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Thermodynamic entropy as an indicator for urban sustainability?

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Abstract

As foci of economic activity, resource consumption, and the production of material waste and pollution, cities represent both a major hurdle and yet also a source of great potential for achieving the goal of sustainability. Motivated by the desire to better understand and measure sustainability in quantitative terms we explore the applicability of thermodynamic entropy to urban systems as a tool for evaluating sustainability. Having comprehensively reviewed the application of thermodynamic entropy to urban systems we argue that the role it can hope to play in characterising sustainability is less general than has been suggested in the past. We show that thermodynamic entropy may be considered as a measure of energy efficiency, but must be complimented by other indices to form part of a broader measure of urban sustainability.

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Keywords: entropy; sustainability; thermodynamics; city; indicators; exergy; second law

1. Introduction

The notion of using thermodynamic concepts as a tool for better understanding the problems relating to "sustainability" is not a new one. Ayres and Kneese (1969) [1] are credited with popularising the use of physical conservation principles in economic thinking. Georgescu-Roegen was the first to consider the relationship between the second law of thermodynamics and the degradation of natural resources [2]. Despite the controversial nature of

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Georgescu-Roegen's work, the idea that the second law, in particular the concepts of entropy and exergy, can be successfully utilised to better understand sustainability remains prominent in the literature [3-8].

Cities are highly complex dynamic entities. They form thermodynamically open systems which facilitate huge flows of mass and energy both within the urban system itself, and across its boundaries. They are also responsible for around 75% of global resource consumption, 50% of global waste, and 60-80% of global greenhouse gas emissions [9]. Work by Wolman [10] and others in the study of urban metabolism has emphasised the similarities of cities to living organisms. This thinking naturally leads to the analogy of thermodynamic dissipative systems which maintain their structure through the constant dissipation of entropy [6, 11-13]. Thermodynamics if properly applied can thus have great potential to bring physical rigour and understanding to the impact our cities have on the environment within the upcoming paradigm of sustainability science. But can it be properly applied? Such a complex system as a city is after all very different from an ideal thermodynamic scenario.

In this work we present a review of the literature, identifying where and how thermodynamic entropy and the second law of thermodynamics have been applied to urban sustainability and related concepts. We believe that the relationship of the second law to urban sustainability has not yet been adequately addressed, something which we hope to achieve in this paper.

The term entropy outside of thermodynamics has long been applied in urban contexts, for example, the spatial entropies of Batty [14] and Wilson [15], as well as the Shannon-like entropy measure used as a recycling metric by Rechberger [16]. Whilst these methods present potential avenues and applications of entropy to urban sustainability, they remain broadly separate from the thermodynamic entropy we focus on in this paper.

2. Entropy and exergy

We first present a brief outline of the concepts of entropy and exergy, and their definitions within the thermodynamic literature.

2.1. Entropy

The concept of entropy is fundamentally rooted in thermodynamics, specifically the second law of thermodynamics, which Clausius stated in 1854 as: "heat cannot by itself pass from a colder to a warmer body" [17]. This law tells us that all real processes are *irreversible*, capturing what Eddington described as the "arrow of time", something hitherto absent from classical physics. The Second Law describes what we know from experience, but how do we quantify the notion of irreversibility?

For a thermodynamic process, the quantity of heat, Q, absorbed by a system depends on the path the process takes from the initial state of the system A to the final state B. Clausius showed however that division of Q by the temperature T at which the heat is supplied, produces a quantity which is path independent, depending only on the initial and final states, he called this quantity entropy, S. The change in entropy of the system being heated is thus given for a reversible process by:

$$\Delta S = S_B - S_A = \int_A^B \frac{dQ}{T}. \tag{1}$$

For a reversible process the total entropy change of the universe is zero, since the entropy gain of the system being heated is equal to the reduction in entropy of the system from which the heat is transferred. In an irreversible process, work is lost resulting in an additional production of entropy. Thus for an irreversible process, the total entropy change of the universe is always positive. This is a restatement of the second law, sometimes known as