Chapter 28

First Step Towards a System Dynamic Sustainability Assessment Model for Urban Energy Transition

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Abstract This paper presents a conceptual model that describes the correlation between an urban energy system and sustainability. The model captures the complexity of the urban energy transition, and the task of achieving sustainable development needs to embrace all aspects of sustainability. This paper portrays the aspects of sustainability as four-dimensional—Environment, Economic, Society, and Technology. The relationship between these four dimensions and the urban energy system is presented in a simplified and aggregated-qualitative based causal-loop diagram. The causal-loop diagram illustrates the causal and interconnective relationships between the four dimensions and their different variables. The causal-loop diagram describes the complex dynamic relationships within a simple urban energy system. The paper also provides a brief description of balancing and reinforcing loops, with the causal-loop diagram present. The conceptual model along with the causal-loop diagrams visually illustrate the dynamic relationship between the four dimensions as well as highlights the complexity and challenging problems that decision-makers are facing today when it comes energy planning and energy system development.

Keywords Energy system · System dynamics · Causal loop diagram · Decision-Making · Sustainability

28.1 Introduction

Today's cities account for 67% to 76% of the global energy consumption and as well as 71% to 76% of the global greenhouse gas (GHG) emission [1]. Majority of energy systems today operate on fossil fuels, fossil fuel resources account for approximately 86% of the total primary energy sources (TPES) in the global energy system. In contrast, renewable energy resources account for approximately 14% of the TPES [2, 3]. Global and local energy systems continue to grow and have become more

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complex over recent years, due to factors such as changes in technology, energy source availability, energy regulation and policies; the environmental impacts of energy development and production have also increased, rising global environmental concerns [4]. Since urban energy systems are still primarily built around using fossil fuel resources for providing electricity, district heating, cooking, as well as public transportation, the global community can still expect to see a growing fossil fuel demand in coming years correlated with an increase in GHG emission [5, 6]. As global trends predict an increased growth in urbanisation, movement and relocation of people from the rural areas into larger community settlements like cities, there is a need to address sustainability issues of energy development, and transition of cities [1].

To achieve an energy transition towards a decarbonised energy system will be challenging as our current social development structure is primarily measured by economic growth, with environmental concerns relegated insignificance [7–9]. In particular, unchecked economic growth may increase the constraints on non-renewable and renewable natural resources and materials in our environmental sphere [10, 11]. In addition, is today's decision-making process, the decision-makers are often affected by "the silo effect", in which a lack of communication between subgroups within an organisation often results in a lack of cooperative decision making [12]. A redesign of the current decision-making process is needed to provide interconnectivity between societal, economic and environmental spheres [13–15].

Modelling and simulation approaches such as Multi-Criteria Decision Analysis, Life-Cycle Assessment and System Dynamics have become widely used to investigate complex issues such as sustainability, climate change and energy transitions to improve decision-making and policy strategies [12, 16, 17]. This paper will provide insight into the early development phase of designing a sustainability assessment model base on system thinking and system dynamics modelling to assess the sustainability of urban energy transition. This paper and its findings aim as well to present insights into the complex and dynamic interlinking relationships between the different aspects of sustainability and energy transition.

28.2 Methods

System dynamics is a method that can be classified as an interdisciplinary, and it applies the theory of system thinking and system structure to investigate complex systems. Researchers have been applying system dynamic modelling to address, understand and define complex and dynamic behaviour, feedback mechanisms, multidimensional aspects and causal relationship of a complex system [16, 18, 19]. A complex system is defined by Mitchell 2009 (p.13) as "a system in which larger networks of components within no central control and simple rules of operation give rise to complex collective behaviour, sophisticated information processing, and adaptation via learning or evolution" [20]. System dynamic analysis is built around

using balancing and reinforcing feedback loops to represent the causal relationship, dynamic feedback and flow pathways within a system in order to identify the dynamics which arise out of these interactions [18, 21]. A Causal loop diagram (CLD) is a tool used in the early stage in system dynamic modelling process to gain visual understanding connection, through using the basic elements of words, phrases, links and loops. By drawing a simple CLD of the problem and the variables within the system become easier to understand the balancing and reinforcing feedback loops and the relationship between different variables, which thereby helps to identify the positive and negative relationships and any potential time delays within the system [22]. A balancing loop describes a relationship that seeks to keep the balance and a stable condition of the system when a change arises by counteracting the effect that leads to balance in the system [21–23]. In comparison, a reinforcing loop seeks to amplify and reinforce changes in the system, which can often lead to exponential growth, which can also leave a negative impact on the whole system [21–23]. The next step is to apply mathematical equations, and computer modelling approaches to describe these feedback loops to be better able to capture and analyse the dynamic elements of this complex system [24–26].

28.3 Results and Discussion

Figure 28.1. presents the conceptual framework of the problem and where the problem of the complexity of achieving a sustainable energy transition is defined in the centre of the conceptual model. The boundaries of the system are defined by the dot-line circle around the four dimensions—Environment, Economic, Society, Technology. These four dimensions represent the metrics sets which are often used and quantified when conducting a sustainability assessment [10, 12, 15, 16].

28.4 System Dynamic Model—Causal-Loop Diagram and Feedback Mechanism

The CLD presented in this paper is a qualitative based model, based on extensive literature review, and derives some of its causal relationships and feedback mechanism from the literature [16, 19, 23]. Figure 28.2 presents a large-scale and abstract CLD view of the evolving system dynamic model and the model's balancing loops and reinforcing loops. This CLD shows the groundwork for a system dynamic model that can conduct a sustainability assessment of energy transition within an urban energy system. The full development of that model will take place in the next steps of the research project.

Fig. 28.1 Conceptual model and boundaries of the modelling system

The balancing loops in Fig. 28.2. illustrate the goal-seeking or stability-seeking causal relationships between the different variable in the model. This causal relationship of the balancing loops is described in the following paragraphs. Balancing loops (3) and (4) show that an increase in energy production will result in an acceleration of overall climate change and the ecological impacts, causing an increase in economic damage of climate change, thereby affecting the investments in energy system development and energy production capabilities.

The reinforcing loops in Fig. 28.2. illustrate the amplifying or self-multiplying causal relationships between the different variables in the model. This causal relationship of the reinforcing loops is described in the following paragraphs. Reinforcing loop (2), population growth increases the number of households requiring energy and energy consumption which grows the energy demand. Growing energy demand,

leads to higher income for the local and national government from energy consumption, giving the local and national governments the opportunities to invest in energy system development that provides an increase in job opportunities, and employment among the population and which increases living quality among the populations.

The delays within the system are presented in Fig. 28.2. by using delays marker, which are represented with two parallel lines. These delays interpret a time delay where a cause leads to an effect that does not immediately have an impact on the system. For example; resource extraction for energy production will over time decrease the resources available for energy production, which then will impact the system abilities to meet the energy demand of the system.

28.5 Future Steps and Conclusion

The conceptual model illustrated in Fig. 28.1 is the basis of the causal loop diagram presented in this paper in Fig. 28.2 and captures the relationship between the three dimensions of sustainability (Economic, Environment, and Society) and the fourth dimension (Technology). The conceptual model and the causal-loop diagram capture and highlight the complex and multi-dimensional aspects of the interconnected relationships existing related to an energy transition within an urban energy system.

The next step in this research will be focused on the following tasks:

- Quantifying the variables presented in the causal loop diagram and expand on the causal loop diagram in more details.
- Make a stock-and-flow diagram based on the causal loop diagram
- Develop a System Dynamic Model using computer software
- Test the system dynamic model using appropriate methods and refine the model to ensure its robustness for assessing urban energy systems sustainable energy transition.

This research is aimed at providing policymakers and academics with a model that can be used to test and simulate the impact and sustainability of future policies in relation to the energy transition.

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