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Estimating exergy prices for energy carriers in heating systems: Country analyses of exergy substitution with capital expenditures

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ABSTRACT

Exergy represents the ability of an energy carrier to perform work and can be seen as a core indicator for measuring its quality. In this article we postulate that energy prices reflect the exergy content of the underlying energy carrier and that capital expenditures can substitute for exergy to some degree.

We draw our line of argumentation from cost and technology data for heating systems of four European countries: Austria, Finland, The Netherlands, and Sweden. Firstly, this paper shows that the overall consumer costs for different heating options, widely installed in those countries, are in the same range. In this analysis we derived an overall standard deviation of about 8%. Secondly, additional analysis demonstrates that the share of capital costs on total heating cost increases with lower exergy input. Based on the data used in this analysis, we conclude that for the case of modern cost effective heating systems the substitution rate between exergy and capital is in the vicinity of 2/3. This means that by reducing the average specific exergy input of the applied energy carriers by one unit, the share of capital costs on the total costs increases by 2/3 of a unit.

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1. Introduction

A variety of technological options exists for converting different energy carriers to useful energy, heat and finally into the energy service of a comfortable room temperature. Historically, the mix of fuels changed from biomass towards oil, gas and coal during industrialization [1]. During the same period, efficiency and emission standards of heating systems as well as comfort levels increased strongly. On the one hand modern heating solutions include systems like thermal solar collectors and heat-pumps. On the other the thermal insulation and air-tightness of buildings are continuously improved, which enables us to render energy sources more economical (see e.g. [2,3]).

The characteristics of these different heating systems lead to different cost structures, regarding capital costs, operating costs and energy costs. The energy costs of energy carriers can differ considerably, as can the quality of energy carriers. One of the core indicators measuring the quality of an energy carrier is its exergy content. It is reasonable to postulate that, when buying energy, people are interested in the portion of the energy capable of performing work for them, namely exergy, and not unusable forms of energy. Therefore, one of our hypotheses is that in a well-functioning energy market with ample choices the price of an energy carrier does reflect its exergy content rather than its energy content. Thus it can be expected that low-exergy energy carriers (e.g. low-enthalpy heat) have a lower price level. However, for a given end use such as heating, the total cost of energy carrier and capital investments necessary to provide the energy service should be about the same for all systems routinely installed, given that the systems provide a similar comfort level and market distortions are negligible. Based on these premises, we state the following hypotheses:

- The total heat generation costs for widely installed systems are generally on an equal level within a country or region regardless of the energy carrier, and
- the prices of well-established energy carriers in the marketplace reflect the exergy content.

The first proposal for using exergy as a criterion for cost allocation was presented in 1932 by Keenan, cited by Lozano and Valero [4], who suggested that the production costs of a cogeneration plant should be distributed among the products (work and heat) according to their exergy. Since then several concepts to contemplate the

Abbreviations: CHP, combined heat and power; DH, district heat.

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Nomenclature

$T_{\text{comb. products}}$	temperature of combustion products (K)
T_0	temperature of the ambient environment, dead state (K)
i_{ex}	exergy factor, dimensionless
e_{ex}	annual exergy content of energy carriers (MWh/yr)
e_{en}	annual energy content of energy carriers (MWh/yr)
c_{en}	variable price for energy carrier excluding taxes (€/kWh)
$c_{en,tax}$	energy related taxes (€/kWh)
$f_{en,tax}$	specific energy tax rate, dimensionless
I_{hs}	investment cost (€)
$c_{O\&M}$	operation and maintenance costs (€/yr)
C_{fix}	annual fixed costs (€/yr)

Greek letters

α	capital recovery factor (yr^{-1})
$\varepsilon_{combustion}$	exergetic efficiency of an ideal combustion process, dimensionless

exergy losses of processes and the exergy content of energy carriers have been developed; they are commonly summarized by the term "thermoeconomics".

Thermoeconomics, introduced by Tribus and Evans [5], combines the second law of thermodynamics with economics by applying the concept of cost to exergy, in order to achieve a better production management with a more cost-effective operation. Within this concept, second law analysis methods based on cost accounting are used to determine actual product cost and provide a rational basis for pricing [6]. Deng et al. [6] also note that to a certain extent, multiple methodologies with different theories and nomenclatures cause confusion and impede the development of thermoeconomics. Based on the achievements of predecessors, Valero et al. [7] developed the structural theory of thermoeconomics, which provides a general mathematical formulation using a linear model and encompasses all the thermoeconomic methodologies developed up to now, and is considered as standard formalism of thermoeconomics [8,9].

Currently, relevant concepts in the field of thermoeconomics are exergy accounting, exergetic cost, exergoeconomics and the concept of exergy prices. Exergy accounting converts the inflow of physical resources into their equivalent exergetic form. Having a homogeneous exergetic basis paves the way for an evaluation of the efficiency of each energy and mass transfer between numerous sectors of society and enables a quantification of the irreversible losses and an identification of their causes [10–14]. In the exergy cost approach, as applied by Xiang et al. [15], the term exergy cost is used as a representation of the units of external resources used (and depleted) to produce a specific product. However, this concept does not explore costs in a monetary meaning. Valero [16] states that the exergetic cost or the cumulative exergy consumption are, in fact, the same concepts as embodied exergy. Valero proposes a logical chain of concepts for connecting physics with economics. Exergoeconomic analyses consider exergy in allocating the (monetary) production costs of a process to the different products it produces. A general methodology for this kind of analysis was presented by Tsatsaronis in 1985 [17], and was later called the exergoeconomic accounting technique [18]. Finally, the concept of exergetic prices or exergy prices calculates the specific monetary prices of energy carriers based on their exergy content instead of their energy content. Such analyses have, for instance, been performed by Wall [19] and Hepbasli [20].

As this brief overview already reveals, it is important to realize that scholars do not always clearly distinguish between processes of cost and price formation and that the terms "cost" and "price" are used in multiple ways in different sources. Valero [16] defines the term "cost" in the physical sacrifices of resources, and argues, that a strongly related money prices would then reflect past resource depletions. Sciubba [11] proposes that it is not capital that ought to measure the value of a product, but exergetic content, because 'economic systems are eco-systems that function only because of the energy and material fluxes that sustain human activities'. He advocates that the monetary 'price tag' (expressed in e.g. \$ or €unit^{-1}) should be calculated on the basis of the extended exergetic content (expressed in kJ unit^{-1}) of a good or service, corrected for environmental impact. Lozano and Valero [4] highlight the need to use exergy to rationally assign costs. They state that the only rigorous way of measuring the physical production cost is the second law of thermodynamics and not its market value, as it provides a unique way to identify, allocate and quantify the inefficiencies of realized processes which are at the basis of cost and resource consumption.

In this article, we distinguish between the terms "price" and "cost". We define energy prices in accordance with the common economic theories as the result of supply and demand intersections on energy and resource markets. Thus, they reflect the relation of supply and demand for different energy carriers. Heating related energy costs are the expenses that consumers have to pay for a heating system. This includes fixed costs (investments, operation and maintenance), energy taxes and costs for energy carriers. The latter are represented by energy prices (in a market driven economy) and energy related taxes.

2. Methodology

2.1. Exergy content of energy carriers

The forms of energy at the disposal of our economy can be classified according to their exergy content, that is, their ability to perform potentially useful work. For energy carriers of extra superior quality such as electricity, the exergy factor is set to 100%, chemical energy carriers such as oil, gas and biomass count as superior and do have a exergy factor in the vicinity of 95% [20,21]. The exergy content of heat depends on the temperature of the energy carrier and the temperature level of applicable ambient (dead state). Chemical energy is a much-used basis for primary energy conversion, often through combustion. The temperature levels that can be reached in such combustion processes determine the amount of the chemical exergy that in practice can be converted into thermal exergy. In other words, in combustion processes there is always a certain amount of unavoidable exergy loss due to the limited degree of achievable temperature levels. The exergetic efficiency $\varepsilon_{ex,combustion}$ of an ideal combustion process is determined by the second law of thermodynamics, and depends basically on the absolute temperature levels of combustion $T_{combustion}$ and of the environment T_0 (see Eq. (1)). Thus, the highest achievable exergetic efficiency of a combustion process indicates the amount of "in practice maximum usable" exergy (i.e. exergy content minus unavoidable exergy losses).

$$\varepsilon_{ex,combustion} = \frac{e_{ex,heat}}{e_{ex,fuel}} = (1 - T_0 \cdot T_{combustion}^{-1}) \quad (1)$$

A maximum exergy of 85% can be derived for a fully oxidized combustion, assuming $T_{combustion} \approx 2000\,K$ and $T_0 \approx 300\,K$. In contrast, the exergy content indicate that chemical energy could in principle be converted into other forms of energy by up to ~95%. The difference defines the exergy destruction that is unavoidable

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