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Perspective Essay

The low-entropy city: A thermodynamic approach to reconnect urban systems with nature

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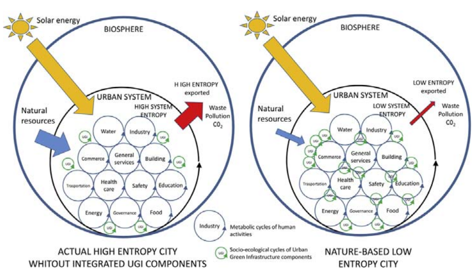
GRAPHICAL ABSTRACT



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ABSTRACT

Starting from the literature regarding the thermodynamics of open systems, the circular economy of Nature and complex socio-ecological systems, we propose a new boundary concept of a low-entropy city as the grounds on which to build actions and political strategies aimed at increasing urban sustainability.

A low-entropy city is defined as a responsive and conscious autopoietic human sociocultural niche that evolves and grows, enhancing its socio-ecological and structural complexity (reducing internal entropy) by adding and optimizing functional elements and synapses among those elements, while wastes (exported entropy to the biosphere) are minimized.

In particular, the low-entropy city concept is explored considering the role of Urban Green Infrastructure (UGI) in reducing city entropy. Following an analysis of the literature and applied research on UGI, the second law of thermodynamics and urban planning, a seminal nature-based planning strategy for low-entropy cities is presented. With appropriate adaptations, the strategy is applicable to all cities, despite the fact that urban systems can have different levels of UGI efficiency, different approaches to sustainability, and different demands for services as well as pressing environmental, social and economic issues. Some new entropy indicators are then presented, based on low-entropy city principles and two exemplificative urban evaluations based on these indicators are examined: urban storm water management and social degradation.

Finally, the low-entropy city concept and its implications in the urban sustainability debate are discussed, considering the possible difficulties that might be encountered when translating it into practice.

1. Introduction

Almost all known physical processes in the universe can be explained by thermodynamics (Ying, 2015), which is probably the most structured discipline for the study of complex systems (Bejan & Errera, 2016). Since the initial works on heat engines within closed and isolated systems, thermodynamic studies have evolved to investigate open systems which are far from equilibrium, such as ecosystems

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(Kondepudi & Prigogine, 2015). Many concepts developed in thermodynamics find applications in other fields, such as ecology and landscape ecology (Cushman, 2015; Gobattoni, Pelorosso, Lauro, Leone, & Monaco, 2011; Ho, 2013; Naveh, 1987), sociology (Mckinney, 2012), economy (Annila & Salthe, 2009; Georgescu-Roegen, 1971; Von Schilling & Straussfogel, 2008), circular economy (Ghisellini, Cialani, & Ulgiati, 2015), industrial ecology (Liao, Heijungs, & Huppes, 2012), organisational systems (Coldwell, 2016) and urban and landscape planning (Fistola & La Rocca, 2014; Leone, Gobattoni, & Pelorosso, 2016; Vandevyvere & Stremke, 2012). The Laws of Thermodynamics have also found applications in architecture and urban design (Braham, 2016; Vallero & Braiser, 2008): see for example the works of Philippe Rahm dealing with air flux dispersal and the consequent climatic and health conditions of buildings and urban parks (Scuderi & Rahm, 2014).

The First Law of Thermodynamics (FLT), also known as the conservation law, states that energy is always conserved across different states. The Second Law of Thermodynamics (SLT), or entropy law, states that during any process, useful energy, also defined as exergy or work capacity, is destroyed and entropy (disorder or waste) is produced. While the FLT focusses on the efficiency of energy transformations, the SLT looks at the direction in which processes are likely to proceed. Indeed, SLT quantifies the irreversibility of processes, providing us with an "arrow of time" of energy conversion and entropy production (Kleidon, 2009; Kondepudi & Prigogine, 2015). In particular, the SLT and the entropy principle provide a theoretical context which could help to a) clarify and unify a wide range of theories and studies, connecting them to fundamental principles of the evolution and functioning of Nature and b) define changes in human-provoked land use and their consequent biosphere alterations to reach the goal of long-term and solid sustainability (Leone et al., 2016).

Several urban planning and governance strategies have been developed to reach sustainability objectives giving social, economic and environmental aspects different weight. Moreover, several epistemologies and approaches have appeared in political and academic discourses with debates among different schools of thought, including, for example, critiques on urban metabolism and urban ecological studies (Bai, 2016; Golubiewski, 2012), and studies on the actual efficacy of proposed actions for the increase in urban sustainability (Premalatha, Tauseef, Abbasi, & Abbasi, 2014; Swyngedouw & Kaika, 2014). Another key point of the urban sustainability debate is the distinction between city and Nature. Following a widely accepted notion, a city is a complex ecosystem with strong human-dominated regulating and governing mechanisms that shape social and ecological processes (Bai, 2016). These mechanisms are partially explained by existing concepts, theories and approaches developed by ecological disciplines. On the other hand, several analogies between human-dominated and natural systems exist and indicators of natural ecosystems can help understand several processes within socio-economic systems such as cities (Bettencourt, 2013; Nielsen & Müller, 2009). Indeed, recognizing cities as part of Nature, i.e., as modified ecosystems, instead of mere human products, may impact the study of ecology in and of cities, and account for the metabolic footprint of urban areas on the whole biosphere (Pincetl, 2012). Finding a key to understanding both Nature and the nature of cities and linking them to global sustainability is therefore a challenge which will require the development of transdisciplinary integrative frameworks between different approaches (e.g. urban ecology and urban metabolism studies) and criteria (e.g. ecological, socio-economic and also architectural). At the same time, Nature in cities, also represented by so-called Urban Green Infrastructure (UGI), plays an important role in delivering a wide range of ecosystem services allowing improvements to quality of life and urban resilience (European Commission, 2013).

Despite numerous studies on thermodynamics, few papers present explicit spatial methods based on urban entropy aimed at supporting practical urban planning (Balocco & Grazzini, 2000; Filchakova, Robinson, & Scartezzini, 2007; Fistola & La Rocca, 2014). To our knowledge, only one work presents a spatial UGI planning based on thermodynamics, though it does not explicitly consider SLT (He, Shen, Miao, Dou, & Zhang, 2015).

In this essay, starting from the literature on the thermodynamics of open systems, we propose a new boundary concept of city (the low-entropy city) as the grounds on which to build actions and political strategies to increase urban sustainability. In particular, the role of UGI in reducing city entropy is explored and a new nature-based planning paradigm for low-entropy cities is presented. The paper is structured in sections: Section 2 illustrates the proposed concept of low-entropy city, while Section 3 describes UGI's potential role within SLT. Section 4 then reports a first low-entropy strategy and new entropy indicators with the aim of operatively supporting UGI planning. Finally, we discuss the low-entropy city concept and its implications in the urban sustainability debate, considering possible difficulties which might be encountered when translating it into practice.

2. The low-entropy city concept

The Laws of Thermodynamics have been identified as the driving force of urban systems' growth by several scholars with increasing consensus from the scientific world (Bristow & Kennedy, 2015; Gobattoni et al., 2011; Marull, Pino, Tello, & Cordobilla, 2010; Prigogine, 1997; Rees, 2012; Rees & Wackernagel, 1996). Furthermore, while economic growth has been correlated with urban development (Glaser, 2011), thermodynamics has been recognized as an essential driving force of economic growth theories (see Herrmann-Pillath, 2015). Indeed, every organism, population and ecosystem, cities included, can be seen as a thermodynamically open system, which grows and evolves, depending on its metabolism. Each system attempts to reduce the energy gradient applied to it, using all the available physical and chemical processes to consume free energy and the available physical and biological resources generated by the sun and photosynthetic activity (Isalgue, Coch, & Serra, 2007; Kleidon, 2010; Lin, 2015; Rees, 2012). Moreover, social cohesion has always been used to solve problems related to uncertainty and resource scarcity (Tanner et al., 2014). Social systems lead to higher complexity and quality levels by contributing to the overall level of system complexity, further channelling and managing energy fluxes (Fath, 2017). Thus, a city is characterised by a social complexity based on (real and digital) networks of people working for innovation and wealth creation, keeping the city from collapse and thermodynamic equilibrium. Urban growth appears therefore as an inevitable process, subjected to periods of crisis (e.g. shrinking phenomenon, see Haase, Haase, & Rink, 2014) and development, but a necessary and spontaneous evolutionary strategy of a technological society that builds its sociocultural niches and wants to satisfy its needs and optimize its energy consumption (Ellis, 2015).

Cities, like natural ecosystems, are self-organizing far-from-equilibrium dissipative structures because they grow and survive by continuously degrading and dissipating available energy and matter from the biosphere and sun (Prigogine, 1997; Rees, 2012). A City, like any other ecosystem, cannot be a self-sufficient system: it always requires matter and energy from outside the fuzzy urban limits while expelling products and waste to maintain levels of complexity, organization, and functionality (Fath, 2017). In order to persist over time and to evolve, a city should therefore be an autopoietic system, i.e. a system that maintains its identity and autonomy while remaining interactionally open to compensate for the inevitable losses due to the SLT with the help of external energy and material input (Pauliuk & Hertwich, 2015). However, while the ecosphere evolves and maintains itself by only feeding on an extra-terrestrial source of energy, and by continuously recycling matter, cities evolve by feeding on the limited natural resources in the rest of the biosphere and ejecting their wastes (e.g. pollution, heat, CO_2) back into it, often without reuse. Actual cities commonly require and employ high value energy (with a high exergy component, e.g. oil, gas) and release unsustainable, scarcely reusable,