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Modelling and Optimization Issues of the Energy Systems of the Future

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In this work, we introduce a novel application of an energy systems engineering framework towards the optimal design of such energy systems with improved energy efficiency and environmental performance. The framework features a superstructure representation of the various energy technology alternatives, a mixed-integer optimization formulation of the energy systems design problem, and a multi-objective design optimization solution strategy, where economic and environmental criteria are simultaneously considered and properly traded off. A case study of a supermarket energy systems design is presented to illustrate the key steps and potential of the proposed energy systems engineering approach.

1. Introduction

Energy is one of the most critical international issues at the moment and most likely to be so for the years to come. As part of the energy debate, it is becoming gradually accepted that current energy systems, networks encompassing everything from primary energy sources to final energy services, are becoming unsustainable. Driven primarily by concerns over urban air quality, global warming caused by greenhouse gas emissions and dependence on depleting fossil fuel reserves, a transition to alternative energy systems is receiving serious attention. Such a tradition will certainly involve meeting the growing energy demand of the future with greater efficiency as well as using more renewable energy sources (such as wind, solar, biomass, etc.). While many technical options exist for developing a future sustainable and less environmentally damaging energy supply, they are often treated separately driven by their own technical communities and political groups.
Energy systems engineering provides a methodological scientific framework to arrive at realistic integrated solutions to the complex energy problems, by adopting a holistic, systems-based approach. This paper demonstrates the potential of an energy systems engineering based approach to systematically quantify different options at different

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levels of complexity (technology, plant, energy supply chain) with emphasis on the optimal design of energy systems in commercial buildings.

2. Energy Systems Engineering Framework in Buildings

Energy systems in commercial buildings have received a lot of attention, with studies on energy efficiency improvement (Andrews and Krogmann, 2009), emissions reduction (Urge-Vorsatz et al., 2007), economic behaviour (Atkinson et al., 2009), process integration (Medrano et al., 2008), primary sub-systems and supporting technologies (Hinnells, 2008), and operability and flexibility (Pedrini et al., 2002). Despite these effort, however, a general and rigorous methodology for systematically addressing the integration issues and possibilities for the optimal design of energy systems in commercial buildings is still rather lacking. In this work, we describe the main features of an energy systems engineering framework for the design of such systems. Similar to energy systems engineering studies in polygeneration energy systems (Liu et al., 2007, 2009a,b) , the framework features:

- A superstructure based representation of the various available energy technologies options
- A mixed-integer programming (MIP) based mathematical modelling representation of the energy systems, and
- A multi-objective optimization strategy, in which optimal energy systems solutions are sought by properly allowing for cost optimality, energy efficiency, and environmental impact minimization

The steps of the methodology are illustrated throughout the paper through their application to supermarkets, as a typical type of commercial building

2.1 Superstructure Representation of Energy Technologies Options

A supermarket usually comprises both on-site energy generation blocks and primary types of energy demand, including refrigeration, space heating, ventilation, and bakery. A superstructure representation of the energy systems in a supermarket is shown in Figure 1. It comprises an energy supply section, an energy conversion section, and an energy savings section. The function of the energy supply section is to provide electricity and heat for the entire energy system. It is further divided into an on-site energy generation subsystem and direct supply of grid electricity and district heat. The on-site energy generation subsystem includes all possible on-site generation technologies available to the supermarket, which produce electricity and heat from all available primary energy resources. The energy conversion section converts electricity and heat obtained from the energy supply section to all energy demand tasks, such as refrigeration, lighting, ventilation, bakery, and space heating. These define the five subsystems, in which all available conversion technologies can be considered. The energy savings section further involves available types of energy savings technologies, such as night blind and weir screen for the refrigeration subsystem. Note that the proposed superstructure representation captures all possible energy systems configurations from the postulated set of technology option alternatives in each section.
It provides a generic design methodology which can be applied to any types of commercial buildings with specific requirements and demands. A compact

mathematical model, which allows to model all these possible configurations, based on MIP optimization is illustrated next.

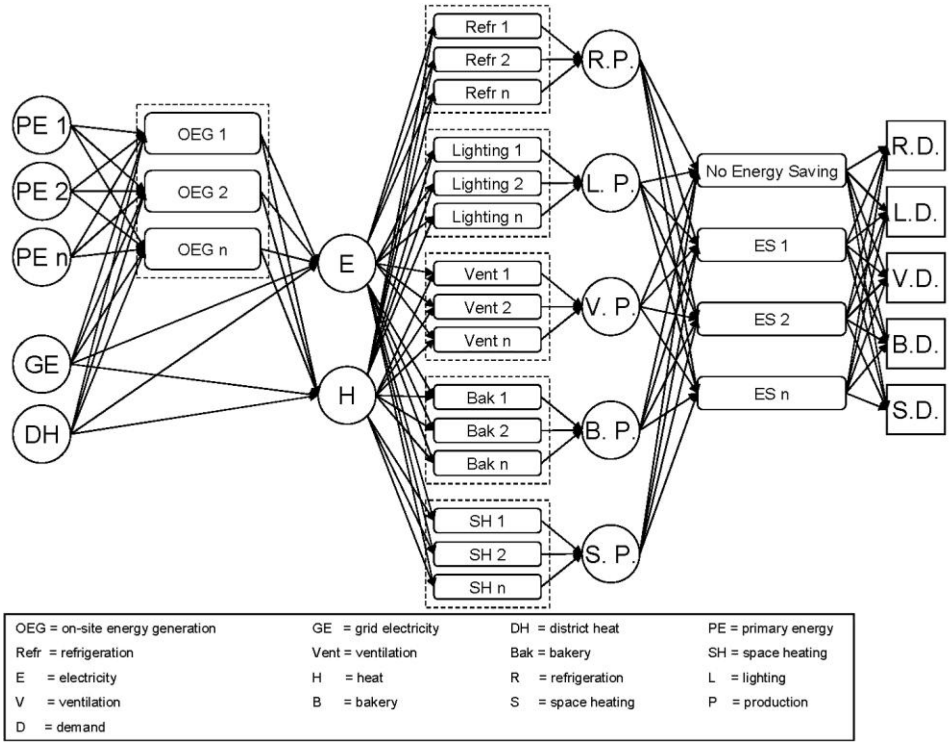

Figure 1: Superstructure representation of the energy system in a commercial building (supermarket)

2.2. Supermarket — Mixed-Integer Programming Mathematical Model

To mathematically represent the supermarket superstructure, MIP modelling strategy, involving both binary and continuous variables, is employed here. For each type of available technology or equipment, a binary variable y is introduced in the model to represent the selection (or not) of the technology or equipment, as follows:

$$y = \begin{cases} 1, \ \textit{if corresponding technology or type of equipment is selected} \\ 0, \ \textit{otherwise} \end{cases} \tag{1}$$

Moreover, to evaluate the O&M costs over the operation stage and life-cycle assessment (LCA) based greenhouse gas (GHG) emissions, the entire operation horizon of the supermarket is divided into a set of time intervals, as follows: $t \in \{t1, t2, \ldots, tn\}$ where corresponding economic and emission parameters are modelled as piece-wise functions over these time intervals. Then, the design optimization problem of a supermarket can be formulated as a multiperiod MIP problem, in the following compact form:

$$
\begin{aligned}
\min \quad & f(y, d, x_{t_1}, \ldots, x_{t_n}) \\
s.t. \quad & h^{dc}(y, d) = 0 \\
& g^{dc}(y, d) \leq 0 \\
& h^{oc}(y, d, x_t) = 0 \quad t = \{t_1, \ldots, t_h\} \\
& g^{oc}(y, d, x_t) \leq 0 \quad t = \{t_1, \ldots, t_h\} \\
& y \in \{0,1\}^m, \; x_t \in \Re^n, \; t = \{t_1, \ldots, t_h\}
\end{aligned}
\tag{2}
$$

Where:

- y is a vector of binary design variables, representing selection (or not) of a certain technology or type of equipment
- d is a vector of continuous design variables, representing continuous decisions to be made at the design stage, for instance, capacity of each section, and the like
- x_t is a vector of continuous operational variables defined on time interval t, for instance, O&M costs and GHG emissions, and the like
- f is the objective function, which could be a scalar or a vector involving cost, profit, energy, and environmental behaviour. If f is a vector, mathematically this problems becomes a multi-objective MIP problem.
- h^{dc} and g^{dc} are equality and inequality design constraints, which involve design variables only
- h^{oc} and g^{oc} are equality and inequality operational constraints, which involve both design and operational variables

The detailed multi-period MIP formulation is given in Liu and Pistikopoulos (2010).

3. Supermarket Case Study

A case study has been conducted to illustrate the modelling and optimization framework for the energy system design within a supermarket. Moreover, both traditional on-site energy generation from fossil fuels, and much cleaner renewable technologies are involved in the case study, and a comparison between them in terms of economic and environmental behaviours is conducted based on the results. All information and data used in this case study are obtained from an operating supermarket. Primary energy resources include natural gas, biomass, and biodiesel. The on-site energy generation section involves two types of electricity generation technologies, two types of heat generation technologies, and five types of co-production technologies. Energy efficiency, capacity constraints, availability, unit investment cost, and unit O&M costs of these technologies are available. Seven electricity driven energy conversion technologies and two heat driven energy conversion technologies are considered to meet the demands of refrigeration, lighting, ventilation, bakery, and space heating. Efficiency, types of energy input, types of utility output, investment cost and O&M costs of these technologies are also given.

Optimal economic and environmental design criteria are presented in the form of a Pareto-frontier in Figure 2. Each point on this frontier represents an optimal design with different economic and environmental behaviours, behind which is a full set of system design in terms of different technology combinations and different capacity. Design A, as labelled in Figure 2, represents the most economic system design, which neglects any requirement on environmental impacts at the design stage. As a result, Design A leads to the highest amount of GHG emissions. On the contrary, Design D provides the most environmentally benign system design, which leads to the highest costs over the entire operation horizon. Moreover, there are several obvious turning points on the Pareto frontier, Design B and C for instance. From Design A to B, the GHG emissions drop by 12.8 % whilst the entire costs increase by 17.5 %. From Design B to C, the GHG emissions are further reduced by 43.9 %, and the increase of costs is 57.7 %. From Design C to D, a huge reduction of 52.1 % of GHG emissions is achieved via an increase of 30.1 % on the costs side. From a governmental viewpoint, subsidies required to encourage the development of environmentally benign energy systems in commercial buildings and their marginal value are illustrated in Figure 3, where the x axis represents the reduction target of GHG emissions, the primary y axis represents the amount of required subsidies to compensate the increased costs caused by installing more advanced environmentally benign technologies, and the secondary y axis represents the marginal value of the subsidies.

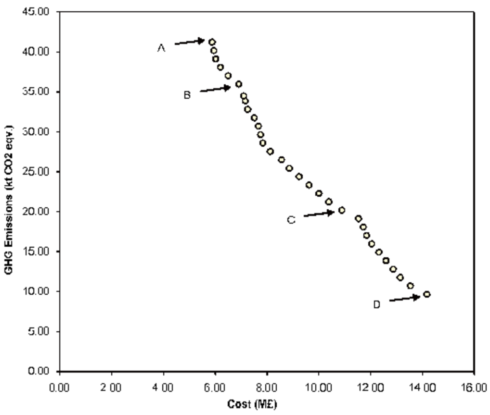

Figure 2: Pareto frontier for the energy system design in a supermarket.

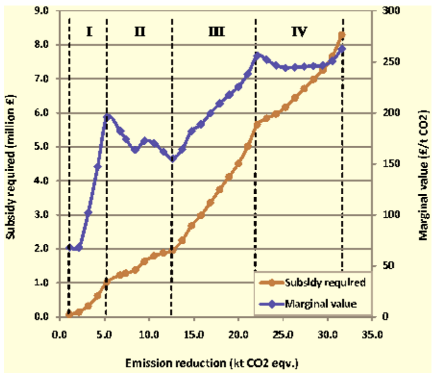

Figure 3: Subsidies required to encourage environmentally benign system designs and their marginal value

Four phases for subsidizing the reduction of GHG emissions can be observed in Figure 3. Phase I is a reduction-moderate phase, where the expected amount of GHG emission reduction is relatively small (up to 12.8 % of total GHG emissions), and the amount of required subsidy is also moderate, but the marginal value of the subsidies increases fast as the expected amount of GHG emission reduction rises. Phase I is especially suitable for a scenario where the constraint on GHG emissions is not very strict and environmentally friendly technologies are still lacking. In Phase II, however, the marginal value of governmental subsidies begins to drop as the expected amount of GHG emission reduction increases. Guidance obtained in this phase can be followed in a stage when the constraint on GHG emissions becomes tight and the local/central government is willing and able to provide more subsidies for further reduction. Phase III and IV can be regarded as post-reduction phases, the requirements on GHG emission reduction are much stricter and the amount of required subsidies increases dramatically. These two phases should only be considered in a scenario where the reduction of GHG emissions become a top priority in designing an energy system.

4. Conclusions

Design of energy systems in commercial buildings is studied from the viewpoint of energy systems engineering. A superstructure based modelling and optimization framework is proposed to simultaneously address the challenging design issues of technology selections, integration between sub-systems, and multi-criteria design. Computational results show that the implementation of this framework as a multi-objective multi-period MIP problem can be solved efficiently. A Pareto frontier can be obtained from the model results, which captures all possible types of system design under any design criteria and conditions, thus provides a decision maker a full set of design tools to guide the design procedure.

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