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# Addressing Energy and Environmental Targets through Combined Process Integration Techniques

Emma Mooney[a,]*, Krum Semkov[a,b], Catherine Adley[a], Conor Mooney[c]

[a]Department of Chemical and Environmental Science, University of Limerick, Limerick, Ireland
[b]Institute of Chemical Engineering, Bulgarian Academy of Sciences, Sofia, Bulgaria.
[c]Department of Civil Engineering and Materials Science, University of Limerick, Limerick, Ireland
emma.mooney@ul.ie

It has been widely recognised that a significant amount of the energy purchased by industry is ultimately released as a low grade waste heat. Minimising the amount of waste heat generated and finding ways to reuse the waste heat has benefits for the industry including reduced costs and emissions and increased efficiency and competitiveness, and on a national level the benefits include reduced waste emissions, reduced energy imports, and importantly assistance with compliance in international emission reduction targets. While there are many methods by which heat sources can be assessed and optimised, most of these are not targeted at low grade heat recovery and those that are however are generally designed around specific processes, thus limiting their field of application.

A new approach presented in this paper is to use existing Process Integration techniques combined with second law analysis, mathematical optimisation, and heuristic methods to develop a General Approach to Low Grade Energy Management (GALGEM). This general method includes a set of guidelines for engineering and design personnel in order to assist correct implementation of the methodology, and thus deliver an optimised thermal management design.

## 1. Introduction

The availability of cheap, environmentally friendly abundant energy is not always guaranteed (Howley et al. 2011). This is a concern as secure reliable and affordable energy is essential to both economic stability and development (IEA 2010). In an economic environment where cost of production is a major driving force in industrial and economic development, any method of reducing cost exposure has to be of interest. In addition there is also the issue of the environmental impact of energy use. Legislation and targets have been set for the control and/or reduction of energy related environmental emissions over the last number of years. This includes national and international targets under the Kyoto protocol, the United Nations Framework Convention on Climate Change and the EU Emissions Trading Scheme (ETS). There are also numerous restrictions and obligations with regard to the use of CFC gases, F-Gases, SOx and NOx emissions, waste stream emissions, and other potentially environmentally damaging emissions relating to energy use.

Studies have found that improving energy efficiency is one of the key methods of tackling climate change, while at the same time leading to an increase in security of energy supply and the promotion of sustainable economic growth (Cahill and Ó Gallachóir, 2012). As approximately one third of all global energy demand is used in the industrial sector (IEA 2012), and as it has been estimated that 57 % of all energy used in industry is either lost or wasted (Chittum et al., 2010), it follows that industrial energy use must be an important target for increased efficiency.

In addressing the high level of 'energy waste' from industry there are, broadly, two methods that can be used, the first is to improve the efficiency of the processes/technology in order to reduce the amount of waste energy generated - in 2008 it was found that through the application of best practices and proven technologies between 18 % and 36 % of the current primary energy use in industry could be saved - (IEA 2008). The second method is to recover/capture the waste energy and to use as much as possible for

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some other use. The two methods are not mutually exclusive. The aim of the presented work is primarily focusing on the latter method.

## 2. General Approach to Low Grade Energy Management (GALGEM) Background

One element of waste energy is waste heat. Practically every industry generates waste heat, in general between 20 % and 50 % of industrial energy consumption is ultimately released as waste heat (USDOE, 2008). The critical fact about waste heat is not only the quantity, but also its value in other terms (e.g. aggregate state, temperature, pressure, location etc. While it is easier to recover heat at high temperatures and pressures, most waste heat is discharged at low temperature and atmospheric pressure. This however does not mean it should be not be considered as a potential resource.

There are many definitions of waste heat available in the literature. Recently (Bendig et al., 2012) defined waste heat as “the amount of heat that can be converted into useful forms like electricity or district heating, without increasing the minimum energy requirement”. However for the purpose of this work, waste heat is described as heat that is emitted from the process to the environment without intention of reuse, in a state that is not deemed to be of use/benefit to the process, prior to the application of any process improvement/integration.

### 2.1 GALGEM

Based on the aforementioned drivers for addressing waste heat and the findings of two industrial collaboration projects, work is ongoing in the University of Limerick to establish a General Approach to Low Grade Energy Management (GALGEM) (Mooney et al. 2011). GALGEM is being developed to be a general tool for the analysis, selection and manipulation of low grade waste streams in order to save energy and gain benefit, allowing the user to maximise the efficiency of the system. The aim is to develop a widely applicable assessment methodology and tool that can be used to identify waste heat recovery opportunities and optimise heat energy use in a wide variety of facilities. Specifically the reuse of low grade waste heat is considered, where the inherent peculiarity is the limited available low temperature driving force. GALGEM will allow the user to assess the actual energy requirement of the process for heating and cooling and the current delivered heating and cooling, which will then be used to identify the best method of improvement for the system. GALGEM is not proposed as a completely new method, but a way in which existing techniques are combined in a methodology for low grade waste heat management, primarily in existing facilities.

### 2.2 Process Integration

Process integration (PI) has been described as a “holistic” approach to process design, retrofitting and operation. El Halwagi (1998) state that PI offers a “comprehensive framework for fundamentally understanding the global insights of the process, methodically determining its attainable performance targets, and systematically making decisions leading to the realisation of these targets.” Studies have found that in most industrial facilities there is significant potential for heat recovery through the use of PI (Bernstein et al., 2007).

The most common methods for assessment of energy through PI are energy balances; pinch analysis; heat exchanger network analysis and mathematical optimisation. In general all of these are based on first law (conservation of energy) analysis. However second law analysis techniques, such as exergy analysis can also be used. The following is a very brief description of these techniques:

(1) Energy Balance - this analysis is based on the first law of thermodynamics and is a basic flow diagram of energy use based on energy in and energy out. An energy balance gives a snapshot overview of energy use in a process, facility or system. In general an energy balance can be described as*:*

$$(Energy\ in) + (G|eneration\ of\ energy) = (Energy\ out) + (Generation\ of\ work) \tag{1}$$

Pinch Analysis - has been identified as a powerful methodology to guide the design of process heat and power systems “It uses fundamental thermodynamic principles to give the engineer an overall picture of the process heat flows and so steer him/her toward thermally efficient process and utility design system” (Linnhoff and Hindmarsh, 1983). Since its original design some limitations of the Pinch Methodology have been identified, a key one being that it describes heat in terms of heat content only, and not heat quality (Bendig et al., 2012). In studies it has been found that Pinch analysis has identified energy savings ranging between 3 % and 50 % with a payback of between 0.6 and 4.7 y (Martin et al., 2000). The enthalpy change in a stream, as used in Pinch Analysis, is described by the equation:

$$Q = mc_p\Delta T \tag{2}$$

Where $Q$ is the enthalpy change, *W, m* is the flowrate, *kg/s*, $c_p$ is the specific heat capacity, *J(kg.K),* and $\Delta T$ is the change in temperature across the stream, *K.*

(3) Heat Exchanger Networks (HEN) - have been defined as a system of utility heaters and coolers and process interchangers (Linnhoff et al., 1994). The general objective is to optimise the entire integrated process or site, but in order to do so individual components must also be optimised (Staine and Favrat 1996). Methods for HEN retrofit typically use either Pinch or Mathematical programming techniques, or a mixture of both (Asante and Zhu, 1996). In terms of a HEN, in general, the performance of a heat exchanger is determined by the main heat transfer equation:

$$Q = UA\Delta T_{LM} \tag{3}$$

*where* $\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{\ln\frac{\Delta T_2}{\Delta T_1}}$*,* $Q$ is the heat transfer between two streams, *kW,* $U$ is the overall heat transfer coefficient, *W/(m$^2$K),* and $A$ is the heat exchange area, *m$^2$.*

(4) Mathematical Optimisation - searches for the best solution to a given problem using mathematical modelling techniques. To correctly formulate and solve an optimisation problem the following must be determined (i) the objective function and optimisation criterion (i.e. what do we want to optimise and in what manner) (ii) the optimisation variables (i.e. what can we change in order to carry out the optimisation) (iii) the constraints (i.e. fixed parameters of the problem under investigation that cannot be changed for the purpose of the optimisation). Once these criteria have been established, the mathematical model of the problem is formulated and this can then be optimised through the use of techniques such as linear programming (LP) non-linear programming (NLP) or Mixed Integer Non Linear Programming (MINLP).

(5) Exergy Analysis - Exergy analysis is based on the second law of thermodynamics, the entropy postulate, that the entropy of an isolated system can never decrease (Kotas, 1985). This means that the entropy of a system will always increase until it reaches equilibrium with the surrounding environment, unless external energy is applied which will reduce the entropy. In general:

$$\Delta E_{system} = E_{in} - E_{out} - I \tag{4}$$

Where $E_{in}$-$E_{out}$ is the net exergy transfer by heat, work and mass, *W*, $I$ is the exergy destroyed in converting exergy to anergy, *W*, and $\Delta E_{system}$ is the change in exergy of the system, *W.*

Exergy describes the potential of an energy source to be converted into other forms of energy, i.e. it includes the quality of the energy source as one of its determining parameters. Unlike energy, exergy is not conserved and decreases until it reaches what is known as the environmental level where there is zero exergy. Loss of exergy leads to loss of quality of energy and thus potential functionality. The overall heat transfer exergy rate*, W* is defined as:

$$\dot{E} = \dot{E}_k + \dot{E}_p + \dot{E}_{ph} + \dot{E}_0 \tag{5}$$

where $\dot{E}$ = heat transfer exergy rate, W, $\dot{E}_k$ = kinetic exergy = $v^2/2$, W, $\dot{E}_p$ = potential exergy = zg, W, $\dot{E}_{ph}$ = physical (thermo-mechanical) exergy = $h-h_0 - T_0(s-s_0)$, W, $\dot{E}_0$ = chemical exergy, W (Kotas, 1985).

In the case of GALGEM, in general, only the physical exergy is of interest. The equation to describe the physical exergy transfer rate of a system is:

$$\dot{E} = \dot{E}_{ph} = h - h_0 - T_0(s - s_0) \tag{6}$$

Where $h$ is the enthalpy, *W*, $h_0$ is the enthalpy at the environmental condition*, W*, $T_0$ is the environmental temperature, *K,* $s$ is the entropy, *W/K*, and $s_0$ is the environmental entropy, *W/K.*

(5) Combined methods - There have been a number of attempts to combine first and second law analysis in order to give an enhanced model of a system, leading to an increase in efficiency and energy savings as demonstrated in (Sorin and Paris, 1997; as well as with pressure consideration in Aspelund et al.,2007). While these have been successful in many cases often they are process specific, have high levels of complexity and require a formidable background in energy analysis techniques and experience (i.e. the decision tree is strongly based on heuristics which are used to guide the process) (Aspelund et al., 2007). For these reasons the methods proposed, while containing elements of interest are not suitable for implementation in GALGEM, which is to be a general approach. In addition the level of detail required and obtained in these models is far beyond the requirement for GALGEM.

## 3. GALGEM Development

The rational for the proposed GALGEM model is to use existing developed and proven techniques, in conjunction with simple second law analysis techniques, to give an improved guide to the engineer/designer at an early stage as to the performance, or more importantly poor performance, of the system under consideration

### 3.1 Overall Exergy Loss

In order to examine exergy loss in a process or unit without resorting to complex analysis the GALGEM system will use the concept of Inevitable *(I)* and Avoidable *($E_{AVO}$)* Exergy loss (Feng and Zhu, 1997). The *I* is defined as “the minimum exergy loss which cannot be avoided technically and economically” - described as the exergy destroyed in Eq(4). It follows that if exergy losses are smaller than *I* the process will not be able to meet the design/desired requirement. The minimum exergy loss, the *I*, is determined by the minimum temperature difference required to account for thermodynamic feasibility, known as the exchanger minimum approach temperature (EMAT). Therefore while the total exergy loss *(EL)* may vary, it will always be more than *I* which will not vary. The difference between the *EL* and the *I* is the $E_{AVO}$.

$$EL = I + E_{AVO} \tag{7}$$

The benefit of using *EL, I* and $E_{AVO}$ in the assessment of the performance of a process or individual unit is that it quickly allows identification of where there is a large $E_{AVO}$ generated. In order to compare performance of different unit it is proposed that a simple Internal Exergy performance factor (ξ) is used, this is defined as:

$$\xi = 1 - \frac{1}{E_Q - E_{AVO}} \tag{8}$$

where $E_Q$ is the Exergy Source, *W*. It is clear that ξ can only be improved through reducing $E_{AVO}$, thus reducing the total *EL* across the process or unit under examination. The use of the Internal Exergy performance factor is included in the GALGEM methodology due to its ability to identify quickly the major sources of thermodynamic imperfections in the process, and prompting the designer/engineer to determine promising areas for modification. However for the purpose of GALGEM the temperature at which the exergy loss occurs is also of interest, as this may assist in determining the reason for the level of $E_{AVO}$ in a unit or process (inappropriate stream matching/use). Therefore, in order to quickly analyse the *EL* and the *I*, in conjunction with the temperature, a composite curve of the temperature versus exergy loss is proposed. This will have two separate curves (i) the Inevitable Exergy Loss (*I*) (ii) the Overall Exergy Loss (*EL*). The difference between the two will highlight the temperature level at which the *INE* occurs and the temperature level at which the *EL* occurs, in addition the diagram can show the decrease in *EL*, due to a reduction in $E_{AVO}$, post process improvement (Figure 1).

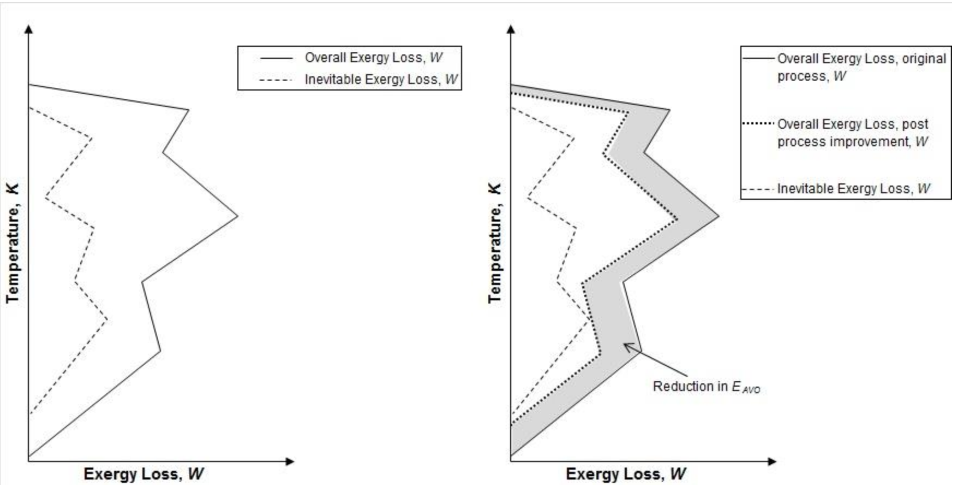
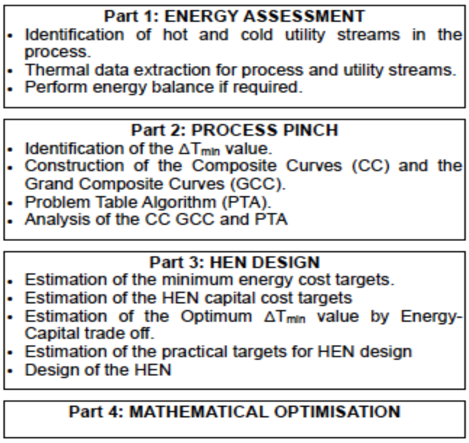


*Figure 1: Composite Curve of Temperature versus Exergy loss*

### 3.2 Model Development

The model proposed follows the sequence as outlined in the overall pinch design method, which combines elements from the energy balance, pinch analysis, HEN design and mathematical optimisation (see Figure 2a). This model works through energy analysis from the basic concepts of an energy balance and the final mathematical optimisation; however as pointed out earlier, all of this analysis is based on first law analysis and unless incorporated by the engineer/designer through heuristic decision making, largely ignores any second law analysis. In order to adapt the model for the realisation of GALGEM, second law analysis is incorporated into the process in the form of exergy analysis. As described in GALGEM the analysis uses the concept of Inevitable Exergy Loss (*I*) and Avoidable Exergy loss ($E_{AVO}$) in order to assess the performance of the item/process, guiding the designer at key stages in the decision making process. Additionally the entire process is adapted to be more applicable to existing processes/facilities, and includes general design guidelines as an integrated part of the method (see Figure 2b).



**Part 1: ENERGY ASSESSMENT**

- Identification of hot and cold utility streams in the process.
- Thermal data extraction for process and utility streams.
- Perform energy balance if required.

**Part 2: PROCESS PINCH**

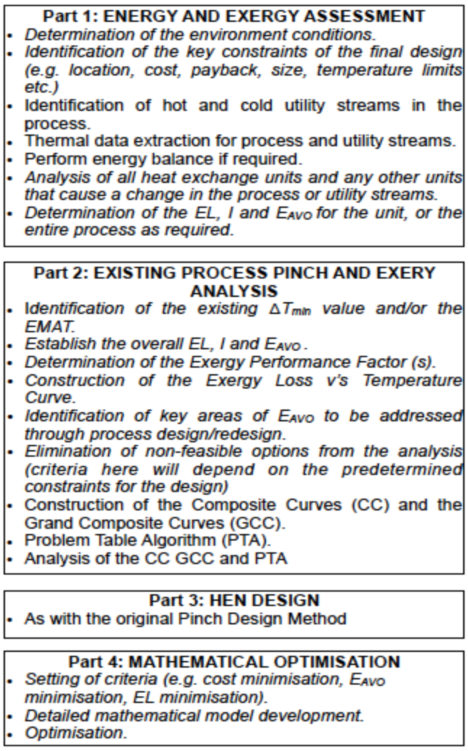
- Identification of the $\Delta T_{min}$ value.
- Construction of the Composite Curves (CC) and the Grand Composite Curves (GCC).
- Problem Table Algorithm (PTA).
- Analysis of the CC GCC and PTA

**Part 3: HEN DESIGN**

- Estimation of the minimum energy cost targets.
- Estimation of the HEN capital cost targets
- Estimation of the Optimum $\Delta T_{min}$ value by Energy-Capital trade off.
- Estimation of the practical targets for HEN design
- Design of the HEN

**Part 4: MATHEMATICAL OPTIMISATION**

*Figure 2a: Pinch Design Method*



**Part 1: ENERGY AND EXERGY ASSESSMENT**

- *Determination of the environment conditions.*
- *Identification of the key constraints of the final design (e.g. location, cost, payback, size, temperature limits etc.)*
- Identification of hot and cold utility streams in the process.
- Thermal data extraction for process and utility streams.
- Perform energy balance if required.
- *Analysis of all heat exchange units and any other units that cause a change in the process or utility streams.*
- *Determination of the EL, I and $E_{AVO}$ for the unit, or the entire process as required.*

**Part 2: EXISTING PROCESS PINCH AND EXERY ANALYSIS**

- *Identification of the existing $\Delta T_{min}$ value and/or the EMAT.*
- *Establish the overall EL, I and $E_{AVO}$.*
- *Determination of the Exergy Performance Factor (s).*
- *Construction of the Exergy Loss v's Temperature Curve.*
- *Identification of key areas of $E_{AVO}$ to be addressed through process design/redesign.*
- *Elimination of non-feasible options from the analysis (criteria here will depend on the predetermined constraints for the design)*
- Construction of the Composite Curves (CC) and the Grand Composite Curves (GCC).
- Problem Table Algorithm (PTA).
- Analysis of the CC GCC and PTA

**Part 3: HEN DESIGN**

- As with the original Pinch Design Method

**Part 4: MATHEMATICAL OPTIMISATION**

- *Setting of criteria (e.g. cost minimisation, $E_{AVO}$ minimisation, EL minimisation).*
- *Detailed mathematical model development.*
- *Optimisation.*

*Figure 2b: Adapted Pinch and Exergy Design Method*

## 4. Discussion

Process integration, and more especially Pinch Analysis, has been established as one of the core methods by which the energy performance of a system can be optimised in order to deliver the requirements of the process while minimising the energy requirement. However it is limited in that the analysis is based on first law analysis, additionally pinch analysis is more suited to new design rather than existing processes, where it can become onerous. The proposed methodology, including some basic exergy analysis in the decision making steps and adapting the technique for easy implementation in existing processes, should allow for more effective design decisions, while avoiding time consuming analysis of non-feasible options. This is the major difference between the proposed technique and other models found in literature. The GALGEM model uses exergy analysis in parallel with pinch analysis to guide and inform the design decisions taken, while using the existing proven tools of pinch analysis, HEN design and mathematical optimisation in determining the final design criteria. In this way the complexity that is involved in many of the methodologies proposed in the literature is avoided and the model is not limited to specific processes but adaptable to various processes.

From the above proposed model it can be seen that the idea is not to adapt the Pinch process to include Exergy analysis in its calculations, but rather to use the information obtained from basic exergy analysis to inform the decision making process in the largely pinch based methodology as proposed above. In this way the strengths of Pinch analysis as a design tool (e.g. its accessibility, its wide potential application, its simplicity) are not diminished by the addition of second law, exergy analysis.

The development of the detailed mathematical evaluation of the overall saving opportunities through the use of the proposed system will be the object of the future work in GALGEM, and will be demonstrated through an industrial case study

## 5. Conclusions

A simple method for the inclusion of second law analysis in the assessment and management of low grade heat has been developed. While this method may not lead to the detailed assessment as carried out by other proposed methodologies, it does lead to more informed decision making in the selection and optimisation of heating and cooling streams and process integration strategies, thus leading to an improved performance. In addition the methodology is not specific to any particular process and is applicable to both new and existing process analysis situations. It is especially more applicable to the range of low grade heat recovery near the ambient temperature

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