CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Hon Loong Lam, Xia Liu, Jiří J Klemeš
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ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761001

Twenty Years of PRES: Past, Present and Future – Process Integration Towards Sustainability

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The paper is targeted to provide an overview of the main achievements and ideas presented at PRES conferences. The conference history is now reaching its first 20 y – from 1998 to 2017. The first 11 y were covered by the previous review presented in 2009 and for this reason, the authors focused mainly on the most recent period starting from 2009. The conference has become one of the main vehicles of spreading Process Integration into various research directions and fields of possible implementation. The conference editions covered numerous important contributions towards sustainability. It is not possible to list all of them. However, at least some can 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) Process Integration with another approach, (iii) Development of heat exchanger systems for Process Integration, and (iv) other extensions of Process Integration for wider Process System Engineering. The paper shows how the Process Interaction tree has grown and branched out during the last twenty years.

1. PRES Conferences

The Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, PRES, was first called and hosted in Prague, Czech Republic, 1998. Since then, every year the conference is attended by leading researchers, renowned speakers, industry experts and accomplished practitioners in the topic. Since the beginning, the conference gained prominence as the forum for showcasing the latest achievements and setting the research agenda in Process Integration. PRES offers a unique and valuable opportunity to explore the latest development of cleaner strategy for energy generation and saving towards sustainability. One of the major attentions of the conference widely covers the applications of Process Integration for energy conservation. The conference has been a vital platform for all experts and researchers to share knowledge, network and initiate a productive and rewarding collaboration. To extend the value of the contribution from this conference, many topics have been updated and added to the discussion list. The complete list of the topics is given in the PRES website <www.conferencepres.com>. These topics completely cover the current trend of applying Process Integration and Process System Engineering (PSE) to a wide spectrum of sustainability issues – relating to resource efficiency and minimisation of environmental impacts. An important step ahead was in 2005 when Chemical Engineering Transactions (CET) for the first time published selected and peer-reviewed manuscripts from PRES'05 (Klemeš, 2005). From PRES'09 (Klemeš, 2009), articles were also assigned a doi identifier, which made possible the inclusion to SCOPUS and consequently also to WoS and WoK. As the first 11 y, until 2008 was overviewed by Friedler (2009) and the extended version Friedler (2010), this contribution has been mainly focusing on the last period starting from 2009.

2. Heat Exchanger Networks (HEN)

The HI had been the topic which initialised the development of Process Integration (Linnhoff et al., 1979). The breakthrough came with the realisation of the most important thermodynamic trade-offs using the Composite Curves. Ultimately, the Pinch Design Method has been widely applied in industry and has become a standard

Please cite this article as: Klemeš J.J., Varbanov P.S., Fan V.Y., Lam H.L., 2017, Twenty years of pres: past, present and future – process integration towards sustainability, Chemical Engineering Transactions, 61, 1-24 DOI:10.3303/CET1761001

part of lecture courses and curricula. An example of such a teaching tool is the representation of the possible heat flows in a process HEN (Figure 1).

2.1 HEN synthesis and targeting

The synthesis and optimisation of HENs have been traditionally an important part of PRES conferences and a considerable number of papers (over 150) tackled this topic. Even after many years of targeted research, there have been still principal issues to be dealt with.

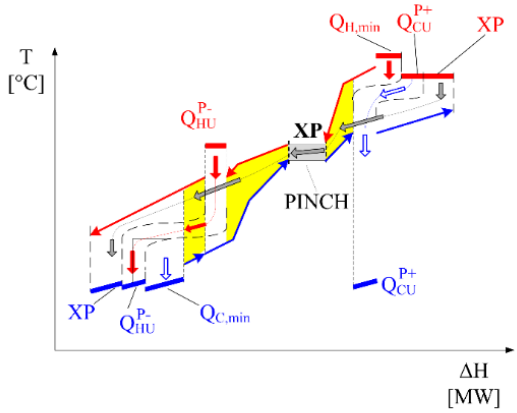


Figure 1: Composite Curves and the Pinch implications (adapted from Klemeš et al., 2014)

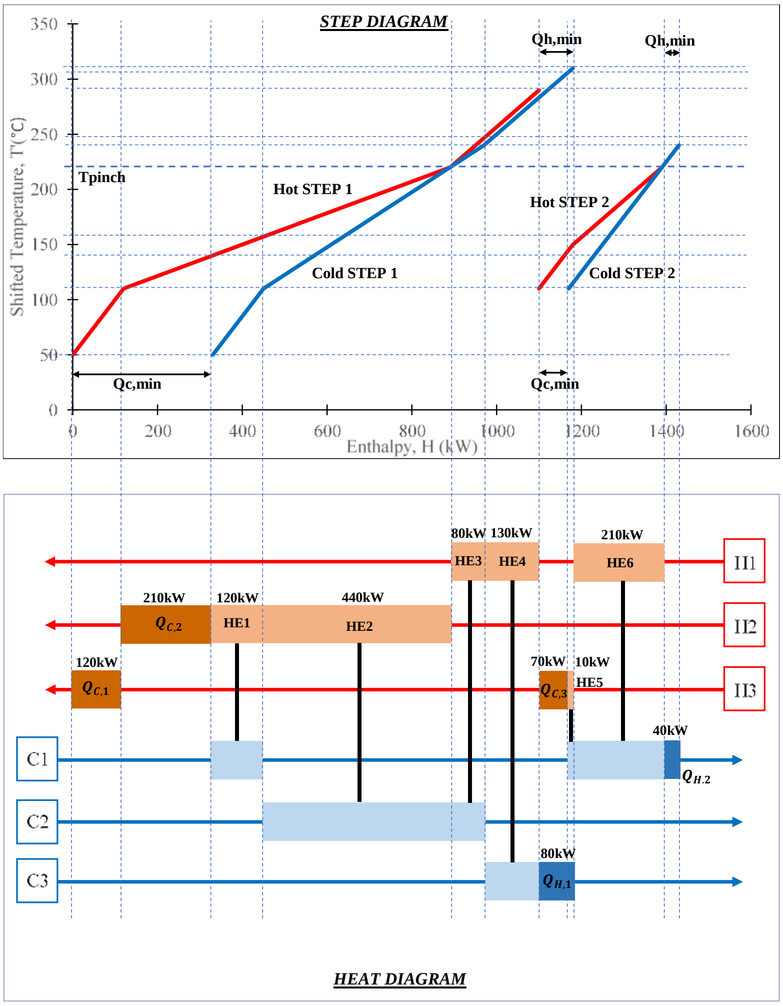


Figure 2: STEP – Simultaneous HEN targeting and design (adapted from Wan Alwi and Manan, 2010)

The Heat Integration methodology has been implemented on HEN synthesis and optimisation. From the previous years, one should at least mention the work of Anantharaman and Gundersen (2007) on the sequential framework for HEN synthesis dealing with the network generation and optimisation. Since the last comprehensive review of the area by Friedler (2009) for the PRES'09 conference, further extended to full-length Friedler (2010), they have been many follow-up developments and new ideas.

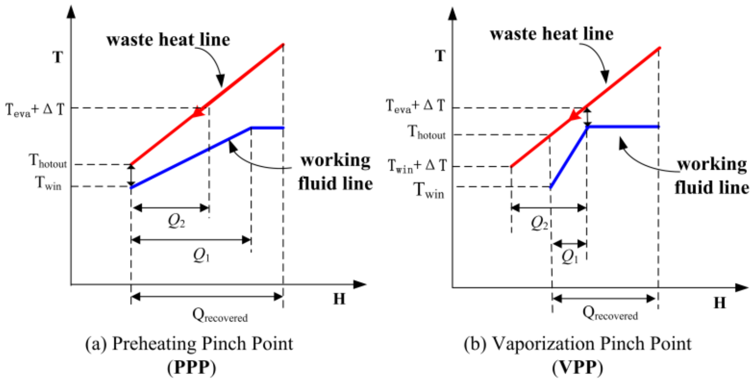


Figure 3: Organic Rankine cycles to recover waste heat (adapted from Yu and Feng, 2015)

Yu and Feng (2014) have investigated the integration of an Organic Rankine Cycle with a process to valorise waste heat (Figure 3). This has been extended to a full method (Yu et al., 2015) for comprehensive design of Organic Rankine Cycles utilising waste heat.

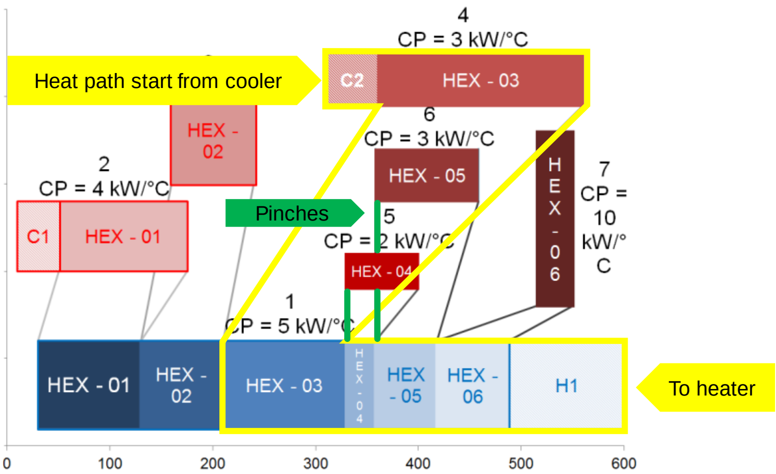


Figure 4: Shifted Retrofit Thermodynamic Diagram (adapted from Yong et al., 2014)

2.2 HEN Retrofit

Yong et al. (2015) studied HEN modification for waste heat utilisation under varying feed conditions and implemented the results on a HEN in an Italian refinery complex. Čuček and Kravanja (2015a) created a new procedure for the retrofitting of large-scale HENS for fixed and flexible designs, as well as under uncertainty (Čuček and Kravanja, 2015b) by considering trade-offs between investment and operating cost. Yong et al. (2014) developed a novel Shifted Retrofit Thermodynamic Diagram (SRTD, Figure 4) as a modification of the traditional tool for retrofitting heat exchanger networks.

The SRTD incorporates thermodynamic feasibility representation as well as minimum allowable temperature difference. Using the diagram allows assessing simultaneously the Pinch points, stream properties and their capacity for additional heat recovery, allowing efficient retrofit and understanding of the retrofit modifications.

Liew et al. (2014a) made another extension of Utility-Heat Exchanger Grid Diagram as a tool for designing the Total Site HEN. Wang et al. (2012) developed an approach for HEN network retrofit through heat transfer enhancement and Pan et al. (2013) introduced heat transfer intensified techniques for retrofitting HENS in industrial implementation. Kukulka and Smith (2016), provided a comparison of heat exchanger designs using

Vipertex 1EHT enhanced heat transfer tubes. Holczinger et al. (2012) contributed by simultaneous HI and batch process scheduling and Morrison et al. (2012) by suggesting ensured cost-effective HEN design for non-continuous processes.

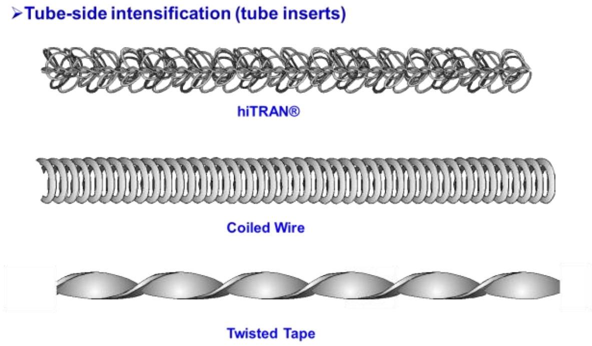


Figure 5: Heat Transfer Enhancement for HEN performance improvement (adapted from Gough, 2012)

Often, it is possible to achieve sizeable heat savings while retaining the current network topology. Gough (2012) has presented a very cost-efficient option of performing such retrofits. By applying Heat Transfer Enhancement (Figure 5) to key heat exchangers in the considered system, those exchangers are de-bottlenecked and sizeable savings can be achieved against low investments.

A particularly interesting development in the analysis and retrofit optimisation of heat-based energy systems, including HENs, is the concept of the Energy Transfer Diagram (Bonhivers et al., 2014). This is a visual tool, which plots the utility heaters and coolers, recovery heat exchangers and heat using/releasing process operations in a unified diagram of heat flow versus temperature. Applied to HENs, this diagram is completely compatible with the Grand Composite Curve for the considered Heat Integration problem. The new diagram is capable of visualising both heat exchangers, as well as processes, stacking the corresponding segments, where the heat exchangers form the Grand Composite Curve and its enclosed area, while process operations are stacked outside, denoting the heat transfer interfaces. This concept has been used by Walmsley et al. (2017a) for illustrating the diagrams application to HEN retrofit.

2.3 HEN Safety and operability

The safety of processing plants is one of the critical issues. Nemet et al. (2017a) presented in their work a good step in this direction, accounting for the risks over the entire plant life time. Another work of Nemet et al. (2017b) considered risk safety during HEN design. Sikos and Klemeš (2009) dealt with the optimisation of HEN maintenance, which can contribute considerably to the safety. Demirskyy et al. (2016) investigated the fouling formation in heat transfer equipment on the example of the sugar industry. The proposed mathematical model enables to predict the fouling formation behaviour in a plate heat exchanger as purified juice heater and to determine the operation term for the cleaning. Kang et al. (2015) presented a synthesis of multi-period HEN considering characteristics of sub-periods. Tangnanthanakan and Siemanond (2014) presented a comparison of sequential and simultaneous approaches for multi period HEN synthesis and application for crude preheat train. Control and operability are the other important issues. Oravec at al. (2015) evaluated and compared several robust model-based control strategies for HENs. Licindo et al. (2015) optimised scheduling for cleaning HENs, which has been an important issue dealing with operability, efficiency and safety. Abu Bakar et al. (2015) made provisions for initial analysis on HENs of fatty acid fractionation plant to optimise energy recovery and controllability.

An interesting direction, which perhaps needs more attention, is the adequate design of the coolers network, that would serve the main HEN. Picón-Núnez et al. (2011) have addressed this gap by analysing existing cooler network and suggesting optimised cooler designs. An analogous study, but for chilled water network synthesis has been developed more recently (Foo et al., 2014). A further elaboration on the optimisation of cooling water networks has been by Sun et al. (2014) – by adding consideration for temperature variation and pressure drop. Sun et al. (2015) added a follow-up development, addressing the trade-off between the parallel-series arrangements of coolers and pumping power consumption. There were also some interesting works based on mathematical programming delivered at PRES conferences. To mention at last a few of them: Short et al. (2015) presented a HEN synthesis including detailed exchanger designs using mathematical programming and heuristics. Jongsuwat et al. (2014) suggested a new HEN design model, however, the work had not been followed up so far. Panjeshahi et al. (2010) dealt with pressure drop optimisation in a multi-stream heat exchanger using genetic algorithms.

3. Total Site Integration (TSI) and Locally Integrated Energy Systems (LIES)

Total Site Integration (TSI) was introduced by Dhole and Linnhoff (1993) – mainly for addressing the need for exchanging waste heat among industrial processes at the level of whole sites. Klemeš et al. (1997) added targets for power co-generation. An important step, conceived for PRES'07 has been the extension of the Total Site (TS) concept (Figure 6) to include the integration of renewable energy sources and adding users other than just industrial (Perry et al., 2007), which has been further developed and gave birth to the concept of the "Locally Integrated Energy Sectors" (LIES) (Perry et al., 2008).

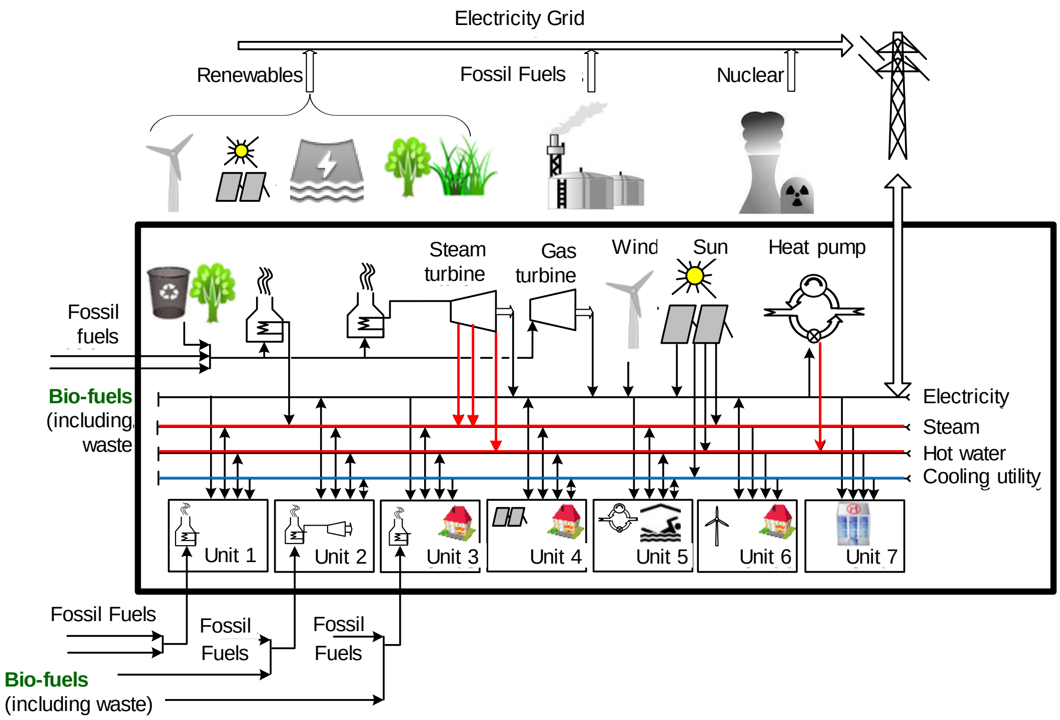


Figure 6: Locally Integrated Energy Sectors (developed from Perry et al., 2007)

3.1 Improvements to the TSI conceptual base

Since 2009, there have been further important developments, to a large extent catalysed by PRES conferences. An interesting direction of improvement has been proposed by Liew and Walmsley (2016), who have considered heat pump integration at the TS level, drawing an analogy from the appropriate placement of heat pumps in process-level HI (Klemeš et al., 2014). Nemet et al. (2016) have attempted a simultaneous synthesis of the HENs at the process and TS levels, accounting for heat losses, piping and its cost, pressure and temperature drop for fluid transport, heat exchanger types. One key development, following the LIES concept, has been the integration of low-grade waste heat with district heating systems (Kapil et al., 2011). The study has evaluated the techno-economic feasibility of over the fence Heat Integration of low-grade heat sourced from an industrial site with district heating network. For hot climates, district cooling is of higher benefit to municipalities.
This is also a good potential user of industrial low-grade heat. Liew et al. (2015) developed a procedure for integrating absorption chillers with industrial TS for simultaneously reduce the site cooling demand and enable district cooling. Specifying a single uniform value for ΔT_{min} for all processes on a Total Site is often too simplistic. This can lead to the underestimation or overestimation of the overall site-wide heat recovery. The results can be infeasible or oversized designs. Tackling this issue, Fodor et al. (2010) initiated a key revision in the Total Site specifications, accounting for the heat transfer properties of each site process using process specific minimum approach temperatures. The idea has been fully developed Varbanov et al. (2012), developing all the concepts and a modified Total Site targeting procedure that allows estimating the heat recovery potential of

Total Sites (Figure 7), which is closer to the reality. Fodor et al. (2012) took the specification a step further to stream specific minimum approach temperatures to help reflect differences in stream heat transfer coefficient.

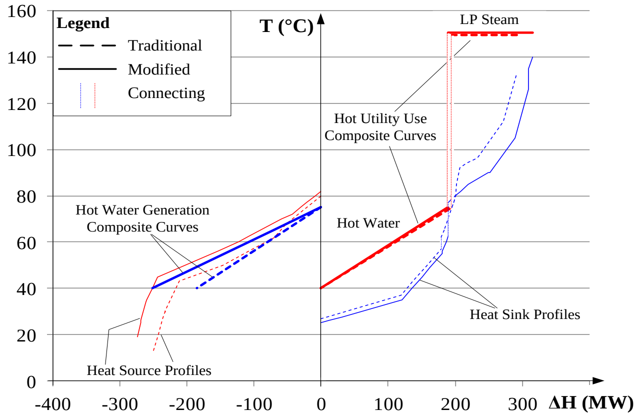


Figure 7: Total Site targeting with process specific minimum temperature difference (after Varbanov et al., 2012)

Methodology development has also occurred by extending the concept of assisted heat transfer to TSI for increase heat recovery and shaft work targets (Walmsley et al., 2016a). In further efforts to bring context to TSI targets, Yong et al. (2016a) discussed the nontrivial matter of data reconciliation for determination of inputs into TSI studies.

A very important part of targeting is total cost estimation. As part of this, (Nemet et al., 2012a) formulated a complete procedure for capital cost estimation at TS level. Wang et al. (2013) have added the consideration of distance into the evaluation. Wang et al. (2014) have further addressed the trade-off between direct HI between processes and indirect integration via the steam system, adding the costs for piping into the model. Mohd Nawi et al. (2016) extended the methodology into Regional and Total Site CO_2 Integration considering purification and pressure drop. Čuček et al. (2012a) added footprint analysis to TSI, to reflect the key environmental footprints, including GHG, water, and Nitrogen Footprints (Čuček et al., 2012d). It has revealed an adversarial relationship between Nitrogen and GHG footprints. That effort has been further followed up (Čuček et al., 2013) by extending the TS scope to the regional scale and applying multi-objective optimisation. Čuček and Kravanja (2014) have also developed a numerical tool framework for energy targeting and retrofitting of TS based on a transhipment model. These ideas have been combined in a comprehensive mixed integer nonlinear programming (MINLP) model for synthesising TS systems with improved sustainability, where the criteria for economic performance, environmental footprints and safety have been considered.

Utility systems energy generation efficiency and optimisation have also played a critical role for industrial sites with low Pinch Temperature processes such as dairy factories (Walmsley et al., 2016b). Tarighaleslami et al. (2016a), following up on (Liew et al., 2014b), proposed additional heuristics for enabling more efficient representation and evaluation of Total Sites using non-isothermal utilities. A key part of TSI is Heat and Power Integration (HPI). An interesting development has been proposed by Chen and Lin (2011) by considering joint energy management of the heat recovery and steam distribution systems on a site. In an effort for improving the overall energy efficiency of utility systems and processes on a TS, Walmsley et al. (2016a) have proposed the concept of “Assisted Heat Transfer”, which exploited the pockets in the process Grand Composite Curves for improved heat recovery and/or improved power cogeneration. Other notable developments have been fine-tuning of the shaftwork targeting model (Ghannadzadeh et al., 2011) as well as of the selection of steam headers (Prashant and Perry, 2012), the application of exergy-economic optimisation to TS analysis (Ghalami et al., 2012). Nemet et al. (2012b) have shown how the TS methodology can contribute to the strategic development and the extension planning of an already existing TS and Nemet et al. (2012c) the methodology for maximising the use of renewables with variable availability. The TS method has also been applied to the optimal synthesis and PI of biorefineries (Pyrgakis and Kokossis, 2016).

3.2 Total Site safety, operability, management and planning

Another direction of improvements has been the consideration of operational flexibility on TS. Liew et al (2013) have considered energy supply and demand variations on the scale of weeks, months and seasons. Safety has been of a serious concern in Process Optimisation (Chew et al., 2013a). Liu et al. (2015) have addressed safety issues for TS heat recovery, comparing direct and indirect modes. The result indicates that indirect HI bears less risk and less unexpected heat loss compared with the direct mode. Nemet et al. (2015) have considered

TS safety issues by applying Mathematical Programming and formulating a MINLP model, also accounting for the economics. That resulted in obtained TS HENs by applying the described methodology were inherently safer and yet economically viable. This work has been supplemented by Nemet and Kravanja (2017), embedding the safety considerations into an overall procedure for HEN synthesis on Total Sites for improved sustainability (Figure 8).

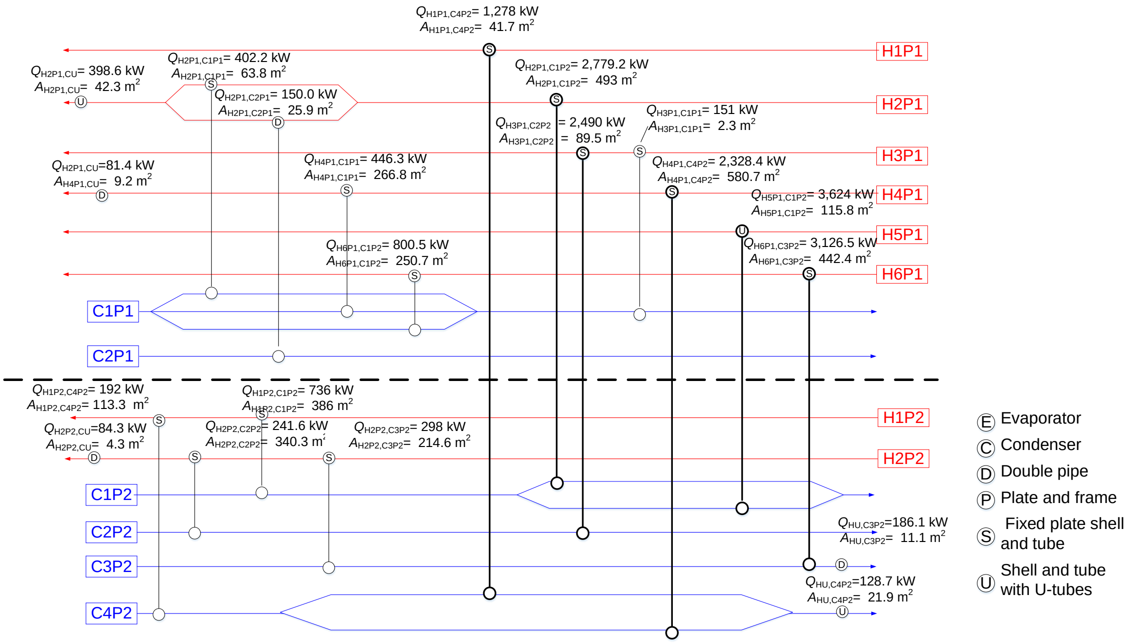


Figure 8: Minimising the risks for sustainability in HEN and Total Site synthesis (after Nemet and Kravanja, 2017)

Investments for TS should be carefully planned, especially when it comes to safety improvement. This has been addressed in (Varbanov et al., 2016), where concepts and procedure for investment planning for safety improvement have been proposed, prioritising the investment instalments by maximising the safety improvement effect within each investment period.

Building on the comprehensive set of tools for utility systems operational optimisation (Varbanov et al., 2004) and synthesis (Varbanov et al., 2005), Smith et al. (2011) investigated the reliability issues related to that. They have developed an optimisation methodology minimising the Total System cost, accounting for utility system failures, maintenance requirements and operating strategies. Process control and implementation of indirect industrial heat recovery systems have also been a feature (Schumm et al., 2016).

3.3 Process improvement using Total Site Integration

The Pinch analogue from process level integration suitably also applies at the Total Site level. Drawing analogy from process-level heat recovery targeting (Klemeš, 2013), Chew et al. (2013b) have used the Total Site Profiles (TSP) and Site Composite Curves (SCC) to apply the Plus-Minus Principle for targeting process modifications. The findings illustrated the usability of the tool for identifying and justifying process modifications achieving improved site heat recovery. That has been further extended by a study (Chew et al., 2014) using process modifications for reduction of site capital cost. Similarly, the heat pump analogue from process-level integration has been extended to TSI using both mechanical and thermal vapour recompression integrated into the steam system (Liew and Walmsley, 2016).

Adding new processes to an existing Total Site requires consideration of the current Total Site Pinch and the Process Pinch locations of the new plant. Where there is a substantial difference between these Pinch locations, Atkins et al. (2015) demonstrated the potential for improved TSI. The integration of geothermal heat similarly follows that it must be integrated above the TS Pinch to reduce hot utility use (Atkins et al., 2016).

One area within TSI for non-continuous processing sites that has received sustained attention is Heat Recovery Loops (HRL). An HRL is a dedicated indirect heat recovery system at the Total Site level that connects multiple processes together (Atkins et al., 2009). Area and thermal storage targets can be set and optimised before design (Walmsley et al., 2012). This was extended to include analysis of storage temperature fluctuations and its effect on Total Site heat recovery (Walmsley et al., 2013b). This was extended to incorporate gaseous waste heat sources to further increase site wide energy efficiency (Walmsley et al., 2014a). This analysis led to investigate the best point of integration between an HRL and solar (Walmsley et al., 2014b) as well as modelling the impact on storage temperature for a fixed storage amount using historical industrial data sets (Walmsley et al., 2015a). The addition of nanofluids as a method for enhanced heat recovery for HRLs was also proposed (Tarighaleslami et al., 2015). The work was extended in a special issue to optimise the concentration of nanoparticles to maximising Total Site heat recovery (Tarighaleslami et al., 2016b).

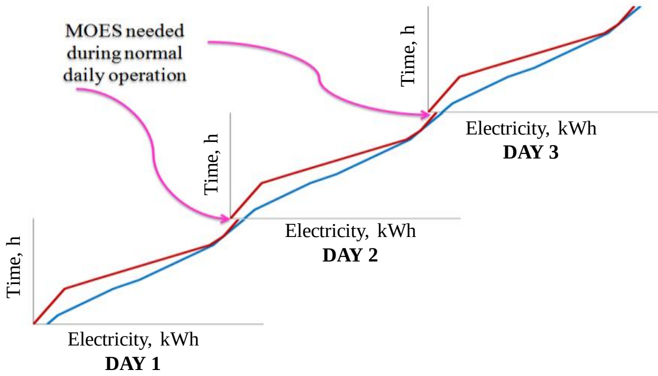


Figure 9: Continuous Power Composite Curves (Wan Alwi et al. 2012)

3.4 Industrial Applications

There have been successful applications of the theoretical developments for TSI. Matsuda et al. (2011) presented an application to a steel production site, where the waste heat from the steel plant has been successfully utilised in other site processes, resulting in primary energy savings. Another successful TSI application by Matsuda et al. (2014) has been used for planning actions for area-wide energy saving over industrial estates in Thailand, as well as heavy chemicals site in Japan (Matsuda, 2015). A TSI application to a chemical plant cluster of low-temperature processes has been presented by Hackl and Harvey (2012), investigating the exchange of low-temperature cooling utilities between the processes.

3.5 Site Power Management

A very important step in site management and planning has been made by the introduction of the Power Pinch Methodology. This has been done by a series of CET contributions, starting with (Mohammad Rozali et al., 2012) providing a method for the Design of Hybrid Power Systems (HPS, Figure 9) with energy losses. That has been followed by a number of other developments – optimisation of pumped hydro storage system for HPS using Power Pinch Analysis (Mohammad Rozali et al., 2013a) and in more extended form by Mohammad Rozali et al. (2013b), Electricity Load Reduction in Hybrid Power Systems Using Power Pinch Analysis (Mohammad Rozali et al., 2014a), Optimal sizing of hybrid power systems using Power Pinch Analysis (Mohammad Rozali et al., 2014b), Expansion of a Diesel Plant into a Hybrid Power System Using Power Pinch Analysis (Mohammad Rozali et al., 2015) and POPA-SHARPS: a new framework for cost-effective design of hybrid power systems (Mohammad Rozali et al., 2017). Giaouris et al. (2014) applied this principle to optimum energy management in smart grids based on Power Pinch Analysis and Chen et al. (2013) used a Process Integration technique for targeting and design of off-grid hybrid power networks. Lee et al. (2015) contributed to sustainable power plant planning using Pinch Analysis approach.

4. Water Integration (WI)

This is a branch of PI (Klemeš et al., 2014), where water sources (suppliers) and water sinks (users) are matched with the purpose of simultaneously minimising the intake of fresh water and the discharge of waste water. In the resulting water networks, in addition to the source and sink nodes, there can also be water purification nodes. The links between the nodes can be also complex, including recycles and complex loops. Poplewski and Jezowski (2009) have applied the strategy of stage wise design of water use networks. First, they propose to synthesise the network considering extreme cases, then, second, merging the designs to form a superstructure and solving the resulting Mathematical Programming problem. That work has been extended by Poplewski (2011) for multiple-contaminant problems, and further by adding regeneration operations (Poplewski, 2014).

Following a similar line, Statyukha et al. (2009) presented a procedure for data collection and preprocessing before a WI study starts. A tool for simplification of a complex water network flowsheet, usually resulting from initial synthesis, has been presented by Li and Chang (2011). It uses graph-based network evolution with the objective of minimum fresh water penalty. An enhanced model of water reuse networks is presented in Deng and Feng (2012), where additional constraints have been added for relating the water intake and the water effluent from the water-using operations. Another interesting innovation has been adding reliability analysis to the water network model (Du et al., 2013). A procedure for obtaining a target for regeneration stream flow rate in water-using networks has been proposed by Zhu et al. (2015) by improving the accuracy and eliminating inconsistent results. As a follow-up, Liu et al. (2016) presented an improvement of the targeting model for water using networks, involving regeneration reuse/recycling. Chen et al. (2009) developed a synthesis method for water reuse networks associated with batch processes. The task involves a combination of optimal design and scheduling, implemented as a MINLP minimising the total annualised cost. A follow-up (Chen et al., 2011) has considered the site-level optimal synthesis of water networks containing batch processes. Another site-level approach, using Genetic Algorithm has been proposed by Alnouri et al. (2014).

Semi-continuous water network optimisation has been addressed in (Dogaru and Lavric, 2011), accounting for water use, costs, storage design and operation schedule. The inter-plant water network optimisation has been further elaborated on in (Jia et al., 2015), accounting for constrained freshwater supply. Another improvement of the synthesis model and procedure for batch water networks has been developed in (Wang et al., 2016), where it is necessary to decide between various waste water treatment model. Pintarič et al. (2014) explored the variation of the results from water network synthesis with changing the objective function in the optimisation. They have reported a spectrum of optimal solutions worth considering and allowing the designers to make more informed choices. Pungthong and Siemanond (2015) have developed a MINLP model for the retrofit of water networks with multiple contaminants, solved in GAMS. (Fan and Liu, 2015) have considered a simple retrofit procedure involving adding water regeneration units. A case study on water management in a pulp-and-paper plant (Francisco et al., 2014), using the Water Sources Diagram (WSD) has been developed. The results indicate the suitability of the WSD to water reduction projects in industry. An interesting work minimising fresh water consumption in steelmaking has been developed (Alcamisi et al., 2015). The study indicates an up to 30 % reduction in water intake. An interesting innovation shedding additional light onto the design of water networks with multiple contaminants has been the introduction of the concept of “Concentration Potential” (Fan and Liu, 2016). Such a concept can be used for bringing the insight-based problem-solving to the multiple-contaminant problems, which are dominated by Mathematical Programming methods. Iancu et al. (2009) present the optimisation of a Waste Water Network for simultaneous minimisation of the freshwater consumption and optimal placement of the regeneration unit, through minimisation of active pipes' length, employing a graph-based tool. An interesting idea (Kollmann et al., 2014) has been to use waste-water treatment plants for generating extra energy and integrating them into regional energy infrastructures. A refinery-based study for wastewater treatment has been presented by Sueviriyapan et al. (2014). They have used MILP and MINLP models for obtaining optimal retrofit solutions. Following the fundamental holistic framework for cost-effective minimum water network design (Wan Alwi et al., 2008). Sujak et al. (2015) present a mixed-integer non-linear programming (MINLP) model for the synthesis of the optimal total water network. The study obtains a network design with minimum overall cost while considering all the essential trade-offs concerning water reuse, wastewater treatment plant and land area needed. The wastewater treatment is assumed to consist of primary and secondary treatment units. A similar study based on “material flow cost accounting” has also been presented by Wan and Ng (2015). Building on the previous water network tools, Fadzil et al. (2017), have developed and will present at PRES’17 a full-fledged WI concept based on the Total Site architecture, defining site-level water mains and optimising the water stream exchanges. A numerical targeting model and procedure have been provided in (Nikolakopoulos et al., 2016), which uses a variation of the transhipment model known from HI. The mathematical models for WHI network synthesis are usually very complex topologically and feature non-linear constraints. Ahmetović and Kravanja (2012) have investigated the possible solution strategies of such models. In comparing, the simultaneous model and solution showed better results than the sequential ones. The idea has been further developed to include the cases of synthesising Pinched and threshold heat-integrated process water networks (Ibrić et al., 2013). Alva-Argaez and Savulescu (2009) have presented a method to screen process water reduction projects for optimal retrofit of industrial energy and water networks, within the context of a pulp and paper plant. Chew et al., (2011) describes an industrial case study, applying combined WHI for a pulp-and-paper plant. They have applied data collection, simulation for data consistency check and then optimised the water network configuration using a commercial optimiser. A case study – on a sugar mill (Cortés et al., 2011) has identified the process flowsheet, the relevant water streams and operations, and has performed an optimisation, identifying water and energy savings above 60 %. An interesting application of WHI has been the design optimisation of seawater reverse osmosis systems by Alnouri and Linke (2013), based on a mathematically encoded superstructure.

5. Hydrogen Integration

Hydrogen Pinch or Hydrogen Integration has been a generic extension of HI. Hydrogen Pinch Analysis (HPA) is a hydrogen management method that originates from the concept of Heat Pinch Analysis. HPA is a systematic technique for reducing hydrogen consumption and hydrogen generation through the integration of hydrogen-using activities or processes in the petrochemical industry, petroleum refineries hydrogen distribution networks and hydrogen purification (Hallale et al., 2003).

The approach was based mainly on works of El-Halwagi et al (1989) and later extended by Hallale (2002). At PRES conferences this methodology was further extended and implemented in various processes. They have been mainly three research centres involved in the development – in Manchester, UK, in China and Iran. Imran et al. (2009) studied multi-period hydrogen management. Hydrogen management had been the research area dealing with the development of methodologies and approaches for the design and optimisation of refinery hydrogen networks.

Hydrogen management technology needed to account for varying operating conditions of hydrogen consuming processes and assumes constant operating conditions. A multi-period approach was developed for the design of flexible hydrogen networks that can remain optimally operable under multiple periods of operation. The proposed multi-period hydrogen management could account for pressure constraints, existing equipment, and optimal placement of new equipment such as compressors and purification units. Jia et al. (2010) developed a rigorous optimisation of refinery hydrogen networks. Optimisation of overall hydrogen networks was required to improve the hydrogen utilisation in oil refineries. Previous work over hydrogen management had developed methodologies for H_2 network optimisation. However, there were considerable limitations affecting the quality of optimisation. To overcome the previous drawbacks, the authors developed a rigorous modelling and optimisation approach has been developed. Light-hydrocarbon production and integrated flash calculation have been incorporated into a hydrogen consumer model. NLP (Non-Liner Programming) and SA (Simulated Annealing) optimisation methods were tested and used. A case study demonstrated the effectiveness of the developed approach. One of the key works was presented by Smith et al. (2012) dealing with hydrogen integration in petroleum refining. They stated that meeting the increased demands for hydrogen could require significant investment in, for example, steam reformers and compression equipment. Yet, most refinery hydrogen systems are inefficient and have significant room for improvement. By modifying the hydrogen network, perhaps with the recovery of hydrogen from tail gas, refiners can often satisfy the increased demands for hydrogen with much significantly reduced operating cost and investment. In recent years, systematic methods for the analysis of hydrogen systems have been developed and are now practised worldwide.

The assessment of hydrogen processes can be presented in a simple, graphical manner, which gives the engineer insight into process design, sensitivity analysis and operations planning. Targets can be set for hydrogen recovery and hydrogen plant production. Targets also give insights into the effective use of hydrogen purification units. Deng et al. (2014) dealt with flowrate targeting for interplant hydrogen networks. The improved problem table (IPT) was used to locate the flowrate targets of interplant hydrogen conservation network. The flowrate targets for individual hydrogen networks were located and the purge gas streams could be identified via IPT. The IPT was utilized to determine the flowrate targets for the overall interplant hydrogen network. The arising problems with multiple resources and purge gas streams were dealt with by IPT. The presented example showed the effectiveness and applicability of the proposed approach. Later Deng et al. (2015) analysed flowrate targeting for hydrogen network with an intermediate header. When hydrogen network of a refinery is integrated with the hydrogen consumption of Vacuum Gas Oil (VGO) hydro-cracking reactor considered and the quantitative relationship diagram is constructed, and the quantitative effect of the raw material oil's sulphur content and the inlet hydrogen flow rate of the VGO hydrocracking reactor to the Pinch location and the utility consumption are identified.

Tahouni et al. (2012) made comprehensive modelling of hydrogen network in petrochemical complexes. Their study was aimed to propose a new optimisation mathematical model for hydrogen management in petrochemical complexes based on setting a comprehensive superstructure model. This superstructure including purifier and compressor of hydrogen plant or catalytic reformer unit offered more improvements. Li et al. (2007) predicting target values of hydrogen networks with purification unit. They stated that when the Purification Pinch of a hydrogen network involving purification does not change, the target values at a certain purified concentration can be predicted easily and accurately based on the known target values at original purified concentration.

Related works dealt with design space approach for storage sizing of hydrogen fuel cell systems through Pinch Analysis (Ghosh et al., 2015). Inayat et al. (2011) used a Heat Integrated flowsheet designed for hydrogen production from oil palm empty fruit bunch (EFB) via steam gasification with in-situ CO_2 capture. The process energy requirement and cost are calculated from the mass balances, energy balances and the economic model of flowsheet. The flowsheet calculation and cost minimisation are carried out using MATLAB. The flowsheet under investigation includes steam generation unit, gasification unit and gas cleaning unit. For Heat Integration studies on the flowsheet, the Pinch Analysis is employed to obtain the energy efficient and self-sustained system. The heat integration study is carried out using SPRINT software.

6. Environmental Footprints

Sustainable development is closely related to the three dimensions namely economic, environmental and social. Since 2009, the environmental footprint has been added to the discussion topic of the conference. The environmental assessment has been the important criteria in considering the sustainability of the integrated system for energy conservation.

Tan and Foo (2009) reviewed the development of Pinch Analysis for the management of carbon emissions and footprint problems, particularly the Carbon Emission Pinch Analysis (CEPA). The extended application of CEPA has been developed on the use of Graphical Pinch Analysis for determining strategies to meet corporate carbon intensity benchmarks. The Pinch Analysis approach was further developed to enable the use of more than one quality index at a time, namely the Multiple Index Pinch Analysis method (Patole et al., 2016). All quality indices (carbon footprint, EROI, land footprint, water footprint etc) were combined. This overcame the limitation of the previously developed Pinch Analysis approaches to sustainable energy system planning.

Čuček et al. (2012c) introduced a procedure to evaluate the key environmental footprint for heating and cooling sites and the heat distribution system. The standard design criteria for TS system has been originally economic in nature, this study includes the carbon footprint which is relatively common, nitrogen footprint as well as the water footprint. It has led to the future work of balancing and reducing key environmental footprints within TS.

Novak Pintarič et al. (2015) proposed a novel approach to economic evaluations of projects where the trade-offs need to be established between the economic efficiency and environmental impacts. The new indicator-marginal footprint was developed. This indicator is useful for investment decision making when balancing the conflicting objectives for process design selection that acceptable to the investors, environment and society.

Francisco et al. (2014) proposed Carbon Sources Diagram (CSD) based on the Source Diagram Concept. The CSD was developed to locate the rigorous targets for both low and zero-carbon energy sources for carbon-constrained energy planning. The CSD algorithm shows equal values as those obtained by other methodologies and reported to have the simplicity to obtain. Al-Mohannadi et al. (2015) presented a multi period carbon integration approach to determine cost optimal carbon allocation networks over time to achieve the overall reduction of footprint. Other than the composite index as presented by Patole et al. (2016) according to the Pinch approach, Environmental Performance Strategy Map has been introduced by De Denedetto and Klemeš (2009). A single indicator namely Sustainable Environmental Performance Indicator was proposed as communication tools. Environmental index (Jamaludin et al., 2016) has also been developed for palm oil mill to enhance the competitiveness of the industry. Waste management is an important area of footprint study.

The improper management contributes the negative impact on the environment while a proper management could offset the burdening effect and the waste can be used as a resource. Ng et al. (2013) proposed a MILP model for MSW allocation networks in small cities and in Ng et al. (2014) it was further worked out. Fodor and Klemeš (2010) studied waste as alternative fuel and minimising emissions and effluents by advanced design. The study considered a range of waste to energy processing. It has been contributed and documented to the study by Tan et al. (2014), as one of the models for solid waste management that optimise on both the economy and environment. Few LCA studies reported the transportation stage produced more carbon footprint than the production. This highlight the potential of carbon emissions footprint reduction through the management of supply chain management.

Čuček et al. (2012d) optimised the biomass energy supply chains through an approach where the number of direct environmental footprints are minimised through correlation. A methodological framework for supply chain carbon footprint management has been developed by Aivazidou et al. (2013). This framework is a stepping stone for implementation in a major manufacturer of insulating materials. The footprints assessment has also been discussed in term of building structure and housing sector. Čuláková et al. (2012) illustrated the floor, exterior wall, ceiling and roof alternatives which have the lower carbon footprint for green design of a house. The carbon and ecological footprint have been considered by Shahzad et al. (2016) in the study of conventional and innovative lighting technology to ensure the energy saving does not compensate with the environmental performance and vice versa.

It is suggested that Light Emitting Diode (LED) lamp decreased the energy consumption by a factor of 1 - 4 and have a lower footprint compared to high-pressure sodium lamp. The percentage contributions of each construction material in carbon footprint were presented by Gardezi et al. (2015). The major carbon footprint was from concrete and bricks where a significant reduction can be achieved by using the recycled materials varied from 25 -100 %. The environmental footprint of food production has also been studied.

Walmsley et al. (2015b) suggested that grains based foods were more environmentally friendly than the animal based food. Analysis of footprints and global flows of energy and water has been performed (Figure 10) – first analysing the international trade (Liu et al., 2015) and then analysing the flows from the viewpoint of product consumption (Liu et al., 2017).

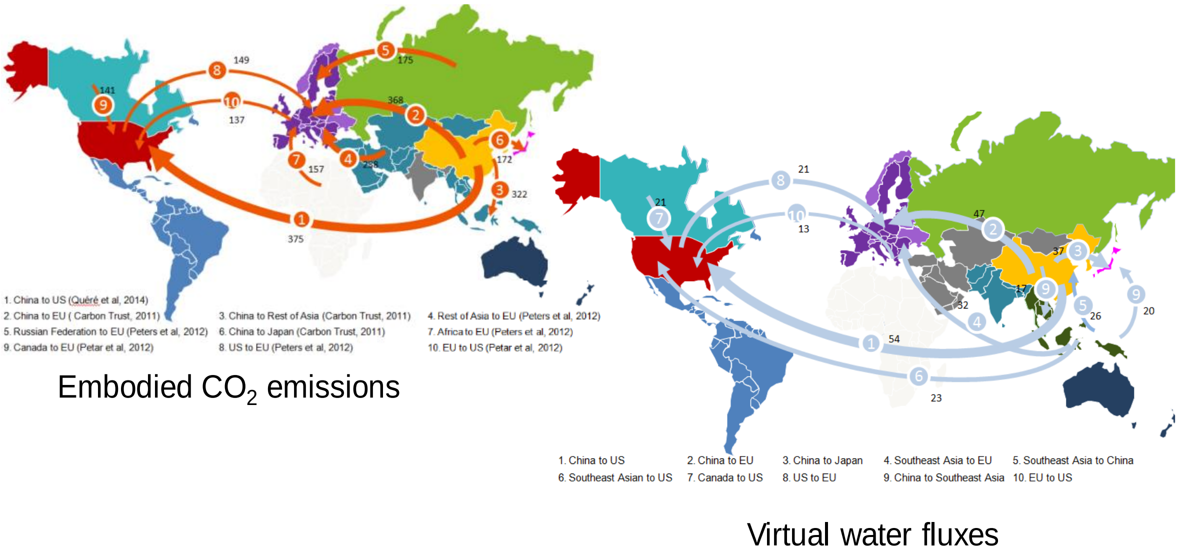


Figure 10: Virtual Carbon and Water Footprints in International Trade (amended from Liu al., 2017)

Klemeš et al. (2017) recently presented a review on the virtual carbon emission and water footprints embodied in the global trade. Their study highlights the importance of considering the virtual footprint in modelling and assessment. The contribution of environmental footprint related study is expected to increase with the global environmental concern.

7. Renewables

The renewables are considered as a very important issue attracting a lot of research attention. PRES conferences have this topic as one of the key issues. Just to demonstrate the attention attracted by renewables: The EU Renewable Energy Directive (2016) established an overall policy for the production and promotion of energy from renewable sources in the EU. It requires the EU to fulfil at least 20 % of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets.

All EU countries must also ensure that at least 10 % of their transport fuels come from renewable sources by 2020. On 30 November 2016, the Commission published a proposal for a revised Renewable Energy Directive to make the EU a global leader in renewable energy and ensure that the target of at least 27 % renewables in the final energy consumption in the EU by 2030 is met.

One group of paper have been dealing with biofuels.

Martínez-Patiño et al. (2012) integrated renewable energy to power, heat and water systems. Their paper presented the integration of photovoltaic power for running a heat and water system. It looked at the effect of power quality upon the efficiency of the pumping system. From the electrical point of view, there were pointed various factors that determine the quality of power; failure to recognise them may result in adverse thermal and throughput effects. Bonet-Ruiz et al. (2010) presented a simulation of a continuous process for biodiesel synthesis from triacylglycerol based on different topologies.

Tangkathitipong et al. (2014) studied hydrogen and methane production from biodiesel wastewater with added glycerine by using two-stage anaerobic sequencing batch reactor (ASBR). The two-stage ASBR system was operated at different COD loading rates (ranging from 33.75 to 84.38 kg/(m^3 d) based on the hydrogen ASBR system or 5.63 to 14.06 kg/(m^3 d) based on the methane ASBR system) to study the effect of organic loading rate on both hydrogen and methane production. The highest hydrogen and methane production performance was found at a COD loading rate of 67.50 kg/(m^3 d) and 11.25 kg/(m^3 d) based on hydrogen and methane reactors. Shahzad et al. (2014) studied biogas production from intercropping (Syn-Energy).

The increased cultivation of energy crops to fulfil energy requirements have led to the necessity of optimisation of bio productivity of the available land use, which should be carried out without compromising on the land quality and environmental conditions. Syn-Energy II was an Austrian national project focussing on the possibilities of synergetic expansion of agricultural biogas production.

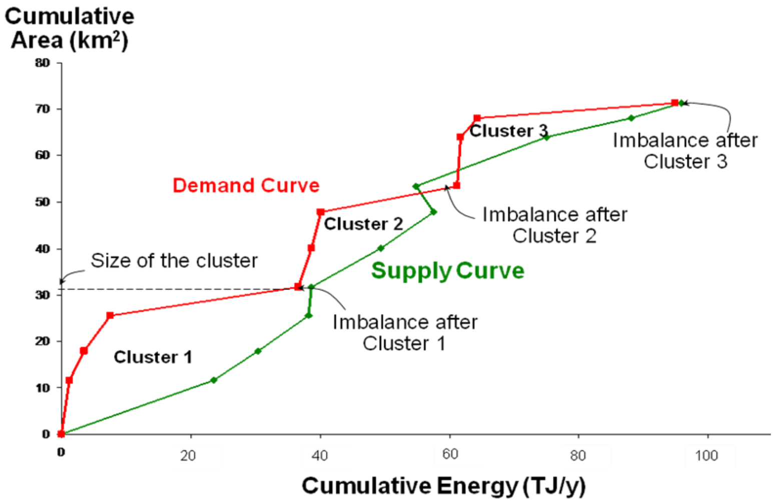


Figure 11: Regional Biomass Supply Chain Curves (amended after Lam et al., 2008)

The field experiment results revealed that cultivation of intercrops for biogas production between the main crops enhances crop rotation yields, while it reduced erosion, GHG emissions and ground water pollution. Similarly, synergetic calculations were made for conservational soil cultivation and biological crop rotation systems. Taking these considerations to the supply chain and regional level, Lam et al (2008) have developed Regional Biomass Supply Chain Curves (Figure 11), allowing to target and plan the regional biomass energy generation and distribution, minimising GHG emissions. This work has been further extended to a method for regional resource management and planning (Lam et al., 2011).

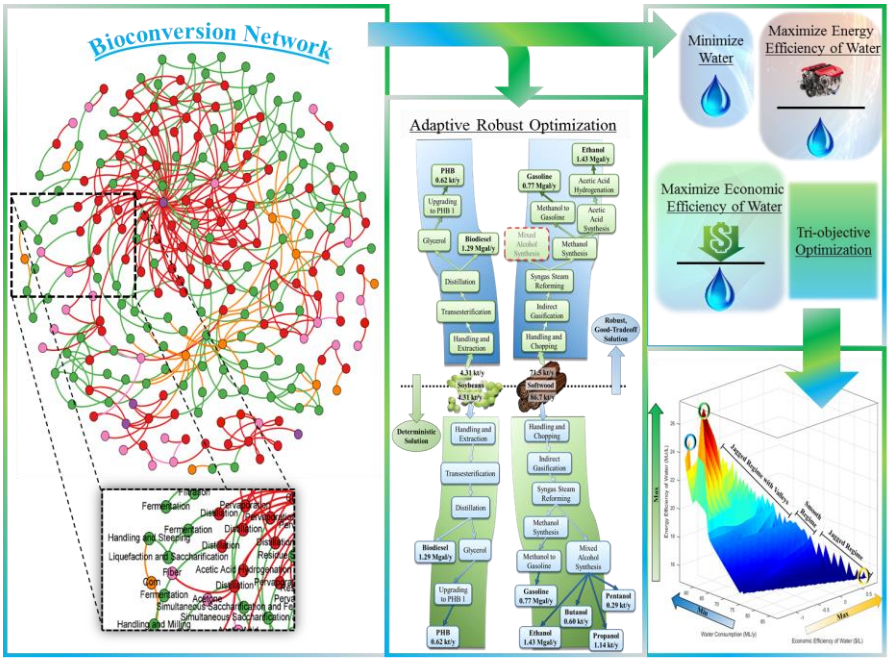
Garcia and You (2015) have investigated the optimisation of the water-energy nexus over the process and product networks (Figure 12). While economics and emissions of these processes have been studied and optimised at length, the critical component of water consumption should be considered, as future water scarcity has been identified as a key challenge. This work compiles a network of hundreds of bioconversion technologies and aims to optimise them over the objectives of production cost and water consumption. The water efficiency of energy (WEE) is also calculated. Water consumption is considered from biomass cultivation to processing, providing a better glimpse into the true consumption of this resource throughout the value chain.

Kiraly et al. (2013) presented a dynamic multi-objective synthesis of companies' renewable biomass and energy supply-networks. The previously developed model has been extended for the use of variable supply and demand. In the case of variable supply, monthly durations of sunlight hours regarding different locations have been considered and the electricity production differs according to time and space. In the case of variable demand, monthly variations have been taken into consideration regarding demands for the more important products. For evaluating the sustainability of the companies' supply networks, different environmental footprints, such as carbon, water, and nitrogen footprints have been included (Kiraly et al., 2013).

An approach measuring the environmental footprints within a LCA-based synthesis was carried-out by considering the total-effects (burdening and unburdening) on the environment (Čuček et al., 2012b). Niemetz et al. (2012) presented RegiOpt conceptual planner Identifying possible energy network solutions for regions. Regions are in the focus for the provision of energy carries like wood, cellulosic material and energy crops. Different regions have a variable setup of resource availability. RegiOpt tried to simulate possible energy network solutions based on the local conditions of every problem definition. The idea was to combine two proven tools to a single user-friendly program. RegiOpt – Conceptual Planner (RegiOpt-CP) is a web based program which is intended to be used by regional actors and decision makers. It offered the possibility to apply a simple way an optimal energy technology structure based on PNS optimisation.

In addition, the optimal solution is evaluated automatically with the SPI method and the results present the ecological footprint information.

A continuous adjustment and variation of calculation values improve the capability of RegiOpt-CP for calculating a set of different scenarios which might be applicable for the specific region. Mian et al. (2014) integrated of supercritical water gasification in combined 1G/2G ethanol production. They investigated the potential conversion of sugar cane into ethanol and synthetic natural gas. The considered conversion path consists in combining ethanol first and second-generation ethanol production plant with a catalytic supercritical water gasification system.



- Comprehensive biomass conversation network with >200 technologies and products with "*big data*"
- Modelling water-energy nexus for biomass utilization and conversation
- Adaptive robust optimization for uncertainty

Figure 12: Water-Energy Nexus for a bioconversion network (adapted after Garcia and You, 2015)

The main steps of the ethanol conversion consider fermentation of sugars (1G) and enzymatic hydrolysis of bagasse (2G). Enzymatic hydrolysis is selected since it represents a promising alternative for 2nd generation biofuels due to its high conversion efficiency. Among streams that are leaving the ethanol production plant are some high watered streams, whose carbon/energy content is not negligible. These streams should be valorised in an efficient way to improve the energy conversion efficiency. In this context, supercritical gasification process allows valorising these flows leaving the ethanol plant. Using supercritical water gasification, it is, in fact, possible to avoid the drying the ethanol production leftovers, thus performing a direct gasification.

Heckl et al. (2015) designed sustainable supply chains in the energy-water-food nexus by the P-graph methodology. This framework was demonstrated as an effective means of generating alternative networks which can represent the nexus of energy, water, and food to identify the most cost effective and sustainable options.

Chen et al. (2015) presented an interesting study of retrofit of a resilient hybrid power system for a remote island. The electricity network used a diesel fuel power plant as the main power source and was be supplemented with wind turbines, where part or all of the generated electricity from the wind turbines is used to pump water into the upper reservoir as storage enabling the continuous and reliable hydro power.

The role of this pumped hydro storage (PHS) is to support the hybrid power system (HPS) and to smooth the unstable and uncontrollable renewable power sources. Based on the proposed superstructures for the hybrid power system, the hybrid power system retrofit problem is formulated as a mixed-integer linear program (MILP) with power losses during the allocation of power generated from power supplies to power loads or PHS. Tarmizi et al. (2015) presented multi-period planning of centralised sewage treatment plant for electricity generation in Iskandar Malaysia.

A source of energy is biogas release from sewage treatment plant (STP) which contains up to 70 % methane. Regretfully, the biogas is commonly flared or release to the atmosphere. The main objective of this study was to develop multi-period planning of centralized sewage treatment plant (CSTP) for electricity generation in Iskandar Malaysia. It can be divided into 5 stages; problem formulation and superstructure construction, data gathering, mathematical modelling, General Algebraic Modelling System (GAMS) coding and result analysis. This model is used to propose the optimal network and location to build CSTP which can meet electricity demand.

An interesting application of P-graph to multi period optimisation (Figure 13) of isolated energy systems has been proposed by Aviso et al. (2016), obtaining economically optimal and flexible network designs.

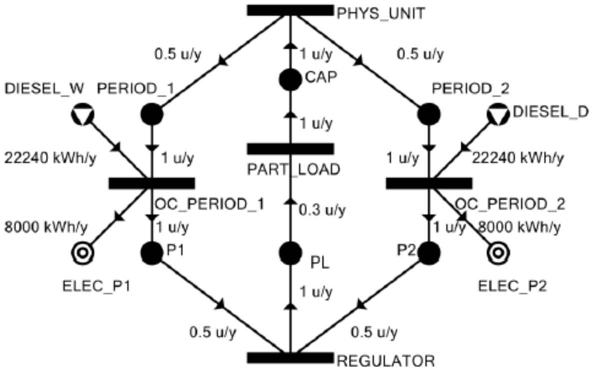


Figure 13: Multi-period P-graph representation for Diesel Engine (Aviso et al., 2016)

Šomplák et al. (2013) presented a logistics model for waste management, intended for decision making (Figure 14). The mathematical formulation has been evaluated and tested on a case study with data from the Czech Republic. The team has further extended the model to a tool for policy making (Šomplák et al., 2014).

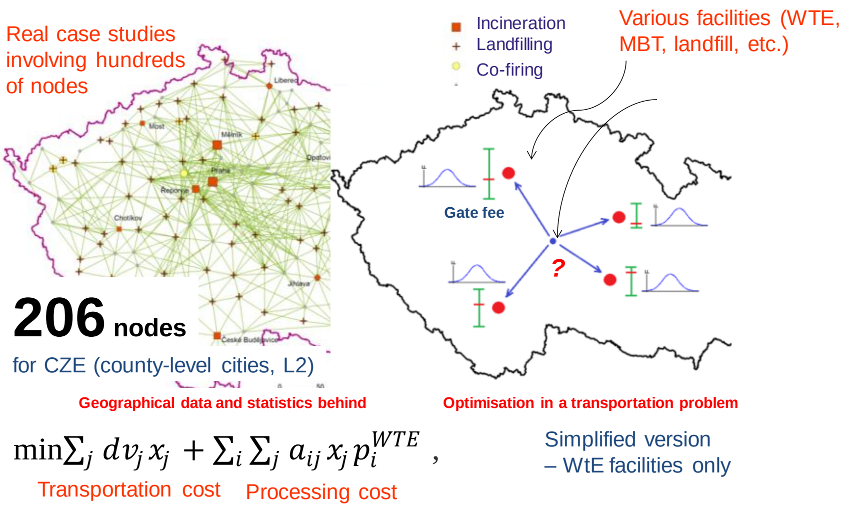


Figure 14: Logistics optimisation in Waste to Energy (after Šomplák et al., 2013, 2014)

8. Industrial applications

Process Integration of Milk Powder Plants has been the subject of several PRES contributions. The challenges involved in the integration of milk powder and other dairy process were outlined by Atkins et al. (2009). These included the semi-continuous operation covering start-up, processing and cleaning, the need for thermal storage, and the seasonal variability of milk feedstock. Walmsley et al. (2013d) showed the practical importance of steam temperatures on heat recovery targets and HEN design for a milk powder plant. Further energy efficiency gains with a 78 % steam reduction in a highly favourable exchange for electricity use were later identified in the multi-effect evaporation system using Pinch Analysis (Walmsley et al., 2016c) and synthesised into a general method using TSI (Walmsley, 2016d). Combining the optimal integration and design of each individual component including the utility system (Walmsley et al., 2016c) and looking to future technological developments, Walmsley et al. (2017b) concluded that future ultra-low energy Milk Power Plants can decrease steam use from 5,265 MJ/t of product to 2,557 MJ/t of product. Energy efficiency plays a significant role as the basic factor of competitiveness and sustainability of a company.

Semkov et al. (2017) identified the opportunities for energy efficiency improvement of a medium sized meat production company. The proposed method that based on process integration, waste heat recovery and reduction technology have greatly improved the overall efficiency improvement. An industrial application of Mixed Integer Non-Linear Programming (MINLP) mathematical model has been developed by Dobrez et al. (2011) to efficiently transform agro-industrial by product and animal waste of a large-scale meat company into biogas for simultaneous heat-integrated biogas process and HEN synthesis. The superstructure model of Yee and Grossman (1990) has been further developed. MINLP approach has also been used to design the reverse osmosis (RO) network. The optimal design parameters and operating policy with the minimum total annualised cost for RO desalination process were presented by Sessi and Mujtaba (2011). The seasonal variation in seawater temperature has a significant effect on the design and operation of RO system.

Aziz at al. (2016) proposed an integrated system for co-production of H_2 and power from brown coal by adopting the enhanced process integration technology. A total energy efficiency of 90 % has been achieved. Other than integration or management approaches, energy efficiency can also be improved by reaction efficiency improvement. Kosivtsov et al. (2016) improved the quality of gaseous products from fast pyrolysis of agricultural waste using zeolite catalysts. The decrease in the tar content, as well as the increase in C1-C4 hydrocarbon and hydrogen concentration of the gaseous product, led to energy efficiency enhancements for an energy intensive industrial process.

Various studies have been conducted to minimise resources consumption without compromising the process performance. The integrated scheme introduced by Tohăneanu et al. (2014) achieved the energy saving of 35 % for hot utilities and 37 % for cold utilities. The proposed design of two-column distillation configuration could produce high purity acetone. Manenti et al. (2013) present a method to increase methane yield and steam generation simultaneously by means of the model-based integrated energy-process optimisation. This energy-process optimisation offers an additional revenue of 3.79 %. There are different available processes for converting the natural gas to synthesis gas.

Chen and Wakelin (2013) studied the optimal combination of process type, production scale as well as the exchange of materials and energy. The potential capital cost savings were identified by integrating different syngas utilising processes with a common syngas plant. However, emission and transportation were not considered in this model, where further development is required. Different control schemes have been introduced to control the complex processes in industry. A multi loop digital plant-wide control scheme utilising PID controllers has been designed by Ipsakis et al. (2013) for an integrated liquefied petroleum gas (LPG) reforming fuel cell accumulator system. It was able to minimise the system start up time, eliminate temperature overshoots as well as effectively alleviate the process disturbances during operation.

Kyriakides et al. (2016) designed an optimal model predictive controller (MPC) scheme for low-temperature methane steam reforming using model predictive control method. The proposed can exploit the predictive properties of the reactor model to compensate for the disturbances affecting the processing system. Further development was suggested to minimise the fuel consumption and maximise the hydrogen separation.

9. Conclusions

PRES conferences have brought, during the 20 y of their annual organisation, a wide spectrum of novel ideas and contributed to extensions of multidisciplinary subjects related to sustainability. Their initial idea was based upon Heat Integration pioneered by the Centre for Process Integration at UMIST, Manchester. That methodology has been consistently extended into the water, combined energy and water, hydrogen and the other fields including environmental footprints and use of renewables. Besides techniques based on Pinch analysis, a substantial contribution also comes from methods using mathematical programming. The methodology has also grown into extension from single processes into Total Sites (TS) and Localy Integrated Energy Systems (LIES) and later even to the integration of sustainable regions (Yong, et al., 2016b). Very important part contributing the verification and further extensions have been industrial implementations.

Much of the success has been due to the Process Integration Research Consortium pioneered and continuously run by UMIST and later by The University of Manchester. However, substantial contributions brought also European Union co-financed projects under several framework programmes and presently H2020. A very substantial step forward for PRES conferences has been the recent growth of participation from Asia. This part of the World has been developing considerably at fast pace employing best practices and new technologies, having a deep impact on the quality of life of substantial part of the world population.

The PRES series of conferences has been the catalyst for a host of developments – all inter-related. The fundamental result has been, of course, the stimulation of creative discussions and further important research – including theoretical development in the traditional Process Integration areas. Many successful and useful industrial and other practical implementations have been performed, resulting in sizeable savings of energy, water and other resources. Moreover, researchers from neighbouring fields have been attracted to the discourse initiated at PRES, bringing their own contributions to the multi-disciplinarily of the conference – including areas such as biomass processing, waste processing, environmental impact assessment and ecological services.

The considerable impact has been realised by many workshops organised before, during and after each of the conference venues, resulting in efficient knowledge transfer and additional exchange of ideas.

Acknowledgments

The research has been supported by the project Sustainable Process Integration Laboratory – SPIL, No. CZ.02.1.01/0.0/0.0/15_003/0000456, funded by European Research Development Fund, Czech Republic Operational Programme Research, Development and Education, Priority 1: Strengthening capacity for quality research. Acknowledged are also all authors who published their innovative works in Chemical Engineering Translations and made PRES conferences successful and continuously running for twenty years already.

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