EXERGY ACCOUNTING AND THE GREENHOUSE GAS EMISSION: A UNIFIED APPROACH

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Abstract. *The exergy concept is introduced by utilizing a general conceptual framework on which are based the model equations for this work. An exergy analysis is performed on a case study: a control volume for a power module is created by comprising gas turbine, reduction gearbox, AC generator, exhaustion ducts and heat regenerator; the implementation of the equations is carried out by collecting test data of the equipment data sheets from the respective vendors; one builds an exergy distribution map for the whole power module for clearly depicting where the exergy losses occur; by utilizing such an exergy map, one proposes both mitigating and contingent countermeasures for maximizing the exergy efficiency. An extended exergy accounting is introduced aiming to show how the exergy concept might eventually be brought up to the traditional money accounting. At last, one devises a unified approach for efficiency metrics comprising the exergy and greenhouse gas emission as well as bridging gaps between the physical and the economical realms.*

Keywords: *efficiency, environment, exergy*

1. INTRODUCTION

Energy is a loophole, it is something which brings about movement in the space-time fabric of the universe, it is omnipresent, it always remains the same and it manifests itself in many forms within a control volume through works, enthalpy flows, heat, etc. On the other hand, exergy means the quality level of a determined energy quantity for being useful depending on the processes occurring either within a control volume or in its nearby surroundings. In actual processes exergy never remains the same because it is partially consumed by the inherent irreversibility of the control volume. When one carries out an exergy balance, the result is never zero and then one creates a quantity termed "exergy destruction" in order for the exergy quantities before and after the control volume to get even. For instance, regarding a heat flow, that one can not be all useful for doing work due to the Second Law of Thermodynamics. When one does an exergy balance, one finds out an exergy loss; nevertheless, there is no energy loss due to the First Law of Thermodynamics.

Figure (1) draws on the conceptual framework of the ISO 13601 [1]: enthalpy flows ΣE_{IN} and works ΣW_{IN} are inserted into a control volume, which then transforms those ones into other works ΣW_{OUT} and other enthalpy flows ΣE_{OUT} and process losses. Those losses are split into two parts, the reversible losses, which can be harnessed for yielding more work, and the irreversible ones or exergy destruction.

Exergy is the maximum energy quantity which can be made useful after discounting the irreversible losses. Also, exergy means a physical/chemical contrast level between a control volume and its nearby surroundings. Finally, exergy means the maximum work which can be extracted from a control volume.

A few words of advice: in the above description considering the works ΣW_{IN}, heat can be considered as incoming work if it is demanded by the control volume for its processes; for instance, radiation, conduction and convection heats. Heat going out of the control volume is classified either as irreversible or reversible loss.

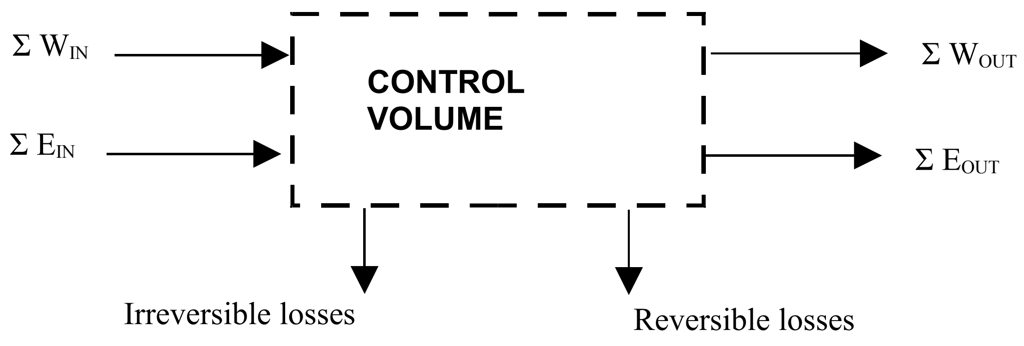

Figure 1. General control volume.

2. MODEL EQUATIONS

2.1. Exergy

The set of Equations (1) is a general one for exergy which comprises the gravity and the electromagnetic forces (thermodynamics, chemical, electric-magnetic), of which the thermodynamic and chemical ones are modeled as to Wall [3]. The variables are: *m*, mass; μ, specific internal energy; *P*, pressure; *v*, specific volume; *T*, temperature; *s*, specific entropy; *c*, chemical concentration; *g*, gravity acceleration; *z*, position.

$$\begin{aligned} E &= E^{Ther\,\mathrm{mod}\,ynamic} + E^{Chemical} + E^{Electromag} + E^{Gravity} \\ \therefore\ E^{Ther\,\mathrm{mod}\,ynamic} &= m\left[(u - u_0) + P_0(v - v_0) - T_0(s - s_0)\right] \\ \therefore\ E^{Chemical} &= m\left[\sum_i (\mu_i c_i - \mu_0 c_0)\right] \\ \therefore\ E^{Gravity} &= mg(z - z_0) \end{aligned} \tag{1}$$

2.2. Exergy flow

Equation (2) stems from Eq. (1) for the exergy flows in thermodynamics, chemistry and gravity; the electric-magnetic exergy is not covered in this work. The new variable here is: *h*, specific enthalpy.

$$\dot{E} = \dot{m}\left[(h - h_0) - T_0(s - s_0) + \sum_i (\mu_i c_i - \mu_0 c_0) + g(z - z_0)\right] \tag{2}$$

2.3. Exergy flow balance

Equation (3) stems from Fig. (1) for the exergy balance in a general control volume. The following convention is used: the control volume incoming variables have positive sign and those ones going out of the control volume have negative sign. The initial parenthesis refers to the exergy balance due to the enthalpy flows in the realm of Thermodynamics and Chemistry; the bracket refers to the thermal exergy flows associated with the thermal flows represented by *Q*, and the exergy destruction or irreversibility, E_D; the last part refers to the net work.

In an isolated control volume with no enthalpy flow or heat or work, the total exergy variation equals to minus the exergy destruction or irreversibility, that is, exergy always decreases (or entropy increases) in an isolated control volume. That is another statement for the Second Law of Thermodynamics, which applies to isolated control volumes only. Also the exergy variation is negative in a control volume in which ΣE_{IN} equals to ΣE_{OUT} and W_{IN} is zero.

By simplifying and rearranging Eq. (3) for a steady-state control volume in which ΣE is zero, one can bring up Eq. (4) in a dimensionless format.

$$\sum E = \sum (E_{IN} - E_{OUT}) - \left[\sum_i \left(1 - \frac{T_0}{T_i}\right) Q_i + E_D\right] - \sum (W_{OUT} - W_{IN}) \tag{3}$$

$$\frac{\sum_{OUT} (E + W)_i}{\sum_{IN} (E + W)_i} + \frac{\sum_i \left(1 - \frac{T_0}{T_i}\right) Q_i + E_D}{\sum_{IN} (E + W)_i} = 1 \tag{4}$$

3. CASE STUDY

Figure (2) shows a control volume for the Petrobras FPU – Float Production Unit P53 power modules. There are three inlets: fuel (Methane or Diesel), atmospheric air and process water; and four outlets: works (electric energy from the AC generator), water process, exhaust gases and heat exchanged in the cooling systems as well as by natural air convection and radiation from the pieces of equipment.

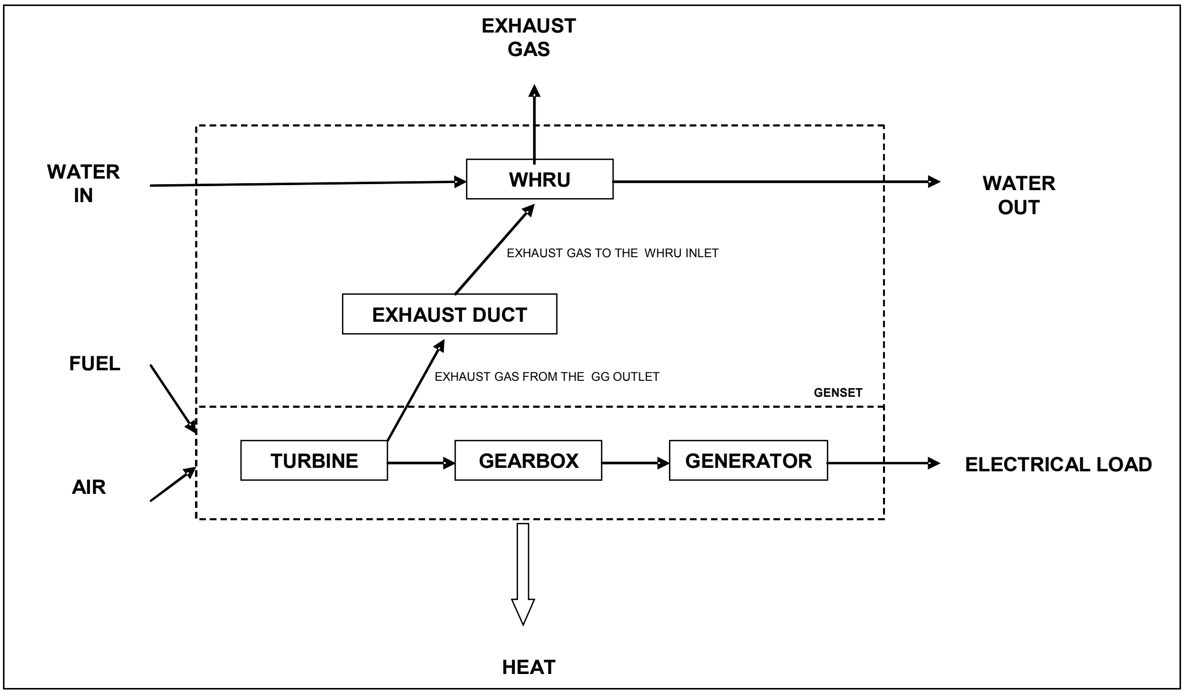

Figure 2. Control volume for the Petrobras FPU P53 power modules; WHRU stands for Waste Heat Recovery Unit.

3.1. Modeling assumptions

For determining the exergy distribution in the Petrobras FPU P53 power modules, one has assumed the following simplifying hypothesis:

1. Steady state operation;
2. Steady control volume;
3. Exhaust gases as ideal ones;
4. Enthalpy flows at chemical balance as to the environment.

3.2. Results

The heat values are determined by applying the energy conservation balance (The First Law of Thermodynamics) to control volumes comprising each piece of equipment in Fig. (2). Then Eq. (4) is utilized to calculate the exergy losses.

As to the exergy of the exhaust gases after the heat regenerator, Eq. (4) is utilized locally over a control volume enveloping it and by making all the works equal to zero.

All such values are based on the data sheets from Petrobras´ vendors, mainly Rolls-Royce, http://www.rolls-royce.com for aero-derivative gas turbine systems. The results are displayed in Figures (3), (4). One should notice the differences among the values of energy, exergy as well as their decreasing values with the increasing of the environment temperature.

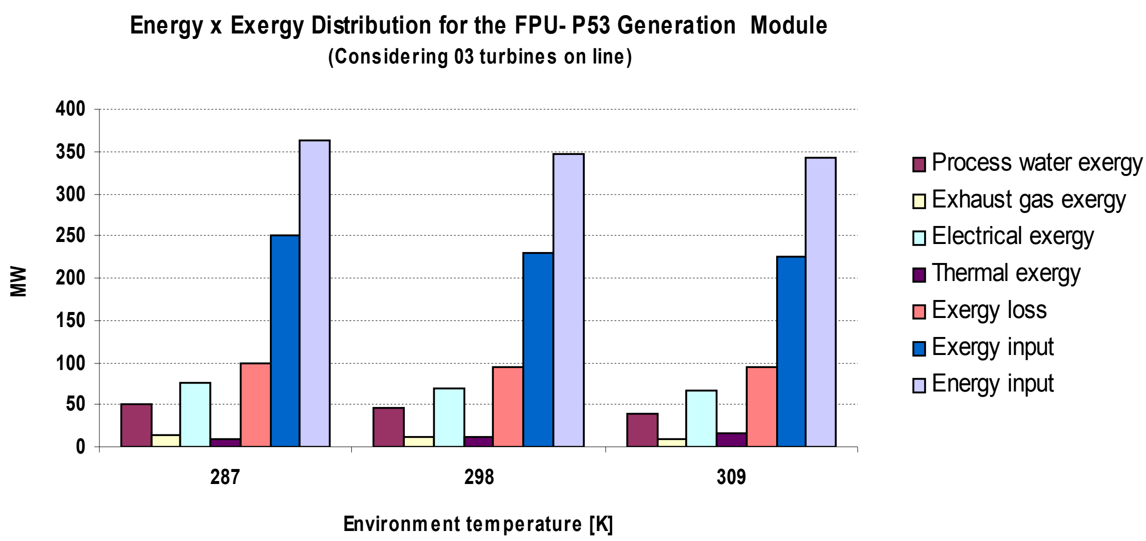

Figure 3. Energy, exergy distribution for the Petrobras FPU P53 power modules.

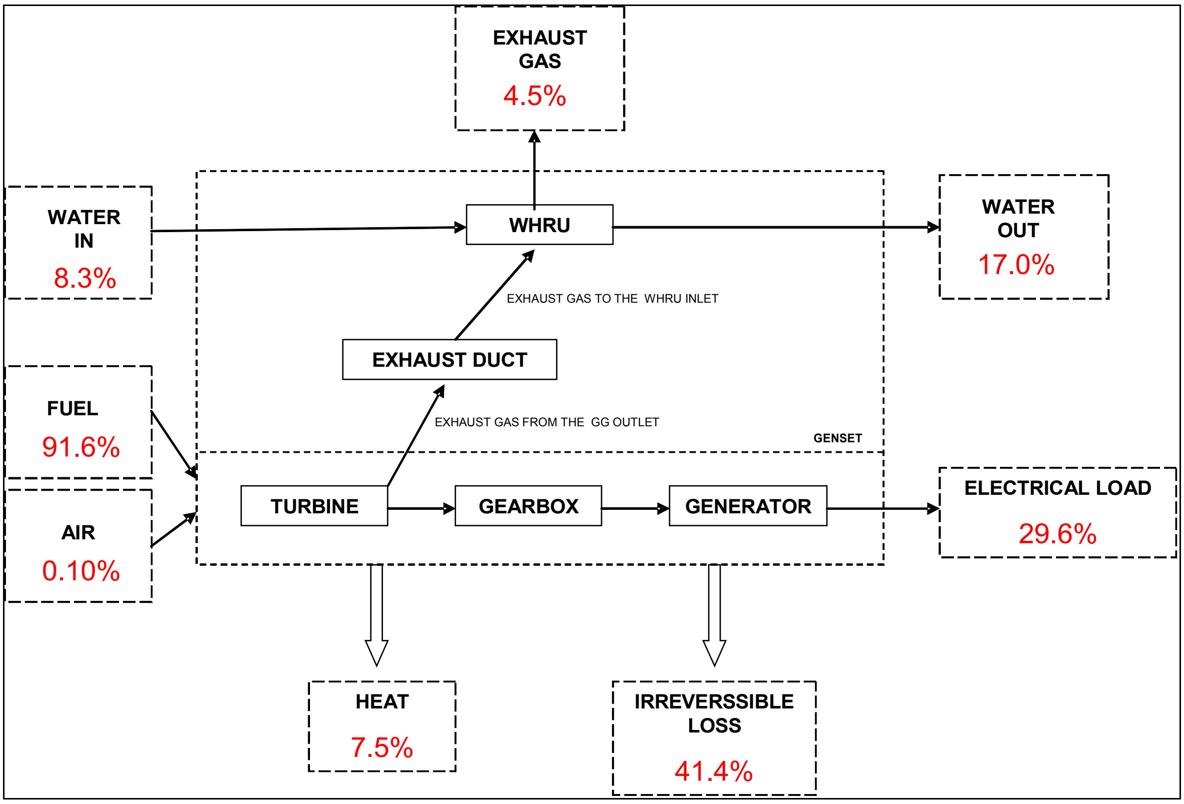

Figure 4. Exergy accounting for the Petrobras FPU P53 power modules at 309K environmental temperature; WHRU stands for Waste Heat Recovery Unit.

3.3. Analysis of the results

In Figure (4) one can carry out two calculations:
-By the traditional energy (not exergy) efficiency metric, the losses happen to be 12% from the heat and exhaust gases carried away to the environment, thus yielding 88% energy efficiency;
-On the other hand, besides the 12% thermal losses, there happen to be 41% irreversible ones as well, which imply 47% exergy efficiency. By the energy method, those 41% irreversible losses are embedded into the output values, thus yielding that 88% energy efficiency.

Considering three turbines operating on-line at steady-state: a) the heat carried away by the exhaust gases after the heat regenerator and by the natural air convection and radiation through the walls of both the exhaust piping and the heat regenerator itself amounts 4.5% out of the incoming exergy, which mean about 10MW; b) the heat carried away by the equipment cooling systems as well as by natural air convection and radiation amounts 7.5% out of the incoming exergy, which mean about 17MW.

In order to reduce the 12% reversible losses only one may have: a) regenerating systems for amine and glycol for the sweetening and dehydrating of the natural gas; b) fuel gas preheating for keeping a safe distance from the dew point of heavy fractions; c) adsorbing cooling system in the inlet combustion air for aiding on more mass flow entering the combustion chamber; d) room warming through heat exchange between hot water from the cooling systems and ambient air.

In order to reduce the 41% irreversible losses only one may have either more efficient combustion chambers or better materials or better fuels able to withstand higher combustion temperatures and pressures.

However, all these depend on both technical, economical studies for new concept designs and on technological advances in the related pieces of equipment as well as on better quality levels in construction and fuels. The 47% exergy efficiency represents the current state-of-the-art for such systems.

4. EXTENDED EXERGY ACCOUNTING

Figure (5) is an illustration only and it exemplifies a typical economical feasibility study. Also Figure (6) is just an illustration doing the same for an extended exergy accounting, which aims to calculate the exergy destructions of a production asset from its installation up to its decommissioning. There shall be a time interval during which the asset operation is to be optimized, with the lowest environmental impacts. For determining mean values at steady state, Eq. (5) is derived from Eq. (3). Therefore, the issue is to minimize the value of Eq. (5), hence minimizing the exergy destruction and thus the environmental impact. As a reference for all the types of flow in several economical sectors, there is the ISO 13601 [1].

For energy efficiency projects, one can use the metric CSE-Cost of Saved Energy, a term borrowed from Lovins [2]. CSE is calculated by dividing the EPC, O&M present discounted costs by the total energy saved throughout the life-cycle of the product (see the Appendix). The price of the energy saved is not part of that calculation in order not to understate the amount of energy saved. Thus the smaller the CSE value the better the project as to energy efficiency.

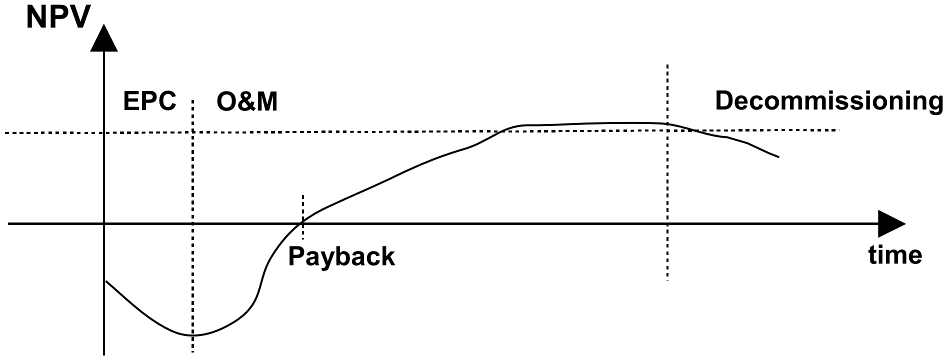

Figure 5. The NPV-Net Present Value over the life cycle of a production asset. EPC stands for Engineering-Procurement-Construction; O&M stands for Operation and Maintenance; illustration only.

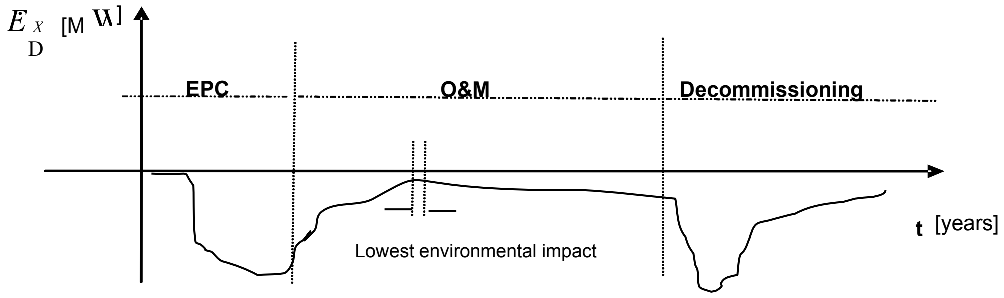

Figure 6. The irreversibility values over the life cycle of a production asset; illustration only.

$$\overline{E}_D = \frac{1}{\Delta t}\int_0^{\Delta t}\left(\sum \left(\dot{E}_{IN} - \dot{E}_{OUT}\right) - \sum_i \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i - \sum \left(\dot{W}_{OUT} - \dot{W}_{IN}\right)\right) dt \tag{5}$$

5. A UNIFIED APPROACH FOR MEASURING THE GREENHOUSE EMISSIONS

Aiming at either benchmarking surveys or project management for improving energy efficiency in production assets, one utilizes efficiency metrics which can vary wildly as to each asset type. One way to enable comparisons among either production assets of the same kind or distinct ones is to utilize the exergy concept, through which one can determine their irreversibility in a common language, in energy units, and also taking into consideration the nearby environment into which they are inserted. To determine the exergy efficiency of a production asset, one takes the first part of Eq. (4), thus deriving Eq. (6). It is worth noting that the two classical laws of Thermodynamics are followed, the one for energy conservation and the other for the irreversibility of the real processes. Such an efficiency metric is also called the Second Law Energy Efficiency, that which accounts for entropy variations as well.

$$\eta_X = \frac{\sum_{OUT}\left(\overline{E} + \overline{W}\right)_i}{\sum_{IN}\left(\overline{E} + \overline{W}\right)_i} \tag{6}$$

As the environmental issue has become urgent for the sustainability of the businesses and the planet in the 21st century, it is worth devising a proper metric to account for that. Usually one takes the division between the mean value of the equivalent mass of carbon dioxide emitted to the environment and the mean value of the energy consumed by the production asset, such a rate having usually the dimension Mte(CO_2)/TWh. One can transform that rate into a dimensionless one by multiplying the numerator by the formation exergy of the carbon dioxide, about 20 kJ/mol [3], and so creating a dimensionless metric, TJe(CO_2)/TJ, as to Eq. (7).

$$\alpha_{CO2} = \frac{\overline{E}_D^{CO2}}{\sum_{IN}\left(\overline{E} + \overline{W}\right)} \tag{7}$$

By making α as other exergy destructions beyond that one due to the greenhouse gas emissions and β as thermal losses, one can reshape Eq. (4) in terms of dimensionless indicators as to Eq. (8).

$$\alpha + \alpha_{CO2} + \beta + \eta_X = 1 \tag{8}$$

The variables in Eq. (8) are not linearly independent on one another: reducing the emission of equivalent carbon dioxide shall imply on reducing the exergy efficiency as well if either heat regenerators or combined cycles or exergy conversion systems with less irreversibility are not added.

Figure (7) is a conceptual plot for showing the evolution of a control volume towards less carbon and towards non-carbon exergy sources, from 2% to 0% for instance as to Eq. (7); note the sum of all values being unity by following Eq. (8). Also such an "exergy disclosure" or an equivalent friendlier format may be added to the conventional accounting balance of an organization in response to the much needed stringent environmental constraints for the planet. T1 may represent a typical asset with relatively high exergy efficiency; T2 may be well the case of an oil-supply chain asset with CCS-Carbon Capture and Storage technology; T3 may represent a "green asset", that with no CO_2 emissions. Note that even in a 100% "green" product, one shall never get rid of the irreversibility issue.

The T3 scenario is the one to use non-carbon energy sources for which the value of Eq. (7) is zero. Nevertheless, a T3 control volume has also irreversibility, as stated shortly before, as well as thermal losses and so it must be worked out in order to minimize the alpha and beta terms from Eq. (8), thus maximizing the value of the exergy efficiency.

Also Eq. (7) can be utilized for valuating environmental impacts in terms of monetary values. For instance, if one considers 1% tax deduction over business revenue for each 1% reduction in CO_2 emission, then $10million/yr shall result as a cost avoidance figure for a one billion/yr business. Symmetrically, a 1% fee over business revenue should hold for each 1% increase in CO_2 emission. The coupling of Eq. (7) to economic figures has to be properly designed, implemented and audited.

Further improvements can be achieved by technological upgrades, breakthroughs in both the EPC and the O&M phases in order to reduce even more both the irreversible losses and the thermal ones. Energy efficiency projects can be ranked by both the CSE and the CCC metrics (see the Appendix). See Lovins [2] for further reading.

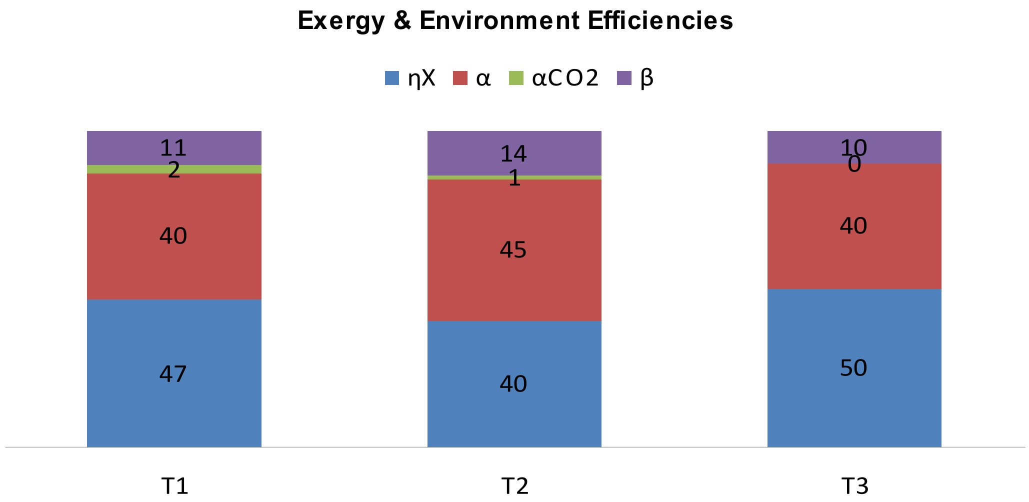

Figure (7). Exergy efficiencies, thermal losses and irreversibility along time in a control volume; conceptual plot

6. CONCLUSIONS

This paper has shown a better metric for energy efficiency by utilizing the exergy concept which brings all the irreversibility up within a control volume. Using the energy concept, one gets 88% efficiency for a power module with heat regenerator. On the other hand, using the exergy concept, one gets 47% efficiency, which is more representative because that value does not hide the irreversibility of the processes within that control volume.

One has derived a metric for environmental efficiency which relates the exergy lost by the carbon dioxide emission to the environment and the exergy in terms of works and enthalpy flows consumed by the control volume. That metric is dimensionless and the lesser such a value the better for the environment and that indicates as well how much it is withdrawn from all the exergy consumed by the control volume.

Also one has shown it is possible and desirable to unite the CO_2 emission metric with economic figures so to bridge a gap between the physical and the economical realms. By devising either a green tax or a green incentive, one can foster energy efficiency projects which in turn may be ranked by the CSE, CCC metrics.

7. BIBLIOGRAFY

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8. RESPONSIBILITY NOTICE

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APPENDIX

The Cost of Saved Energy-CSE is generally calculated as to the expression below.

$$CSE = \frac{\sum_{j}^{n} C_j \left(1 + i_j\right)^{-j}}{\sum_{j}^{n} S_j}$$

n: number of time periods, usually in years
j: time period index
i_j: interest rate at the j^{th} time period
C_j: either EPC or differential O&M costs at the j^{th} time period
S_j: saved energy at the j^{th} time period, usually in kWh

The same concept can be applied to a Cost of CO_2 Captured – CCC by replacing the saved energy by the captured CO_2 in MT (megatons).

A simpler CSE calculation stems from making constant the cost, the saved energy and the interest rate. For a zero interest ratio, CSE equals to the C/S ratio.

$$CSE = a_{n/i}\left(\frac{C}{S}\right)$$

$$\therefore \; a_{n/i} = \frac{1 - (1 + i)^{-n}}{i}$$

For instance, an over 5-year energy efficiency project with $1million/yr EPC, differential O&M costs estimated to save 40GWh/yr has about $0.075/kWh CSE for a 20% yearly interest rate. If one compares that value with a $0.20/kWh price, one concludes it is cheaper saving energy than buying additional one. That project would be paid back roughly in 8 months after its completion.

Actually both CSE and CCC metrics should be used to rank green projects.