Investment and Upgrade in Distributed Generation under Uncertainty

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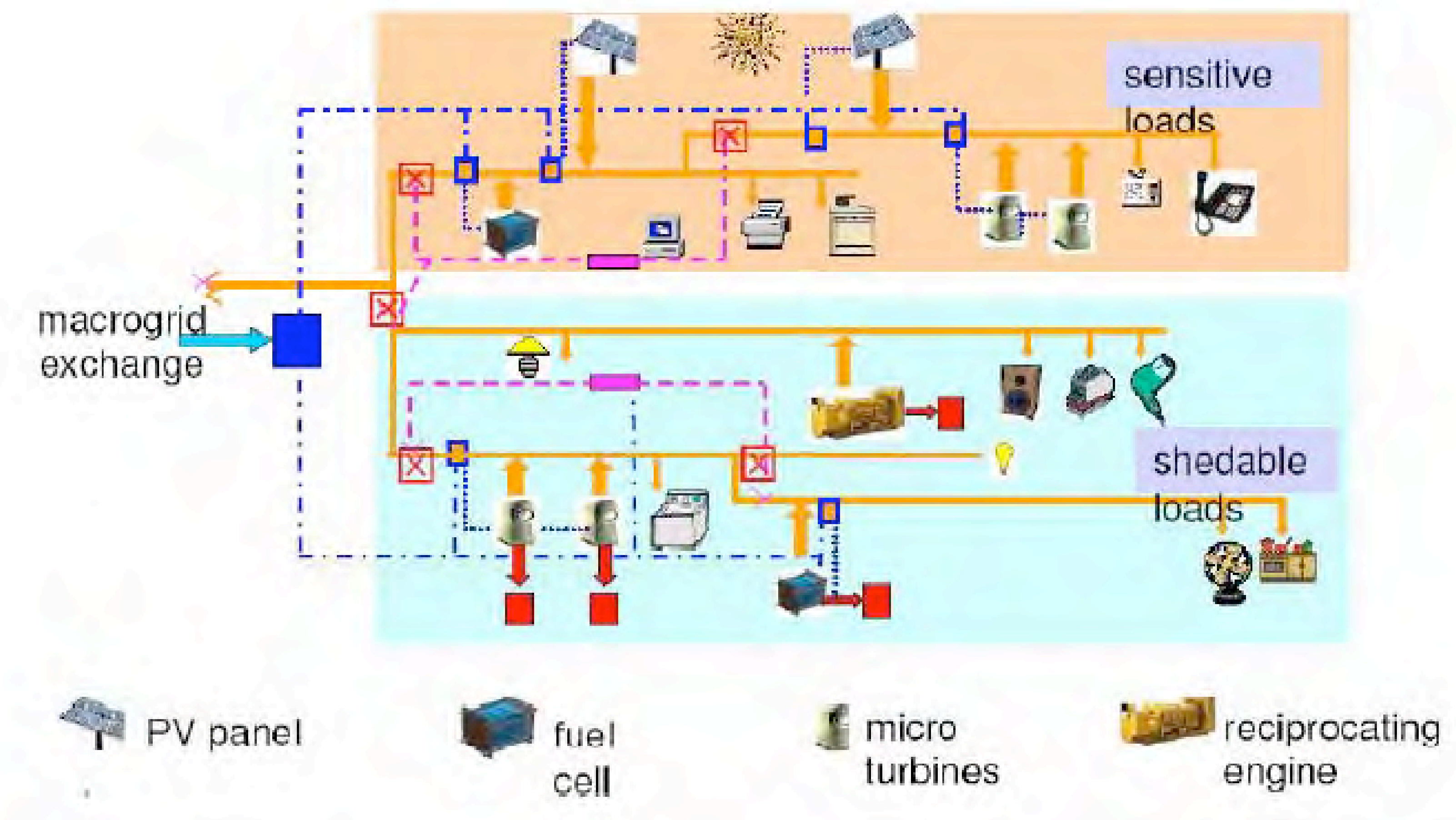
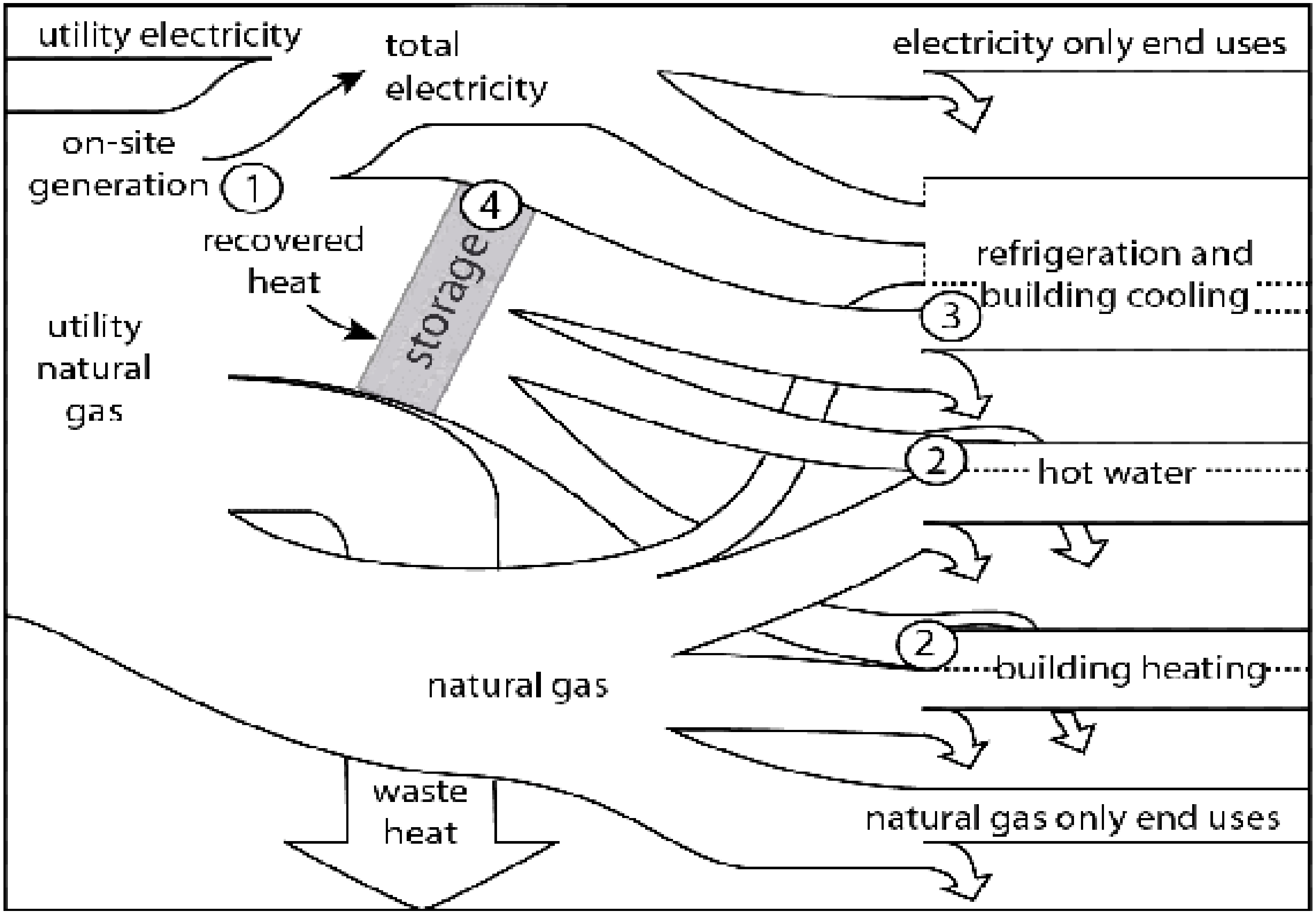
Background

- Electricity industry deregulation aims to improve economic efficiency by providing market signals to participants (see Wilson (2002))
  - Traditionally, vertically integrated IOUs operated in a hierarchical fashion on the basis of fixed retail rates
  - Marnay and Venkatarmanan (2006) describes how investment in capacity lagged in the 1960s, thereby causing deadweight losses
- Distributed generation (DG) offers opportunity for market participants to use price signals to invest in capacity that is more tailored their needs
  - Microgrids: localised networks of DG and combined heat and power (CHP) applications matched to local energy demands
  - Operate semi-autonomously from the wider macrogrid

Background: Typical Microgrid

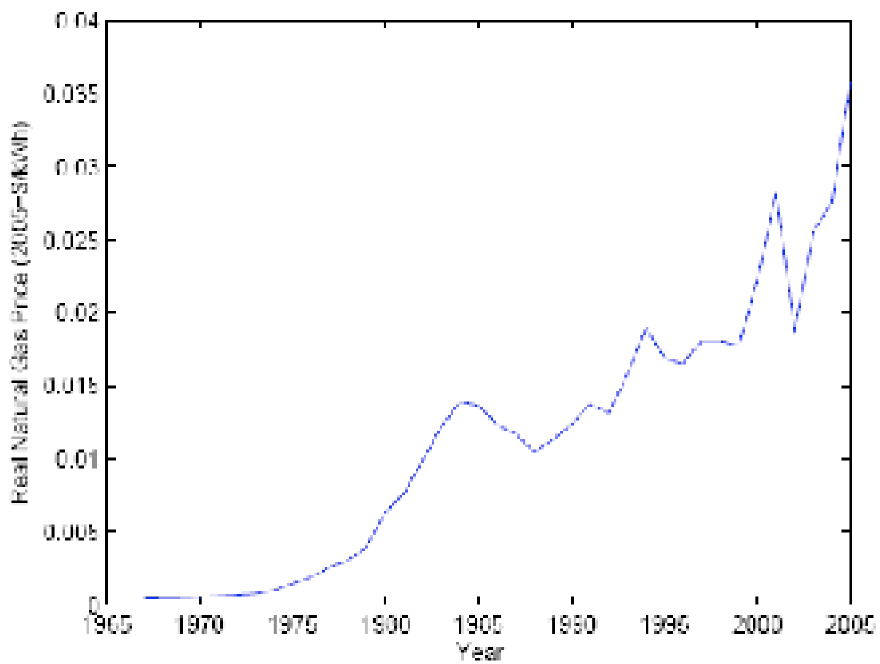


Background: Energy Flows



Background: Effect of Uncertainty

- A microgrid investing in gas-fired DG must consider both electricity and natural gas (NG) prices
  - The former may be largely fixed by the incumbent utility
  - By contrast, the latter may be subject to considerable monthly volatility
- Data: NG price for commercial users in CA from EIA (average volatility is 17.82% with an average growth rate of 13.44%)



Research Objective

- Use the real options approach (see Dixit and Pindyck (1994)) to examine the behaviour of a SF-based microgrid
- Given uncertainty in NG price, what should be the microgrid's DG investment and upgrade strategy?
  - Detailed, but deterministic, models recommend installation of large systems (see Siddiqui *et al.* (2005))
  - A more abstract, stochastic model suggests delaying investment to capture value of information (see Siddiqui and Marnay (2006))
- Here, we investigate how a microgrid proceeds under uncertainty if it is able to modularise DG installation
  - Compare various investment strategies for different levels of uncertainty
  - Find that at moderate levels of uncertainty, a sequential approach facilitates investment
  - Analysis is largely economic and avoid regulatory issues

Illustrative Example: DG Investment Only

- Microgrid with constant electric load $Q_{EB}/8760 \text{ (in kW}_e)$
  - Meet electric load using either utility purchases (P (in \$/kWh$_e$)) or DG output (C_t (in \$/kWh))
  - DG unit can cover the entire load if installed
  - Capital cost is I_{EB} (in \$)
  - Assume that the DG unit has an infinite lifetime once installed
- Real options approach: construct risk-free portfolio, Φ, consisting of one unit of the option to invest, $V_0(C)$, and short $V_0'(C)$ units of natural gas
- Equate the instantaneous risk-free return on Φ to the expected appreciation of Φ less any dividend payments

Illustrative Example: Solution

- Two states of the world
  - Before investment, in which case the microgrid holds the option to invest in DG, $V_0(C)$, but receives no incremental electricity cost savings
  - After investment, in which case the microgrid's PV of cost savings is $V_1(C) = \frac{PQ_{EB}}{r} - \frac{C_{EB}Q_{EB}}{\delta}$
- Bellman equation is $r\Phi dt = E[d\Phi] - \delta C V_0'(C) dt$
- Applying Itô's Lemma to the right-hand side yields

$$\frac{1}{2}\sigma^2 C^2 V_0''(C) + (r-\delta) C V_0'(C) - r V_0(C) = 0$$

- Since $\lim_{C \to \infty} V_0(C) = 0$, the solution is $V_0(C) = A_2' C^{\beta_2}$, where

$$\beta_2 = \frac{1}{2} - (r-\delta)/\sigma^2 - \sqrt{\left[(r-\delta)/\sigma^2 - \frac{1}{2}\right]^2 + 2r/\sigma^2} < 0$$

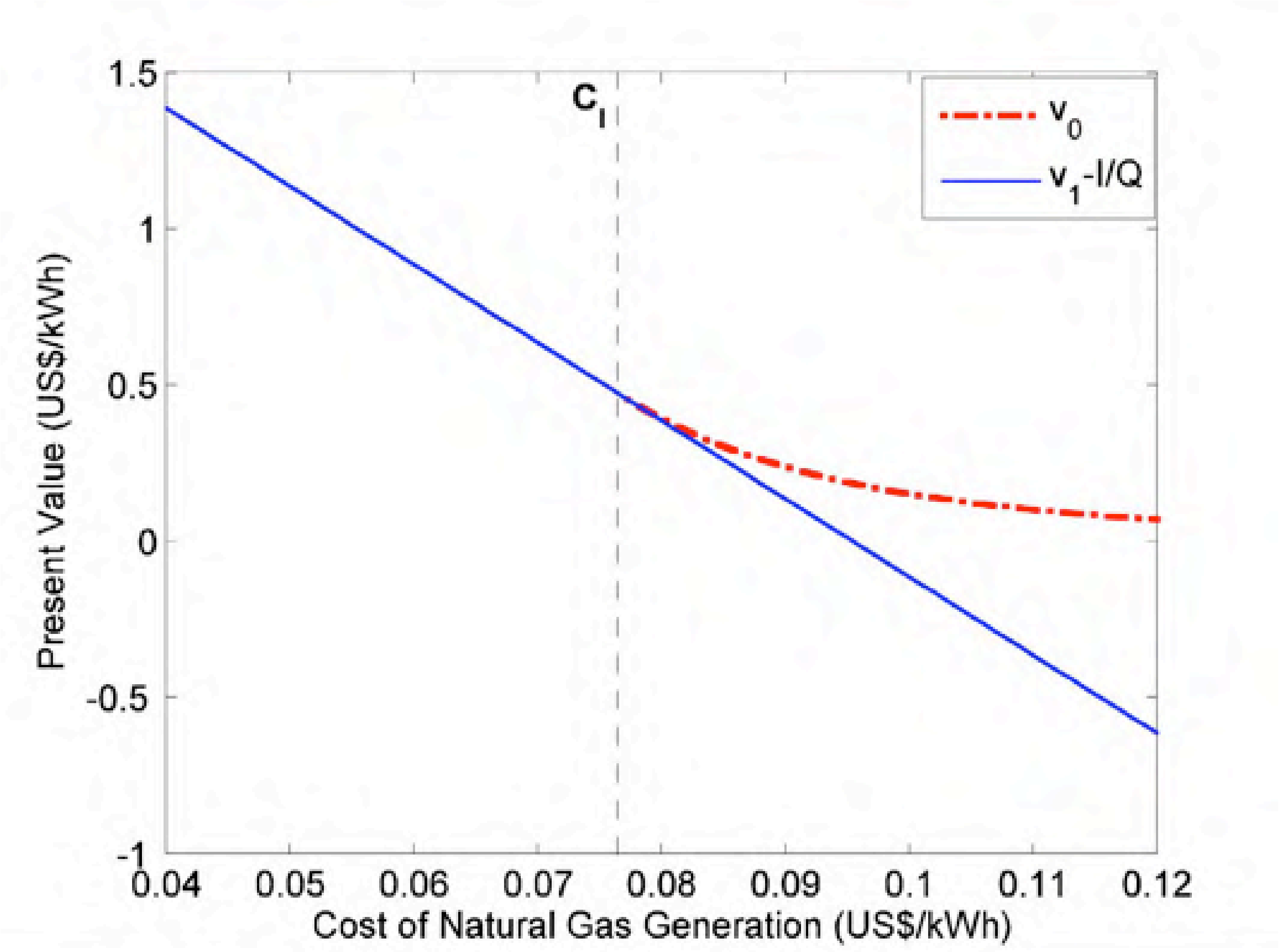
- Apply value-matching and smooth-pasting conditions:

$$V_0(C_I) = V_1(C_I) - I_{EB} \qquad V_0'(C_I) = V_1'(C_I)$$

Illustrative Example: Data

Parameter	Value
P	US\$0.10/kWh
I	US\$0.50M
$\frac{Q}{8760}$	500 kW
σ	0.06
δ	0.04
r	0.04

Illustrative Example: Result



Evidence of DG: Joseph Gallo Dairy Farm

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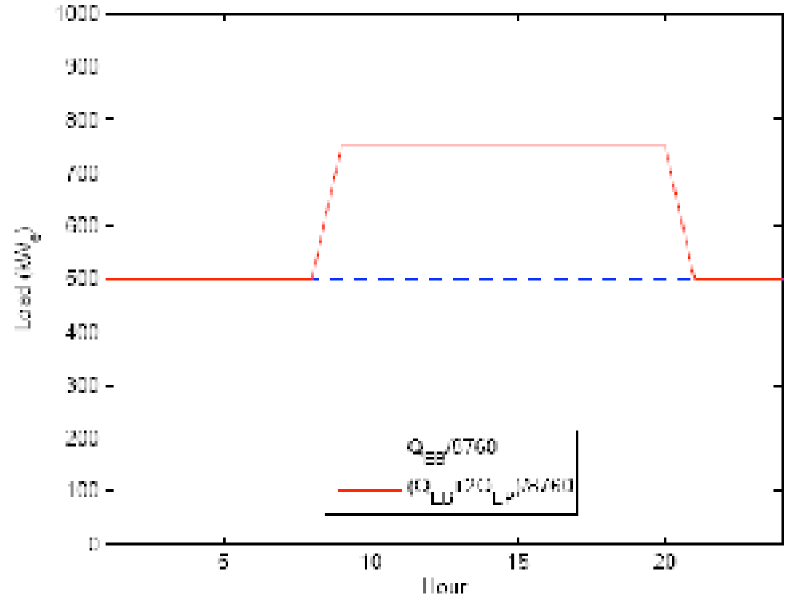
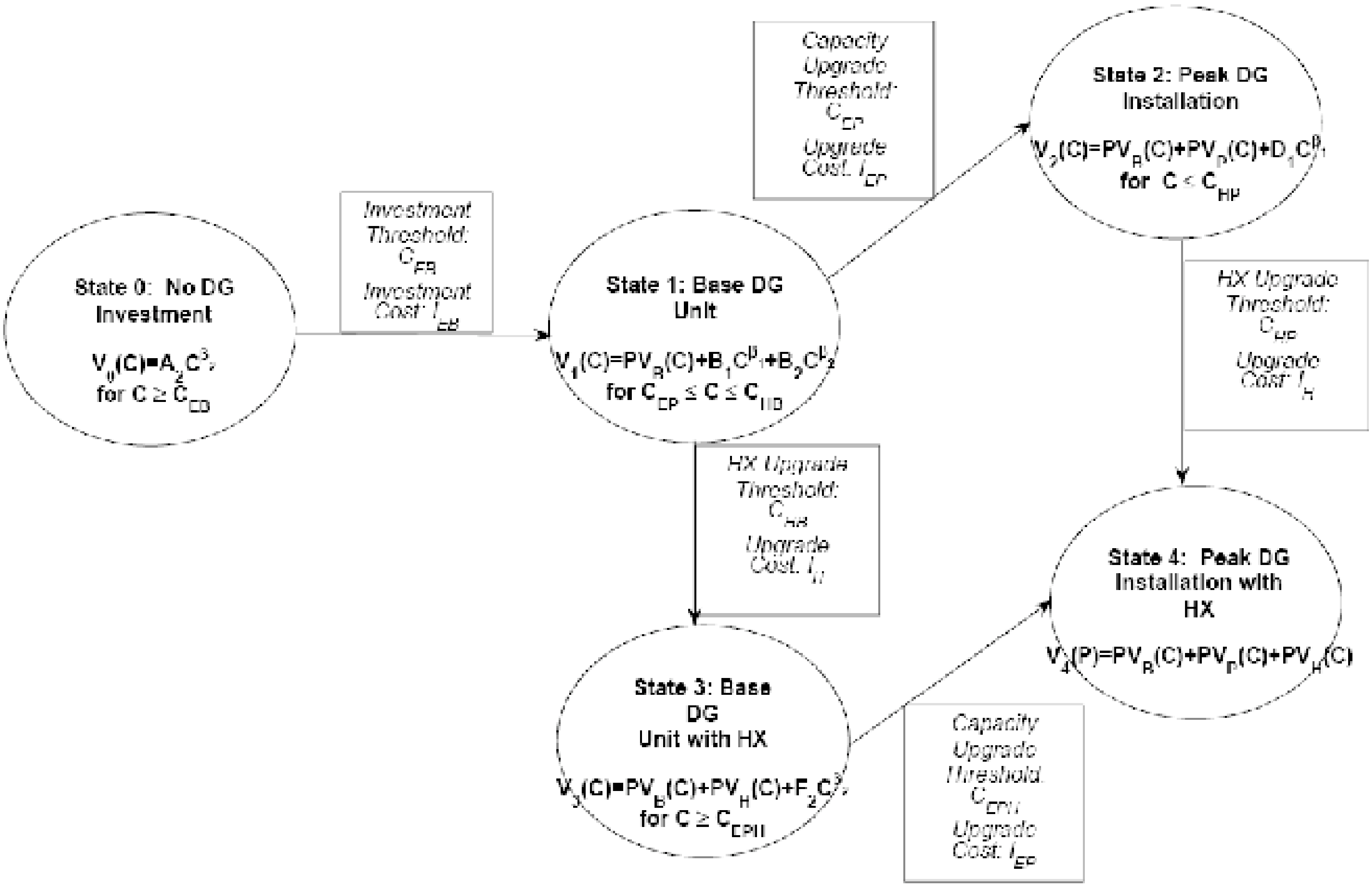
Problem Formulation

- Microgrid with electric load $(Q_{EB} + 2Q_{EP})/8760 \text{ (in kW}_e\text{)}$ and heat load $Q_H/8760 \text{ (in kW)}$
  – Meet electric load using either utility purchases ($P \text{ (in \$/kWh}_e\text{)}$) or DG output ($C_t \text{ (in \$/kWh)}$), where $dC_t = \alpha C_t dt + \sigma C_t dz_t$
  – If heat exchanger (HX) installed, then use recovered heat
  – Given capital costs, equipment efficiencies, and tariff structure, how should the microgrid proceed with investment?



Investment and Upgrade Strategies



Investment and Upgrade Values with Modular Strategy

- In state 0, the value of the DG investment opportunity is $V_0(C) = A_2 C^{\beta_2}, \text{ if } C \geq C_{EB}$
- If the NG price decreases to the threshold, then investment in a base DG unit is made (enter state 1)
  - PV of cost savings is $\frac{P}{r}Q_{EB} \quad \frac{C}{\delta}\epsilon_B Q_{EB} + \frac{D_E}{8760r}Q_{EB}$
  - Plus, the microgrid has the options to upgrade either capacity or to a HX:

$$V_1(C) = PV_B(C) + B_1 C^{\beta_1} + B_2 C^{\beta_2}, \text{ if } C_{EP} \leq C \leq C_{HB}$$

- In state 2, the entire electric load is covered
  - Additional PV of cost savings is:

$$PV_P(C) = \frac{P}{r}Q_{EP} - \frac{C}{\delta}\epsilon_P Q_{EP} + \frac{D_E}{8760r}2Q_{EP} + X_E/r$$

  - Plus, the microgrid has the option to upgrade to a HX:

$$V_2(C) = PV_B(C) + PV_P(C) + D_1 C^{\beta_1}, \text{ if } C < C_{HP}$$

Investment and Upgrade Values with Modular Strategy

- Alternately, from state 1, the microgrid could upgrade to a HX (enter state 3 instead of state 2)
  - Additional PV of cost savings is $PV_H(C) = \frac{C}{\delta} \min\{Q_H, \gamma Q_{EB}\}$
  - Plus, the microgrid has the options to upgrade capacity:

$$V_3(C) = PV_B(C) + PV_H(C) + F_2 C^{\beta_2}, \text{ if } C \geq C_{EPH}$$

- Finally, in state 4, all of the equipment is installed:

$$V_4(C) = PV_B(C) + PV_P(C) + PV_H(C)$$

- There are ten unknowns: five NG price thresholds and five endogenous constants
- Since there are five interfaces between states, it is possible to write a total of ten equations (five each of value-matching and smooth-pasting conditions)
  - Highly non-linear system of equations
  - Solve for most of the unknowns numerically

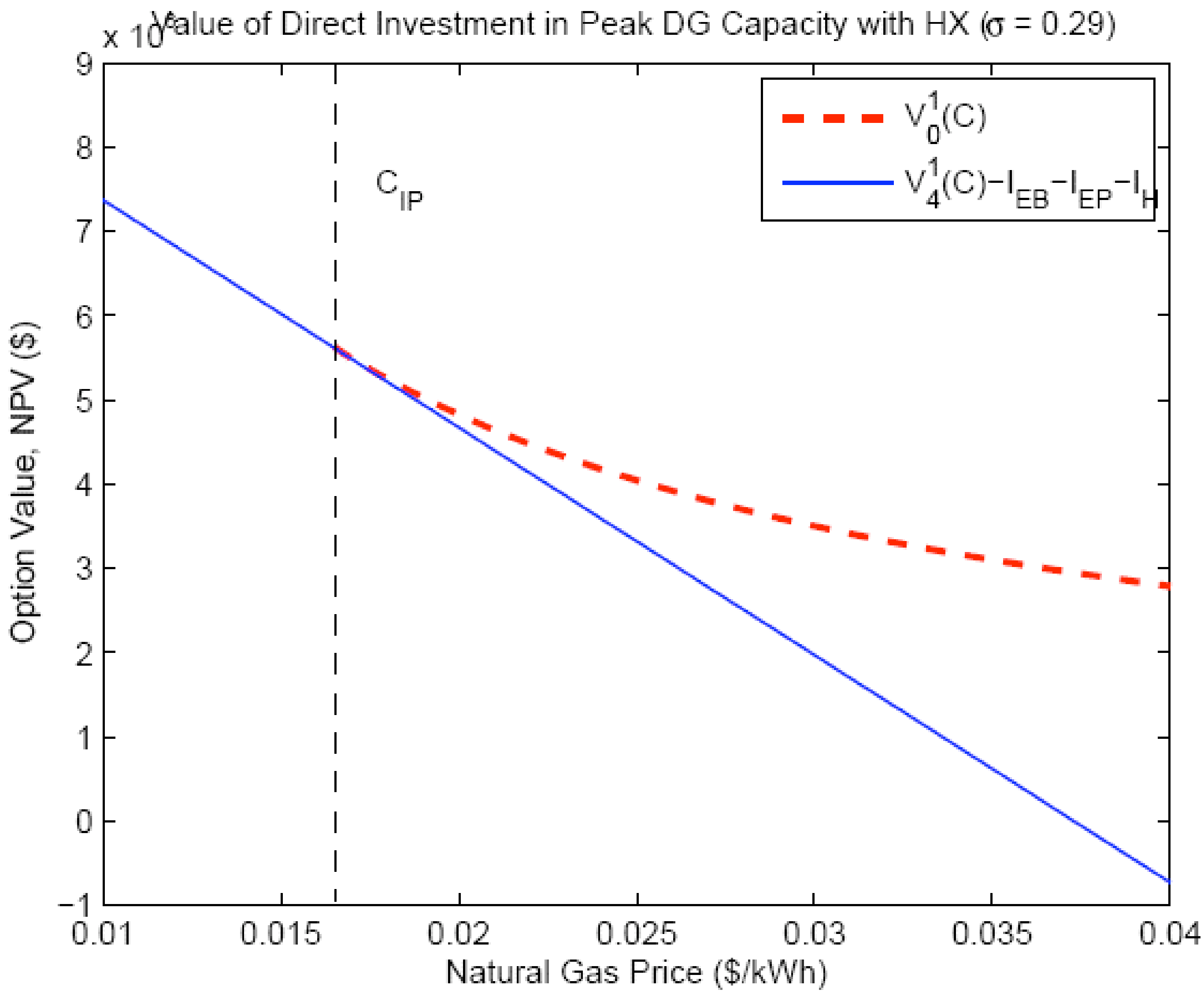
Numerical Example: Parameter Values

- Tariff structure for a commercial microgrid in CA

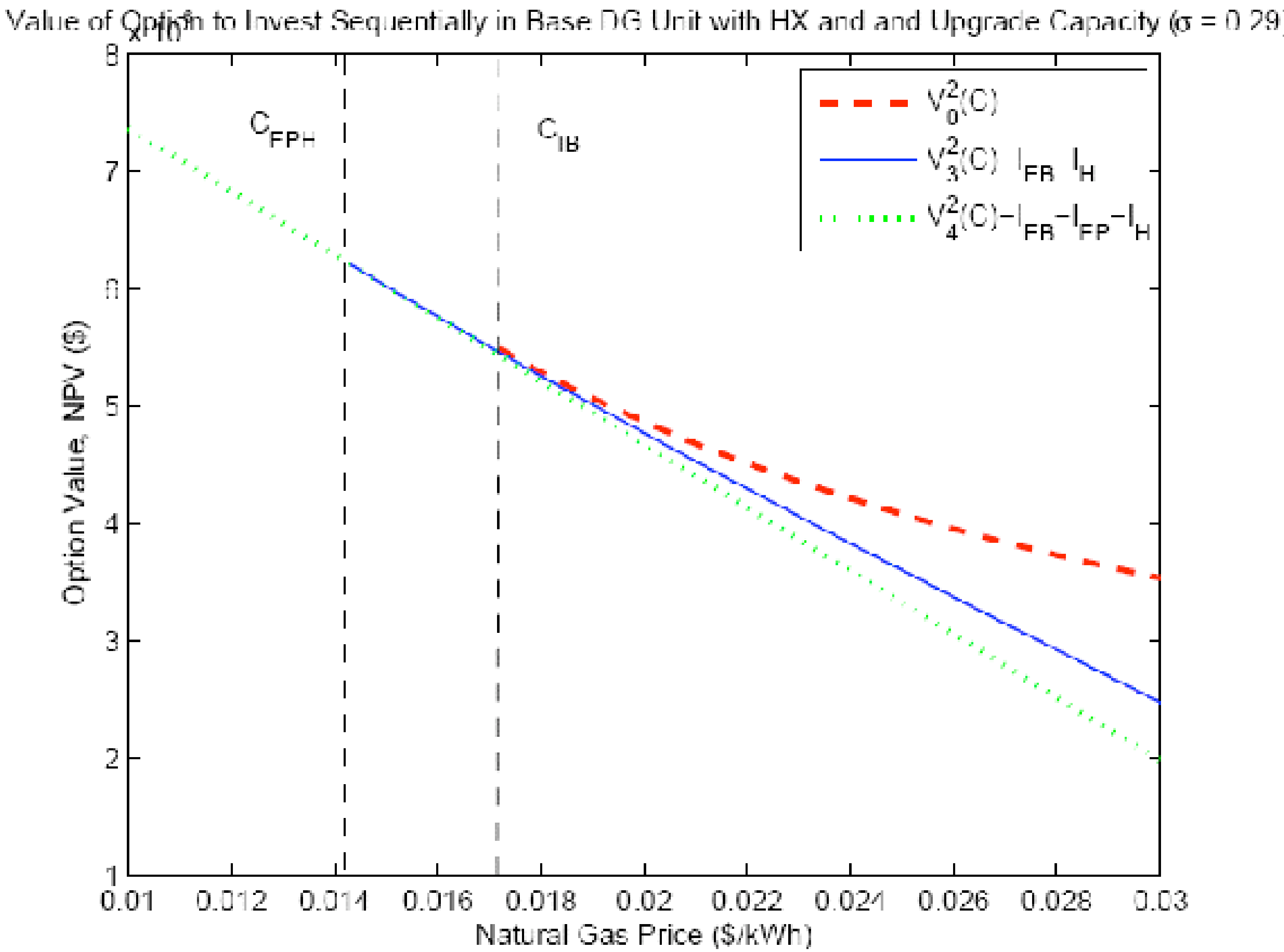
Parameter	Value
P	$\$0.10/\text{kWh}_e$
D_E	$\$144/\text{kW}_e$
X_E	$\$2100$

- Base and peak electric loads are 500 kW_e and 250 kW_e, respectively, while heat load is 100 kW
- Available equipment: 500 kW_e reciprocating engine (\$795/kW_e and $\epsilon_B = 3.01$), 250 kW_e microturbine (\$1400/kW_e and $\epsilon_P = 3.57$), and 500 kW_e HX for base DG (\$270/kW_e and $\gamma = 1.55$)
- Others: both risk-free interest rate and convenience yield of 6%/a, $C_0 = \$0.0324/\text{kWh}$

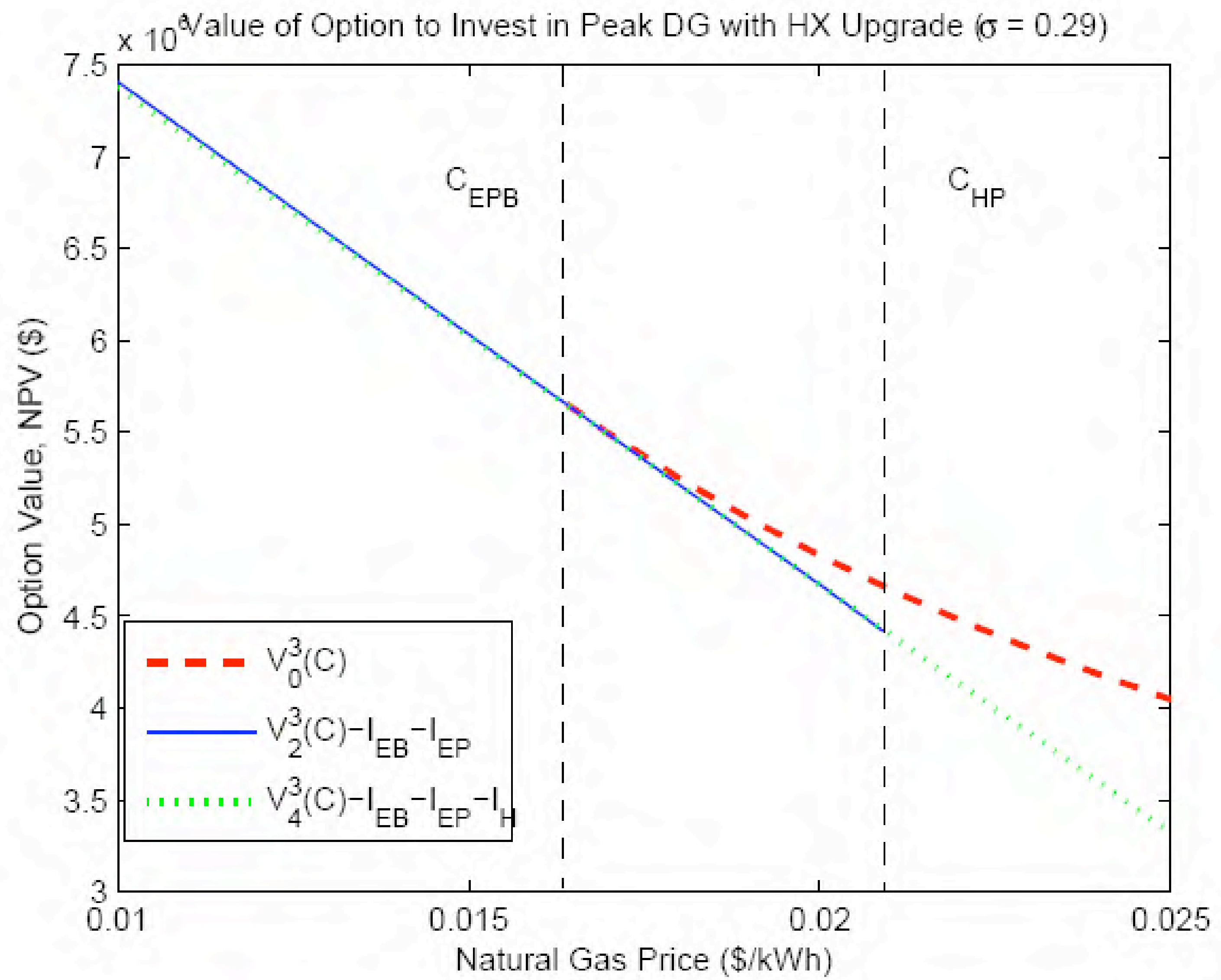
Numerical Example: Strategy 1



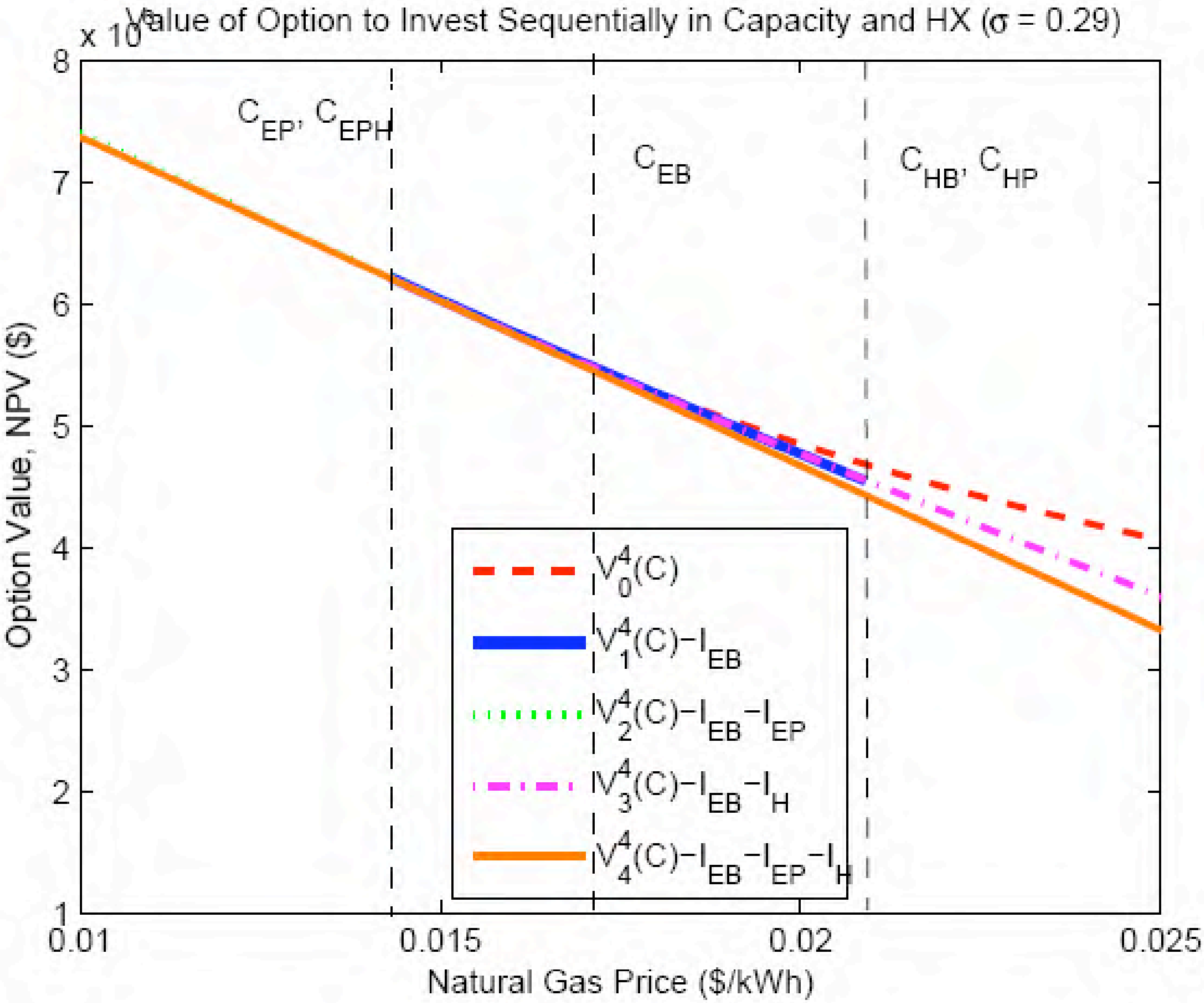
Numerical Example: Strategy 2



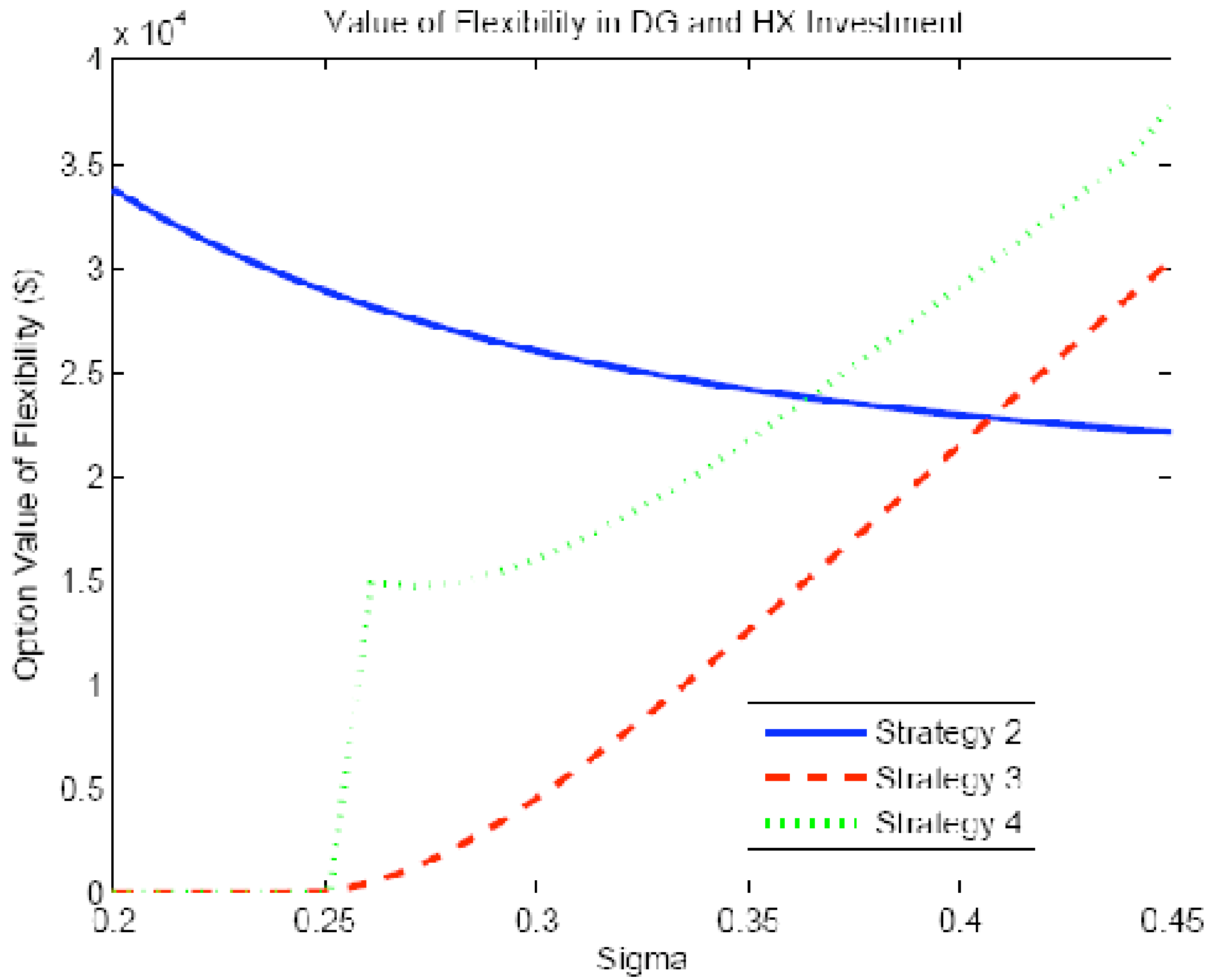
Numerical Example: Strategy 3



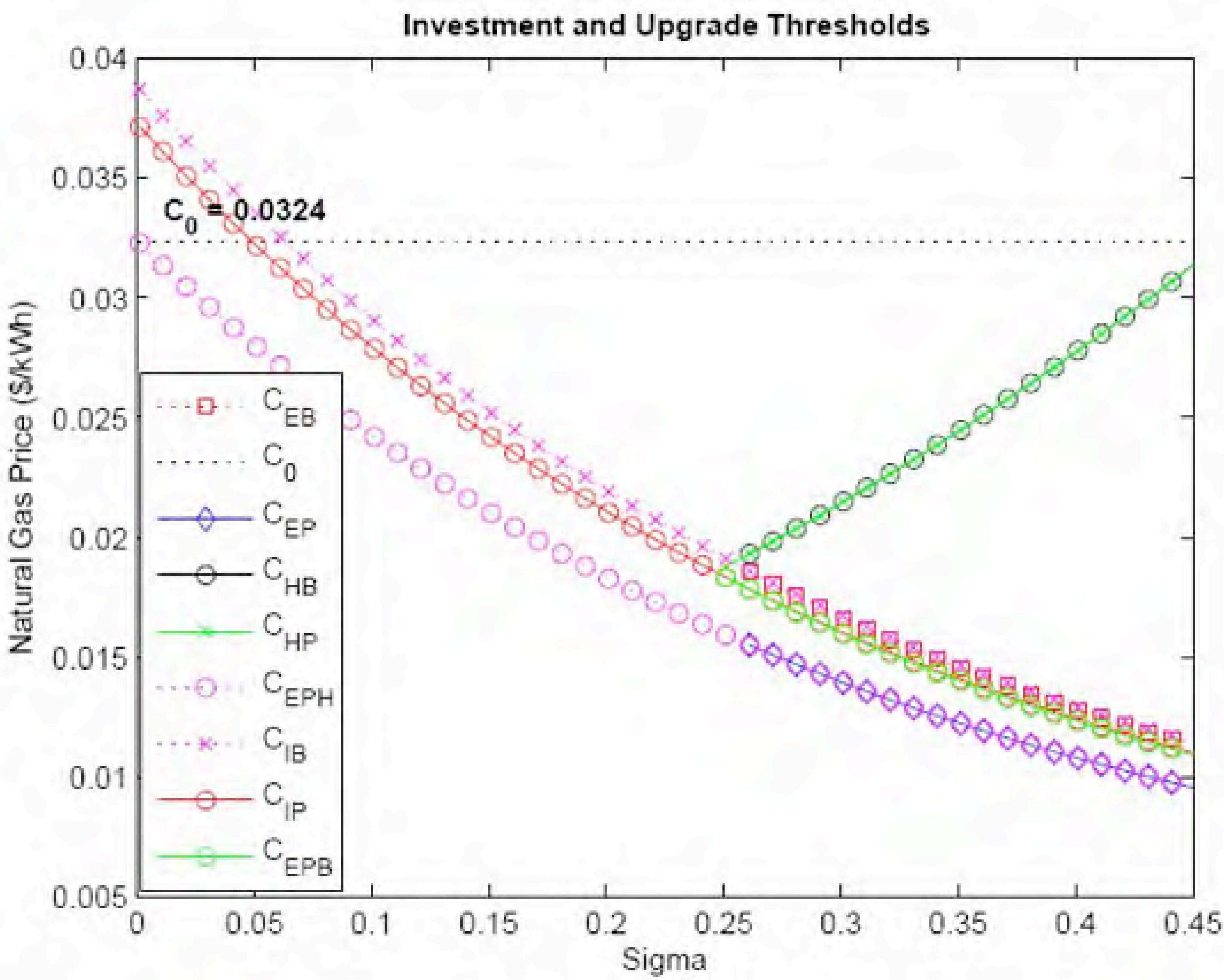
Numerical Example: Strategy 4



Numerical Example: Option Value of Flexibility



Numerical Example: NG Thresholds



Summary

- Take a real options approach to compare the investment and upgrade strategies of a CA-based commercial microgrid
- Find threshold NG prices for triggering investment in DG and both capacity and HX upgrade
  - Modularity facilitates investment, i.e., higher initial investment threshold than direct strategy
  - Strategy 2: as NG price volatility increases, lower cost savings outweigh benefits of lower risk
  - Strategy 3: most exposed to NG price, but increases in value with NG price volatility because higher cost savings possible via HX
  - Strategy 4: able to combine the benefits of both modular strategies with greater precision
- Directions for future research:
  - Include cooling loads and stochastic electricity price
  - Incorporate options to sell electricity back to the grid