INSPIRED BY THERMODYNAMICS: TOTAL SITE INTEGRATION FOR ENERGY SAVINGS AND REDUCTION OF GREENHOUSE GAS, WATER AND NITROGEN FOOTPRINTS

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ABSTRACT

Large amounts of energy are generated and used, most of them relying on fossil fuels. The resulting costs and emissions are reduced to a large degree by applying heat recovery. Process Integration (PI) was developed originally from Heat Integration, which remains the cornerstone for PI continuous advance – especially into Total Site Integration. It has been closely related to the development of Chemical Engineering Mechanical and Power supported by the extended implementation of mathematical modelling, simulation and optimisation, and by the application of information technology. Its development has accelerated over the years as its methodology has been able to provide answers and support for important issues regarding economic development – better utilisation and savings regarding energy, water, and other resources. This contribution provides an overview of the research developments and the software packages, mapping the developments to the new challenges posed by the need to account for the process sustainability.

INTRODUCTION

Reducing and economising of resource consumption can be achieved by increasing the internal recycling and re-usage of energy and material streams. Projects for improving process resource efficiencies have proven to be beneficial and potentially improve the public's perceptions of companies. Motivating, launching, and carrying out such projects, however, involves proper optimisation, based on adequate process models. Several methodologies have emerged during the1970s as a response to the industrial and societal challenges connected with the oil crises and a need to use resources more economically. One was "Process Integration" (PI) – at that time more precisely "Heat Integration" – HI [1]. HI was first formulated within the book presented by Linnhoff et al. [2] that has been reprinted several times – last updated edition was in 1994. Its development was further contributed to by a number of works from UMIST, Manchester, UK and other research groups in the US, Europe, and more recently by a strong contribution from Asia [3].

PI, which covers a wider scope of tasks, is a family of methodologies for combining several parts of processes or whole processes for reducing the consumption of resources or harmful emissions into the environment. It started mainly as Heat Integration (HI) stimulated by the energy crises of the 1970s. HI has been extensively used in the processing (as chemical, petrochemical, pulp and paper, food and drinks, steel making) and power generating industries over the last 40 years. It examines the potential for improving and optimising the heat exchange between heat sources and sinks in order to reduce the amount of external heating and cooling, together with the related cost and emissions. It provides systematic design procedures for energy recovery networks. PI has several definitions, almost invariably referring to the thermal combinations of steady-state process streams or batch operations for achieving heat recovery via heat-exchange. More broadly, the definition of PI, as adopted by the International Energy Agency [4] reads as:

'Systematic and General Methods for Designing Integrated Production Systems ranging from Individual Processes to Total Sites, with special emphasis on the Efficient Use of Energy and reducing Environmental Effects.'

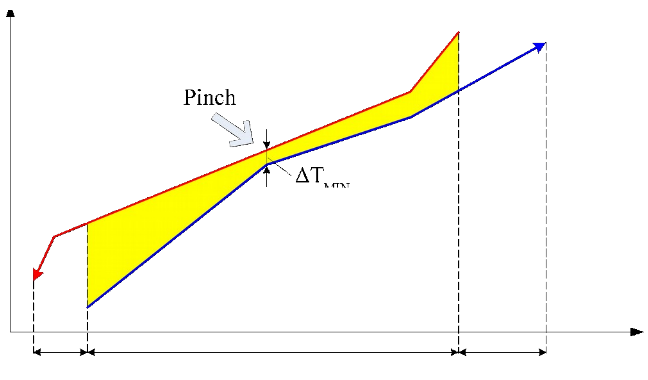

Figure 1. Composite Curves for intra-process heat recovery (after [2])

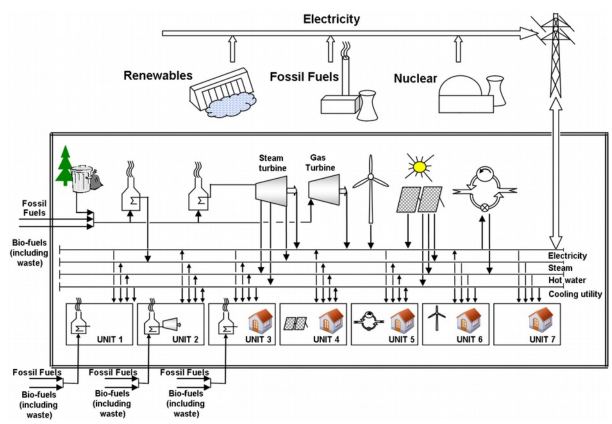

Figure 2. Locally Integrated Energy Sectors (after [7])

The PI methodologies started with HI, where the main innovation has been setting heat recovery targets before proceeding to the system synthesis – based on the concept of Composite Curves (Figure 1). Setting targets for HI was widely publicised by Linnhoff et al. [2], followed by

Klemeš [3]. There has been a very extensive development of the PI family of methods [5] and one of the most used is Total Site Integration (TSI) [6], which has united inter-process heat recovery at the site level with power co-generation on-site, providing tools for targeting and synthesis of the utility system and Locally Integrated Energy Sectors [7] , as well as targeting which site processes have the highest marginal benefit for potential HEN retrofit (Top-Level Analysis) [8].

The current contribution provides an overview of the historical development of the PI and TSI methodologies and analyses which extensions are necessary, to respond adequately to the contemporary challenges in terms of sustainability evaluation and improvement.

DEVELOPMENT OF THE CONCEPTS AND TOOLS

TSI considers an industrial site as a set of processes exchanging utilities – process heating, cooling, refrigeration, power, water via the site utility system as a marketplace.

Total Site (TS) interfaces

Analysing a TS involves identification of the process heating and cooling requirements, estimation of the targets for minimum fuel use, power cogeneration and power import. Heat Sinks and Heat Sources represent the process heating and cooling demands. They are characterised by starting and final temperatures, and enthalpy changes. Initially, the TS data extraction was performed graphically using the process Grand Composite Curves [6]. After introducing the TS Heat Cascade [9], the TS Problem Table Algorithm [10] performed this numerically. These works reveal requirements to the software tools for supporting data transfer between the various stages: simulation, synthesis, simulation and optimisation, site-level studies.

Site-wide heat recovery

The other developments are process-specific minimum-allowed temperature differences incorporated in the targeting procedure [11]. Liew et al. [10] proposed concepts and an algorithm for obtaining the targets numerically. They include the TS Problem Table Algorithm and evaluation of the system sensitivity.

Cogeneration within the Site Utility System

The cogeneration targeting using the SUGCC in [12] uses "the T-H model" – based on equivalent heat flows through the steam system. A power generation model developed by Mavromatis and Kokossis [13] for backpressure turbines, was extended by Shang and Kokossis [14] to condensing steam turbines and steam boilers. Varbanov et al. [15] presented a refinement of the steam turbine model, adding models for gas turbines and the complete steam networks, using them for utility system synthesis [16]. Luo et al. [17] have modelled utility systems containing multiple extraction steam turbines in GAMS [18]. Pouyan Rad et al. [19] studied the design and optimisation of utility systems accounting for reliability.

Utility system synthesis, analysis retrofit and planning

This aspect has been researched for a few decades using mainly mathematical programming. Among the numerous works have been multiperiod formulation [20], complete utility system synthesis [16]. Luo et al. [21]) treat the utility system and process heat recovery simultaneously. Top-Level Analysis [7] is used to select the processes for most profitable heat recovery retrofit by building a set of curves for the marginal steam prices. Liew et al. [22] presented the framework for targeting retrofits of the utility system and process changes employing algorithmic estimates of the thermal efficiency. Planning of utility systems has been addressed by Liew et al. [23]. They considered potential storage of utilities, variation scenarios, sizing of the main facilities and backup generators.

Power Planning for Total Sites

Wan Alwi et al. [24] developed power planning method for systems comprising hybrid energy sources determining the targets for minimum outsourced power storage. The further development also includes optimising process modifications and load shifting [25] and accounting for power losses [26]. Zahboune et al. [27] presented sizing autonomous power management system, harvesting wind and solar sources. A study combining Total Site heat recovery with power and CO_2 emissions management has been also published [28].

CHALLENGES AND INDICATORS TO CONSIDER

It can be seen that from the viewpoint of concepts and algorithms, the PI and TSI areas have developed well, with diverse applications. However, beside the realisation of the direct link between fuel use, fuel savings and CO_2 emission reduction, the evaluation of the environmental impact and sustainability contributions of the processes have not seen strong development. It is necessary to add the consideration of appropriate indicators and embed them in the system models. Such indicators can be [29] Carbon footprint, Water footprint, energy footprint, GHG footprint, Nitrogen footprint. An initial attempt to perform such an evaluation has been performed by Čuček et al. [30], where Total Site Integration has been evaluated as a trade-off among GHG (Greenhouse gas) and Nitrogen Footprints.

CONCLUSIONS

Energy saving is performed by either reducing the inherent energy demand of the core operations in a process or by recycling waste heat in HENs. At the site level this task is usually accomplished via the steam system interacting with the power generation facilities. There have been a number of methodological developments emphasising on the core energy saving and GHG concepts. However, there is a need to further extend the area by adding considerations for other footprints beside GHG – Water and Nitrogen are the recommended minimum. All indicators can be liked via thermodynamic considerations – including entropy generation minimisation, and chemical potential or energy requirement for pollution reduction.

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