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Heiselberg, Per Kvols

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Addressing Different Approaches for Evaluating Low-Exergy Communities

Sabine Jansen[#1], Forrest Meggers[*2]

[#]*Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Architectural Engineering + Technology, Julianalaan 134, 2628 BL Delft, The Netehrlands.*

[1]s,.c.jansen@tudelft.nl

[*] *Princeton University, School of Architecture & Andlinger Center for Energy and the Environment, Princeton, NJ, 08544, USA*

[2] *fmeggers@princeton.edu*

Abstract

The IEA Annex 64 focusing on low-ex communities aims at the improvement of energy conversion chains on a community scale, using exergy analysis as the primary evaluation mode. Within this Annex the participants discuss important aspects and available methods for energy and exergy assessment as well as the added value of aiming for low exergy (LowEx) communities. The reason to exploit the exergy approach is that it provides critical insight into how the maximum potential of energy resources can be used, resulting in a reduced need for high quality energy sources. This insight cannot be obtained with energy analysis. However, other aspects play a role when designing an optimal energy system, such as costs or CO_2 emissions. There can be reasons that justify exergy destruction. To address these issues the working definition for the annex is that "a LowEx community is a community for which the energy system is designed in such a way that exergy destruction is minimized, or that all exergy destruction is justified by other reasons (e.g. economic / social, other sustainability reasons)". This paper gives more background on the definition and presents a general overview of exergy analysis of energy systems in the built environment. Different approaches and opinions are discussed, including how these affect the results. The aim is to create a common ground for consideration low exergy systems at the community scale by setting clear precedents for defining evaluation methods, system boundaries, and input classification.

Keywords – exergy, low-ex, community energy system.

1 Introduction

The scope of Annex 64 covers the improvement of energy conversion chains on a community scale, using exergy as the primary indicator. Subtask A is focused on the exergy demand of single buildings as part of multifarious community supply systems. Subtask B provides the necessary framework for exergy analyses of sources and supply within communities through the identification of concepts allowing a flexible supply of different demands with maximal share of local and renewable energy sources.

Exergy analysis provides critical insight into the maximum potential of energy resources. This insight cannot be obtained with energy analysis based solely on the first law of thermodynamics. When exergy losses are minimized, the required input of high-quality resources is also minimized. It can thereby minimize fossil fuel inputs or improve renewable and sustainable systems. However, exergy analysis does not inherently include other objectives such as maximizing the use of renewables or minimizing emissions. This paper presents the discussions of participants in Annex 64 related to the added value of exergy analysis in the context of communities and districts. In particular, we frame in three aspects on how to leverage exergy optimization effectively and discus the independent overarching objectives for sustainable development and greenhouse gas reduction.

1. *Evaluation methods* - Exergy analysis related to other objectives
2. *System boundaries* - The implications of a chosen system boundary
3. *Input classification* - How to treat the difference between renewable and non-renewable resources of exergy

2 Background

2.1 Definitions

When discussing exergy, this paper considers the thermodynamic definition of exergy: Exergy is the maximum amount of work obtainable from a system (or amount of energy) by bringing this into equilibrium with the environment [1]. It is a thermodynamic concept, which quantifies the work potential of a given form of energy. In line with this, 'low-ex' or 'low quality' energy sources refer to sources with a small exergy content relative to the energy content. The exergy factor (f_{ex}) is defined as exergy content divided by energy content.

According to the thermodynamic definition, the work potential is independent of any history of how this energy is produced. In other words: 1 kW of electricity is 1 kW of exergy, independent of whether it comes from solar energy or from a gas fired power plant. To understand the amount of exergy that was needed to produce this kW of electricity, the chain of preceding processes has to be analyzed.

Within the Annex the working definition for a LowEx community is "a community for which the energy system is designed in such a way that exergy destruction is minimized, or that all exergy destruction is justified by other reasons (e.g. economic / social, other sustainability reasons)".

2.2 Basic characteristics of an exergy analysis for communities

Exergy analysis has evolved from a term developed in the 1950's to support a method of thermal plant optimization that minimized entropy generation and systematic losses [1,2] to a wide range of applications for energy system optimization including the building sector [3,4]. An exergy analysis for buildings differentiates itself from thermal plants in the low quality nature of the demand, leading to the term low exergy in reference to buildings. The current IEA EBC Annex 64 focuses on low exergy communities, which is buildt on the previous IEA Annexes at the scale of buildings (Annext 34 and Annex 49 [5,6]). An exergy analysis for buildings considers the chain of energy flows through the various systems and avoids not only direct energy losses, but also losses in quality related to the system temperature, and quantified by exergy. Likewise, an exergy analysis for communities includes consideration of the chain of energy utilization. In a community it becomes even more critical as there are greater opportunities and more systems for potential exchange. The objective can be characterized as one that strives to match a source of energy with a demand for energy of the same quality, resulting in minimization of temperature differences.

2.3 Exergy losses and ideal improvement potential

For each process the exergy content of the input can be compared with the exergy content of the output. When doing this, it will be seen that in addition to the losses revealed by energy analysis, there are is also exergy destroyed; hence, while energy cannot be destroyed, exergy can be. Moreover, in real processes exergy always will, to a certain extent, be destroyed. Only in ideal thermodynamic processes is no exergy destroyed. The essential difference between energy and exergy is the fact that for any process energy input equals energy output, while for exergy input equals exergy output plus exergy destroyed. This is thoroughly explained in many publications [1,2,3,4,7].

The most straightforward way of using exergy analysis is to determine the exergy losses through a chain of processes. As in an ideal system no exergy is destroyed. In a non-ideal system exergy losses represent the potential for improvement. The insight in improvement potential at each step in a basic energy chain can be considered the main added value of exergy analysis.

2.4 Determining an 'exergy efficiency'

The exergy efficiency of a system considers not only the ratio of energy output (or 'product', referring to the utilized output) to energy input, but also the exergy value of the product relative to the exergy value of the input. An extensive review on exergy efficiency definitions is given by Torio et al. [8]. The exergy efficiency (ψ) as used in this paper as well as in many works related to Annex 37 and Annex 49 is the exergy content of the product divided by the exergy content of the input. It can be calculated by multiplying the energy efficiency (η) with the ratio of the exergy factors (f_{ex}), which are the ratio of exergy to energy content, of the output (product) and the input, as shown in equation 1 [1,7]

$$\psi = \frac{En_{product} \cdot f_{ex,product}}{En_{input} \cdot f_{ex,input}} = \eta \cdot \frac{f_{ex,product}}{f_{ex,input}} \qquad (1)$$

The exergy efficiency exposes the fraction of the full potential of an input that is being utilized. Still, it is subject to definitions of the system boundaries and the reference environment outside, so any direct comparisons between exergy efficiencies must ensure that these conditions are the same, as is also discussed in section 4.

3 Evaluation Methods - Exergy optimization related to other objectives such as CO_2 and costs

Exergy is a performance indicator for energy systems, since it indicates how well the potential of resources is being used. But in real systems the final aim is rarely to use the maximum potential of our resources. Other criteria are usually more important such as costs, emissions, environmental impacts etc. Exergy can be linked to these, but is not inherently connected.

Some literature studies have tried to extend exergy considerations to other objectives, as is also mentioned by Favrat et al [9]. The present paper, like [9], takes the approach of regarding exergy according to its thermodynamic definition as described previously, and looking at exergy as one indicator amongst others. The connection to other objectives, such as primary energy or emissions, should be made through the exergy optimization steps. In some cases there can be reasons that justify the destruction of exergy. In order to address these issues, the working definition given in 2.1 is used in the context of Annex 64.

Two examples that demonstrate how other objectives than exergy optimization can play a role connected to, but not part of an exergy analysis, are described below.

3.1 Example 1: Passive House

Passive house buildings have the objective to be supplied by heat from mainly passive gains. The criteria is that the remaining demand for space heating does not exceed 15 kWh/m² on an annual basis. This demand is reduced to such a degree that it justifies an ‘exergy inefficient’ way of producing this small amount of heat, for example with a conventional boiler or with joule heating. Placing a highly exergy efficient but also highly expensive component to supply this small demand could be undesirable. In other words: the total primary energy input needed for a passive house is low due to the maximum reduction of the demand and not due to an exergy efficient energy chain. The passive house is actually an example where the energy objective to reduce heat loss to an explicit level is independent of consideration for upstream sources of heat and potential exergy matching.

An exergy analysis can show how rather than 0.5 m thick walls, a efficient heat pump connected to a low temperature radiant heating system may result in the same primary energy input as the operating passive house [10]. But again, outside the exergy analysis, the cost of the heat pump must be considered in comparison to the use of insulation. Still, underneath these costs, the exergy analysis provides the method for comparing the true effectiveness of each within the chain of energy utilization.

3.2 Example 2: New achitectural laboratory at Princeton University

We are building a new architectural laboratory at Princeton and have used low exergy community thinking. The building is being built adjacent to a larger chemistry research building, which is part of the campus steam distribution system. Often the condensate return temperatures are >°60 C. We designed a radiant heating system in the architectural laboratory that can utilize the condensate from the adjacent chemistry building to provide all the heating for the new architectural laboratory. This does not create the need for additional capacity on the plant. It also increases the performance of the plant turbines by decreasing the condensate return temperature, thereby improving the heat rejection from the turbine engine. Princeton operates with a self-enforced CO_2 tax on projects, and by calculating the avoided emissions after the exergy analysis had shown the opportunity to cascade the systems together, we were able to achieve a higher performance metric than the originally proposed high efficiency natural gas furnace. Still, we must recognize that the fact that the condensate heat is a waste source is not an aspect of the exergy analysis itself. In this case, the waste aspect tells a further backstory as to how the supply integrates with the district heating system, and requires further consideration for the systems boundaries.

4 System Boundaries - The Implications of a Chosen System Boundary

In the context of the Annex 64 a robust discussion has arisen around the need to have clear methods for setting system boundaries for analysis of community systems. In principle, for a complete analysis of how well we are using our resources, the complete energy chain from primary sources (referring to sources as they can be found in nature) to final demand has to be analysed. However, often the aim of analysis is only to improve a certain part of a system, in which case the system boundaries may enclose only a part of the entire chain. For individual buildings, subsystems such as a heat pump may be analyzed component by component using exergy analysis, and the system boundaries may reside inside the building entirely. But in general a more holistic view of the connection to upstream supply is needed to understand the impacts and to make the right design choices.

The necessary step for any exergy analysis is to make a clear definition from outset of the system boundaries. This is especially true for complex community scale systems like the campus described. By clearly fixing the boundaries, alternate scenarios can be explored that use the same framework for the analyses and enable direct comparison of alternatives.

Figure 1 provides an example of how the system boundary can shift interpretations. Considering system boundary 1, the system exergy efficiency will improve when low temperature heating and a low temp district heating will be used. This means the entire system has the *potential* to have a better exergy performance. It does not mean that it *does* perform better than a higher temperature district heating system. Considering system boundary 2, the effect on the entire system is evaluated. If the performance of the cogeneration does not increase as a result of the lower temperature demanded, there is no benefit and also no increase in exergy efficiency of the entire system.

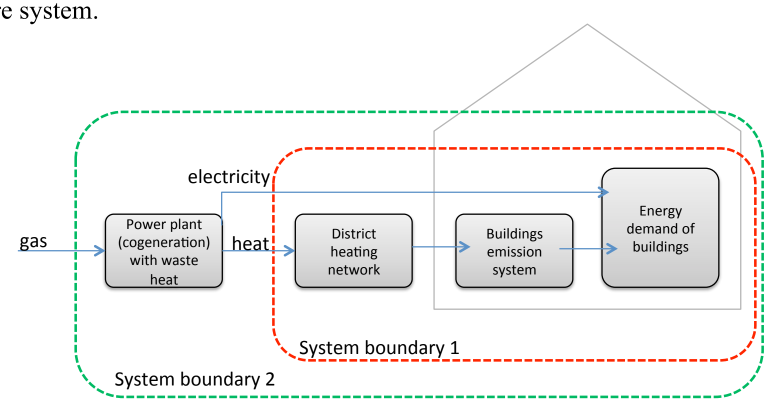

Figure 1: Comparison of two different system boundaries for a cogeneration system.

For system boundaries of exergy analysis one must consider:

- A system exergy efficiency is only meaningful when the system boundaries are clearly defined, particularly in case-studies.
- If only part of the energy chain is evaluated, exergy destruction can still increase outside of the chosen system boundary.
- Once the exergy factor of the input into a defined system boundary is changed, the upstream processes need to be considered. As long as the form of energy and the exergy factor of the system input is

unaltered, an exergy optimization within the system boundaries is valid.

5 Input Classification - Difference between Renewable and Non-Renewable Resources

It can seem easy to claim that exergy is inherently an indicator for renewability, since renewable resources are often freely available. The argument also sometimes mentioned is that exergy destruction of renewables is less problematic than exergy destruction of non-renewables. We would like to disprove this argument by stating that if we want to fulfil all needs with renewable resources, we must also use them to the best of their potential. But even if in some cases exergy destruction of renewables can be justified, we argue that this should not be achieved by artificially classifying renewable resources as low exergy sources, but by adding the indicator of renewability, in line with the discussion under section 3.

Figure 2 shows the chain of exergy utilization for a building and how renewable production can be a key input into the analysis [3]. Still, the analysis itself is independent of whether the exergy flow is from a renewable source, and the primary energy can have a variety of emission factors depending on the upstream source.

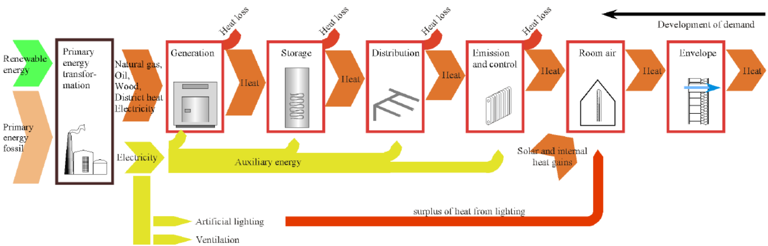

Figure 2: chain of exergy utilization for a building [3].

In other words: It can be the case that an energy system is fully based on renewables, but is exergetically very inefficient. It must be mentioned that this is an advantage of an exergy analysis: it can also be used to maximize the use of the potential of our renewable resources. Hence, in addition to the exergy performance, the renewability is a separate indicator.

Another criteria to classify energy inputs is the ‘storability criteria’. The storability criteria refers to the fact that some energy sources can be stored, such as coal, sensible heat or gas, while other by nature cannot. The latter include for example solar radiation or wind; energy flows that are lost anyhow for utilization once they have not been used directly. These sources need to be converted to a storable form of energy. It is obviously that storable forms of energy have more value in some respect than non-storable forms of energy. However, this value is not equal to the thermodynamic value of exergy (work potential). Also in this case the most logical approach is to consider the storability criteria as an additional classification of an energy input, in addition to its exergy content. Subsequently, it can then be argued that exergy destruction of non-storable forms of energy is more easily justified than exergy destruction of storable forms of energy. This is for example the case when using joule heating in a power to heat solution that makes use of an excess of electricity production, for example from wind energy. But it is still of interest to gain insight in the exergy destruction, since this gives energy systems designers the opportunity to improve their energy systems.

5.1 Example using renewable inputfor domestic hot water

Figure 3 shows two potential configurations for meeting a hot water demand (DHW) with an input of solar energy. In the first case the DHW is directly supplied with a solar thermal collector, providing hot water at 60°C at an energy efficiency of 47.5% (exergy efficiency of 47.5* $f_{ex,out}/f_{ex,in}$ = 47.5*0,15/0,95 = 7,5%). The second option is using the same solar energy to provide the same amount of DHW, but in this case with a chain of solar PV cells and a heat pump.

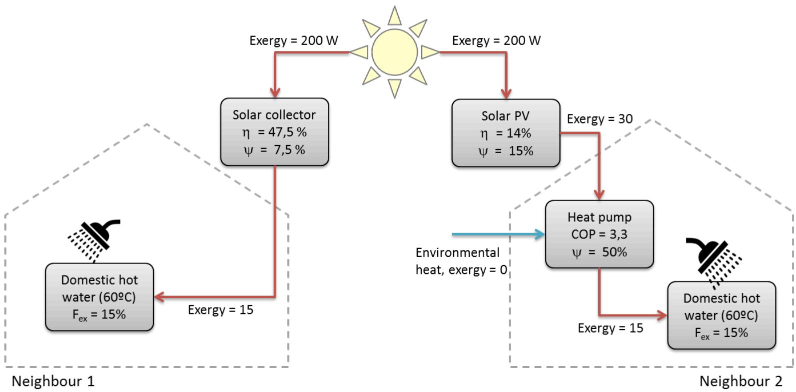

Figure 3: Comparison of two different systems for supplying hot water with renewable input

For neighbour 1 the exergy destruction of renewable (non storable) input would be (200-15) = 185 units. The destruction within the building components is 0 in this simplified example. For neighbour 2 the destruction of renewable (non-storable) input is (200-30) = 170 units. The destruction within the building components is 15 units.

When taking the output from the PV or the collector as the system input (meaning the house represents the system boundary) and neglecting the destruction of renewable input, the system of neighbour 1 seems exergetically better. However, from a total system point of view they are exergetically the same. The system of neighbour 2 is the less optimal option has nothing to do with exergy, but is more due to the use of materials and money. (Even in case the exergy performance of neighbour 2 would be better due to a higher COP for example, material and financial reasons may favour the system of neighbour 2.)

Moreover, this example shows that the added value of the exergy analysis is not mainly to point out the best system, as many other aspects than exergy can play a role, but to point out where either system can be improved. Insight in this improvement potential is also useful for the conversion of renewable energy [10].

5.2 Example of an additional indicator for freely available inputs

In previous work Meggers and Leibundgut [11] extended fundamental exergy analysis and exergy efficiencies to consider the availability of inputs into the system. If the inputs were freely available to the local environment, then they were not considered exergy inputs into the system. At the scale of a whole building, and more so for large communities, local resources like geothermal heat and diurnal cooling of air or mass can be shifted spatially and temporally to within system boundary of the building. There the free resource actually has a physical exergy value. This resulted in the concept of an exergy utilization coefficient, which incorporates an element of input classification as an additional layer to qualify the basic exergy analysis.

Here the exergy analysis still provides the underlying comparison of the value of heat in the boiler of Figure 3, but an additional evaluation of some of the inputs helps to characterize the system better in the context of the value, impacts, and relevance of the inputs. Renewable energy inputs can easily be classified as freely available and locally dispersed. Humanity's objective is to simply attempt to get as much as we possibly can out of those higher quality flows before they dissipate. Exergy analysis provides the physics to do the analysis on that absolute potential, and additional metrics like the exergy utilization coefficient can help classify the inputs.

6 Conclusions and recommendations

In summary, we conclude that exergy analysis as a thermodynamic concept is a useful tool to evaluate and improve energy systems. Exergy optimization leads to a minimization of resource input, which supports other objectives such as reducing costs and emissions. However, as extensively discussed in this paper, exergy optimization is not inherently the inclusive of these other objectives and should be viewed in conjunction with other evaluation methods in a final evaluation. Furthermore, examples are given to show how the choice of system boundaries can influence the results, since the classification of system inputs and inclusion of additional indicators are closely related.

It is requisite in exergy analyses to clearly describe the system boundaries to contextualize results and to make valid comparisons. At its core, the exergy analysis will always provide the fundamental physical analysis of the system, and through good evaluation methods that define metrics, clearly state system boundaries, and provide effective input classification, a holistic approach can evolve. This will help avoid problematic conflation of “Low Ex” with “renewable” or “sustainable.” Rather, we can allow those external aspects to be informed by results from exergy analysis while remaining methodologically independent. This aim is supported by robust considerations and clear protocols being developed for analysis of low exergy communities in the Annex 64.

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