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# Quantifying the Sustainability of Integrated Urban Waste and Energy Networks: Seeking an Optimal Balance between Network Efficiency and Resilience

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**Abstract**

With limited natural resources and infrastructures in urban regions, rapid urbanization is arguably one of the most important challenges to sustainable development. To better tackle these challenges there is an urgent need for the development of new approaches where the integration of different urban infrastructural systems leads to resource savings and synergy. Specifically the development and testing of new modeling techniques emphasizing the network sustainability of integrated urban systems is warranted. Past modeling techniques such as emergy, exergy, and extended exergy analysis highlight the sustainability of the urban ecology from an accounting perspective, however there have been few research inroads in utilizing information indices for urban ecological modeling whereby sustainability from the network perspective is evaluated. This paper proposes a conceptual model for an integrated urban waste and energy network composed of 8 compartment and 28 process flows that may be used in future studies in quantifying the sustainability of the integrated network through an emphases of the network's overall resilience and efficiency.



*Keywords:* Ecological network analysis; Urban ecosystems; Integrated urban systems; Sustainability quantification

## 1. Introduction

The rapid urbanization of the global population may perhaps be viewed as one of the most challenging issues of sustainability in this age, for as while cities continue to be vital centers for economic and social growth they also place significant pressure on the natural environment and threaten its sustainability. To

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better tackle the challenges posed as a result of urbanization, there is an urgent need for the development of new approaches and tools that can be used to analyze the inner dynamics of urban ecosystems. Specifically, there is a need for approaches that can lead to the design of integrated urban systems that are both efficient in utilizing resources and also resilient in response to disruptions.

Recent studies in urban design planning promote system integration where greater optimization and synergy may be achieved through the connectivity of urban infrastructures such as transportation, energy, water, and waste management at various network nodes [1]. Each node in an urban system can be viewed as an opportunity for multi functionality, substitution, looping, and cascading of resources in conjunction to other urban systems; however considering the efficiency and resilience of the integrated system as a whole, the opportunity provided by each node may be limited and a careful analysis is warranted. This paper introduces key conceptual issues in relation to the integration of waste management network with electric power network, in what is called waste to electricity, in an urban region and attempts to investigate the integrated system's sustainability through the employment of information indices through ecological network analysis.

## 2. Urban Ecological Modeling Tools

In their attempt to gain a better understanding of the dynamic functioning of cities, a growing number of researchers are adopting concepts and methods from the discipline of ecological studies in constructing models of an urban ecosystem. The concept of an urban ecosystem is more than mere analogy and in essence an urban entity can be defined as maintaining a metabolic functioning akin to that of biological system whereby the input and output of energy and matter flows can be quantified [2,3]. However, the urban ecosystem, unlike most other organisms, is highly heterotrophic, i.e. it requires highly diverse sources of energy for it's functioning to be flowed into its system from outside. For the purposes of urban ecological modeling, specifically the quantification of the flows of energy and matter, the heterotrophic nature of the urban ecosystem poses a difficult challenge, as this requires the translation of the various processes at hand into a common denominator. In this light, past advancements in the field of urban ecological modeling has seen the application of emergy analysis [4,5] and extended exergy analysis [6,7] in order to unify various flows and evaluate the urban ecosystem's sustainability. These methods successfully highlight the sustainability of the urban ecosystems from a systems perspective, however their definition of sustainability stems from a environmentally accounting perspective through which the network efficiency and resilience of the system is not emphasized.

The introduction of ecological network analysis (ENA), a modeling technique that focuses on the transfer of flows of energy, material, and information between various nodes in a system [8], has come to the attention of researchers in the field of urban ecological modeling. ENA allows the modeling of complex ecosystems from a systems perspective where specifically attention is directed towards the systems ability to direct resources efficiently in maintaining its integrity whilst also maintaining a reserve capacity to meet disruptions to its network of flows. Researchers emphasize that an optimal balance between these two essential and complementary attributes of a network must be reached, i.e. a balance between efficiency and resiliency in the network structure [9,10]. By concentrating on the roles of both efficiency and resilience in the sustainability of an ecosystem, the sustainability of various urban infrastructural networks can be evaluated. Past studies in this vein include the conceptual development of urban metabolic system [11] and also the evaluation of Beijing's water consumption system using information indices [12].

## 3. Waste To Energy Network Model

Given the shortage of land and public opposition to the construction of new landfills, countries are increasingly taking into consideration waste incineration technologies. In addition to eliminating urban waste and reducing the environmental impact of landfills, incineration technologies have the added benefit of generating heat and electricity to be fed back as a resource flow into the city. Nevertheless, incineration technologies also produce green house gases and also require a certain amount of waste flows as input for them to be economically feasible. In an urban waste disposal system, as different processes at each network node transform the waste and allow it to flow to other compartments, the construction of a network-like structure is arguably possible. Here, the sustainability of the network can be quantified using ecological network analysis and employed as an evaluatory tool for the sustainable development of urban waste systems. Given the ability of incinerator technologies to generate electricity, the integration of the urban waste disposal systems and urban energy systems in this network may also be realized. In this light, it is warranted to construct a model of the urban waste and energy networks to evaluate the sustainability of the two integrated networks based on a balance between the efficiency and resiliency of the overall network. Such a model can be valuable in adding to the discussions surrounding planning policies in regard to urban waste and energy networks. Given Japan's advanced status in the use of incineration technologies where 74% of the country's waste disposal relies on incineration technologies, the highest percentage among developed countries, an urban area in the country can be a good case study for the testing and further development of this model.

Based on an analysis of the flows of matter and energy in an urban waste to energy network, a conceptual ecological network model is constructed. This model is constructed of 8 individual compartments. Compartment 1 (i=1) represents the industrial sector; compartment 2 (i=2) represents the household sector; compartment 3 (i=3) represents the agricultural sector; compartment 4 (i=4) represents landfills; compartment 5 (i=5) represents incinerators; compartment 6 (i=6) represents recycling centers; compartment 7 (i=7) represents the electricity generation sector; compartment 8 (i=8) represents the environment which provides the urban area with material energy for processing and also receives unrecoverable wastes and emissions from other compartments within the network. These eight individual compartments are connected to each other in multiple paths to form a dense network structure representing the urban waste to energy network in which various flows of waste and energy exchanges take place. The sustainability quantification method forwarded in information indices through an ecological network analysis can be utilized for this model in analyzing a balanced state between network efficiency and resilience. In this model, 28 ecological pathways can be defined which reflect the transfer of flows among the eight compartments of the proposed network (Fig. 1). In this model ($f_{ij}$) denotes the flow from compartment (i) to compartment (j) and the proposed model can be tested using a city which maintains an advanced waste to energy network.

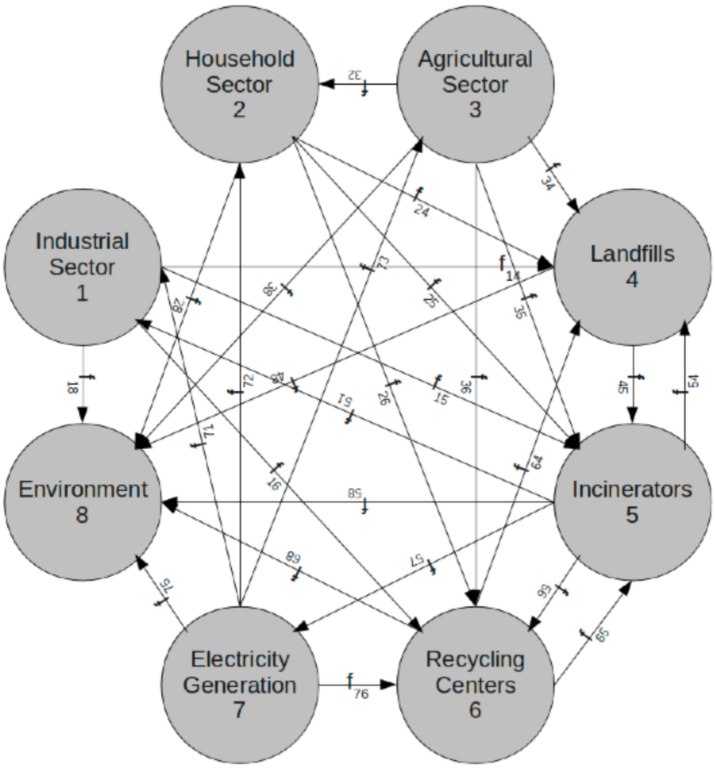


Fig. 1. Ecological flows for the integrated urban waste and electricity network model.

## 4. Conclusion

In this paper a conceptual network model for urban waste and energy network was proposed. The model is composed of 8 compartments, industrial sector, household sector, agricultural sector, landfills, incinerators, recycling centers, electricity generation sector, and 28 ecological flow pathways between these compartments. While past studies on urban ecological modeling have employed emergy, exergy, and extended exergy analysis for evaluating the urban ecosystem's sustainability, however the definition of sustainability in these past studies stemmed from the perspective of environmental accounting where the network sustainability was not emphasized. Recent development from ecological network analysis, specifically concerning the sustainability of ecosystem in terms of the systems efficiency and resilience can be applied in this light to urban metabolic research, especially where the integration of two or more urban systems is concerned. The development of modeling techniques that may evaluate the sustainability of urban systems, especially the sustainability of integrated urban systems, can aid city planners in better confronting the challenges posed by rapid urbanization. The employment of information indices through ecological network analysis may potentially provide valuable insights in this regard and offer the field of urban ecological modeling an opportunity to develop more resourceful policy oriented research.

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