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Stochastic control and real options valuation of thermal storage-enabled demand response from flexible district energy systems

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HIGHLIGHTS

- We calculate the real option value of flexibility from CHP-thermal storage.
- Stochastic optimal feedback control problem is solved under uncertain market prices.
- Efficient real-time numerical solutions combine simulation, regression and recursion.
- Clear, interpretable feedback control maps are produced for each hour of the day.
- We give a realistic UK case study using projected market gas and electricity prices.

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ABSTRACT

In district energy systems powered by Combined Heat and Power (CHP) plants, thermal storage can significantly increase CHP flexibility to respond to real time market signals and therefore improve the business case of such demand response schemes in a Smart Grid environment. However, main challenges remain as to what is the optimal way to control inter-temporal storage operation in the presence of uncertain market prices, and then how to value the investment into storage as flexibility enabler. In this outlook, the aim of this paper is to propose a model for optimal and dynamic control and long term valuation of CHP-thermal storage in the presence of uncertain market prices. The proposed model is formulated as a stochastic control problem and numerically solved through Least Squares Monte Carlo regression analysis, with integrated investment and operational timescale analysis equivalent to real options valuation models encountered in finance. Outputs are represented by clear and interpretable feedback control strategy maps for each hour of the day, thus suitable for real time demand response under uncertainty. Numerical applications to a realistic UK case study with projected market gas and electricity prices exemplify the proposed approach and quantify the robustness of the selected storage solutions.

1. Introduction

In multi-energy systems [1], different energy vectors are modelled in an integrated manner so as to optimise the overall energy system. Within this context, distributed multi-generation plants [2,3] and especially Combined Heat and Power (CHP) plants play a key role, particularly to set up district energy systems. While traditionally such plants have been operated and designed in a load-following mode with boiler back-up, new opportunities are arising from active participation in energy markets. More specifically, multi-generation plants that can deploy flexibility from arbitraging between energy vectors can provide real-time Demand Response (DR) [4,5] to external market signals, thus boosting their overall business case with respect to classic "passive" load-following operation. In this outlook, thermal energy storage can provide a significant degree of flexibility to CHP-based systems [6–9] by allowing decoupling of supply and demand as well as time arbitrage to buy/sell energy to/from markets (gas and electricity) in real-time. However, many uncertainties arise in different time scales for district energy systems, namely, large scale uncertainties mostly from energy price evolution in the planning horizon/long run, and small scale uncertainties from load and energy price variations in the operational horizon/short run (for a comprehensive analysis of these issues, please refer to [10,11]). In this context, while engineering techniques often encounter serious challenges

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Nomenclature

Acronyms
CHP Combined Heat and Power
DR Demand Response
RO Real Options
DCF Discounted Cash Flow
LSM Least Squares Monte Carlo regression

Price models (Symbols: Principal nomenclature used in the text. Where possible subscripts, superscripts and function notation have been suppressed to aid clarity.)
μ linear slope
f seasonal component
X Ornstein–Uhlenbeck process
k speed of mean reversion
σ volatility

Stochastic control problem
$\mathbf{u}$; u set of feedback controls; one feedback control
$t; T$ current time; end time
r financial discount rate
$\psi(u_t)$ net expenditure rate on gas and electricity
E mathematical expectation operator
V average total operational cost

Dynamic programming
s time in dynamic program
C level of stored heat
$E; G$ electricity price; gas price
D system state (s, G, E, C)

Discretisation and regression
$c_1, \ldots, c_L$ heat storage levels
$h; M$ time step size; number of time steps
N number of simulated price paths
$\xi_1, \ldots, \xi_z$ operational modes for generation assets
$B; \alpha$ basis functions; regression coefficients

to cope with such uncertainty modelling, mathematical finance provides efficient computational techniques that can address uncertainties in both operation and planning aspects concurrently. This is important to capture because short term flexibility can change the long term business case, while the long term investment plan can enable short term flexibility.

On the above premises, following preliminary work done in [12], this paper proposes a model based on stochastic optimal control theory [13] which provides an innovative integrated approach to optimally and dynamically (in the sense of providing real time DR) controlling CHP plants with heat storage in the presence of uncertain market prices, with no requirement for separation of the operational and investment timescales. In fact, the constrained linear stochastic optimal control algorithm used for operational optimisation explicitly considers interactions with measured and predicted external price signals in both the short run and the long run. By doing so, it also performs at the same time Real Options (RO) [14] valuation of thermal storage for planning purposes, thus fully capturing and valuing the flexibility that thermal storage makes available in CHP systems. In this respect, in fact, Discounted Cash Flow (DCF) methods that are traditionally used to value investment projects generally fail to properly model uncertainty and operational flexibility, by adopting the typical solution of increasing the project discount rate to account for risk. In contrast, in district energy systems that are capable to provide DR a substantial share of their operational value arises from the fluctuations across energy prices and over different time scales, which are excluded from DCF valuation and for which RO is most suitable. In this perspective, several applications of RO to energy systems have been provided in the last years, for instance in Australia and New Zealand for network investment projects [15]. Similar examples can be found in [14,16,17]. Relevant to the problem discussed here, RO valuation is applied in a multi-energy system scheme in [18] by carrying out a series of daily independent optimal scheduling calculations for distributed energy resources; however, this approach does not take into account the effect on scheduling for subsequent time periods (and the relevant opportunity costs), nor optimises DR strategies by taking into account price prediction and feedback from real-time information. In contrast, in the model put forward here, hour-by-hour control solutions are obtained in feedback form [19] (taking into account real-time price information) and do not separate the investment and operational timescales, instead working with a single timescale irrespective of the duration. The price models used are realistic and calibrated to the current market view via inference from quoted UK electricity and gas futures prices. Further, computational efficiency is discussed and achieved through combining forward simulation with regression modelling and backward dynamic programming [20]. A key and innovative output of the proposed model is our use of statistical stationarity to produce high quality real time control strategy maps: in contrast to classical dynamic programming, these are not defined on any discrete lattice but their resolution is adaptive and guided by the statistical price models themselves, deliberately giving higher-quality information in areas of state space which are statistically more likely to occur, while still covering more unlikely system states. These high quality control maps can be automatically built at each considered operational time step and take into account both the long term prediction of market prices as well as real-time price information.

The paper is organised as follows. Section 2 provides an introduction to the relevant control problem and the modelling aspects. Section 3 discusses the Least Squares Monte Carlo Regression (LSM) method used for computationally efficient numerical solution. Section 4 presents a realistic UK based case study application, whose results are shown and discussed in Section 5. Section 6 contains the concluding remarks.

2. Problem description and modelling

The value of heat storage lies in its ability to effectively move heat demand through time. In the presence of flexible CHP and energy markets (such as the district energy system in Fig. 1) this

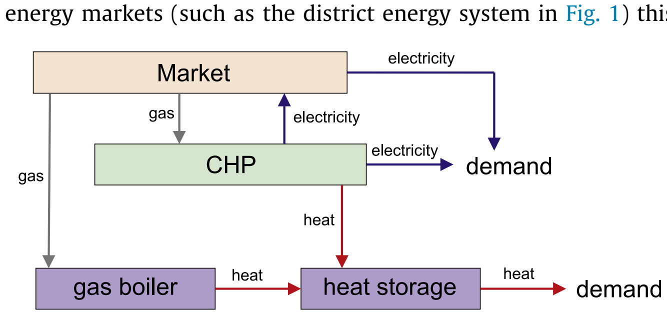

Fig. 1. The multi-component district energy system modelled in the case study.