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Transforming cities towards sustainable low-carbon energy systems using emergy synthesis for support in decision making

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HIGHLIGHTS

- Key concepts of present city development trends towards sustainability are examined.
- Emergy synthesis is examined and applied as a tool for policy and decision makers.
- Emergy model of a small city is developed, along with submodels for renewable energy sources and buildings.
- Simulation of 5 different projects shows impacts on overall city sustainability in a comparable manner.
- Increase in emergy sustainability index is confirmed after presumed implementation of simulated projects.

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ABSTRACT

Recognized as implementation actors of operative measures for transition towards a low carbon economy, cities must establish a development roadmap integrating local resources with local energy development plans. A systematic approach does not exist yet and cities develop their plans individually, which is difficult for small and medium sized cities due to limited development capacities. Conventional city planning approaches do not integrate considerations on energy, economy and environment in transition plans in an easily comparable way, yet making decisions with regards to these parameters is vital to determine outcomes of planned developments on future sustainability of the city.

The paper presents a framework model based on emergy synthesis which integrates energy, economic and environmental city systems in the decision making process, examining associated theoretical challenges and application limitations. The method is applied on the city of Sisak in Croatia which has developed plans to implement several initiatives geared towards creating a smart energy city. The model enables simulation and assessment of impacts of individual projects targeting the development of a smart energy city on city sustainability expressed through emergy performance, used as a tool for evaluating local development alternatives within the boundary of local resources.

1. Introduction

The focus on cities as points of mitigating climate change is essential, as the United Nations estimates that already over 50% of the global population lives in cities (United Nations, 2014). Cities occupy only 2% of the Earth's surface but are the point of use of 75% of all resources required for everyday life and generate 75% of all waste (Sudjic, 2008). Crucially, they produce 80% of global greenhouse gas emissions. Sustainable future of the civilization depends to a great extent on changes in patterns of energy use and supply in cities.

Even though the large majority of the urban population lives in medium-sized cities, the main focus of research in sustainable urban development tends to be on the 'global' metropolises. As a result, the challenges of smaller cities, which can be rather different, remain underexplored. Medium-sized and small cities, which have to face the competition of the larger metropolises on corresponding issues, are less well equipped in terms of critical mass, resources and organizing capacity (Lazaroiu and Roscia, 2012). Working within this complex domain, city leaders have a responsibility to take action. A great deal of research and development is being done on sustainable energy systems for cities, under the joint umbrella of terms „smart cities“ or „smart energy cities“ (Lugaric et al., 2010). However, little research and development is done in a manner which would holistically address multiple facets of city transformation. Research institutions, development agencies, and various international organizations address each issue individually in a singular way. For example, public

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and private entities involved with the building sector focus on certain technologies to reduce building energy losses, while others deal with pollution, transportation, environment, or social issues. There is a gap in research being done to integrate already existing studies from various sectors of intellectual activity.

The approach presented in this paper seeks to incorporate important aspects of a development of a smart energy city. Emergy theory is used to integrate three separate concepts – energy, economy and the environment and deliver a model where future effects of decisions made today can be examined in an easy to understand way and will help to gain insight on the transformation of a city towards a low-carbon energy system, highlighting implications of individual developments towards increasing sustainability. The model is targeted at supporting city leaders in navigating the unknown territory of creating a sustainable low-carbon energy system, which in this paper is named smart energy city.

2. Key concepts

2.1. Smart energy city

In a city, most citizens live by performing work in industry, commercial trades and services, in contrast to rural settlements such as villages where most of economic activities is based on agriculture. Developed cities overcame traditional environmental problems such as waste water removal, sanitation, water supply and indoor air pollution. Thus the attention has turned to their impact on ecosystems in the surrounding area. Cities in the developing world are more concerned with other issues, such as inefficient modes of resource use, i.e. in the energy or water supply. For the city as a low carbon system, the point for considerations is the energy mix of a city, both at the supply and demand sides. Globally, the supply mix is still dominated by fossil fuels, which is still valid for all countries in the world (IEA, 2015). If the global consensus on the need for change of this fact will materialize in concrete action, a unified method of comparison of projects targeting the transformation to smart energy cities must be developed and utilized.

Based on these considerations, definition of a smart energy city in this paper is of a city which optimizes utilization of locally available energy resources and makes use of the competitive advantages of a locality to stimulate productivity in resource value chains while promoting sustainable development, in order to reduce its impact on ecosystems in surrounding area.

2.2. City as a low-carbon energy system

According to (Rifkin, 2008; Saifi and Drake, 2008; Yuan et al., 2011) a city which is a low carbon system implements the following 5 fundamental pillars of development in all sectors of human activity in the area which it occupies (city, state, region):

1. Energy efficiency: all energy losses must be either eliminated or minimized in accordance with best available technologies;
2. Renewable energy sources: solar, wind, hydro, geothermal, biomass, ocean waves and tides;
3. Buildings as active consumers: Buildings that generate most of their energy needs from locally available renewable energy sources;
4. Developing smart cities: An integrated effort of improving social, economic, environmental systems in cities, with energy infrastructure transformed first, as an enabler of further developments;
5. Electro mobility: Electric vehicles, deployed as means of transportation but also as energy storage units throughout the city.

When these five pillars come together, they make up an indivisible sustainable development platform – an emergent system, whose properties and functions are qualitatively different than the sum of its parts. Model presented in this paper creates a platform for analysis of impacts of individual projects which stem from these five pillars on sustainability of a city. In this paper, special focus is put on points/pillars 1–3 and point 4 is addressed. Transport presents a separate challenge with regards to emergy modeling, especially as vehicles should be simulated as both modes of transport and energy storage units. This work stream will be pursued in future research and results added as an additional module to the full model presented in the rest of the paper.

From the smart energy city roadmap viewpoint, city transformation towards a low-carbon system can be summed up as shown in Fig. 1.

2.3. Emergy and application to evaluation of system sustainability

Emergy is the available energy of one kind that is used in transformations directly and indirectly to make a product or service (Odum, 1996). Emergy is an extensive function, and its correspondent is the (solar) transformity (abbreviated τ), which represents energy quality and is defined as the solar energy required to make one joule of a service or product. It was originally defined as the ratio of input emergy to output energy and then revised as the ratio of input emergy to output exergy (Sciubba and Ulgiati, 2005) to take into account different abilities to perform work by different energy types. The term emergy may also be considered as "energy memory", referring to the memory of all solar energy used up during a process of making a service or a product.

In the emergy synthesis method a system is considered through diagramming, determining flows of energy, resources and information, performing emergy algebra to determine emergy flows and finalizes with emergy accounting of the observed system. Flows are categorized according to their type and at highest levels of aggregation can be grouped according to the diagram shown in Fig. 2. Non-renewable environmental contributions (N) represent the emergy storage of materials, renewable environmental inputs (R), and inputs from the economy as purchased

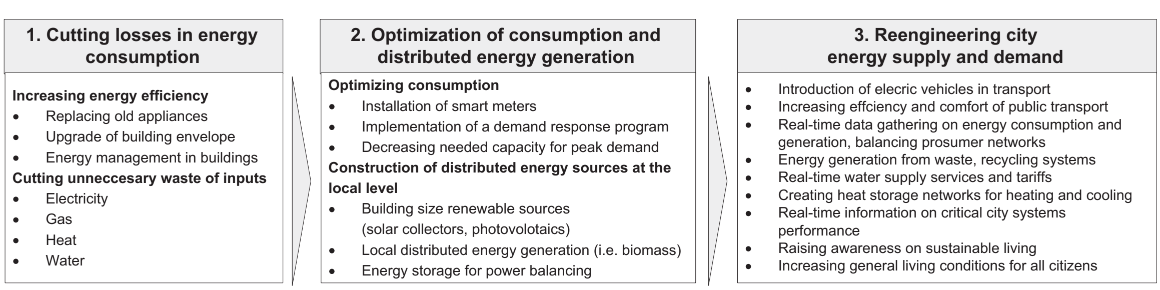

Fig. 1. Three groups of activities for transition to a smart energy city.