DYNAMIC OPTIMIZATION

Energy System Planning under Uncertainty

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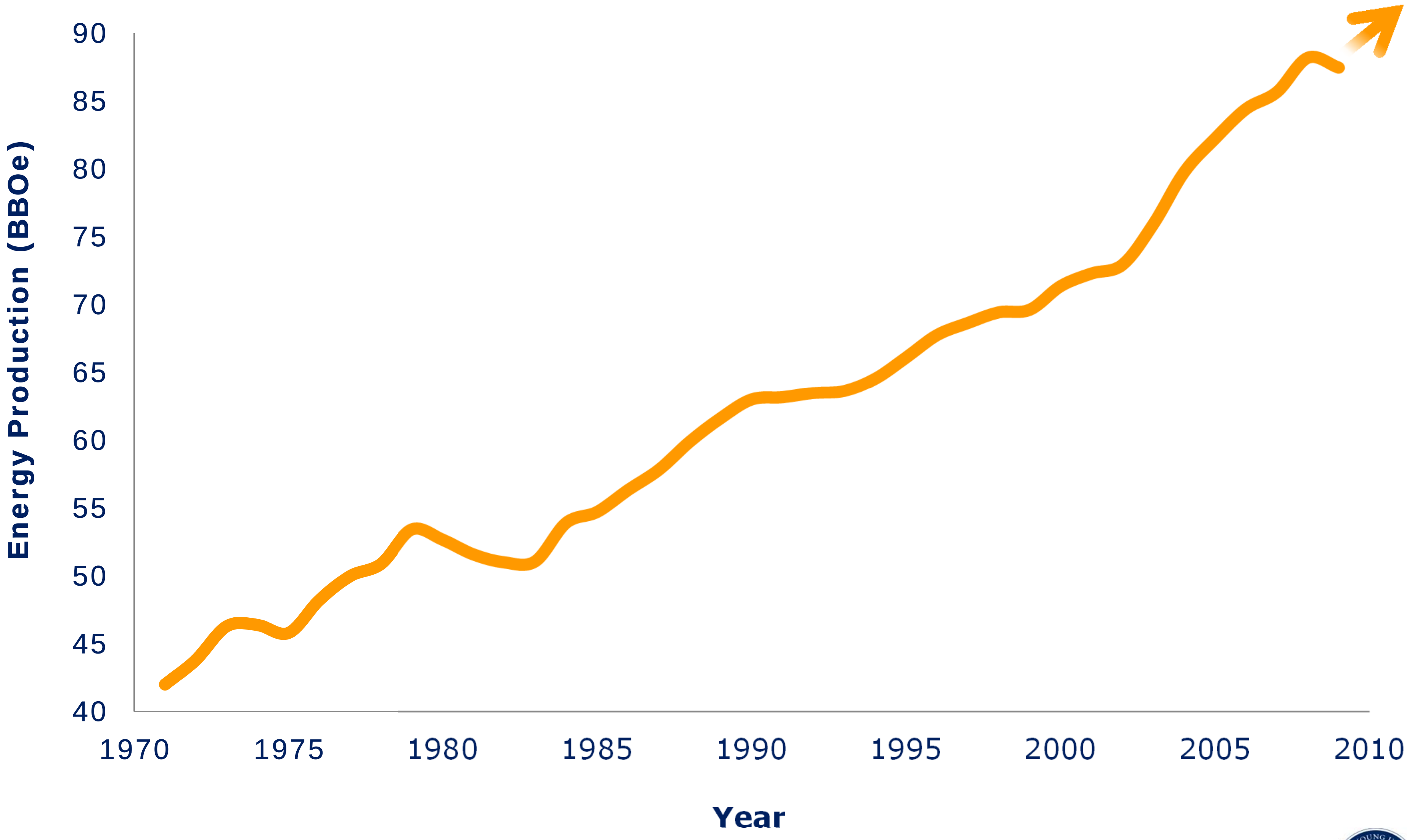
Global Energy Production



http://data.worldbank.org/indicator/EG.EGY.PROD.KT.OE?cid=GPD_31

Overview

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

PRISM Group

- Methods
  - Mixed Integer Nonlinear Programming (MINLP)
  - Dynamic Planning and Optimization
  - Uncertain, Forecasted, Complex Systems
- Research Applications
  - Unmanned Aerial Vehicle (UAV) control
  - Systems biology and pharmacokinetics
  - Oil and gas exploration and production
  - Hybrid and sustainable energy systems

Problem Formulation

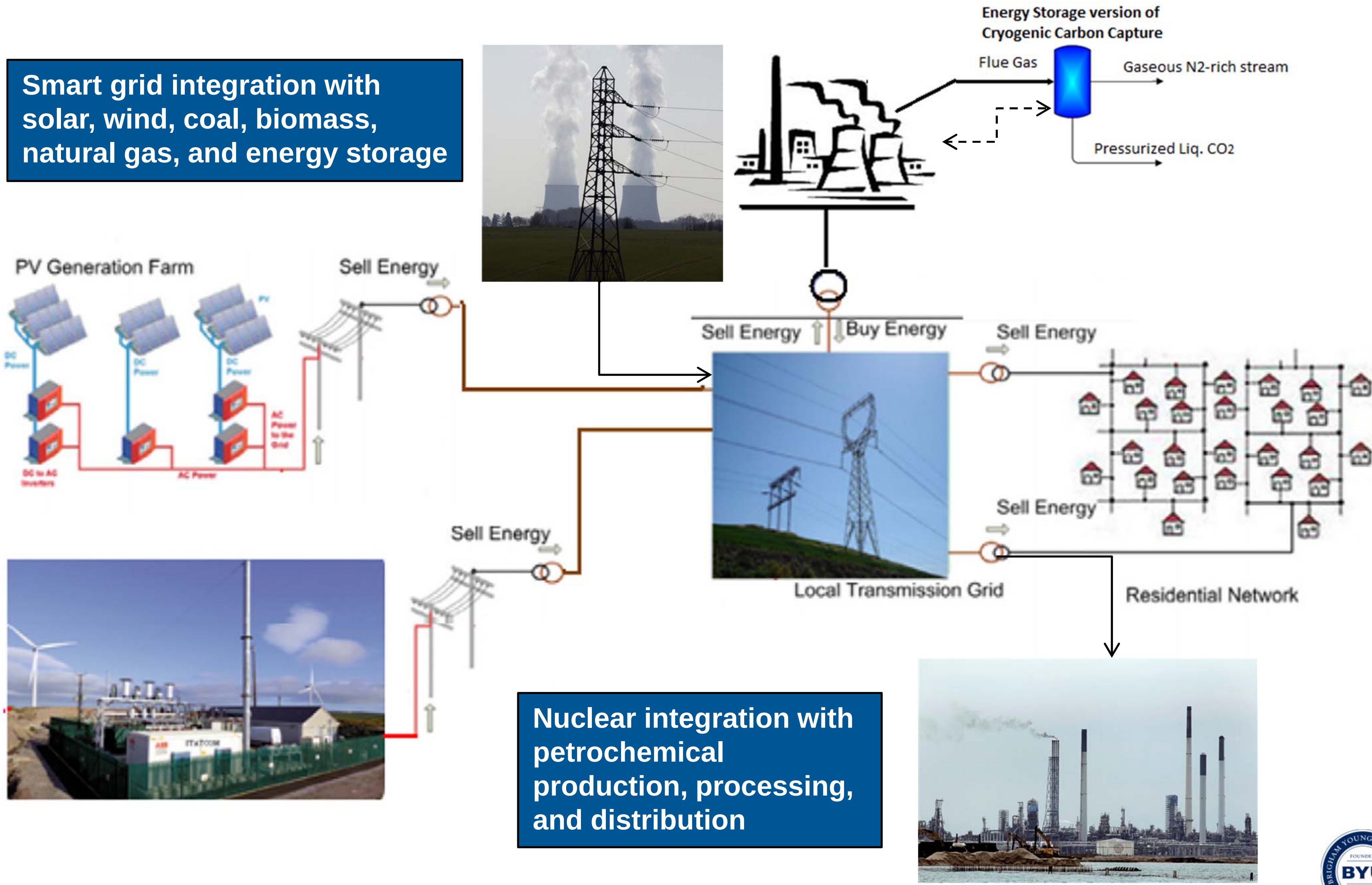
- Standard Problem Formulation

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

- 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 MINLP problems (100,000+ variables)

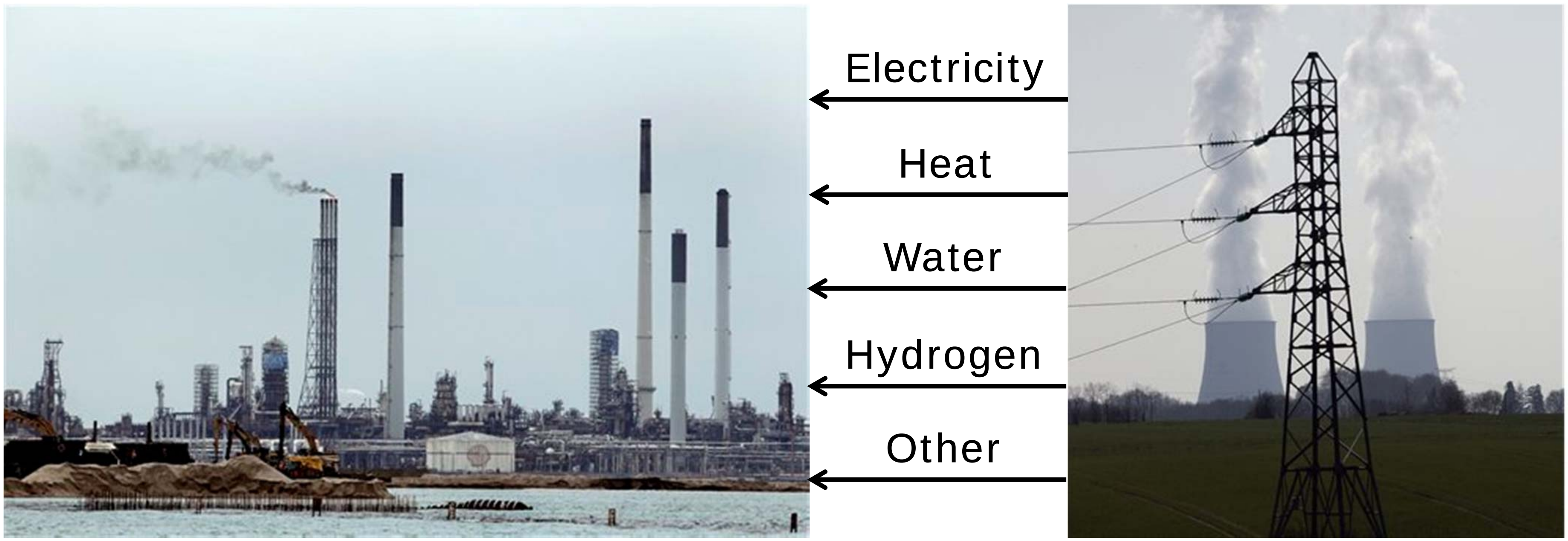
Smart Grid Optimization

Smart grid integration with solar, wind, coal, biomass, natural gas, and energy storage



Nuclear integration with petrochemical production, processing, and distribution

Nuclear with Petrochemical Industries

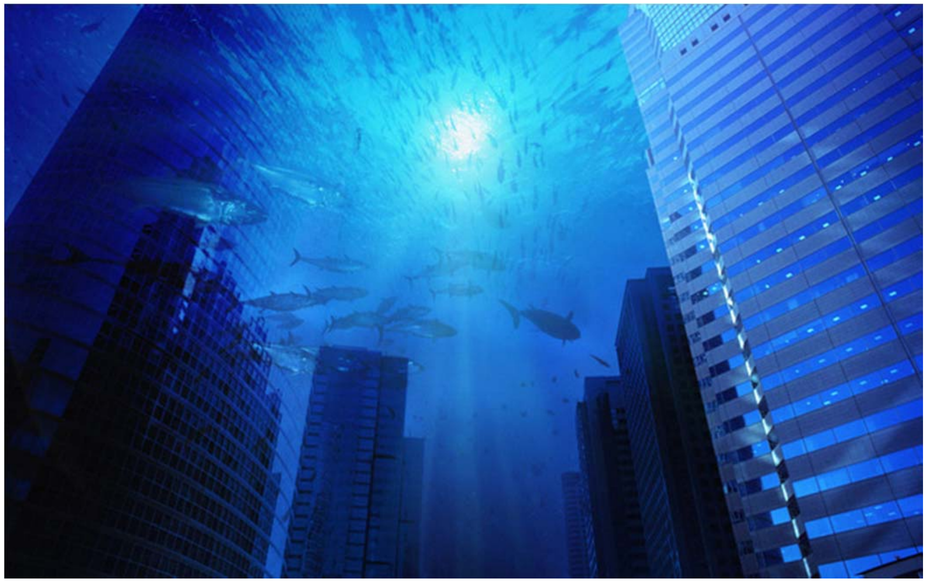


- 12% of total U.S. energy use from refining and chemicals
- $57 billion annually on energy
- Potential refinery and nuclear integration with electricity, heat, hydrogen, and other production-consumption pairings
- Transportation fuels are 28% of U.S. energy total

Underwater Oil Rigs

- Petrobras, a Brazilian oil company, plans to use unmanned, highly automated underwater oil rigs beginning in 2020

- Nuclear reactors for:
  - Electricity
  - Heated pipe in pipe to discourage hydrate formation
  - Gas, water, oil processing



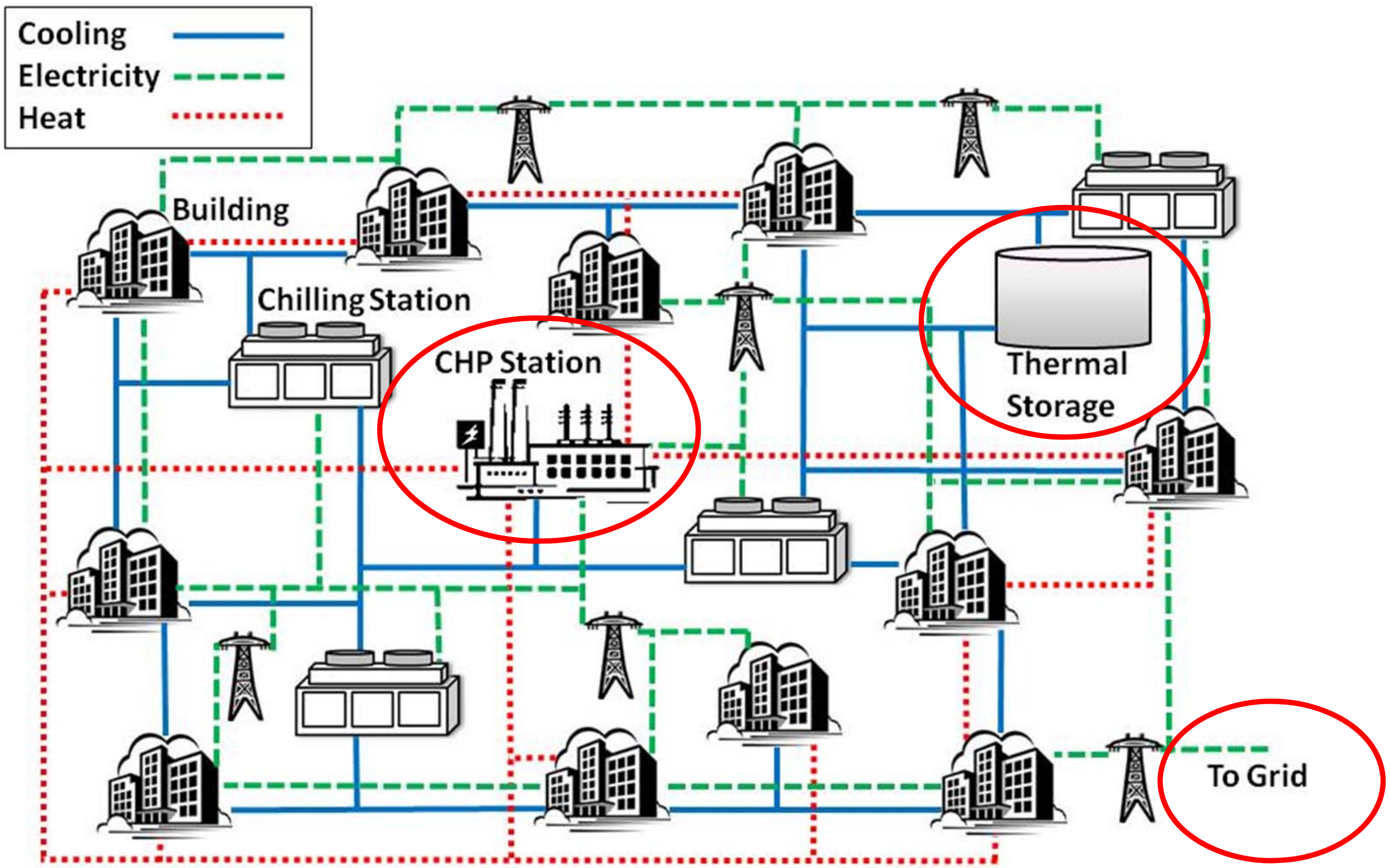
Nuclear for Water Purification

- Cooling towers purify and consume 1.05 gal/kW-hr
- Several nations have access to nuclear power, but limited amounts of renewable fresh water

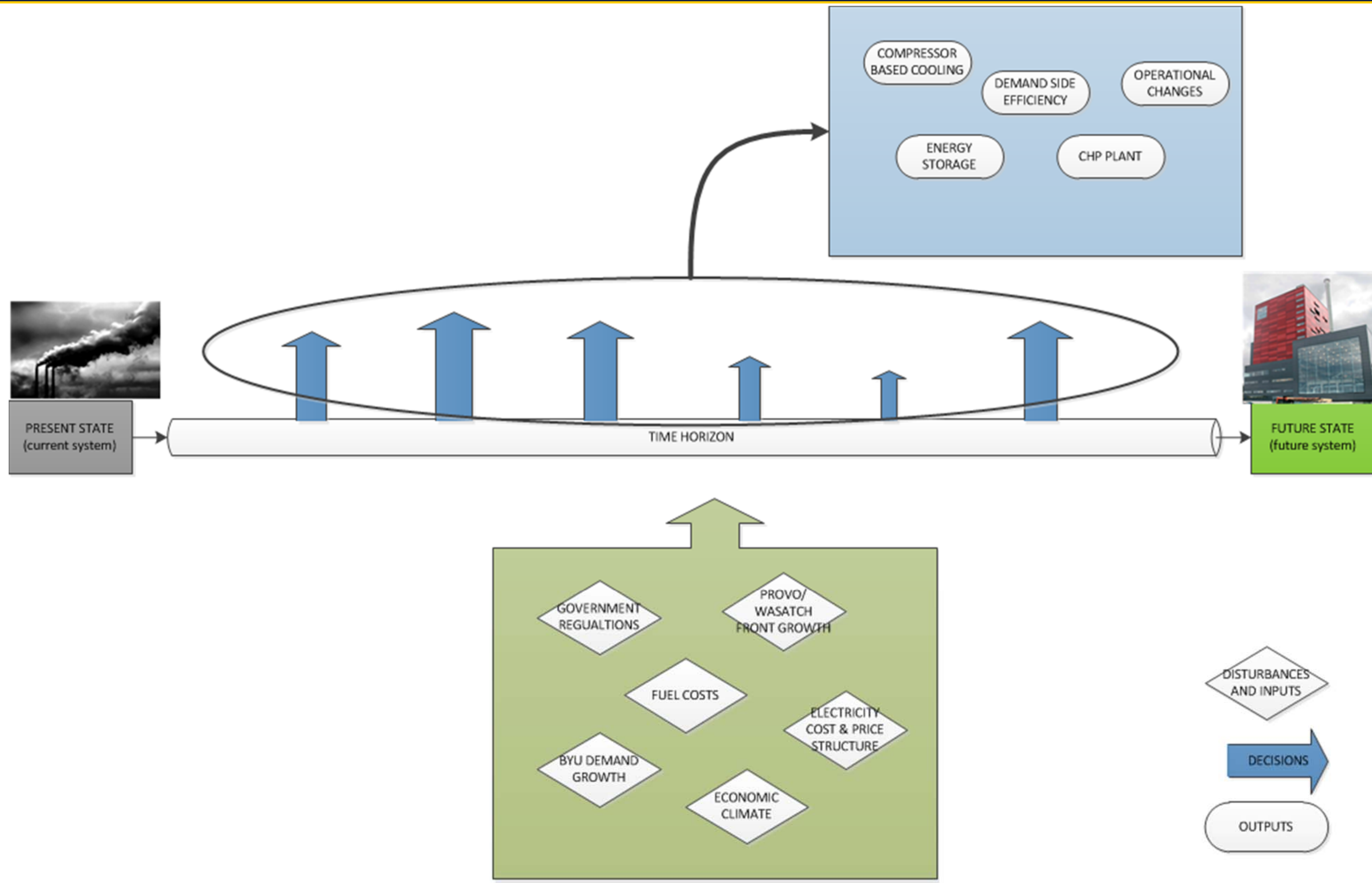
World's largest desalination facility in Saudi Arabia to produce electricity and water (July 2013)

KSA desalination consumes 300,000 barrels of oil per day at $3.20/m^3$

District Heating and Cooling

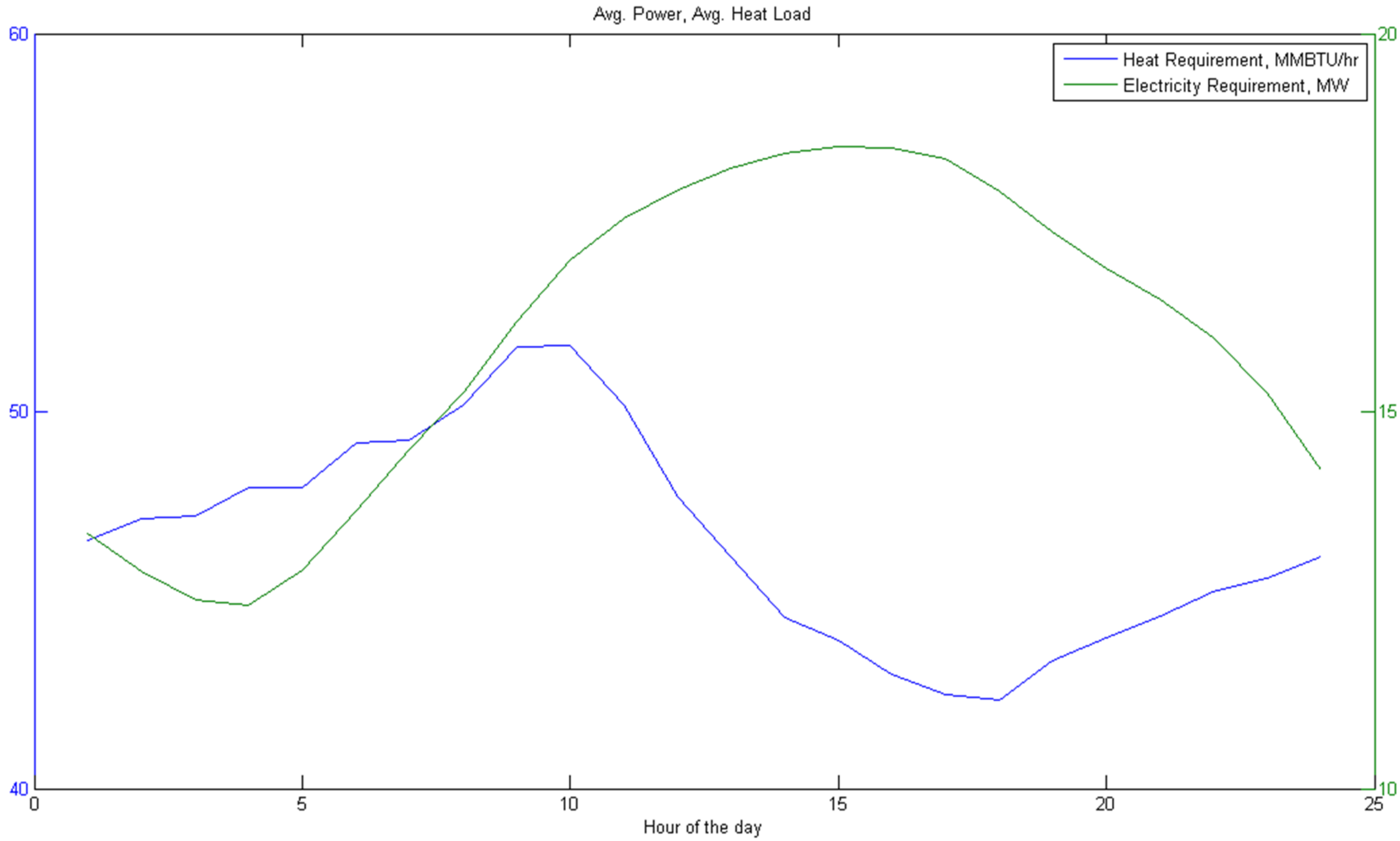


Planning of Investment Decisions



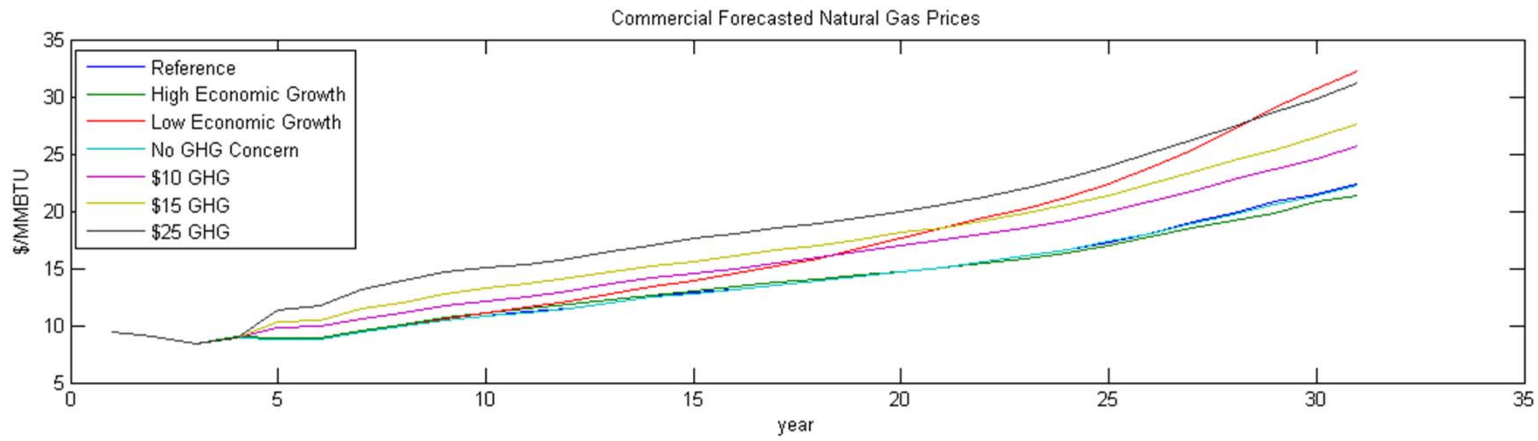
District Energy Profiles

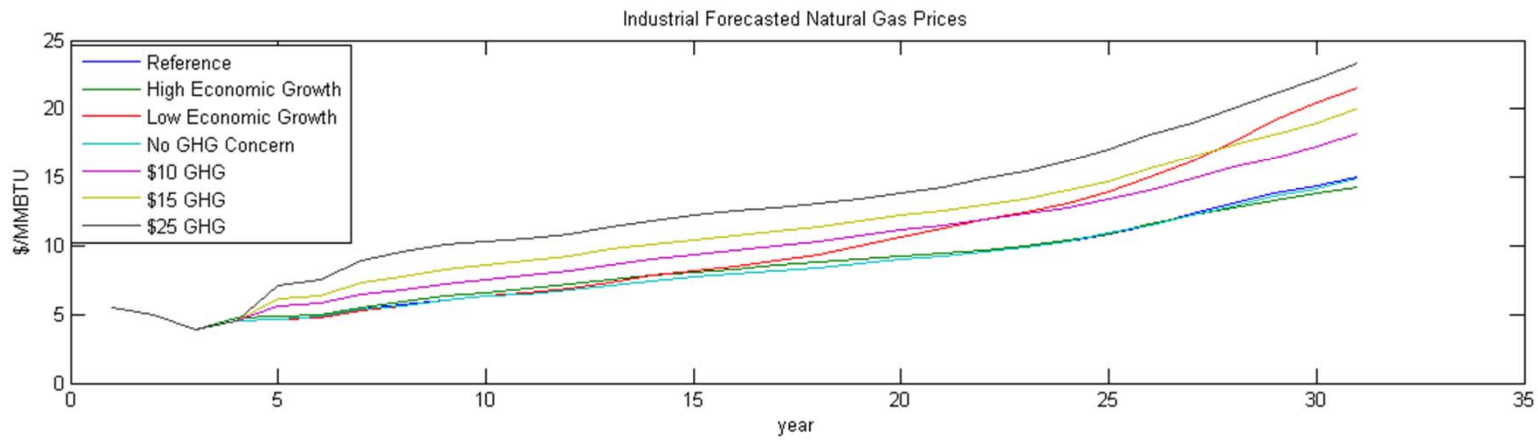
Heat Demand (MMBTU/hr)



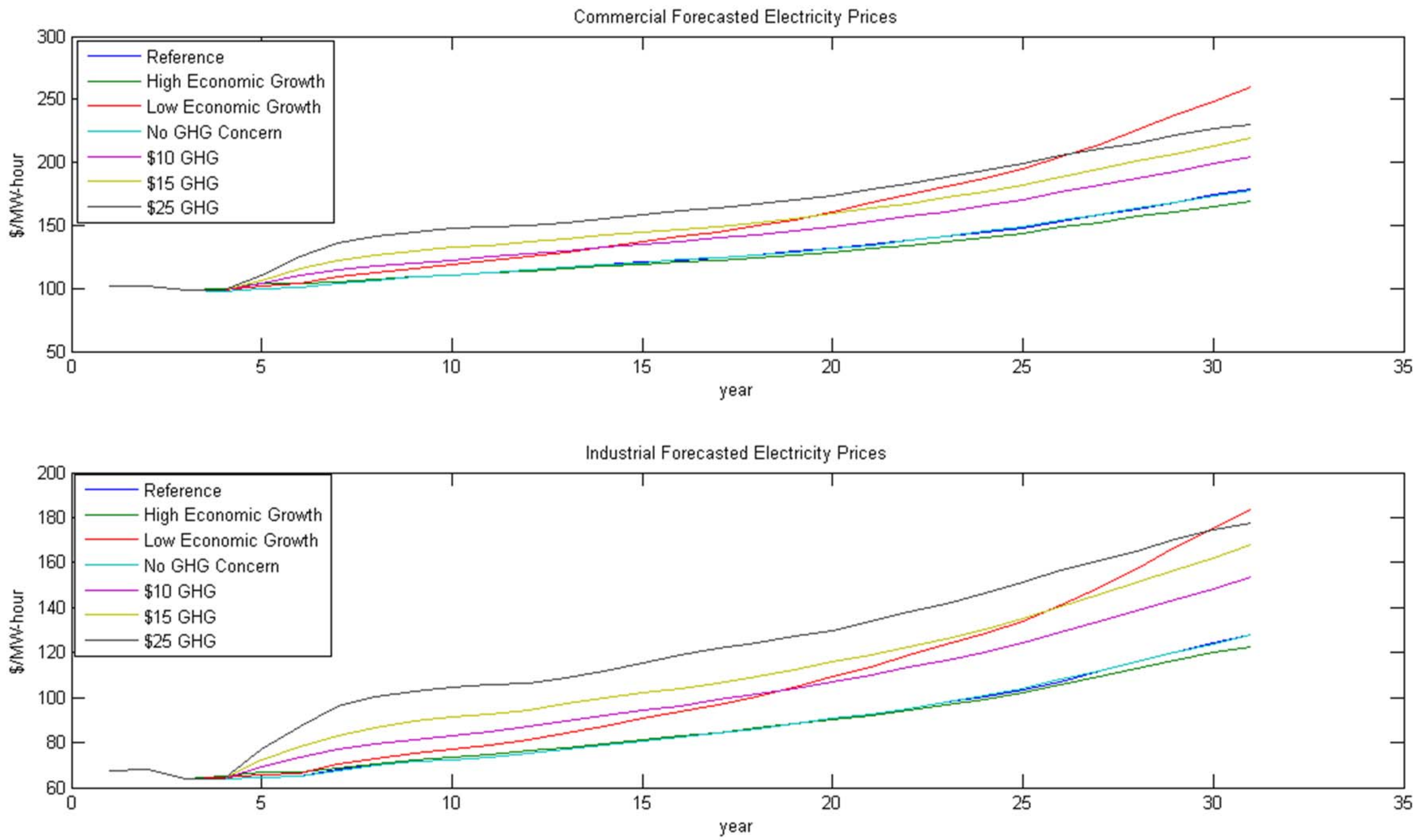
Electricity Demand (MW)

Uncertainty in Natural Gas Prices



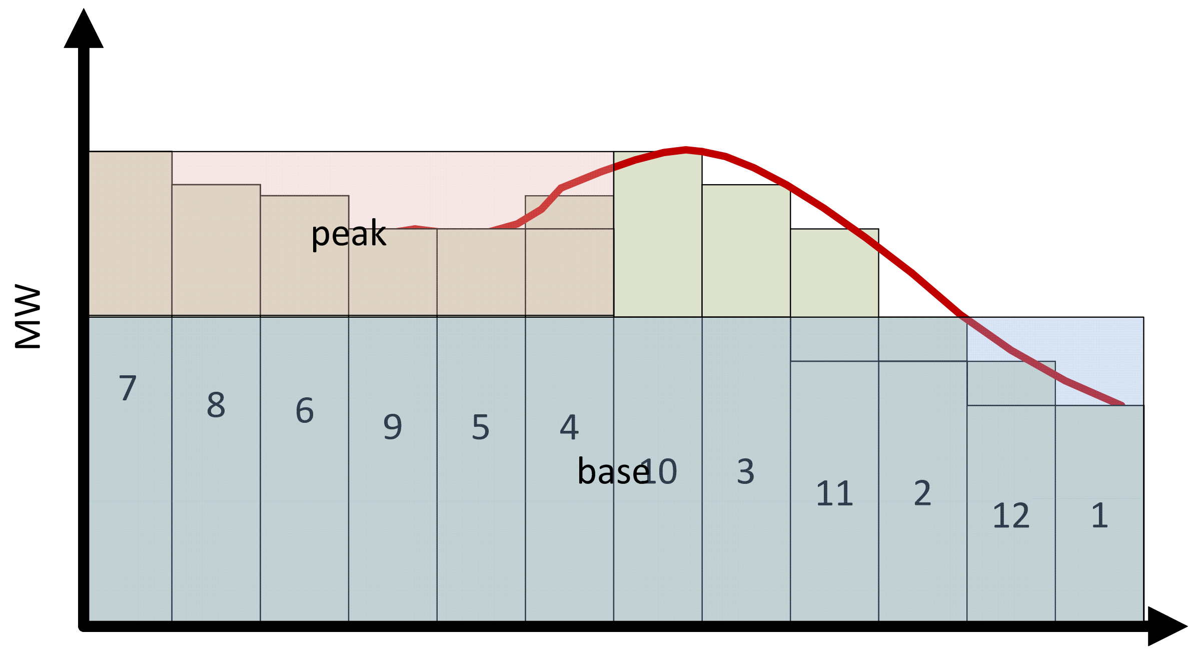


Uncertainty in Electricity Prices

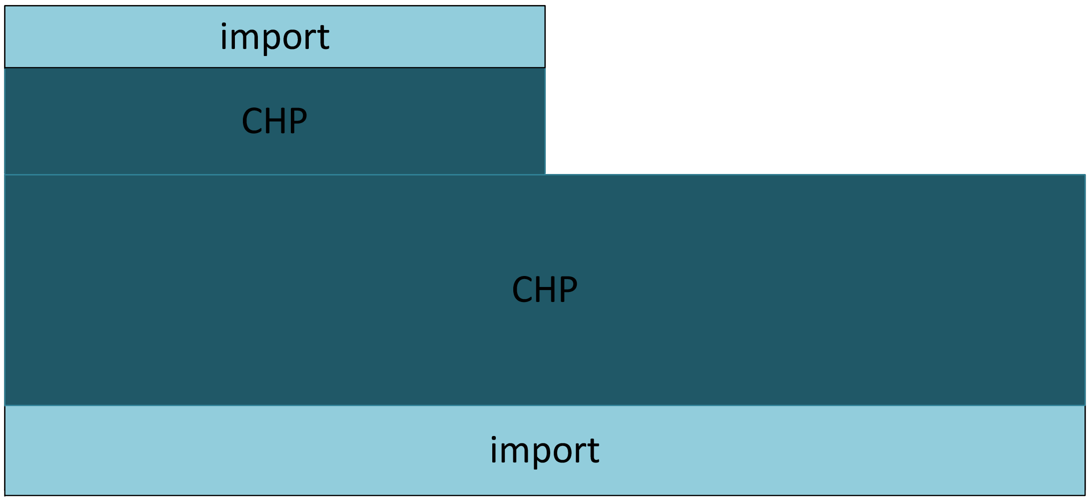


Simplifying System

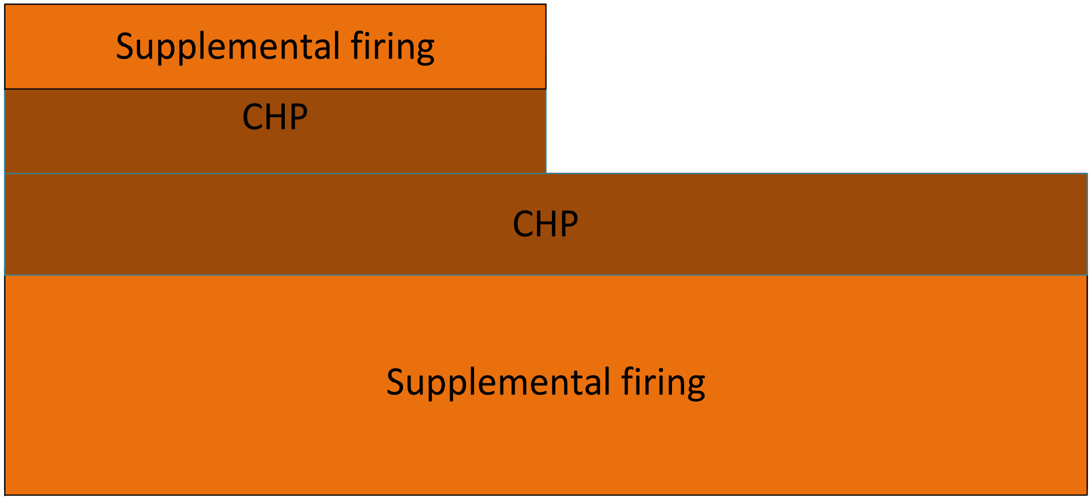
- Create Model:
- Electric and Heating Demand Model (winter and summer)



Allocation of energy supply

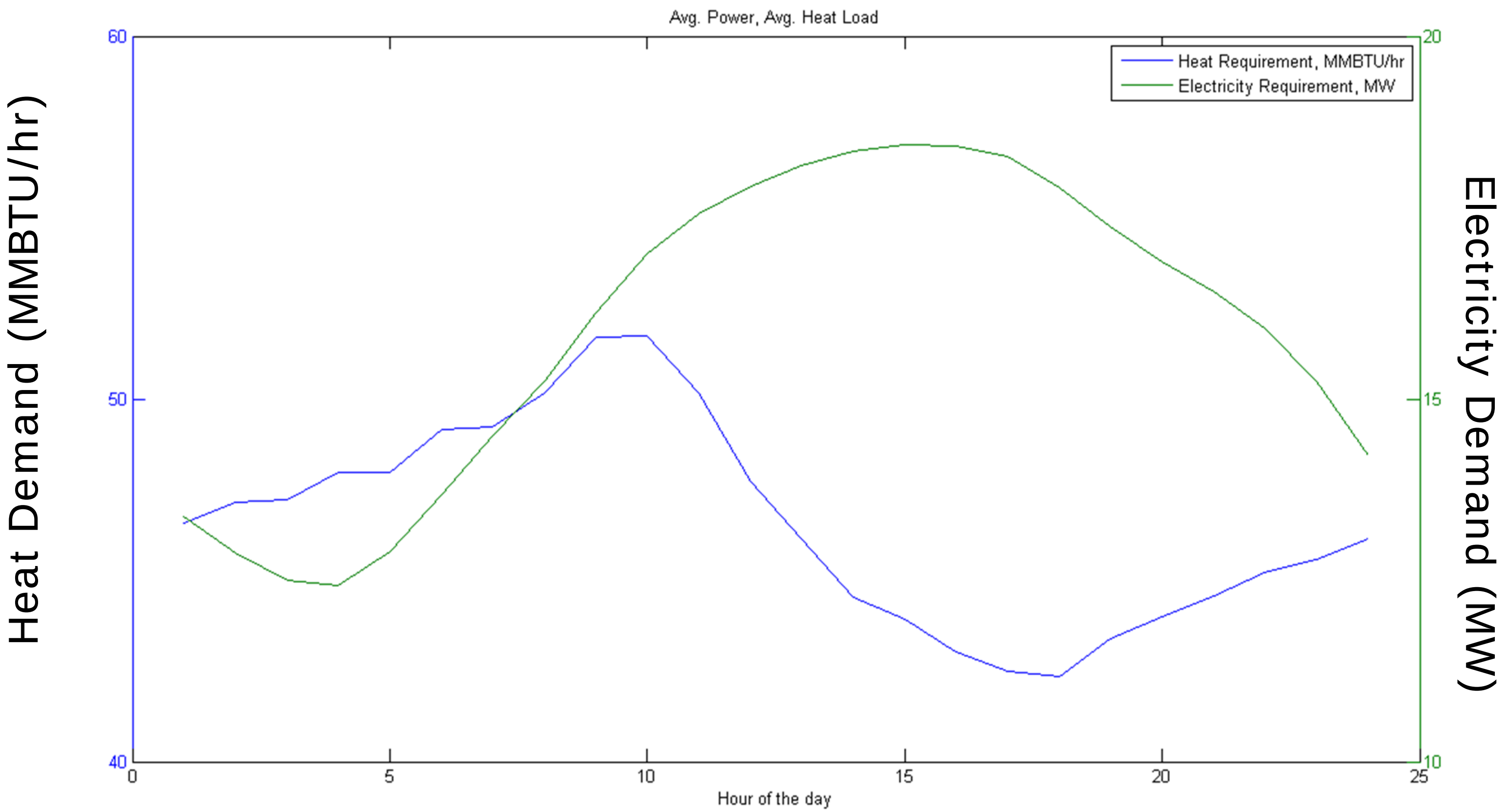


Summer Electricity Supply Allocation?



Winter Heating Capacity Allocation?

Dynamic Model for Dynamic System



Nonlinear DAE

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

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

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

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

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

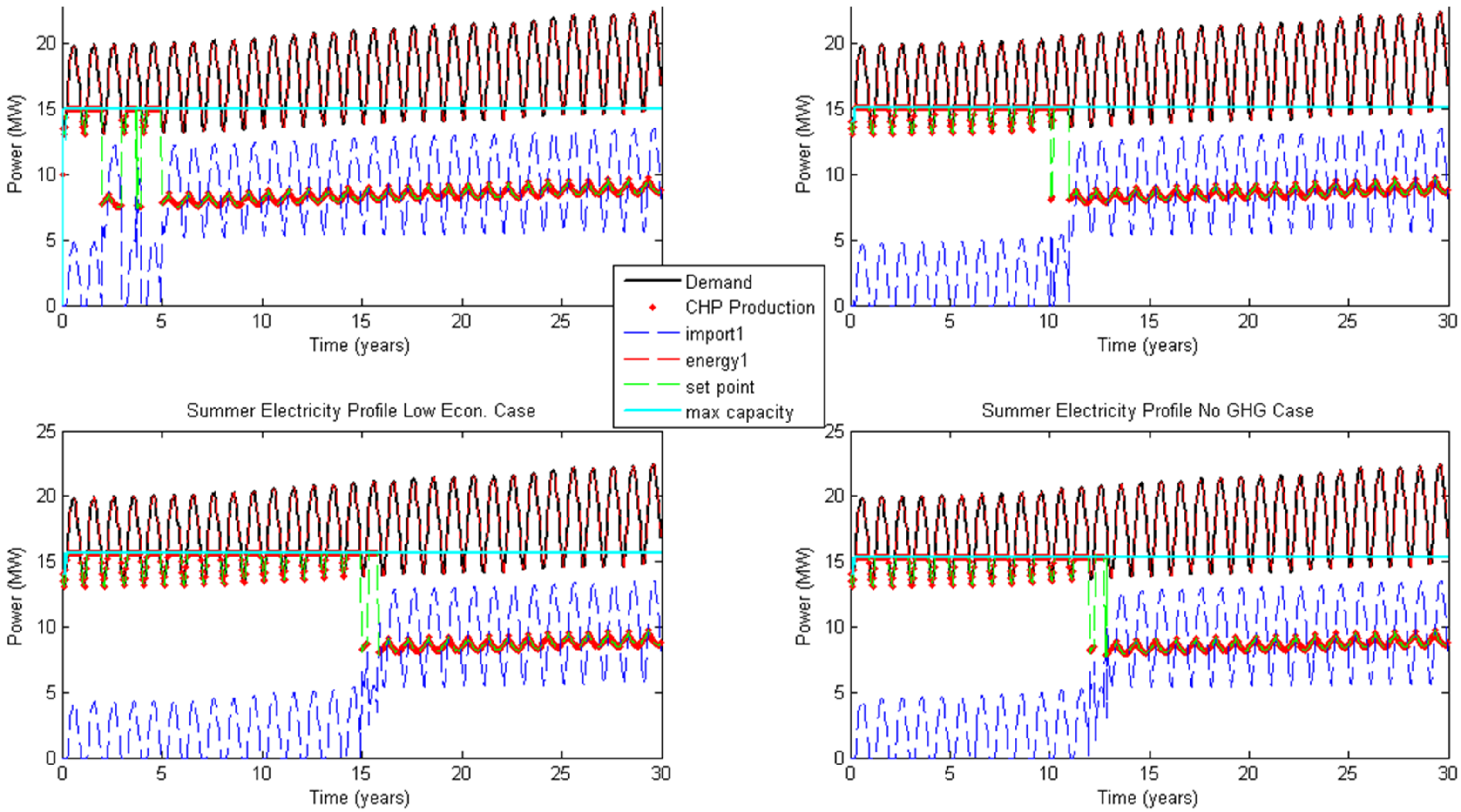
Nonlinear Cost functions

Turbine and boiler dynamics

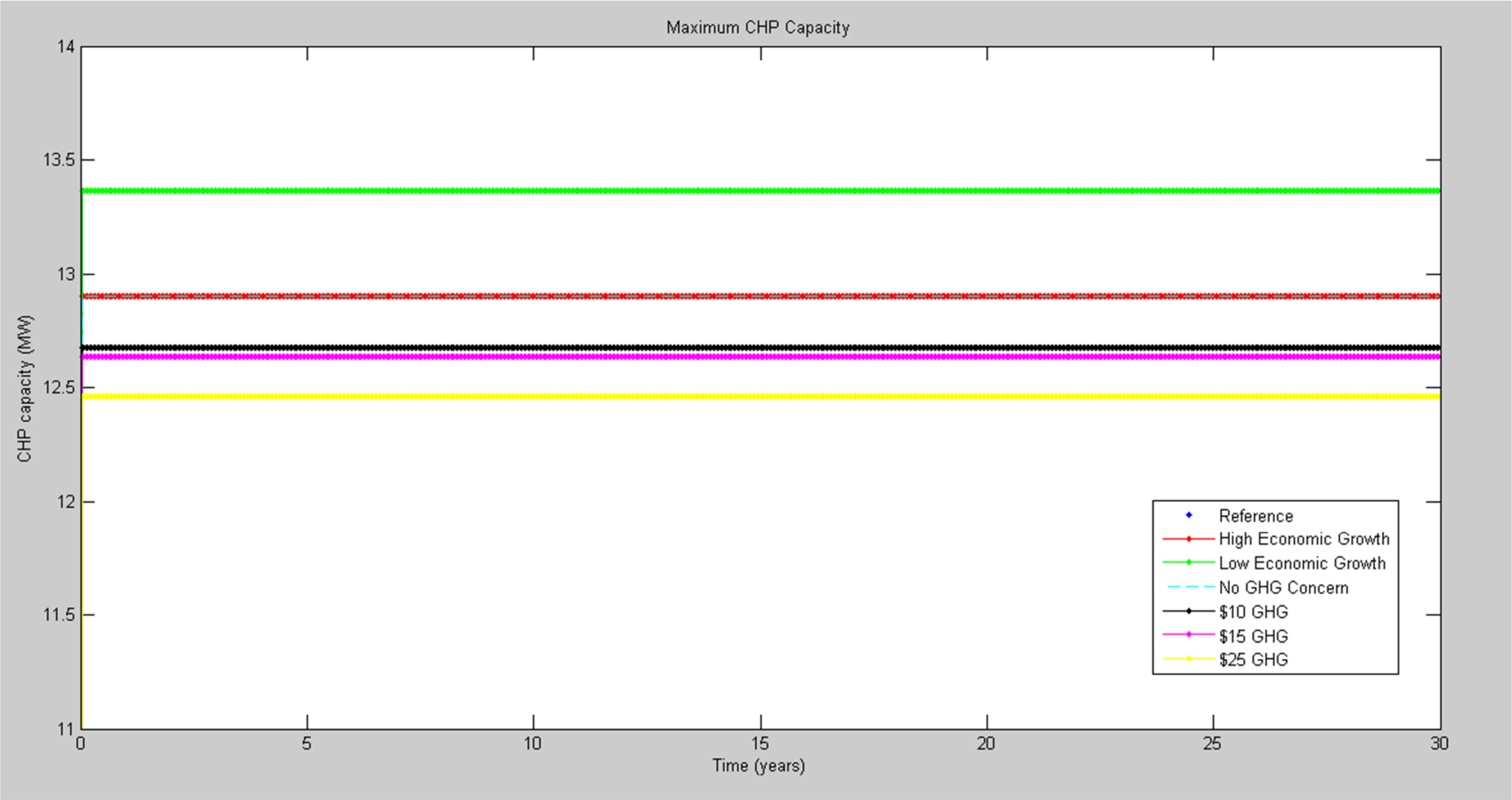
Demand and operating constraints

Dynamic Optimization Results

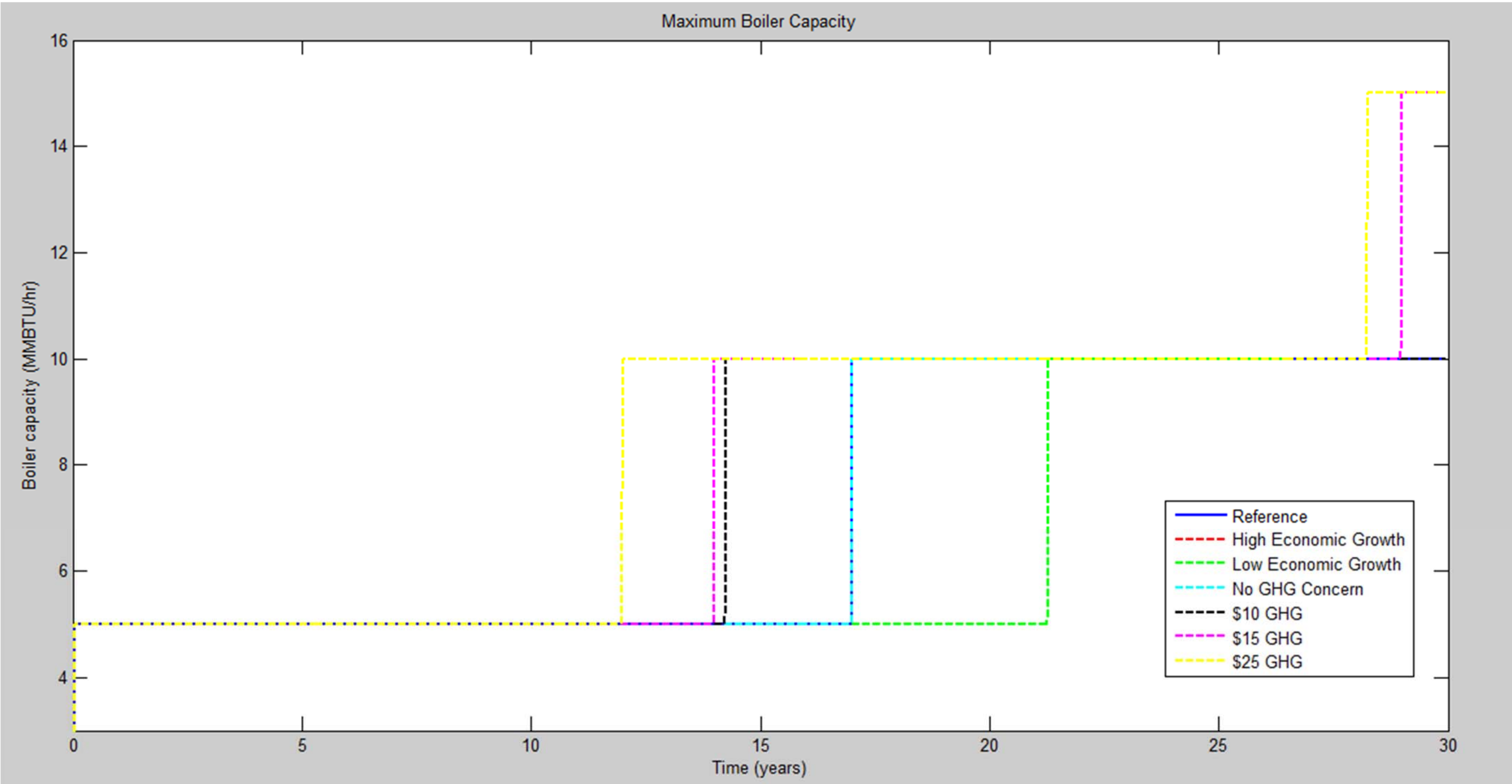
Both capacity increase and cost effective mode of operation over a long term horizon



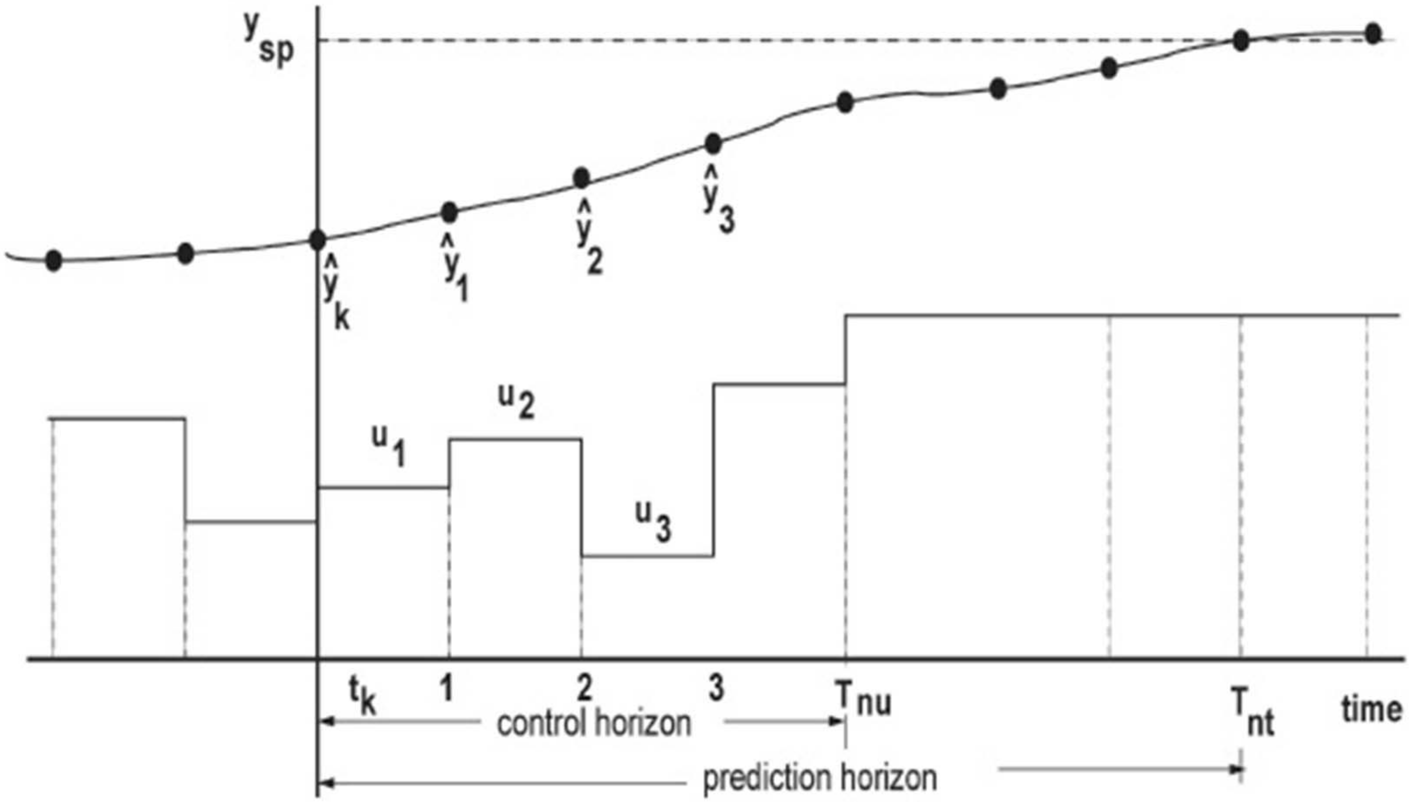
Turbine Max Capacity



Supplemental Boiler Firing Capacity



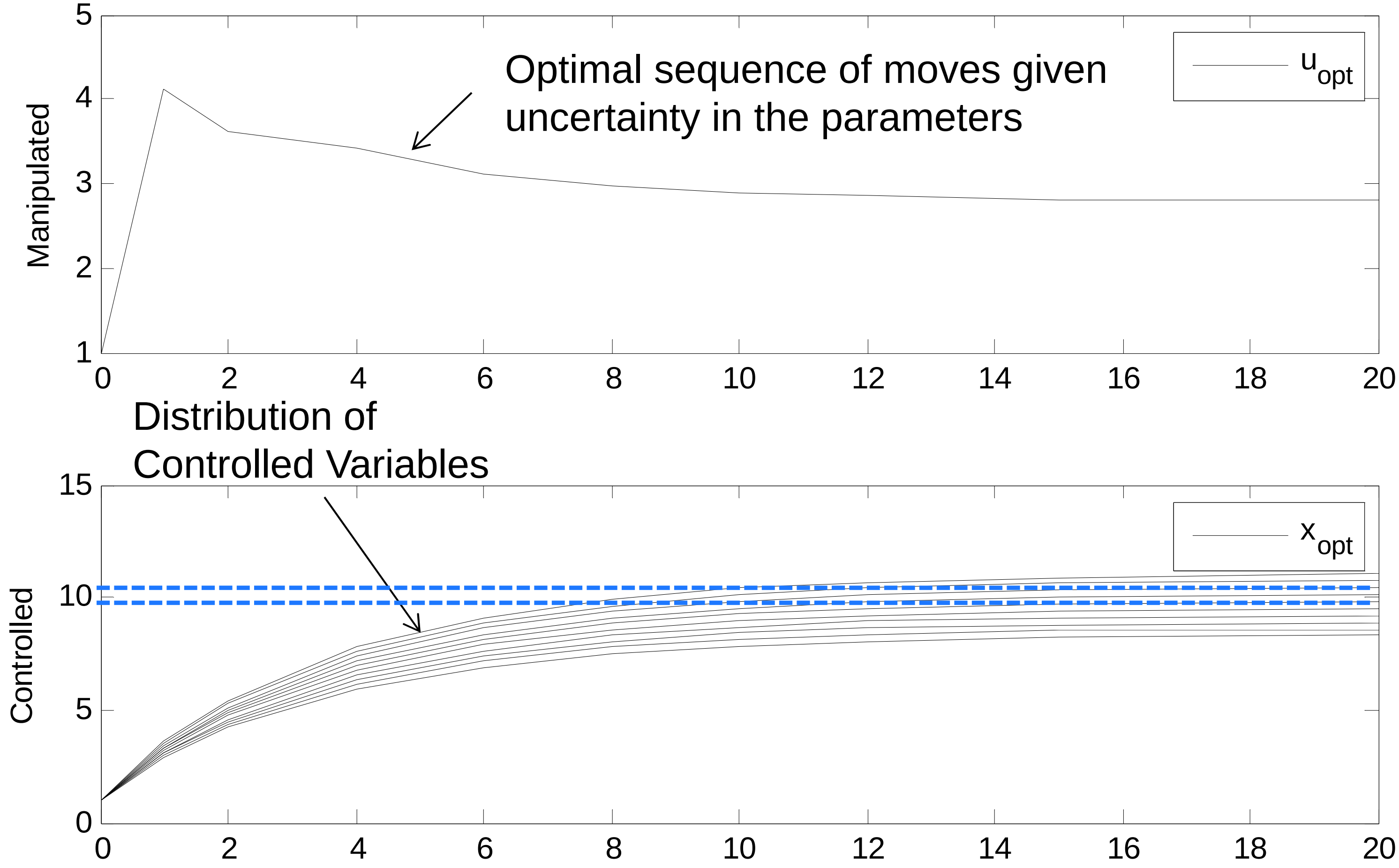
Model Predictive Control Approach



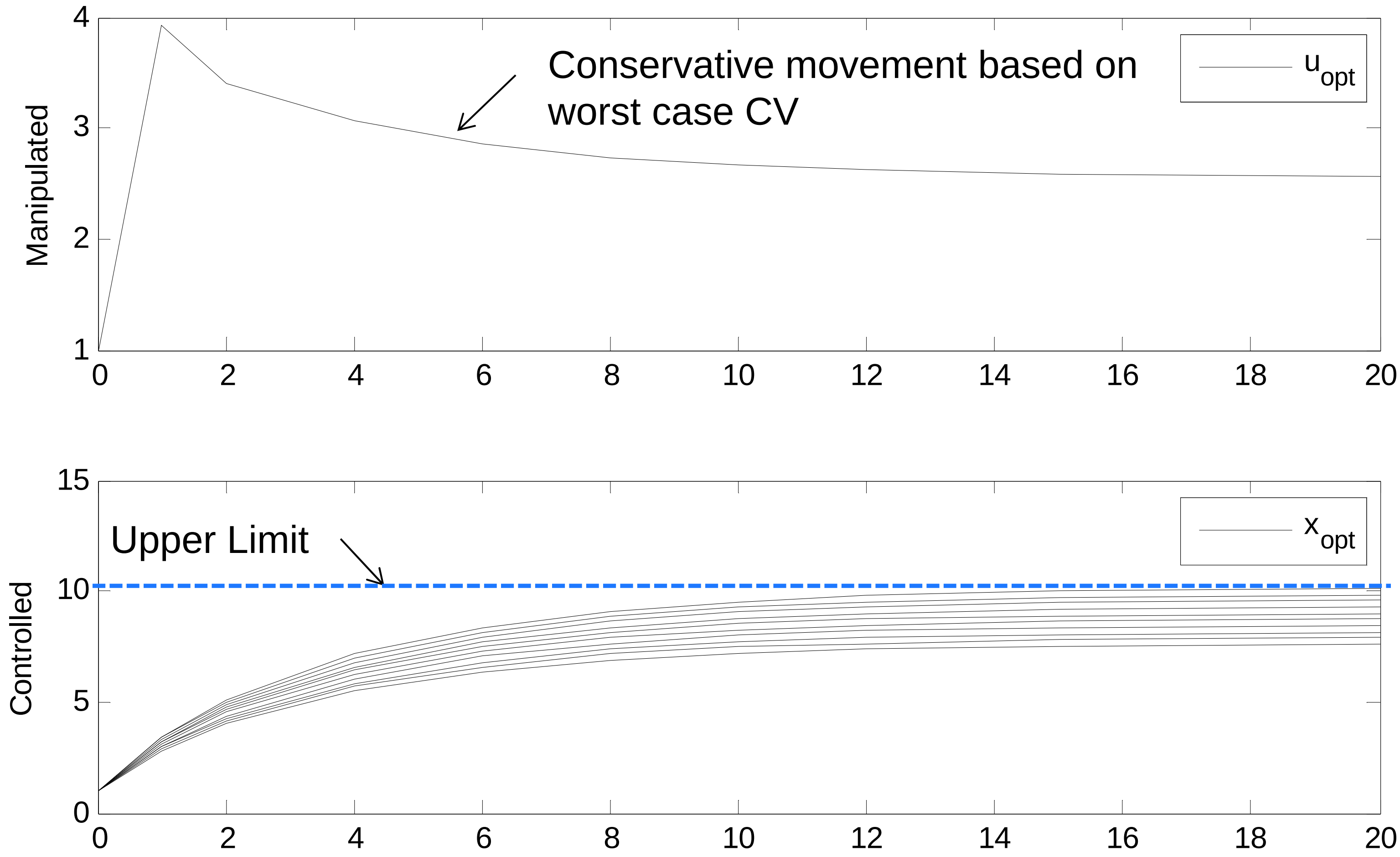
L1 Norm formulation

$$
\begin{aligned}
&\min\left(obj + se_{hi} + se_{lo} + sc_{hi} + sc_{lo}\right)\\
&s.t.\\
&0 = f(\dot{x}, x, d)\\
&m_{gap} = \frac{m_{hi} - m}{2}\\
&m_{gap} = \frac{m - m_{lo}}{2}\\
&e_{hi} = x - m_{hi} + se_{hi}\\
&e_{lo} = m_{lo} - x + se_{lo}\\
&c_{hi} = x - \hat{x} + sc_{hi}\\
&c_{lo} = \hat{x} - x + sc_{lo}\\
&obj = w_{meas}\left(e_{hi} + e_{lo}\right) + w_{model}\left(c_{hi} + c_{lo}\right) + (Cost_{capital} + Cost_{operating} + Cost_{environmental})\\
&se_{hi}, se_{lo}, sc_{hi}, sc_{lo} \geq 0\\
&e_{hi}, e_{lo}, c_{hi}, c_{lo} \geq 0
\end{aligned}
$$

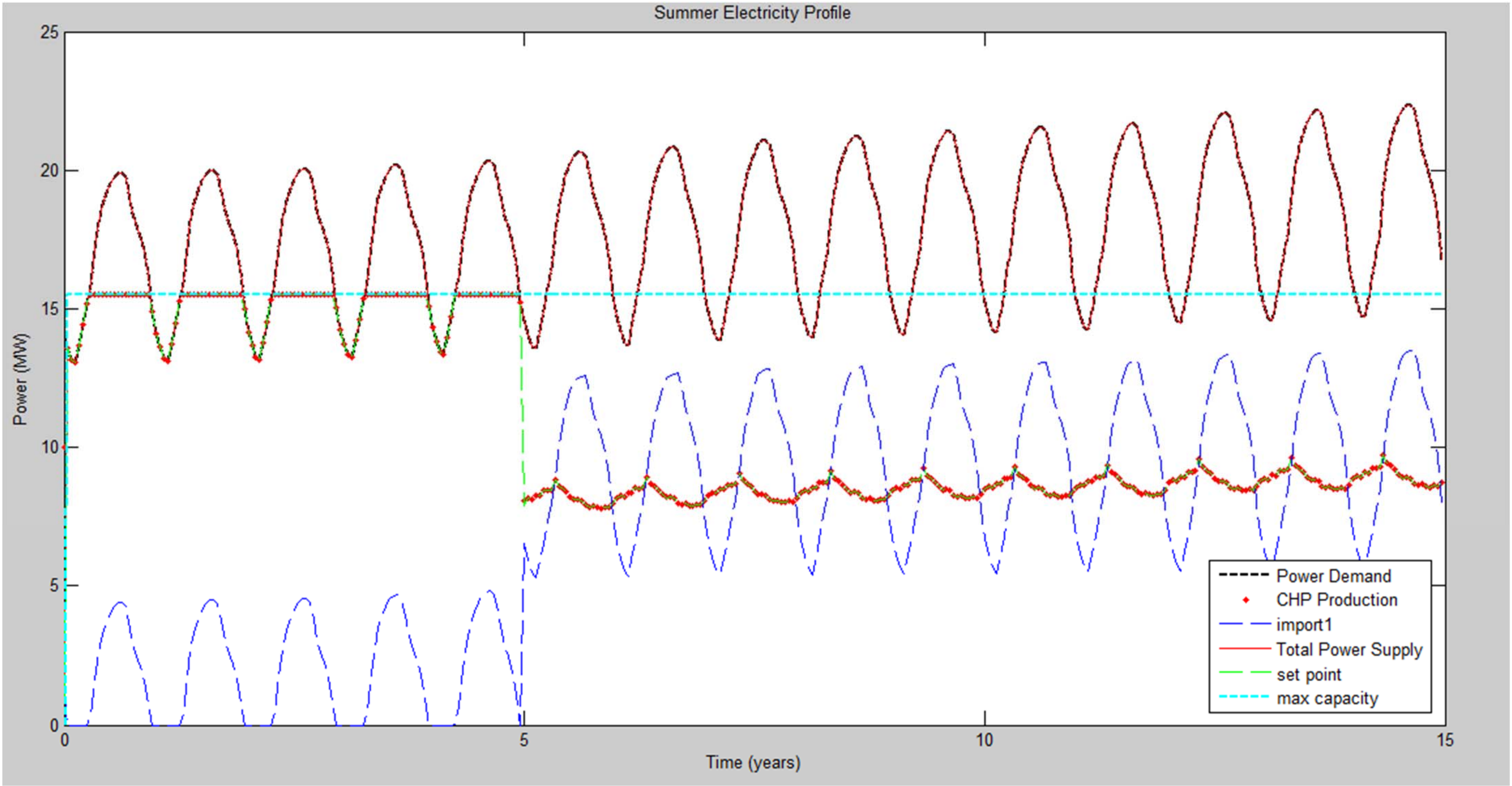
Optimize to a Target Range



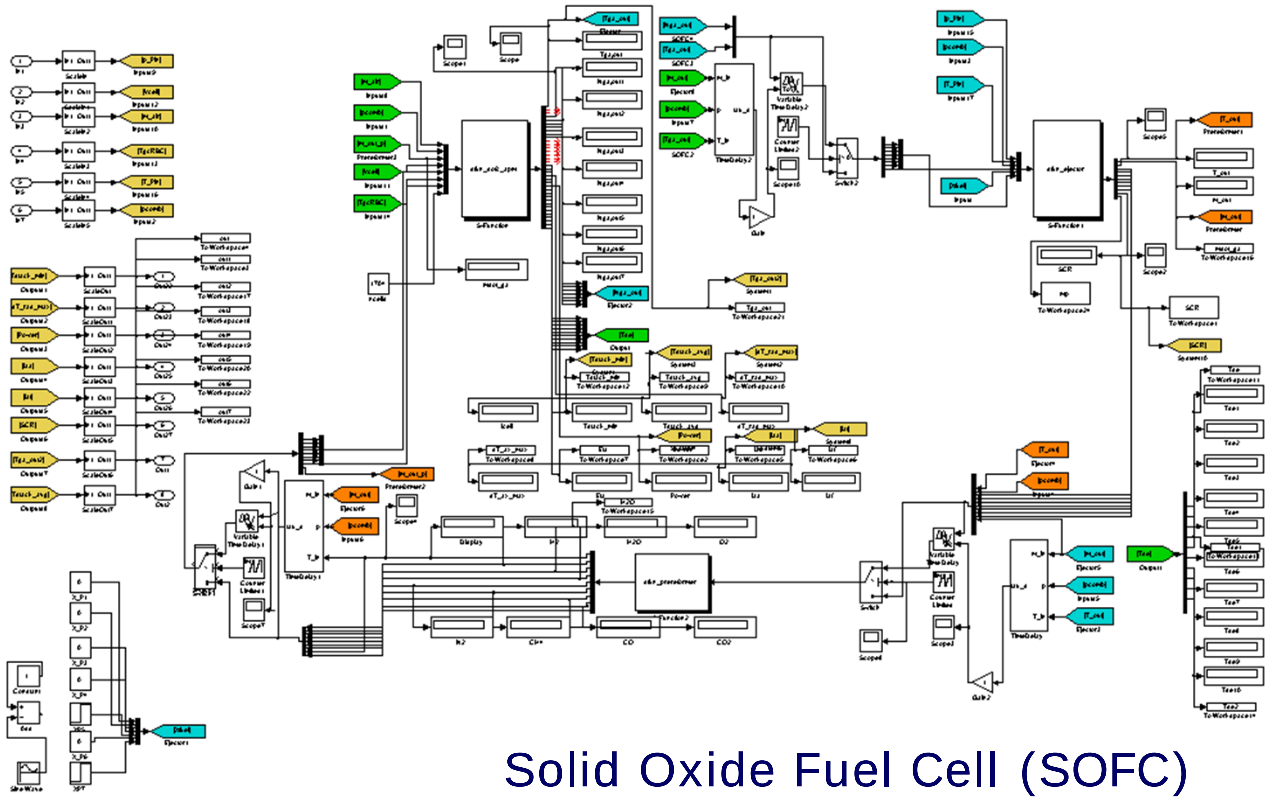
Optimize to a Limit



Dynamic Solution



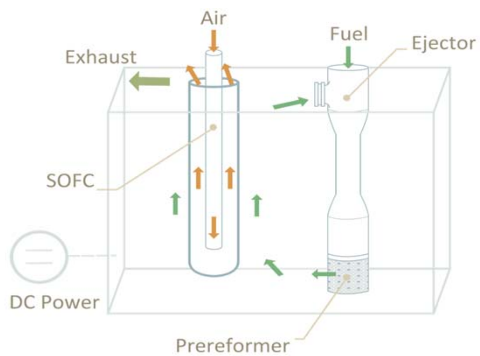
Dynamic Energy System Tools

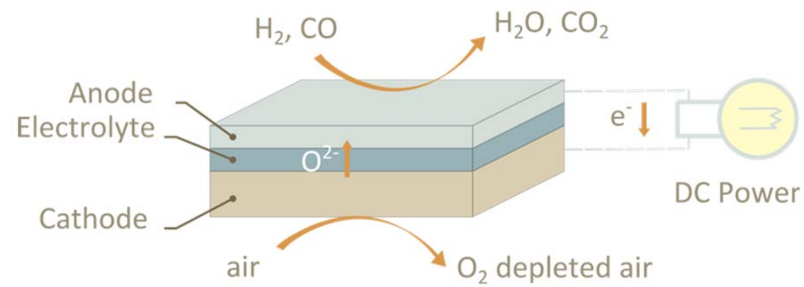


Toolbox for Object Oriented Modeling in MATLAB, Simulink, and Python

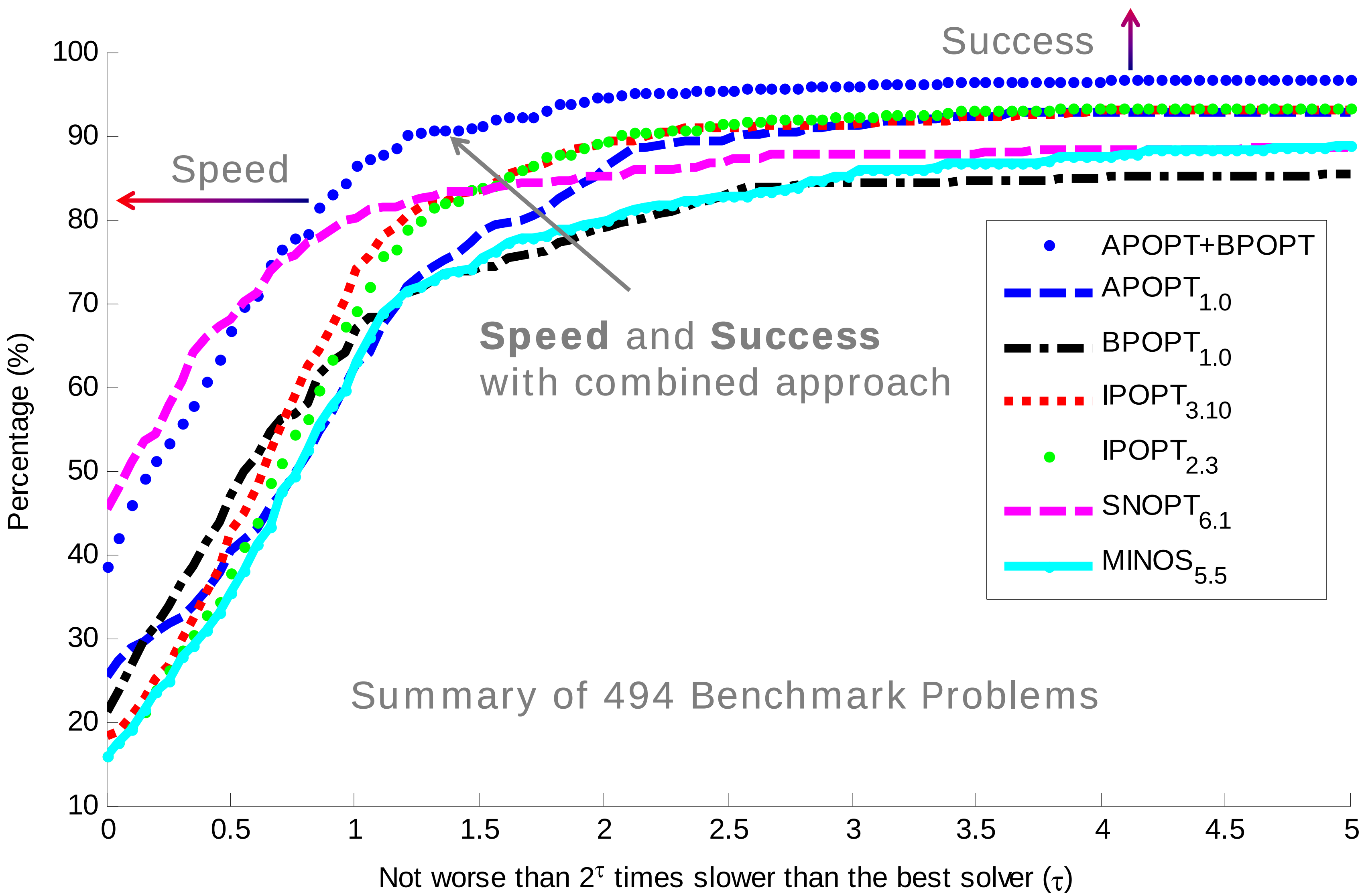
Advanced tools are required for collaborative modeling and high performance computing

Solid Oxide Fuel Cell (SOFC)





Optimization Benchmark



Conclusions

- Powerful insights can be gained from modeling and data reconciliation over long periods of historical data
- When data, modeling, and optimization are combined, hidden savings are discovered through dynamic optimization
- MPC approach can allow for other control variables to be accounted for directly in optimization
- Simulation and optimization of energy system can give stake holders realistic options to evaluate risks and rewards with minimum cost
- Simulation results can then be directly applied to control applications

Development Needs

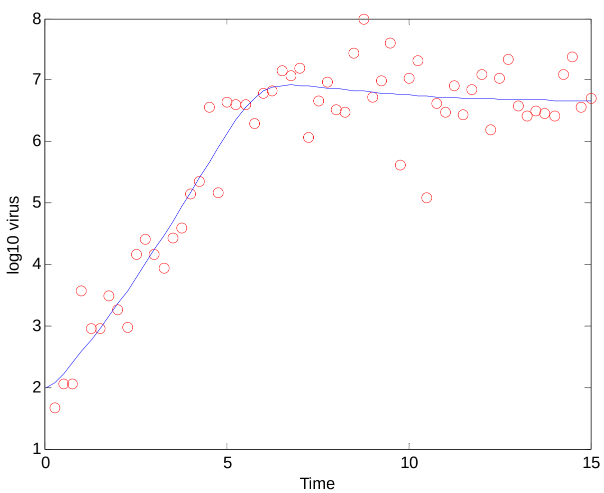
- Collaborative modeling tools
- Library of high quality models that are open source and can be adapted to new problems
- Improvements to methods to simulate and optimize large-scale and complex systems
- Interface with operations and subject matter experts – need to know the process for effective modeling and optimizing

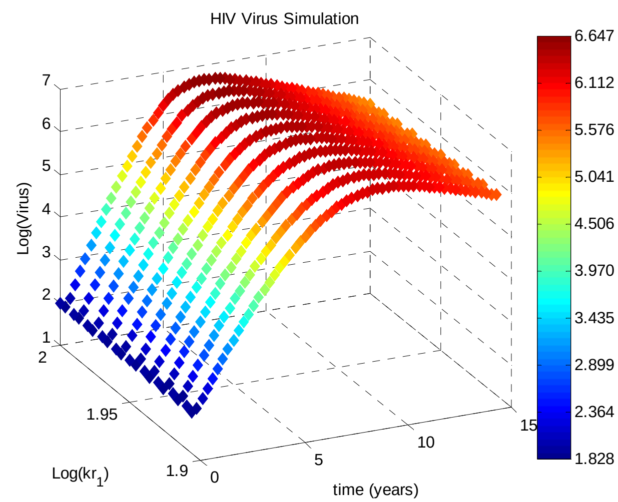
Acknowledgements

Extra Slides

Systems Biology

- Objective: Improve extraction of information from clinical trial data
- Dynamic data reconciliation
  - Dynamic pharmacokinetic models (large-scale)
  - Data sets over many patients (distributed)
  - Uncertain parameters (stochastic)





Energy System Model

Parameters :

$e_p = existing\ capacity\ of\ plant\ type\ p\ [MW]$

$cc_p = daily\ fraction\ of\ capital\ cost\ of\ plant\ p\ [MW]$

$oc_p = daily\ operating\ cost\ of\ plant\ p\ [USD/MWh]$

$ic_{k.s} = electricity\ import\ cost\ [USD/MWh]$

$d_{k.s.i} = instantaneous\ energy\ demand\ [MW]$

$du_{k.s.i} = duration\ of\ demand\ [h]$

$r_{k.s.i} = required\ energy\ [MWh]$

$f_{hrg} = recovered\ heat\ factor\ [unitless]$

where the parameter r_k is defined as $r_{k.s.i} = (d_{k.s.i} - d_{k-1.s.i}) \cdot du_{k.s.i}$

Indices :

p plant type $\{chp,\ boiler\}$

k demand category $\{base\ load,\ peak\ load\}$

s season $\{summer,\ winter\}$

i energy type $\{electric,\ thermal\}$

Variables :

$x_p = new\ design\ of\ plant\ type\ p\ [MW]$

$y_{p.k.s} = allocation\ of\ capacity\ to\ demand\ [MW]$

$z_{k.s} = import\ of\ electricity\ [MW/h]$

LP (Linear Programming)

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 :

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

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

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

$$x_p \geq 0$$

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

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

Example of Results

CapacityAllocationPlan [MW] summer

	c1 Plan I	c1 Plan II	c1 Plan III	c1 Plan IV	c2 Plan I	c2 Plan II	c2 Plan III	c2 Plan IV	c3 Plan I	c3 Plan II	c3 Plan III	c3 Plan IV	c4 Plan I	c4 Plan II	c4 Plan III	c4 Plan IV
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
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

	c5 Plan I	c5 Plan II	c5 Plan III	c5 Plan IV	c6 Plan I	c6 Plan II	c6 Plan III	c6 Plan IV	c7 Plan I	c7 Plan II	c7 Plan III	c7 Plan IV
boiler												
base												
peak												
chp												
base	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	2.4	1.8	2.0	2.0	2.3	0.9	2.0	2.0	2.1		2.0

CapImportedPlanMW [MW]

	c1 Plan I	c1 Plan II	c1 Plan III	c1 Plan IV	c2 Plan I	c2 Plan II	c2 Plan III	c2 Plan IV	c3 Plan I	c3 Plan II	c3 Plan III	c3 Plan IV	c4 Plan I	c4 Plan II	c4 Plan III	c4 Plan IV
base																
summer																
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
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

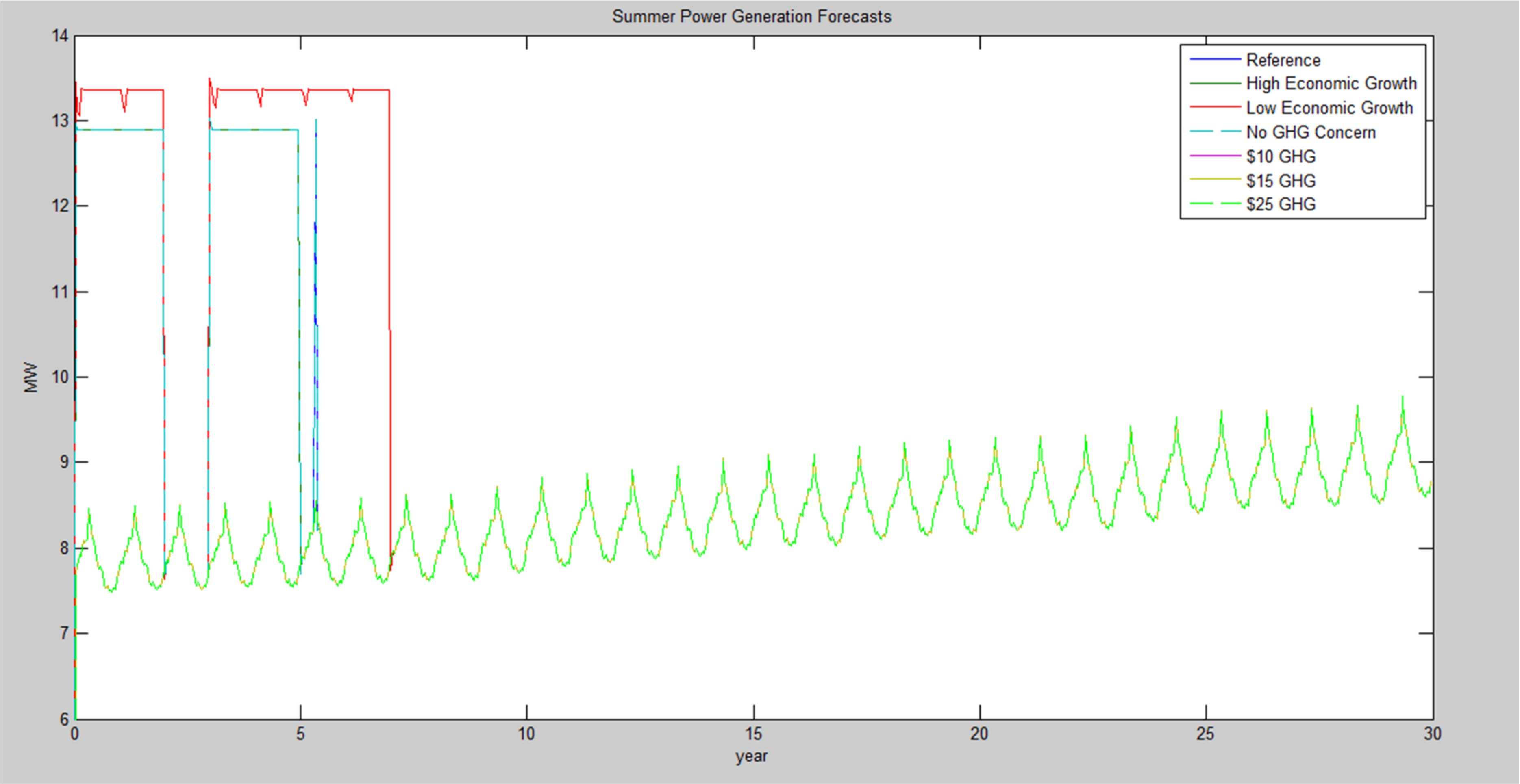
	c5 Plan I	c5 Plan II	c5 Plan III	c5 Plan IV	c6 Plan I	c6 Plan II	c6 Plan III	c6 Plan IV	c7 Plan I	c7 Plan II	c7 Plan III	c7 Plan IV
base												
summer											0.10	
winter												
peak												
summer	3.00	2.80	4.31	4.00	3.00	3.00	5.53	4.00	3.00	3.20	6.70	4.00
winter	1.53	1.60	1.88	1.53	1.53	1.62	2.97	1.53	1.53	1.62	4.12	1.53

NewCapPlan [MW]

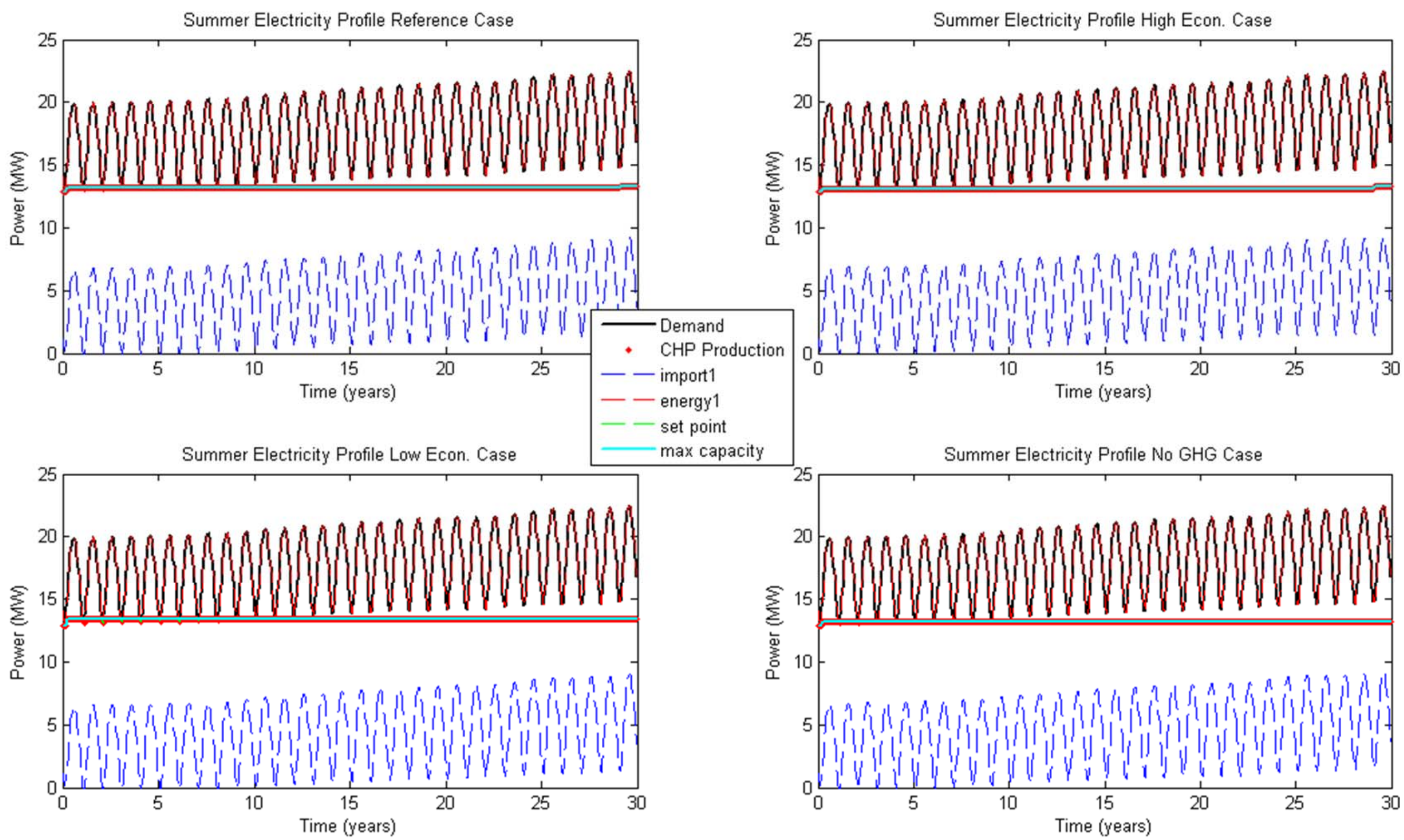
	Plan I	Plan II	Plan III	Plan IV
boiler				
c1				
c2				
c3				
c4				
c5				
c6				
c7				
c8				
chp				
c1	17.0	18.0	20.0	20.0
c2				
c3				
c4				
c5				
c6				
c7				
c8				

LP or NLP formulation, optimizing through discrete scenarios to account for uncertainty. Lacks system dynamics.

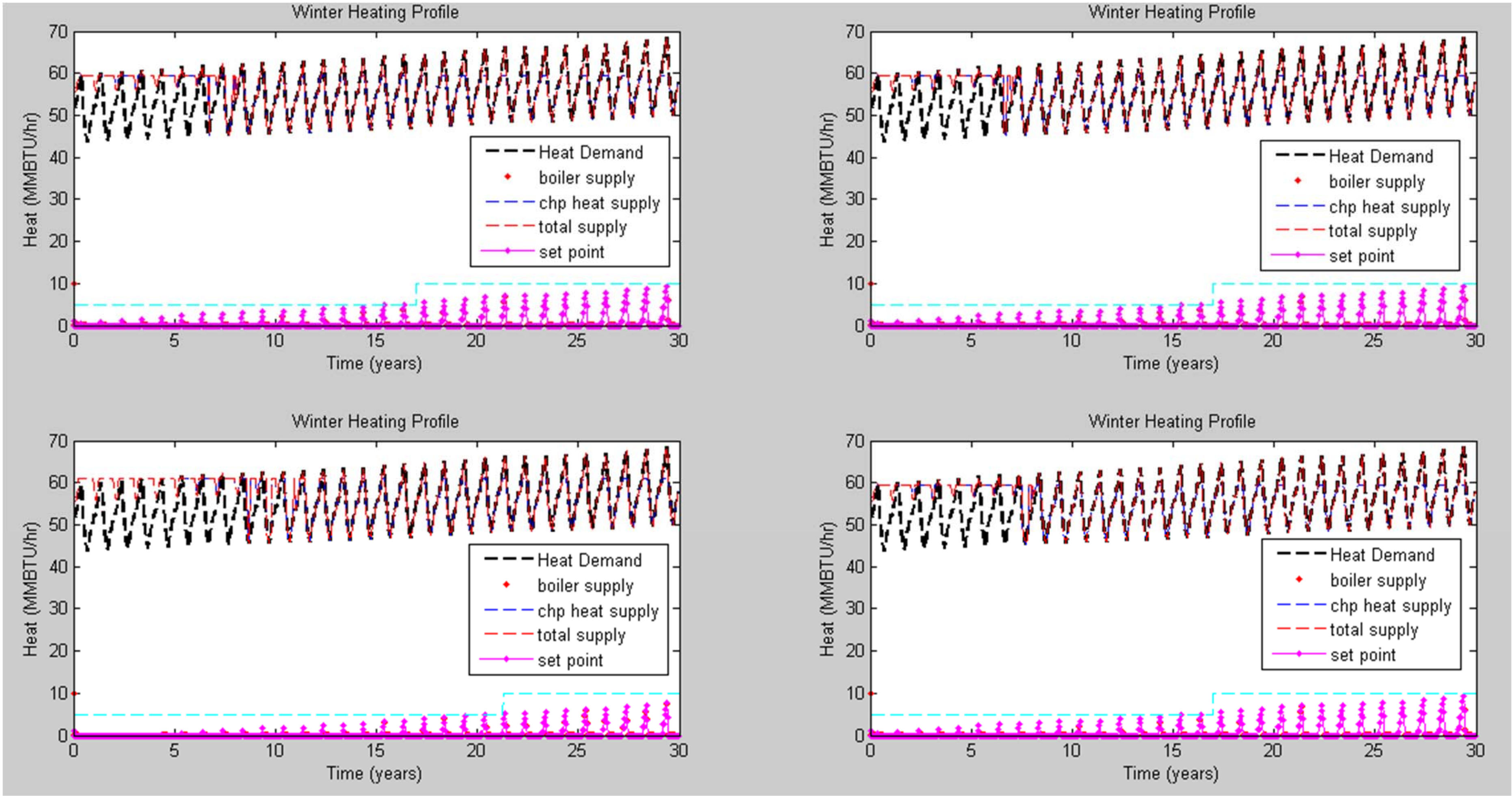
Electricity Generation Forecasts



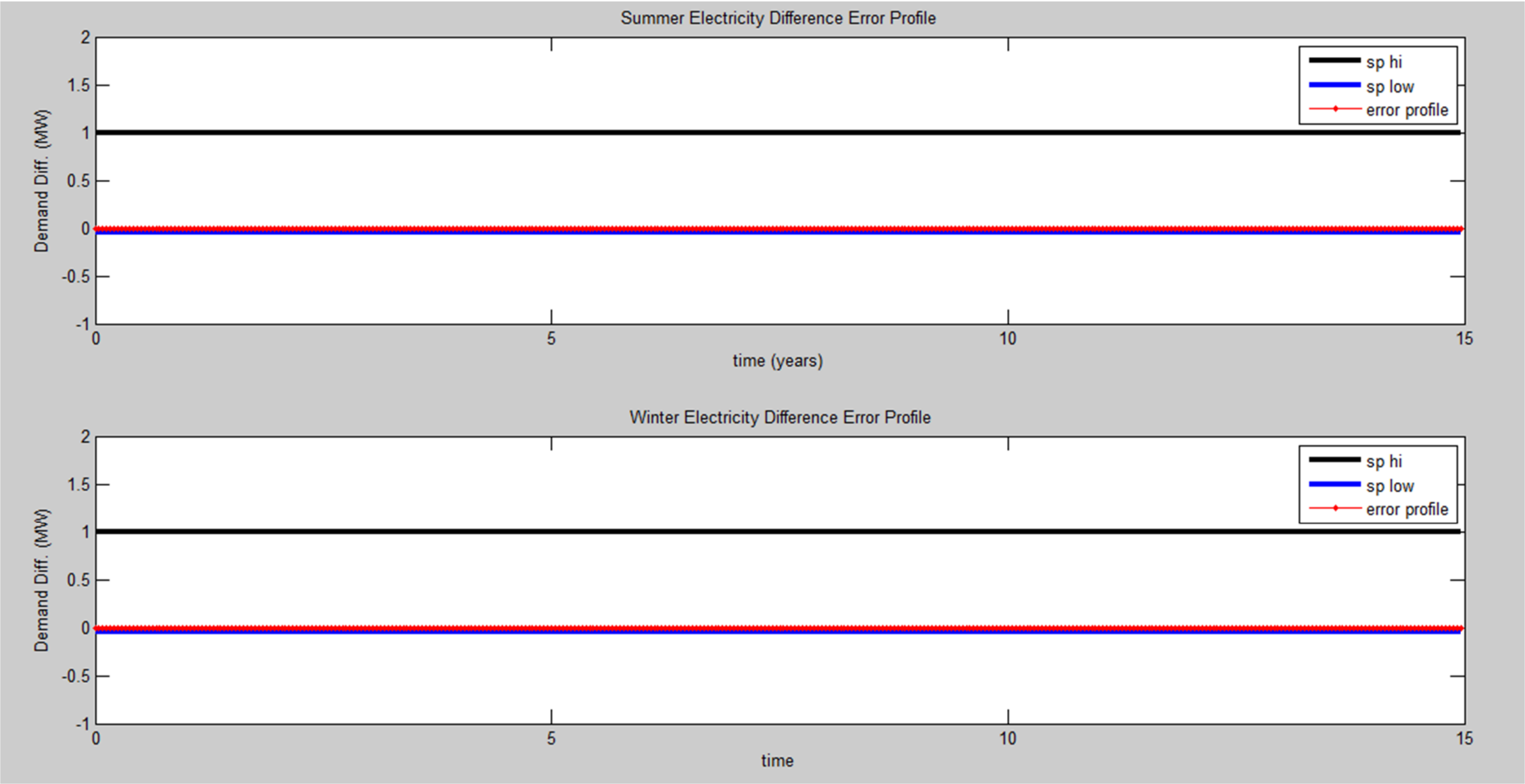
Optimize capacity at CHP's most efficient operating point



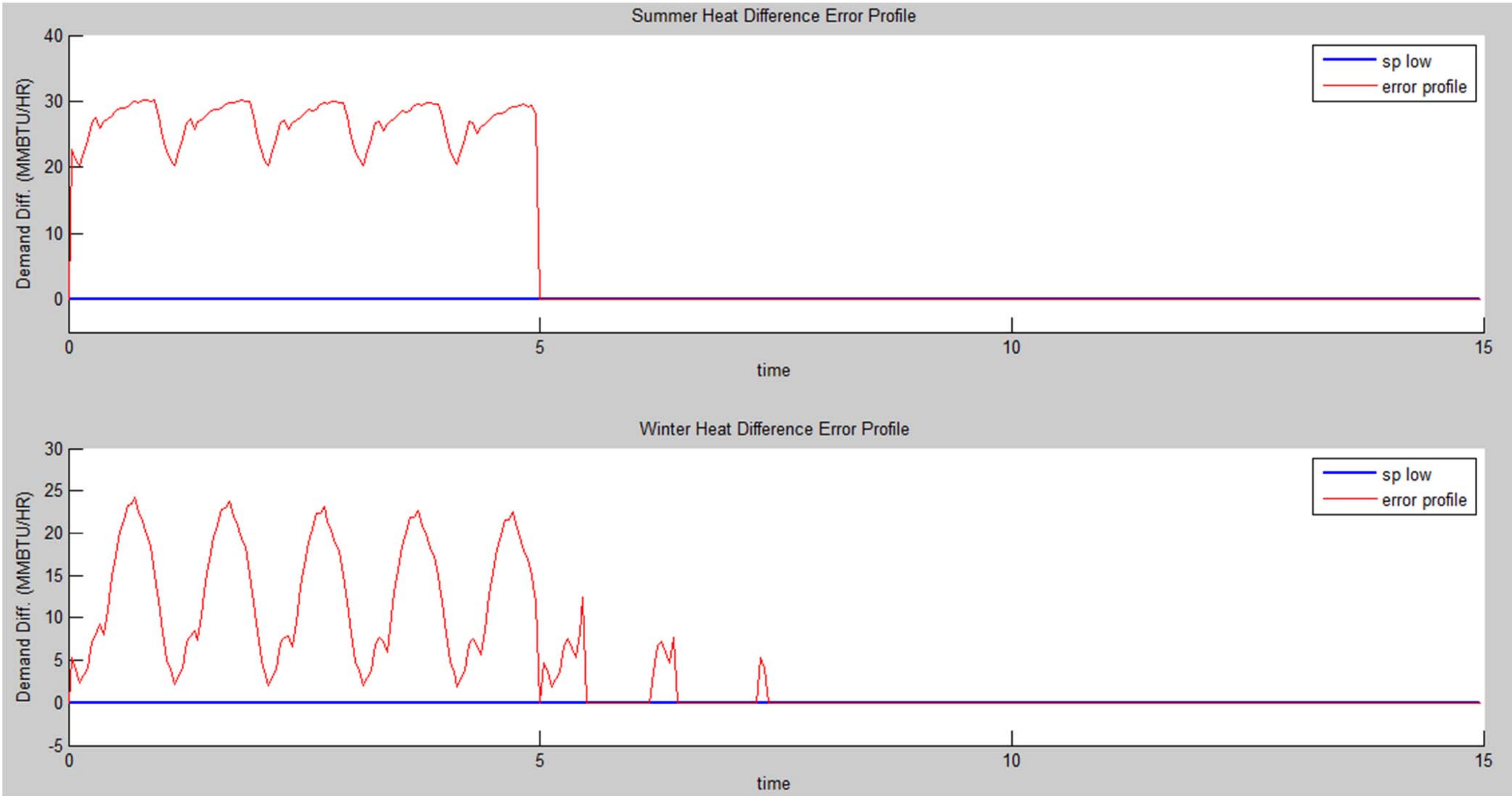
Heat load is optimized simultaneously



Optimize to a Target



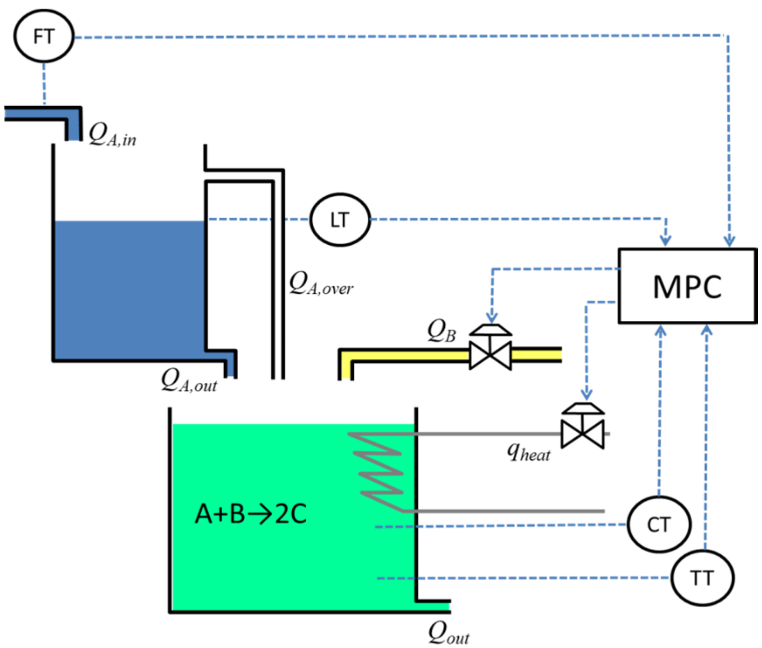
Optimize above a Limit



Simultaneous vs. Sequential

Table 1: Computational results from the sequential and simultaneous solution methods. Computations for each method are executed using an Intel ® Core 2 Duo ™ (2.54 GHz) processor with 4 GB RAM.

	Sequential	Simultaneous
Objective function value	0.0094	0.0108
System model evaluations	3,336	1
Computation time (s)	331.6	1.1



K.M. Powell, J.D. Hedengren, T.F. Edgar, A Continuous Formulation for Logical Decisions in Differential Algebraic Systems using Mathematical Programs of Equilibrium Constraints, Industrial and Engineering Chemistry Research, Submitted, 2013.

Survey of DAE Solvers

Software Package	Max DAE Index	Form	Adaptive Time Step	Sparse	Partial-DAEs	Simultaneous Estimation / Optimization
APMonitor	3+	Open	No	Yes	No	Yes
DASPK / CVODE / Jacobian	2	Open	Yes	No	No	No
gProms	1 (3+ with transforms)	Open	Yes	Yes	Yes	No
MATLAB	1	Semi-explicit	Yes	No	No	No
Modelica	1	Open	Yes	Yes	No	No

DAE = Differential and Algebraic Equation