CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216
DOI: 10.3303/CET2188001

Twenty-Four Years of PRES Conferences: Recent Past, Present and Future-Process Integration Towards Sustainability

Jiří Jaromír Klemeš[a,*], Petar Sabev Varbanov[a], Yee Van Fan[a], Panos Seferlis[b], Xue-Chao Wang[c], Xuexiu Jia[a]

[a] Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Czech Republic
[b] Aristotle University/CPERI.CERTH, Greece
[c] Faculty of Geographical Science, Beijing Normal University, Beijing, PR China
jiri.klemes@vutbr.cz

This paper reviews the Process Integration (PI) development related to the recent Conferences on Process Integration for Energy Saving and Pollution Reduction (PRES conferences) and makes suggestions for the future growth of PI branching out in the future. The conference history is now close to a quarter of the century– from 1998 to 2021, and has been flourishing despite the difficult COVID-19 period. The paper overviews the progresses in Process Integration with Pinch Analysis, heat exchangers and Process Integration, extensions of Process Integration for wider process system engineering, integration of renewable energy sources, Circular Economy, extended environmental footprints, extended water-energy nexus contribution to environmental assessment, COVID-19 pandemics environmental consequences, and ecosystem remediation and waste stream clean-up. Considerable progress in Process Integration has also been achieved thanks to PRES conferences. This overview is an attempt to demonstrate the contribution delivered and make suggestions for the future growth of the PI branching out during the next years. It has become apparent that further improvements of the PI technologies are necessary and possible for achieving sufficient reductions of resource demands and pollution so that available renewables and end-of-pipe cleaning can serve them, minimising the environmental impacts. The key methodology developments enabling this are multi-constraint Pinch Analysis and the joint use of several PI methods for delivering comprehensive macro-analyses.

1. Introduction

The paper focuses on the main achievements and ideas presented at PRES conferences and resulting from them during the most recent period. The developments during the first 11 y were covered by the previous review presented in 2009 (Friedler, 2009), and the second-period overview was presented in 2017 (Klemeš et al., 2017). Another five years have seen very substantial and successful development, albeit sometimes turbulent, and it is time for another assessment. The conference has become one of the main vehicles of spreading Process Integration (PI) into various research directions and fields of possible implementation.
A thorough review of the PRES series of conferences contribution to Process Integration has been given by Friedler (2010). It stressed both the theoretical and practical pillars of the research performed for the conference or related to it. The classical Heat Integration using Pinch Analysis has been reviewed, followed by Mass and Water Integration, Hydrogen Pinch, Oxygen Pinch, Total Site Heat Integration (TSHI). The article then proceeds to overview the main highlights of the PRES series of conferences until 2009.
More recently, at the 20-year Jubilee of PRES – for PRES'17, (Klemeš et al., 2017) has thoroughly analysed the contributions of the conference to energy saving and pollution reduction. Pinch Analysis (PA) based works are part of the analysis. The key achievements resulting from the PRES conferences until PRES'17 are highlighted and analysed – including the novel representations of Heat Exchanger Networks (HEN) – as the Shifted Retrofit Thermodynamic Diagram, the STEP method combining HEN targeting and design, PA of Organic Rankine Cycle, intensified heat transfer, TSHI targeting with individual allowed temperature differences

Paper Received: 10/09/2021; Revised: 19 September 2021; Accepted: 19/09/2021
Please cite this article as: Klemeš J.J., Varbanov P.S., Fan Y.V., Seferlis P., Wang X.-C., Jia X., 2021, Twenty-Four Years of PRES Conferences: Recent Past, Present and Future-Process Integration Towards Sustainability, Chemical Engineering Transactions, 88, 1-12 DOI:10.3303/CET2188001

for every site process, targeting of power systems operation, the inclusion of environmental footprints and integration of renewable energy sources.

The conference editions covered numerous important contributions towards sustainability and Circular Economy in the last period challenged by COVID-19 pandemics. At least some should be highlighted, but they are not the only contributions. Even this very short selection demonstrates the substantially extended scope of Process Integration, which has been achieved thanks to PRES conferences.

Those reviewed include

(i) Process Integration with Pinch Analysis
(ii) Extended Process Integration
(iii) Heat exchanger systems and Process Integration
(iv) Extensions of Process Integration for wider Process System Engineering, and recently
(v) Circular Economy
(vi) Environmental footprints and nexuses
(vii) COVID-19 pandemics environmental consequences
(viii) Ecosystem remediation and waste stream clean-up.

2. PRES achievements

The conferences PRES have contributed to many topics aiding in achieving and keeping a sustainable development trajectory of the world economy. The coverage spans from fundamental research – such as heat and mass transfer, end-of-pipe treatment, ecosystem recovery (e.g. soil remediation), to Process Integration methods for industrial, agricultural and residential systems. The Process Integration methods have been following the two main pillars – Pinch Analysis and mathematical modelling, some works focusing entirely or predominantly on one of the pillars, other balancing and exploiting the strengths of both of them.

Another comprehensive review of the Process Integration developments during 2013-2018 is provided in (Klemeš et al., 2018a). It summarises the achievements cutting across multiple engineering fields (chemical, mechanical, environmental) and application domains. The development has accelerated further since the last overview 5 y ago. The VSI of Energy from PRES'19 (Seferlis et al., 2021) featured articles on several thematic areas – including heat and power integration, sustainable design of energy materials and processes, novel high-performance heat exchangers, control solutions, energy storage, CO_2 capture. The analysis suggested the evaluation and reduction of energy losses in the systems by Life Cycle stages.

2.1 Process Integration with Pinch Analysis

The development since 2017 has been marked by publishing the second edition of "Sustainable Process Integration and Intensification" (Klemeš et al., 2018b). The book provided an updated presentation of the fundamentals of key areas of both Process Integration and Process Intensification. The reader can also find illustrated working sessions for a deeper understanding of the material. The further developments discussed next are stem from contributions of the PRES conference venues and outstanding contributions of the PRES-Family authors in journals affiliated with the conference.

2.1.1 Process Integration with Pinch Analysis for energy consumption optimisation

A useful thermodynamic tool – the Modified Energy Transfer Diagram, has been presented in (Walmsley et al., 2018) as an extension of the initial Energy Transfer Diagram (Bonhivers et al., 2014). It has been shown that the diagram can be considered as an implementation-level variation of the Grand Composite Curve. Lai et al. (2020) recently provided a useful case study on the implementation of the STEP method for HEN retrofit. The STEP method application has found HEN retrofit options missed by other methods, resulting in higher heat recovery. The Carbon Emission Pinch Analysis (CEPA) developments have been analysed by Tan et al. (2018), and a further extension of CEPA has been presented for optimal electricity trading using CEPA (Tan et al., 2020).

A case study implementing the CEPA to the United Arab Emirates has been presented in (Lim et al., 2018). The article demonstrated the applicability of the method to an entire country. The considered potential scenarios for future development were reported. They showed that the scenario with a high share of renewable energy sourcing reduced both the energy cost and the Water Footprint (WFP). The alternative with dominating natural gas as an energy source featured significantly higher energy cost and WFP.

CEPA is a flexible tool, and it is suitable also for targeting and optimising industrial sectors, provided that their entities are of sufficient total capacity and well connected. This logic was followed by Gomilšek et al. (2020), who presented a CEPA study from the aluminium industry in Slovenia – using graphical and numerical procedures. They have also performed a mathematical optimisation of the same system. The results of all three evaluations corroborate their results. The study has identified the scope for replacing approximately 2.2 MWh/t fossil-based energy for aluminium production with renewables.

Jamaluddin et al. (2019) introduced an extension of the Total Site concept from Total Site Heat Integration (TSHI) and CHP to Trigeneration. The work combines the numerical tools for Total Site targeting with an extended visualisation of the utility exchanges – adding mains for hot and chilled water and the local electricity grid to the traditional steam mains. The case study demonstrates that up to 28 % energy savings are achievable compared to the traditional TSHI with CHP.

Fu et al. (2018) have analysed the area of the simultaneous integration of work and heat as a sub-area of Process Integration. They have pointed out the complexity of the resulting combined problem due to the interactions of the heat and power conversion operations via the heat and power flows. The main challenges identified by the authors include: (a) the lack of success in the targeting of energy, exergy and numbers of units ahead of design; (b) scalability of the visualisations and the visual design methods is limited; (c) the available mathematical models are complex and difficult to solve.

2.1.2 Process Integration with Pinch Analysis for water use optimisation

A key development has been the Pinch approach for targeting multi-contaminant material recycle/reuse networks (Chin et al., 2021). With this work, water/wastewater minimisation has made significant progress. This is an indirect contribution to energy demands minimisation, reducing the energy demands via the process hierarchy. The method allows seamless integration of the targeting into the network design and optimisation. That development has been supplemented by the Two-Stage Regeneration Recycling Water Networks with Parallel Structure (Ding and Feng, 2020), which showed the importance of the water mains representation in the targeting and design stages.

Regional water scarcity alleviation has been treated in (Jia et al., 2020). The article introduced the Water Scarcity Pinch Analysis (WSPA) to quantify the regional water scarcity. Following the principles of Pinch Analysis, a staircase-type Grand Composite Curve (GCC) is proposed as visualisation and a decision-making tool, complemented by the Water Quality Cascade. The method combines water quantity and quality in the accounting. This enables the decision-makers to easily evaluate and compare scenarios with water upgrades and water dilution to find the optimal solutions for their regions.

2.1.3 Process Integration with Pinch Analysis for waste management

Ch'ng et al. (2021) have focused on Eco-Industrial Parks. They have proposed a sequential procedure applying the various PI tools in turn – starting with Waste Management Pinch Analysis - WAMPA (Ho et al., 2017) and proceeding to TSHI and cogeneration, Power Pinch Analysis, CO_2 reuse integration, water minimisation. The illustrative case study reports tangible waste and resource reductions. WAMPA has been adapted to regional waste management (Fan et al., 2019a), where the waste supply and treatment capacity are matched at the regional level for emission minimisation and demonstrated through that time EU-28 case study. Total EcoSite Integration (Fan et al., 2021) is also proposed for symbiosis in Circular Economy, where Solid Waste Integration is developed and combined with other Process Integration methods – e.g. Heat Integration and Water Integration, maximising the use of resources before the end of life stage.

2.1.4 Heat Pump integration

Heat Pump integration is a traditional area of HI (Klemeš et al., 2018b). In the typical evaluations, heat pumps of the vapour compression and absorption types are assumed. Other heat pump types can be useful as well. Gai et al. (2020) has performed a Pinch Analysis of the suitability of the main heat pump types for integration with various unit processes. The traditional vapour compression heat pumps have been found to be suitable mainly for flatter T-H profiles of the main process, while for significant slopes of the profiles, more suitable are the Joule-Cycle heat pumps whose working fluid is entirely in the gaseous phase.

2.1.5 Others

There have been a couple of lines, partly complementary, of applying together and evolving the base Process Integration methods for the optimisation of industrial and combined industrial-urban clusters, geared towards sustainability. This is reflected in their terminology, including the prefix "eco".

The other innovation in (Fan et al., 2019a) considered a similar problem but from a different angle. It modelled the overall symbiosis network as a pair of interacting subsystems – an industrial cluster and an urban cluster. The method proposes an extension of the Locally Integrated Energy Systems – LIES (Perry et al., 2008) concept, evolving it to the pair of clusters and exchanging materials, water and energy and applying a hierarchical integration principle introduced with the TSHI (Klemeš et al., 1997). The provided case study demonstrates a similar saving of energy and resources on the order of 20 % after applying the proposed integration measures. That work clearly illustrated the principle of extending the previous works and reusing the

knowledge. The previously developed PI tools have been incorporated in the new method by interfacing them with the user and with one another. This has been a major step forward in the development of PI as an integrated system of tools for resource-saving and emission reduction. The future development can follow, e.g. the process design hierarchy expressed in the Onion Diagram (Klemeš et al., 2018b).
Wang et al. (2020a) developed an extension of the Shifted Retrofit Thermodynamic Grid Diagram for HEN retrofit by introducing the “Shifted Temperature Range” modification. This allows engineers to add a selection of the heat exchanger type in addition to the topology retrofit steps. This is an additional degree of freedom in retrofit optimisation. Such flexibility allowed to obtain a 10.7 % additional heat recovery compared to a selected literature example using the traditional HEN retrofit workflow and representation.

2.2 Heat exchangers and Process Integration

Efficient heat exchangers at minimum unit cost constitute a necessary condition for obtaining credible solutions for heat recovery systems. In this context, Guo et al. (2019) have investigated a vibration application for enhancing heat transfer in Moving Bed Heat Exchangers. For the configuration of a vertical gravity flow, the investigation identified an up to 36 % increase of the heat transfer coefficient by applying horizontal vibrations.
The heat transfer behaviour of enhanced-surface tubes of varying diameters for condensation and evaporation has been investigated experimentally (Aroonrat and Wongwises, 2019). The condensation experiments showed up to a 64 % increase of the heat transfer coefficients compared with smooth tubes, at moderate pressure drop increases. Evaporation results showed the opposite trend – a reduction of the heat transfer coefficients of up to 200 %.
Taking a broader view, Klemeš et al. (2020b) analysed the developments in heat transfer intensification from the viewpoint of HEN retrofit and operation. The key findings have been the need to bridge the gap between the solutions offered by mathematical optimisation methods and the HEN retrofit actions that would produce economically viable networks in practice. The paper reasons that further tools are necessary with increased fidelity, practicality, and visualisation capability, clearly communicating to the engineers the recommended actions and the reasons for them.

2.3 Extensions of Process Integration for wider Process System Engineering

Process Integration has been considered simultaneously with the selection of innovative materials that both enhance process performance and improve process sustainability (Seferlis et al., 2021). This has opened new pathways for a holistic approach to the efficient design of Process Systems. The selection of materials may involve solvents for the recovery of use or the removal of harmful substances from a waste stream, facilitating solvents for the separation of components in extractive processes, the working medium in energy conversion systems or reactive components in heterogeneous or homogeneous catalysts.
The work of Papadopoulos et al. (2010) in PRES 2010 has set the foundation for a systematic synthesis and search of suitable working fluids in Organic Rankine Cycles using a Computer-Aided Molecular Design (CAMD) approach that explicitly accounted for the fluid properties and process performance criteria. Papadopoulos et al. (2020) expanded the CAMD approach to involve complex solubility properties, reactivity potential and sustainability metrics in CO_2 capture. In such a context, Wang et al. (2020b) investigated the Process Integration in a reactive distillation system for the production of cumene, where the reaction heat excess is utilised for power generation by an Organic Rankine Cycle (ORC). The work evaluated several working fluids for the ORC in terms of economic performance and energy efficiency.
Heat Integration options have been evaluated in (Dong et al., 2020), where supercritical operating conditions have been considered for heat recovery by ORC systems. The selection of the working fluid greatly improved the economics of the process, necessitating the augmentation of the design space. Sustainability criteria in the selection of suitable phase change solvents for CO_2 capture have been introduced by Shavalieva et al. (2021), where Life Cycle Analysis assessment as well as environmental, health, and safety hazard analysis of the employed solvent have been incorporated in addition to processing performance-related criteria. The analysis indicated the solvent properties that contribute the most to the sustainability profile of the selected materials.
The integration of a process system with simultaneous CO_2 capture and subsequent carbon storage or CO_2 utilisation for the production of valuable chemicals is identified as a distinctive way to reduce the carbon footprint of energy-intensive and emission producing processes. To this end, Roussanaly et al. (2020) investigated the economics of carbon capture and carbon sequestration in a geological formation for hydrogen production using steam-methane reforming. The most significant cost item was that of CO_2 capture due to the large energy demand. Definitely, the development of energy-efficient carbon capture processes and their integration into existing plants remains a challenge.
Oluleye (2020) set a framework for the optimal selection of the fuel that results in the lowest carbon footprint while satisfying the economic viability of the processing system. In this way, the potential cost of carbon capture can be constrained through the reduction of the associated emissions. Bayomie and Bouallou (2018) developed

a framework for the enhancement of CO_2 utilisation in the production of methanol through hydrogenation. Advancing the integration of CO_2 utilisation and storage in process systems, Zhang et al. (2019) considered an optimisation framework for the reduction of global warming potential of various technologies for capture, transportation, utilisation and injection of CO^2 into the storage containment. It takes a holistic approach in the carbon dioxide supply chain through which the most sustainable strategies can emerge.

Shehab et al. (2019) studied the integration of a series of plants within a generalised framework that determines the optimal coordinated operation in order to meet specific CO_2 emission specifications. The framework incorporates synergies through the integration of resources and the proper distribution of energy with the option of energy storage and CO_2 utilisation. The evolution of this work led to the multi-objective optimisation of industrial clusters (Ahmed et al., 2021), where material and energy resource integration is employed for a set of sustainability criteria. In addition, green technologies and renewables are incorporated for the maximum economic output, minimum CO_2 emissions and minimum water footprint. Even though such approaches look at the wider picture, further improvements are essential for achieving sufficient sustainability performance. They concern the intensification of reactive processes that integrate materials, energy and water streams in different forms. Such a case is the investigation of Jia et al. (2021) of a ceramic tube module for heat and water recovery in coal-fired power plants. Structural optimisation of the membrane module achieved at least a 60 % recovery rate for water. It is apparent that ambitious targets in sustainability can be achieved through a combination of process-wide and plant-wide strategies. The incorporation of advanced control strategies in Sustainable Process Integration is of paramount importance as it maintains the desired performance level under all exogenous and inherent forms of disturbances and uncertainty. Clearly, uncertainty is a major factor that can cause significant deterioration of process performance. In addition, as the level of integration among process units or different plants increases, interactions become stronger among the various subsystems, and consequently, disturbances can easily propagate within the processing system. The control of a highly integrated system is extremely challenging and requires a significant level of understanding of the physical system as well as ingenuity in the development of the control scheme. Data-driven modelling approaches offer an alternative way to build appropriate process models for difficult to model processes with a large degree of uncertain parameters. That facilitates the application of Model Predictive Control for the effective compensation of process interactions under disturbances. Chen and You (2020) employed such a system for temperature control in a greenhouse that was also configured to ensure constraint satisfaction for the worst case of the disturbance scenario. Liu et al. (2020) presented a novel approach in the synthesis of heat exchanger networks through the explicit consideration of the ability of the network to perform satisfactorily under the presence of disturbances. The idea of controllability in the form of the relative gain array was combined with a superstructure optimisation approach to provide high performing Heat Integration solutions. Another method for Process Integration and process network design is P-graph, which has been constantly developed and presented in PRES conferences. The P-graph application areas range from chemical processes to supply chains optimisation, crisis management, evacuation plant and regional resource planning, as summarised in Varbanov et al. (2017).

2.4 Integration of renewable energy sources

Integration of renewable energy sources in energy-related activities has attracted a lot of attention. To this end, Wu et al. (2021) optimised the configuration of an offshore floating wind turbine farm in order to supply renewable energy for gas hydrate mining activities. Based on the wind speed and direction, the grid of the wind farm was adapted so that the maximum power output was obtained. A multi-period optimisation formulation accounted for the variability in the wind speed and direction.

Energy storage is identified as a key element for power systems that incorporate renewable energy sources (Rozali et al., 2015). This is mainly attributed to the intermittent nature of renewables and also the variation in the power demand. Among the various forms of thermal energy storage, i.e. sensible, latent and thermochemical, thermochemical storage shows the greatest energy density (Li et al., 2020).

Concentrated solar power integration with calcium looping (Karasavvas et al., 2020) offered an efficient way to store solar energy in the form of chemical energy via the calcination reaction in a calcium looping scheme. The energy can be readily released through the carbonation reaction. Carbonation pressure, CO_2 stream temperature and CaO storage temperature are the key parameters that affect the operation of the system. In more recent work, Karasavvas et al. (2019) developed a one-dimensional model for the fast carbonation reaction where the range of the CO_2/CaO ratio was examined. The study provided useful insights related to the operating conditions which facilitated the construction and operation of such reactors.

Stampli et al. (2020) employed a superstructure-based framework for the optimisation of energy storage where numerous storage units are available that can exchange heat with multiple sources and sinks. The optimisation-based approach enabled the implementation of the storage strategy for batch process systems with non-continuous energy use and release. Electrochemical storage is also another efficient way to compensate for energy supply and demand surges and plunges. Jiang et al. (2020) investigated the optimal allocation of different types of batteries in hybrid power systems through a systematic optimisation approach. The employed technique considered battery health degradation and battery replacement policies for minimum capital and operating costs explicitly. In more recent work, Jiang et al. (2021) studied the configuration of a network of photovoltaic units with batteries for power smoothing. The optimisation of the configuration enabled the selection of the proper PV and battery type combination. It was shown that a combination of different types of PV allowed a lower fluctuation in power and a lower overall cost level.

A critical element in the full integration of biomass in the energy system is the robustness and agility of the biomass supply chain. A critical review of key elements pertaining to the biomass supply chain can be found in (Nunes et al., 2020). How and Lam (2018) developed an optimal transportation design based on economic and environmental criteria using a statistical model and a hierarchical analytical process in which the priority of the targets could be manipulated. Such an approach resulted in supply chains with economic potential while maintaining the environmental impact below an acceptable level. Biomass is relatively bulky and of variable quality. Therefore, transportation operations are hindered by the environmental impact, whereas products from biomass conversion processes are prone to large levels of variability. Microalgae biomass may be a competitive solution to the production of biofuels. Peralta-Ruiz et al. (2018) investigated the production of biodiesel and bioethanol from microalgae using chemical flocculation. The process is studied from energy efficiency and exergy analysis point of view, indicating that 0.26 g of bioethanol can be derived from 1 g of microalgae with an exergy efficiency of 86 %.

Hybrid energy networks utilising renewable and fossil sources have been synthesised by Aviso et al. (2017). The P-graph tool (P-graph, 2021) was used for multi-period optimisation of the networks. They have illustrated the suitability of the P-graph framework for optimising hybrid energy networks. This can be complemented in the future with the method accounting for the key footprints – e.g. GHG Footprint (Lam et al., 2010).

2.5 Circular Economy

Circular Economy focuses on keeping materials or resources circulating in the system as long as possible through designing products for durability, reuse, remanufacturing, recovery or recycling. Various efforts have been performed in line with the vision of a Circular Economy. Cogollo-Herrera et al. (2018) extract chitosan, which can be used for different purposes, including a sorbent in wastewater treatment from shrimp shell waste that will otherwise be disposed of. A techno-economic analysis is conducted to identify the feasibility of large-scale production. It is suggested that the economic viability has to be improved and is highly dependent on the price of chitosan. On the other hand, Bong et al. (2020) summarise the conversion of waste to biochar in materialising the Circular Economy. Several identified co-benefits of waste minimisation are carbon sequestration, fuel, soil amendment and adsorption of pollutant remediation. However, Fan et al. (2019b) highlighted that the sustainability of biochar is highly dependent on the sourcing of biomass. The ecotoxicological aspect of biochar has also been discussed by Godlewska et al. (2021). Igboamalu et al. (2019) utilised sludge from wastewater treatment as an inoculum for microbial fuel cell power. The influence of pH on microbial growth and eventually power production is addressed, suggesting pH = 9 as the optimum. García-Martíneza et al. (2019) utilising fisheries wastewater as a media for algae production. This is consistent with the circular economic initiatives where the wastewater is fully utilised and the discharge is minimised. Pietrelli et al. (2019) recover heavy metals, including lead and zinc, from hazardous leather sludge, minimising the environmental pollution and resources depletion, as well as the human health risk (Ahmad et al., 2021)

The Circular Economy is a system that discourages disposal, forming a linear system. Waste to resources or waste to energy could generally contribute to a lower environmental footprint (e.g. GHG footprint) (Fan et al., 2020). However, it should be noted that the degree of circularity should not be the blind focus and a wide variety of environmental footprints in maintaining the circularity needs to be assessed.

2.6 Extended environmental footprints and nexus contributions to environmental assessment

Environmental footprints, such as the ecological footprint, water footprint, and carbon footprint (GHG emission footprint), etc., have been continuously developed and widely applied to evaluate the environmental performance of human activities (Čuček et al., 2012). As the environmental issues become increasingly complex, the environmental footprint methods have been facing challenges to cover the various aspects of these issues. A considerable number of studies investigating the footprint methodologies and applications have been presented at the PRES conference. For example, Angeles et al. (2017) investigated the Carbon and Nitrogen Footprint of ammonia as an automotive fuel and found that ammonia produced from the biomass-based process with dimethyl ether as the secondary fuel results in the best well-to-wheel fuel pathway. Yap et al. (2018) proposed a heuristic-based technique for carbon footprint reduction for the production of multiple products. The method is developed based on the Carbon Footprint Composite Curves and extended the application to the more general case of multiple products. Fan et al. (2019b) proposed a graphical break-even based decision-making tool (BBDM) to minimise the GHG footprint of biomass utilisation and illustrated the case study with biochar by pyrolysis. Makarova et al. (2019) presented an improved method for the accurate evaluation of the footprint of chemical pollutions on a global scale and assessed the global mercury footprint as a case study. In addition, the increase in water pollution can reduce water availability and contribute to water shortage issues, along with water scarcity caused by a shortage of renewable water resources. However, in the conventional water footprint and water scarcity assessments, water scarcity and water pollution are usually separately discussed. The linkages between the two aspects of the issue are not addressed. Wang et al. (2021) provides an overview of the water footprint methodology developments and pointed out the current research gap and potential directions in future research. Jia et al. (2019) extended the definition of Water Availability Footprint integrating water quality and quantity and proposed a brief framework to illustrate its application, which has been one of the initial efforts to integrate the water quality and quantity in water use environmental impact assessment. To build an intermediary between the environmental and economic aspects of the issue, Jia et al. (2021) proposed a cost-based Quantitative-Qualitative Water Footprint (QQWFP) that enables the trade-off evaluation between environmental performance and economic benefits. Comparing with existing water footprint assessment tools, the outcome of QQWFP, including the Quantitative Water Footprint (WFqt) and Qualitative Water Footprint (WFql), provides more insightful guidance for the users and manages to identify the bottleneck and provide insights for possible solutions to reduce the overall water use impact.

2.7 Extended water-energy nexus contribution to environmental assessment

Challenges of more water saving, higher energy efficiency, low-carbon emissions, waste management and food saving have been considerable pressures on both regional and global sustainable development. Nexus thinking provides a proper idea for addressing relevant challenges or problems (Nathaniel and Khan, 2020). It emphasises the interrelationships rather than an isolated system, which plays an essential role in Sustainable Development Goals (SDGs) (Wang et al., 2021). It is an approach to environmental resources management assessing the interrelatedness and interdependencies and their transitions and fluxes across spatial scales and between compartments. Based on the extended water-energy nexus thinking, regional water-energy nexus in China's industrial sector was assessed, combing an interactive meta-frontier data envelopment analysis approach (Ding et al., 2020). The study explored the industrial water-energy nexus in China. The industrial water and energy utilisation efficiency in the processes of industrial production and wastewater treatment from 2011 to 2015 were identified. They found that most regions have relatively low wastewater treatment efficiency, while the eastern and central regions have higher industrial production efficiency.

The recent study from the PRES family, Wang et al. (2020b), explored the water-energy-carbon emissions nexus of the EU27, revealing the unsustainable imbalances and inequities in carbon-water-energy flows across the EU. There are environmental inequalities across the EU27 and have significant impacts on the rest of the world. The EU27 countries can contribute 64.5 Gm^3 less water utilisation, 1.4 Gt less CO_2 emissions and 49 EJ less energy consumption, compared to the rest of the world while generating the equivalent economic output, which has dramatic effects upon the global environment. Regarding the EU27 scale, Germany, France, and Italy are the biggest beneficiaries. Based on this, Wang et al. (2020b) further assessed the efficiency of the water-energy-carbon nexus of all EU27 countries, identifying the water and energy efficiencies and carbon emission intensity of different countries in the EU27. In their study, the embodied water consumption coefficients embodied energy consumption coefficients and embodied CO_2 emission coefficients are systemically analysed. Both the direct and indirect values of the above indicators were identified. Water efficiency, energy efficiency and CO_2 emission index per capita of each EU27 country were calculated as well. EU27 countries depend on importing products and services from the global chain perspective. A huge amount of embodied water and embodied energy are imported by the EU27, transferring a huge amount of embodied CO_2 emissions to the upstream regions during the international trade. The nexus thinking is applied to analyse the sectoral and regional supply of water and energy (Naderi et al., 2021) and the sectoral efficiencies. This trend is also apparent from the work of Lim et al. (2018). By constraining the GHG emissions of UAE to the 2012 levels, the resulting climate-water-energy nexus is resolved to renewables domination for energy supply.

2.8 COVID-19 pandemics environmental consequences

The COVID-19 pandemic has been exerting increasing environmental consequences related to plastic use, energy consumption, carbon emissions and follow-up waste, but more urgent health issues have far overshadowed the potential impacts. The study by Klemeš et al. (2020a) provided expert insight for dealing with COVID-19 plastic use and waste, introduced the idea and benefits of Plastic Waste Footprint, which can provide an idea to capture the environmental footprints of a plastic product throughout the entire life cycle. They assessed the impact of the pandemic and epidemic following through the life cycles of various plastic products, particularly those needed for personal protection and healthcare. The energy, plastic and other environmental footprints of these product systems have been increasing rapidly in response to the surge in the number of

COVID-19 cases worldwide. The increasing demand for ensuring the destruction of residual pathogens in medical and household waste has caused rising pressures and issues for critical hazardous waste management. The emerging challenges in waste management during and after the pandemic were discussed by Klemeš et al. (2020a) from the perspective of novel research and environmental policies. The most recent research from Klemeš et al. (2021) explored the energy and environmental impacts of COVID-19, focusing on the pandemics in the second stage, assessing the energy and environmental impacts related to the vaccination. The vaccination for pandemic control in the current phase is prioritised over all other decisions, including energy and environmental issues. It revealed that the COVID-19 vaccination should be implemented in maximum sustainable ways, as the vast numbers related to the worldwide logistics, production, disinfection, implementation and waste treatment are reaching significant figures. The more sustainable supply chain model that responds to an emergency arrangement, considering equality as well, should be emphasised for mitigating the environmental footprints of vaccination. COVID-19 has significant impacts on various social and economic aspects. Some of the impacts are beneficial to the environment; however, the long-term impacts are yet to be unfolded (Zambrano-Monserrate et al., 2020). One of the apparent changes is the dependency on digitalisation systems and virtual events, which is critical during the implementation of lockdown and movement restriction. Digitalisation and virtual events could reduce emissions from transportation; however, it could shift to another problem such as e-waste, consumption of rare metals, and increased energy consumption related to the rebound effects (Masanet et al., 2020). Nevrlý et al. (2020) proposed a mathematical model to identify the optimal conference locations with a minimal environmental footprint, applying to the case of the PRES conference. The unexpected COVID-19 changes the practicability of the result as the other format of conferences, such as hybrid and virtual, are not considered in the proposed model. There have been several attempts to assess the environmental performance of the virtual and physical conference. The environmental footprint of virtual conferences stimulated by COVID-19 is generally lower (Jäckle et al., 2021). However, the results could be greatly affected by the assessed boundary, duration, and social consequences should be taken into account. It deserves a continuous evaluation and identifying a way forward for a sustainable digital lifestyle (Obringer et al., 2021).

2.9 Ecosystem remediation and waste stream clean-up

Nanomaterials play an increasing role in different applications, including supporting renewable energy development (Chen et al., 2012). The rapid development, as for other resources consumption, poses an impact on the environment. Reverberi et al. (2017) assessed several green methods for metal nanoparticle synthesis. The potential drawbacks of using reductants, processes involving high temperature and pressure, have been highlighted for future work. Carbon neutrality has been widely introduced, and carbon emissions capture technologies are critical for implementation. Cormos et al. (2020) assessed the conceptual design, modelling, Process Integration, and environmental assessment in reducing the carbon footprint of coal-based processes through CO_2 capture. It is suggested that a reduction of 60 - 90 % in CO_2 emissions could be achieved. However, the potential pitfall of considering merely carbon or carbon emissions could lead to other non-climate change issues such as air pollution, biodiversity loss, soil contaminant, water pollution. It is important that environmental sustainability should not be targeted merely on the carbon emission (greenhouse gases) and should be minimised or considered simultaneously (Luderer et al., 2019).

3. Discussion

The review papers related to the PRES conferences have revealed the need to further investigate energy savings, Circular Economy and reduction of user demands as the means to bridge the gap between the energy demands and the capability of renewable energy sources to cater for the demands. Novel visualisation tools – Modified Energy Transfer Diagram and the “Shifted Temperature Range” modification to the Shifted Retrofit Thermodynamic Grid Diagram have provided valuable tools to the engineers for thermodynamic and topological reasoning in the process of retrofitting HENs. Heat pump integration has seen further development with the systematic analysis classifying the main heat pump types and their suitability for various HEN types. Combined work and Heat Integration has been the subject of improvements but still needs a robust method. Process Integration contributions of CEPA have been provided to an extended area - for electricity trading, as well as a practical implementation case study for Slovenian industry has been presented, identifying tangible energy savings alongside GHG emission limitation. Extending that, Process Integration has been spread to the systems for capture, storage and utilisation of CO_2 – at the levels of processes and industrial sites. Considerably improved Pinch Analysis methods for Water Integration have been developed to handle systems with multiple contaminants and multiple water mains, allowing further extensions and generalisations to multiple-constraint analyses. Added to that is the WSPA method, allowing regional planners to assess and mitigate water scarcity issues. There has been a significant methodological breakthrough in scaling-up Process Integration methods on the example of the WAMPA analysis. This is a promising development that can lead to the Process Integration of Process Systems up to the level of smart regions.

4. Conclusions

PRES conferences have been run successfully for 24 y, contributing to a wide spectrum of multidisciplinary subjects related to sustainable development. From the initial idea of Heat Integration, along with Process Integration, environmental footprints, mathematical programming, etc., the scope of PRES conferences has been much extended. Circular Economy, extended Water-Energy Nexus, SDGs, and major global challenges like the COVID-19 pandemic have been systematically and continuously explored by PRES conference contributions. There have been major development trends pointing to the future directions for research and development: overcoming the limitation of constraints and contaminants in Water Integration as well as the integration of basic Process Integration procedures into macro-procedures by interfacing them. These developments bear the potential of upscaling Process Integration for bringing more tangible resource intake and pollution reduction.

Acknowledgements

This research is supported by the EU project "Sustainable Process Integration Laboratory - SPIL", project No. CZ.02.1.01/0.0/0.0/15_003/0000456 funded by EU "CZ Operational Programme Research, Development and Education", Priority 1: Strengthening capacity for quality research under the collaboration agreements with Beijing Normal University and Aristotle University.

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