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Primary exergy efficiency—Effect of system efficiency environment to benefits of exergy savings

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ABSTRACT

Improving energetic performance is a key factor in making societies more sustainable. One way to analyze energetic performance is to use methods based on the second law of thermodynamics. Exergy analysis is such a method. With exergy analysis thermodynamic losses of the studied system can be found. For a specific process decreasing the exergy losses decreases the need for exergy inputs and production costs. Exergy analysis can also be used to analyze the life cycle of a process or product, but then it is necessary to model the total production system. For this reason, it is important to have efficiency analysis methods that can simultaneously analyze the studied system or process and the surrounding environment around this system. The objective of this article is to present such a method where the whole energy chain needs not to be modeled, but still the effect of an energy improvement or change in a studied process can be analyzed with respect to the whole energy chain. This method is called PeXa and it combines exergy analysis and primary energy analysis. In this work we show that also the system environment affects the benefit of exergy savings in the system level depending what production does this exergy saving replace. A district heating (DH) network with different DH producing units having different exergy efficiencies is used to show the concept. It is shown that in some cases basic exergy analysis and PeXa will give different results assuming that the objective is to consider the primary energy effects of society. By considering this broader concept of environment in exergy analysis companies and societies can direct limited resources into investments that maximize primary exergy savings.

1. Introduction

There is a constant need to improve production processes, so that they are more economical, efficient and sustainable. In order to understand which processes accomplish these improvements, different types of indicators that can compare these processes, are needed. On way to make processes more efficient, is to improve energetic performance of the system in question. A key issue in studying energetic performance is to apply appropriate assessment methods, which should be able to consider efficiency so that possible improvements are considered objectively and in a correct manner. Additionally the assessment methods should consider the overall production chain in order to avoid sub-optimization.

One way to analyze energetic performance is to use methods based on the second law of thermodynamics. One such method is exergy analysis (EXE) that can be used to analyze thermodynamic losses of the studied system. EXE shows the maximum useful work potential that a system has at a given state and at a given environment. Thus exergy is a combination property of the system and the environment, meaning that the system in the same state in different environments has different exergy values. For a specific process decreasing the exergy losses decreases the need for exergy inputs. An comprehensive reference of using exergy on analyzing and improving production systems can be found in Szargut et al. [20] and Dincer and Rosen [6]. A brief commented history of exergy analysis including the fundamental early contributions from Carnot [1], Gibbs [7], Rant [15] and Clausius [4] can be found in Sciubba and Wall [18].

Exergy can be used to analyze the overall production chains from the sustainability perspective and many exergy based assessment approaches to accomplish this have been developed. In a review of these approaches Romero and Linares [16] divides these methods into two types: user-side approaches that according to Romero and Linares [16] can be considered to address weak sustainability and to donor-side approaches that can be considered to address strong sustainability. The difference between weak and strong sustainability lies in the attitude of using environment as produced capital. In weak sustainability natural capital or the environment

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Nomenclature

Abreviations

CEC	cumulative exergy consumption
CHP	combined heat and power
DH	district heating
ECEC	ecological cumulative exergy consumption
EEA	extended exergy analysis
ELCA	exergetic life cycle assessment
EMERGY	emergy analysis
EXE	exergy efficiency or analysis
HOB	heat only boiler
LCA	life cycle analysis
LCEA	life cycle exergy analysis
LHV	lower heating value
PE	primary energy
PEE	primary energy efficiency or analysis
PEF	primary energy factor
PeXa	primary exergy efficiency or analysis
REMM	rational exergy management model
THC	thermoecological cost
THE	thermoeconomy

Symbols

0	state of environment
1	state of studied process or flow
η	efficiency
ρ	power to heat ratio
ch	chemical exergy
dry	dry fuel
ENV	environment
Ex, *ex*	exergy
ext	external
h	enthalpy
i	process assessed
i	product assessed
in	incoming flow
int	internal
j	external
k	kinetic
l	products
loss	loss
out	out flow
ph	physical
pot	potential
Q	heat energy
T	temperature
w	moisture content
water	water
wet	wet fuel
El	electricity
F or Fuel	fuel
P	power
PER	period of a year
SYST	system
TOT	total annual time

can be replaced by produced capital, when in strong sustainability the environment is not replaceable with produced capital. According to Romero and Linares [16] Life-Cycle Analysis (LCA) based approaches Life Cycle Exergy Analysis (LCEA) [23] and Exergetic Life Cycle Assessment (ELCA) [5], together with Exergoeconomics based approaches Cumulative Exergy Consumption (CEC) [19] and Exergoecology [21], can be considered as user-side approaches. Ecosystem ecology based approaches Emergy Analysis (EMERGY) [14], Ecological Cumulative Exergy Consumption (ECEC) [8] and Extended Exergy Accounting (EEA) [17] can be considered as donor-side approaches. In addition to these approaches the concept of thermo economy (e.g. [13,22]) can be considered as important contributions to exergy-based sustainability analysis. All the above mentioned methods share in common the assumption that the overall production system or chain needs to be modeled in detail.

Primary energy efficiency (PEE) is another method that is used to evaluate energetic performance of energy conversion systems. It is based on the first law of thermodynamics and it considers all the primary energy input to a production system that is required for yielding a certain product at the system boundary. The primary energy factor of a product PEF is the sum of all PE input to the energy system divided by the considered useful energy delivered at the system border. The basis for the analysis lies in the EU standard EN 15603 [3] and related standards (e.g. EN15316 series). Primary energy analysis is a product-oriented analysis method, unlike for example exergy analysis, which is a process oriented analysis method. Thus PEE is a valuable tool comparing efficiencies of a same product that has been produced with different production chains, because PEE can compare the amount of primary energy the overall chain has consumed. PEE has been applied in analyzing end-user or building energy efficiency, but it has also been applied to multi-product applications [11] and [12]. In Kohl et al. [12] three different energy indicators (exergy, energy, PEE) are compared and the clear conclusions is that exergy analysis seems to be advantageous when it comes to detailed (sub-) process analysis whereas the primary energy analysis offers the advantage of showing how the system is influencing the global primary energy resources. Another conclusion from the work is that a combination of PEE and exergy could offer a more holistic energy efficiency indicator. Kilkis and Kilkis [10] came to the same conclusion, and integrated Rational Exergy Management Model (REMM) with the PEE approach in order to improve and analyze the Combined Heat and Power (CHP) processes and integrate these with heat pumping and cooling systems [9].

In this work the objective is to combine the benefits of EXE and PEE, so that the whole energy chain needs not to be modeled, but still the effect of an energy improvement can be analyzed with respect to the whole energy chain. This approach is called Primary Exergy Analysis (PeXa) and it is generally a basic exergy analysis method where losses outside the studied process are calculated with factors obtained from PEE. These factors are similar to the ones in Emergy analysis. This way the exergy of a product that is made up from many production routes depends on the portions of these routes used to make up the product. The fact that factors are used for products (that can be either material needed in the process or competing products) differentiates the method from basic exergy analysis. The fact that the primary exergy can be something else than suns exergy, differentiates the method from emergy analysis. The method resembles the REMM approach integration to PEE [10], although in the Pexa approach the exergy efficiencies are obtained with real exergy values, not as rational exergy efficiencies dependent on the overall system in hand that needs to be modelled. Also the PeXa factors consider the efficiency of the competing products (like the electrical efficiency in the grid), but these that are not modeled in as a part of the process studied.

2. Methods

In this chapter the basic idea of the PeXa method is presented. Before that the two methods that PeXa is based on, i.e. PEE and EXE, are presented.