New Methodology of Assessing Wasted Energy in Industrial Sector: Assessing Industrial Systems contribution to Thermal Pollution

Constantin Pitis*

BC Hydro, 900-4555 Kingsway, Burnaby, BC V5H4T8, Canada

Abstract: Thermal Pollution represents "the release into the environment of substances that are innocuous themselves but at a temperature higher than the ambient altering the physical characteristics of the air or water with which they mix" (Science Dictionary). The quantity of the heated air dumped in the atmosphere is intrinsically related to efficiency of industrial systems, processes and industries. Increasing efficiencies of industrial systems, processes and industries will directly reduce the thermal pollution.

In other words, all energy savings obtained by increasing energy efficiency of industrial systems and processes (IS&P) represents avoided Thermal Pollution.

To date, studies of energetic performances of industrial systems and industries have lagged behind those used in the commercial and institutional sectors due to:

- Variability and complexity of IS&P,
- Variability of material and environmental conditions,
- The absence of a large population of comparable data required for a regression-based approach that would enable the normalization of material and environmental conditions, and thus allow for a useful comparison of energy performance at the process level.
- The reluctance of industrial firms to share data on industrial processes that is often considered proprietary.

Paper proposes: an energetic assessment of Thermal Pollution by using a new rating system model describing the energy efficiency of any industrial equipment, system drive or process independent of a comparison with other processes. Comparative element across an industrial sector that is traditionally used, is replaced with a theoretical goal. The rating is then solely based on how close the true energy consumption within an industrial process gets to that ideal state.

Proposed methodology splits energy consumption in 2 (two) specific components: Ideal energy (E_{Ideal}) and Energy at Risk (E@R) – that represents actually the Thermal Pollution (Th.P). By considering these two energy types Benchmark Energy Factor (BEF) can be defined.

The (BEF) will enable a new approach towards energy efficiency in the industrial sector and help level the playing field for energy management reducing the waste energy and therefore Thermal Pollution. It will be demonstrated that Energy at Risk (Thermal Pollution) variation is embedded in (BEF).

Once Energy at Risk (E@R) is known, it will be logical proceeding with benchmarking plants, industrial systems or/and processes assessing their capability of managing E@R (waste energy or Th.P) by focusing on in-situ testing and making educated decision towards reducing wasted heat and thermal pollution.

Case studies on proposed methodology are presented at the level of equipments, industrial system drives, plants, processes, and industries. The methodology of determining the magnitude of thermal pollution is applied to a typical national industrial system by using conservation potential obtainable when Integrated Industrial System Drives (IISD) are to be used.

The scope of this paper is to uncover Th.P. as new pollutant that can be included in EPA Clean Air Act making available to consultants, designers, end-users, utility programs and environmental organizations reliable criteria of reducing thermal pollution of the existing or new industrial systems or plants as part of the climate change mitigation.

Keywords: Benchmarking, Conservation Potential, Energy at Risk, Industrial Systems and Processes, Measurements & Verification, Thermal Pollution, Waste Energy.

1. INTRODUCTION

Two thirds of the electric energy production (amounted in 2009 at 20,300 TWh) [1] is consumed by industrial system drives (ISD) with overall efficiencies ranging from 80% to as low as 25% [2, 3]. For an average efficiency value of 60% the waste energy is estimated at 8,120 TWh generating annual thermal pollution of 7,000,000 Tcal/year – equivalent of thousands "Little Boys" (Hiroshima's atomic bomb) [4].

Since 2007, Intergovernmental Panel on Climate Change (IPCC) working groups focus on reduction of energy use by conservation. United Nations Industrial Development Organization (UNIDO) start developing a

*Address correspondence to this author at the BC Hydro, 900-4555 Kingsway, Burnaby, BC V5H4T8, Canada; Tel: 604-230-8915; Fax: 604-453-6286; E-mail: Constantin.pitis@bchydro.com

E-ISSN: 2311-8741

new approach to industrial energy efficiency called industrial energy systems optimization (IESO). Such types of initiatives are intended to reduce waste energy, generating energy savings (avoided Thermal Pollution) while production outputs remain unchanged.

A large variety and sizes of Industrial Systems and Processes (IS&P) require sustainable and consistent approach. From an economic standpoint, sustainability concepts favor high-efficiency systems, as any energy-efficient system translates into higher effective productivity with less Thermal Pollution (Th.P).

By definition, traditional benchmarking is considered to be the practice of being humble enough to admit that someone else is better at something ("best practice"). Utilities, governmental and international organizations still estimate energy savings applied to the entire energy consumption (E_{Used}) as a whole by using "best practice" as targets. Energy efficiency benchmarking (EEB) of industrial systems, processes, products and industry sectors is traditionally based on Best Practice Technologies (BPT) and various energy indicators. Operational Benchmarking is the process of continuously measuring and comparing one's business processes against comparable processes in leading organizations to obtain information that will help the organization identify and implement improvements [5]. A prominent industrial benchmark rating systems is developed by the U.S. DoE's Energy Star Certification for Plants Program [6]. Based on traditional methodology assessing system efficiencies, the Energy Star Program developed "Energy Performance Indicators" or benchmark ratings for different industrial facility types, by using a laborious and tedious methodology[1]. Since 2010, overall efficiencies of IS&P are assessed by using Energy Usage Index and, by Superior Energy Performance[cm] (SEP) – in a certification program that provides industrial facilities with a transparent, globally accepted system for verifying energy performance improvements and management practices. Central element of SEP is implementation of the global energy management standard ISO 50001. Energy efficiency certification is obtained by verifying energy performance through measurement and verification (M&V).

These traditional methodologies have large variability of benchmarking factors generated by baseline inaccuracies that requires permanent and tedious update works with.

The ultimate target on these initiatives is reduction of power/energy losses i.e. Thermal Pollution while, at the time of measurement, their magnitude (absolute value) is still unknown!

This issue is addressed by the new proposed method accurately predicting Th.P magnitude.

Figure **1** shows a generalized overview of an IS&P. Material of a certain quality entering the system is being transformed to a higher quality material/product (value added) that leaves the system. Among others, energy is used to process the material while Thermal Pollution (Th.P) is inherently present.

It becomes apparent that the energy consumption for a given industrial process does not depend on the equipment and the system design alone but also on boundary conditions such as $(\text{Material})_{In}$, $(\text{Material})_{Out}$, $(\text{Energy used})_{In}$ and $(\text{Heat Losses})_{Out}$. System boundary is to be considered for:

- Measuring (using traditional methods) energy used, $\mathbf{E_{Used}}$ – that is electric input representing the actual energy consumed by Industrial System Drive (ISD) or process; this energy is traditionally measured by power meters.

- Estimating accurately ideal (theoretical) energy $\mathbf{E_{Ideal}}$ required accomplishing the task inside the system by using adequate (well known) laws of physics chosen function of the work performed by Drive End-use Equipment (DEE), that is considered one of the novelties proposed by this paper.

Proposed methodology splits energy consumption E_{Used} in 2 (two) specific components: Ideal energy (E_{Ideal}) – used as Reference and Energy at Risk (E@R). Ideal energy (power) can be accurately calculated by using laws of physics chosen function of the work type performed by DEE (see Figure **2**), therefore a solid reference for benchmarking system is available. That will eliminate large variability on baselines using "best practice" or other traditionally used criteria while Thermal Pollution can be accurately assessed.

2. DEFINING (BEF), IDEAL ENERGY AND ENERGY AT RISK (THERMAL POLLUTION)

By definition, Benchmark Energy Factor (BEF) represents overall invested energy E_{Used} that is

[1]The core of the current interpretation of Benchmarking Energy Efficiency for IS&P requires the following works: Study the System (Process), Finding Benchmarking Partners, Analyze & Compare, Setting Key Performance Indicators, Do conventional Benchmarking, Implementation, M&V using IPMVP methods, Certification.

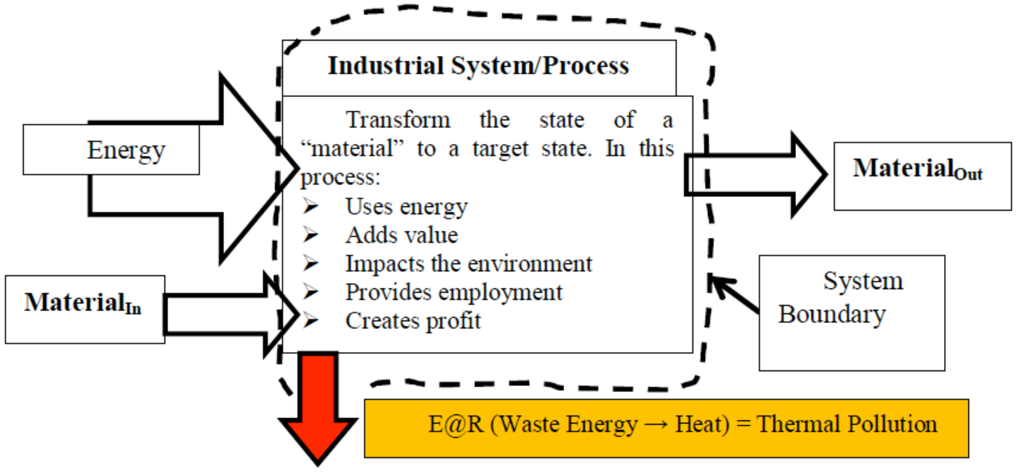

Figure 1: Generalization of Industrial System or Process (IS&P).

compared to the required energy to obtain the desired output (for simplicity sake considered in this paper as E_{Ideal}). This depends on how "well" the overall system produces the output as well as of some boundary conditions[2]. For a single source of energy/power [7]:

$$BEF_{system} = \left.\frac{E_{used}}{E_{ideal}}\right|_{@\ given\ input\ parameters} \qquad (1)$$

BEF splits effectively the energy consumption (E_{Used}) up into productive energy and non-productive energy.

The Ideal energy (power) E_{Ideal} is productive energy representing the theoretical energy (or power) required to accomplish the task (or manufacture the products) for what system was designed. Considered as reference, this quantity cannot be minimized being intrinsic related to the scope of process defining energy which is technology independent, while BEF is production volume independent[3]. Ideal energy (or power if time factor is excluded) can be accurately calculated by using adequate, well known laws of physics [11] chosen function of the work type performed by Drive End-use Equipment (DEE), for example:

- E_{Ideal} = M x g x h, for Potential Energy (power)
- E_{Ideal} = (M x v^2) / 2, for Kinetic energy (power)
- E_{Ideal} = M x c x ΔT, for thermal energy (power)
- AHP (per stage) = 0.043*(Zs+Zd)*Q*Ts*k* ([Pd/Ps)((k-1)/k)]-1), for Adiabatic Compression Power

Where: M is mass [kg], g is gravitational acceleration constant [m/s2], h is height [m], v is velocity [m/s], c is specific heat [J/kg.C], ΔT is temperature difference [C], AHP is adiabatic compression power [hp], Q is flow [MMscfd], T is temperature [°K], K is ratio of specific heats, Z is compressibility factor

Note 1: The values of these mechanical quantities are to be converted to electrical quantities

Theoretical (idealized) system uses only the energy that is required to obtain the result, E_{Ideal}, (with no losses), while the real system uses more energy to overcome the losses embedded in the system itself.

A major assumption inspired by reality is made by the author: "when industrial system is functioning, the user takes always the risk of spending extra energy in losses".

Therefore proposed method defines these energy losses as Energy at Risk (E@R):

E@R = (Electric input Energy, $\mathbf{E_{Used}}$) – (Ideal Energy, $\mathbf{E_{Ideal}}$) (2)

Energy @ Risk (E@R) of an industrial system or process could also be defined as "non-productive energy". It represents the waste energy (that is Thermal Pollution) spent by any ISD to accomplish the

---

[2]Although it can never be achieved, a BEF value of 1.0 indicates essential energy required for process equal to E_{Used}, would be an ideal, no-loss system
[3]However, $\mathbf{E_{Ideal}}$ energy values can be dependent sometimes on one or more specific variables [6] like: material, environmental conditions, personnel, equipment condition, thermal insulation condition, transportation, lighting, etc. In the case $\mathbf{E_{Ideal}}$ value will be re-evaluated it will be increased to a new value named essential energy $\mathbf{E_{Essential}}$, this value replacing ideal values of energy $\mathbf{E_{Ideal}}$ in (1) resulting in adjustment of BEF value (see chapter 5). This adjustment enables real BEF values that will be used for M&V purposes. $\mathbf{E_{Ideal}}$ adjustment to $\mathbf{E_{Essential}}$ can be done by using 5 (five) Essentials of Application Engineering (5 EAE) methodology [9, 10].

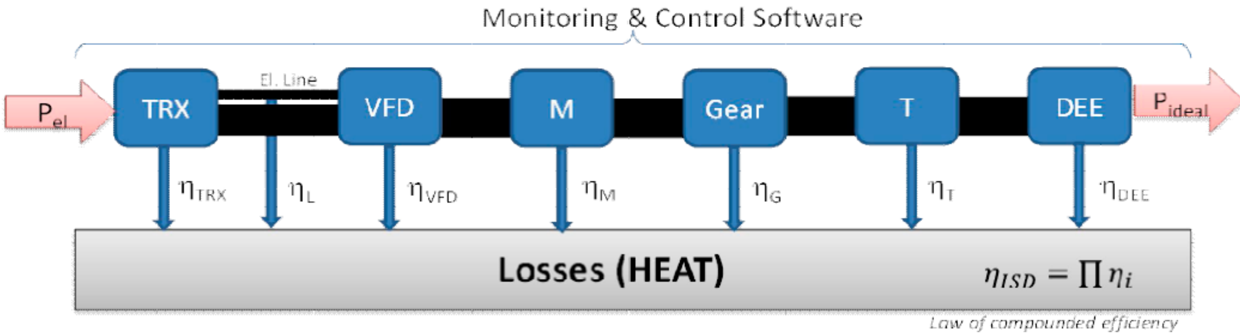

Figure 2: Schematic power flow of an Industrial system Drive.

task for what system was designed. As a conjugate of ideal energy, E_{Ideal}, the Energy at Risk (E@R) or Thermal Pollution variation is embedded in Benchmark Energy Factor (BEF).

With reference to Figure **2**, when electric power is the only source of energy of ISD, the used power P_{used} represents the actual electric power $P_{Electric}$ used by ISD or process to accomplish the required task P_{ideal}. Therefore, in terms of power, the total Losses of a typical Industrial System Drive can be expressed as:

$$\sum P_{losses} = P_{used} - P_{Ideal} \quad (3)$$

This is a corollary of the Law of Compounded (overall) efficiency for series power chain components [11], as shown in figure 2 (abbreviations are in the foot note 4) [7].

By using the overall efficiency of ISD (shown in Figure **2**), Thermal pollution Th.P is defined as:

$$\text{Th.P [kcal]} = P_{Electric}\text{ [kW] x Time [hours] x } (1 - \eta_{ISD}) \text{ x [860 kcal/kWh]} \quad (4)$$

For a typical ISD[4]: $\eta_{TRX} = 0.98$, $\eta_L = 0.996$, $\eta_{VFD} = 0.97$, $\eta_{Motor} = 0.95$, $\eta_G = 0.88$, $\eta_T = 0.95$, $\eta_{DEE} = 0.74$, $\eta_{ISD} = 0.55$, hence Thermal Pollution is 45 % of the input energy (power), while $E_{Ideal} = 0.55 \times E_{Used}$

3. CASE STUDY: DEFINING THERMAL POLLUTION (E@R) FOR AN INDUSTRIAL EQUIPMENT

Consider an industrial water heating equipment shown in Figure **3** [8].

The equipment consumes 15 MWh/year. Energy at risk, E@R represents the difference between energy consumption of such real system, E_{Used} = 15 MWh and energy consumption of theoretical (idealized) system E_{Ideal} = 9.3 MWh (estimated based on heat transfer thermodynamics law):

$$Q[MWh] = M[kg] \times c[J/C.kg] \times \Delta T[C] \times 278 \times 10^{-9}[kWh/J] \times 10^{-3}[MWh/kWh] \quad (5)$$

Based on (2) and (1) the energy at risk E@R and BEF are:

E@R (Th.P) = 15 MWh – 9.3 MWh = 5.7 MWh (Th.P = 4900 Mcal) with

$$BEF = \frac{E = 15}{E_{Ideal} = 9.3} = 1.61$$

For an upgraded (with improved thermal insulation) similar system, annual energy consumption is reduced from E_{Used} = 15 MWh to the E_{Used}' = 14 MWh.

Energy at Risk (Thermal Pollution) has been reduced to a lower level (E@R)', i.e. 4040 Mcal:

E@R' (Th.P)' = 14 MWh – 9.3 MWh = 4.7 MWh (4040 Mcal), with new (BEF)' = 1.505

Benchmarking concept of the two (old and upgraded) equipments (systems) has been created as indicated by vertical arrows in Figure **3**. Second system benchmarked by a smaller (BEF)' = 1.505 performs better by managing a reduced value of E@R (Thermal Pollution) with its variation being embedded in (BEF).

Avoided Thermal Pollution Δ Th.P, can be defined as an incremental difference of (E@R):

Δ Th.P = Δ (E@R) = [(E@R) – (E@R)'] = 5.7 MWh – 4.7 MWh = 1 MWh = 860 Mcal or (6)

Δ Th.P = (Th.P) – (Th.P)' = 4900 Mcal – 4040 Mcal = 860 Mcal, or

Δ Th.P = E_{Ideal} [kWh] x [(BEF) – (BEF)'] x 860 [kcal/kWh] = 9.6 x[1.61 – 1.505] x860 = 860 Mcal (7)

---

[4]In Figure **2**, typical ISD power chain components are: transformer (TRX), line (L), variable frequency drive (VFD), motor (M), gear, transmission (T) and drive end-use equipment (DEE) with overall efficiency of $\eta_{ISD} = \Pi\eta_i$

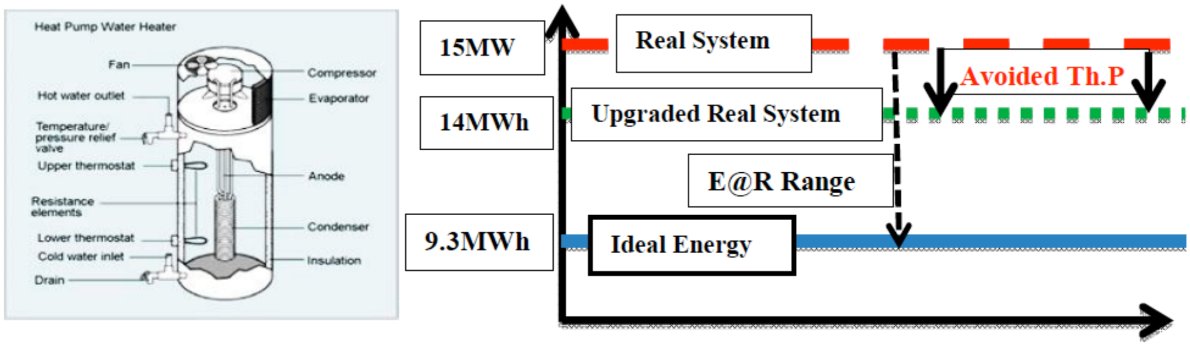

Figure 3: Explanatory diagram to E@R and Avoided Thermal pollution.

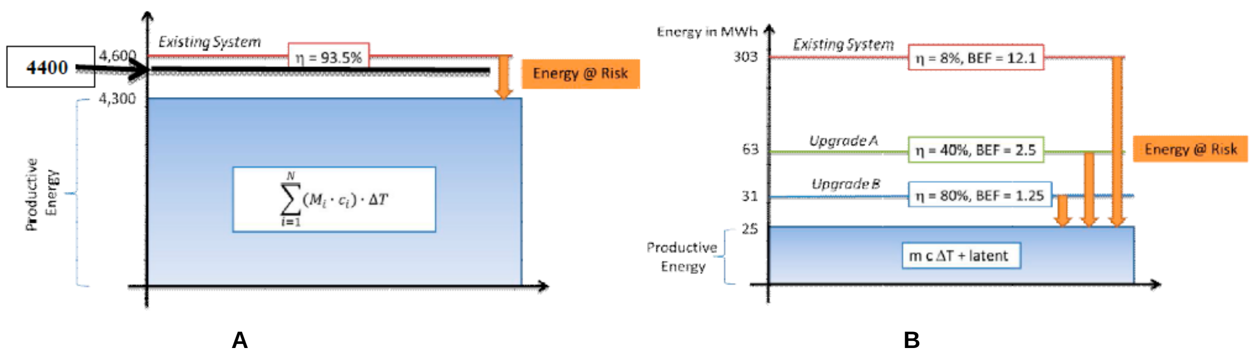

Figure 4: Assessing conservation potential of 2 (two) similar industrial processes: Plant **A** (left), Plant **B** (right).

4. CASE STUDY: ASSESSING WASTE ENERGY (TH.P) AND CONSERVATION OPPORTUNITIES FOR TWO REFRIGERATION PLANTS

Case study is inspired by energy managing decisions made on two plants dealing with heat transfer processes as shown in Figure **4**. Energy consumptions, E_{Used} are 4,600 MWh/y for Plant A and 303 MWh/y for Plant B.

Traditionally used assumption that energy studies may identify energy savings averaging about 10% E_{Used}, suggests savings potential in Plant A (≈ 460 MWh) would even be greater than the annual energy consumption in Plant B (≈ 30 MWh). This assumption creates impression that, in terms of addressing Thermal pollution reduction, Plant A is more attractive than Plant B.

Proposed methodology uncovers hidden reality when appropriate decision can be taken by applying the E@R, Δ Th.P and BEF analysis.

Proposed Methodology

By estimating ideal energy E_{Ideal} (5) and Energy at Risk (2) for the two plants, it becomes apparent that, in relative units, the E@R for Plant A is rather small while for Plant B it is quite significant. BEF analysis would have led to a more informed decision shown in Table **1**.

Note 2: BEF values could be adjusted according to material, environment conditions with possible allowance for lighting, personnel, transportation and equipment condition

- What use of Ideal energy, (E@R), Δ Th.P and BEF concepts reveal?
- Proper identification of conservation opportunities for base case and for upgrade options (as for Plant B)[5]
- Proper assessment of wasted energy and thermal pollution versus blindly use of traditional assumptions.
- Conservation potential of a plant or industrial system is not related to its energy consumption:

---

[5]Using E@R and BEF analysis would have led to correct decisions for utilities and government organizations managing energy efficiencies and conservation programs aiming reduction of Thermal Pollution:
- Programs Priorities: which industrial process to be studied first
- E@R value and its management (energy savings), i.e. Total and Avoided Thermal pollution
- Study costs & Energy Conservation Measures (ECM) Types and Costs in [$/saved kWh or kcal]
- Benchmarking Energy Factor: gaining experience for further assessments of similar applications
- Feedback to customer: how efficient their processes are, magnitude of Thermal Pollution

Table 1: Comparative Assessment of Avoided Thermal Pollution (ΔE@R) for 2 (Two) Plants

#	Item	Plant A	Plant B	Plant B (considered after first upgrade)
1	BaseLine Consumption, E_{Used} [MWh]	4600	303	63
2	Ideal energy E_{Ideal} [MWh]	4300	25	25
3	Energy @ Risk [MWh] (or Th.P)	4600 – 4300 = 300	303 – 25 = 278	63 – 25 = 38
4	E@R (Th.P) as [%] of Baseline	6.52 %	91.75 %	60.32 %
	BEF (E_{Used}/E_{Ideal})	1.07	12.12	2.52
5	Upgraded E_{Used} consumption [MWh]	4400	63	31
6	Energy saved, [MWh]	200MWh = 172Gcal	303 –63 = 240MWh	63 – 31 = 32 MWh
6b	Avoided Therm. Pollution (Δ Th.P)	172 Gcal/year	206 Gcal/year	28 Gcal/year
7	Energy Saved as [%] of Baseline	4.35 %	79 %	51 %
8	Upgraded BEF (upgraded E_{Used}/E_{Ideal})	1.02	2.52	1.24
9	Energy @ Risk – Waste [MWh]	4600 – 4300 = 300	303 – 25 = 278	63 – 25 = 38
10	E@R reduction [MWh]	4600 – 4400 = 200	303 – 63 = 240	63 – 31 = 32
11	Avoided Thermal Pollution [%] E@R	200/300 = 66 %	240/278 = 86%	32/38 = 84%

- o Conservation potential in Plant B (having less consumption than Plant A) has comparable magnitude to that of the Plant A, i.e. 278 MWh + 38 MWh = 316 MWh versus 300 MWh.
- o In terms of [%] of the baseline, Thermal Pollution (E@R) in Plant B is 91.75 % or 60.32 % (after first upgrade) of the total consumption – see raw 4

➢ As benefit of proposed methodology is that a “magnifying glass” can be applied when conservation potential is to be evaluated by representing avoided Thermal Pollution as [%] of E@R (lines 6b and 11). **Corollary:** *Analysis of avoided Thermal Pollution is more transparent and reliable measurement, than using total energy consumption analysis using “best practice” as reference requiring tedious adjustment works.*

5. CASE STUDY: EVALUATING MELTING PROCESS OF AN ELECTRIC ARC FURNACE (EAF)

Electrical Arc Furnaces (EAFs) can be rapidly started and stopped and allows steel to be made from scrap metal feedstock allowing plants to vary production according to local demand. During financial meltdown in 2009, an estimated quantity of 1 (one) million tonne was produced in USA by using EAF technique [12].

Average annual production of this specific EAF (in metric tonne) is:

P = 18,000 pounds/melt = 8.19 mt/melt x 11 melts/day x 5 days/week x 50 weeks/year ≈ 22,500 mt/y

Site measurements recorded for 2 (two) consecutive years indicate specific energy consumption in kWh/mt of steel E_{Used} = 720 kWh/mt and Specific Energy Losses distribution only for melting process, as follow:

➢ TRX and Regulator — 90 kWh/mt

➢ Cable — 40 kWh/mt

➢ Ancillaries & controls — 30 kWh/mt (theoretical estimations)

➢ Furnace Insulation — 160 kWh/mt (estimated from the balance)

Energy flow diagram has been constructed [13] with equipments/process generating losses as shown in Figure **6**, indicating overall EAF efficiency of η_{EAF} = 53.6% (as a product of components’ efficiencies).

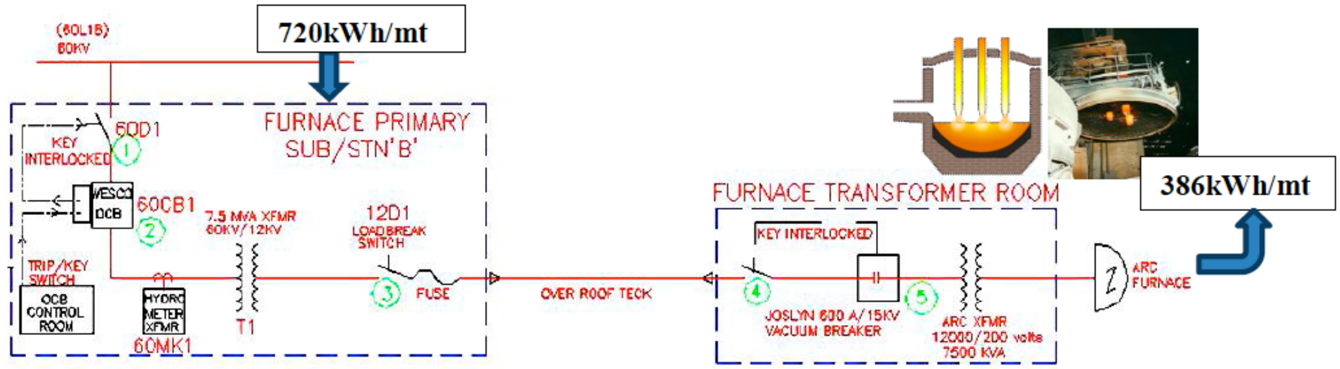

Figure 5: Single line diagram of EAF.

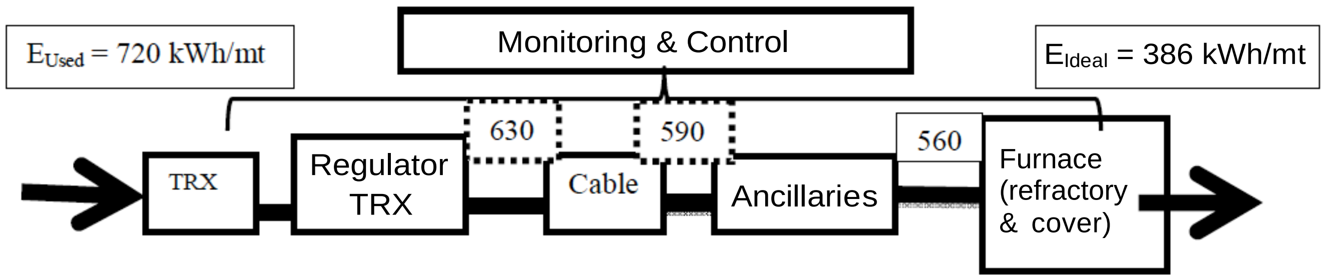

Figure 6: Specific energy flow throughout EAF main components (η_{EAF} = 0.875 x 0.9365 x 0.949 x 0.689 = 0.536).

Note 3: Other auxiliary end-uses (Air compression, Tool heating, Heat treatment, air & water systems) have been placed outside the System Boundary assuming same energy consumption in baseline or other ECM options.

Essential specific melting Energy including 15 % allowance due to some factors variability (foot note 6) is estimated at E_{Ideal} = 386 kWh/mt[6]

Therefore theoretical minimum amount of energy required to melt a tonne of scrap steel, (as is used by this specific application) is estimated to be around 386 kWh/mt [14, 15].

Current value of specific electric energy for best practice is currently estimated at 440kWh/mt [16, 17].

Performing E@R and BEF Analysis on Melting Process

For the Baseline case, Conservation potential (thermal pollution) can be found by estimating the E@R (3):

E@R = 720 – 386 = 334 kWh/t.

For Baseline case Benchmark Energy Factor, BEF is:

$$BEF = \frac{E_{Used} = 720}{E_{Ideal} = 386} = 1.865$$

A number of 2 (two) Energy Conservation Measures (ECMs) have been implemented:

- ECM # 1 – Use of Higher efficiency transformer (TRX) with improved regulation
- ECM # 2 – Reducing Cable losses (reducing current density, skin effect and proximity effect)

New (BEF) and avoided Thermal Pollution are calculated (by using 630kWh/mt and 590kWh/mt as references – see Figure **6**) as shown in Table **2**. As a result E_{Used} values have been reduced to 685kWh/t (after ECM #1) and further to 668 kWh/t (after ECM # 2).

[6]Steel composition determines its thermodynamic parameters; average values are considered based on metallurgical certificates that indicate variation of steel composition within +/- 3%. It results specific heat varies nonlinear from 450J/kg°C @ 20°C (T_0) to 710 J/kg°C @1520°C (T_m) and 740J/kg°C @ 1620°C (T_{ovload}). Specific latent heat value is λ = 76 kWh/mt [14]. Calculations are based on the second law of thermodynamics for 3 (three) intervals, i.e. ambient to melting temperature, latent regime and to overheating (formulae are manipulated in order to obtain same units of specific energy - kWh), resulting total average value of 336kWh/mt at which extra allowance of 15 % has been added due to quality materials variability (3%), stacking factors (6%), and averaging environmental conditions (6%)

$$Q_{0-m}[kWh] = P[kg] \times c[J/C.kg] \times (T_m - T_0)[C] \times 278 \times 10^{-9}[kWh/J]$$

$$Q_{latent}[kWh] = P[kg] \times L[J/kg] \times 278 \times 10^{-9}[kWh/J]$$

$$Q_{m-overheat}[kWh] = P[kg] \times c[J/C.kg] \times (T_m - T_{0vload})[C] \times 278 \times 10^{-9}[kWh/J]$$

Table 2: Estimates of Avoided Thermal Pollution (ΔE@R) and BEF after ECMs Implementation

#	Item, ECMs	Baseline	ECM # 1	ECM # 2
1	E_{Used}	720 kWh/t	685 kWh/t	668 kWh/t
2	TRX and Regulator	87.5 %	**92 %**	
3	-Losses [kWh/t] (Thermal pollution)	90 (77Mcal/t)	**55 (47Mcal/t)**	55(47Mcal/t)
3	Cable	93.65 %	93.65 %	
	-Losses [kWh/t] (Thermal pollution)	40 (34Mcal/t)	39 (34Mcal/t)	23(20Mcal/t)
4	E_{Ideal}	386 kWh/t	386 kWh/t	386 kWh/t
5	E@R[kWh/t], Th.P (Mcal/t)	334 (287)	299 (257)	282 (243)
6	BEF	1.865	1.775	1.730
7	Energy saved, ES [kWh/mt] or **Δ Th.P**	NIL	35 (30Mcal/mt)	52(45Mcal/mt)
8	ES as [%] of Baseline		5.1 %	7.6 %
9	Avoided Th.P [%] of E@R & annual		11.7%=675Gcal/y	18.1% =1Tcal/y

Note 4: Efficiencies values of retrofit equipments with new losses are in bold.

Line 9 reveals the novelty of proposed methodology in estimating Avoided Thermal Pollution (E@R) value (1 Tcal/y = 6.345GWh/y), making the results more transparent and reliable when used for M&V purposes.

6. ESTIMATING AVOIDED THERMAL POLLUTION OF A NATIONAL INDUSTRIAL SYSTEM

Consider a typical country with electric energy consumption EEC = 500 TWh/year evenly distributed between residential, commercial and industrial sectors (distribution factor DF = 33 % each).

Theoretical researches and reports performed by utilities, reputable corporations and other organizations indicate potential power savings in [%] of the power flow through industrial systems (as shown in Table **3**). Such savings can be obtained at components level as parts of Integrated Industrial System Drives (IISD) [18] in compliance to 5 EAE (Five Essentials of Application Engineering) [9, 10] (Table **3** columns 3…7).

When designing or retrofitting ISD to IISD, 5 (Five) Essentials of what is called Application Engineering (5 EAE) must be taken in consideration:

- #1 EAE: **Matching downstream conditions** (electrical or mechanical load) - the most complex tenet, requiring compliance to the load conditions;
- #2 EAE**: Matching upstream conditions** means the power converter must comply with incoming electrical or mechanical power conditions while also considering ISD's influence on the incoming power;
- #3 EAE: **Matching environmental conditions** means the equipment must not be destroyed by its surroundings; conversely, it must not, in turn, inflict environmental damages.
- #4 EAE: **Matching reliability and efficiency indicators** enable end-user in planning repair and maintenance (R&M) activities, preserving system performances, with reference to alteration or rapid deterioration system performance during its lifetime, minimizing operating expenses. Reliability is the reciprocal of failure, and failure is a random event mainly influenced by heat transfer and losses, therefore efficiency can significantly influence reliability, also with direct effect on Thermal Pollution magnitude.
- #5 EAE: **Matching conditions of business sustainability** by using life-cycle costing methodologies to establish total cost of ownership (both capital and operating costs) promotes energy efficiency options. Business sustainability requires mutual benefits to the OEM ("premium" rewarded for value added system) and to the customer.

In addition of compliance to 5 EAE the main characteristics of IISD designs are:

- Reduced number of power converters or system components (shorter power train);
- Use of premium efficiency products and controls;

Table 3: Potential Avoided Thermal Pollution (Conservation Potential) Obtainable with IISD [10]

Equipment (power converter)	Av. Efficiency $\eta_{Av,\ init}$ // $\eta_{Av.\ after}$	Estimated Efficiency improvements by compliance to 5 EAE					Total Effic Improvements	Efficiency Increment
		#1	#2	#3	#4	#5	(Σ η)	(Δ)
TRX + lines	97 %//98%	7 %	1.5 %	3.5 %	8 %	12.5 %	32.5%	1.0 %
Motor (VFD)	94 %//95%	12%			Heat: 2%		14 %	≈ 1% %
Power Trains	60.0%//72%	45%					45 %	18 %
Total	55 %//67%	23.5%	1.5 %	3.5%	10 %	12.5 %	51.0 %	≈ 20…21 %

- Properly matched power converters during design and retrofit activities
- Enable process automation and performance optimization;
- Stability of high efficiency values of IISD over large range of loading profiles
- Performance stability (even after maintenance and repair activities)
- Lean maintenance targeting the lowest cost of ownership through life-cycle costing
- Reduced Thermal Pollution (reduced E@R), i.e. waste energy

Typical overall efficiency of IS&P (ISD) was estimated at $\eta_{Av,\ init}$ = 55 %, see Chapter 2, Figure **2**; the column 2 in Table **3** indicates initial and after improvement efficiency values ($\eta_{Av,\ init}$ // $\eta_{Av.\ after}$).

New efficiency value ($\eta_{Av.\ after}$) is estimated as, $\eta_{Av.\ after} = \eta_{Av,\ init} - \Delta$

The Efficiency incremental increase (Δ) is estimated as $\Delta = (1 - \eta_{Av,\ init}) \times (\Sigma\ \eta)$ in [%]

Wasted energy (E@R) converted in Thermal Pollution can be estimated as:

$(Th.\ P)_{initial} = EEC \times DF \times (1 - \eta_{Av,\ init}) = 500 \times 0.33 \times (1 - 0.55) = 74$ TWh = 63,640 Tcal/y

Average efficiency obtainable with IISD promotion may reach 67 % and waste energy becomes:

$(Th.\ P)_{New} = EEC \times DF \times (1 - \eta_{Av.\ after}) = 500 \times 0.33 \times (1 - 0.67) = 54.5$ TWh = 46,870 Tcal/y

Therefore in a typical country with electric energy consumption of EEC = 500 TWh/year evenly distributed between sectors, thermal pollution can be reduced with 16,770 Tcal/year if IISD are promoted.

Potential Avoided Thermal Pollution Δ (Th. P) = $(Th.\ P)_{initial} - (Th.\ P)_{New}$ = 16,770 TWh/y (8)

Proposed methodology can be applied to the industry, plant or any industrial system drive level

7. USING E@R AND BEF CONCEPTS IN MEASUREMENT AND VERIFICATION PROCESS

From a measurement and verification (M&V) perspective, due to complexity of industrial systems the fundamental equation used to calculate energy savings is often related to the term for '+/- Adjustments's [19]:

$$Energy\ Savings = Energy\ Consumed_{Before} - Energy\ Consumed_{After} \pm Adjustments \quad (9)$$

As IPMVP states, "adjustments are derived from identifiable physical facts". These variables have been mentioned in Chapter 6 where it has been demonstrated how they influence BEF values *via* E_{Ideal} [7].

By using proposed concepts of ideal energy E_{Ideal} and Energy at Risk (E@R) approach no further adjustments are necessary because fundamentally these adjustments are embedded in the ideal energy model and established through the BEF.

In terms of the ideal energy and the energy at risk the fundamental equation (9) becomes:

$$Energy\ Savings = (E_{Ideal} + E@R)_{Before} - (E_{Ideal} + E@R)_{After} \quad (10)$$

By using proposed concepts, the comparative element across an industrial sector is replaced with a theoretical goal. The rating is then solely based on how close the true energy consumption within an industrial process gets to that ideal state. No further reference adjustments are necessary since the essential energy already compensates for these highly variable material conditions

Therefore in terms of the Benchmark Energy Factor the fundamental equation can be simplified to:

$$Energy\ savings = \left(E_{Ideal}\middle|@_{same\ input\ parameters}\right) \times \left(BEF_{Before} - BEF_{After}\right) \quad (11)$$

An important benefit of this type of benchmark energy factor analysis is that the relatively small energy savings from a consumption basis can be represented as a rather large reduction of in the energy at risk or energy losses. By applying (11) to the EAF case study (lines 4 and 6) specific avoided thermal pollution is:

Δ Th. P (Energy savings) = 386 kWh/mt x (1.865 – 1.730) = 52 kWh/mt

This analysis of the difference in energy losses is considered a more transparent and reliable measurement of the reduction in energy than the total energy consumption analysis with variable (adjusted) baselines.

8. CONCLUSIONS

While DSM programs are considering the energy consumption (E_{Used}) as a whole, proposed method splits energy in two specific components: Ideal energy E_{Ideal} and Energy losses defined as Energy at Risk E@R.

The paper presents a new method of assessing Thermal Pollution due to energy losses enabling useful benchmarking of similar industrial systems and/or processes by using Benchmarking Energy Factor (BEF) and new concept of Energy at Risk (E@R).

It was found that Avoided Thermal Pollution (Energy at Risk variation) is embedded in (BEF).

The method uses well-known physical laws of science and physics to determine theoretical minimum required or ideal energy, E_{Ideal}. The methodology can be expanded defining essential energy, E_E that is technology independent but depending on material, environment conditions with allowance for lighting, personnel, transportation and equipment condition.

Once E@R is known, it will be logical proceeding with benchmarking plants, industrial systems or/and processes assessing their capability of managing Energy at Risk by focusing on in-situ testing.

Salient benefits of proposed method are:

- Ability to estimate Thermal Pollution (E@R) under variable material and environmental conditions
- Benchmarking and compare similar processes over their operating profile
- Ability to manage the Thermal Pollution (Energy at Risk) by setting SMART targets
- Ability to calculate the Avoided Thermal Pollution (energy savings) consistently, repeatable & accurately with dynamic reference (baseline) adjustments
- Measure continuous improvement results with improved ability to model and compare current state (baseline) and future state (target)

Basics of engineering and physics laws indicate that only (E@R) can be controlled; therefore Thermal Pollution Management can be one of the ultimate conservation goals for governments, utilities and customers [20].

REFERENCES

[1] World's Electricity Consumption - 2009, http://en.wikipedia.org/wiki/Electric_energy_consumption

[2] DoE, USA ''Energy Independence and Security Act of 2007'', Industrial Energy Efficiency, HR6-132, http://www.afdc.energy.gov/laws/eisa 2007

[3] Appavou F. Energy Efficiency in Industry – Show me the money. Presentation 2011. http://eemo.gov.mu/English//DOCUMENTS/EFFICIENCY.PPT. [Accessed Sep. 2013].

[4] Wellerstein A. The Hiroshima-Equivalent 2013. http://blog.nuclearsecrecy.com/2013/06/07/a-modest-proposal/

[5] US DoE and EPA. ENERGY STAR Helps Manufacturers Improve the Energy Performance of their Operations 2010. Available from: http://www.energystar.gov/ia/business/industry/estar_and_manufacturers.pdf?e2de-517a [Accessed Nov 2012].

[6] U.S. Council for Energy-Efficient Manufacturing. A Roadmap for Achieving Continual Improvements in Energy Performance 2012. Available from: http://www.superiorenergyperformance.net/ [Accessed Jan 2013]

[7] Gosman N, Pitis CD, Rosemann A, Zeller M. Energy at Risk: Opportunities for applying benchmark energy factors in the industrial sector. ACEEE Summer Study on Energy Efficiency in Industry, paper # 81, Available: aceeeconf@aceee.org<mailto:aceeeconf@aceee.org?subject=RE:%20Your%20submission%20to%20the%202013%20ACEEE%20Summer%20Study%20on%20Energy%20Efficiency%20in%20Industry>, ACEEE, USA 2013.

[8] Hepbaslia A, Kalinci Y. A review of heat pump water heating systems. Renew Sustain Energy Rev doi:10.1016/j.rser., Available:http://www.ecaa.ntu.edu.tw/weifang/hp/heatpumpEng/A%20review%20of%20heat%20pump%20water%20heating%20systems.pdf, [Accessed Oct 2011].

[9] Pitis CD Kleingeld M, van Rensburg J. A new approach to the efficiency concept in South African Industry. J Energy Southern Africa Proc 2007; 18(1): 51-63. Cape Town, South Africa, Available from: http://www.uct.ac.za/ JESA, 2007.

[10] Pitis CD. Power Savings obtained with Integrated Industrial System Drives. IEEE International Systems Conference SysCon 2012, Vancouver 2012; Paper #1569517381, Available from: http://ieeesyscon.org/content/sessions, 2012.

[11] Artobolevskii II. Teoriia mekhanizmov i mashin, 2nd ed. Moscow-Leningrad 1952.

[12] Schifo JF, Radia JT. Theoretical/Best Practice Energy Use Metal casting operations. US DoE – EERE 2004; pp. 19-24. http://www1.eere.energy.gov/manufacturing/resources/metal casting/pdfs/doebestpractice_052804.PDF [Accessed Feb. 2011].

[13] Jones JAT, Bowman B, Lefrank PA. Electric Furnace Steelmaking. in The Making, Shaping and Treating of Steel, R.J. Fruehan, Editor, The AISE Steel Foundation: Pittsburgh. USA 2004; pp. 525-660, 1998.

[14] Saburo U. On the Specific Heat of Carbon Steel"-Bibliothek Frankfurt am Main 4 B 13.76 2010; ISSN: 0040-8778, Sendai –University, Japan, Available: http://digital-b.ub.uni-frankfurt.de/frontdoor/index/index/docId/14044, [Accessed Feb. 2011].

[15] Ruth E, Caamano R. Environmental performance benchmarking of manufacturing plants in Mexico and the United States. ProQuest Dissertations and Theses; ProQuest 2001. Available from: http://www.ce.cmu.edu/greendesign/docs/ruth-reyna-caamano.pdf 2005.

[16] Advanced Melting Technologies. Energy Saving Concepts, Opportunities for the Metal Casting Industry BCS Inc Columbia, MD report for DoE – Energy Efficiency & Renewable Energy 2005. [Accessed Feb. 2011] http://www1.eere.energy.gov/manufacturing/resources/metal casting/pdfs/advancedmeltingtechnologies.pdf

[17] Schifo JF. Theoretical/Best Practice Energy Use In Metal casting Operations" USA, Keramida Environmental, Inc., 2005; p. 4.

[18] Pitis C. Using General Efficiency Concept in Selection Decisions of Dedicated Equipments. IEEE – EPEC2010, Paper 27, Halifax 2005; http://www.ieee.ca/epc10/index.htm, August 2010.

[19] International Performance Measurement & Verification Protocol (IPMVP) Volume I: Concepts and Options for Determining Energy Savings (2012) – National Renewable Energy Laboratory 1617 Cole Blvd.Golden, CO 80401-3393 Available from: http://www.nrel.gov/docs/fy02osti/31505.pdf, [Accessed Jan 2013].

[20] Environmental Protection Agency (EPA) USA: http://www.epa.gov/air/caa/index.html

Received on 07-10-13 Accepted on 02-12-13 Published on 29-01-2014

DOI: http://dx.doi.org/10.12974/2311-8741.2013.01.01.3