EKSERJİ VE UYGULAMALARI YAZ KURSU

(SUMMER COURSE ON EXERGY AND ITS APPLICATIONS)
(2-4 May 2024)
Pamukkale University, Denizli

Exergy Efficiencies and Parameters for Energy Systems

Enerji Sistemleri İçin Ekserji Verimleri ve Parametreler

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Nasıl Atıflanacağı

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- **Başka kaynaktan bir çalışmayı kullandığınız zaman, atıf yapmayı lütfen unutmayınız.**

Notlar:

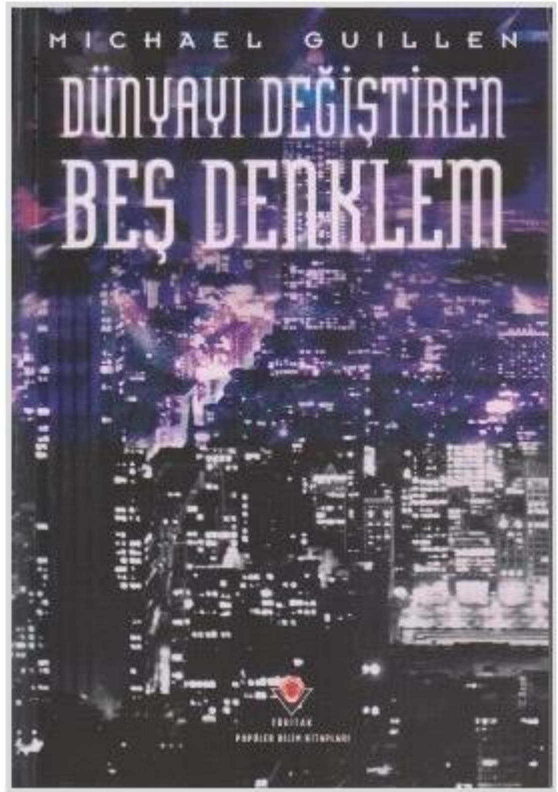
- **Sunumun bazı slaytları Türkçe, bazıları ise İngilizcedir.**
- **Tüm sunumlarımı seve seve etkinlik yetkilisinden edinebilirsiniz.**

Outline

1. Introduction
2. Dead State Definition
3. Various Types of Exergy
4. Exergy-based Analysis and Assessment Methods
5. Modeling
6. Case Studies
7. Some Exergetic Considerations
8. Sankey (Energy Flow), Grassmann (Exergy Loss and Flow) and Cost Flow Diagrams
9. Concluding remarks

1. Introduction

Dünyayı Değiştiren Beş Denklem



Kitap

Dünyayı Değiştiren Beş Denklem

Orjinal isim: Five EquationsThat Changed The World - The Power and Poetry of Mathematics

Michael Guillen

TÜBİTAK Yayınları / Popüler Bilim Kitapları

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Definitions and nomenclature in exergy analysis and exergoeconomics

George Tsatsaronis*

Technische Universität Berlin, Institute for Energy Engineering, Marchstr. 18, 10587 Berlin, Germany

What is Exergy ?
(Various Exergy Definitions)

- The quality of energy
- The capacity of energy to cause change
- The maximum work that can be obtained from a given form of energy using the environmental parameters as the reference state
- A measure of the departure of the state of the system from the state of the environment

Sources:

Leskinen, M. Low Exergy Sources for Heating and Cooling & IEA Annex 37

Tsatsaronis, G and Cziesla, F. Thermoeconomics, 2003.

Exergy is the elixir of life. Exergy is that portion of energy available to do work. Elixir is defined as a substance held capable of prolonging life indefinitely, which implies sustainability of life.

Source: https://www.semanticscholar.org/paper/Chapter-1-Exergy-Sustainability-for-Complex-Systems-Robinett-Wilson/5546e4a98800bcbc487b7901e5219fc5ebf1dd60. Access date: May 2, 2023.

E — **E**xergy is the quality of energy, and uses the potential of energy for causing changes.

X — **X**-Ray is the best illustration of **its** difference from energy.

E — **E**valuation of performances through analyzing **it** is more meaningful compared to energetic analyses.

R — Reversibility is a thermodynamic idealization while irreversibility is due to **its** consumption.

G — **G**ain (benefit or product or desired effect) divided by fuel is **its** efficiency (i.e., exergetic efficiency).

Y — **Y**ielding higher performance improvements is achieved through **it**.

Acrostic of EXERGY written by Arif Hepbasli (April 3, 2022)

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Renewable and Sustainable Energy Reviews
12 (2008) 593–661

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A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future

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Table 1
Various exergy definitions [18,56–74].

Investigators/sources	Exergy definitions
Rant [56]	Exergy is defined as that part of energy that can be fully converted into any other kind of energy
Rickert [57]	Exergy is the shaft work or electrical energy to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged only with the environment at temperature T_0
Szargut et al. [58,59]	Exergy is a measure of a quality of various kinds of energy and is defined as the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature
Kotas [60]	The work equivalent of a given form of energy is a measure of its exergy, which is defined as the maximum work, which can be obtained from a given form of energy using the environmental parameters as the reference state
Shukuya [14]	Exergy is defined as a measure of dispersion potential of energy and matter, while entropy is defined as a measure that indicates the dispersion of energy and matter
Bejan [18,61]	Exergy is the minimum theoretical useful work required to form a quantity of matter from substance present in the environment and to bring the matter to a specified state. Exergy is a measure of the departure of the state of the system from that of the environment, and is therefore an attribute of the system and environment together
Moran and Shapiro [18,62]	Exergy is the maximum theoretical work that can be extracted from a combined system consisting of the system under study and the environment as the system passes from a given state to equilibrium with the environment - that is, passes to the dead state at which the combined system possesses energy, but no exergy
Connely and Koshland [18,63]	The property exergy defines the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surroundings through a reversible process
Honerkamp [64]	The maximum fraction of an energy form, which (in a reversible process) can be transformed into work is called exergy. The remaining part is called anergy, and this corresponds to the waste heat
Ala-Juusela [18,65]	Exergy is the concept, which quantifies the potential of energy and matter to disperse in the course of their diffusion into their environment, to articulate what is consumed within a system
Tsatsaronis [66]	Exergy of a thermodynamic system is the maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only
Gunnewiek and Rosen [67,68]	Exergy can be viewed as a measure of the departure of a substance from equilibrium with a specified reference environment, which is often modeled as the actual environment. The exergy of an emission to the environment, therefore, is a measure of the potential of the emission to change or impact the environment. The greater the exergy of an emission, the greater is its departure from equilibrium with the environment, and the greater may be its potential to change or impact the environment
Cengel and Boles [69]	The exergy of a person in daily life can be viewed as the best job that person can do under the most favorable conditions. The exergy of a person at a given time and place can be viewed as the maximum amount of work he or she can do at that time and place
Wordiq [70]	Exergy is the maximum amount of work that can be extracted from a physical system by exchanging matter and energy with large reservoirs in a reference state.
Wikipedia [71]	In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir
Wiktionary [72]	In thermodynamics, exergy is a measure of the actual potential of a system to do work, while in systems energetics, entropy-free energy
Geoseries [73]	Exergy expresses the quality of an energy source and quantifies the useful work that may be done by a certain quantity of energy
Clickstormgroup [74]	In thermodynamics, the exergy of a system is the maximum work possible during a process that brings the system into equilibrium with a heat reservoir

2. Dead (Reference) State Definition

Equilibrium

- Thermal: $T=T_o$
- Mechanical: $P=P_o$
- Chemical: $\mu=\mu_o$

$$(T,P,\mu) \rightarrow \underbrace{(T_o, P_o, \mu)}_{\text{Restricted dead state}} \rightarrow \underbrace{(T_o, P_o, \mu_o)}_{\text{Dead state}}$$

Thermomechanical exergy — Chemical exergy

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Sistem ile Çevresi Arasında Mekanik, Isıl ve Kimyasal Denge:

Dead State (Sistemin Basınç, Sıcaklık ve Kimyasal Potansiyelleri Çevreninkine Eşit)

Sistem ile Çevresi Arasında Mekanik ve Isıl Denge : Restricted Dead State (Basınç ve Sıcaklık)

Source: Moran MJ. Availability analysis: a guide to efficiency energy use. Englewood Cliffs, NJ: Prentice-Hall; 1982.

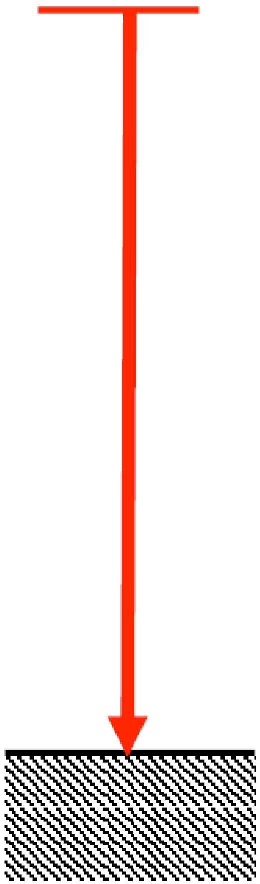
- It should be noticed that exergy is always evaluated with respect to a reference environment (i.e., dead state).
- When a system is in equilibrium with the environment, the state of the system is called the dead state due to the fact that the exergy is zero. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied: the pressure, temperature, and chemical potentials of the system equal those of the environment, respectively.
- In addition, the system has no motion or elevation relative to coordinates in the environment. Under these conditions, there is neither possibility of a spontaneous change within the system or the environment nor an interaction between them. The value of exergy is zero..

Dead (Reference) State Definition (Cont'd)

- Another type of equilibrium between the system and environment can be identified. This is a restricted form of equilibrium, where only the conditions of mechanical and thermal equilibrium (thermomechanical equilibrium) must be satisfied. Such state is called the restricted dead state.
- At the restricted dead state, the fixed quantity of matter under consideration is imagined to be sealed in an envelope impervious to mass flow, at zero velocity and elevation relative to coordinates in the environment, and at the temperature T_0 and pressure P_0 taken often as 25 °C and 1 atm.
- The selection of dead state conditions is arbitrary, but depends on some criteria.

Please note that we will call only the dead state throughout the course.

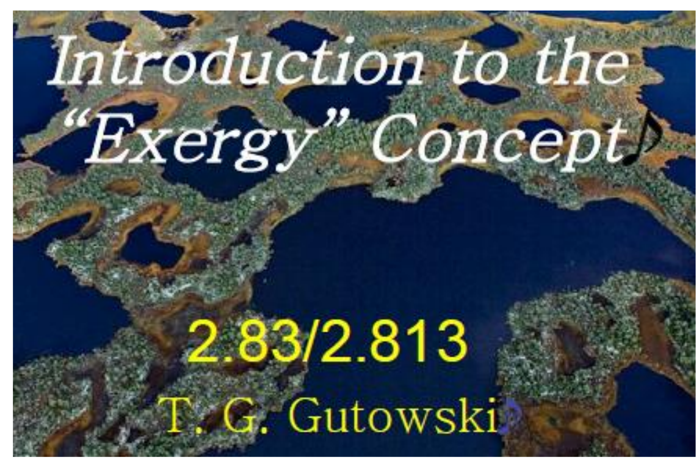
Source: Moran MJ. Availability analysis: a guide to efficiency energy use. Englewood Cliffs, NJ: Prentice-Hall; 1982.

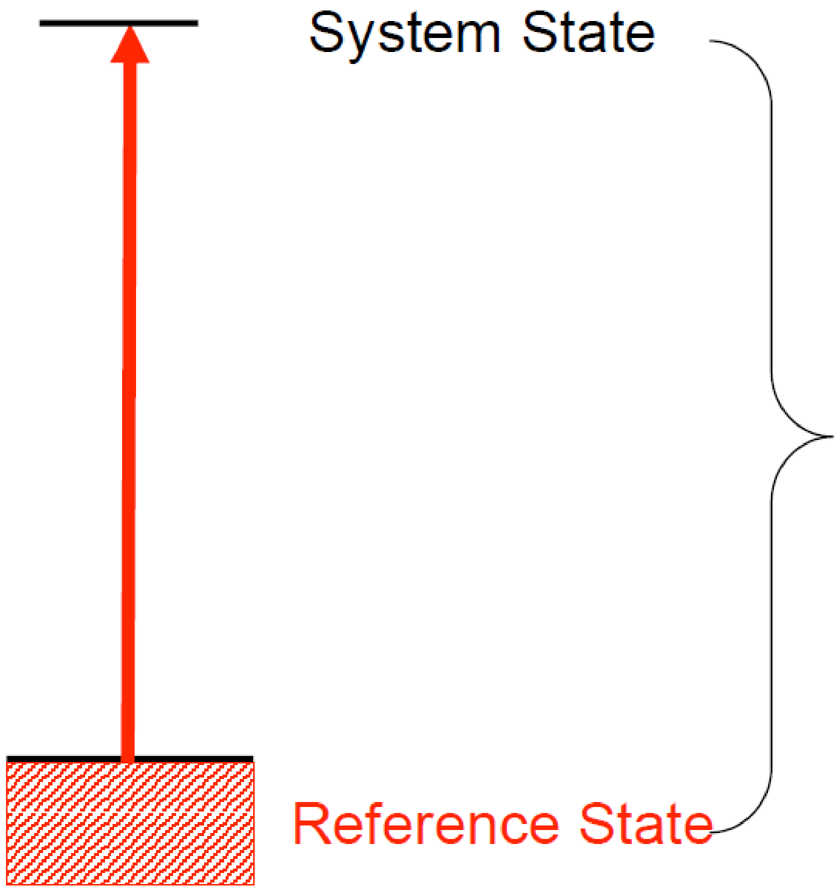


System State

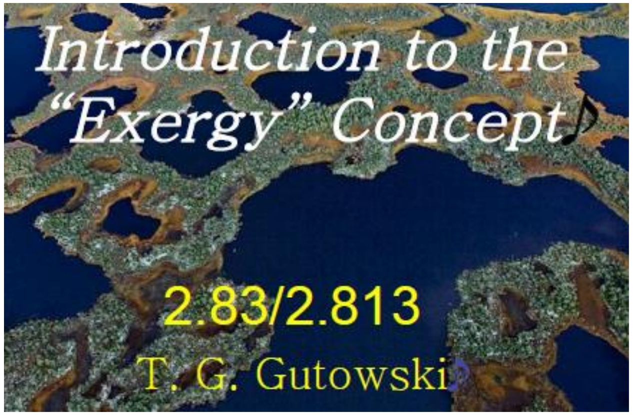
Reference State

Maximum work obtainable between System and Reference States.





The minimum work needed
to raise System from the reference
state to the System State



3. Various Types of Exergy

Total exergy of a system:

$$Ex_{sys} = Ex_{PH} + Ex_{KN} + Ex_{PT} + Ex_{CH}$$

Physical Kinetic Potential Chemical *

Total specific exergy on a mass basis:

$$ex_{sys} = ex_{PH} + ex_{KN} + ex_{PT} + ex_{CH}$$

*Please note that the chemical exergy has NOT been included in this course, while it is given here for your information only.

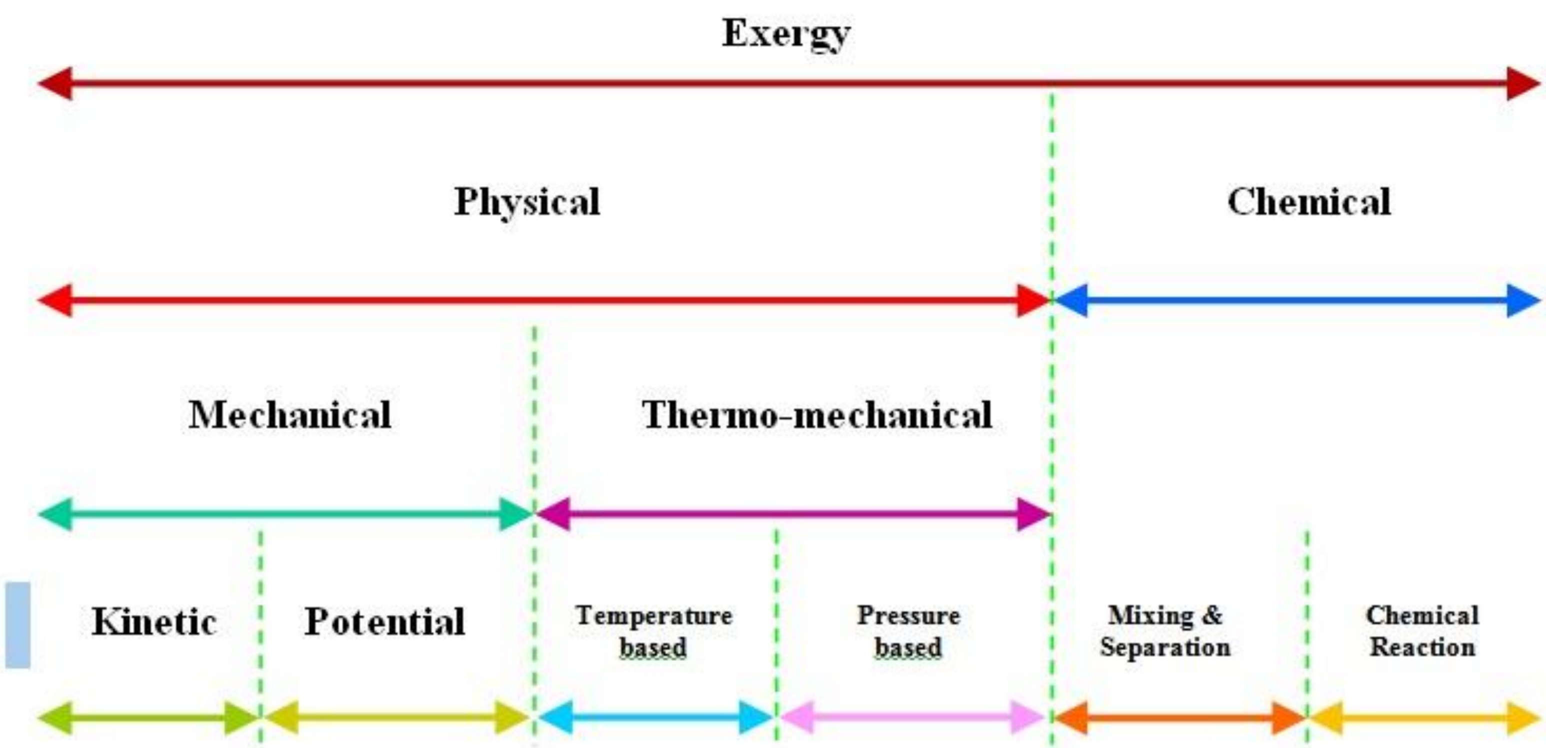


Figure (1.5) Classification of exergy for PVT systems [5]

Source: https://www.researchgate.net/post/Exergy-analysis-on-Thermodynamic-system, accessed on April 30, 2023.

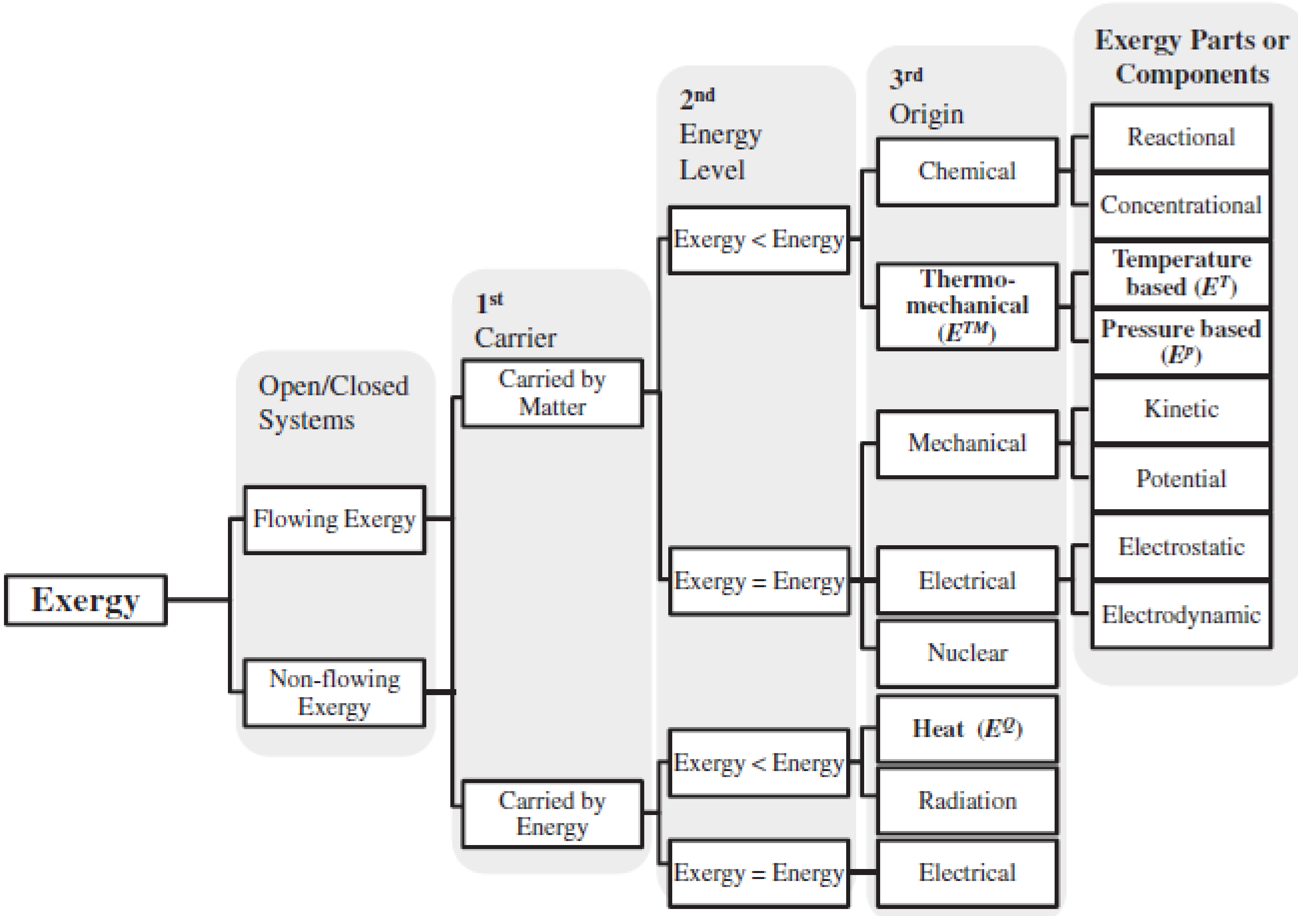


Fig. 1. Classification and decomposition of exergy according to its energetic origin.

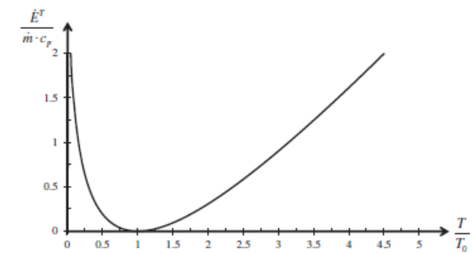


Fig. 3. Temperature based part of thermo-mechanical exergy.

$$\dot{E}^Q = \left(1-\frac{T_0}{T}\right)\dot{Q} \quad \text{if } T \ge T_0$$
$$\dot{E}^Q = \left(\frac{T_0}{T}-1\right)\dot{Q} \quad \text{if } T \le T_0 \qquad (7)$$

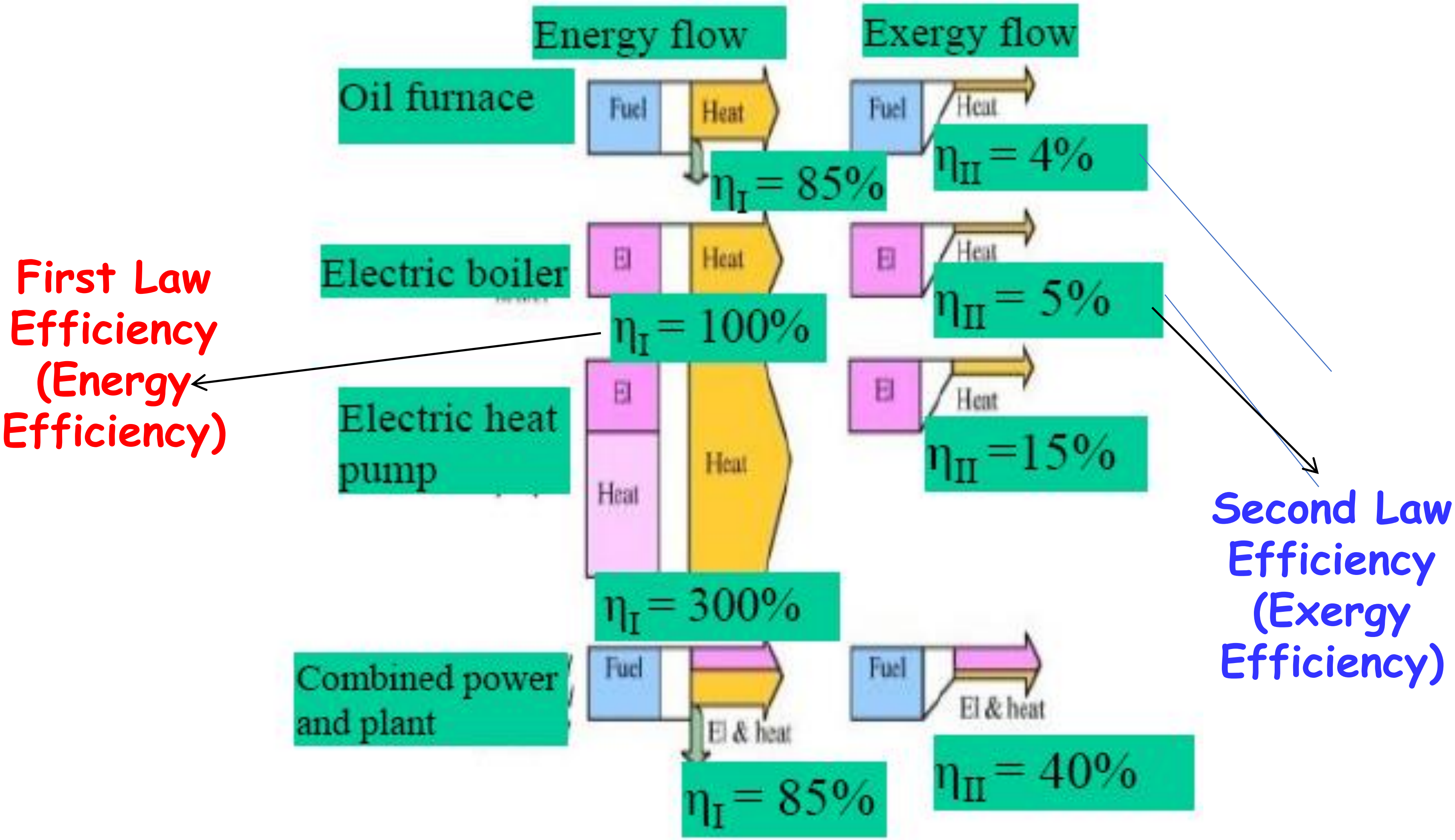
D. Marmolejo-Correa, T. Gundersen / Energy 44 (2012) 477–489

Exergy function for different energy stream conditions [35].

Description	Expression
For a pure substance	$\dot{X}. = \dot{m}\left[(h - h_o) - \dot{T}_o(s - s_o)\right]$
For a solid fuel (semi-empirical correlation)	$\dot{X} = \left[(LHV).\left(1.0438 + 0.0013.\frac{x_H}{x_C} + 0.1083.\frac{x_O}{x_C} + 0.0549.\frac{x_N}{x_C}\right) + 6740.x_S \right]$
For a gas phase (flue gas)	$\dot{X} = \dot{m}\left[(h - h_o) - T_o(s - s_o) + \sum \dot{x}'_k.e_k^{CH} + \overline{R}.T_o.\sum x'_k.\ln x'_k\right]$

R. Kumar / Engineering Science and Technology, an International Journal 20 (2017) 283–292

Energy and Exergy Flow Diagrams



Source: Wall, G; Zvolinschi, A.

4. Exergy-based Analysis and Assessment Methods

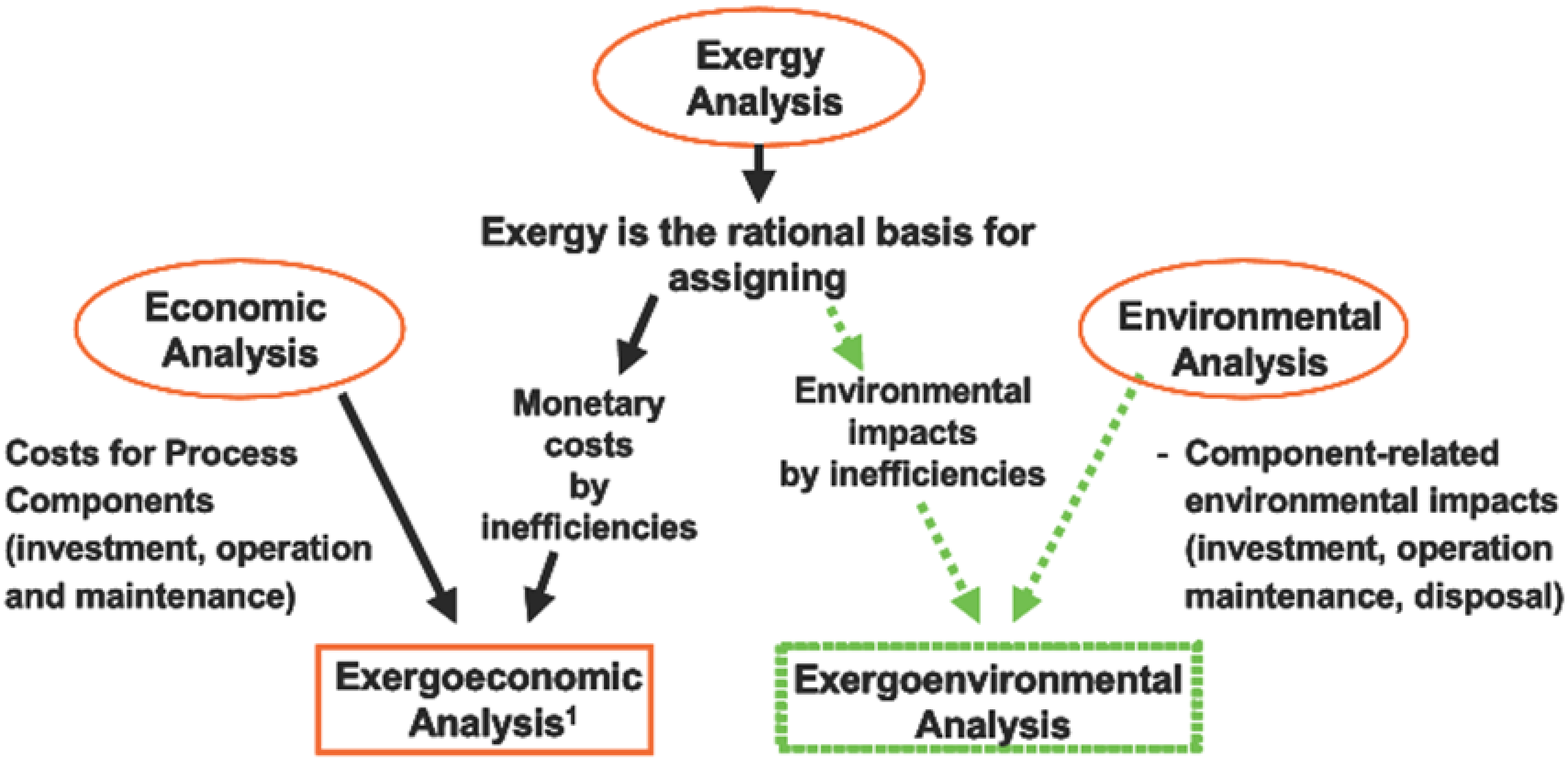
Conventional and advanced exergy-based analyses

Energy analysis
Exergy analysis
Economic analysis
Life cycle assessment

Exergoeconomic analysis
Exergoenvironmental analysis
Exergetic life cycle assessment

Advanced (enhanced) exergy analysis
Advanced (enhanced) exergoeconomic analysis
Advanced (enhanced) exergoenvironmental analysis

Thermo-ecological cost



Analogy between Exergoeconomic and Exergoenvironmental Analysis

[1] Source: Bejan, A., Tsatsaronis, G., Moran, M., 1996, Thermal Design and Optimization. New York: John Wiley.

https://www.hemensaglik.com/makale/kalp-hastaliklari-ve-doktor-kontrolü, Erişim Tarihi: 26.4.2019.

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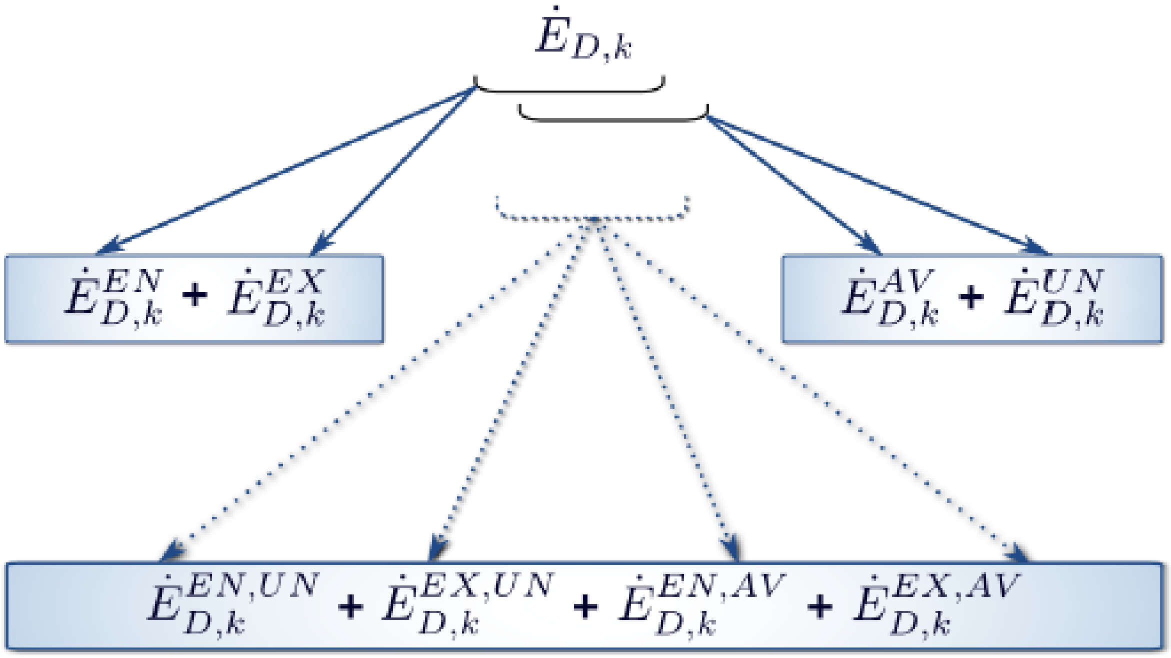
MR (Manyetik Rezonans)

Kaynak: Hepbaşlı, A.: ‘’Enerji Çözümünde Enerji Yönetiminin Rolü‘’, 22 slayt, Türkiye’de Enerji Çözümleri Çalıştayı ve Paneli, Bursa Teknoloji ve Koordinasyon ve AR-Ge Merkezi, Bursa, 3 Mayıs 2019 (Yayınlanmamış).



A diagrammatic representation of the splitting of the exergy destruction of a component *k* into its endogenous/exogenous and unavoidable/avoidable parts

Sources: Kelly, S. Energy Systems Improvement based on Endogenous and Exogenous Exergy Destruction. Berlin, 2008.

Tsatsaronis, G. Advanced Exergoeconomics-1. In *Proceedings of the 4th "European Congress Economics and management of energy in industry"* (Porto, Portugal, November, 27-30 2007). CD-ROM, 10 p.

- **Cumulative Exergy Demand (CExD)**

This method was proposed by **Szargut et al.** [25]. **It is defined as the sum of exergy of all supplies required to produce a product or provide a service [7]**. CExD is related to Cumulative Energy Demand (CED), but unlike CED, it can account for materials and quality of energy inputs. In addition to this advantage, CExD analysis can provide insight into potential improvements and for comparing alternative products, by accounting for exergy use throughout the life cycle.

Source: Nwodo, M.N. and Anumba, C.J. Exergetic Life Cycle Assessment: A Review. Energies 2020, 13, 2684; doi:10.3390/en13112684.

- **Thermo-Ecological Cost (TEC)**

This method accounts only for the cumulative consumption of non-renewable primary exergy resources. It is expressed in exergy units and not in monetary units. This method was developed with the premise that it is essential to determine and reduce the depletion of non-renewable natural materials in the field of ecological applications of exergy [42].

Source: Nwodo, M.N. and Anumba, C.J. Exergetic Life Cycle Assessment: A Review. Energies 2020, 13, 2684; doi:10.3390/en13112684.

- **Cumulative Exergy Extraction from Natural Environment (CExENE)**

This method is an extension of the boundaries of CExD to include land use. CExD accounts for energetic supplies and materials traditionally considered non-energetic such as mineral, water, and metal, but ignores land use. CED only accounts for materials, which may be used as energy carriers [43]. Therefore, CExENE is quantitatively the most comprehensive resource indicator of the three, because it evaluates energy carriers, non-energetic supplies, and land occupation. Conceptually and qualitatively, CExENE differs from CExD and therefore leads to a different evaluation. CExD measures the exergy that is transferred into the technological system from nature, while CExENE accounts for total exergy that is deprived of the natural system [43] which may or may not be transferred into the technological system.

Source: Nwodo, M.N. and Anumba, C.J. Exergetic Life Cycle Assessment: A Review. Energies 2020, 13, 2684; doi:10.3390/en13112684.

- **Industrial/Ecological Cumulative Exergy Demand (ICExD/ECExD)**

This method is an extension of the CExD method to emphasize on industrial and ecological processes, respectively [44,45]. ICExD reports the exergy of natural wealth consumed by each industrial sector both directly and indirectly, while ECExD reports the exergy used up in ecological systems to produce each natural wealth [46]. For a production chain, ECExD analysis improves on ICExD analysis by including exergy losses in the industrial as well as ecological stages [46]. This method defines the mathematical form of economic and ecological systems through fiscal and physical input-output tables. Like the economic input-output model, the main advantage of this method is probably the availability of the necessary macroeconomic data for each sector. However, there is lack of details of individual processes in these sectors, which can lead to aggregation error [46].

Source: Nwodo, M.N. and Anumba, C.J. Exergetic Life Cycle Assessment: A Review. Energies 2020, 13, 2684; doi:10.3390/en13112684.

- **Extended Exergy Accounting (EExA): Genişletilmiş Ekserji Muhasebesi**

As proposed by Sciubba [47], **the Extended Exergy Accounting (EExA) method is used to compute a commodity value based on its resource equivalent value instead of its fiscal cost**. This method is based on two essential assumptions: (a) that the cumulative exergy content of a product or service is the sum of the exergies of the product's constituents, in addition to a weighted sum of the exergies of the production process of the product, and (b) that non-energetic costs such as labor, capital, and environmental emissions can be reformulated in terms of exergy from global system balances. While (a) is a paraphrase of Szargut's CExD, (b) is the original contribution of EExA. A theoretical and practical advance in EExA can be found in Dai et al. [48].

Source: Nwodo, M.N. and Anumba, C.J. Exergetic Life Cycle Assessment: A Review. Energies 2020, 13, 2684; doi:10.3390/en13112684.

Genişletilmiş Ekserji Muhasebesi: Bu fikir Sciubba tarafından (Sciubba, 2005) eksergo-ekonomik analizler için ortaya atılmıştır. Bejan vd. (1996) tarafından tanımlanan eksergo-ekonomik analizlerinde, bir sistemin ekserji analizi tamamlandıktan sonra her bir ekserji akımı için bir özgül maliyet ($/kJ) hesaplanmakta ve bu ilgili ekserji akış oranı ile çarpılarak o akımım maliyeti bulunmaktadır. Burada sermaye ve iş gücü gibi ekserji analizine doğrudan katılmayan maliyetler ise ekstra olarak eklenmektedir. Sciubba (2005) bu yaklaşımın iki adet zayıflığı olduğunu belirtmiştir. Birinci zayıflığın ekserji ile para gibi çok farklı iki göstergenin birleştirilmeye çalışılması, ikinci zayıflığın ise birinciye bağlı olarak çevresel etkilerin bu analizler ile çok doğru bir şekilde değerlendirilemediği olarak belirlemiştir.

Kaynak: Alpman, E. and Gögüş, Y. HAVACILIKTA SÜRDÜRÜLEBİLİR GELİŞME GÖSTERGELERİ https://dergipark.org.tr/tr/download/article-file/701053. Access date: May 2, 2023.

Table 2. Comparison of the exergy-based methods.

Exergy-Based Method	Scope	Limitations
Cumulative exergy demand	Measures energy quality, exergy losses of materials, and emissions	Limited to exergy losses of natural resource; excludes that of the ecological system
Thermo-ecological cost	Focus on cumulative consumption of non-renewable primary exergy resources	It does not include renewable primary exergy resources
Cumulative exergy extraction from natural environment	Measures quality of energetic and non-energetic resources, and land occupation	It does not track exergy transferred into the technological system
Industrial/ecological cumulative exergy demand	Focus on exergy losses in the industrial and ecological stages of a production chain	It is limited to production processes
Extended exergy accounting	Resource equivalent value of a commodity including labor, capital, and environmental emissions	It is intrinsically limited to time and region

Source: Nwodo, M.N. and Anumba, C.J. Exergetic Life Cycle Assessment: A Review. Energies 2020, 13, 2684; doi:10.3390/en13112684.

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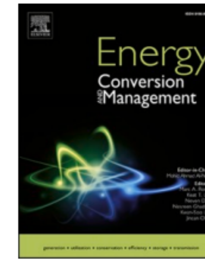

Novel combined extended-advanced exergy analysis methodology as a new tool to assess thermodynamic systems

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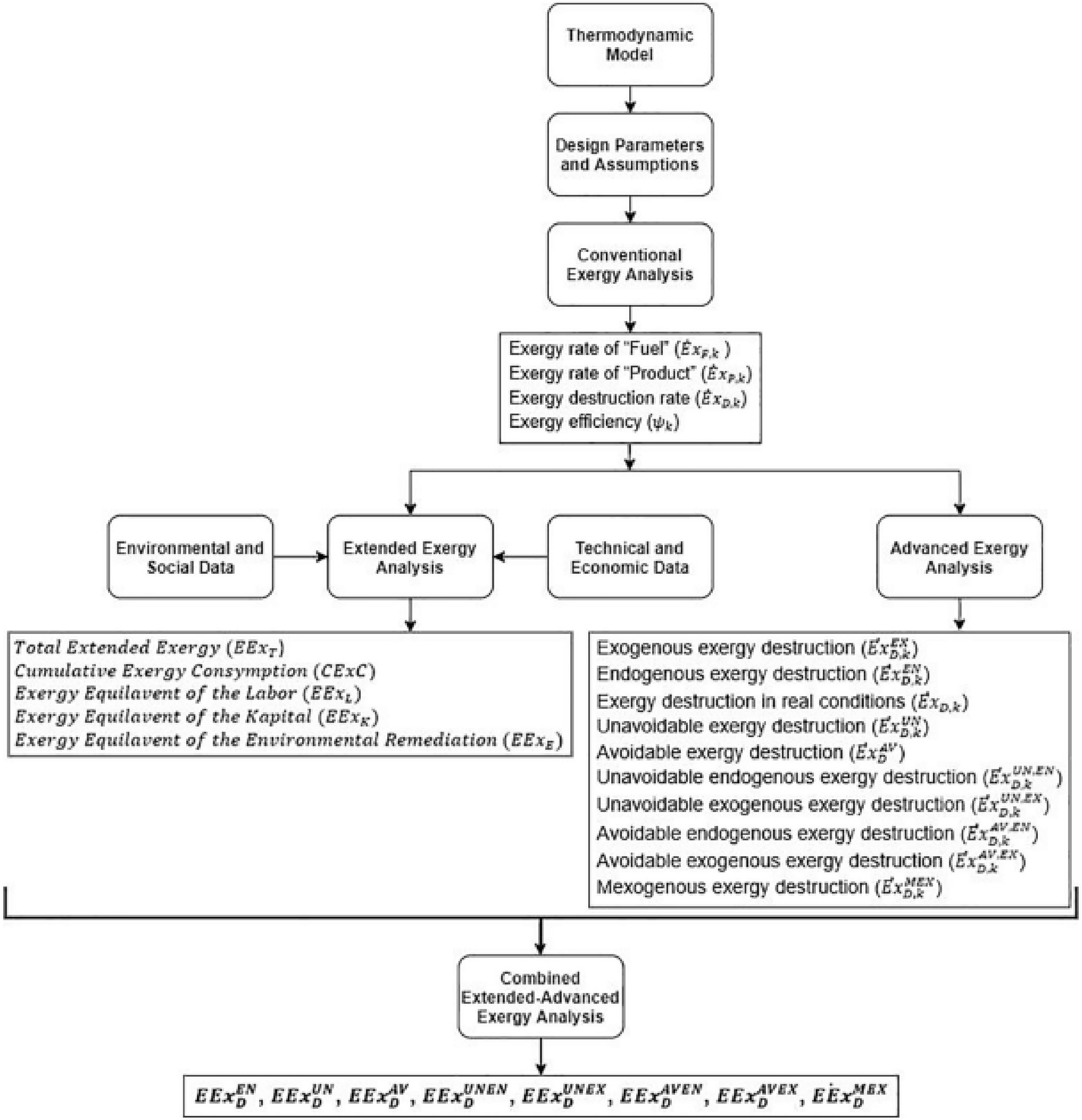

Thermodynamic Model
Design Parameters and Assumptions
Conventional Exergy Analysis
Exergy rate of "Fuel" ($\dot{E}x_{F,k}$)
Exergy rate of "Product" ($\dot{E}x_{P,k}$)
Exergy destruction rate ($\dot{E}x_{D,k}$)
Exergy efficiency (ψ_k)
Environmental and Social Data
Extended Exergy Analysis
Technical and Economic Data
Advanced Exergy Analysis
Total Extended Exergy (EEx_T)
Cumulative Exergy Consymption ($CExC$)
Exergy Equilavent of the Labor (EEx_L)
Exergy Equilavent of the Kapital (EEx_K)
Exergy Equilavent of the Environmental Remediation (EEx_E)
Exogenous exergy destruction ($\dot{E}x_{D,k}^{EX}$)
Endogenous exergy destruction ($\dot{E}x_{D,k}^{EN}$)
Exergy destruction in real conditions ($\dot{E}x_{D,k}$)
Unavoidable exergy destruction ($\dot{E}x_{D,k}^{UN}$)
Avoidable exergy destruction ($\dot{E}x_{D}^{AV}$)
Unavoidable endogenous exergy destruction ($\dot{E}x_{D,k}^{UN,EN}$)
Unavoidable exogenous exergy destruction ($\dot{E}x_{D,k}^{UN,EX}$)
Avoidable endogenous exergy destruction ($\dot{E}x_{D,k}^{AV,EN}$)
Avoidable exogenous exergy destruction ($\dot{E}x_{D,k}^{AV,EX}$)
Mexogenous exergy destruction ($\dot{E}x_{D,k}^{MEX}$)
Combined Extended-Advanced Exergy Analysis
EEx_D^{EN}, EEx_D^{UN}, EEx_D^{AV}, EEx_D^{UNEN}, EEx_D^{UNEX}, EEx_D^{AVEN}, EEx_D^{AVEX}, $E\dot{E}x_D^{MEX}$

Various Exergoeconomic (in Europe) or Thermoeconomic (in the U.S.) Approaches

Classified into the three fields: cost allocation, cost optimization, and cost analysis.

- Exergy Economics Approach (EEA) [1]
- First Exergoeconomic Approach (FEA) [1]
- Thermoeconomic Functional Analysis (TFA) [1]
- Exergetic Cost Theory (ECT) [1]
- Engineering Functional Analysis (EFA) [1]
- Last-In-First-Out Approach (LIFOA) [1]
- Structural Analysis Approach (SAA) [1]
- **Specific Exergy Costing (SPECO) Method (SPECOM) [1]**
- **Exergy, Cost, Energy and Mass (EXCEM) [2]**
- Modified EXCEM [3]
- CGAM Method (derived from the initials of a group of concerned specialists, namely C. Frangopoulos, G. Tsatsaronis, A. Valero, and M. von Spakovsky) [4]

Sources:

[1] Meyer et. al. Application of Exergoeconomic and Exergoenvironmental Analysis to an SOFC System with an Allothermal Biomass Gasifier. Int. J. of Thermodynamics 12 (4): 177-186 (2009).

[2] Rosen MA, Scott DS. A methodology based on exergy, cost, energy and mass for the analysis of systems and processes. In: Proceedings of the meeting of nternational society for general systems research, Vol. 8.3, Toronto, 20–22 May; 1987. p. 1–13.

[3] Gaur, A, Tiwari, GN. Exergoeconomic and enviroeconomic analysis of photovoltaic modules of different solar cells. Journal of Solar Energy. Hindawi Publishing Corporation. Volume 2014, Article ID 719424, 8 pages, http://dx.doi.org/10.1155/2014/719424

[4] Kim, D.J. A new thermoeconomic methodology for energy systems. Energy 35(1):410-422 (2010).

5. Modeling

Mass balance equation: $\sum \dot{m}_{in} = \sum \dot{m}_{out}$

General energy balance: $\dot{E}_{in} = \dot{E}_{out}$

General entropy balance: $\dot{S}_{out} - \dot{S}_{in} = \dot{S}_{gen}$

General exergy balance: $\dot{Ex}_{in} - \dot{Ex}_{out} = \dot{Ex}_{dest}$

The Gouy-Stodola relation:

Exergy destruction is proportional to entropy generation

$$\dot{I} = \dot{Ex}_{dest} = T_0 \dot{S}_{gen}$$

Some examples of efficiencies applied to the Rankine cycle and the vapor compression refrigeration cycle

Cycle Type	Rankine		Vapor Compression	
First Law	$\eta_I = W_{net}/Q_h$	(2.5)	$COP = Q_c/W_{in}$	(2.8)
Exergy	$\eta_{exergy} = W_{net}/E_{in}$	(2.6)	$\eta_{exergy} = E_c/W_{in}$	(2.9)
Second Law	$\eta_{II} = \eta/\eta_{rev}$	(2.7)	$\eta_{II} = COP/COP_{rev}$	(2.10)

Second Law Efficiency

Second law efficiency is defined as the ratio of the efficiency of the cycle to the efficiency of a reversible cycle operating between the same thermodynamic conditions.

$$\eta_{II} = \eta/\eta_{rev}$$

Source: VIJAYARAGHAVAN, S. Thermodynamic Studies on Alternate Binary Working Fluid Combinations and Configurations for a Combined Power and Cooling Cycle. Ph.D. Thesis, University of Florida, 2013.

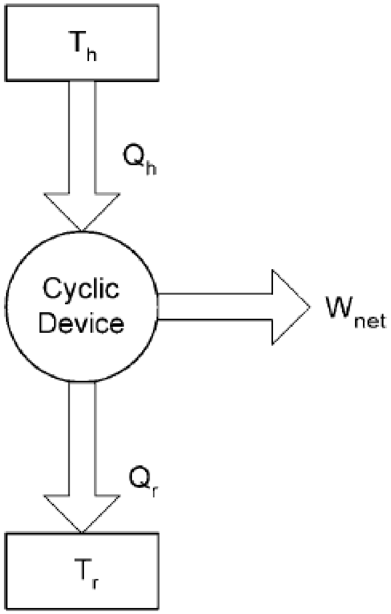


Fig. 2.1 A cyclic heat engine working between a hot and cold reservoir

The exergy efficiency and second law efficiency are often similar or even identical. For example, in a cycle operating between a hot and a cold reservoir (see Fig. 2.1), the exergy efficiency is

$$\eta_{exergy} = \frac{W_{net}}{Q_h\left(1 - T_0/T_h\right)}$$

Where T_0 is the ambient or the ground state temperature. For the special case where the cold reservoir temperature T_r is the same as the ground state temperature T_0, the exergy efficiency is identical to the second law efficiency.

while the second law efficiency is

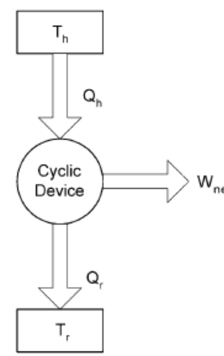
$$\eta_{II} = \frac{W_{net}}{Q_h\left(1 - T_c/T_h\right)}$$

The exergy efficiency and second law efficiency are often similar or even identical. For example, in a cycle operating between a hot and a cold reservoir the exergy efficiency is

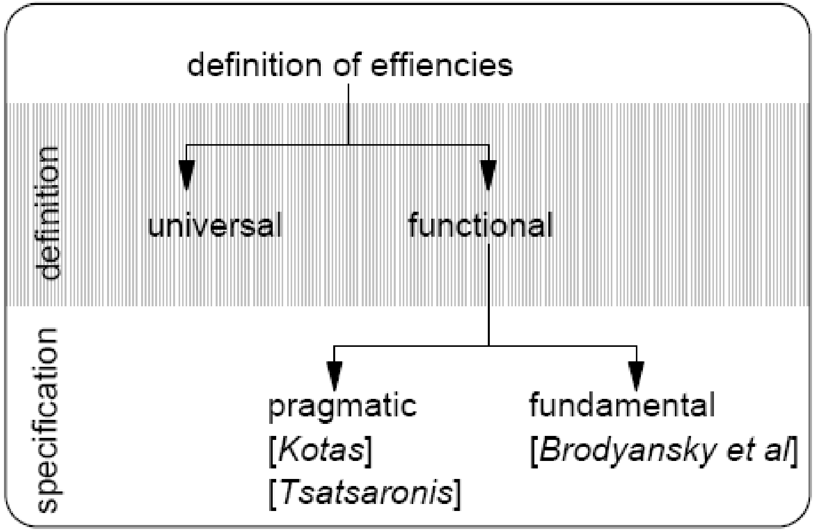
$$\eta_{exergy} = \frac{W_{net}}{Q_h\left(1 - T_0/T_h\right)}$$

while the second law efficiency is

$$\eta_{II} = \frac{W_{net}}{Q_h\left(1 - T_c/T_h\right)}$$



A cyclic heat engine working between a hot and cold reservoir



Exergy Efficiency = Product/Fuel

Exergy Efficiency = Desired Effect/Fuel

Exergy Efficiency = Benefit /Fuel

Exergy Efficiency = Product /Source

The *universal efficiency* is defined as follows:

$$\eta_{Ex,\mathrm{u}} = \frac{\sum Ex_{\mathrm{out}}}{\sum Ex_{\mathrm{in}}}$$

In which:

$\sum Ex_{\mathrm{out}}$ is the exergy of the energy flows leaving the system

$\sum Ex_{\mathrm{in}}$ is the exergy of energy flows entering the system

A general definition of *functional efficiency* is:

$$\eta_{ex,\mathrm{f}} = \frac{\sum Ex_{\mathrm{product}}}{\sum Ex_{\mathrm{source}}}$$

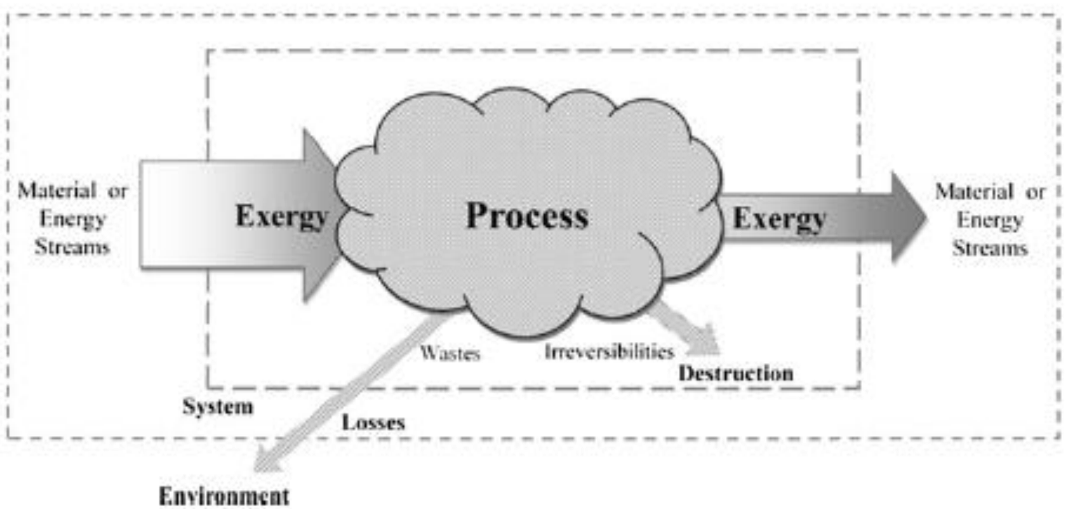
$\sum Ex_{\mathrm{product}}$ is the exergy of that part of the outgoing energy flows that can be considered to be the product of the system;

$\sum Ex_{\mathrm{source}}$ is the exergy of that part of the ingoing energy flows that can be considered necessary for making the product in the present process.

Input–output efficiency

$$\eta = \frac{\sum \text{Exergy out}}{\sum \text{Exergy in}} = 1 - \frac{\sum \text{Exergy Destroyed} + \sum \text{Exergy Lost}}{\sum \text{Exergy in}}$$

$$\eta = \frac{\sum \text{Exergy out}}{\sum \text{Exergy in}} = 1 - \frac{\sum \text{Exergy Destroyed}}{\sum \text{Exergy in}}$$



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Consumed-produced efficiency

Grassmann [3]

$$\varepsilon_{\mathrm{I}} = \frac{\text{Useful Exergy Output}}{\text{Useful Exergy Input}}$$

Szargut et al. [10]

$$\varepsilon_{\mathrm{II}} = \frac{\text{Exergy of Useful Products}}{\text{Feeding Exergy}}$$

Baehr [4,24] and Kotas [9]

$$\varepsilon_{\mathrm{III}} = \frac{\text{Desired Output}}{\text{Necessary Input}}$$

Tsatsaronis [18] and Bejan et al. [12]

$$\varepsilon_{\mathrm{IV}} = \frac{\text{Exergy of Products}}{\text{Exergy of Fuel}}$$

Brodyansky et al. [5]

$$\varepsilon_{\mathrm{V}} = \frac{\text{Exergy out} - \text{Transit Exergy}}{\text{Exergy in} - \text{Transit Exergy}}$$

For a control volume at steady state whose exergy rate balance reads

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \tag{12}$$

the exergetic efficiency is

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_D + \dot{E}_L}{\dot{E}_F} \tag{13}$$

where the rates at which the fuel is supplied and the product is generated are $\dot{E}_F$ and $\dot{E}_P$ respectively. $\dot{E}_D$, and $\dot{E}_L$ denote the rates of exergy destruction and exergy loss, respectively. Exergy is destroyed by irreversibilities within the control volume, and exergy is lost from the control volume via stray heat transfer, material streams vented to the surroundings, and so on.

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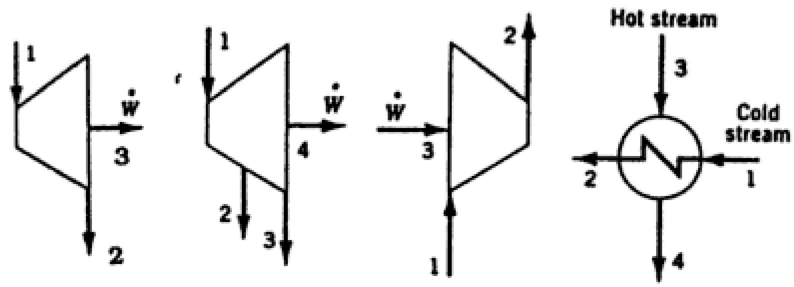
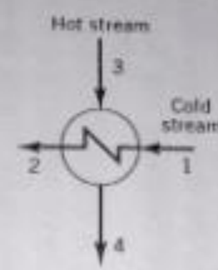
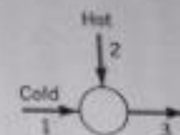
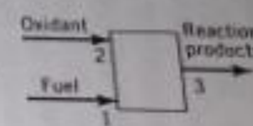
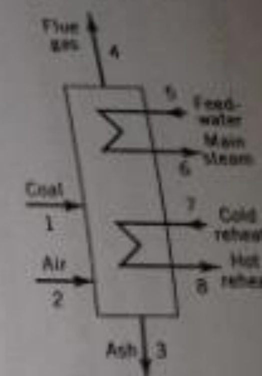
	Turbine or Expander	Extraction Turbine	Compressor, Pump, or Fan	Heat Exchanger[b]
Component				
$\dot{E}_P$	$\dot{W}$	$\dot{W}$	$\dot{E}_2 - \dot{E}_1$	$\dot{E}_2 - \dot{E}_1$
$\dot{E}_F$	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_1 - \dot{E}_2 - \dot{E}_3$	$\dot{W}$	$\dot{E}_3 - \dot{E}_4$
ε	$\dfrac{\dot{W}}{\dot{E}_1 - \dot{E}_2}$	$\dfrac{\dot{W}}{\dot{E}_1 - \dot{E}_2 - \dot{E}_3}$	$\dfrac{\dot{E}_2 - \dot{E}_1}{\dot{W}}$	$\dfrac{\dot{E}_2 - \dot{E}_1}{\dot{E}_3 - \dot{E}_4}$

a) For discussion, see [2].
b) This definition assumes that the purpose of the heat exchanger is to heat the cold stream ($T_1 \geq T_0$).

Table 3.3 Exergy rates associated with fuel and product for selected components at steady-state

Component	Compressor, Pump, or Fan	Turbine or Expander	Heat Exchanger[a]	Mixing Unit	Gasifier or Combustion Chamber	Boiler
Schematic						
Exergy rate of product, $\dot{E}_P$	$\dot{E}_2 - \dot{E}_1$	$\dot{W}$	$\dot{E}_2 - \dot{E}_1$	$\dot{E}_3$	$\dot{E}_3$	$(\dot{E}_6 - \dot{E}_5) + (\dot{E}_8 - \dot{E}_7)$
Exergy rate of fuel, $\dot{E}_F$	$\dot{W}$	$\dot{E}_1 - \dot{E}_2 - \dot{E}_3$	$\dot{E}_3 - \dot{E}_4$	$\dot{E}_1 + \dot{E}_2$	$\dot{E}_1 + \dot{E}_2$	$(\dot{E}_1 + \dot{E}_2) - (\dot{E}_3 + \dot{E}_4)$

[a]These definitions assume that the purpose of the heat exchanger is to heat the cold steam ($T_1 \geq T_0$). If the purpose of the heat exchanger is to provide cooling($T_3 \leq T_0$), then the following relations should be used: $\dot{E}_P = \dot{E}_4 - \dot{E}_3$ and $\dot{E}_F = \dot{E}_1 - \dot{E}_2$. For simple coolers or condensers see discussion in text.

Table 1
Summary of exergy efficiency expressions for some unit operations.

	Compression	Expansion	Throttling	Heat exchange
			Input–output	
Any T	$\frac{\dot{E}^{TM}_{out}}{\dot{W}+\dot{E}^{TM}_{in}}$	$\frac{\dot{W}+\dot{E}^{TM}_{out}}{\dot{E}^{TM}_{in}}$	$\frac{\dot{E}^{TM}_{out}}{\dot{E}^{TM}_{in}}$	$\frac{\dot{E}^{TM}_{C,out}+\dot{E}^{TM}_{H,out}}{\dot{E}^{TM}_{C,in}+\dot{E}^{TM}_{H,in}}$
			Consumed–produced	
$T > T_0$	$\frac{\dot{E}^{TM}_{out}-\dot{E}^{TM}_{in}}{\dot{W}}$ [a,b,c]	$\frac{\dot{W}}{\dot{E}^{TM}_{in}-\dot{E}^{TM}_{out}}$ [a,b,c]	$\frac{0}{\dot{E}^{TM}_{in}-\dot{E}^{TM}_{out}}$ [a,b,c]	$\frac{(\dot{E}^{T}_{C,out}-\dot{E}^{T}_{C,in})-(\dot{E}^{P}_{C,in}-\dot{E}^{P}_{C,out})}{(\dot{E}^{T}_{H,in}-\dot{E}^{T}_{H,out})+(\dot{E}^{P}_{H,in}-\dot{E}^{P}_{H,out})}$ [a,b,d]
				$\frac{\dot{E}^{T}_{C,out}-\dot{E}^{T}_{C,in}}{(\dot{E}^{TM}_{H,in}-\dot{E}^{TM}_{H,out})+(\dot{E}^{P}_{C,in}-\dot{E}^{P}_{C,out})}$ [c]
$T < T_0$	$\frac{\dot{E}^{TM}_{out}-\dot{E}^{TM}_{in}}{\dot{W}}$ [a]	$\frac{\dot{E}^{T}_{out}-\dot{E}^{T}_{in}+\dot{W}}{\dot{E}^{P}_{in}-\dot{E}^{P}_{out}}$ [a,c]	$\frac{\dot{E}^{T}_{out}-\dot{E}^{T}_{in}}{\dot{E}^{P}_{in}-\dot{E}^{P}_{out}}$ [a,c]	$\frac{(\dot{E}^{T}_{H,out}-\dot{E}^{T}_{H,in})-(\dot{E}^{P}_{H,in}-\dot{E}^{P}_{H,out})}{(\dot{E}^{T}_{C,in}-\dot{E}^{T}_{C,out})+(\dot{E}^{P}_{C,in}-\dot{E}^{P}_{C,out})}$ [a,d]
	$\frac{\dot{E}^{P}_{out}-\dot{E}^{P}_{in}}{\dot{E}^{T}_{in}-\dot{E}^{T}_{out}+\dot{W}}$ [c]			$\frac{\dot{E}^{T}_{H,out}-\dot{E}^{T}_{H,in}}{(\dot{E}^{TM}_{C,in}-\dot{E}^{TM}_{C,out})+(\dot{E}^{P}_{H,in}-\dot{E}^{P}_{H,out})}$ [c]
Across T_0 [c]	$\frac{\dot{E}^{T}_{out}+(\dot{E}^{P}_{out}-\dot{E}^{P}_{in})}{\dot{E}^{T}_{in}+\dot{W}}$	$\frac{\dot{E}^{T}_{out}+\dot{W}}{\dot{E}^{T}_{in}+(\dot{E}^{P}_{in}-\dot{E}^{P}_{out})}$	$\frac{\dot{E}^{T}_{out}}{\dot{E}^{T}_{in}+(\dot{E}^{P}_{in}-\dot{E}^{P}_{out})}$	$\frac{\dot{E}^{T}_{H,out}+\dot{E}^{T}_{C,out}}{\dot{E}^{T}_{C,in}+(\dot{E}^{P}_{C,in}-\dot{E}^{P}_{C,out})+\dot{E}^{T}_{H,in}+(\dot{E}^{P}_{H,in}-\dot{E}^{P}_{H,out})}$

[a] Kotas [9].
[b] Tsatsaronis [18] and Bejan et al. [12].
[c] Brodyansky et al. [5].
[d] Grassmann [3], Moran [8] and Moran and Shapiro [13].

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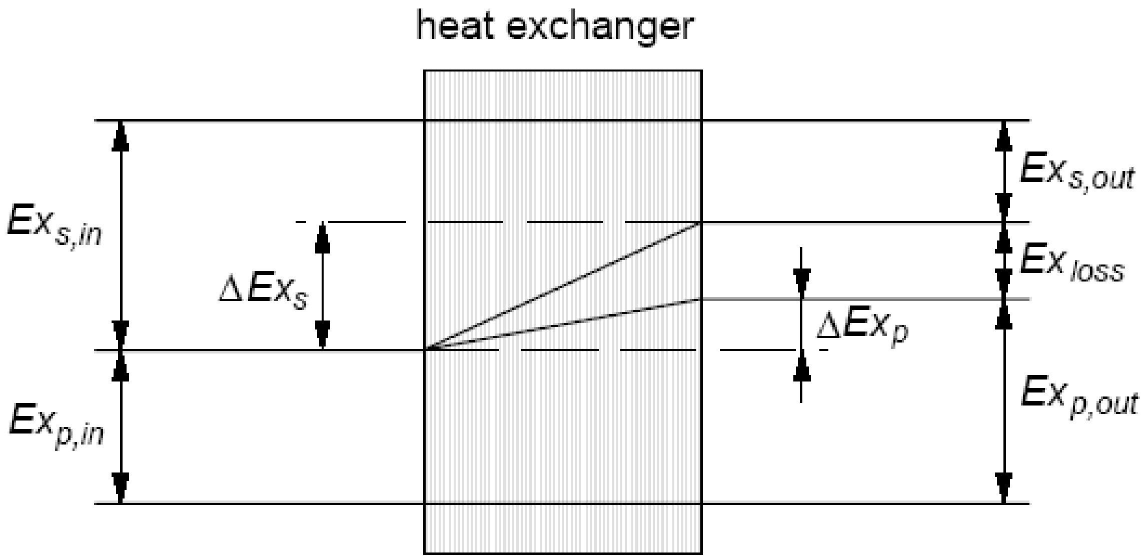


Figure 6.12 *Change in exergy quantities during heat transfer*

The universal exergy efficiency for this heat exchanger

$$\eta_{ex,u(\text{heat exchanger})} = \frac{Ex_{\text{s,out}} + Ex_{\text{p,out}}}{Ex_{\text{s,in}} + Ex_{\text{p,in}}}$$

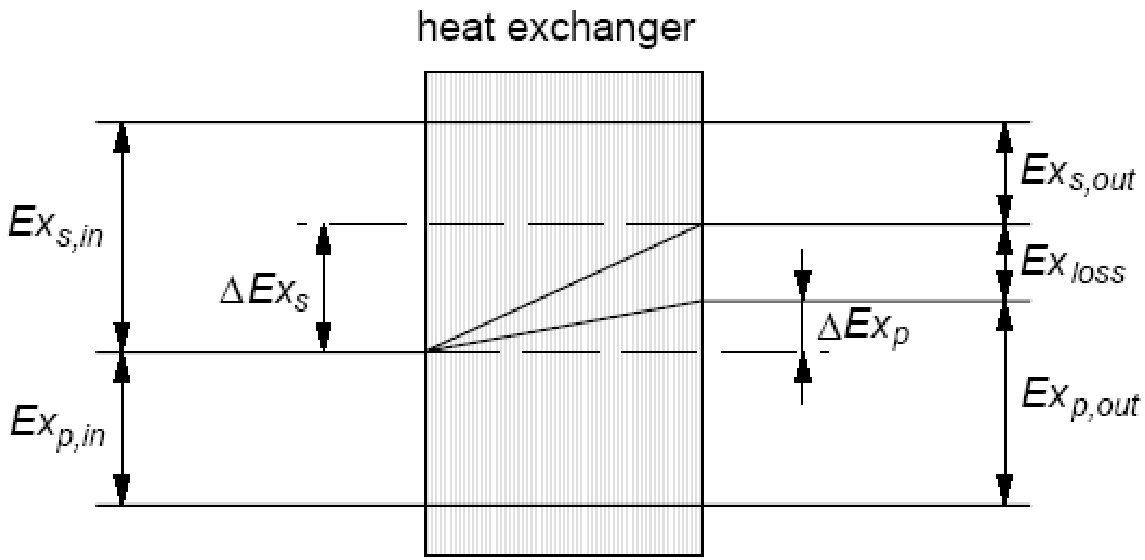
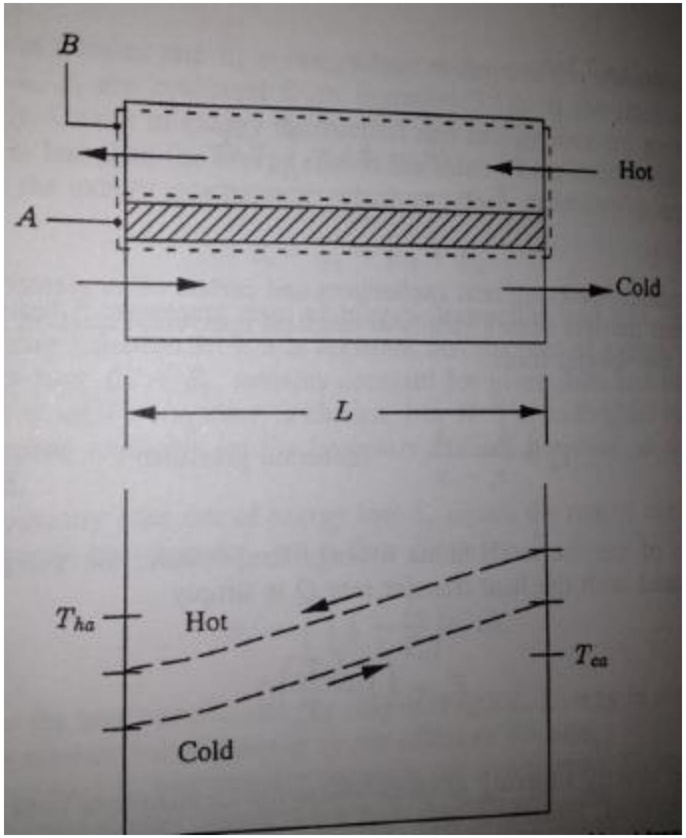


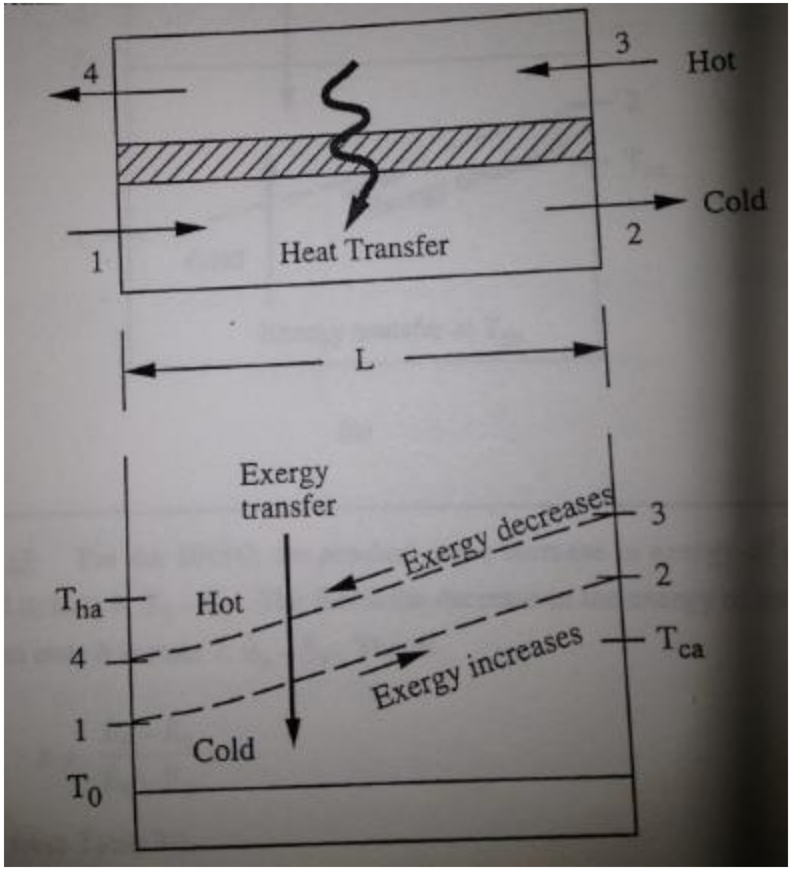
Figure 6.12 *Change in exergy quantities during heat transfer*

for the functional exergy efficiency of the heat transfer process

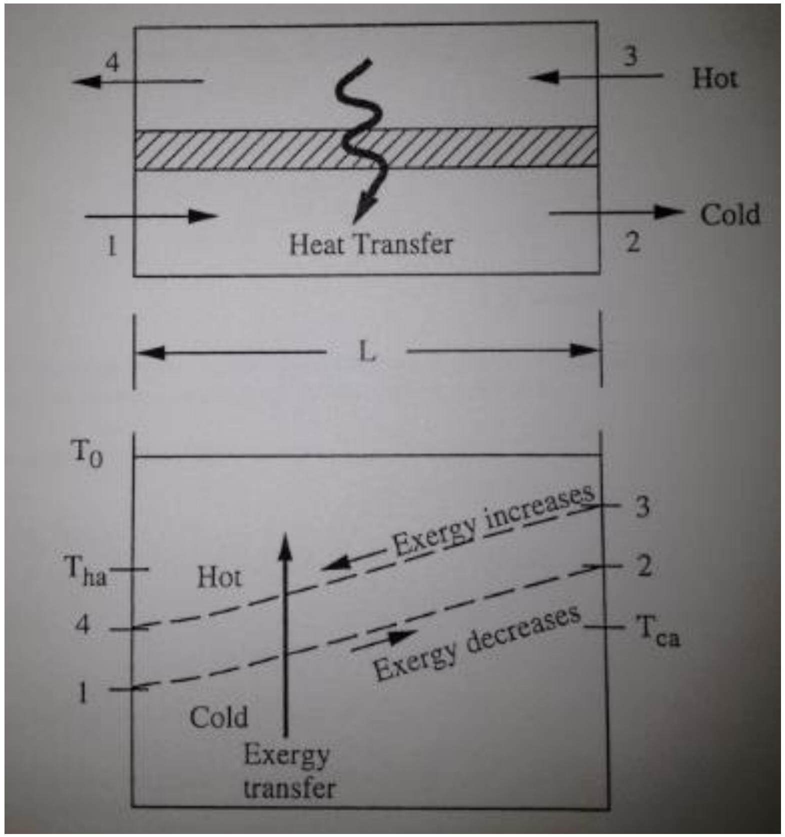
$$\eta_{Ex,\mathrm{f(heat\ exchanger)}} = \frac{\Delta Ex_{\mathrm{p}}}{\Delta Ex_{\mathrm{s}}} = \frac{Ex_{\mathrm{p,out}} - Ex_{\mathrm{p,in}}}{Ex_{\mathrm{s,in}} - Ex_{\mathrm{s,out}}}$$



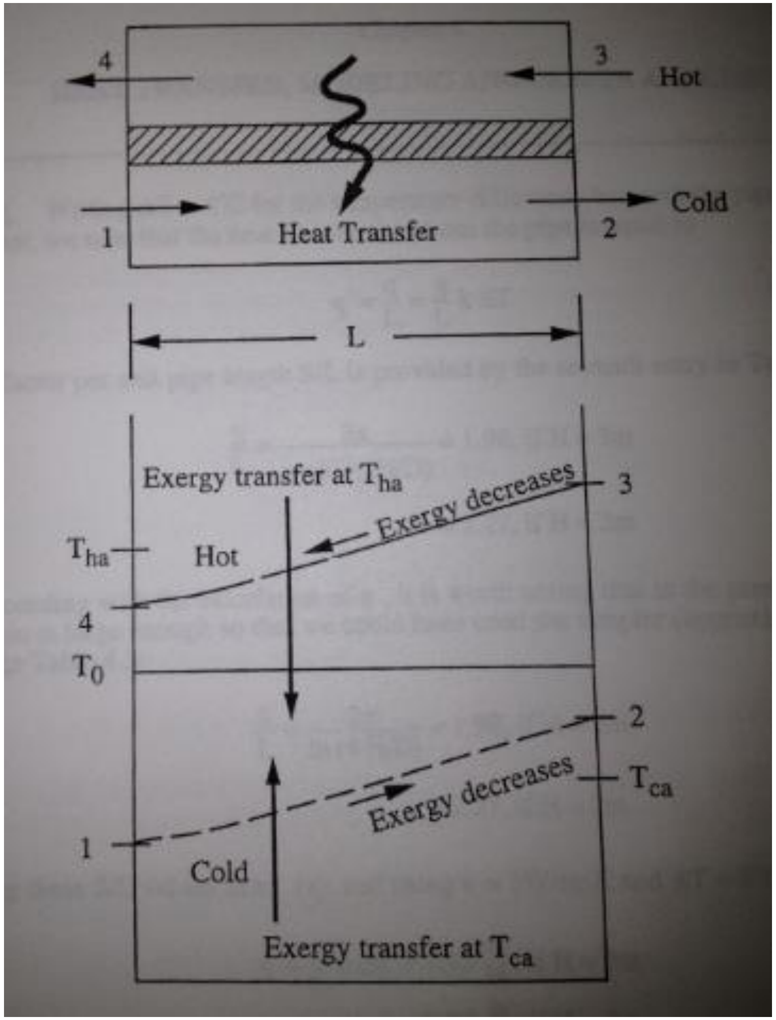
Bejan et al.



$$\varepsilon = \frac{\dot{E}_2 - \dot{E}_1}{\dot{E}_3 - \dot{E}_4} \quad \text{(heat exchanger; } T_1 \geq T_0\text{)}$$



$$\varepsilon = \frac{\dot{E}_4 - \dot{E}_3}{\dot{E}_1 - \dot{E}_2} \quad \text{(heat exchanger; } T_3 \leq T_0\text{)}$$



4. No meaningful product, and thus no meaningful exergetic efficiency, can be defined for a heat exchanger that allows heat transfer across the temperature of the environment T_0—that is, heat transfer between two streams at $T > T_0$ and $T < T_0$, respectively. Cost considerations might sanction the use of such a heat exchanger, however, even though this would appear to be a design error from an exergy perspective.

(c) In this case, the temperature of each stream is brought closer to T_0 as the stream flows through the heat exchanger, and thus the exergy of each stream *decreases*. For purposes of defining the exergetic efficiency, then, there is no exergy *product*.

6. Case Studies

Exergy Efficiency

There are mainly two ways of formulating exergetic efficiency for drying systems (Syahrul *et al.*, 2002, 2003; Midilli and Kucuk, 2003; Akpinar, 2006). The first one can be defined as the ratio of the product exergy to exergy inflow as follows (Midilli and Kucuk, 2003; Akpinar, 2006):

$$\eta_{ex} = \frac{\text{Exergy inflow} - \text{Exergy loss}}{\text{Exergy inflow}} = 1 - \frac{\dot{E}x_{loss}}{\dot{E}x_{in}} \quad (22a)$$

The second one may be defined on the product/fuel basis. The product is the rate of exergy evaporation and the fuel is the rate of exergy drying air entering the dryer chamber. In this regard, exergy efficiency may be written as follows (Syahrul *et al.*, 2002, 2003).

$$\eta_{ex} = \frac{\dot{E}x_{evap}}{\dot{E}x_{da}} \quad (22b)$$

$$\dot{E}x_{evap} = \left[1 - \frac{T_0}{T_m}\right] \dot{m}_w h_{fg}$$

Table IV. Comparison of exergy efficiency values in drying various products.

Investigators	Type of dryer	Product dried			Air			Exergy efficiency	
		Type	Initial moisture content (%)	Final moisture content on dry weight basis (%)	Velocity ($m\,s^{-1}$)	Temperature (°C)	Relative humidity (%)	Eq. No.	Value (%)
Syahrul *et al.* (2002, 2003)	Fluidized bed dryer	Red-spring wheat Corn	31.7–32.6 24.6–25.6	15	1.95 2.22–2.24	40.2–65 50–63	18.5–21.1 15.2–17.5	(22b)	4–12 2–16
Midilli and Kucuk (2003)	Solar drying cabinet	Shelled/ unshelled pistachios	26.95/29		1.23	40–60	37–62	(22a)	10.86–100
Akpinar (2004)	Convective-type dryer	Red pepper slices		10	1.5	55 60 70		(22a)	71.00–96.68 69.81–97.12 67.28–97.92
Akpinar *et al.* (2005a)	Cyclone-type dryer	Potato		11	1.5	60 70 80	10–20	(22a)	15.44–100 19.45–100 18.32–100
Akpinar *et al.* (2005b)	Cyclone-type dryer	Apple slices		11	1.5	60 70 80	10–20	(22a)	36.27–100 39.66–100 43.46–100
Akpinar *et al.* (2006)	Cyclone-type dryer	Pumpkin slices		6 4	1.5	60 70 80	10–20	(22a)	30.81–100 37.89–100 46.97–100
Present study	Ground-source heat pump dryer	Laurel leaves	94.4	12	0.5	40 50 40 50	16–19	(22b)	81.35–87.48 9.11–15.48

Source: Hancioglu E and Hepbasli A. Exergetic Evaluation of Drying of Laurel Leaves in a Vertical Ground-source Heat Pump Drying Cabinet. Int. J. Energy Res. 31(3)219-228, 2007

Case Study 3

Energy 53 (2013) 153–164

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Methodology for the physical and chemical exergetic analysis of steam boilers

Idehai O. Ohijeagbon [a,*], M. Adekojo Waheed [b], Simeon O. Jekayinfa [c]

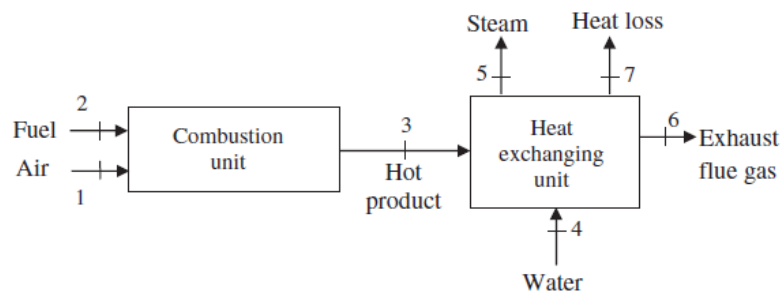

Fig. 3. Schematic diagram of combustion and heat exchanging units in a boiler.

Table A1
Computed thermodynamic properties of materials streams in a boiler using LPFO.

Point	Substances	Mass flow rate (kg/s)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)
1	Air, $\dot{m}_a$,	3.3744	80.63	354.53	1.8684
2	Fuel, $\dot{m}_f$	0.2109	1,084.82	40,515.15	2.0009
3	Hot products, $\dot{m}_p$	3.5853	275.73	2,716.92	4.9513
4	Feed water, $\dot{m}_w$	2.5308	100.00	419.10	1.3070
5	Steam, $\dot{m}_s$	2.5308	168.89	2,767.60	6.6759
6	Exhaust flue gas, $\dot{m}_g$	3.5853	152.95	231.00	2.0516

air ($\dot{m}_a$), fuel ($\dot{m}_f$), hot products ($\dot{m}_p$), feed water ($\dot{m}_f$), steam ($\dot{m}_s$) and exhaust flue gases ($\dot{m}_g$), respectively.

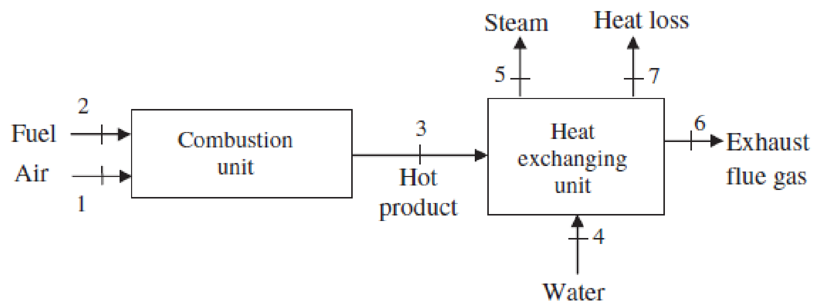

Fig. 3. Schematic diagram of combustion and heat exchanging units in a boiler.

Table A3

Summary of exergetic parameters of combustion unit.

Exergetic equations	Exergetic values and efficiencies
1. Energy input (kJ/s)	9740.97
$E_{in} = \dot{m}_f h_f + \dot{m}_a h_a$	
2. Adiabatic energy efficiency (%)	100.00
$\eta_C = \dfrac{\dot{m}_p h_p}{\dot{m}_f \times \text{HHV}}$	
3. Exergy destruction (kJ/s)	3103.92
$\dot{I}_C = \dot{m}_a[(h_a - T_0 s_a) + \varepsilon^{ch}_{a_1}] - \dot{m}_p(h_p - T_0 s_p) + \dot{m}_f\left[\left(h_f - T_0 s_f\right) + \varepsilon^{ch}_{f_2} - \varepsilon^{ch}_{f_3}\right]$	
4. Exergy efficiency (%)	55.35
$\psi_C = \dfrac{\dot{m}_p(h_p - T_0 s_p)}{\dot{m}_f[(h_f - T_0 s_f) + \varepsilon^{ch}_{f_2} - \varepsilon^{ch}_{f_3}]}$	

$$\psi_C = \frac{\dot{m}_p \varepsilon^{ph}_{p_3}}{\dot{m}_f\left[\varepsilon^{ph}_{f_2} + \varepsilon^{ch}_{f_2} - \varepsilon^{ch}_{f_3}\right]}$$

air ($\dot{m}_a$), fuel ($\dot{m}_f$), hot products ($\dot{m}_p$), feed water ($\dot{m}_f$), steam ($\dot{m}_s$) and exhaust flue gases ($\dot{m}_g$), respectively.

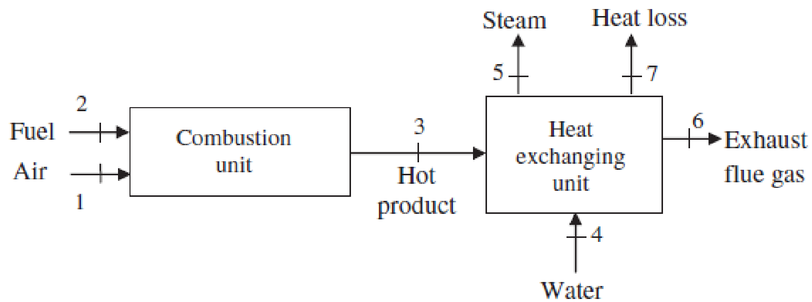

Table A4
Summary of exergetic parameters of heat exchanging unit.

Exergetic equations	Exergetic values and efficiencies
1. Heat loss (kJ/s)	2969.19
$Q_{H(loss)} = \dot{m}_p(h_p - h_g) - \dot{m}_w(h_s - h_w)$	
2. Energy efficiency (%)	66.69
$\eta_H = \frac{\dot{m}_w(h_s - h_w)}{\dot{m}_p(h_p - h_g)}$	
3. Exergy destruction (kJ/s)	2182.44
$\dot{I}_H = \dot{m}_p(h_p - T_0 s_p) + \dot{m}_w[(h_w - T_0 s_w) + \varepsilon^{ch}_{w_4}]$ $-\dot{m}_s\left[\left(h_s - T_0 s_s\right) + \varepsilon^{ch}_{s_5}\right]$ $-\dot{m}_g\left[\left(h_g - T_0 s_g\right) + \varepsilon^{ch}_{g_6}\right]$	
4. Exergy efficiency (%)	58.69
$\psi_H = \frac{\dot{m}_s[(h_s - T_0 s_s) + \varepsilon^{ch}_{s_5}] - \dot{m}_w[(h_w - T_0 s_w) + \varepsilon^{ch}_{w_4}]}{\dot{m}_p(h_p - T_0 s_p) - \dot{m}_g[(h_g - T_0 s_g) + \varepsilon^{ch}_{g_6})]}$	

$$\psi_H = \frac{\dot{m}_s\left[\varepsilon^{ph}_{s_5} + \varepsilon^{ch}_{s_5}\right] - \dot{m}_w\left[\varepsilon^{ph}_{w_4} + \varepsilon^{ch}_{w_4}\right]}{\dot{m}_p\varepsilon^{ph}_{p_3} - \dot{m}_g\left[\varepsilon^{ph}_{g_6} + \varepsilon^{ch}_{g_6}\right]}$$

air ($\dot{m}_a$), fuel ($\dot{m}_f$), hot products ($\dot{m}_p$), feed water ($\dot{m}_f$), steam ($\dot{m}_s$) and exhaust flue gases ($\dot{m}_g$), respectively.

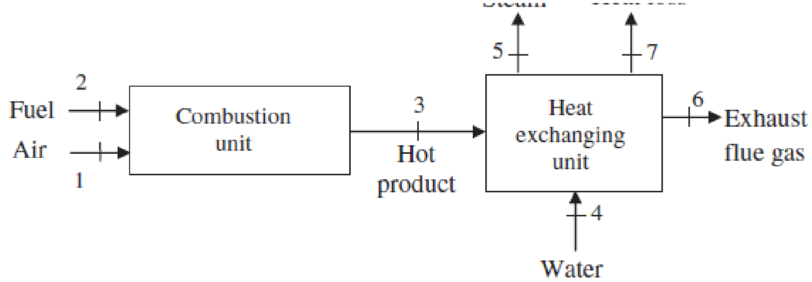

Fig. 3. Schematic diagram of combustion and heat exchanging units in a boiler.

$$\psi_B = \frac{\dot{E}_{desired\ output}}{\dot{E}_{used}}$$

$$\psi_B = \frac{\dot{m}_s\left[\varepsilon_{s_5}^{ph} - \varepsilon_{w_4}^{ph} + \varepsilon_{s_5}^{ch} - \varepsilon_{w_4}^{ch}\right]}{\dot{m}_f\left[\varepsilon_{f_2}^{ph} + \varepsilon_{f_2}^{ch} - \varepsilon_{f_3}^{ch}\right]}$$

Table A5
Summary of exergetic parameters of entire boiler.

Exergetic equations	Exergetic values and efficiencies
1. Energy efficiency (%) $\eta_B = \frac{\dot{m}_s(h_s - h_w)}{\dot{m}_f h_f}$	69.56
2. Overall exergy destruction (kJ/s) $\dot{I}_B = \dot{I}_C + \dot{I}_H$	5286.35
3. Overall exergy efficiency (%) $\psi_B = \frac{\dot{m}_s[(h_s - T_0 s_s) - (h_w - T_0 s_w) + \varepsilon_{s_5}^{ch} - \varepsilon_{w_4}^{ch}]}{\dot{m}_f[(h_f - T_0 s_f) + \varepsilon_{f_2}^{ch} - \varepsilon_{f_3}^{ch}]}$	38.57

Case Study 4

Energy and Buildings 40 (2008) 702–709
www.elsevier.com/loca

Energetic and exergetic performance investigation of the Bigadic Geothermal District Heating System in Turkey

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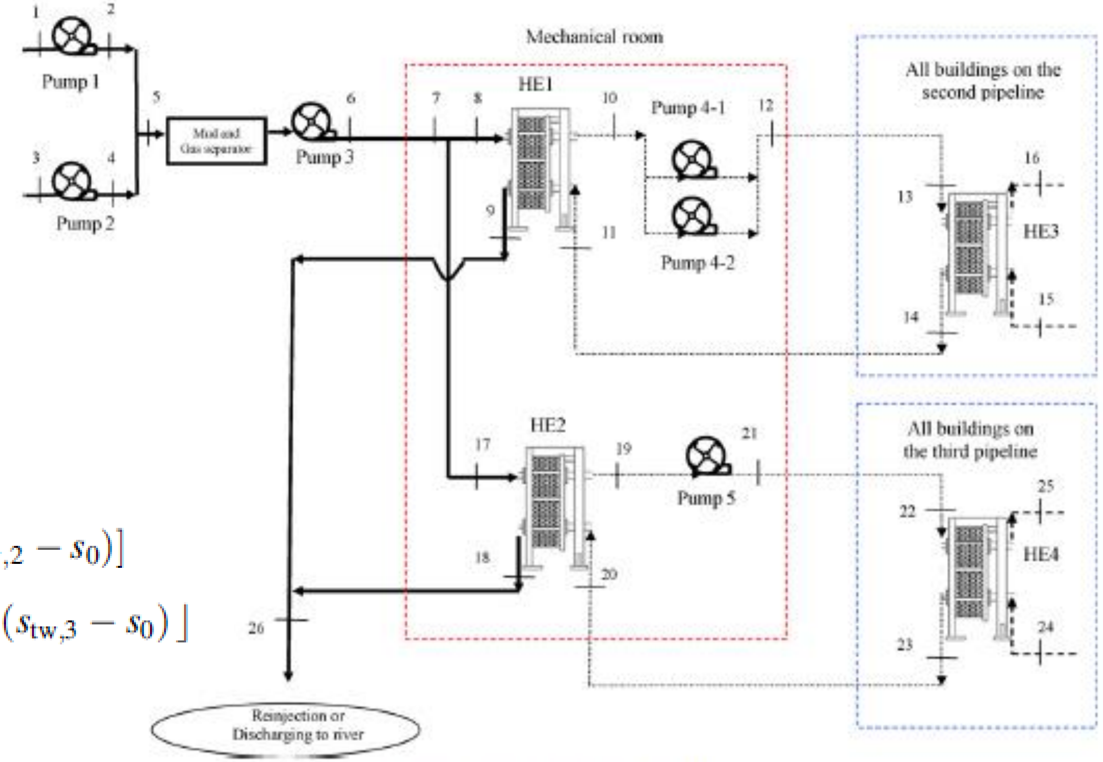

Fig. 1. Flow chart of the Bigadic GDHS.

$$\varepsilon_{sys} = \frac{\dot{E}x_{T,out}}{\dot{E}x_{T,in}}$$

$$\dot{E}x_{T,in} = \dot{m}_{tw,2}[(h_{tw,2} - h_0) - T_0(s_{tw,2} - s_0)] + \dot{m}_{tw,3}\lfloor (h_{tw,3} - h_0) - T_0(s_{tw,3} - s_0) \rfloor$$

SLIDE NUMBERS 66-71

Energy and exergy analysis of solar heat driven chiller under wide system boundary conditions

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Special session devoted to the memory of Professor Jan Szargut

Energy 168 (2019) 440–449

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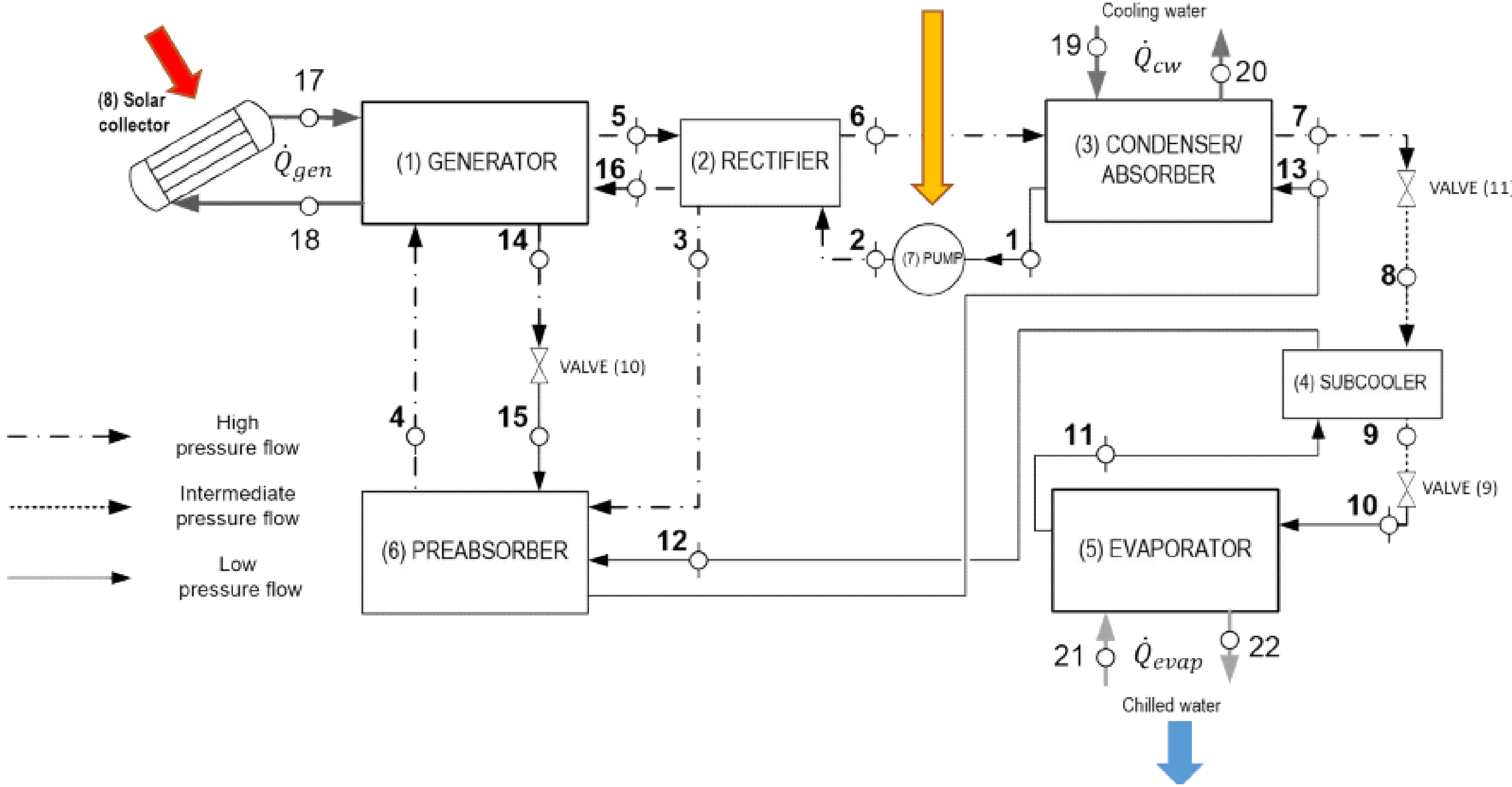
Energy and exergy analysis of solar heat driven chiller under wide system boundary conditions

Check for updates

Karolina Petela*, Andrzej Szlek

Silesian University of Technology, Institute of Thermal Technology, Konarskiego 22, Gliwice 44-100, Poland

- Single stage solar heat driven ammonia-water chiller
  23 kW cooling power



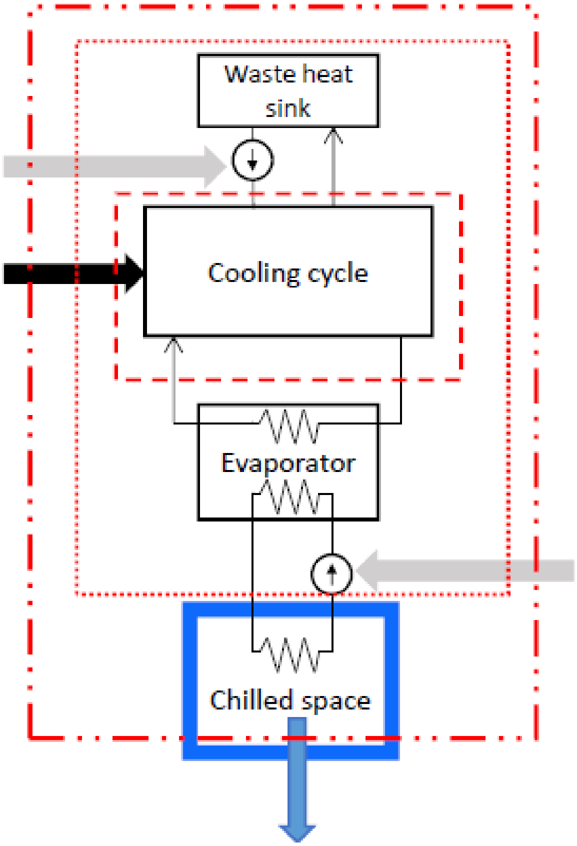
Exergy indicators of the chiller

- Exergy efficiency of an absorption chiller
- Variable boundaries to be adapted while assessing the process excellence:

1st Boundary – gross exergy efficiency

2nd Boundary – net exergy efficiency

3rd Boundary – general exergy efficiency



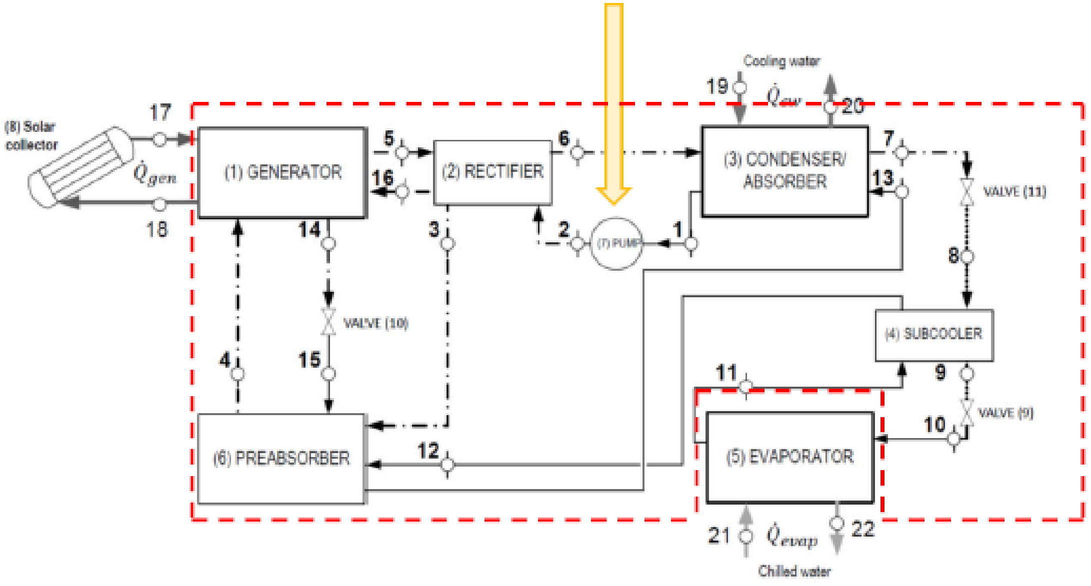
Gross exergy efficiency

1st Boundary

- A measure of how close the thermodynamic transformations in the chiller approach ideality

$$\eta_{ex}^{gross} = \frac{\dot{m}_{10}(ex_{10} - ex_{11})}{\dot{E}x_F}$$

$\dot{E}x_F$ - exergy of driving heat stream and the driving electric power of circulation pump inside the boundary.



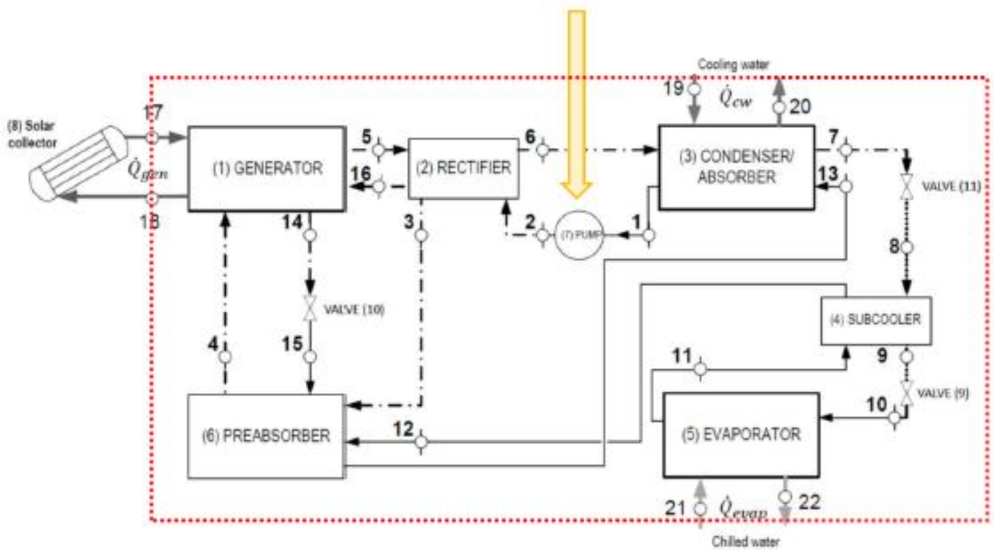
Net exergy efficiency

2nd Boundary

- Including exergy spent on auxiliary components, and exergy increase in evaporator

$$\eta_{ex}^{net} = \frac{\dot{m}_{21}(ex_{22} - ex_{21})}{\dot{Ex}_F + N_{aux}}$$

N_{aux} - chilled and cooling water pumping power



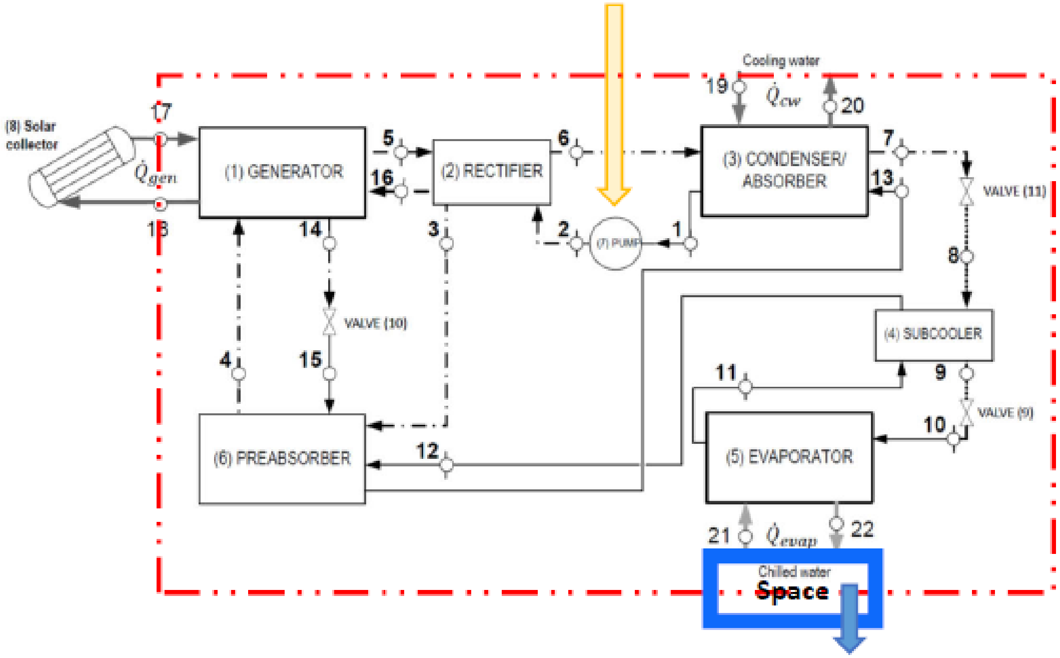
General exergy efficiency

3rd Boundary

- Including exergy spent on auxiliary components, and exergy increase in evaporator

$$\eta_{ex}^{gen} = \frac{\Delta Ex_{chilled\ space}}{\dot{E}x_F + N_{aux}}$$

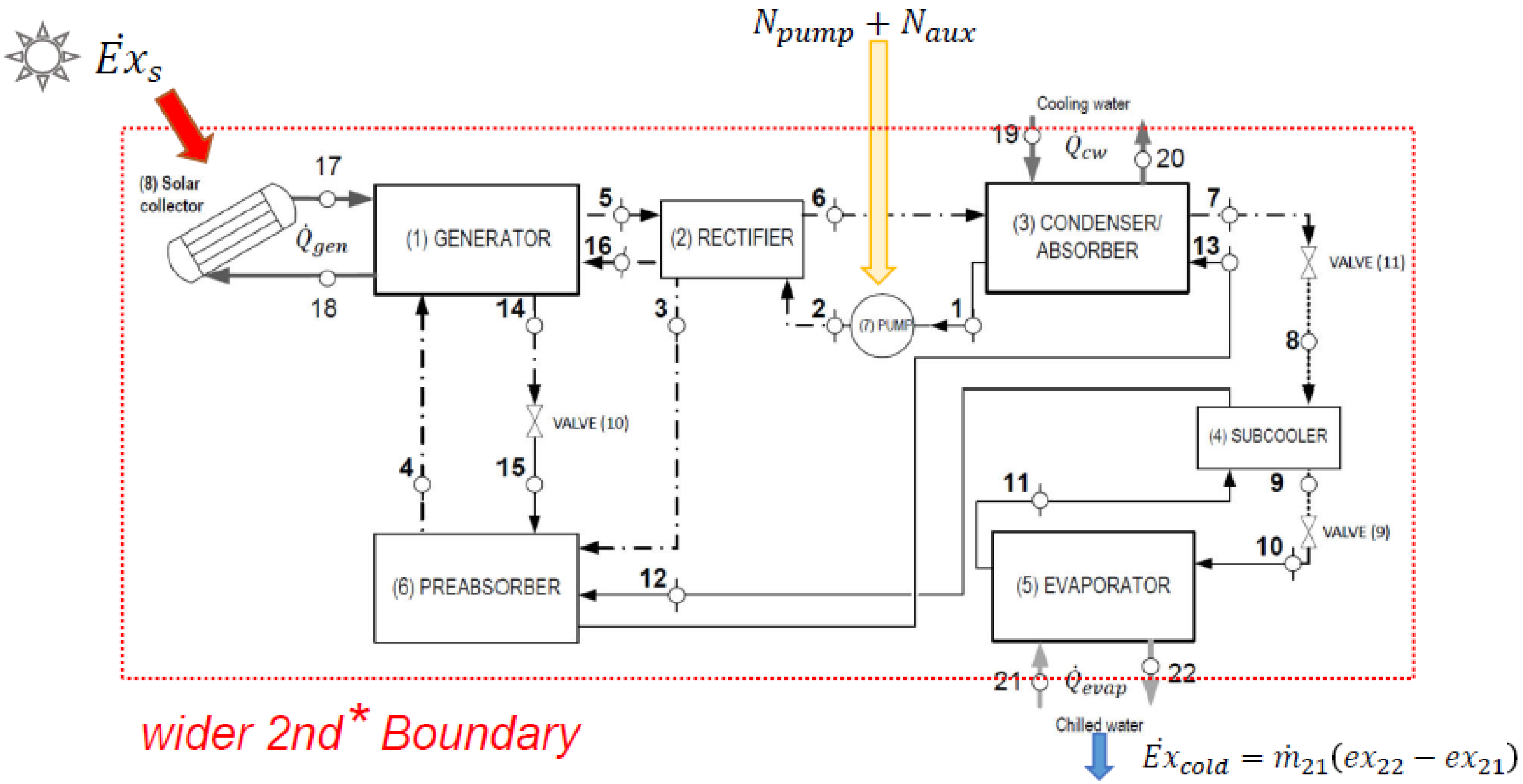
$\Delta Ex_{chilled\ space}$- exergy increase of the chilled space or chilled matter



Modified boundary conditions

To take into account the effect of utilizing solar radiation as driving energy:

2nd boundary widened with the **solar collector** component



7. Some Exergetic Considerations

Choose the correct answer !

Which of the following statements is correct (true) ?

a) The value of the exergy destruction cannot be negative.

b) Exergy destruction is not a property.

c) Exergy is a property and the change in exergy of a system can be positive, negative, or zero.

d) Exergy is not conserved, but is destroyed by irreversibilities.

e) All statements are correct. **Reply: (e)**

$$X_{destroyed}: \begin{cases} > 0 & \text{irreversibilities present with the system} \\ = 0 & \text{no irreversibilities present within the system} \end{cases}$$

$$X_2 - X_1 : \begin{cases} > 0 \\ = 0 \\ < 0 \end{cases}$$

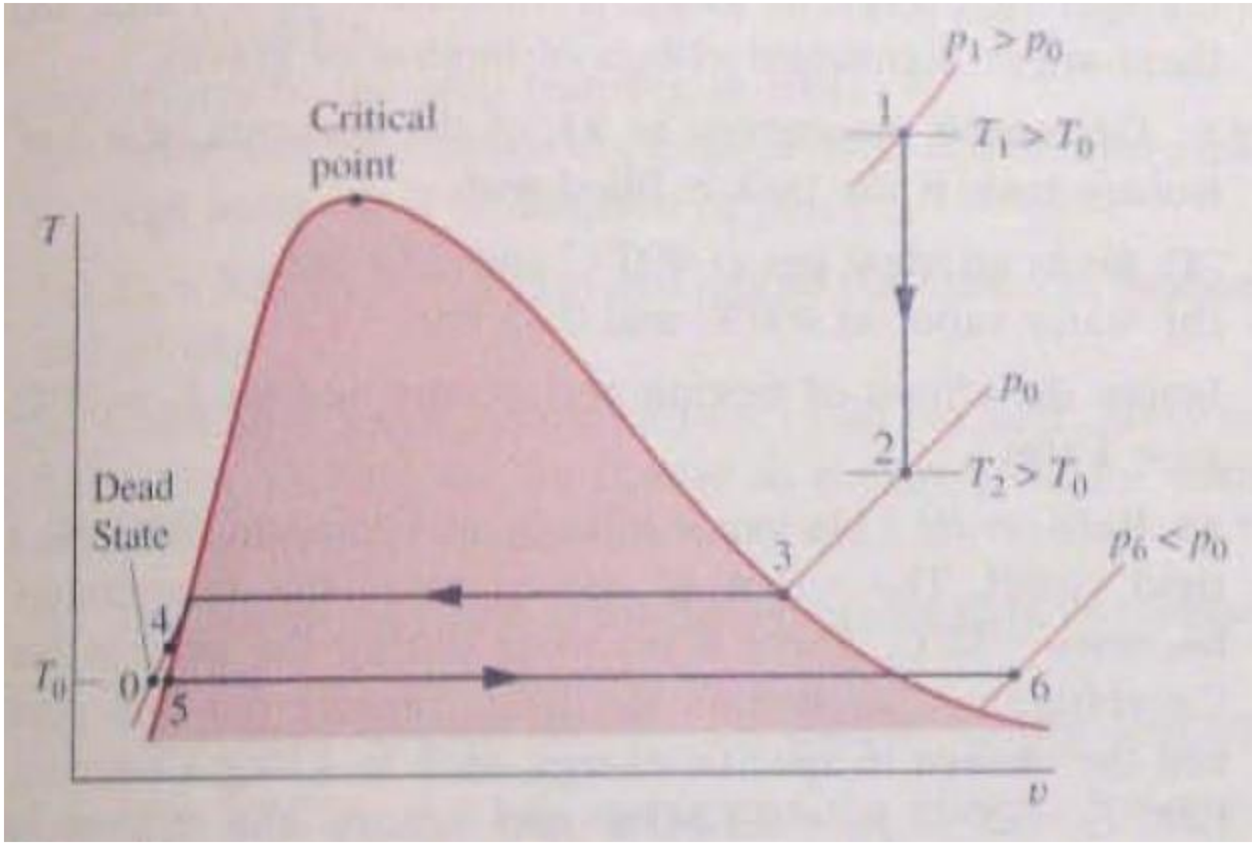
Since the exergy destruction must be positive in any actual process, the only processes of an isolated system (no heat or work interactions with the surroundings) that occur are those for which the exergy of the isolated system decreases.

- Exergy is a measure of the departure of the state of a system from that of the environment. It is therefore an attribute of the system and environment together. However, once the environment is specified, a value can be assigned to exergy in terms of property values for the system only, so exergy can be regarded as a property of the system.
- The value of exergy cannot be negative. If a system were at any state other than the dead state, the system would be able to change its condition *spontaneously toward the dead state*; this tendency would cease when the dead state was reached. No work must be done to effect such a spontaneous change. Accordingly, any change in state of the system to the dead state can be accomplished with *at least zero work being developed*, and thus the *maximum work (exergy) cannot be negative.*

Moran et al.

- Exergy is not conserved, but is destroyed by irreversibilities. A limiting case is when exergy is completely destroyed, as would occur if a system were permitted to undergo a spontaneous change to the dead state with no provision to obtain work. The potential to develop work that existed originally would be completely wasted in such a spontaneous process.
- Exergy has been viewed thus far as the *maximum theoretical work obtainable from* the combined system of system plus environment as a system passes *from a given* state *to the dead state while interacting with the environment only*. *Alternatively*, exergy can be regarded as the magnitude of the *minimum theoretical work input* required to bring the system *from the dead state to the given state.*

Moran et al.



- Process 1-2: Exergy decreases. P $\longrightarrow$ P_0 while T moves to closer to T_0
- Process 3-4: Exergy decreases. T moves to closer to T_0 while P = P_0
- Process 5-6: Exergy increases. P moves away from P_0 while T_0 while T = T_0

Moran et al.

Exergy (availability)	*Energy*
1. Exergy does not follow the law of conservation.	1. Energy follows the law of conservation.
2. It is function of states of the matter under consideration and the 'environment'.	2. It is function of the state of matter under consideration.
3. It is estimated with respect to the state of reference imposed by environment.	3. It may be calculated based upon the assumed state of reference.
4. Exergy always depends upon pressure.	4. In case of ideal gas energy does not depend upon pressure.
5. Exergy increases with temperature drop at low temperatures. For constant pressure processes exergy attains minimum value at the temperature of environment.	5. Energy increases with rise of temperature.
6. Exergy has positive value for ideal vacuum.	6. Energy is zero for an ideal vacuum.

A vacuum space has some exergy (relative to the reference environment), even if it has no energy associated to its zero mass.

Szargut, J. Morris D R, Steward, F R. 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes. Springer-Verlag, New York, 1988.

Moran et al.

- In everyday usage, **vacuum** is a volume of space that is essentially empty of matter, such that its gaseous pressure is much less than atmospheric pressure.[1] The word comes from the Latin term for "empty". A **perfect vacuum** would be one with no particles in it at all, which is impossible to achieve in practice. Physicists often discuss ideal test results that would occur in a perfect vacuum, which they simply call "vacuum" or "free space", and use the term **partial vacuum** to refer to real vacuum. The Latin term **in vacuo** is also used to describe an object as being in what would otherwise be a vacuum.

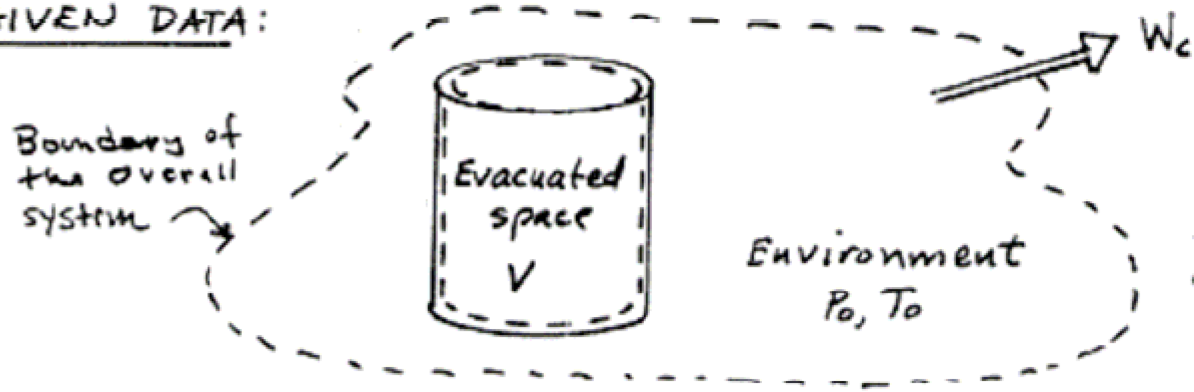
- Source: http://en.wikipedia.org/wiki/Vacuum

7-3 Consider an evacuated tank of volume V. For the space inside the tank as the system, show that the exergy given by $E = p_0V$. Discuss.

KNOWN: An evacuated container of known volume is under consideration.

FIND: For the space inside the tank, determine the exergy.

SCHEMATIC & GIVEN DATA:



ENGR. MODEL: (1) An overall system is considered consisting of the evacuated space (a closed system) and the environment. (2) The volume of the overall system is constant. (3) For the overall system, $Q = 0$. (4) For the environment, p_0 and T_0 are constant. (5) The effects of gravity and motion are ignored.

ANALYSIS: Consider a process where the evacuated space collapses and work is developed by the overall system. An energy balance for the overall system reduces with assumption 3 to give

$$W_c = -\Delta E_c$$

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Since $\Delta U = 0$ for the evacuated space, $\Delta E_c = \Delta U_e$. With Eq. (c) of p. 334, we get

$$W_c = -[T_0 \Delta S_e - p_0 \Delta V_e]$$

By assumption 2, $\Delta V_e = -\Delta V = -(\cancel{V_0}^{0} - V) = V$. Further, an entropy balance for the overall system gives

$$\Delta S_c = \sigma_c \Rightarrow \cancel{\Delta S}^{0} + \Delta S_e = \sigma_c$$

Collecting results

$$W_c = p_0 V - T_0 \sigma_c$$

Since $\sigma_c \geq 0$, the maximum theoretical work, or exergy, is obtained when $\sigma_c = 0$. Thus

$$\mathsf{E} = p_0 V \qquad (1)$$

Alternatively, Eq. (1) can be regarded as the minimum theoretical work required to produce the evacuated space.

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8. Sankey (Energy Flow), Grassmann (Exergy Loss and Flow) and Cost Flow Diagrams

Sankey Diyagramları

- Sankey diyagramlar, ismini, İrlandalı Kaptan Matthew Henry Phineas Riall Sankey (1853-1921)'den sonra aldı. Sankey, 1898 yılındaki bir yayınında, buhar türbinlerinin verimini analiz etmek için enerji akışlarının hacimle orantılı gösterimini kullanan ilk kişiydi.

- Siyah ve beyaz olan ilk diyagramlarla tek tip bir akışın (örneğin; buhar) gösterimi yapılırken, farklı tipteki akışlar için renklerin kullanımı Sankey diyagramlarına başka bir boyut kazandırdı (Wikipedia, 2008; Chemical Engineering, 2008).

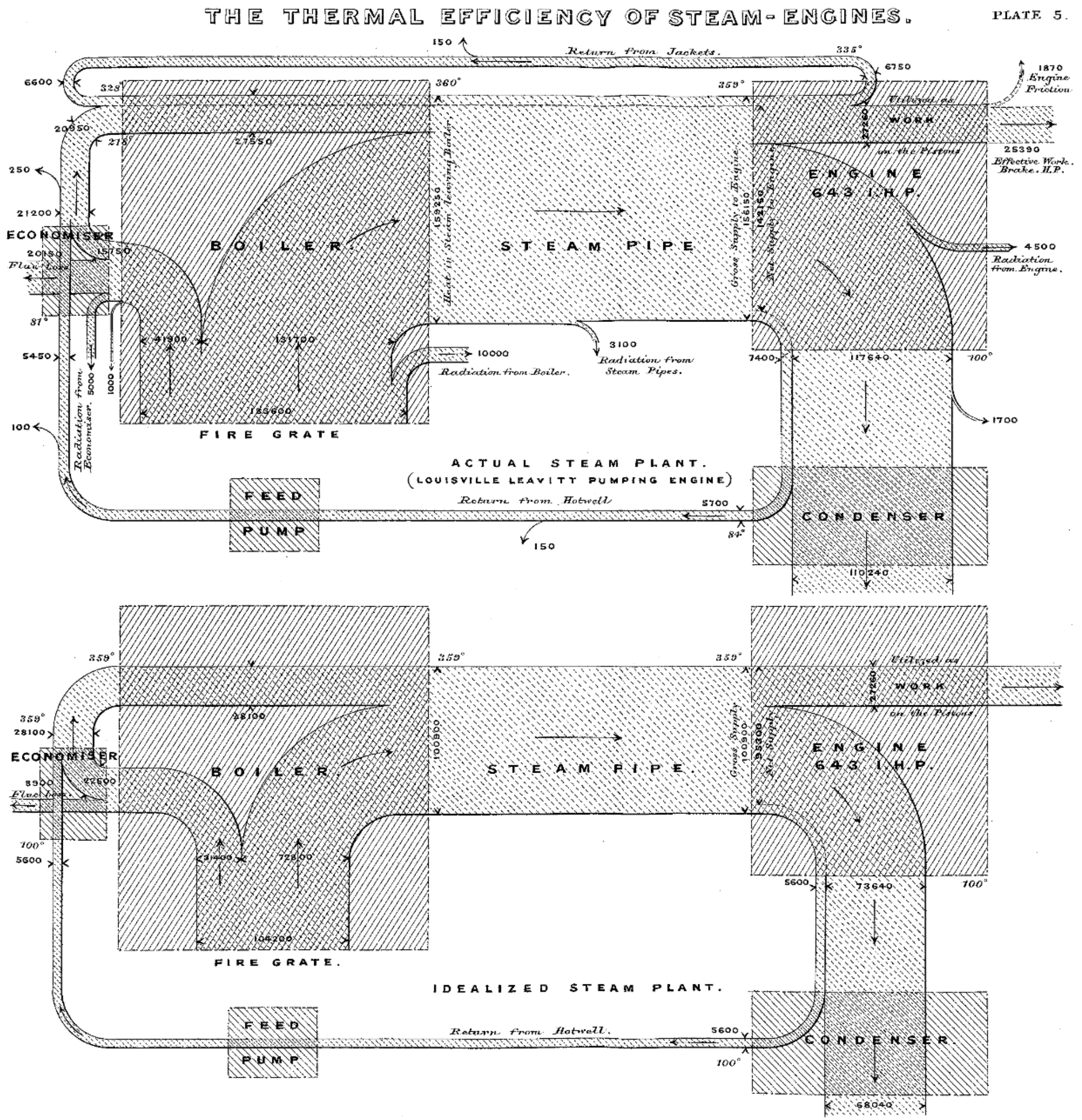
Sankey diyagramları ile ilgili olarak, literatürde değişik tanımlamalar yapılmış olup, bunların bazıları aşağıda verilmiştir:

- Sankey diyagramları, okların genişliğinin akış miktarıyla doğru orantılı olarak gösterildiği, belirli tipteki bir akış diyagramıdır. Bunlar, prosesler arasındaki enerji veya madde transferlerini göz önünde canlandırmak için kullanılır (Wikipedia, 2008).

- Sankey diyagramı, akımların genişliğinin akış miktarıyla doğru orantılı olduğu ve bir dizi olaylar veya aşamalarla akışların kombine edilebildiği, ayrıldığı ve izlenebildiği yönle gösterilen akış diyagramlarıdır (SD, 2008).

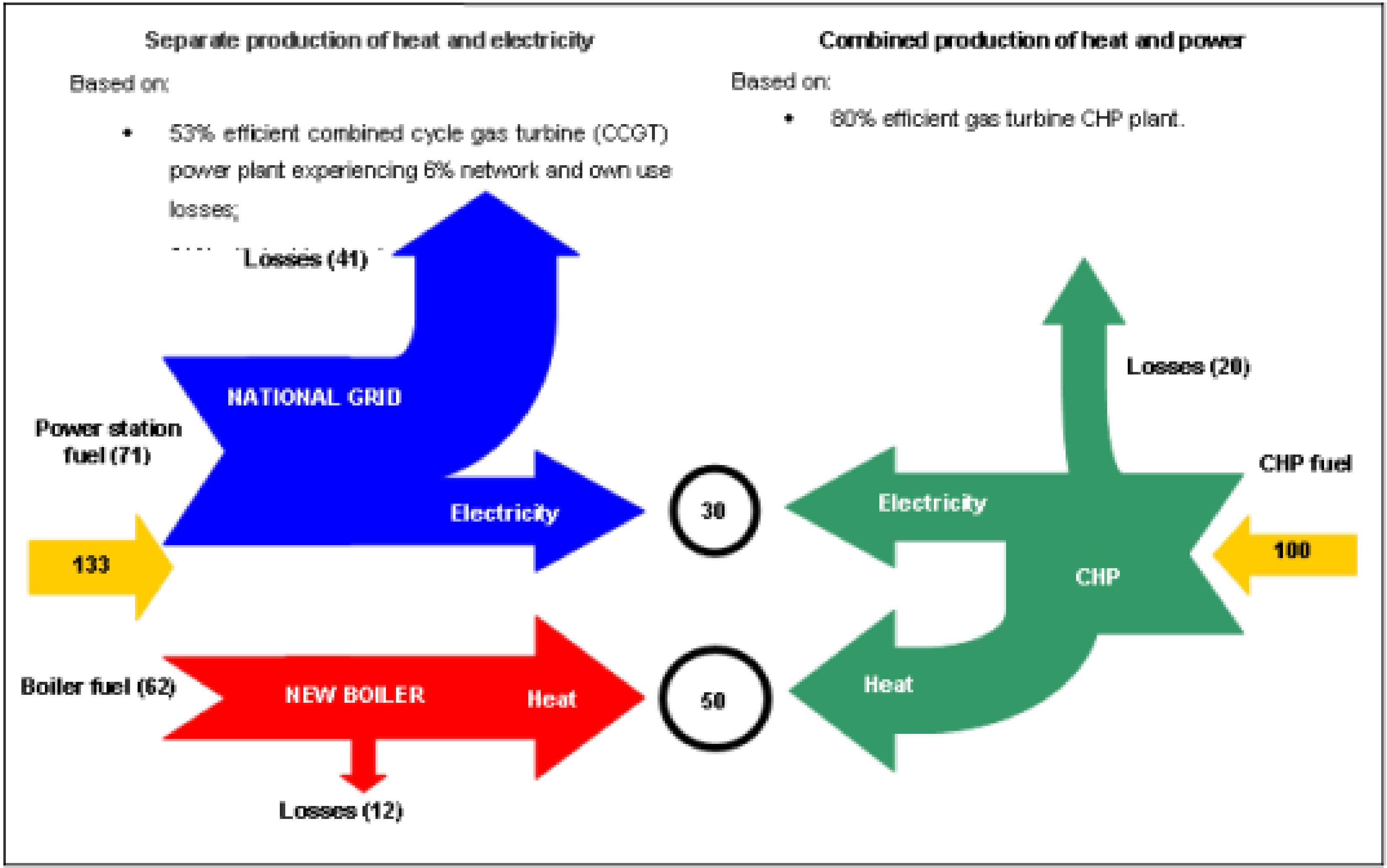
- Bir resim, 1000 sözcük değerindedir. Sankey diyagramları, bir prosesteki madde ve enerji dağılımlarını ve kayıplarını hızlı gözde canlandırmağa yardımcı olan, dikkat çekici diyagramlardır.
- Diyagramda kullanılan çizgilerin genişliği, madde veya enerji miktarıyla doğru orantılıdır. Sankey diyagramı, enerji denkliliği hesabı yapıldıktan sonra, kazanlar, yakıtlı ısıtıcılar, fırınlar gibi herhangi bir ekipman veya sistemdeki enerji akışını göstermek için kullanılan çok uygun bir araçtır. Enerji yöneticileri önem sırası şeklinde iyileştirmeleri bulmaya odaklanabilsin diye, bu diyagramla, değişik çıkanlar ve kayıplar görsel olarak gösterilir. Sankey diyagramı, aynı zamanda, bir gruptaki ve üst yönetime düşüncelerin ve fikirlerin anlatılmasında güçlü bir araçtır (Chemical Engineering, 2008).

The first Sankey diagram

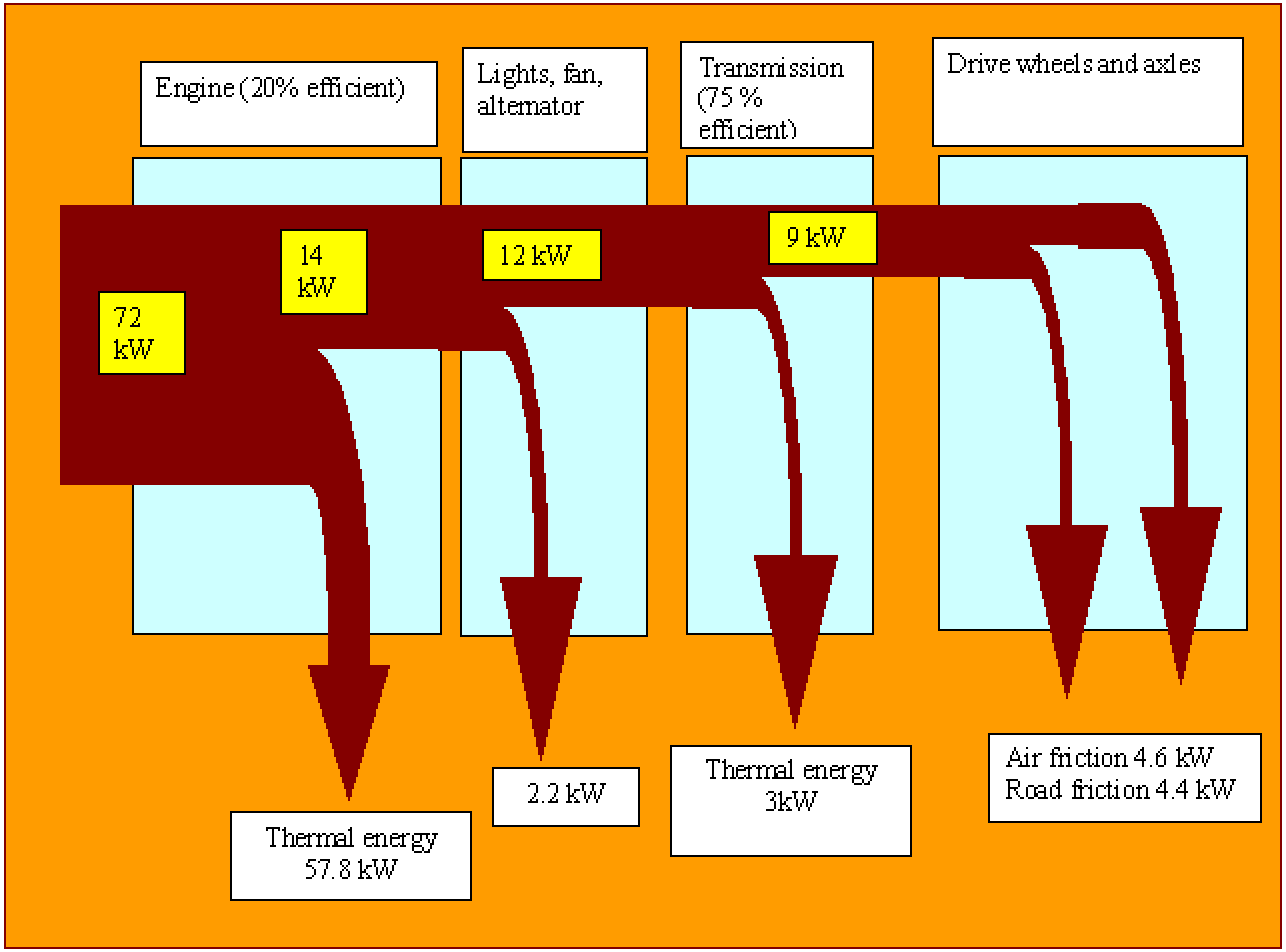


Minutes of Proceedings of The Institution of Civil Engineers, Vol: CXXXIV Session 1897-98. Part IV.

http://upload.wikimedia.org/wikipedia/commons/1/10/JIE_Sankey_V5_Fig1.png

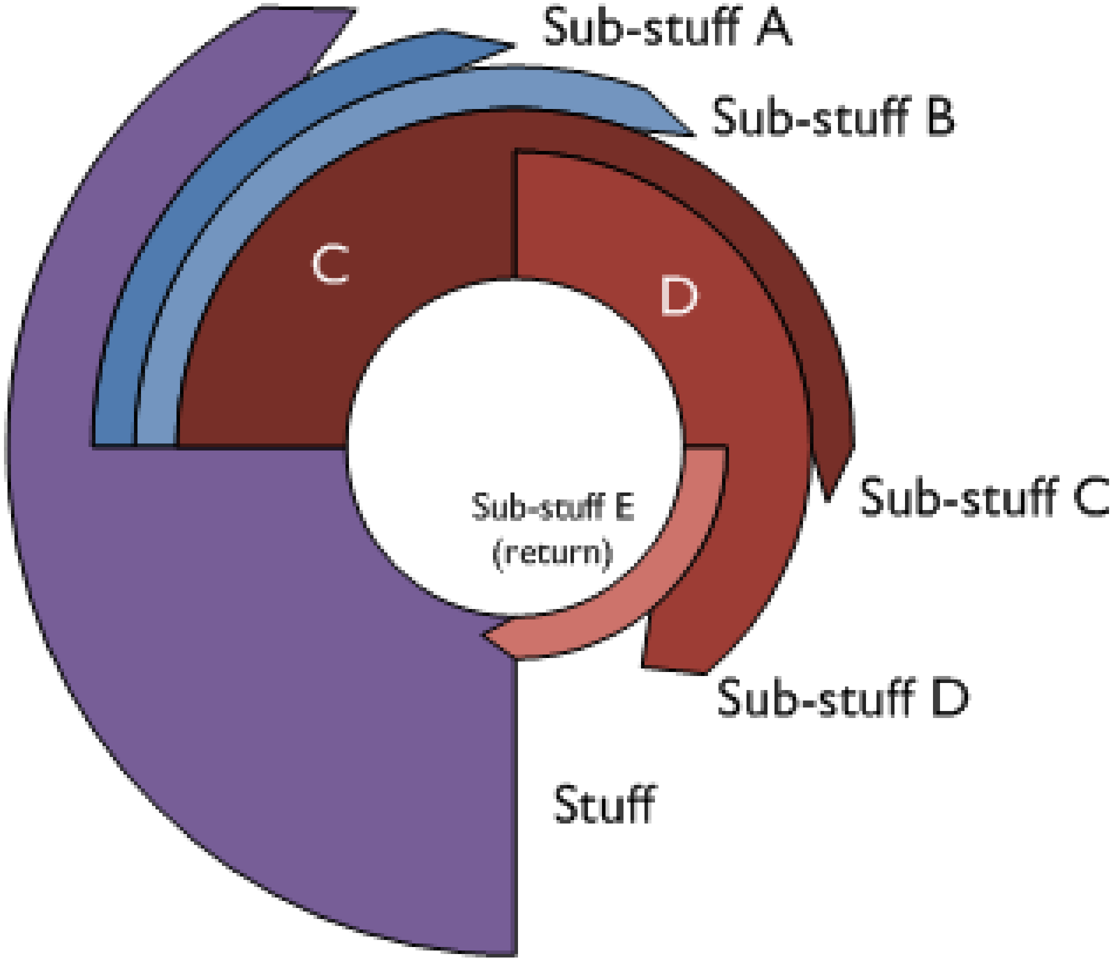


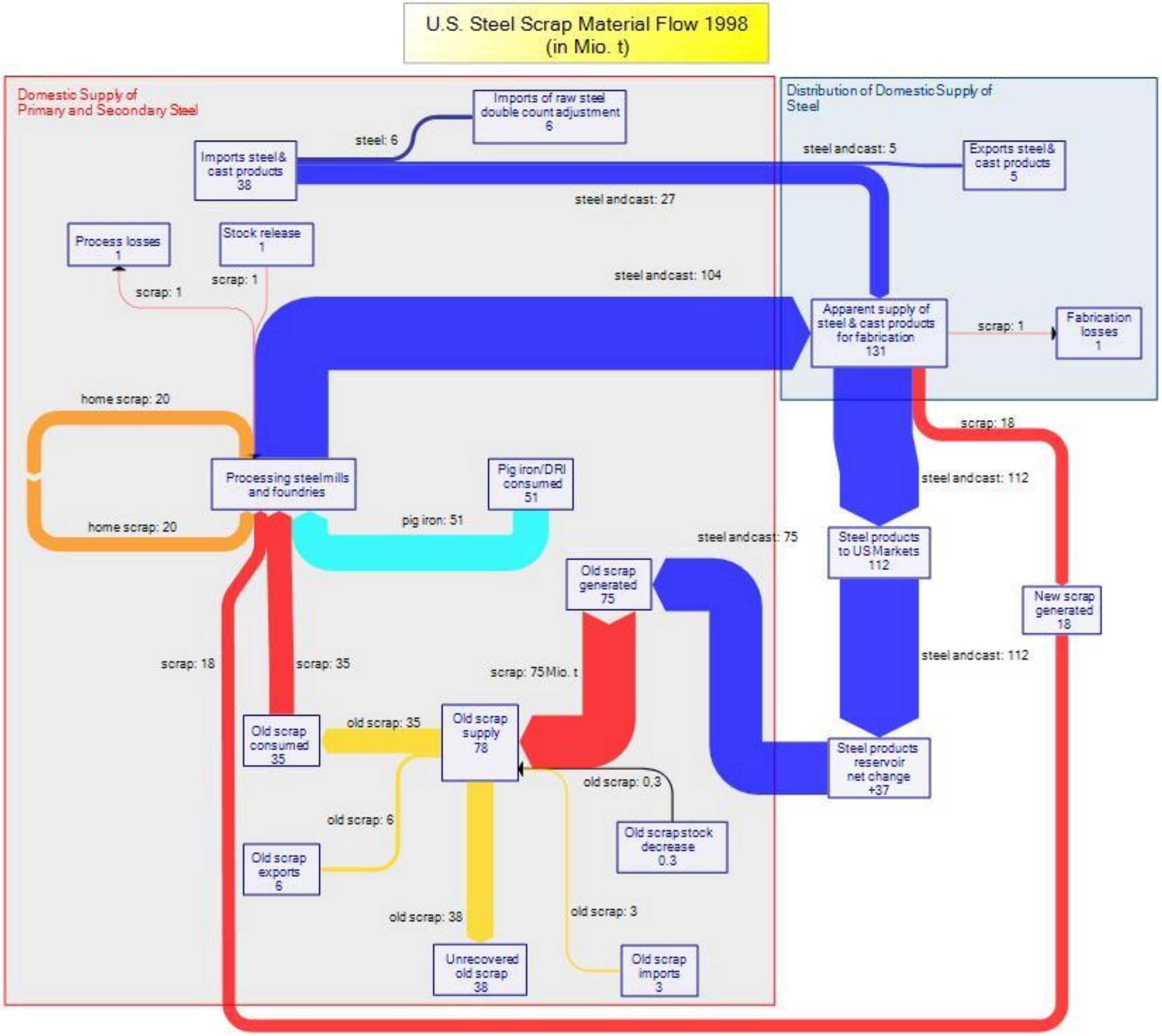
http://www.sei.ie/uploadedfiles/CHP/Sankey%20diagram2.png



In this diagram, called a **Sankey Diagram**, we can see that of 72 kW of power from the fuel, only 9 kW are used in actually driving a car along a road. The rest is lost as low grade heat.

http://www.antonine-education.co.uk/Physics_A2/Options/Module_7/Topic_5/Sankey.gif


Sub-stuff A
Sub-stuff B
C
D
Sub-stuff C
Sub-stuff E
(return)
Sub-stuff D
Stuff



Source: Fenton, M. D.: Iron and Steel Recycling in the United States in 1998
http://pubs.usgs.gov/of/2001/of01-224/of01-224.pdf

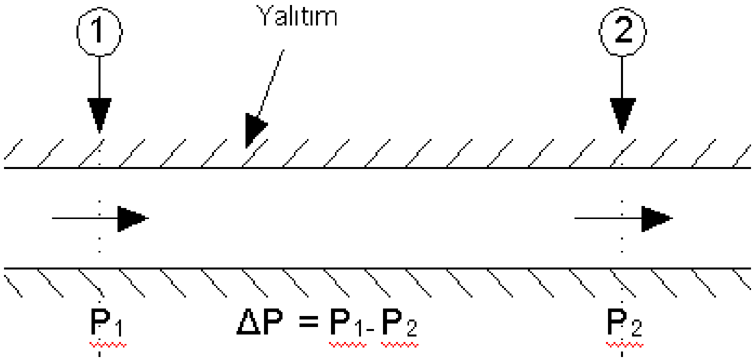
http://www.e-sankey.com/export/pics/e-sankey/esankey_scrap_material_flow.png

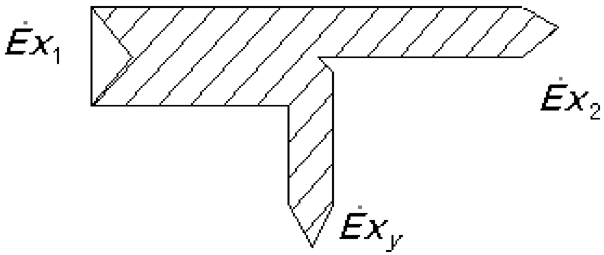
Grassmann (Ekserji Akış ve Kayıp) Diyagramı

- Bir sistemdeki bileşen tersinmezliklerinin listelenmesi, basit bir tesisin performansının değerlendirilmesine yardımcı olur. Bununla beraber, daha karmaşık tesislerde, bu bilginin şekil olarak sunulması ayrı bir yarardır (Kotas, 1995).

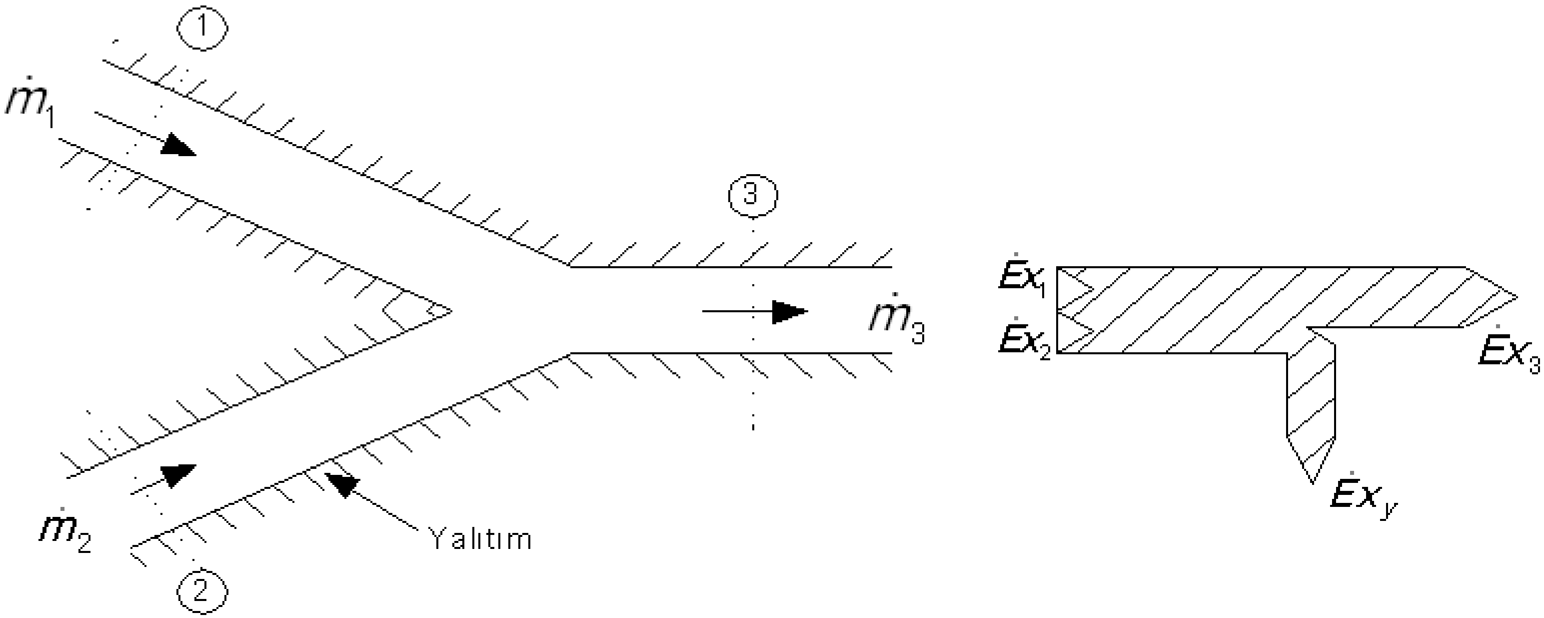
- Bu çerçevede, ekserji akış ve kayıp diyagramı olarak da adlandırılan Grassmann diyagramı, Sankey diyagramının bir uyarlanmasıdır. Bu diyagramda, sadece kayıplar gösterilmez; aynı zamanda ekserji akımlarının ayrılması ve ekserjinin tekrar dolaşımı da gösterilir (Koolen, 2000).

- Aynı zamanda, grafiksel olarak, orijinal ekserji girişin bir kısmının enerji dönüşümün birbirini izleyen aşamalarda nasıl dağıldığı gösterilir. Her bir alt bölgedeki kayıplar, farkın oluştuğu farklı tiplerdeki diğer alt bölgelere ayrılabilir (Kotas, 1995).

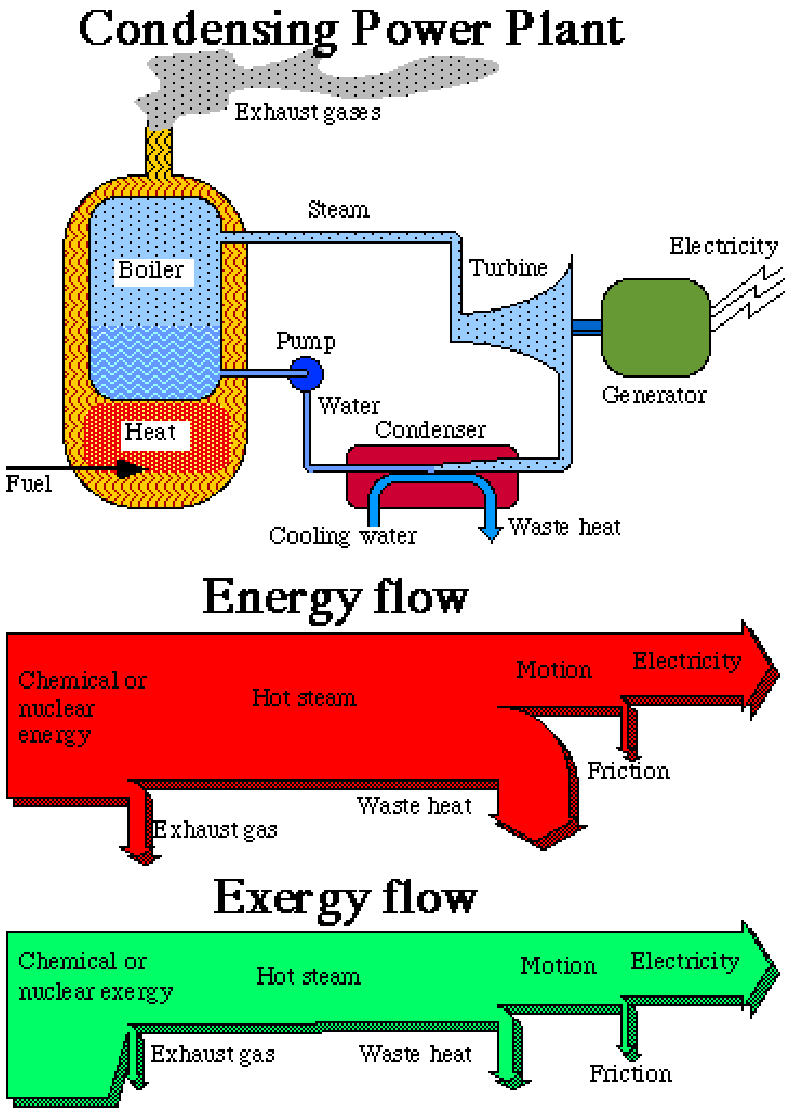




Akışkan sürtünmesiyle bir kanaldaki Grassmann diyagramı



Akımların Karışımında Grassmann Diyagramı



http://exergy.se/goran/thesis/paper1/f34.gif

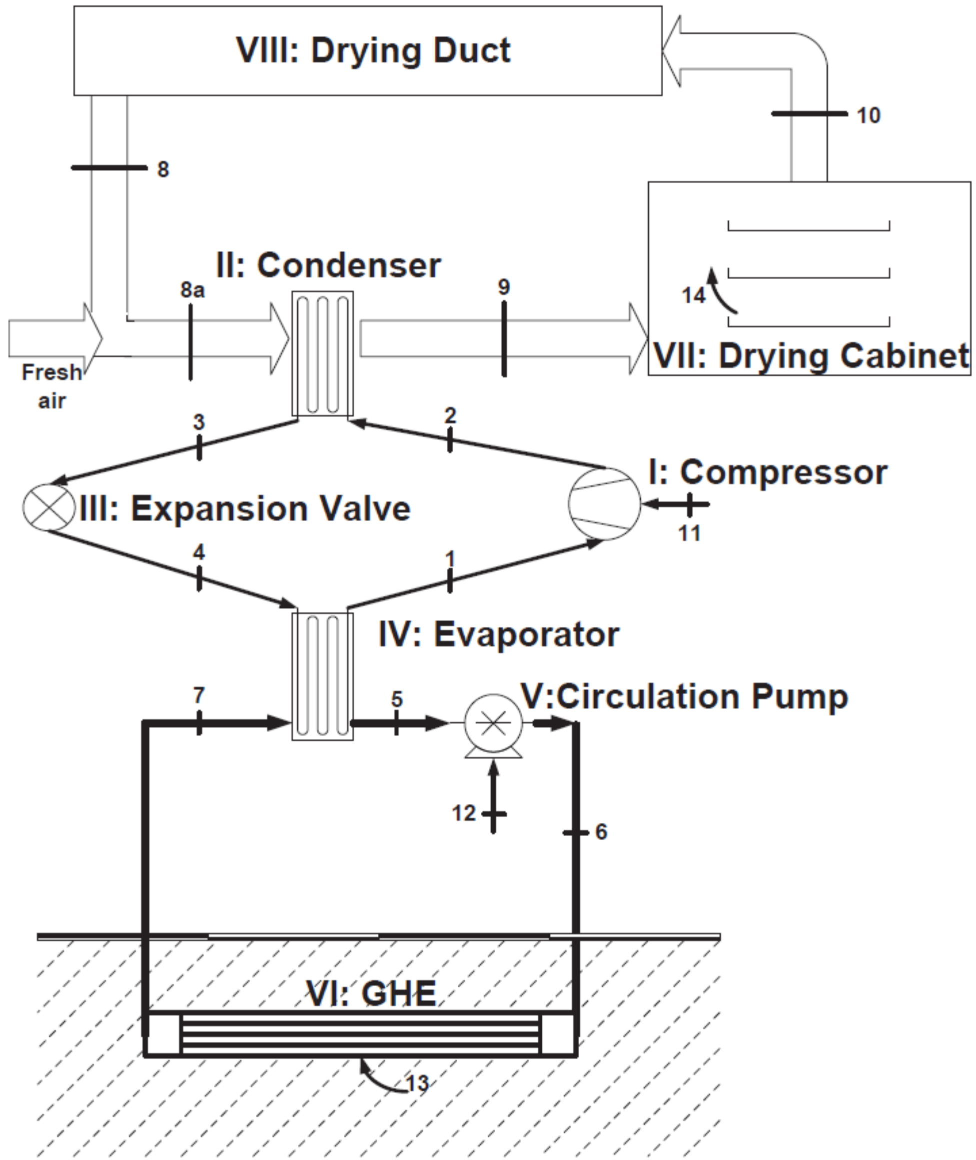


Fig. 1. Schematic drawing of GSHP food drying system with enumerated locations used in equations of analyses (modified from Ref. [9]).

Sankey (Energy Flow) Diagram

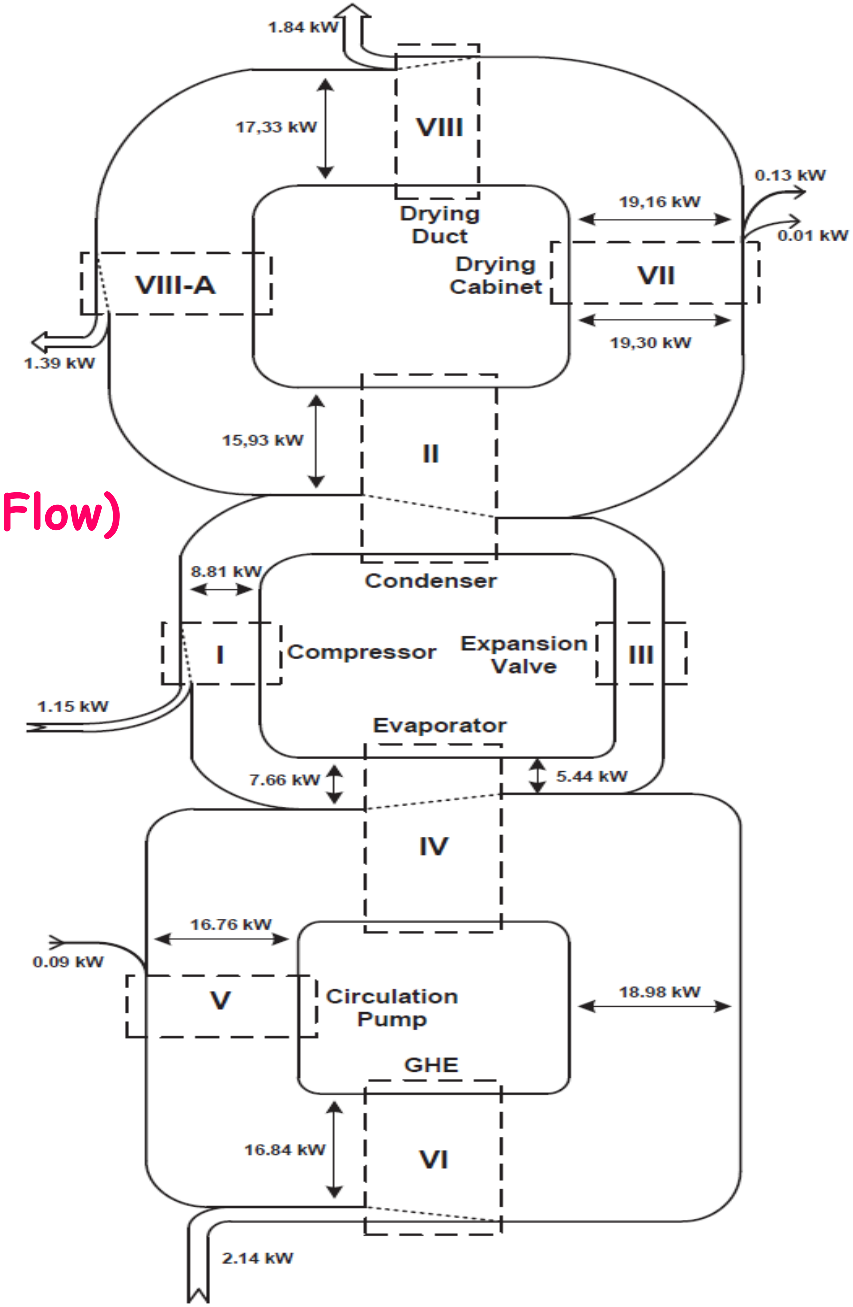


Fig. 3. The Sankey (energy flow) diagram for the GSHP food drying system.

Grassmann (Exergy Loss and Flow) Diagram

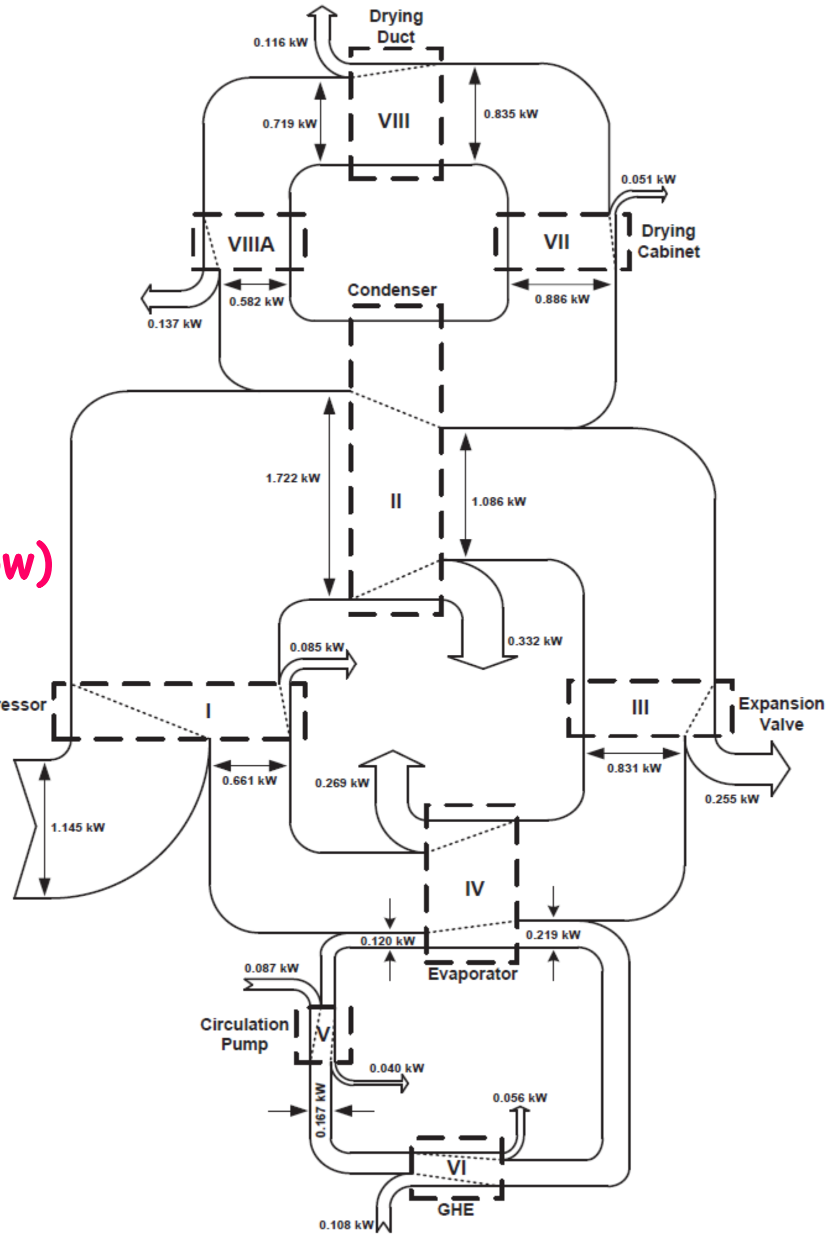


Fig. 4. The Grassmann (exergy loss and flow) diagram for the GSHP food drying system.

Cost Flow Diagram

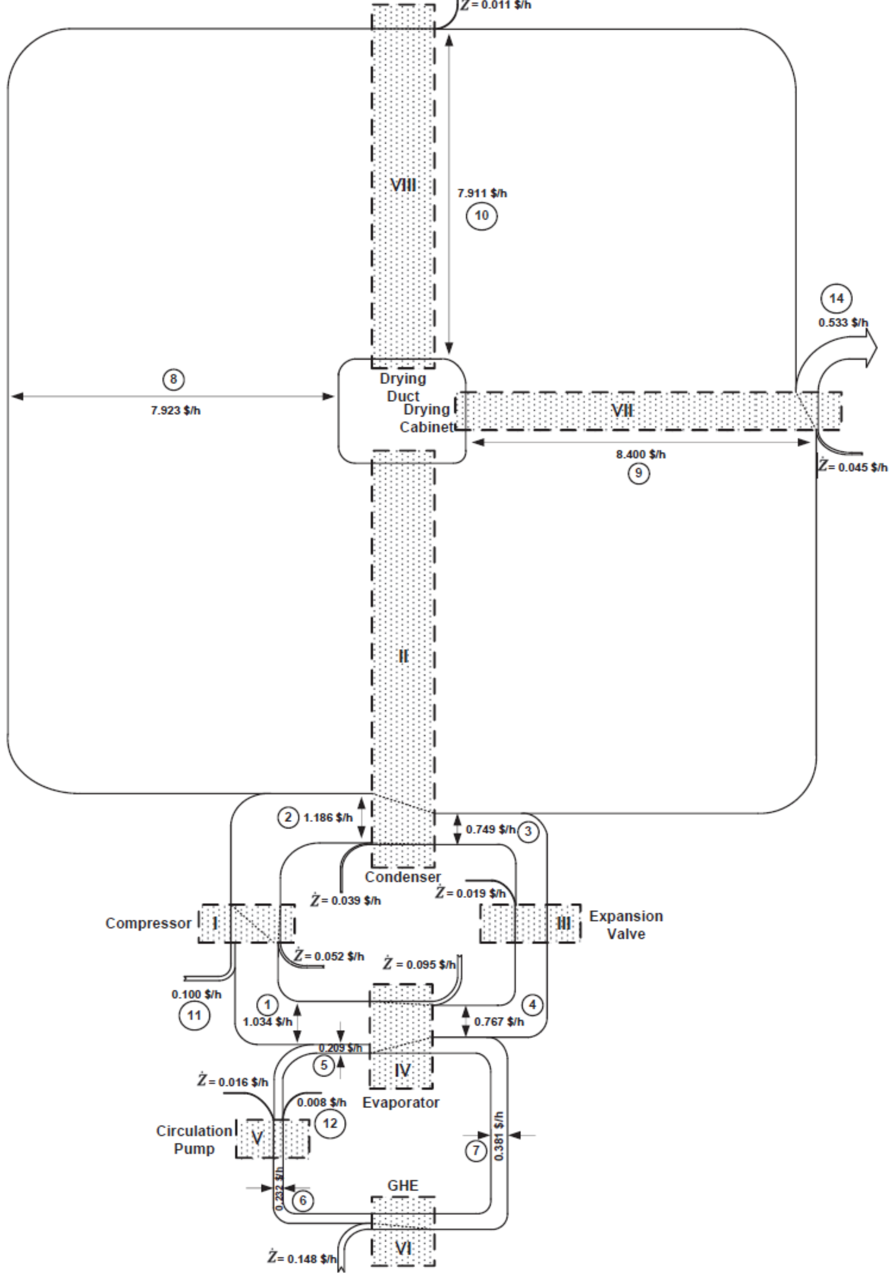


Fig. 5. The Sankey (cost flow) diagram for the GSHP food drying system.

9. Concluding Remarks

- Main drivers highlighted here should be considered as a whole.
- Policy makers, educators, investigators, stakeholders, and citizens are encouraged to consider energy and resources on the base of exergy.
- *We need to adapt our path to new challenges, so that we could not be out of business. This means think exergetically, not energetically.*
- All roads lead to Rome, namely exergy when talking about sustainabiliy.

- Different symbols are used for exergy and exergy efficiency.
- Different classifications are used to distinguish between exergy types.
- Different terms are used for the same type of exergy.
- Different expressions for exergy efficiency have been suggested.
- Some exergy efficiencies are defined in a generic way which opens up for different interpretations when applied to specific processes or unit operations.
- Heating value is sometimes used instead of chemical exergy for the fuel of a process (such as a power plant), thereby introducing errors in exergy analyses.

D. Marmolejo-Correa, T. Gundersen / Energy 44 (2012) 477–489

QUESTIONS ???

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THANK YOU VERY MUCH FOR YOUR STAYING HERE TILL THE END

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QUESTIONS ???