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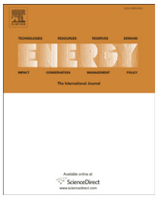

Modelling and optimization of retrofitting residential energy systems at the urban scale

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ABSTRACT

Local governments and property developers are increasingly seeking robust models for strategic planning of retrofitting residential energy systems. Strategic planning here infers making decisions on technology upgrades at the concept design stage. This represents a problem with many degrees of freedom. Optimization models offer a solution. The presentation of the tool RESCOM is the focus of this paper, a MILP (mixed integer linear program) that builds upon previous models of urban energy systems and extends these efforts by incorporating both demand side technologies, and explicit spatial and temporal resolution.

A test case for a London borough describes the result of applying spatial optimization and demonstrates the accessibility of this program to decision makers. Results provide the optimal configuration of supply side and demand side technologies required to satisfy thermal energy requirements for a range of scenarios. The presented approach solves retrofit problems at urban scale in an efficient and thorough manner, providing an expandable framework towards providing solutions for the selection and operation of complex energy systems.

1. Introduction

The value of examining energy systems strategy earlier in the design process can be implicitly recognized through the recent upsurge in practitioners' interest in analysis — at the stage when technological concepts are still being decided upon [1,2]. Recent academic research has arguably pre-empted this trend [3]. Of the suite of tools available, optimization models have a powerful role to play by helping assist decision makers with plans for making major alterations to existing energy systems. This can be confirmed by the temporal and spatial extent of the studies under consideration [4–7]. Where competing solutions exist, thorough assessment of energy systems via optimization models offers an impartial method for determining the optimal arrangement of technologies to meet the energy needs of an area. This is particularly true for decisions in retrofit, where there are a multitude of solutions on offer (e.g. see Difs et al. [8]).

There is a primary conflict when considering the impact of an energy system retrofit decision in buildings: whether to improve the efficiency of supply side technologies, or whether to invest in demand side technologies with the intention of reducing primary energy requirements, and maintaining the embedded value of the incumbent supply side technologies. The focus of this paper is to present an approach towards modelling and optimizing these decisions for residential energy systems. Residential buildings are the building sector under study for two primary reasons: i) the thermal loss model of a residence in a UK climate can be reasonably simulated by use of linear relationships, and ii) residential buildings are at the forefront of the sustainable development/climate change agenda if government policy is taken as a proxy. The MILP (mixed integer linear programming) approach is thought suitably representative of reality, based upon calibration of a London test case and keeping in mind the level of rigour required prior to the detailed design stage. The results of this spatial optimization are described by four scenarios for upgrading the residential buildings of the test case over the period 2011–2020.

Results impress the scale of the challenge in significantly altering current energy systems upon the decision maker. Nineteen spatial nodes provide details of optimized investments in distributed and supply side models. One early conclusion is that such output can be used by a local authority to frame area-specific tendering details for future work. The advantages of a strategy to mitigate against expected greenhouse gas emissions are obvious: i) lower residential bills for space heating, and ii) a more secure energy system due to decreased primary energy requirements. However, both the logistical arrangements and financial requirements are significant. In two

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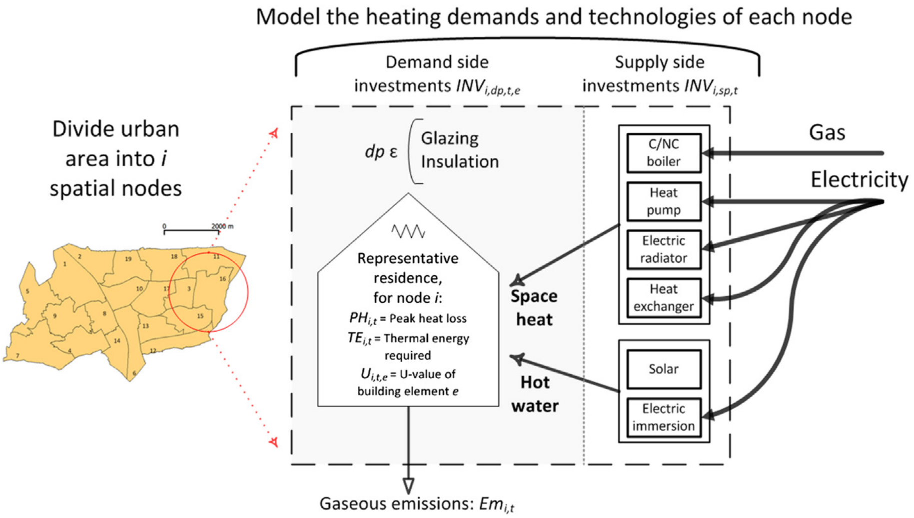

Fig. 1. Schematic diagram of the Residential Energy System Concept Design Stage Optimization Model (RESCOM).

final scenarios, the impact of a doubling of gas prices is investigated, both with and without centralized heating plant. With investments in a centralized heating network permitted, a borough wide heating network is introduced — on the basis of an electricity led profitable margin for the plant owner and slightly cheaper residential heat supply for end-users. Without such a network available, the best strategy is to invest heavily in new condensing boilers, operate existing technologies as efficiently as possible, and to reduce the average heat loss of residences by purchasing materials with lower thermal transmittance values.

These results are not all easily understood at the outset. However, on reconsideration of the results, energy system scenarios can help draw out the salient superstructures and associated constraints of practical relevance. The modelling approach is now described in detail and the test case is presented in Section 3. Results are given in Section 4, before conclusions are offered in Section 5.

2. Description of the model

Urban energy systems comprise large distributed systems. These distributed systems constitute supply side and demand side technologies, i.e. those that limit the rate of supply via resource conversion ratios and those that dictate the rate of demand via the mechanisms of heat loss. The number of alternative arrangements of technologies introduces many degrees of freedom, particularly where large numbers of buildings and networks are in play. Optimizing the heating equipment required for a single residence may be solved in a few iterations of Gaussian elimination on a small sized matrix, but the problem becomes significantly more onerous to solve if choosing when, where, and in what type of heating equipment to invest in an area of, say, fifty thousand residences. This is where optimization can help.

A RESCOM (residential energy system concept design stage optimization model) has been formulated as a MILP to both deal with integer variables and to allow for large scale modelling efforts. Integers are necessary to represent discrete investments, such as purchases of pipelines. Residential buildings are defined here to be inclusive of houses, flats, and any other form of residence. The boundary conditions of RESCOM can handle both the existing heating demand of residential buildings, and the heating equipment and networks required to meet this demand. The system is calibrated to a base time period's gas and electricity consumption. After this initial calibration, changes to the system by means of investment in supply side or demand side technologies are the result of the solution of RESCOM.

Optimization modelling of residential energy systems allows the tradeoff between alternative energy systems to be made explicit. Commercial buildings are not modelled because these buildings tend to include cooling services, usually provided by means of mechanical ventilation or air-conditioning. Modelling space cooling loads requires a dynamic analytic procedure [9], an analysis that would introduce a number of nonlinear relationships. One of the purposes of this research is to test whether optimization software can deal with large distributed systems — inferring numbers of variables and constraints in the hundreds of thousands. Hence in order to allow for a large number of integers representing logical constraints and discrete investments, it is thought a sensible approach to minimize the number of nonlinear relationships in order to keep the analysis tractible. In summary, commercial buildings are omitted from RESCOM and the scope is limited to the heating systems of residential buildings.

A schematic diagram of the model is given in Fig. 1. The objective function of the model represents minimization of costs, discounted to today's value (i.e. at time $t = 0$), and is described in Section 2.1. Costs are due to both maintaining and operating technologies, where technologies are defined by the set $\mathcal{P}$, (operating costs) and due to investment in new technologies (capital costs). Furthermore, capital costs result from investment INV in demand side technologies $dp \subset \mathcal{P}$ and/or supply side technologies $sp \subset \mathcal{P}$. Investments are indexed by technological, spatial, and temporal sets: Table 1 provides indicative elements for these sets.

Table 1
Illustrative technological, spatial, and temporal sets.

Supply side technology *sp*	Demand side technology *dp*	Spatial element *i*	Temporal element *t*
Incumbent boiler	Wall insulation	City	Year
Incumbent electric heater	Additional-pane glazing	Borough	Season
Condensing boiler	Loft insulation	Ward	Hour
Heat pump	Door insulation		
Solar thermal collector	Floor insulation		
Combined-cycle gas turbine	Hot water storage cylinder		

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