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Exergetic and thermo-ecological assessment of heat pump supported by electricity from renewable sources

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ABSTRACT

Heat pumps (HP) represent an attractive option as a heat source, since they utilise "free" ambient heat. However, as they need to be driven by electric energy, their ecological efficiency depends not only on their performance, but also on the energy mix used for electricity generation. Effectiveness of HP can be improved by applying renewable energy sources (RES) providing electricity to drive the system. In order to properly assess such a system, it should be evaluated within a global balance boundary reaching the level of primary resources. The authors propose the use of thermo-ecological cost (TEC) indices for exergo-ecological assessment. TEC is defined as cumulative consumption of non-renewable exergy connected with the fabrication of a particular product. TEC also includes additional consumption of non-renewable natural resources which results from the necessity of compensating environmental losses caused by rejection of harmful substances to the environment. Within the paper, a HP system has been analysed from the ecological point of view. The system consists of a heat pump driven by electricity, and photovoltaic panels or wind turbines as a basic source of electricity. The balance of electricity demand for HP is complemented by electricity from grid. To evaluate this system, real environmental data on solar radiation, wind and ambient temperature deciding on heat demand have been taken into account. The authors present the ecological benefits resulting from supporting heat pumps by electricity generated in RES. It has been demonstrated by comparing results obtained within local and global balance boundaries, that the second approach should be consequently applied when systems based on a mix of renewable and non-renewable energy are analysed, since the first approach may lead to misleading conclusions.

1. Introduction

The need to apply a rational management of natural resources, as well as the necessity to achieve the energy and climate goals set by the EU for 2030 [1] require the application of more sustainable energy transformation systems [2,3]. The use of renewable energy sources is a key solution to achieve these goals. Heat pumps (HP) represent an attractive option as a heat source, since they utilise "free", renewable ambient heat. However, as they need to be driven by electric energy, their ecological efficiency depends not only on their performance, but also on the energy mix used for electricity generation. The effectiveness of HP can be improved by applying a renewable energy source (RES), such as photovoltaic panels (PV) or wind turbines (WT) providing electricity to drive the system. Due to the random character of operation of renewable energy technologies, the balance of electricity demand for HP should be complemented by electricity from the grid. In other words, the mix of electricity supplying HP consists of non-renewable and renewable energy sources. For the proper assessment of thermodynamic and ecological effectiveness of such system, some advanced thermodynamic tools have to be applied from the range of system analysis [4]. First of all, exergy analysis has to be applied to evaluate different quality of energy carriers. Exergy [5] is the maximum ability of an energy carrier to perform work in respect to the common environment or the minimum theoretical work required to obtain the substance with given parameters and composition.

Cooperation of renewable sources of electricity with heat pumps is widely studied in the literature. For example, in Ref. [6] authors performed calculations of a solar assisted geothermal heat pump a and small wind turbine systems for heating agricultural

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and residential buildings, while in Ref. [7] authors investigated optimal control of a wind–PV-hybrid powered heat pump water heater. Similarly, in Ref. [8] or [9], a standalone wind power driven heat pump with battery electric energy storage was studied. However, no exergy or similar analysis has been performed in these studies. In Ref. [10], a heat pump supported by wind turbine is assessed from techno-economic point of view. The authors calculate the exergy efficiency of such system, which turns out to be rather low. Similarly, in Ref. [11], authors analyse a rooftop wind solar hybrid heat pump system for buildings. The expression to calculate the exergy efficiency of the system contains exergies of both "renewable" electricity and electricity supplied from the grid, which obfuscates the results from the global (ecological) point of view. In order to compare the ecological effectiveness of such systems, CO_2 emissions or elements of Life Cycle Assessment [12] are usually used.

While direct energy or exergy approach is enough to compare systems using the same source of energy, in case of comparing various heating systems, rather than using exergy analysis in a local balance boundary, the balance boundary should be extended to reach the level of extraction of natural resources from nature, as proposed in Ref. [13] or [14]. In addition, as direct exergy analysis fails to show the exergetic results of interactions between system components, complex energy systems should additionally be analysed with the tools offered by Thermo-Economic Analysis (TEA) [15–18]. The analysis should be further supplemented with a common indicator of non-renewable natural resource quality. Szargut [19] extended the exergy analysis from a single process to the whole production chain by proposing a concept of cumulative exergy consumption, and subsequently he extended this concept to Thermo-Ecological Cost (TEC) [5,20,21], which applies exergy analysis to address environmental problems as well. TEC expresses the cumulative consumption of non-renewable exergy of natural resources burdening the fabrication of any useful product [20]. Szargut's method (in contrast to other methods of ecological assessment, which represent environmental impacts as a series of independent indicators such as ozone depletion potential, human toxicity, acidification or global warming potential [22]), can bring all environmental impacts into one measure which is the exergy of consumed natural, non-renewable resources. The TEC method fulfils the requirement of life cycle assessment; moreover, the minimization of TEC [21,23] ensures mitigation of the depletion of non-renewable resources.

Within the paper, a heat pump system in a typical family house has been analysed from the ecological point of view. The system consists of a heat pump driven by electricity, and photovoltaic panels or wind turbines as a basic source of electricity. The balance of electricity demand for HP is complemented by electricity from grid. To evaluate this system, real environmental data on solar radiation, wind and ambient temperature deciding on heat demand have been taken into account. The thermo-ecological cost (TEC) has been applied for exergo-ecological assessment. The main aim of the paper was to prove, by comparing results obtained within local (direct exergy analysis) and global (system exergy analysis) balance boundaries, that the second approach should be consequently applied when systems based on mix of renewable and non-renewable energy are analysed.

The main section of this paper is organised as follows. Firstly, the fundamentals of exergy cost and thermo-ecological cost are explained and the values used in further calculations are adduced. Then, the studied case is described and simulation of work of the analysed system for the whole year is carried out. Finally, exergy and TEC analyses are performed and results of both of them are compared.

2. Fundamentals of exergy cost and thermo-ecological cost analysis

Exergy cost and Thermo-Ecological Cost (TEC) analyses are based on the concept of exergy cost, which in general is defined as [20,24,25]:

$$k_j^* = \frac{B_j^*}{B_j} = \frac{b_j^*}{b_j} \tag{1}$$

where:

B exergy flow, kW
B^* cumulative exergy flow, kW
b specific exergy, kW/unit of mass

The dimensionless cost k^*_j expresses the total cumulative exergy expenditures of resources required to obtain the specific exergy b_j of j-th useful product. The cumulative exergy cost is higher than the local exergy cost expressing the specific exergy consumption *loco* considered process. The higher is the exergy cost, the less favourable is the analysed system or component from the point of view of saving the natural resources.

The most important condition during the cost calculation is the definition of a balance boundary. In the presented paper, two cases are compared to demonstrate this importance. The first possible boundary comprises only the analysed system. Such formulation is acceptable from the point of view of TEA analysis. In TEA, the following presupposition to determine the exergy cost of external resources is commonly used: "*The exergy cost is relative to the resource flows. In the absence of external assessment, the exergy cost of the flows entering the plant equals their exergy. In other words, the unit exergy cost of resources is one.*" [18,25]. Hence, in the classic TEA $k^*_{ext} = 1.0$.

In the case of systems driven by a mix of non-renewable and renewable resources, this assumption is not correct and can lead to misleading conclusions [4]. In such a system, the boundary has to be extended and reach the level of natural resources. Moreover, the analysis should be based on the concept of thermo-ecology. In this approach, the exergy cost of non-renewable primary resources $TEC_{ext} > 1$, while for renewable primary resources $TEC_{ext} < 1$. This takes into account the fact, that harvesting renewable energy does not deplete its resources [26].

The fundamentals of TEC analysis are explained in the next part of this section. Additionally, the analysis for the investigated system has been performed for both approaches to demonstrate the possibility of drawing misleading conclusions due to a wrong definition of the balance boundary. Both analyses require the information about the specific exergy of all flows involved in the system.

The TEC (Thermo-Ecological Cost) proposed by Szargut [5,20] is an evaluation tool applied to measure the efficiency of management of natural resources. It combines a cumulative calculus and exergy as a resource's quality indicator. TEC of a product, fulfilling the rules of exergy cost theory, is expressed in units of exergy per unit of product, and is defined as the cumulative consumption of non-renewable natural resources burdening this product, increased by a supplementary component accounting for the necessity to abate or compensate the negative effects of rejection of harmful wastes to the natural environment [20,23,27]. The value of TEC can be calculated from a balance of cumulative non-renewable exergy consumption. The total value of TEC_j burdening the products of the j-th process results first of all from the direct consumption of non-renewable exergy supplied to the process. TEC_j results also from the