE-centred review of environmental footprinting and sustainability assessment (Guillén-Gosálbez et al., 2019), as well as the use of Pinch Analysis in solving industrial, municipal and regional resource problems (Klemeš et al., 2018).

The revealed picture shows that the overall complex problem of the global cycles, their disruptions, pollution and the potential measures to mitigate their effects, has been approached from various departure points, providing in many cases partial views of the problems and the potential solution measures. Ideally, tackling simultaneously all the issues discussed in this review would produce solutions that are most suitable for solving them. While exchanging knowledge and information between engineers on narrow sets of topics are relatively easier, such an undertaking for solving a wide host of issues would require the interaction of diverse stakeholders and the assembly of large and diverse teams. Putting together and managing diverse teams is possible for solving specific problems of limited scope, but is getting exponentially difficult for a wider research scope.

For this reason, the series of conferences PRES has followed a hybrid approach, tackling a wide host of the analysed issues, but centred around the topic cluster of Energy Saving and Emission Reduction. This provides a broad enough scope for knowledge development, uniting various topics:

- **Energy-related**: Heat Integration and energy-saving, Total Site Integration, Renewable energy and utility systems, heat exchangers and heat transfer, power systems design and optimisation, sustainable energy planning, Waste-to-Energy, Energy Storage
- **Industrial process improvement**: process retrofit and optimisation, Circular Economy and Integration
- **Synthesis, Design and Operation of Process Systems**: process synthesis, operations and supply chain management, process dynamics and control
- **Process analysis and modelling**: process simulation, Mathematical Programming (optimisation)
- **Focus on emission reduction** by process improvement or end-of-pipe treatment: cleaner production, footprint minimisation and mitigation, Waste and wastewater management
- **Process unit, materials and phenomenological research**: reactor and catalyst engineering, fluid dynamics, sustainable materials

Based on the analysis, it is necessary to obtain a representative indication of the recent development trends of the issues and the tools for solving the issues, giving positive examples of collective problem solving, which treat the targeted scope of engineering topics, that contribute to energy saving and pollution reduction. The current review performs exactly this type of analysis, clearly showing the contributions of the current Virtual Special Issue to the scientific discourse on this topic cluster.

2. Recent development trends and tools

The recent trends in emission release can be considered in the example of China. A recent analysis (Maji and Sarkar, 2020) has revealed a gradual decrease in the concentrations of major air pollutants, as detected by monitoring stations across China. However, these decreases are very modest, and it is difficult to foresee what factors can bring about more substantial pollution reduction. One possibility is that, while the government policies favour more responsible use of fossil fuels, the energy conversion technologies used remain the same as world-wide – mainly based on traditional combustion-based thermal cycles. Another factor is that most of the attention is paid to the energy supply to the economy and not so much to the efficiency of energy use.

These factors have been in the focus of the series of conferences PRES, which provide a platform for knowledge development and exchange on technology advances for better energy efficiency and pollution reduction, spanning the Life Cycles of the considered products and services. The conference reached in 2017 its twentieth year (Klemeš et al., 2017) of continuous service to the cause of sustainable development via energy-saving and reduction of footprints from industrial, residential and commercial facilities. The conference started with the idea of widening the results achieved by Heat Integration (Linnhoff et al., 1994) – including Total Site Integration (Klemeš et al., 1997). The methodology has been consistently extended to other resource types and media – such as water, GHG emissions, the use of renewables, and footprints. Pinch Analysis and other Process Integration approaches have been further advanced and extended for wider Process System Engineering. Environmental footprints, especially GHG emissions footprint and water footprint methods, have been further improved to provide more systematic assessment results.

2.1. Process Integration and optimisation

Improving regional energy use efficiency is critical to minimise GHG emissions. Liew et al. (2017) conducted a thorough review of energy consumption targeting methodologies using Total Site Heat Integration, which also identifies the potential directions for further investigation in Total Site Heat Integration. One of the new challenges for the further development of Process Integration and Optimisation tools is to integrate multiple aspects when perusing systematic sustainability, such as the economic aspects, system reliability, and environmental impacts, renewable energy systems, etc.

Zhang et al. (2020) proposed a combined graphical Pinch Analysis and mathematical programming method for the coupling integration of reactors and threshold Heat Exchanger Network (HEN). The proposed method also considered the reactor kinetics, mass and energy balance. The proposed method is able to increase a 27.82% net annual revenue of the steam-reforming process after optimisation.

In addition to reutilising the high-grade waste heat, the potential of low-grade waste heat has also been investigated. Santin et al. (2020) introduced a parametric approach to investigate the economic feasibility limit of waste heat utilisation in District Heating and Cooling (DHC) vs power generation. The authors conducted a water-energy-carbon nexus analysis and identify power generation is economically feasible with the threshold distance for 30 MW waste heat flows for Italy and Austria are 10 km and 20 km for 30 MW waste heat flows. In the case of DHC, the economically feasible threshold distance in longer for Italy at 30 km. In another work, Tian et al. (2020) proposed a multi-plant indirect heat exchanger network model with Differential Evolution (DE) algorithm. The model uses a two-layer optimisation process to obtain the best HEN design. DE algorithm and MINLP is used for the outer layer, and an inner layer to determine the HEN configurations and total annual cost (TAC) values. The proposed optimisation model evaluated the trade-offs among the heat exchanger, utility and pipeline cost to solve the complicated MINLP problems.

In addition to energy (heat), integration and optimisation in conventional energy carriers such as steam, systematic integration of renewable energy has also been investigated. Xiao et al. (2020) proposed the Wind-Thermal-Storage-Transmission (WTST) concept aiming to improve the efficiency of remote transmission of large-scale wind power and reduce wind energy curtailment. The study also proposed an optimal model to simulate and optimise the configuration of various power facilities, especially for long-distance transmission of intermittent energy sources. Poblete et al. (2020) assessed the performance of a BioGas-Combined-Cycle (BGCC) power plant with Carbon Capture and Storage (CCS) and dynamic Compressed Air Storage (CAS). The study claimed that the BGCC-CCS-CAS system is bioenergy with carbon capture and storage system with negative carbon emissions. The study also proved the economic and environmental feasibility of small-scale biogas fired combined-cycle power plants in rural areas.

2.2. Environmental impact assessment and reduction

Environmental impact assessment has been the pioneering topic related to the issues of pollution and its impact on the environment. This has since grown into a comprehensive discipline on assessment and reduction of the impacts. The recent developments are reviewed in this section.

2.2.1. GHG footprint and nitrogen footprint assessment

GHG emissions footprint (Wright et al., 2011) or carbon emissions footprint (Wiedmann et al., 2016), has become a critical indicator in environmental impact assessment. The GHG emission inventory is the critical step of GHG emission footprint calculation. For consumption-based accounting methods, the most effort has been the focus of the IPCC (Krey et al., 2014), Input-Output Analysis (IOA) and the Life Cycle Assessment (ISO, 2006) models (Arioli et al., 2020), and most of the recent developments are based on these existing methods. Hybrid LCA methods have been applied for determining both production- and consumption-based GHG emissions (Ibrahim et al., 2012). Harris et al. (2020) determined and compared the production-based and consumption-based GHG emissions of 10 European cities, and found that the most emissions are external (which means emissions from cities out of the studied cities). The results also highlighted a notable disparity between the two sets of accounting methods and raised the point that consumption-based results should be more addressed in future studies.

Nitrogen oxides have been increasingly investigated as one of the most critical GHG effect factors. The Nitrogen Footprint (NF) concept and assessment methodology have also been proposed and developed following the GHG emissions footprint assessment path. For example, Noll et al. (2020) assessed and compared the NF of the organic food and conventional food in the United States and found that there is an only slight difference between the organic and conventional food production in terms of Nr (reactive Nitrogen) loss and the total NF. Liang et al. (2019) investigated the Nitrogen Footprint and nitrogen use efficiency of greenhouse tomato production in North China and claimed that NF could facilitate the tracking of N inputs and provide helpful information for the farmers and policymakers. However, it is still challenging to make a breakthrough in the assessment methods because nitrogen-related environmental impacts are complex and difficult to quantify (Einarsson and Cederberg, 2019).

2.2.2. Water resources assessment and optimisation tools

Various methods and approaches have been proposed and applied to the water resources assessment. These methods can be divided into three categories regarding the aim of assessment, namely the post-assessment tools, optimisation tools and the hybrid tools aiming to provide assessment result and support water use optimisation. The Water Pinch Analysis (Wang and Smith, 1994) was proposed to improve industrial water reuse and has been one of the widely applied graphical water integration method (Klemeš et al., 2011). The Water Pinch Analysis has been further improved to cover multiple contaminants with applications of water reuse headers (Fadzil et al., 2018). Water footprint (Hoekstra et al., 2012) is the most applied water use assessment tools and consists of Green Water Footprint, Blue Water Footprint, and Grey Water Footprint considering different water sources.

The Water Footprint concept was then further developed to adapt it to the Life Cycle Assessment framework (ISO, 2014), and aims at evaluating the environmental impact of water use. The ISO (2014) Water Footprint consists of Water Availability Footprint for water quantity assessment, and Water Degradation Footprint for the environmental impact assessment of water use. Hybrid methods, aiming to assess the impact of water use and implement water integration, have also been proposed. For example, Jia et al. (2015) proposed the Water Footprint Pinch Analysis, using a graphical method to analyse and target Water Footprint minimisation. Jia et al. (2020) proposed the Water Scarcity Pinch Analysis, which evaluates the quantitative and qualitative use of water and targets at freshwater use minimisation with the supporting of the assessment results. The methods are summarised in Table 1.

Besides the methods widely used in the process and regional scale research, advanced tools have also been developed to investigate the water issues on a global scale (WRI, 2020). For example, the Aqueduct Tools for global-scale analysis. The Aqueduct Water Risk Atlas (Fig. 9) is one of the tools for water assessment. It presents the baseline and future water risk with monthly and annual temporal resolution. In the tool, 13 water risk indicators—including quantity, quality, and reputational risks—are combined into a composite overall water risk score, and the results are presented in the form of an interactive map. The Water Risk Framework covers Physical Risks Quantity (e.g. Water Stress, Water Depletion, Interannual Variability etc.), Physical Risks Quality (e.g. Untreated Connected Wastewater, Coastal Eutrophication Potential), and Regulatory and Reputational Risk (Unimproved/No Drinking water, Unimproved/No Sanitation, etc.).

The Water Sense Calculator (US EPA, 2020) – see Fig. 10, developed by the United States Environmental Protection Agency (US EPA), is a simple calculator to estimate the water, energy, and money savings by installing WaterSense labelled products in-home or apartment building. A list of WaterSense labelled products (e.g. toilets, showerheads, bathroom faucets, etc.) are backed by independent, third-party certification and meet US EPA's specifications for water efficiency and performance. The calculator provides an online calculator and Excel calculator for different users.

With inputting the number of people in the household, type of toilet and type of energy used for to heat the water, the calculator estimate the annual saving of water, electricity, money, and potential reduction of GHG emissions. The calculator can help with improving public awareness of the importance of increasing water and energy use efficiency.

2.2.3. Other footprints/integrated footprint criteria

Since the Earth contains interlinked ecosystems and human societal systems, there are many interactions and many system properties to be monitored. For that reason, tracking only GHG or Water Footprints alone is insufficient to capture the state of the studied system. Instead, a selection of footprints has to be monitored, combined with an economic criterion – cost- or profit-based. This principle has been well reasoned and established by De Benedetto and Klemeš (2009) in the definition of the criterion named "Environmental Performance Strategy Map". This principle allows one to consider multiple aspects and obtain more complete representations of the solutions. However, not all footprints should be added to the objective function in optimisation models. Most of the footprints are inter-related, and only a few of them are independent. In follow-up developments, the footprints to include in the objective function have been analysed, and a method has been developed to select only the independent ones (Čuček et al., 2014). This strategy has been implemented in work on the synthesis of a company supply chain accounting for multiple footprints (Vujanović et al., 2014).

Following the logic of footprint family modelling, Vanham et al. (2019) selected and defined a specific footprint family for assessing the environmental sustainability of systems from local up to planetary level. The selection has been tailored to help to measure the progress towards the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2020). The selection includes Carbon Footprint, Water Footprint, Ecological and Land Footprints, Nitrogen Footprint, Phosphorus Footprint, Material Footprint, Biodiversity Footprint, PM2.5 and PM10 Footprint, Ozone Footprint, Energy Footprint, Emergy Footprint.

2.3. Waste management and integration

Reducing waste generation and transforming waste to useable resources is another direction towards sustainability contributions by reducing the resources consumption and pollution effects simultaneously. Efforts have been contributed to improving waste management, resource extraction and energy recovery from waste (Moustakas et al., 2020). Sharma et al. (2020) investigated the potential of producing bio-hydrogen using waste materials such as industrial wastewater, sludge, farming waste and food waste, etc. Dark and photo fermentation are the major biological processes of waste-to-hydrogen. The study also analysed the economic cost of the transformation process. The results showed that the cost of waste-to-biohydrogen with present technologies is considerably higher than the conventional hydrogen transformation paths, but it is an excellent alternative to solve waste issues and increase the material circularity.

Khalil et al. (2019) investigated the potential of producing biogas from animal waste and claimed that organic waste is a promising source of biogas production. The study showed that in Indonesia, the annual biogas production from animal waste (including manure, blood, and rumen content) reaches up to 9597 Mm^3/y,

Table 1
Summary and comparison of different water resources assessment and optimisation tools.

Category	Representative methods	Remark
Optimisation tools	Water Pinch Analysis (Wang and Smith, 1994) and further developments (El-Halwagi et al., 2003)	Water integration and optimisation
Assessment and Optimisation Hybrid tools	Water Footprint Pinch Analysis (Jia et al., 2015)	Volumetric water use assessment and integration
	Water Scarcity Pinch Analysis (Jia et al., 2020)	water use assessment and integration considering water quantity and quality
Post-Assessment tools	Water footprint (Hoekstra et al., 2012)	Volumetric water use assessment
	Life cycle water footprint assessment (ISO, 2014)	Water use of environmental impact assessment

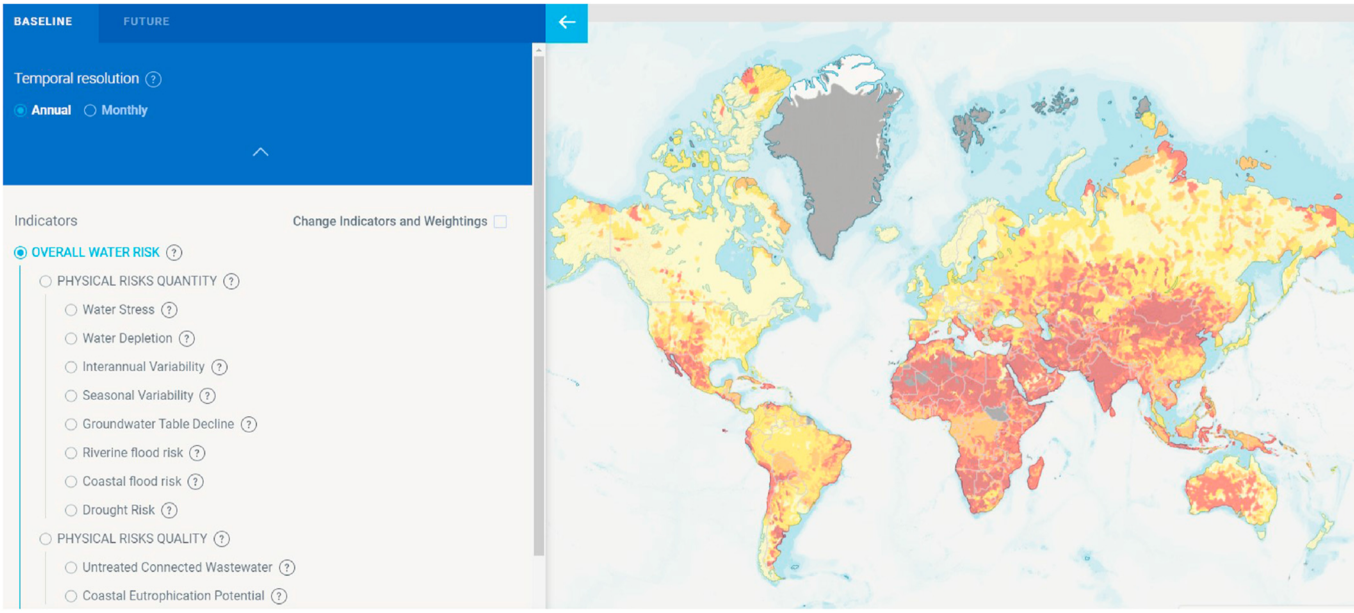


Fig. 9. Screenshot of the Aqueduct Water Risk Atlas Interface (WRI, 2020). Source: www.wri.org, under the CC BY 4.0 International licence (Creative Commons, 2020a).

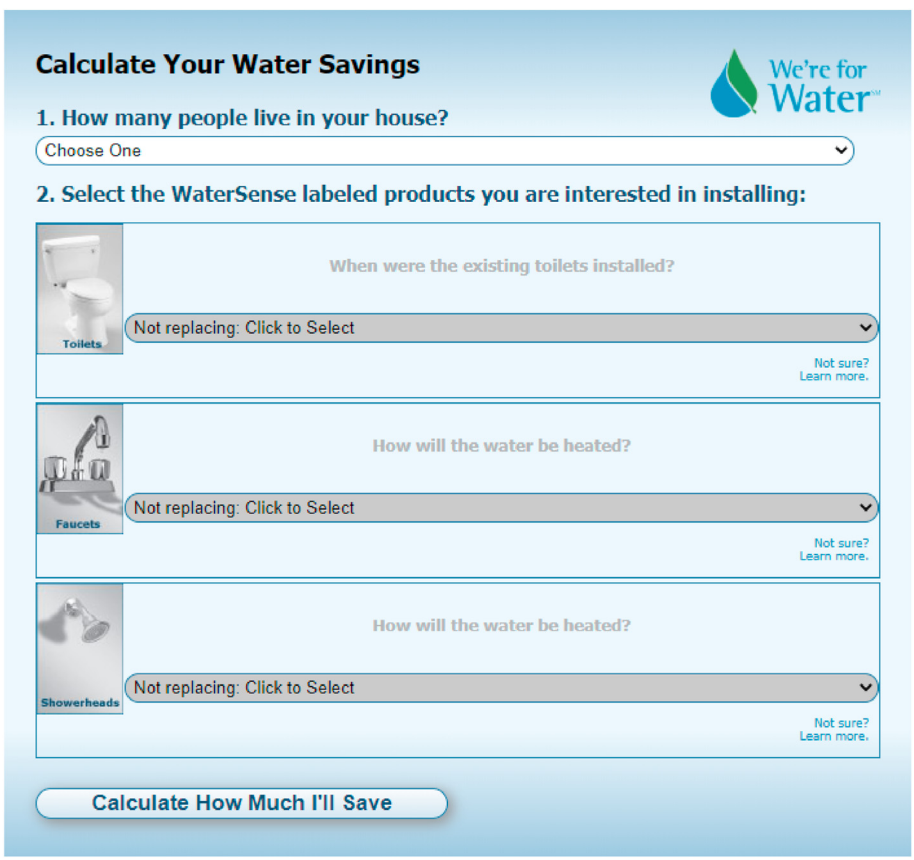


Fig. 10. Screenshot of the WaterSense Calculator input interface (US EPA, 2020).

which has the potential to be converted to more than 17 TWh/y of electricity. Food waste is another major waste with a high potential to be the first reduced and reused once generated. Ma and Liu (2019) presented a systematic review of the technologies of transforming food waste to energy and other resources. It is highlighted that biological approaches have remarkable potential in food waste-to-energy/resources, and the environmental and economic feasibility of these processes should be addressed.

Targeting this issue, Carneiro and Gomes (2019) comprehensively reviewed the feasibility evaluation methodologies and proposed a 4E (energy, exergy, environmental and economic) analysis method to evaluate the feasibility of hybrid waste-to-energy plants. The 4E method is applied to a Waste-to-Energy/Gas Turbine (WTE-GT) plant, and the results revealed that WTE-GT has a considerable lower specific investment cost compared with single fuelled WTE facilities in Europe. Efforts are also made to investigate the additional benefits of Waste-to-Energy (WTE) processes. For example, Durán et al. (2020) developed a mathematical model and studied the CO_2 capture from a WTE plant. The model is validated using experimental data. The authors reported 95% CO_2 recovery with a purity of 40% using a pine sawdust adsorbent.

With the increase of the human population as well as the shifting of lifestyle, the amount of waste has been ever-increasing. Waste management is critical for both ordinary time but especially for a pandemic period such as the COVID-19. Klemeš et al. (2020d) presented the initial assessment and discussion of waste, especially plastic waste management and its environmental footprints related to the COVID-19. The study showed that the pandemic has led to major challenges in the handling of Municipal Solid Waste (MSW) and hazardous medical waste, for example in China, the amount of MSW decreased by 30% due to the disease outbreak, but the medical waste increased 370% only in Hubei Province. The accumulated medical waste in all of China from 20 January to 31 March 2020 is estimated as 207 kt, and the total incineration cost is estimated as 7.29 MUSD (Klemeš et al., 2020d).

2.4. Green technology

"Green Technology" is a relatively recent term, gaining popularity. It refers to any technology that provides products and services with significantly reduced footprints (Green Technology Magazine, 2020). The term is sometimes also shortened to "Green Tech" (Kenton, 2020).

Considering the variability of renewable energy availability from nature (Varbanov and Klemeš, 2011), as well as the need for electricity storage in mobility applications (Winslow et al., 2018), the importance of energy storage has been rising in the last decades. The electricity storage in batteries has been making significant progress – as can be seen from Tesla's Megapack (O'Kane, 2019) and from the recent developments on the so-called "million miles" batteries (SCMP, 2020). The latter are battery packs with a long battery life of an increased number of recharge cycles and longer durability. These developments are expected to bring two-fold benefits. On the one hand, the environmental footprints (GHG, Water, Nitrogen) of battery manufacturing are spread over a longer service period, resulting in much lower overall Life-Cycle footprints. On the other hand, the increased durability comes with an increase in the reliability and increased trust of the users, which helps in the wider technology adoption – as can be seen from the recent announcements of utility-scale battery adoptions (Utility Dive, 2020b) as well as from the clearly exponential upward trend of electric car ownership worldwide (Fig. 11) as plotted based on the data from (IEA, 2020).

Another pillar of lowering emissions is effective demand-side management. A policy shift in this direction has been taking place in the recent years – including the "Nearly zero-energy buildings" policy of the European Union (EC, 2014) and the policy initiatives in the United States – on the example of California (Utility Dive, 2020c).

On the energy supply side, it is also possible to use the variable speed of the wind turbines and the kinetic energy stored in the rotors, in order to provide a more agile load-tracking behaviour of the turbines and to minimise the disruptions of the power grid. This idea has been recently investigated (Zhao et al., 2020) and has been widely discussed in the UK media (University of Birmingham, 2020).

Energy storage is another major factor used on the path to achieving sustainable energy systems and the sustainable economy overall. Typical efficiencies achieved by the various technologies have been summarised by Liu et al. (2020), citing values of up to 75% for storing energy as sensible heat, latent heat or in thermochemical storages, while Compressed-Air Energy Storage reaches up to 65% (Mei et al., 2015) or 70% (Wang et al., 2017).

Another interesting possible development is to enable the wider application in industry of electrical power also for heating and cooling, in addition to driving devices and lighting, or even to chemical power reactions via electrochemistry (Barton, 2020). The significance of this approach is in the potential for coupling power from renewable sources with the chemical processes at very high efficiency. This match has the potential to drastically reduce GHG and other footprints associated with the chemical processes and even to accommodate the intermittent nature of the renewable sources.

3. The papers in the Virtual Special Issue (VSI) from PRES′19

The current VSI includes 31 high-quality articles, developed on the basis of the works presented at the 22nd Conference on Process Integration. Modelling, and Optimisation for Energy Saving and Pollution Reduction – PRES′19. The selection of articles, discussed here, features a wide spectrum of topics and is representative of the interdisciplinarity achieved by the joint platform between the series of conferences PRES and the Journal of Cleaner Production. The wide host of topics, related to the presented overview has been organised within the following groups:

- **Emissions Mitigation and Environmental Impact Analysis.** Tools and impact analysis methods conducted to mitigate GHG emissions, as well as to reduce emissions via carbon capture, utilisation and storage, emissions analysis of power plants, development of national heating plant for Chile, Life Cycle Assessment on a cheese plant, and an economic vs environment impact study for Economic Community of West African States.
- **Process Improvement.** This topic groups articles related to process improvement, including modelling and optimisation on methanol production from shale gas and solvent discovery in a distillation column, a new predictive tool for a distillation column, a new graphical tool to calculate exergy losses including sub-ambient process, and laboratory research to study the impact of Zirconium location on bio-based chemical production.
- **Energy Conversion and Storage.** This part presents research works related to the analysis on energy storage and energy conversion, including an optimisation work to determine the retirement point of electric vehicle batteries, performance analysis for shell and tube latent heat thermal energy storage, a sorbent-based closed thermochemical energy storage reactor, and a Phase-Change-Material-based heat exchanger.
- **Bioresource to Energy Conversion.** Under this group are discussed the works related to the utilisation of bioresources for energy, including a new procedure to design the biomass network, an economic feasibility study of biomethane injection to grid with the proposed feed-in-tariff, and review work on biogas valorisation and utilisation systems.
- **Water Management** is another topic group of high importance. The presented works include an iterative design approach for multi-regeneration units water network, water consumption impact analysis of adapting dry cooling in the steel industry, GHG emissions impact analysis due to dissolved oxygen control

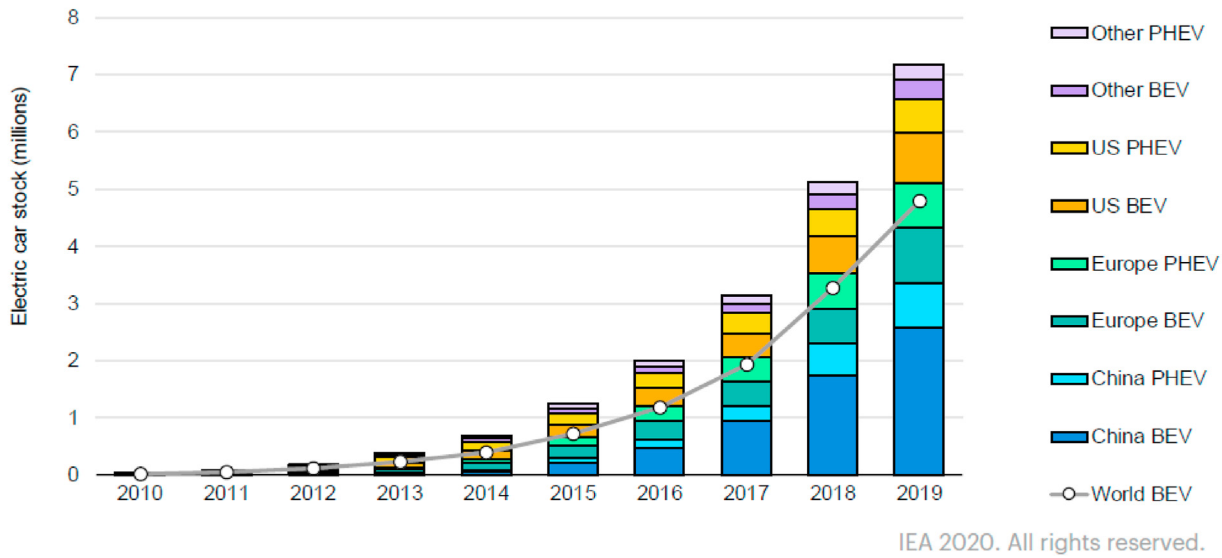


Fig. 11. Electric car ownership trend reproduced from (IEA, 2020). Notes: PHEV: Plug-in Hybrid Electric Vehicle; BEV: Battery Electric Vehicle. The Other covers: Australia, Brazil, Canada, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand. Europe includes: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

in a waste treatment plant, and enzyme-based wastewater treatment technology for hospital and healthcare facilities.

- **Waste Management** is another key issue and is discussed in several works, including a novel approach to forecast the waste generation and a mathematical modelling optimisation work to decide the waste management strategy in the Czech Republic, a review work to evaluate the potential of municipal solid waste as a feedstock for a waste-to-energy project in India, laboratory research to evaluate the potential of electrokinetic remediation to decontaminate the soil polluted with petrochemicals, and technical feasibility analysis of recovering the heavy metal from solid waste produced by treating tanning sludge with plasma pyro-gasification.
- **Business Process Management.** This group comprises works related to organisation management, including the proposal of an adaptive model to implement a lean and green strategy in companies, to solve dynamic Industry 4.0 problems, application of the existing framework to study the interrelationship among various circular economy driver factors, and discussion related to sustainable business model innovation.

3.1. *Emissions mitigation and environmental impact analysis*

A research team from De La Salle University of Philippines, led by Raymond Tan, discussed “A Hyperbox Classifier Model for Identifying Secure Carbon Dioxide Reservoirs”. This work applied a hyperbox framework as an alternative machine learning approach to classify CO_2 storage site. In previous research, Xu and Papageorgiou (2009) solved classification problems using the hyperbox concept, where the samples are enclosed in the same category or classification by hyperboxes, and a series of hyperboxes are added in iterations to improve the quality of classification. In the current research work, the researchers developed the Mixed Integer Linear Programming model based on previous hyberboxes concept to generate a set of IF-THEN rules based on fuzzy logic (Green, 2018). There are two key contributions to Tan’s research teamwork. These include the ability to account for Type 1 (false positive) and Type II (false negative) errors in classification, and the ability to attribute reduction. In the demonstrated case study, the set of rules was generated using three hyperboxes to correctly identify all three insecure CO_2 storage sites. However, an alternative set of rules which only use one hyperbox has falsely predicted two out of three insecure sites as positive sites.

Linlin Liu led a research team from the Dalian University of Technology to investigate the “Multi-objective optimisation for the deployment of carbon capture utilisation and storage supply chain considering economic and environmental performance”. The problem was formulated into a multi-objective Mixed-Integer Linear Programming (MILP) model and solved it using the ε-constraint method. The objective function of the model was to minimise the total annualised cost comprising items for of capture, transport, injection of the CO_2, as well as revenue from CO_2-based enhanced oil recovery while minimising the global warming potential over the process life cycle. By applying the model on a case study of Northeast China, the most cost-effective solution was determined at $ 24.89/t CO_2 with GHG emissions of 36.65 Mt CO_2-eq, while the most-environmentally friendly solution was determined at $ 67.84/t CO_2 with GHG emissions of 19.35 Mt CO_2-eq. Future work could be carried out to evaluate CO_2 chemical utilisation pathways to increase the economic viability of CCUS technology.

Joe Mammen John and Daniel Ikhu Omoregbe from the Cape Peninsula University of Technology of South Africa and Sharifah Rafidah Wan Alwi from Universiti Teknologi Malaysia presented “Techno-Economic Analysis of Carbon Dioxide Capture and Utilisation Analysis for an Industrial Site with Fuel Cell Integration”. The authors proposed a framework featuring the following key steps: 1) Identification of the most cost-effective post-combustion system, 2) Evaluation of the cost of carbon capture, 3) Evaluation of the optimal CO_2 chemical fixing plants, and 4) Cost analysis of the proposed system. Based on the Carbon Capture and Utilisation (CCU) case study in South Africa, among the CO_2 chemical fixing plants of baking soda production, methanol production, the calcium carbonate production plants and the Direct Methanol Fuel Cell (DMFC), only the baking soda production plant is able to generate a profit of 2 M$/y, while the other plants are operating with a financial loss. From the environment perspective, the CCU system is able to achieve an annual CO_2 abatement of 38,000 t/y. The economic performance of the proposed CCU case study could be more viable if the products could be sold at a premium price due to the positive image of CCU or lower operating cost due to recently implemented carbon tax mechanism in South Africa.

Emissions from combustion in the electricity generation and industrial sectors are among the primary sources of SO_2 atmospheric pollution (Bhander and Jozewicz, 2017). In the context of South Africa, Sangeetha and Sivakumar (2019) conducted a long-term temporal and spatial analysis of SO_2 over the Gauteng and Mpumalanga monitoring sites. There is no study that directly investigates the effects of sulphur content in coal samples on the SO_2 emissions in South Africa. Seshibe Stanford Makgato and Evans Chirwa, from the University of Pretoria, presented their work on “Recent Developments in Reduction of Sulphur Emissions from Selected Waterberg Coal Samples used in South African Power Plants”. They conducted sample testing based on coal samples and evaluated the effects of sulphur content on SO_2 emissions of power plants in South Africa. The results revealed that a sulphur content of 1.45 wt% lead to emissions of 3716 mg/Nm^3, while a lower sulphur content of 0.50 wt% reduces the emissions to 1280 mg/Nm^3. With bio-desulphurisation treatment, 72.4% of sulphur reduction efficiency could be achieved.

In the context of Chile, Jakob Thellufsen led a research team from Aalborg University for the investigation on “Heat Roadmap Chile: A national district heating plan for air pollution decontamination and decarbonisation”. They developed a national heat roadmap with a horizon by 2050 for Chile, using the EnergyPLAN software tool to investigate the impact of incorporating district heating into the energy system. The study revealed that by shifting 40% of future heat demand by 2050 to district heating, the Particulate Matter (PM) and CO_2 emissions could be reduced by 40% and 34%. More importantly, the district heating would be able to be implemented without a significant increase in the total energy system cost.

Researchers from the University of Waikato in New Zealand and Maastricht University in Germany, led by Amir Tarighaleslami, conducted research entitled “Environmental Life Cycle Assessment of a Cheese Production Plant towards Sustainable Energy Transition: Natural Gas to Biomass vs Natural Gas to Geothermal”. They performed an exergy-aided Life Cycle Assessment (LCA) and Monte Carlo Simulation to evaluate the environmental burden of power generation from biomass and geothermal sources, for a cheese processing plant. It was found that a scenario with 33% of alternative renewable energy led to the most significant reduction of the environmental impact, compared to a base case scenario with 100% natural gas supply.

Hesam Kamyab from University Teknologi Malaysia worked with co-researchers from Umaru Musa Yar’adua University in Nigeria and Ton Duc Thang University in Vietnam to propose a work entitled “Re-examining the Environmental Kuznets Curve hypothesis in the Economic Community of West African States: A panel quantile regression approach”. They used a pane quantile approach to examine the Environmental Kuznets Curve (EKC) hypothesis in the Economic Community of West African States (ECWAS). EKC hypothesis was first proposed by Grossman and Krueger (1991), which models the environmental degradation versus per capita income as an inverted U-shaped pattern. Unlike many previous works focusing on financial capital only, the current work incorporated human and natural capital as well to examine the EKC hypothesis. Also, this study utilised a panel quantile regression technique that could provide more reliable estimates compared to a mean estimation approach, such as the ordinary least squares method. The results show that the EKC is not applicable for ECWAS countries, where the economic growth and GHG emissions present a U-shaped pattern at all quantiles. This show that economic growth will contribute to the increase in GHG emissions unless there is a change in the composition of economic activities.

3.2. Process improvement

Jian Du from the Dalian University of Technology led the other team members and presented a work on “Process evaluation and optimisation of methanol production from shale gas based on kinetics modelling”. They developed kinetics-based reaction models of methane reforming and methanol synthesis to simulate methanol production from shale gas. Key parameters such as temperature and pressure are then optimised by considering the trade-off between economics and CO_2 emissions. Based on the research, a partial oxidation reactor operated at 1000 °C and 30 bar, and a synthesis reactor operated at 50 bar are determined as the optimum selections to satisfy both objective functions related to the economics and the CO_2 emissions.

Bence Nemeth, Peter Lang, and László Hégely from the Budapest University of Technology and Economics (Hungary) presented their research on “Optimisation of Solvent Recovery in Two Batch Distillation Columns of Different Size”. They proposed a rigorous modelling and optimisation method to optimise a batch distillation column system with two columns, minimising the specific energy demand of the system. The authors used the ChemCAD professional flow-sheet simulator coupled with a GA to perform the optimisation. Subsequently, the authors used an RSM based on the optimisation results to predict the optimal operational parameters of the two-column batch distillation process for various feed compositions. Compared to a single column, the two-column system is capable of achieving 30% higher processing capacity, and 12% higher profit, with a reduction of CO_2 emissions by 20%.

Sungwon Hwang from Inha University (Republic of Korea), Robin Smith from the University of Manchester and Yeonju Shin, bridging both institutions, presented their research entitled “Development of Model Predictive Control System using An Artificial Neural Network: A Case Study with A Distillation Column”. The authors proposed a new method based on the integration of an Artificial Neural Network (ANN) model with Model-Predictive Control (MPC) to improve the accuracy of predicting the behaviour of non-linear systems. The proposed method was applied to a depropaniser in an offshore plant and returned with an accurate result with a total mean square error of 1.19×10^{-8}. The performance of such controller system was validated against conventional Proportional-Integral (PI) controller, and able to achieve a settling time of 35 min, which is significantly better than the PI controller system with 92 min.

Nassim Tahouni led the other research team members from the University of Tehran to present on the “Development of a New Graphical Tool for Calculation of Exergy Losses to Design and Optimisation of Sub-Ambient Processes”. Based on the earlier developed concept of energy level Ω (Feng and Zhu, 1997), the authors proposed the Omega Composite Curve and the Omega Grand Composite Curve. All thermal exergy losses can be easily calculated from these curves, as the curves are linear, resulting in enclosures of rectangular shape between the curves. By applying the proposed procedures on an industrial ammonia plant case study, the exergy loss could be potentially reduced by 15.31% compared with the base case.

Tuangrat Leungcharoenwattana and Sirirat Jitkarnka from Chulalongkorn University in Thailand conducted a research work on “Bio-Based Chemical Production from Glycerol Conversion with Ethanol Co-Feeding Over Zr-Promoted Mgal-Layered Double Oxide Catalysts: Impact of Zirconium Location”. They studied the impact of zirconium location of Zr-containing layered double oxide catalyst on the production of 1,2-propanediol by using glycerol hydrogenolysis for different feed compositions. It was found that $Zr_{0.38}Mg_{4.43}AlO$ catalyst with Zr located in the layered structure can produce more 1,2-propanediol, compared with the case where $ZrO_2/Mg_{4.41}AlO$ catalyst with ZrO_2 clusters is located on the LDO support, while in both cases pure glycerol feed was supplied. In another case of 20% ethanol and 80% glycerol feed, $ZrO_2/Mg_{4.41}AlO$ catalyst was found to exhibit a greater production yield than $Zr_{0.38}Mg_{4.43}AlO$ catalyst. The authors also suggested that a modification of metallic catalysts, which enables higher yield in specific production pathways with high in-situ H_2 formation, should be further investigated to improve the production yield.

3.3. Energy conversion and storage

Yongzhong Liu and his team from the Xi'an Jiaotong University conducted a research work entitled "Determination of Retirement Points by Using a Multi-objective Optimisation to Compromise the First and Second Life of Electric Vehicle Batteries". They developed a multi-objective optimisation model to determine the optimum retirement point of the Electric Vehicle (EV) batteries by exploring two scenarios: minimisation of the cost of the EV batteries and minimisation of the cost of their second life application in an energy storage system. There are three key components in their model – including the operation of batteries in an EV, the operation of retired EV batteries in the energy storage facility of a power generation system, and the degradation characteristic of both stages of EV battery lives. The proposed model was applied to a case study for a city bus in Zhengzhou China. The authors found that the optimum retirement point of EV batteries is in the state of health range between 71.5 % and 86.4%.

A collaboration group of researchers from the Xi'an Jiaotong University and the University of Toronto, led by Min Zeng, analysed the "Charging Time and Energy Storage Rate Analysis of Fin Effect Inside the Horizontal Tube for Thermal Energy Storage". They evaluated the enhancement effects of fin configuration inside the tube of thermal energy storage by applying enthalpy-based Lattice Boltzmann Method (LBM), combined with an extrapolation method. LBM was proposed by Jiaung et al. (2001) to solve a phase change energy storage problem. Guo et al. (2002) then incorporated the extrapolation method to solve the curved boundary treatment problem. The LBM, coupled with an extrapolation method, has since been used to model and evaluate various configurations of thermal energy storage. Zeng and his co-researchers reported a 40% improvement of energy storage efficiency could be achieved by implementing proper fin configuration for shell and tube latent heat thermal energy storage.

Another collaboration – between researchers from the Xi'an Jiaotong University and the Brno University of Technology, resulted in a work on "Performance analysis of consolidated sorbent based closed thermochemical energy storage reactor for environmental sustainability". The authors developed a 3D adsorption thermochemical energy storage to simulate the pressure effect in dehydration and hydration kinetics. Based on the reference case, the overall thermal coefficient of performance and the exergy coefficient of performance achieved were 80.9% and 27.7%. This study proved that such energy storage setup is technically feasible.

Tianrui Deng and the co-authors from the Xi'an Jiaotong University led by Wang presented their research on "Controlling Effect of Phase Change Material Based Heat Exchanger on Supercritical CO_2 Brayton Cycle". They developed a novel type of heat exchanger, based on a Phase Change Material (PCM). They designed a Printed-Circuit Heat Exchanger (PCHE) for the application of a SCO_2 recompression Brayton cycle. The authors developed a dynamic model for the proposed heat exchangers using the MATLAB/Simulink environment, based on their previous work (Deng et al., 2019), to evaluate the controlling effects. The simulation shows that the proposed PCM-PCHE type of heat exchangers can effectively reduce the disturbance amplitude of the working temperature in the main compressor and re-compressor by 77% and 62%. Also, it can reduce the disturbance range of cycle efficiency by 94%.

3.4. Bioresource to energy conversion

A collaboration team from Malaysian universities – University of Nottingham Malaysia Campus, Curtin University Malaysia, Swinburne University of Technology Sarawak, Universiti Kebangsaan Malaysia and Universiti Tunku Abdul Rahman, united by Hon Loong Lam presented their development "An Integrated Approach to Prioritise Parameters for Multi-Objective Optimisation: A Case Study of Biomass Network". They proposed a two-stage integrated approach combining Principal Component Analysis (PCA) and Analytical Network Process (ANP) to obtain the optimal values of the decision variables by considering both quantitative and qualitative input data. The authors first implemented the PCA and then applied the ANP to determine the priority weightage of the sustainability components. At the second stage, the authors then obtained the optimal solution by reducing the range of feasible solutions and optimising the model using a min-max approach. The model used three evaluation criteria – economic (cost), environmental (a composite index of emitted pollutants) and social (job creation). The authors found that the search ranges of economic, environmental and social optimal parameters have been reduced by 57%, 25% and 91%. The obtained balanced solution satisfies the requirements on all three criteria, considering both quantitative and qualitative aspects of the input data.

Haslenda Hashim and her co-researchers from University Teknologi Malaysia and the National University of Singapore the evaluation work on "Towards circular economy: Economic feasibility of waste to biomethane injection through proposed feed-in tariff". The authors estimated the minimum Feed-in Tariff (FiT) for a biomethane project in Malaysia, estimating the Levelised Cost of Electricity by setting the net present value to zero. The estimate is obtained based on biomethane production amount, total operational and maintenance cost, and capital cost for the biogas plant. Comparing against the grid-pipe natural gas price of 28.85 MYR/GJ, the proposed FiT (34.02–141.79 MYR/GJ) is economically infeasible to be considered without additional financial incentives from the government. It is recommended that carbon mitigated through biomethane to be accounted for as a factor, to enable dedicated premium pricing on biomethane. Alternatively, the mitigated carbon could be traded on the carbon market to generate an additional revenue stream.

Ashok Kumar from Jaypee University of Information Technology (India) collaborated with researchers from the Indian Institute of Technology, Jawaharlal Nehru University (India), Universiti Teknologi Malaysia, Duy Tan University (Vietnam), Kyonggi University (Republic of Korea), to work on "Advances in biogas valorisation and utilisation systems: A comprehensive review". They reviewed the biogas cleaning and upgrading methods and identified the opportunities and barriers for utilisation of biogas and its conversion products. The valuable by-products include biomethane, bio-CO_2 and syngas, which can be further upgraded for different applications. For example, biomethane can be used to power vehicles, to be injected in the gas grid, or to generate power. Bio-CO_2 can be converted into biofuel and biomaterials such as biodiesel – using algae, $CaCO_3$, biosurfactants and biopolymers. The syngas can be used for generating H_2-rich streams. The authors highlighted that further development of policies, standards and regulations are required to promote the implementation of biogas as a transportation fuel. More research could be carried out to investigate the catalytic route of converting biogas into syngas and carbon nanofibres. The latter could be applied in transistors, solar cells, supercapacitors and sensors (de Llobet et al., 2012). Despite the potential of utilising biogas as bioenergy and biomaterial, technology readiness and economic feasibility still need to be evaluated, apart from examining the impact on sustainability.

3.5. Water management

Zhi-Yong Liu presented the collaborative work of researchers from the Hebei University of Technology and the Brno University of Technology in the Czech Republic resulting in “An iterative design approach for water networks with multiple regeneration units”. The key step in the proposed method is to determine the quasi allocation ratio value of each source and demand stream and prioritise the source-demand mapping based on highest quasi allocation ration value. The proposed method able to generate a design with less interconnection or regenerated stream flowrate in comparison with the existing method. The comparison with existing Mathematical Programming methods shows that the proposed method obtains the same and better results, at much lower computation complexity.

Lubomír Klimeš led a research team from the Sustainable Process Integration Laboratory and the Energy Institute of the Brno University of Technology to investigate the “Dry cooling as a way toward minimisation of water consumption in the steel industry: A case study for continuous steel casting”. The authors identified the water reduction potential in continuous steel casting by implementing Water Spray and Dry Cooling (WSDC). The heat transfer loss was simulated using 3D heat transfer and a solidification model. WSDC consumed 189% higher total water usage than Water Spray Cooling (WSC) but, in this case, the water source is mainly from reusable water in the closed water cooling loop. The benefit of implementing WSDC is clearly demonstrated as it required 48% lower freshwater consumption in comparison with WSC.

Wenhao Shen led a team of researchers from South China University of Technology and Aristotle University of Thessaloniki investigating the “Impacts of dissolved oxygen control on different GHG emission sources in wastewater treatment process” They developed on-site GHG emission models for sub-processes in a Waste Water Treatment Plant. The modelled unit processes include endogenous decay, biochemical oxygen demand removal, nitrification, and denitrification. They estimated the off-site GHG emissions due to energy consumption and sludge disposal. Based on the simulation results, the overall GHG emissions of 844 kg CO_2-eq/h are emitted, of which 25.83% are from the on-site process, and the remaining is due to off-site GHG emissions. The authors also found that by applying a proportional-integral strategy to control the concentration of dissolved oxygen, it will reduce the GHG emissions by 2%.

Maja Leitgeb presented the collaborative work of researchers from the University of Maribor and the University Medical Centre Maribor (Slovenia) entitled “Immobilized laccase in the form of (magnetic) cross-linked enzyme aggregates for sustainable diclofenac (bio)degradation”. The authors proposed to use Cross-Linked Enzyme Aggregates (CLEAs) and magnetic Cross-Linked Enzyme Aggregates (mCLEAs) of laccase immobilisation to remove diclofenac (DFC) presented in wastewater from hospitals and healthcare facilities. Based on the results, both CLEAs and mCLEAs offer DFC removal capacity of 15.6 ± 0.4 μg DCF/$g_{laccase}$ and 13.6 ± 0.4 μg DFC/$g_{laccase}$, which is much better than native laccase with 11.5 ± 0.3 μg DCF/$g_{laccase}$. However, the effectiveness of the proposed mechanism in a continuous reactor should be further investigated in future work.

3.6. Waste management

Veronika Smejkalová, representing a joint research effort by Brno University of Technology and Charles University in Prague, published an assessment study on “Trend forecasting for a waste generation with a structural break”. The authors proposed a novel approach to using data with a structural break for forecasting the generation of waste by human activities. Based on a case study from the Czech Republic, the forecast model showed that the separation potential in some regions could reach 100% by 2030. They estimated that the average biowaste production in micro-regions could be increased to 156 kg/cap/y in 2030, i.e., a 133% increment in comparison with 2017. Future work should focus on determining the confidence intervals for waste generation per person for each territory, to reduce the uncertainty on population prognosis and waste production. Such regional studies are important, for obtaining parameter estimates useful in estimating the regional potential for reducing GHG footprints from energy supply by utilising renewables (Zirngast et al., 2019) and proper waste management (Fan et al., 2020b).

Radovan Šomplák and his collaborators from the Brno University of Technology investigated the “Strategic Decisions Leading to Sustainable Waste Management: Separation, Sorting and Recycling Possibilities”. The authors developed a Mathematical Programming model with multiple objectives to identify the optimal location of waste treatment and related facilities. Based on data about waste production of the Czech Republic in 2017, the model suggested 42 sorting lines for paper, of which 14 facilities can sort both paper and plastic. The model also suggested 20 Waste-to-Energy facilities. The authors suggested including other waste components in the evaluations — such as metal and biowaste in future research.

Quang-Vu Bach from the Ton Duc Thang University, Vietnam, collaborated with researchers from various agencies and universities from India, Republic of Korea, and Malaysia to compose “A Review on Municipal Solid Waste as a Renewable Source for Waste-to-Energy Project In India: Current Practices, Challenges, And Future Opportunities”. The authors reviewed various Waste-to-Energy (WTE) technologies such as RDF, incineration, anaerobic digestion, gasification and pyrolysis in the context of India. They highlighted the challenges of WTE in India — including lack of an integrated approach to Solid Waste Management (SWM) and energy recovery from waste, enhancing public awareness about the separation process, funding problems, and implementation of related rules and regulations. To improve the prospect of WTE in India, the authors made suggestions — such as proper planning and analysis for technology implementation, public awareness and education, the inclusion of SWM as a subject in the curriculum of the academic and technical institutions.

Brian Gidudu and Evans Chirwa from the University of Pretoria (South Africa) investigated soil cleaning and presented the article entitled “The combined application of a high voltage, low electrode spacing, and biosurfactants enhances the bio-electrokinetic remediation of petroleum contaminated soil”.They conducted an experiment to evaluate the potential of electrokinetic remediation. The authors identified the correlation between voltage, electrode distance, and application of biosurfactants on the decontamination efficacy. The results show that the combination of high voltage, short distance between the electrodes, and the application of biosurfactants can effectively improve the efficiency of decontamination up to nearly 80%. Further research needs to be performed evaluating the potential of *in-situ* biosurfactant production by the locally available microbes to apply the method on an actual site.

Marco Vocciante and Andrea Reverberi from Università Degli Studi di Genova, Italy, collaborated with researchers from ENEA Research Center and Ecas4 Australia Pty Ltd on a method for

"Removal and Recovery of Heavy Metals from Tannery Sludge Subjected to Plasma Pyro-Gasification Process". They proposed a treatment process for recovering heavy metals from solid waste produced by treating tanning sludge with plasma pyro-gasification. The proposed treatment starts with simple washing with water and leaching phase with 6 M HCl to fully recover Cd and Pb, 96.3% of Zn and 22.6% of Fe content. The solution from the leaching process is further treated by using fractional precipitation to remove Fe, Pb and Zn, before sending the stream to a final adsorption unit for the removal of Cd. It was also found that the solid residue from the earlier leaching process can be utilised as the material of ceramic production or sent to landfill due to its inert characteristic.

3.7. Business process management

A collaboration between University of Nottingham Malaysia Campus, Brno University of Technology (Czech Republic), Swinburne University of Technology Sarawak Campus (Malaysia), Universiti Kebangsaan Malaysia, Universiti Teknologi Malaysia, and University Malaysia Pahang, led by Hon Loong Lam resulted in the article "Enhancing the Adaptability: Lean and Green Strategy towards the Industry Revolution 4.0". They proposed an enhanced adaptive model to implement the lean and green strategy in the processing sector to solve dynamic Industry 4.0 problems. The developed model enables the decision-maker to target the specific performance indicators and propose the optimum process pathways based on targeted Lean and Green Index (LGI) – a composite indicator, summing up improvement contributions. Based on the case study on combined heat and power plants, the implementation of the proposed model improved LGI index by 18.25%.

Aristotle Ubando with researchers from De La Salle University, Philippines, and Far Eastern University Institute of Technology presented the study on "Sector Perception of Circular Economy Driver interrelationships". The researchers applied the Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) framework to consider the causality strength and to evaluate the intensity of the interrelationships among the circular economy drivers including government support, company culture, consumer demand, social recognition and economic attractiveness. Based on the case study of industry and service sectors in the Philippines, it was found that economic attractiveness is the key influencing driver with the highest net cause/effect strength of 1.15. On the other hand, company culture has the lowest net cause/effect strength of −1.23, implying it is the weakest influencing factor.

Feybi Ariani Goni, Abdoulmohammad Gholamzadeh Chofreh and Jiří Jaromír Klemeš from the Brno University of Technology, Czech Republic, collaborated with researchers from Universiti Teknologi Malaysia, COMSATS University Islamabad, Pakistan, and the University of South Florida, the United States, and presented a discussion on the "Anatomy of sustainable business model innovation". The authors identified the analogies among the Business Model, Business Model Innovation, Sustainable Business Model, and Sustainable Business Model Innovation (SBMI). The provided analysis identified research gaps such as dedicated metrics from SBMI, the interdependent nature of SBMI components based on sustainable value innovation and feedback loop between internal and external environment (e.g., stakeholders). The authors concluded that those aspects have to be addressed to bridge the gaps between theories and implementation.

4. Discussion and the way forward

The current epidemiological situation with the COVID-19 disruption has shown a sharp change in the types (Fan et al., 2020a) and the volume (You et al., 2020) of waste being generated. This also triggers a potentially lasting behavioural change of the consumers, giving higher priority to the health safety and paying lower attention to the issues of appropriate waste reduction, separation, reuse, recycling. This situation calls for designing and implementing new protocols for handling materials and products in the supply chains, as well as embedding robustness mechanisms in these supply chains.

One such robustness measure is to change the philosophy of the product supply from the "chain" to the "network" paradigm – emphasising the need for ensuring more than one supply route and additional degrees of freedom, such as cross-links and storages for materials and energy, playing the roles of strategic and tactical buffers.

Another important direction is to shorten some parts of the supply chains for energy and products. This is important for two reasons:

(i) Increasing the security of supply
(ii) Reducing the related "overhead" footprints related to the transportation, transmission and conversion stages of the longer supply chains

One option to do this in the domain of energy supply is the local power generation, as illustrated in (Rostampour et al., 2019), where the importance of energy storage for enabling the footprint reductions has been shown.

The issues caused by the pandemic, while acute and with potentially lasting consequences, do not eliminate the global issues linked with the severe disturbances in the global material cycles and the pervasive material pollution – GHG emissions, nitrogen pollution, water scarcity and pollution, solid waste pollution. The reviewed previous work and the research presented in the current VSI address a host of issues and promise to achieve reasonable emission and pollution reductions.

Significant research has been published on Process Integration – Heat Integration, including Total Site (Liew et al., 2017). Recent examples include industrial heat recovery in HENs (Zhang et al., 2020), District Heating and Cooling (Santin et al., 2020), thermal energy storage, batteries – including in the current VSI, the combination of renewables use and CCS (Poblete et al., 2020). The current VSI has contributed a comprehensive set of research articles, aimed at emission mitigation and analysis of the environmental impact, process improvement, energy conversion and storage, the use of bioresources for energy supply, water and waste management, Business Process Management.

However, the majority of the published sources discuss how to deal with pollution and waste once generated. Insufficient attention has been paid to the efficiency of the main production and delivery processes or to the demand-side management. This is corroborated by the published analyses on food waste in the worldwide, as demonstrated in (Wagner, 2018) – see Fig. 12, as well as by the statistical flowchart of the United States economy-wide energy balance published annually by the Lawrence Livermore National Laboratory (2020). The food waste statistic demonstrates actual food waste (according to official national data) in the range between 10% and 25%, while the energy flowchart reveals an even more serious problem – more than 2/3 of the overall sourced energy in the United States economy is wasted at various supply chain stages, and only about 1/3 is spent on useful services. The latter United States-based statistic is also corroborated by a world-wide study (Forman et al., 2016), demonstrating very close proportions. This analysis calls for increased attention to the energy and resource efficiency of the production and resource conversion processes, to obtain resource-efficient core process systems, which in turn will pose a much easier task to the systems for resource

Fig. 12. Food waste summary from (Wagner, 2018), published by Statista Inc and reproduced under the terms of the Creative Commons License CC BY-ND 3.0 (Creative Commons, 2020b). Notes: Estimation by 18,000 heads of households in 20 countries (aged 22–60 years), 2017/2018. Qualitative research in 20 family and 10 single households; 2017/2018. (Source: Movinga).

supply/recovery, waste management and end-of-pipe treatment.

In addition, the base review of the main issues in the Introduction section revealed a deficit of studies that would relate quantitatively the rate of waste recycling to the reduction of footprints, energy expenditure and the economic performance. This is another important direction of potential future work that, combined with the research on minimising waste generation, should contribute significantly to the reduction of all main environmental footprints.

To summarise, a lot of research results have been presented on the increase in the share of renewable sources in the supply of energy, food and materials. This is a profound challenge, which combined with the current epidemiological situation caused by COVID-19, poses unique tasks to simultaneously optimise the production processes, the integrity of the supply chains and the continued preservation or even improvement of the research and development capacity for solving the discussed global issues. These challenges are being considered in the formulation of the research priorities of the coming PRES'21 conference.

5. Conclusions

This special issue discussed recent advancement on tools and research related to Process Integration and Optimisation, environmental impact assessment and reduction, waste management and recycling, as well as green technology. The published work in articles of this VSI, offering follow-up investigations based on the papers presented at PRES'19 (Conferences PRES, 2019), has been discussed. The potential contributions to the advancement of cleaner production in 7 key areas have been analysed, including emission mitigation and environmental impact analysis, process improvement, energy conversion and storage, bioresource-to-energy conversion, waste management, waste management, and business process management.

The research published in the current VSI and the wider state of the art have been analysed, indicating significant progress. The examples include 72.4% sulphur reduction efficiency of power plant flue gases, the potential reduction of 40% and 34% of PM and CO_2 emissions in Chile, reduction of CO_2 emissions by 20% in methanol production, significant benefits from extending the life of batteries from transportation to stationary use after retirement from mobile applications, 40% round-trip efficiency of thermal energy storage, reduction of freshwater consumption by 48% in the steel industry, the potential to achieve complete municipal waste separation.

The discussion-analysis following the review has identified key patterns of state of the art and the currently developing COVID-19 situation. One such pattern is the changing consumer behaviour related to the pandemic and the need to change the design and operating philosophy of the systems for resource and product supply, where the main measures are expected to increase the health safety and the robustness of the systems. The other potential for future development is to encourage the research and development of solutions focusing on the resource efficiency of the main production and conversion processes, aiming to reduce the load on the supply, cleaning and disposal systems for goods and services supply. Another key problem is to develop a system of measures for a sharp reduction of the waste of materials, energy and products (food waste being the chief concern). Such measures should be considered to target not only consumer behaviour but also the design of the product and the processes over the entire supply chains.

These considerations are the basis for updating the topics for the coming PRES'21 conference, to be held in Brno – the Czech Republic during early November 2021. PRES'21 will be the twenty-fourth in the series, building upon a successful host of past venues and the mutually beneficial collaboration with renown journals. This constant update of the research agenda will also be combined with the continuous collaboration of the PRES conferences with the Journal of Cleaner Production, for providing the research and development contribution of the Process Integration and Pollution Reduction research family to achieving the United Nations Sustainable Development goals.

CRediT authorship contribution statement

Petar Sabev Varbanov: Conceptualization, Writing - review & editing, Conceptualization, Writing and editing, Proofreading. **Xuexiu Jia:** Writing - original draft, Writing - review & editing, Visualization, Writing and Visualization. **Jeng Shiun Lim:** Writing - review & editing, Writing and editing, Proofreading.

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.

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Nomenclature

5G/6G	Fifth- or sixth-generation (mobile communications)
ANN	Artificial Neural Network
ANP	Analytical Network Process
BEV	Battery Electric Vehicle
BGCC	BioGas-Combined-Cycle
CAS	Compressed Air Storage
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDIAC	Carbon Dioxide Information Analysis Centre
CLEAs	Cross-Linked Enzyme Aggregates
DEMATEL	DEcision-MAking Trial and Evaluation Laboratory
DHC	District Heating and Cooling
DMFC	Direct Methanol Fuel Cell
ECWAS	Economic Community of West African States
EKC	Environmental Kuznets Curve
EV	Electric Vehicle
FiT	Feed-in Tariff
GCP	Global Carbon Project
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEN	Heat Exchange Network
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
LBM	Lattice Boltzmann Method
LCA	Life Cycle Assessment
LGI	Lean and Green Index
mCLEAs	magnetic Cross-Linked Enzyme Aggregates
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Non-Linear Programming
MPC	Model-Predictive Control
MSW	Municipal Solid Waste
NF	Nitrogen Footprint
OECD	Organisation for Economic Cooperation and Development
PCA	Principal Component Analysis
PCHE	Printed-Circuit Heat Exchanger
PCM	Phase Change Material
PHEV	Plug-in Hybrid Electric Vehicle
PI	Depending on the context: Process Integration Proportional-Integral (control)
PM	Particulate Matter
PRES	Conferences on PRocess Integration for Energy Saving and Pollution Reduction
PSE	Process Systems Engineering
SBMI	Sustainable Business Model Innovation
SDGs	United Nations' Sustainable Development Goals
SOC	Soil Organic Carbon
SWM	Solid Waste Management
US-EPA	The United States Environmental Protection Agency
VSI	Virtual Special Issue
WRI	World Resources Institute
WSC	Water Spray Cooling
WSDC	Water Spray and Dry Cooling
WTE	Waste-to-Energy
WTE-GT	Waste-to-Energy/Gas Turbine
WTST	Wind-Thermal-Storage-Transmission

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