A Model Predictive Control Approach for Long Term Planning of Capacity Investments in a District Heating System

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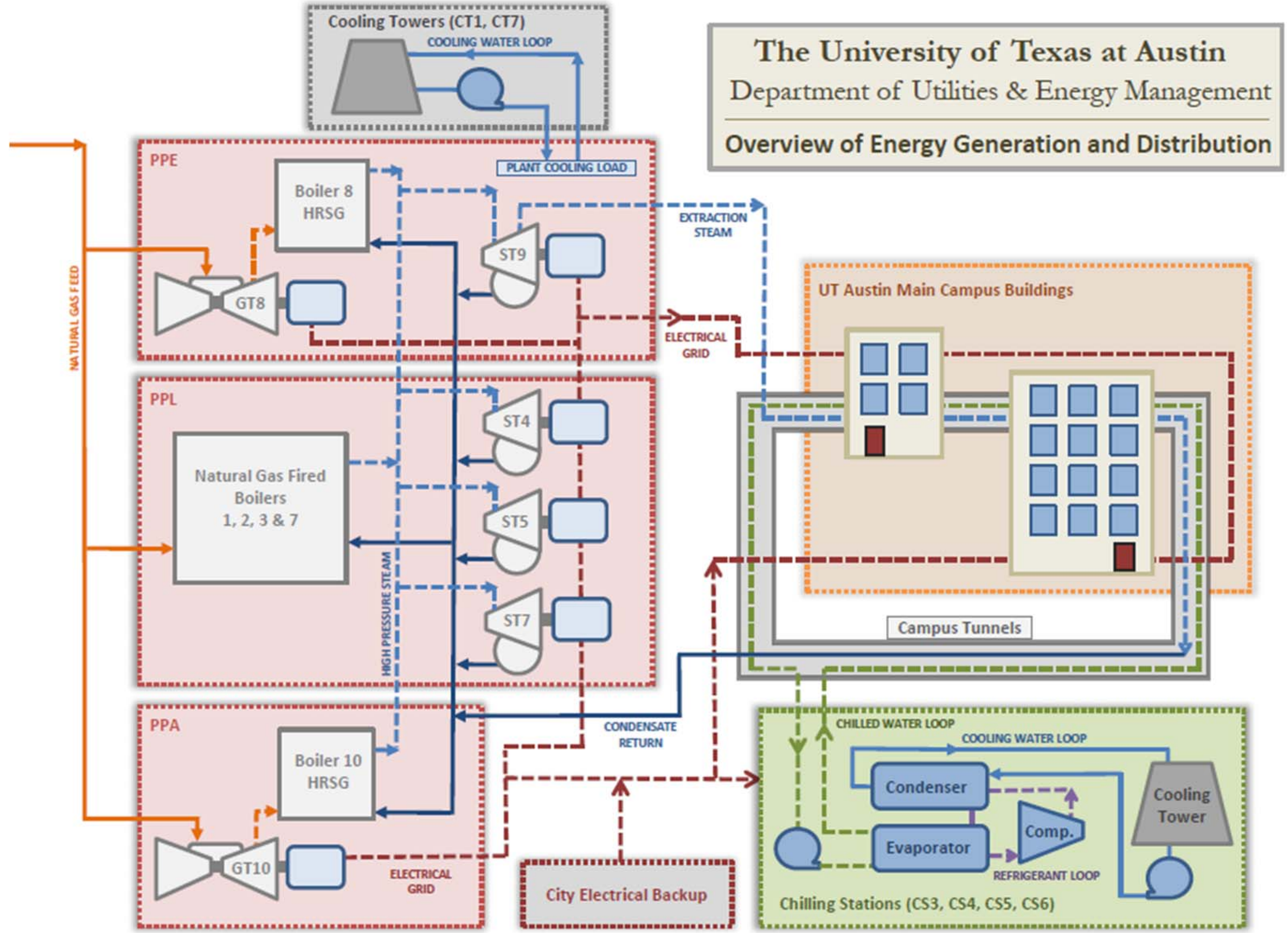
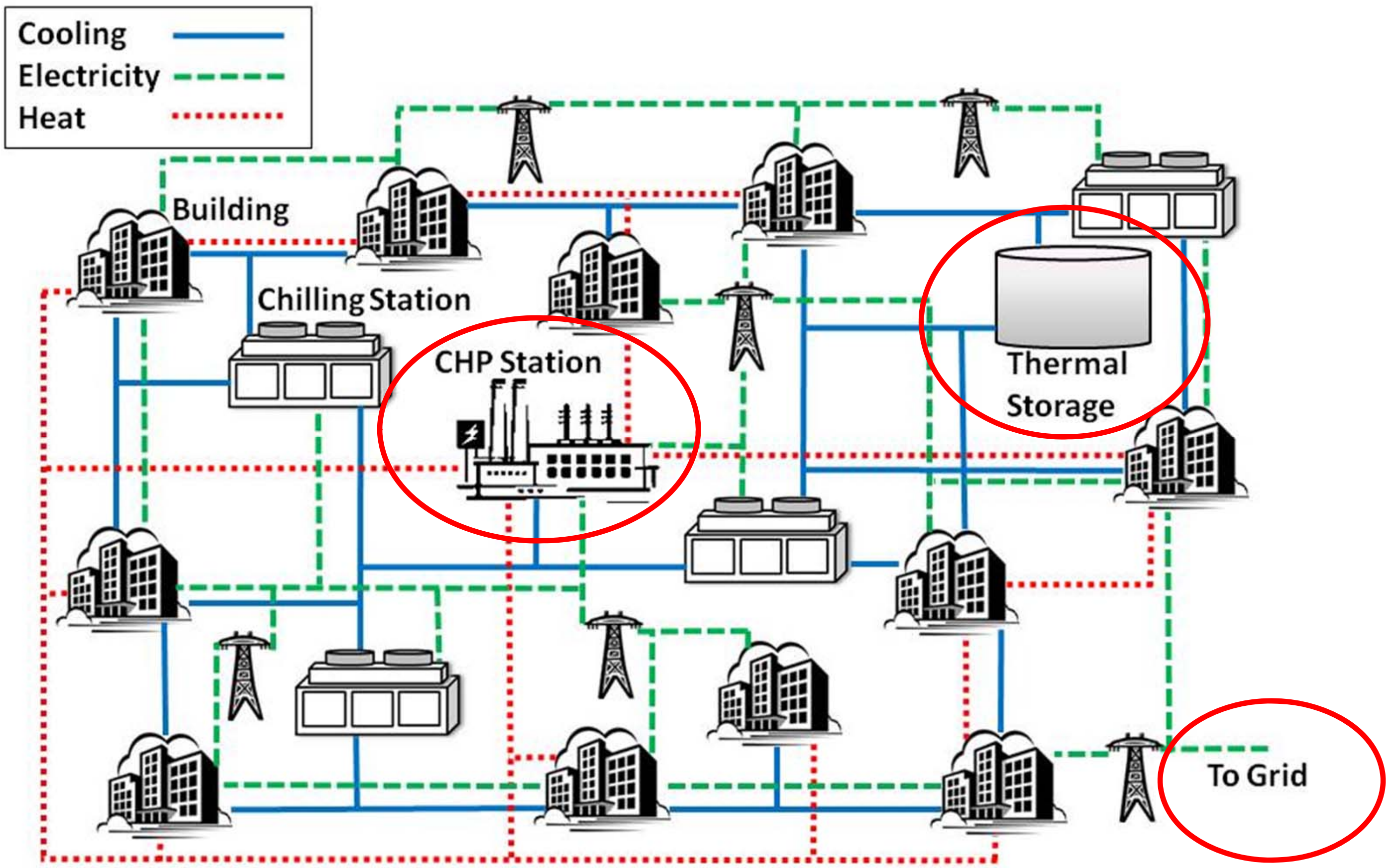
BYU Advanced Control and Optimization

- BYU PRISM Group Overview
- Dynamic Optimization for:
  - Advance Control for Oil Drilling Operations
  - Unmanned Aerial Vehicles
  - Systems Biology
  - Solid Oxide Fuel Cells
  - Energy Storage and the Smart Grid
  - Energy Systems Planning Under Uncertainty
- Needs and resources for dynamic optimization

District Energy System



Planning for a CHP system



CHP Capacity Planning Challenges

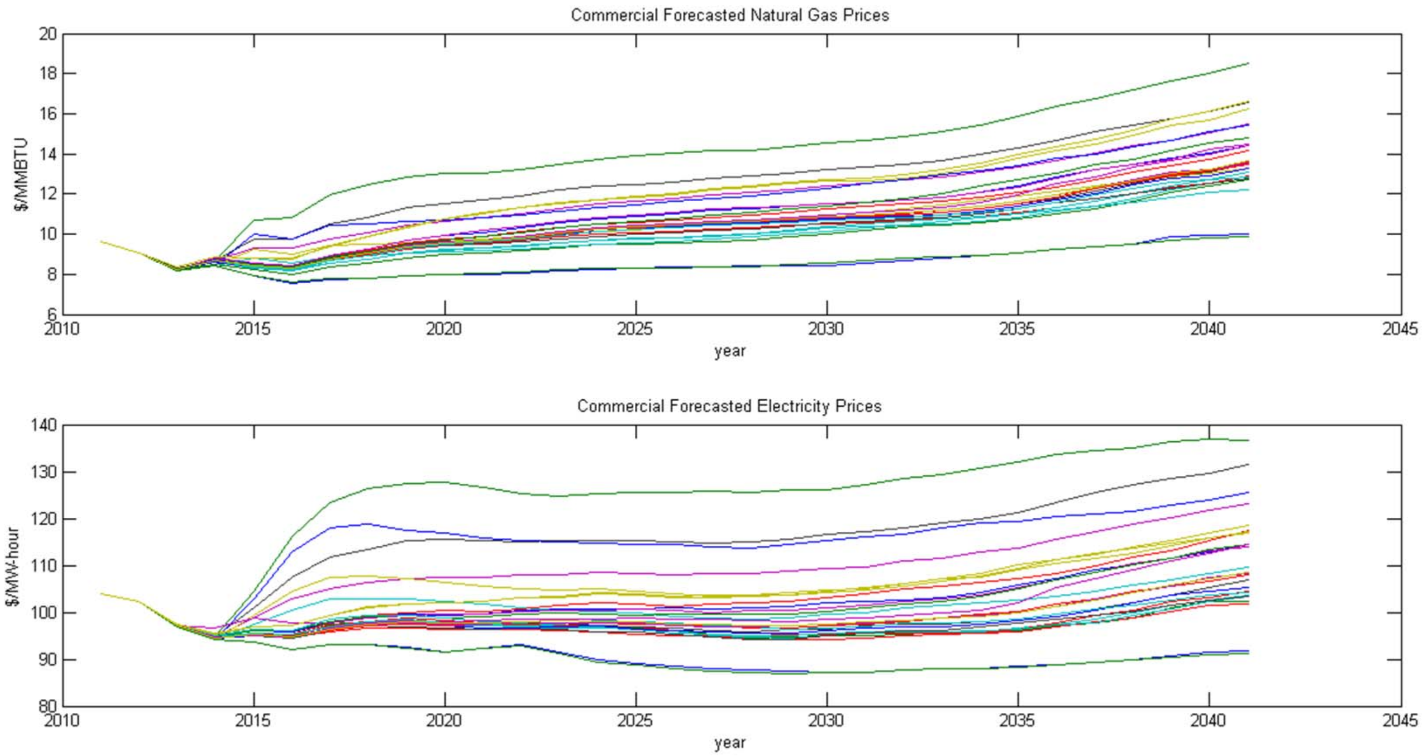
- Institutions and businesses invest in CHP systems to reduce energy costs.
- When to invest and capacity of CHP?

Utah State University (2004)
- Designed to cover electrical and thermal base load
- When natural gas prices are high, plant does not economically operate as designed and must operated as a peak shaver

University of Utah (2008)
- Strong financial analysis should consider that electricity and natural gas prices are variable
- Consider sizing of system to meet all electrical or thermal load
- Consider room for growth

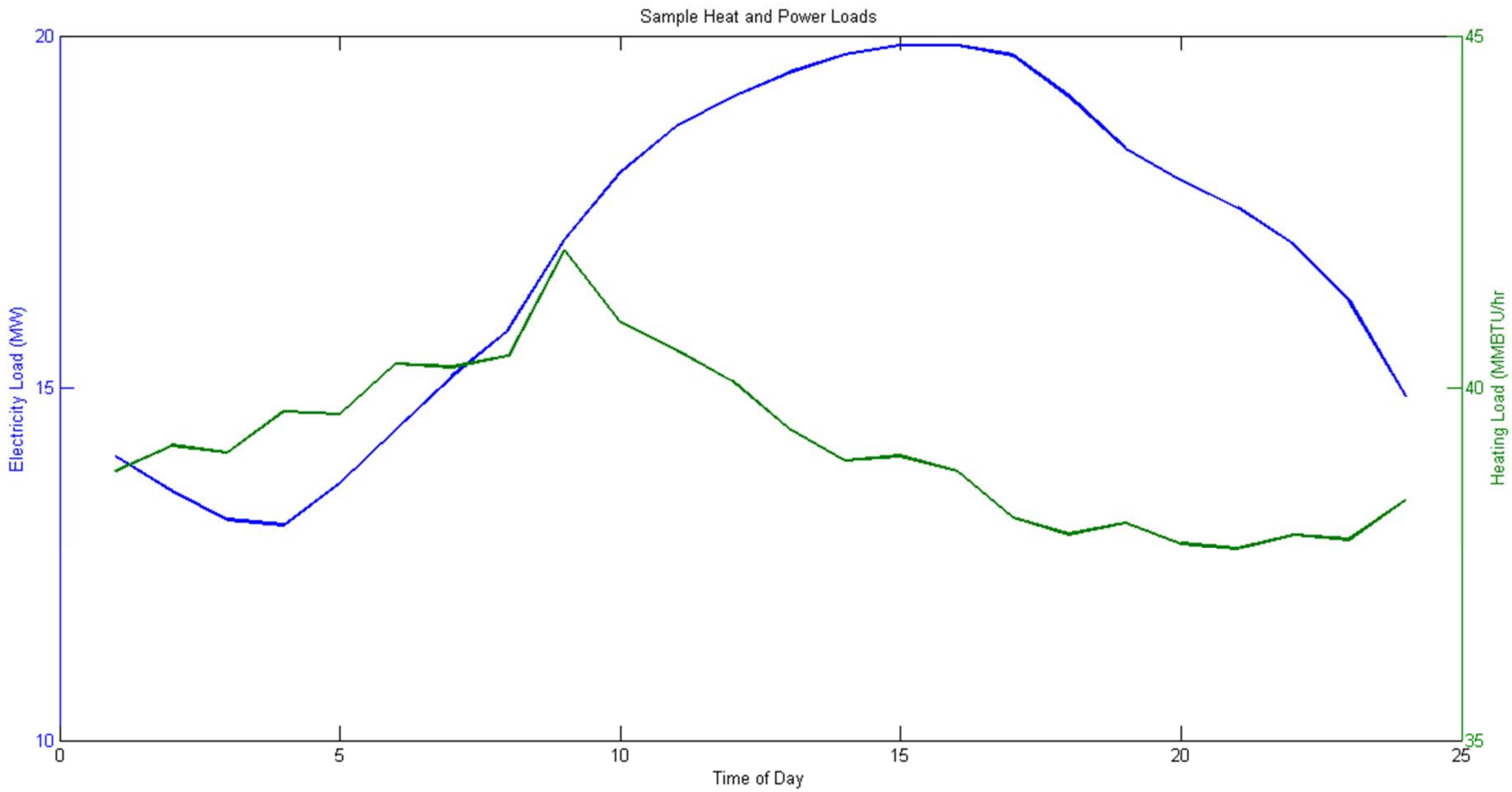
Source: DOE Clean Energy Application Center

Uncertain Energy Prices



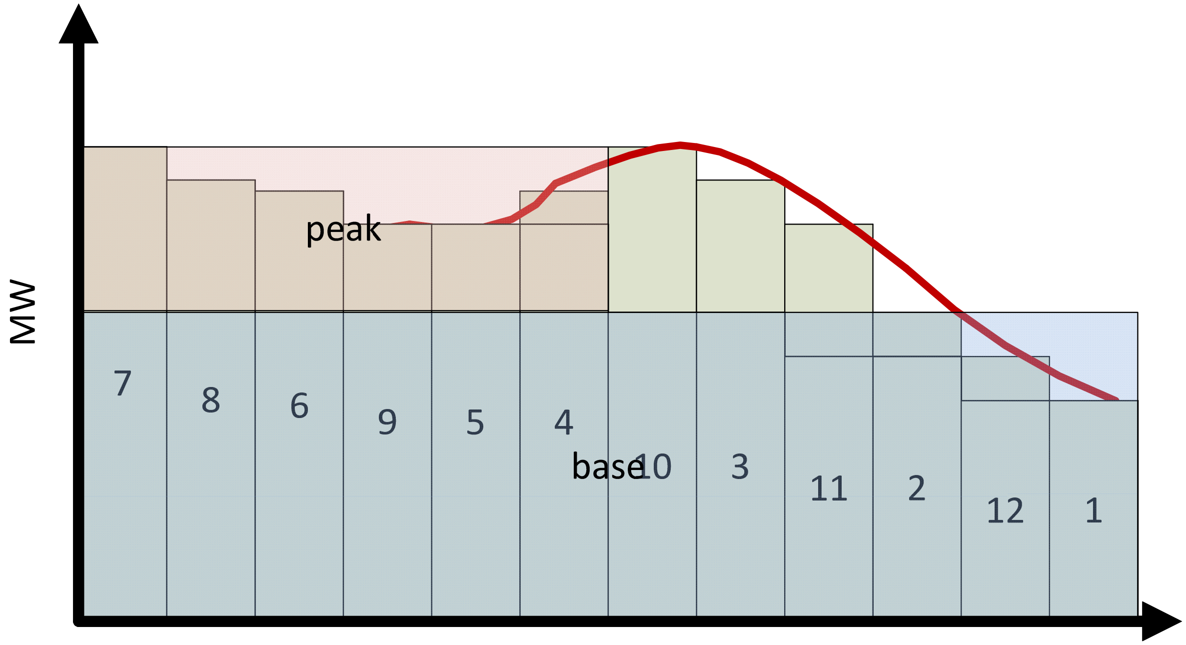
Source: EIA.gov

Energy Load Profiles for Campus



Traditional Approach

- Create Model:
- Electric and Heating Demand Model (winter and summer)



Traditional Model Formulation

Minimize :

$$\sum_p cc_p(e_p + x_p) + \sum_k \sum_s ic_{k.s} \cdot z_{k.s} + \sum_k \sum_s \sum_i du_{k.s.i}(\sum_p oc_p \cdot y_{p.k.s})$$

Subject to :

$$e_p + x_p \geq \sum_k \sum_s y_{p.k.s} \quad for\ all\ p$$

$$r_{k.s.electric} = z_{k.s} + du_{k.s.electric}(\sum_p y_{chp.k.s}) \quad for\ all\ k.s$$

$$r_{k.s.thermal} \leq du_{k.s.electric}(\sum_p y_{boiler.k.s} + y_{chp.k.s} \cdot f_{hrg}) \quad for\ all\ k.s$$

$$x_p \geq 0$$

$$y_{p.k.s} \geq 0$$

$$z_{k.s} \geq 0$$

Traditional Results

CapacityAllocationPlan [MW] summer

	c1				c2				c3				c4				c5				c6				c7				
	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	P
boiler																													
base																													
peak																													
chp																													
base	15.0	15.0	15.0	18.0	15.0	15.1	15.8	18.0	15.0	15.3	16.5	18.0	15.0	15.5	17.4	18.0	15.0	15.6	18.2	18.0	15.0	15.8	19.1	18.0	15.0	15.9	20.0	18.0	
peak	2.0	2.6	2.6	2.0	2.0	2.7	2.8	2.0	2.0	2.7	2.9	2.0	2.0	2.5	2.6	2.0	2.0	2.4	1.8	2.0	2.0	2.3	0.9	2.0	2.0	2.1		2.0	

CapImportedPlanMW [MW]

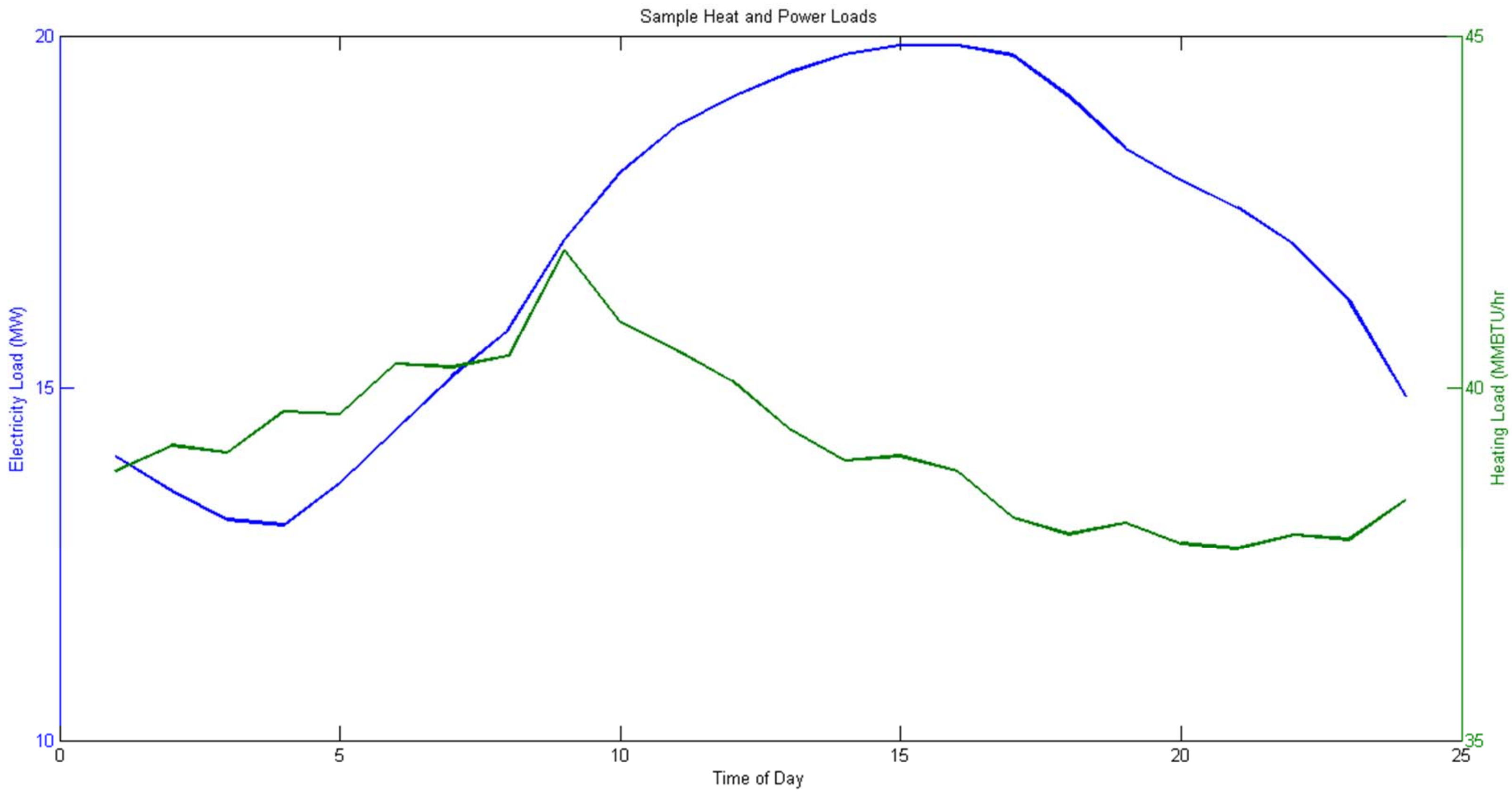
	c1				c2				c3				c4				c5				c6				c7			
	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV	Plan I	Plan II	Plan III	Plan IV
base																												
summer																											0.10	
winter																												
peak																												
summer	3.00	2.35	2.35	4.00	3.00	2.38	2.47	4.00	3.00	2.40	2.59	4.00	3.00	2.60	3.15	4.00	3.00	2.80	4.31	4.00	3.00	3.00	5.53	4.00	3.00	3.20	6.70	4.00
winter	1.53	1.53	1.53	1.53	1.53	1.54	1.61	1.53	1.53	1.56	1.69	1.53	1.53	1.58	1.77	1.53	1.53	1.60	1.88	1.53	1.53	1.62	2.97	1.53	1.53	1.62	4.12	1.53

NewCapPlan [MW]

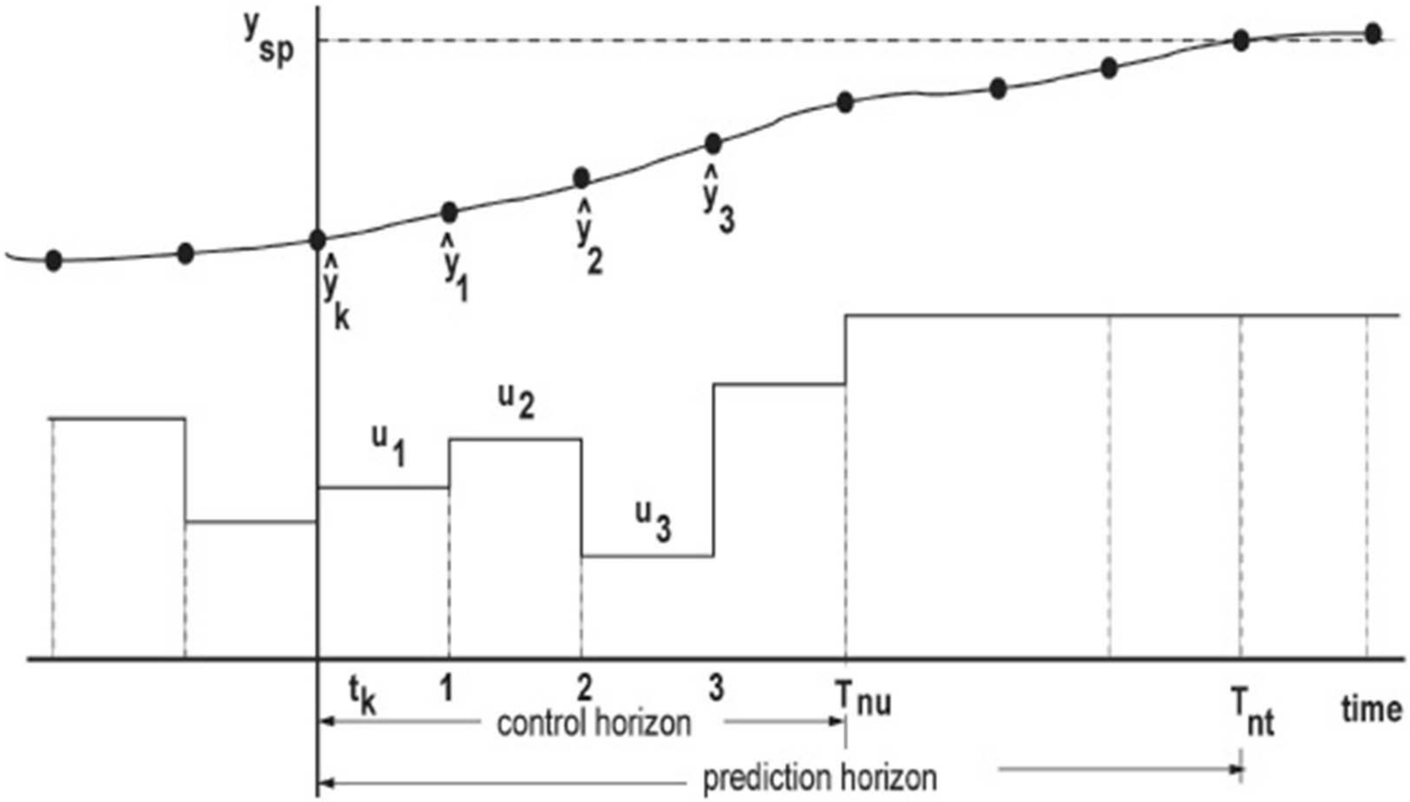
	Plan I	Plan II	Plan III	Plan IV
boiler				
c1				
c2				
c3				
c4				
c5				
c6				
c7				
c8				
chp				
c1	17.0	18.0	20.0	20.0
c2				
c3				
c4				
c5				
c6				
c7				
c8				

LP or NLP formulation, optimizing through discrete scenarios. Lacks system dynamics.

Energy Load Profiles for Campus



Model Predictive Control (MPC)



Problem Formulation Overview

- Standard Problem Formulation

$$\max \quad f(x)$$
$$\text{subject to } g\left(\frac{\partial x}{\partial t}, x, u, p\right) = 0$$
$$\text{h}\ (x, u, p) \leq 0$$

- Objective Function (*f(x)*)
- Dynamic model equations that relate trajectory constraints, sensor dynamics, and discrete decisions
- Uncertain model inputs as unmodeled or stochastic elements
- Solve large-scale NLP or MINLP problems (100,000+ variables)

Dynamic Nonlinear DAE Problem

Nonlinear Objective function

$$\min J(x,y,u) = (Cost_{capital} + Cost_{operating} + Cost_{environmental})$$

$$s.t.\ \ 0 = f\left(\frac{\partial x}{\partial t}, x, y, u\right)$$

Turbine and boiler dynamics

$$0 = g(x,y,u)$$

$$0 < h(x,y,u)$$

$$x, y \in \Re^n \ \ u \in \Re^m$$

Nonlinear demand and operating constraints

MPC Framework

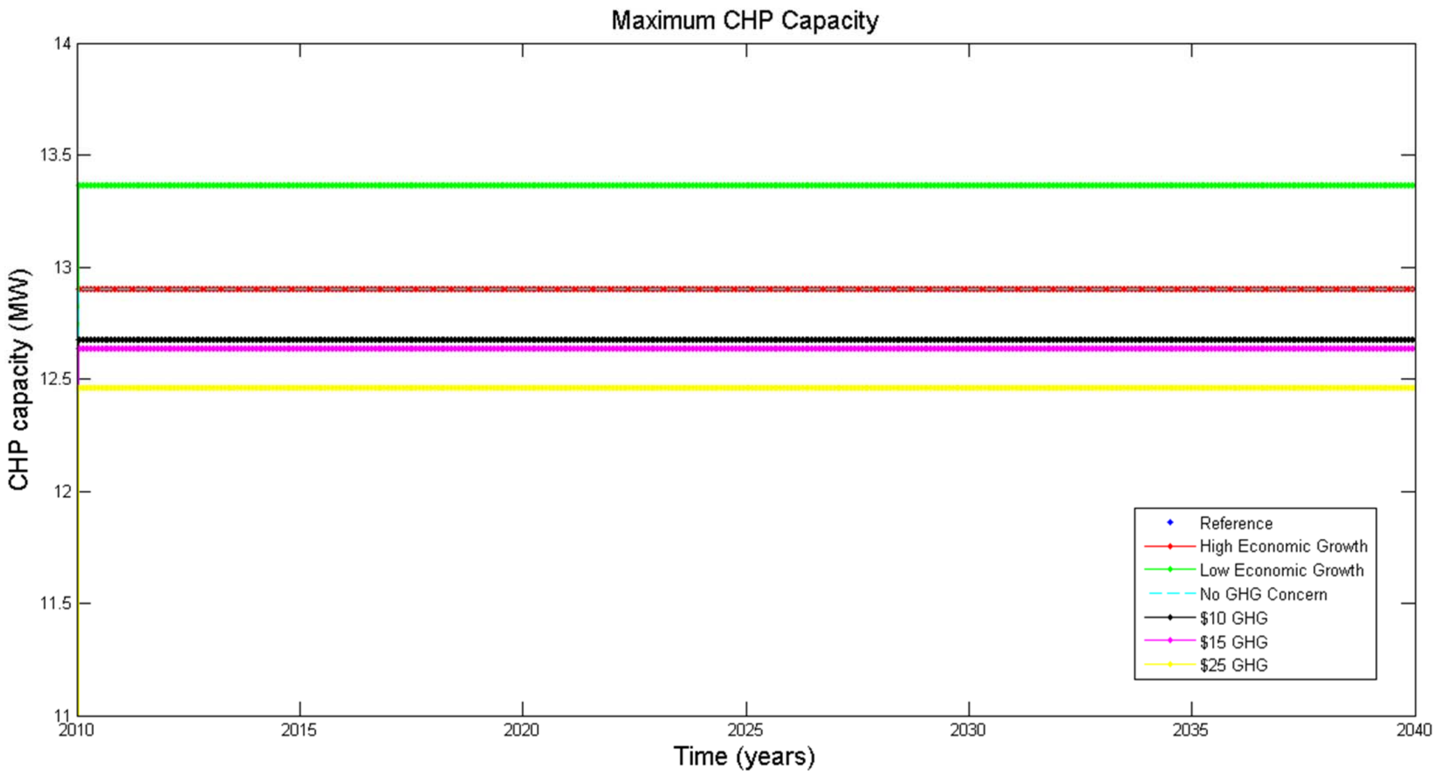
Control ℓ_1-norm Objective

$$\min_d \Phi = w_{hi}^T (e_{hi}) + w_{lo}^T (e_{lo}) \ldots$$
$$\ldots + (y_m)^T c_y + (u)^T c_u + (\Delta u)^T c_{\Delta u}$$
$$\text{s.t.} \quad 0 = f(\dot{x}, x, u, p, d)$$
$$0 = g(y_x, x, u, d)$$
$$a \geq h(x, u, d) \geq b$$

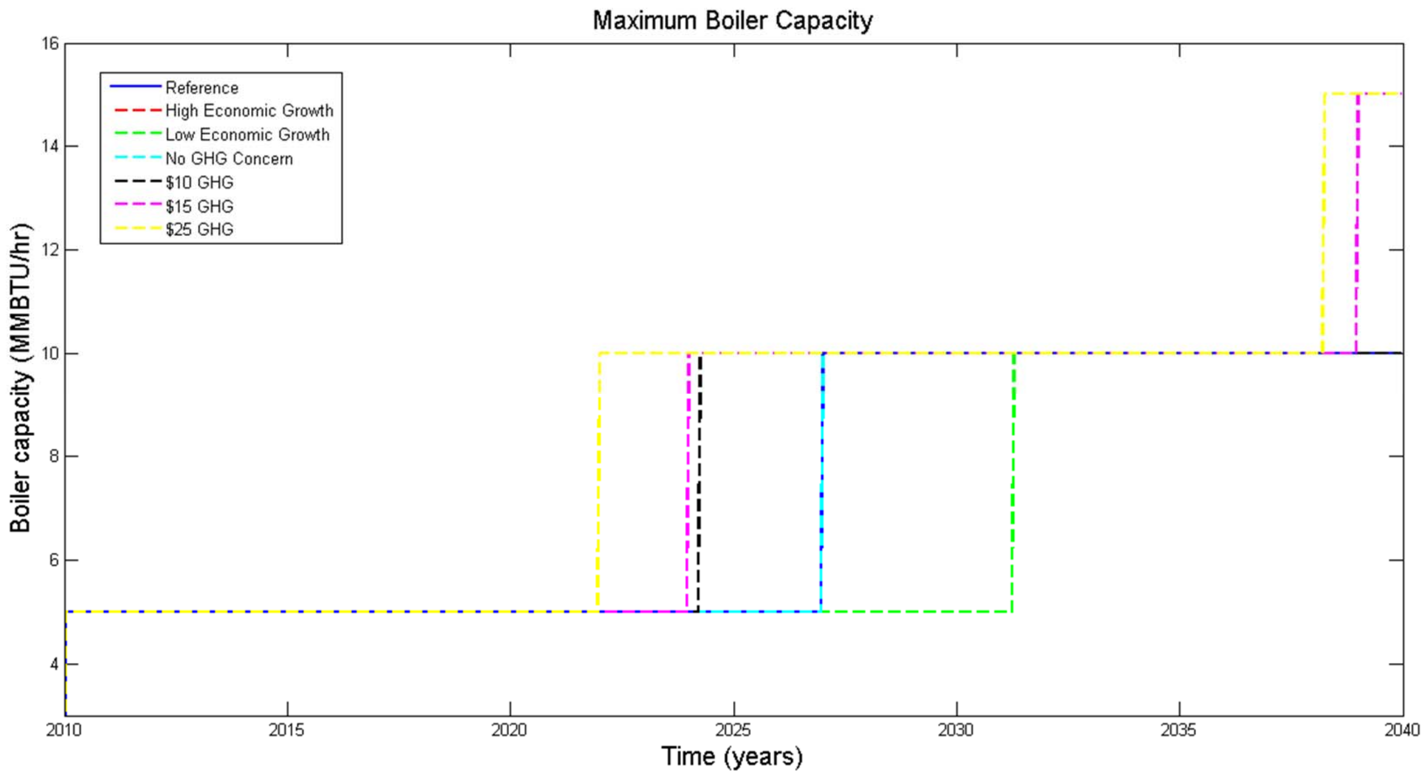
$$\tau_c \frac{\partial y_{t,hi}}{\partial t} + y_{t,hi} = sp_{hi}$$
$$\tau_c \frac{\partial y_{t,lo}}{\partial t} + y_{t,lo} = sp_{lo}$$
$$e_{hi} \geq (y_m - y_{t,hi})$$
$$e_{lo} \geq (y_{t,lo} - y_m)$$

Hedengren, J.D. and Asgharzadeh, R .Implementation Details for Nonlinear Modeling, Data Reconciliation, and Dynamic Optimization

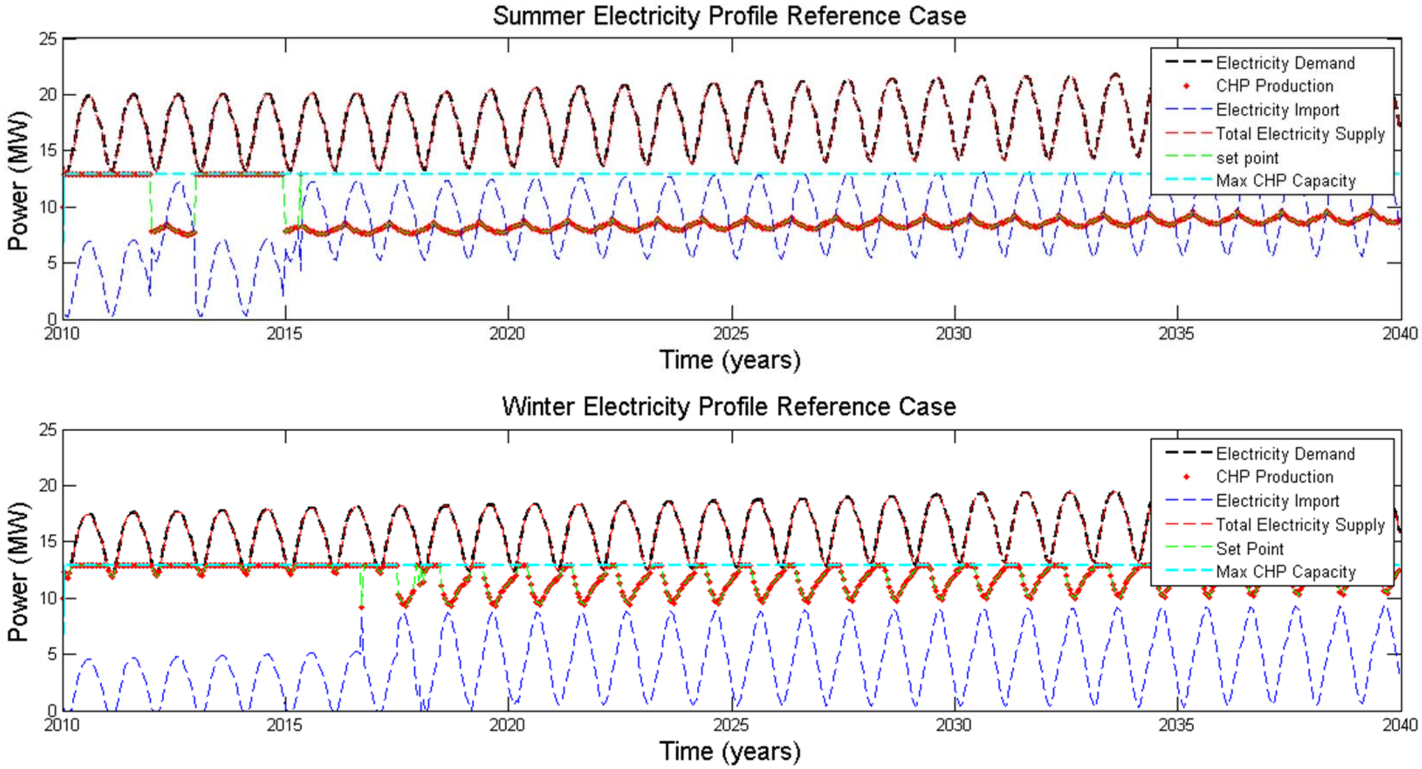
Dynamic Optimization Results



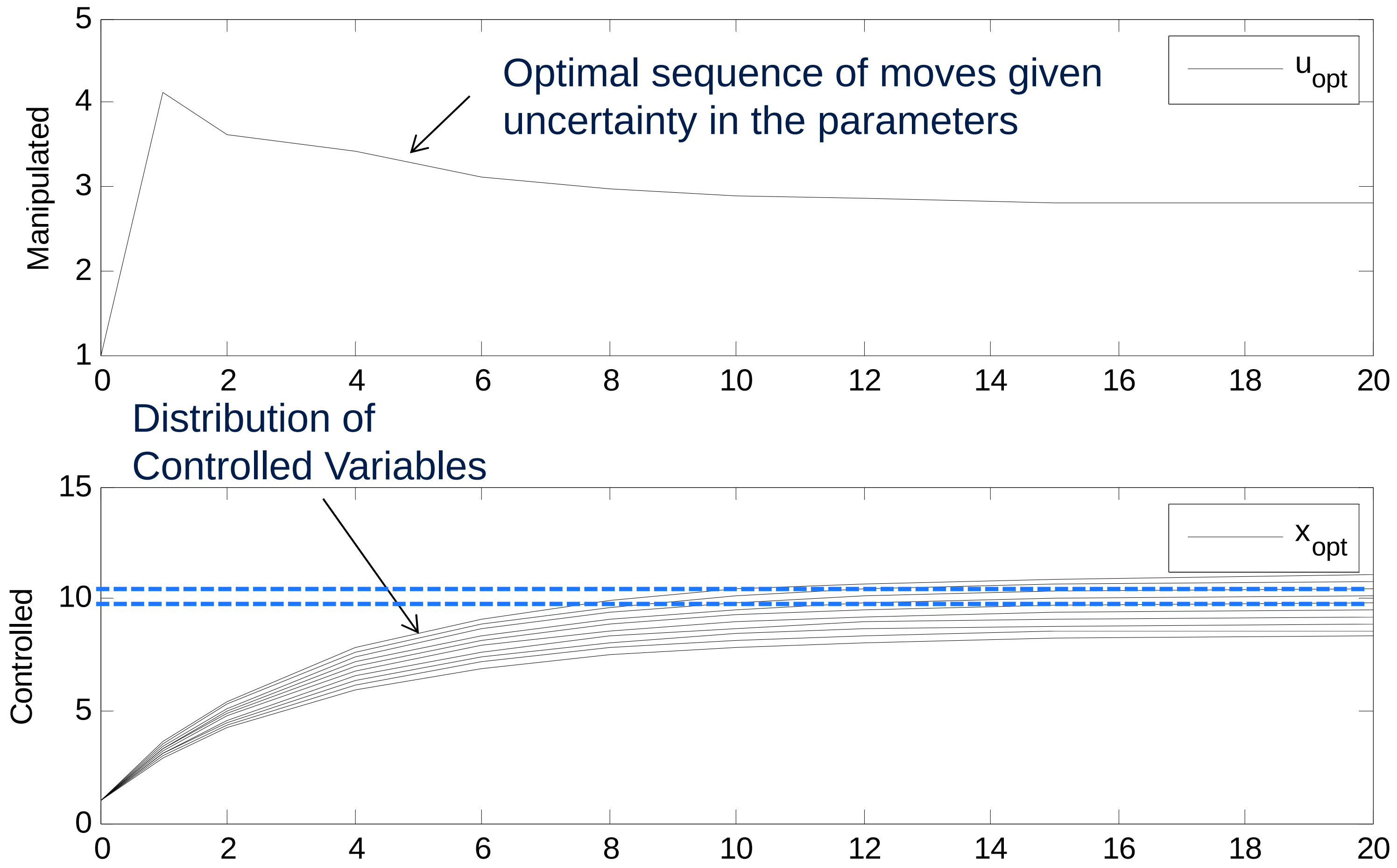
Dynamic Optimization Results



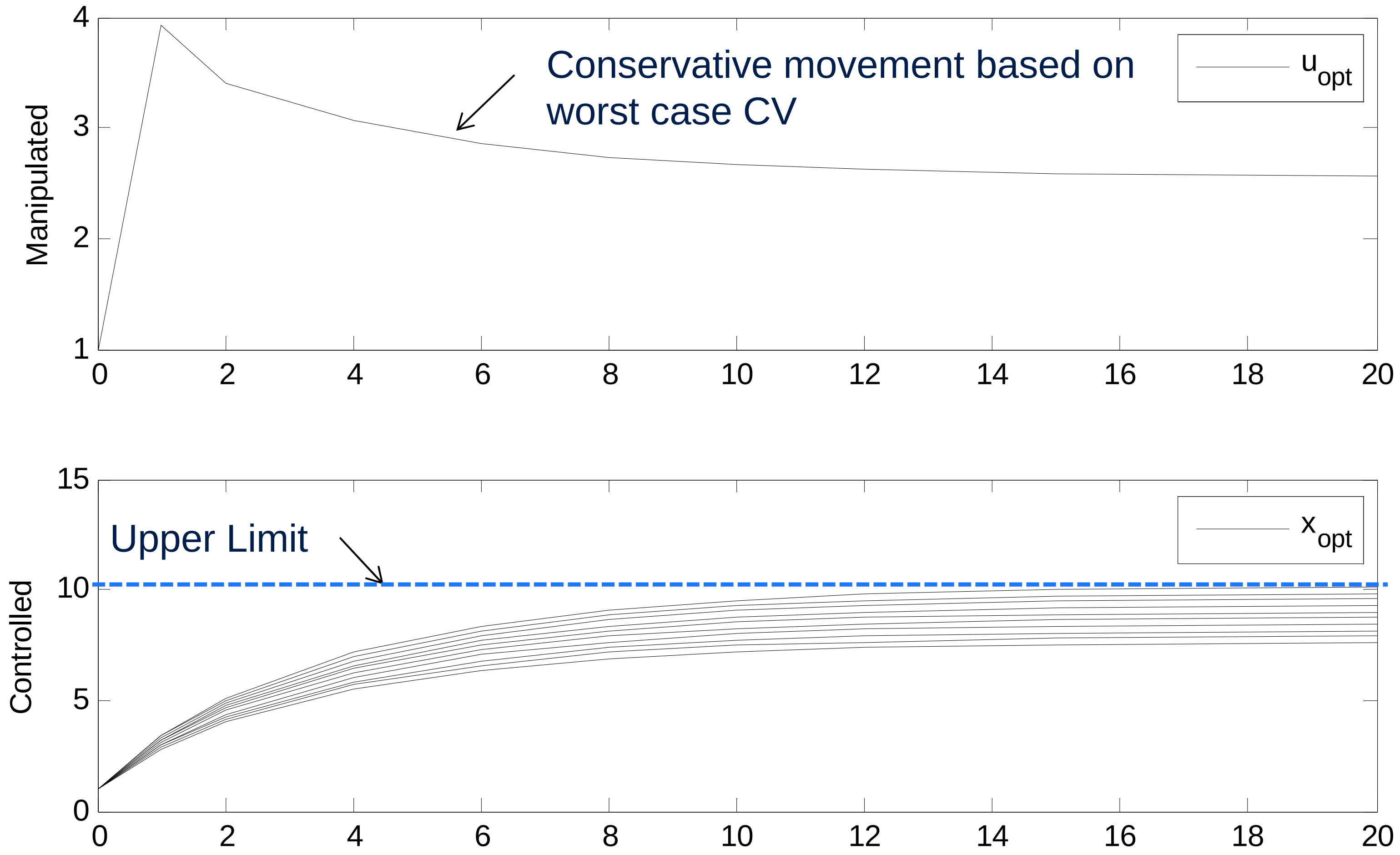
Utilization of Capacity



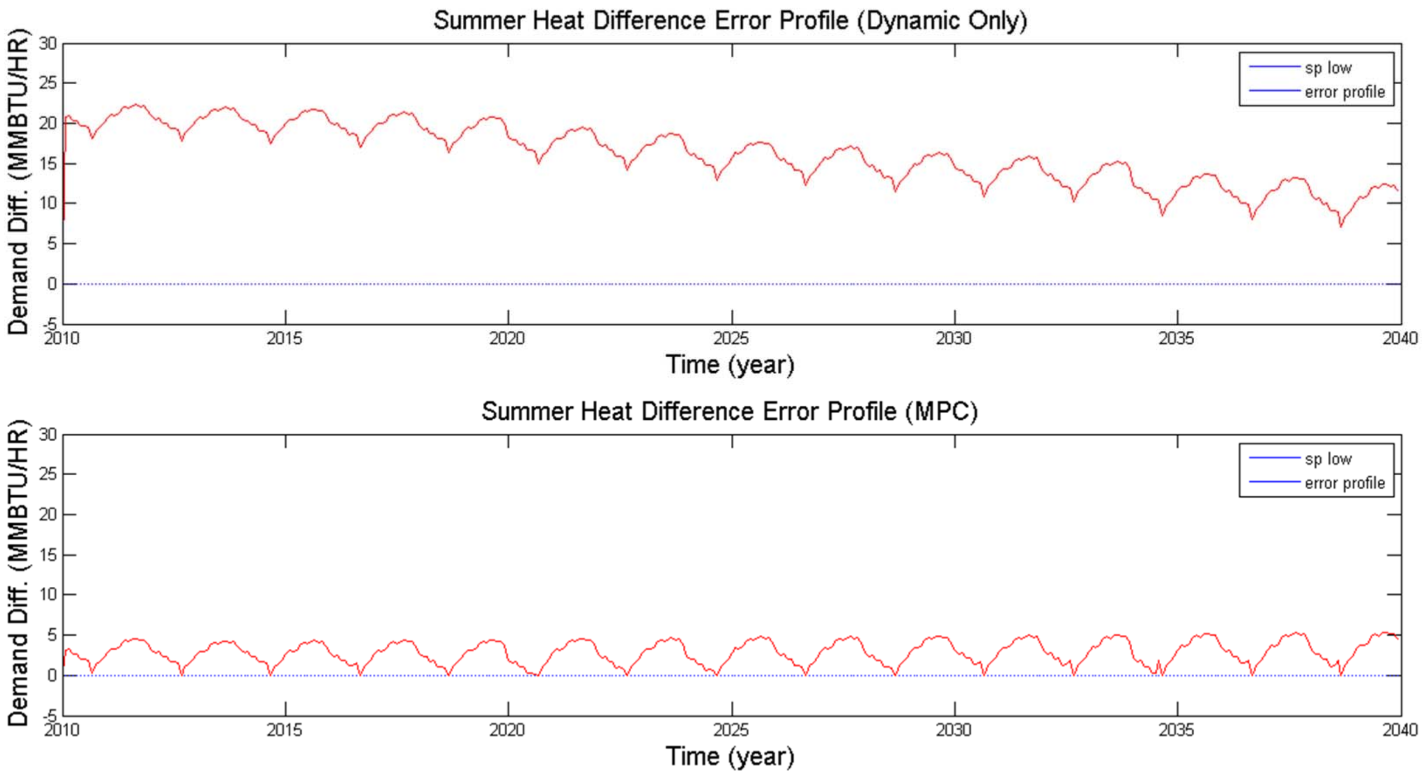
Optimize to a Target Range



Optimize to a Limit

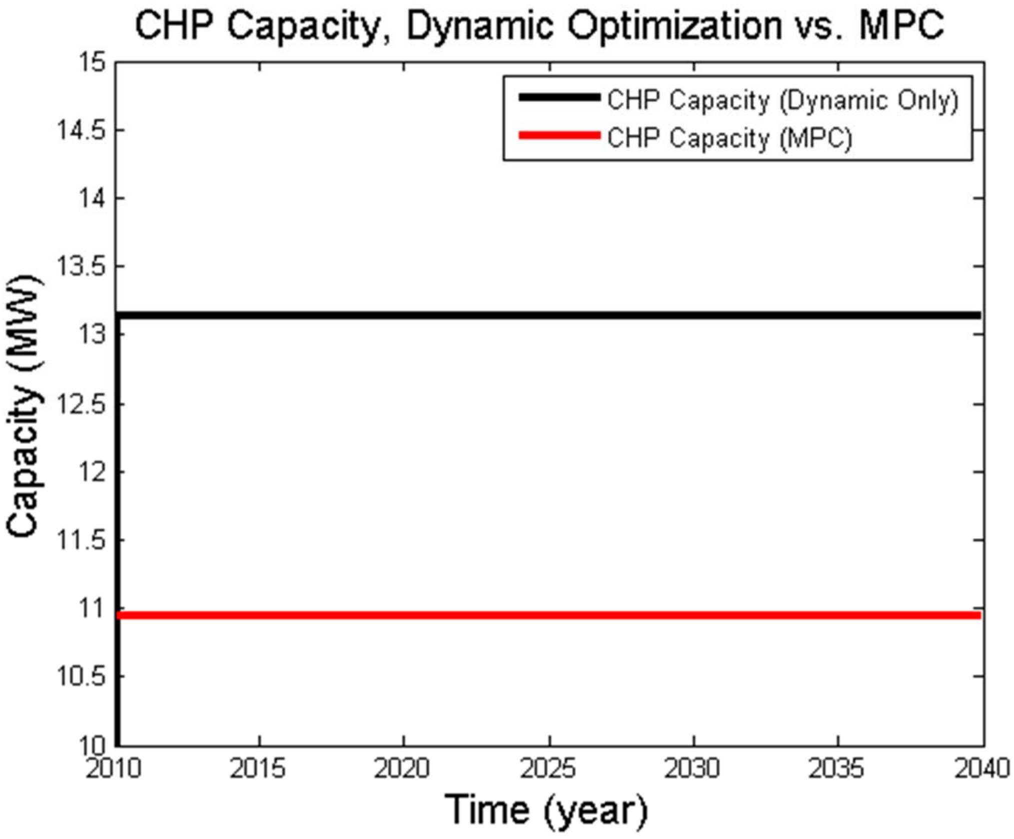


MPC



Summer Heat Difference Error Profile (Dynamic Only)
sp low
error profile
Demand Diff. (MMBTU/HR)
30
25
20
15
10
5
0
-5
2010
2015
2020
2025
2030
2035
2040
Time (year)
Summer Heat Difference Error Profile (MPC)
sp low
error profile
Demand Diff. (MMBTU/HR)
Time (year)

Effects on CHP Capacity Planning



APMonitor Optimization Suite

The APMonitor Modeling Language is optimization software for mixed-integer and differential algebraic equations. It is coupled with large-scale solvers for linear, quadratic, nonlinear, and mixed integer programming (LP, QP, NLP, MILP, MINLP). Modes of operation include data reconciliation, real-time optimization, dynamic simulation, and nonlinear predictive control. It is available through MATLAB, Python, or from a web browser interface.

Future Development

- Simultaneous Optimization of cases to account for uncertainty in natural gas and electricity prices.
- Effects of selling power to the grid.
- MINLP formulation for more realistic capacity optimization.
- Simulate a true control problem with disturbance variables (variable costs) to simulate uncertainty.