A Framework for Integrated Energy Systems, Infrastructure and Services Optimization with Visualization and Simulation Platform for Low-carbon Precincts

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Abstract: The energy informatics can be enhanced to support decision-making, communication and benchmarking of the energy performance both in design and operational phases. To enable engineers, developers and policy-makers to better understand the implications of energy systems and services, computer-generated visualization is a powerful tool to inform a range of technological options and to analyze the effects of energy system strategies. Visualization increases the transparency of results and the understanding of interactions between users and energy systems. This paper presents a novel conceptual framework for integrating energy systems, infrastructure and services optimization with a visualization and simulation platform. It focuses on the development of a tool for low-carbon energy systems and high quality energy services at precinct scale. The paper describes the vision and architectural design for the integrated framework. It is expected to serve as a next generation approach to managing energy services, carbon emissions and efficient resource use in the built environment. This will help to deliver new environmentally sustainable infrastructure and achieve carbon neutrality in urban development.

Key words: Energy Systems and Services; Low-carbon Precincts; Simulation; Visualization

I. Introduction

There is a growing interest in improving the energy performance of urban areas so that environmental impacts are reduced while maintaining economic competitive capacity and quality of life. In recent years, different cities, local authorities and developers have shown the interest in virtual 3D urban models. Some of the experiments have been applied for applications in urban planning. There is a need for a tool that offers the holistic energy visualizing at the urban district or precinct scale, not only from the building perspective. This will enhance the understanding of the urban energy systems and the analysis of energy competitions between resources and services.

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A number of studies have been done on the development of simulation-based optimization modeling tools for decision-making processes in the area of built environment. However, most of the previous studies are focused on a building scale. As noted by Ref. 5 there is a need for tools that can help to assess and design more efficient urban energy systems. Some existing tools include SUNtool,[1] SynCity,[2] EnerGIS,[3] and DESDOP.[4] Ref. 8 stated that the realization of integrated urban design tools requires advanced multidisciplinary modeling, interoperability of computation models and collaborative research for the optimal integration of energy systems. A brief review suggests that modeling tools can be differentiated according to their contributions and systems (energy, water and land-use) addressed.

This research was motivated by the need to optimize energy systems to achieve a carbon neutral urban development and to visualize the findings in a 3D environment. This paper focuses on the development of an optimization tool for integrated energy systems, infrastructure and services. The integrated platform would offer a next generation approach to assist the design, analysis and evaluation of energy, carbon emissions and resource consumption in the built environment.

II. Conceptual Framework

The framework developed in this research is based on techniques of three domains: building energy modeling; energy systems modeling; and geographical information systems (GIS). The conceptual framework of the research is presented in Figure 1. Urban systems are complex issues, thus a combination of these techniques enables to visualizing the demand of energy services, cost and emission indicators resulting from different system configurations integrating into urban infrastructure. Visualization increases the transparency of results and creates a better understanding of the interactions between different sub-systems. This is expected to provide a means for engineers to handle multiple parameters elements in the planning processes allowing a large number of stakeholders with different interests such as architects, developers, environmentalists, and local authorities, to discuss the issues and to find an optimal solution regarding supplying energy services. It is expected to serve as a powerful tool to support decision-making, performance assessment, communication and benchmarking.

According to Figure 1, building energy performance can be modeled with a variety of building energy performance softwares such as TRNSYS, EnergyPlus, DOE2.1E, IDA ICE.[5,6] Hourly load profiles include demand for heating, cooling, hot water and electricity. GIS is today commonly used tool in urban planning. It has been integrated with energy and environmental models for the development of sustainable urban energy systems.[3,7] In this research, we are developing the energy systems and services optimization model to provide information services integrating with other sub-models within the framework. Therefore, this paper explains briefly the simulation-based optimization energy systems that currently being developed at our division to find a set of optimal combinations.

In designing energy systems, there are often conflicting objectives between different stakeholders involved in the planning process. Thus, we are employing multi-objective optimization techniques to find a set of optimal solutions. For example, typical objectives in the energy systems planning are to minimize the life cycle cost and CO_2 emissions. These objectives

are naturally competitive: the (first) cost of environmentally friendly energy technologies often exceeds the corresponding cost of conventional solutions, at the same time as the energy-efficient technologies may be less environmental friendly than other technologies that are less efficient. The European Energy Performance of Buildings Directive recast targets two objectives: the primary energy consumption and the life cycle cost to be assessed to find the environmental and economic impacts of buildings.[8] Our interest in this research is to maximize exergy efficiency while minimizing the environmental impacts of energy systems.

The solution of the multi-objective problem is a set of non-dominated solutions, known as the Pareto set with the plot of Pareto optimal solutions referred to as the Pareto front. This will give decision-makers the opportunity to assess the trade-off between conflicting objectives. Multi-objective optimization problem can be solved by several optimization algorithms, for example multi-objective genetic algorithms such as NSGA-II (elitist non-dominated sorting genetic algorithm). The algorithms can be solved by either customized or generic optimization tools, for example MultiOpt,[5] MATLAB,[9] DAKOTA,[10] and MOBO.[11]

This research is developed to interface with the MUtopia (www.mutopia.unimelb.edu.au) simulation platform to provide decision-making support, communication and benchmarking of the energy performance of low-carbon precincts. MUtopia is an information technology-based platform tool for supporting the assessment of urban sustainability metrics at different scales. It is an urban design modeling and visualization platform, which displays in 3D the actual appearance of an urban development, It operates in a virtual environment based on 3D geospatial technologies and capable of visualizing inputs (energy, infrastructure and transport) and outputs (such as energy use and carbon emissions). It provides an online visualization platform that represents data and results in 3D environment, including the provision of real-time, effective and high quality visual representations of urban scenes and objects. Thus, MUtopia enables stakeholders from different disciplines to collaboratively test innovative concepts, tools and processes in a single virtual environment (www.mutopia.unimelb.edu.au). The link between energy systems modeling and MUtopia enables the development of strategies for visualizing the energy performance of buildings and precincts. It is expected to serve as a powerful tool for creating a better understanding of the interactions between different sub-systems. It should be noted that the goal of this research is to develop the energy systems and services optimization (multi-objective optimization algorithm) that can be integrated to MUtopia in order to evaluate a set of design variables which provide the optimum solution to supply energy services for achieving a carbon-neutral urban development.
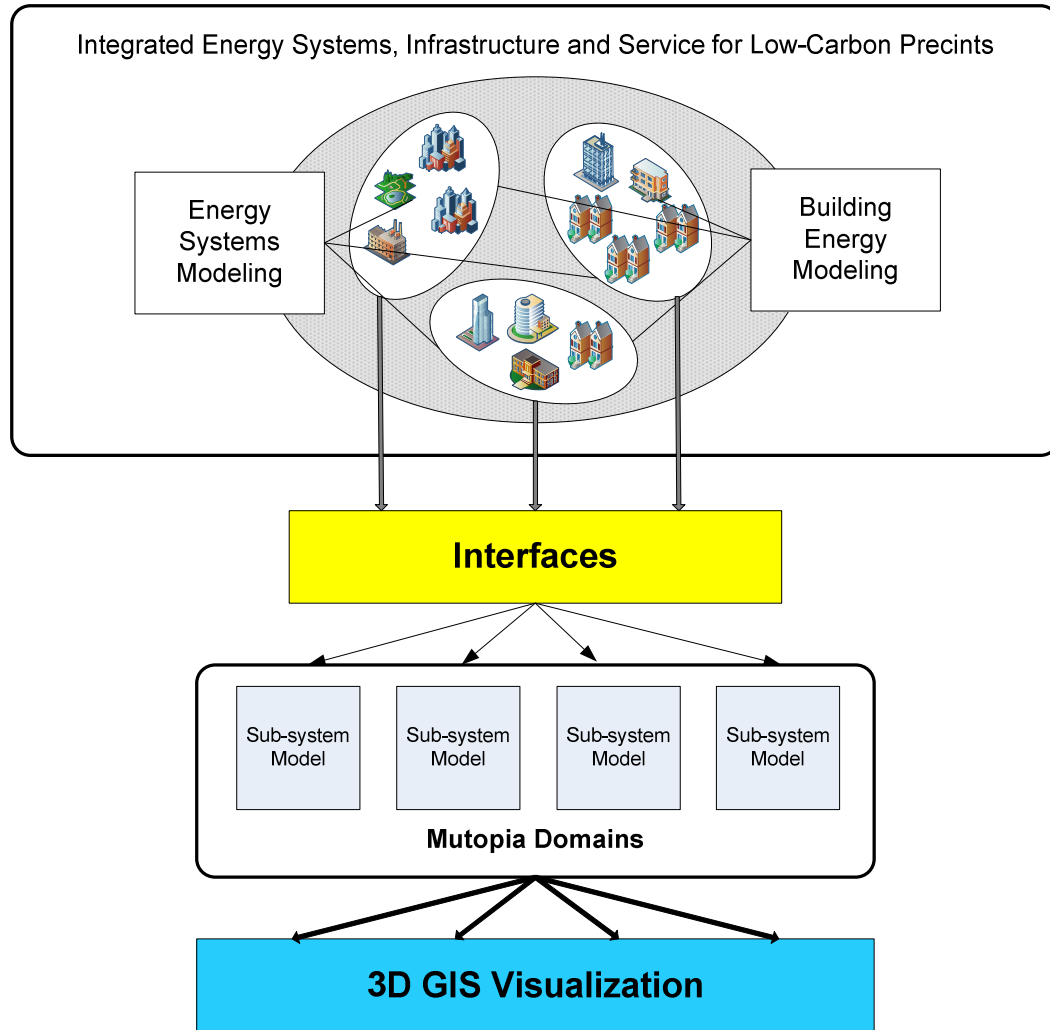
Figure 1. **Conceptual framework of this research**

III.   Steps Toward the Framework Implementation

   Energy systems are connected with different supply technologies to provide building services. Buildings have been the core of built environment research while the interest in 3D geographic tool is growing. By way of demonstration, the framework will be applied to a new urban development project–Albano which is located in Stockholm, Sweden. The purpose of the developed framework is to implement for evaluating and visualizing the results of the energy systems modeling. Albano is a university campus area under in Stockholm, Sweden currently under development to provide approximately 150,000 m^2 of educational and research facilities, housing for students and visiting scholars, and premises for commercial services such as restaurants. The overall goal is for the area to serve as a living laboratory for sustainable urban development in which different innovative concepts can be tested. Albano aims to achieve a neutral balance in CO_2 emissions caused by energy systems by 2030.

   Thus, Albano will be a hypothetical test site. It is expected that all buildings are to be built to passive house standard. The energy system has to supply energy services to meet the demand.

Therefore, it is a vital importance to understand detailed information on local energy demand so as to achieve a satisfying performance of the energy system. The energy systems model requires hourly energy demand profiles for each building as input. The hourly energy demand profiles are obtained through a building energy performance program named IDA ICE (IDA Indoor Climate and Energy).[12] We are interested in a cluster of buildings, so taking one representative building for each of the building type. Then, we create energy load profiles of a representative day for each month and assume that each day in a month follows the same demand pattern of the representative day, consisting of the electricity and heating demand (kW). The demand pattern of a representative day is averaged though that month. Moreover heating is not required during the summer, and cooling is neglected.

The case study will be tested on the question: what is the impact of installing local combined heat and power (CHP) plants in comparison to investing solely in electrified heating? To address this question two scenarios will be modeled and compared to a reference case.

- Reference: conventional energy system, with heating demand from district heating network and electricity purchased from the national grid.
- CHP: an energy system that contains only CHP technologies, with generation in a building cluster and distribution permitted between buildings in that cluster.
- Electrification: an energy system that install distributed energy resource (DER) system, such as heat pumps, PV and wind turbines, with distribution permitted between buildings in a cluster.

The application of the optimization model allows for the analysis of several issues, for example analyses of economic and environmental impact of the energy systems. The main outputs from the analytical model can be visualized in 3D through the use of MUtopia platform.

IV. Conclusion

This paper aims to present the development of a tool integrating the optimization of energy systems and services for urban districts, with the Mutopia visualization and simulation platform. The tool is intended to be tested on the case of the Albano Campus , a new urban development in Stockholm, Sweden. A series of Pareto optimal solutions is expected to identify, which can help to get a better understanding of the trade-off relation between different objectives. The proposed framework combines interoperable models for energy systems design and evaluation and connects with information systems for visualizing the results and monitoring. This will allow analysts to go beyond the traditional work on urban energy modeling that focused on computing technical aspect and related issues. In our view, the integrated energy systems, infrastructure and services optimization with visualization and simulation platform has the potential to serve as a tool for decision-making in the context of low-carbon urban development. It will allow to inform a range of technological options and to analyze the effects of energy system strategies.

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