Energy and Buildings xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

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

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ARTICLE INFO

Article history:
Received 12 December 2010
Received in revised form
16 September 2011
Accepted 24 September 2011

Keywords:
Exergy
Energy prices
Buildings
Heating

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.

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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doi:10.1016/j.enbuild.2011.09.034

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).

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

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

Table 1
Exergy content of the energy carriers analysed in this paper.

Energy carrier (temperature level)	Temperature level	Reference temperature level	Exergy content as used in this paper
Oil, coal, gas	1500 °C	0 °C (−20 °C/+20 °C)	85% (86%/83%)
Biomass	800 °C	0 °C (−20 °C/+20 °C)	75% (76%/73%)
Electricity	–	–	100%
District heat inlet flow	100 °C	0 °C (−20 °C/+20 °C)	27% (32%/21%)

for thermodynamic causes and the highest achievable combustion temperatures with current technologies. Comparing secondary energy carriers such as electricity and district heat solely on the basis of their exergy content would lead to some bias, as it would not include exergy destruction upstream the system boundaries. It would also exclude energy carriers which still contain some exergy that cannot be utilized by any means.

Hence, we also consider the thermodynamic losses associated to the temperature limits imposed by current technology for large scale utilization. For electricity production from natural gas the exergy efficiency is determined by the most efficient available power plants, which today have a net power generation efficiency of 58% and above. Using this approach is reasonable when investigating a specific component or subsystem. Yet, when looking at a broader system, such as an energy supply system for district heating (DH), it may overlook the overall efficiency gains of using surplus thermal energy, such as heat supplied from a cogeneration heat and power (CHP) plant to the DH grid.

For natural gas or oil, combined cycle CHP have a high exergetic efficiency, which depends on the turbine inlet and environmental temperatures, T_{inlet} and T_0. Even in most recent gas turbines, the turbine inlet temperature must not exceed a temperature T_{inlet} of about 1700 K as the hot gas would degrade the turbine blades quickly. Similarly, for coal-fired high temperature processes (e.g. from metal melting), usual temperatures are in the vicinity of 1400–1500 °C. For biomass combustion, the maximum temperature level on which flue gas can be utilized is mainly determined by impurities. Fluidized bed reactors, nowadays one of the most advanced biomass combustion processes, usually operate at temperature levels not above 800 °C for unconverted, solid biomass.

The choice of the reference state, as revealed by Eq. (1) also influences the exergy content of an energy carrier. If the state of the energy carrier is close to the reference state, choosing an appropriate dead state is of crucial importance. Torío et al. [22] concludes that even though several authors propose and performed a dynamic calculation of the exergy content based on the ever changing ambient temperature, most reviewed papers apply a steady-state approach based on seasonal or annual average temperatures. In our case, the seasonal average temperature during the heating period appears to be appropriate. The average outdoor temperature, weighted by monthly heating degree days, are: Vienna (Austria) 4.9 °C, Stockholm (Sweden) 2.3 °C, Amsterdam (The Netherlands) 6.5 °C, and Helsinki (Finland) 0.2 °C. Appling these ambient temperature levels to a heat source with 100 °C, the exergy content would differ by less than 1.7%. Considering the fact that the supply line temperatures are varying themselves and that within the selected countries different climate zones exist, we set the reference temperature to $T_0 = 273$ K (0 °C). Yet, to present the effect of a varying dead state, Table 1 includes the specific exergy content of the analysed energy carriers also for the reference temperature levels of ±20 °C.

Based on the Eq. (1) and the assumptions presented above, we estimate overall values for the highest exergetic efficiencies converting the energy carriers into the desired forms of final energy. As described above, we are using these values as "in practice usable" exergy (i.e. exergy content minus unavoidable losses due to temperature limitation).

2.2. Model framework

Methods and approaches from energy economics and from energy accounting are combined to compare consumer prices and exergy content. Combining these two approaches, we believe, leads to new and interesting insights into the extent to which current energy market prices take into account the exergy content of energy carriers. In doing so, we consider the following critical aspects to this approach:

- The comparison of the analysis in different countries is not straightforward, given the differences in climate, housing stock, adopted technologies and economic conditions. A brief overview of these parameters is given in Section 2.3. We then define a characteristic building type along with common heating systems using different energy carriers to be compared in the analysis.
- Energy related taxes on energy carriers differ in each country and have considerable impact on the outcome of our analysis. Therefore, within the cases prices with and without those taxes are distinguished. However, our figures do not include value added tax (VAT) as it is always placed on top and has no impact on price comparisons within a country.
- Energy prices have shown considerable volatility within the last few years. While price volatility has not been the same for all energy carriers, the level of energy prices strongly affects the ratio of capital to energy costs. We are aware that the reference year for energy prices is of crucial impact as a parameter. In order to not reflect on the strong price volatility of the years 2007 and 2009, the energy price levels of the year 2005 are used in all investigated case studies.

2.3. System boundaries and monetary costs of heat generation

The core idea of this paper is to examine the trade-off between two basic inputs: an energy carrier with its exergy content and the technology for converting it into the required energy service. This trade-off is investigated both from an exergetic, physical point of view as well as from an economic perspective (Fig. 1).

In order to conduct research on the exergy content of energy carriers the system boundaries are drawn around the final consumer, namely a typical reference building for each country. The energy, exergy and financial streams passing through the system boundaries will be analysed. The system boundary has important

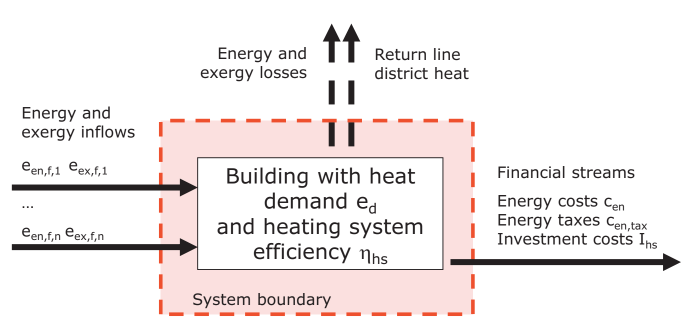

Fig. 1. System boundary used in this work.

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implications on the following analysis. Firstly, upstream energy losses (e.g. in the electricity grid or during electricity production) are not considered. Secondly, all financial streams and the underlying prices and costs are based on consumer prices. Finally, upstream infrastructure (e.g. electricity or heating grids) and its related cost structure are not analysed. We assume that the costs of the infrastructure are incorporated in the consumer prices. For grid connected energy carriers a considerable part of the energy price consists of a base price, which is independent of the actual energy consumption. This base price can actually be understood as an element to take into account the up-front investments into the infrastructure.

2.4. Monetary costs of heat generation

We distinguished between the following financial flows in this article:

- variable price for energy carrier c_{en} excluding taxes
- energy related taxes $c_{en,tax}$ based on the energy tax rate $f_{en,tax}$:

$$c_{en,tax} \quad [€\,MWh^{-1}] = c_{en} f_{en,tax} \tag{2}$$

- total fixed costs C_{fix} (Eq. (3)), consist of
- levelized investment costs of the heating system I_{hs} (€), using the capital recovery factor α. For calculation of the levelized investment costs we used a depreciation time (T) of 20 years (lifetime of heating systems) and varied the discount rate i in a range of 0–10% and;
- annual operating and maintenance costs $c_{O\&M}$ (€/yr), including the annual fixed amounts paid to the energy supply company regardless of the actual energy consumption.

$$C_{fix} \quad [€\,yr^{-1}] = c_{O\&M} + \alpha I_{hs} \tag{3}$$

The total specific heating costs c_{tot} (Eq. (4)) are defined by:

$$c_{tot} \quad [€\,MWh^{-1}] = c_{en} + c_{en,tax} + C_{fix} \quad e_{en,f}^{-1} \tag{4}$$

Subsidies and other promotion schemes also have an impact on the competitiveness and total heat generation costs of different heating systems. In our analysis they could have analogous effects to energy taxes. In order to focus on the key issues we do not take into account the impact of subsidies in this study.

To test the first hypothesis, we measure the variability of the total heat generation costs by calculating the standard deviation σ (Eq. (5)) and the relative range R_{rel} (Eq. (6)).

$$\sigma^2 = \frac{1}{\sum_{j=1}^{Countries} Tech_j - 1} \sum_{j=1}^{Countries} \sum_{i=1}^{Tech_j} \left(\frac{c_{tot,i,j}}{c_{tot,mean,j}} - 1 \right)^2 \tag{5}$$

$$R_{rel} = \frac{c_{tot,max} - c_{tot,min}}{c_{tot,mean}} \tag{6}$$

with average costs $c_{tot,mean,j}$ within a country j:

$$c_{tot,mean,j} \quad [€\,MWh^{-1}] = \frac{1}{Tech_j} \sum_{i=1}^{Tech_j} c_{tot,i,j} \tag{7}$$

2.5. Final exergy consumption and overall exergy factor

For the second hypothesis, we look at the relation between the exergy input and the share of the energy related costs $c_{en} + c_{en,tax}$ on the total heating costs c_{tot}. For our analysis, we define a parameter i_{ex}, the overall weighted exergy factor (Eq. (8)), which represents the ratio between all annual incoming exergy and energy flows considered in the building and its heating system (e.g. including ambient energy for the case of heat pumps).

$$i_{ex} = \sum_{i=1}^{n} e_{ex,i} \left(\sum_{i=1}^{n} e_{en,i} \right)^{-1} \tag{8}$$

The annual exergy content $e_{ex,i}$ is based on the energy demand $e_{en,i}$ and the energy carrier specific exergy content shown in Table 1. The annual final energy demand $e_{en,i}$ for heating is defined by the heat demand of the building and the efficiency of the heating system.

3. Case studies

3.1. Analysed data

Our analysis uses data from Austria, Finland, The Netherlands, and Sweden. These countries show large similarities regarding the physical quality of buildings, energy consumption per capita, gross domestic product per capita. In contrast there are differences in climate, heating system traditions and building stock. In view of the above-mentioned objectives, data for these countries can be seen to provide a robust base for a first comparative analysis.

3.2. Austria

For our analysis we selected a common single family house (150 m^2 gross floor area) with an annual heating energy demand of 20 MWh resulting in a specific energy demand of 133 $kWh\,m^{-2}\,yr^{-1}$. This corresponds to a single family house of the construction period 1981–1991 or an older building after related thermal renovation measures. About 40% of single and double family houses in Austria are equipped with an oil heating system, followed by 32% using a biomass based system (mainly wood log). In this buildings segment, gas holds a share of 15%, DH 6%. In the remaining buildings mainly direct electric heating and heat pumps are used for space heating purposes (Statistic Austria [23], own calculation). For the Austrian case study we selected the following heating systems: district heating, heat pumps (air/water; brine/water), biomass heating systems (based on wood log or wood pellets), fossil based heating systems (gas, oil), and direct electric heating.

3.3. Finland

The data for the Finnish example building are based on the norm house as it is defined by the Finnish government energy efficiency promotion corporation Motiva in its heating energy calculator. The building represents a typical contemporary Finnish single-family house with a gross floor area of 147 m^2 and an annual energy demand for heating of 20 MWh. This results in a specific heat demand of 136 $kWh\,m^{-2}\,yr^{-1}$. More details are available from Motiva [24]. In single-family houses direct electric radiator heating has the largest share, 44% followed by oil heating (25%) and solid fuels (21%) [25]. In newly constructed single family houses, direct electric heating still holds a share of 40%. The share of heat pumps has risen to 37%, district heat gets a share of 12% [26]. The remaining share is mainly covered by biomass based systems [27]. Therefore the following heating systems were selected for the Finish case study: wood pellets boiler, oil boiler, district heating, heat pumps (air/water, ground/water), direct electric heating, partially storing electric heating.

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Table 2
Energy costs, consumer prices and technology data for the heating systems considered in the case studies.

Austria		Wood log boiler	Wood pellets boiler	Natural gas boiler	Oil boiler	District heat	Heat pump air	Heat pump ground	Direct electrical radiator	Electric storage radiator
Variable energy price	€/MWh	23	29	40	40	31	83	83	83	73
Energy taxes	€/MWh	0	0	5	11	0	17	17	17	17
Investment costs	tds. €	10.7	13.6	10.9	10.3	11.1	11.4	16.4	2.6	3.8
O&M costs	€/a	297	352	202	270	443	233	194	21	30

Sources: Own calculations based on data taken from [31–33]. Electricity and natural gas prices represent average prices throughout various suppliers for an annual energy consumption of 20 MWh.

Finland		Wood pellets boiler	Oil boiler	District heat	Heat pump air	Heat pump ground	Direct electrical radiator	Electric storage radiator
Variable energy price	€/MWh	34	33	31	53	53	53	48
Energy taxes	€/MWh	0	14	2	9	9	9	8
Investment costs	tds. €	12.8	10.6	10.1	7.8	13.7	3.0	4.0
O&M costs	€/a	124	96	43	92	126	64	76

Sources: [24,34,35].

The Netherlands		Natural gas boiler	District heat	Direct electric radiator
Variable energy price	€/MWh	38	50	125
Energy taxes	€/MWh	16	23	42
Investment costs	tds. €	11.9	10.6	3.5
O&M costs	€/a	81	50	13

Sources: [36,40]; based on the different components of typical Dutch energy bills: base fee, metering costs, energy taxes, discount on taxes, administration costs; the electricity price represents a typical mix (20 MWh/yr) of night and daytime tariff.

Sweden		Wood pellets boiler	Oil boiler	District heat	Heat pump ground
Variable energy price	€/MWh	34	38	36	65
Energy taxes	€/MWh	0	32	0	24
Investment costs	tds. €	12.4	10.7	19.8	15.8
O&M costs	€/a	323	215	120	161

Investment costs of central heating systems include boiler costs and the heat distribution costs inside the building (5500 €). Assumed exchange rate: 9.28 SEK/€ (due to high volatility of the exchange rate in the last few years, direct comparison should be made with caution). For electricity and natural gas, the energy price corresponds to an annual consumption of 20 MWh.

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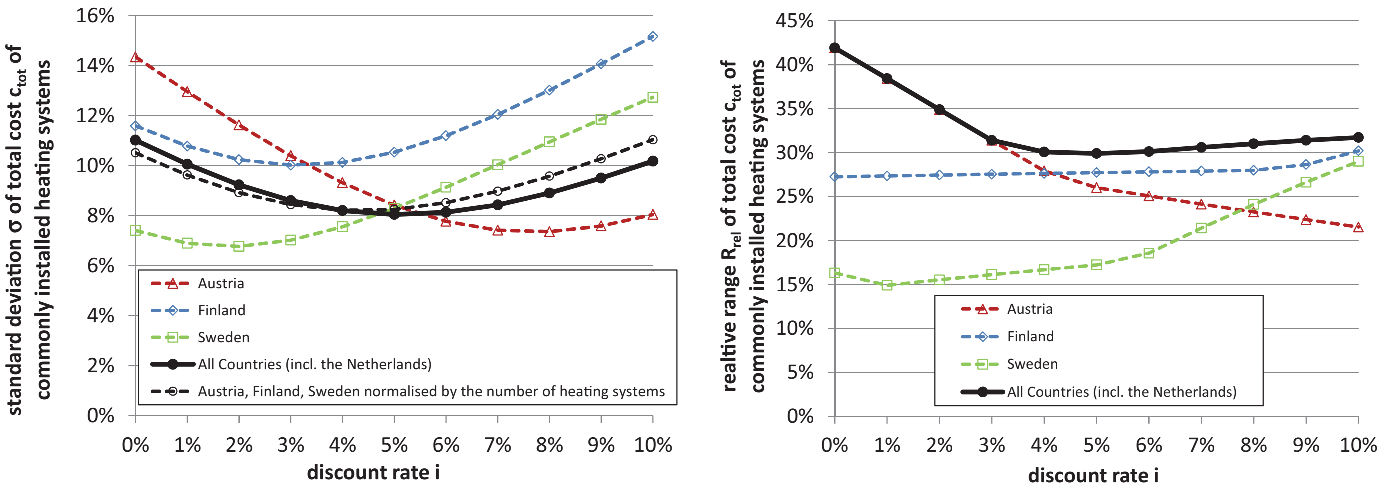

Fig. 2. Standard deviation and relative range R_{rel} of total heating costs c_{tot} of heating systems commonly installed in the analysed building types.

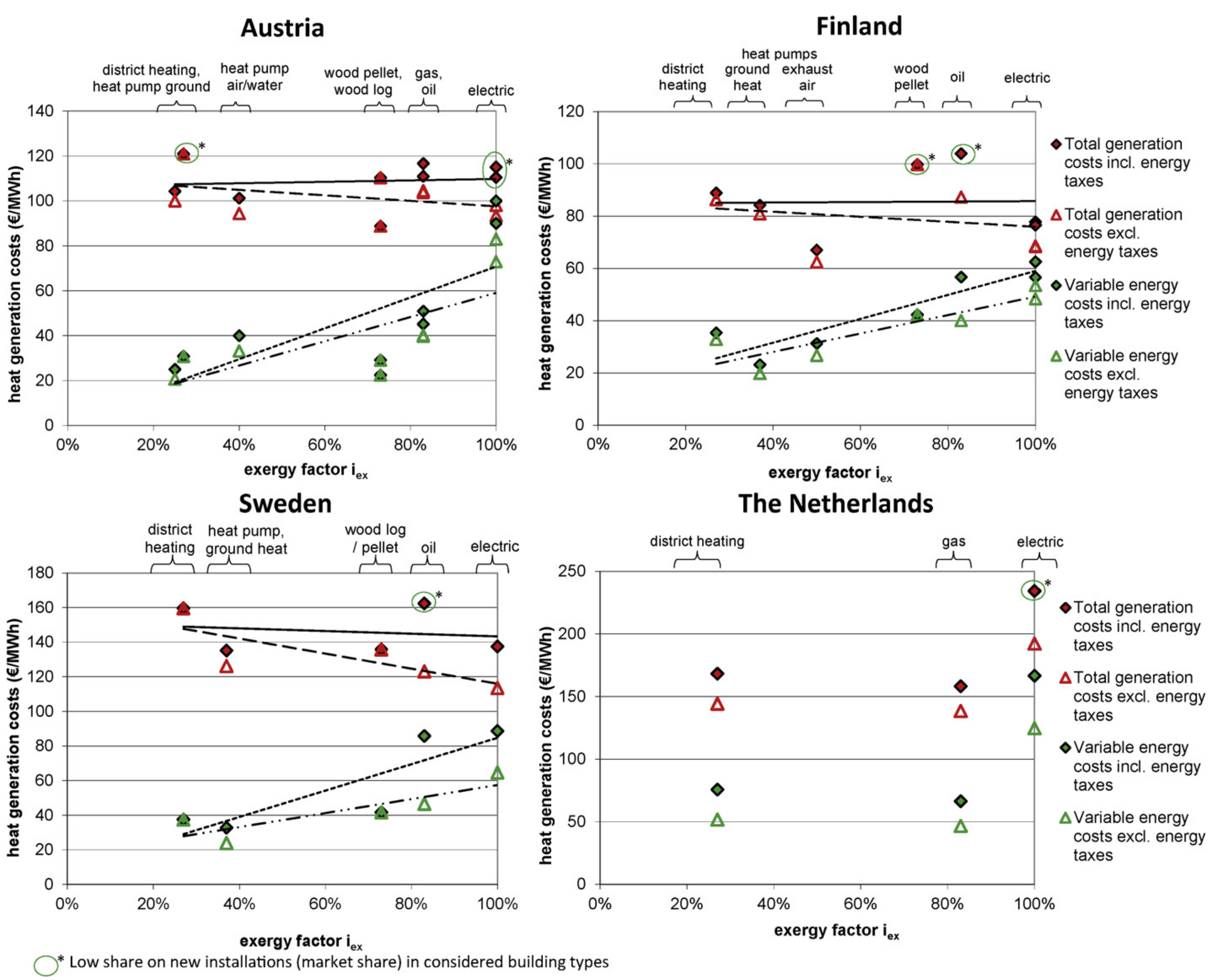

Fig. 3. Components of heat generation costs vs. exergy factor for various heating systems for the countries analysed in this studies, based on a discount rate of 5%.

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3.4. The Netherlands

The Dutch example building is a typical row house built between 1980 and 1988. The houses have in general a gross floor area of 89 m^2, the average annual energy demand for heating of these buildings results to 14.7 MWh/yr, or 164 kWh m^{-2} yr^{-1}. Additional information can be found at SenterNovem [28]. Since the nineteen sixties, the most common energy carrier for space heating is natural gas (∼85%). 10% of all dwellings are connected to district heating; a small fraction of the building stock uses electric energy for space heating. Therefore, the following heating systems were selected for the Dutch case study: district heating, natural gas boiler, electric heating.

3.5. Sweden

The Swedish model building is a standard single family house built in the nineteen nineties with a gross floor area of 140 m^2 and an annual heat demand of 14 MWh/yr (101 kWh m^{-2} yr^{-1}) [29]. In small houses, i.e. one- and two-dwelling buildings, heat is provided mostly by means of biomass (∼30%), heat pumps (∼25–30%) and direct electric heating (25%), while district heating accounts for only 12% [30]. In newly constructed buildings, the shares of direct electric heating (water based heat distribution system) and biomass are in the range of 35%. Heat pumps hold a share of about 20%, DH gets about 8% [29]. Based on this distribution the following heating systems have been selected for the Swedish case study: district heating, oil boiler, wood pellets, direct electric heating, and heat pumps. Despite their common use in previous decades, oil boilers are basically not installed in Sweden anymore. As it holds for Finland as well, the use of natural gas is strongly constrained by the lack of a wide-spread natural gas grid.

Table 2 lists the input data that have been used for the heating systems investigated for our case studies. Prices are averages for 2005; the variable energy prices exclude taxes.

4. Results and discussion

Based on the data shown in the previous section, we calculate indicators to test our hypotheses. To do so, an estimation of the underlying discount rate has been calculated. Empirical studies provide evidence that households do not apply all available cost-effective energy efficiency technologies. Therefore literature often suggests that households use high discount rates in energy-related decisions (see e.g. Feldmann [37]). In contrast, Howarth and Sanstad [38] conclude that 'market failures related to asymmetric information, bounded rationality, and transaction costs are major contributors to the so-called "efficiency gap."' We pursue their line of argumentation. We expect market failures to be small in the area analysed within this paper. This is, because the chosen heating systems, their costs and performances are well known, as they are commonly installed. Furthermore, it was not analysed whether or not a decision to install a heating system had been taken, but if it had been, the kind of technology adopted is of interest. Finally, as all four countries are generally relatively wealthy, availability of capital is not expected to be a major obstacle. We therefore expect the discount rate to be somewhere in the lower range. Based on a depreciation time of twenty years (approximately the lifetime of heating systems), the discount rate has been varied in a range of 0–10%.

Results shown in Fig. 2 support the first hypothesis. The overall costs of well-established heating systems are within the same range in each country. Depending on the discount rate applied, the standard deviation of total heating cost is in the range of 8–11%, calculated based on all countries. The minimal dispersion stems from

Table 3
Statistical dispersion of total heating costs c_{tot} of most common heating systems per country based on a discount rate of 5%.

	Relative range R_{rel}	Standard deviation σ
Austria (excl. district heat and electr. radiators[a])	26%	8.4%
Finland (excl. biomass and oil boilers[a])	28%	10.5%
Sweden (excl. oil boilers[a])	17%	8.3%
The Netherlands[b]	–	–
All countries (incl. The Netherlands)	30%	8.0%
Austria, Finland, Sweden (normalized by the number of heating systems)	30%	8.2%

[a] Low market shares in the considered building types.
[b] Direct electric heating is not common (anymore), district heating: tariff structure based on total heating costs of natural gas based boilers.

applying a discount rate of 5%, resulting in standard deviation of 8%. On the level of the individual countries, this discount rate results in relative ranges R_{rel} between 17% (Sweden) and 28% (Finland). The estimated standard deviation is in a range of 8.3% (Sweden) to 10.5% (Finland), as shown in Table 3.

Yet, these results also suggests that the costs might not be the only decision criteria and others, such as availability of energy carriers, past decisions (tradition), convenience differences, individual preferences and, at least for the case of air source heat pumps, diffusion barriers of new technologies, influence the investment decision as well. Based on a discount rate of 5%, the national results for the total costs and the energy related costs, both with and without taxes, are shown in Fig. 3. The x-axis represents the overall exergy factor as defined by Eq. (8). The y-axis indicates the cost components based on Eqs. (2)–(4). The slope of the corresponding regression lines can be understood as a rough indicator to which extent these components of the heat generation costs are based on the exergy content of the energy carriers.

To test the second hypothesis, the share of investment costs on the total heating costs has been calculated. The results shown in Fig. 4 support the hypothesis that there is a strong relation between investments needed to supply the desired useful heat and the exergy factor i_{ex} of the applied energy carrier or carriers. Major digressions can be explained by taking into account the drawn system boundaries. Since we used the price structure of retail consumers, at least some part of the upfront investments do account for variable energy costs. This is particularly evident for the tariff structure of DH in Sweden and The Netherlands. The

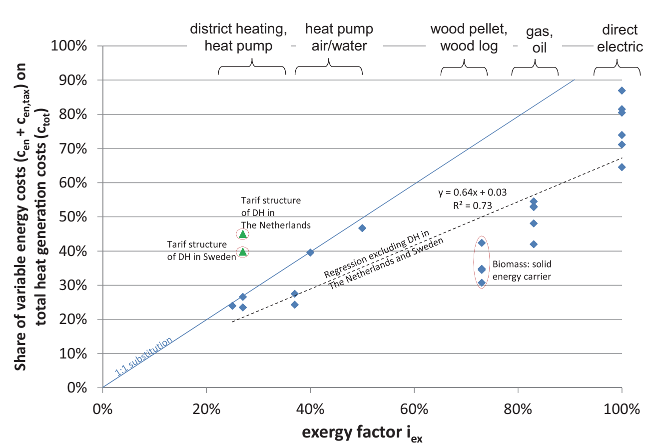

Fig. 4. Share of variable energy costs on total heat generation costs for all technologies and countries analysed.

Netherlands has regulations regarding the maximum consumer price of DH, stating that the fares should not be higher than for natural gas heating. The energy bills of comparable houses and households connected to the gas grid or DH grid should therefore be the similar. Nevertheless, when we regard the exergy factor, due to this tariff system the DH energy price is relatively high compared to natural gas, as initial investment costs are included in the variable cost components. This is the case for the Swedish price data as well. A significant share of investment costs is included in the energy price as opposed to the infrastructure related price components. Another group of outliers are the biomass technologies, especially wood log boilers. Due to the system boundaries drawn in this study, these systems are using a raw energy carrier compared to the other technologies, which again means, that all the necessary purification, ash handling and other comparable processes, which take place upfront for the other technologies, have to be done within the chosen system boundaries and by doing so increasing the investment costs of the installed system.

The conducted regression results in a capital-expenditures-to-exergy substitution rate of 64%. Furthermore, the data support the plausible assumptions that the value and consequently, the energy price of a hypothetical energy carrier with a very low exergy content would be virtually zero. In turn, the effort and value would have to be invested into the heat supply technology.

5. Conclusions

This analysis has shown that the total costs of heating systems widely installed are, compared on a national level, in the same range, resulting in a standard deviation of 8–11%. Furthermore we have shown that there is a close correlation between the specific energy related costs and the average exergy factor of the applied energy carriers. This shows that the lower the exergy factor, the higher the investment and capital needs for making use of this low-exergy energy source.

This can also be formulated in terms of the possibility to substitute exergy with capital and hence reduce the consumption of high-exergy resources by additional capital input.[1] For the cases studied here, this supports the proposition that exergy and capital can be substituted for each other to some extent. Based on the data used in this analysis, we conclude that for the case of current, from an economical point of view, relatively efficient 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.

Several open questions are left for further research. In particular they refer to the following issues:

- extending the sources of energy carriers and systems (e.g. thermal solar collectors and micro cogeneration systems),
- extending the system barrier (e.g. including the capital costs for gas or DH network),
- extending the exergy concept to the exergy needed for an investment (e.g. boiler, DH network, etc.).

The results of this analysis and the proposed approach, as well as further research on this topic, could be used to provide policy recommendations on how to adjust energy carrier taxation as well as other policy instruments so as to stimulate the use of low-exergy carriers to meet low-exergy demands in buildings.

[1] The question, to which extent the material consumption for this additional capital input again implies exergy consumption, is left for further research [39].

Acknowledgements

This publication was enabled by action C24 (www.costexergy.eu) of COST, a European framework enabling international cooperation between scientists conducting nationally funded research (www.cost.esf.org) as well as IEA ECBCS Annex 49 (www.annex49.com).

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Please cite this article in press as: A. Müller, et al., Estimating exergy prices for energy carriers in heating systems: Country analyses of exergy substitution with capital expenditures. Energy Buildings (2011), doi:10.1016/j.enbuild.2011.09.034