DYNAMIC OPTIMIZATION OF ENERGY SYSTEMS WITH THERMAL ENERGY STORAGE

PRELIMINARY RESEARCH PROPOSAL

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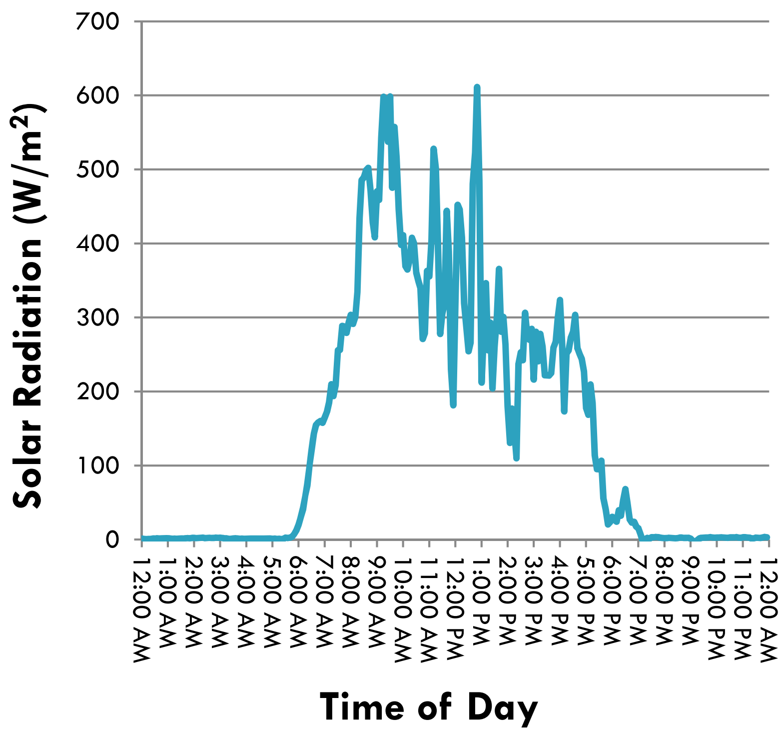
Motivation

Why Energy Storage?

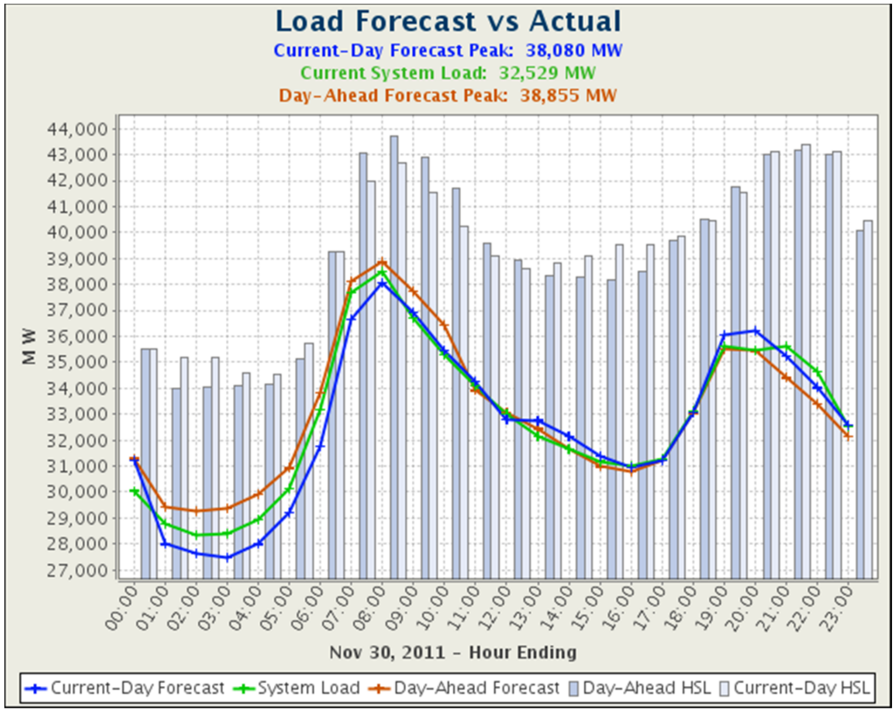
- Intermittency
  - Dispatchable power
- Supply/Demand Mismatch
  - Load shifting
- Smart Grid
  - Grid reliability
  - Integration of renewables
  - Optimal grid performance



Motivation

Dynamic Optimization Using Forecasts

- Dynamic Optimization: Optimal control with long time horizon (days/weeks)
- Why dynamic optimization and forecasts?
  - Transient systems
  - Subject to disturbances
  - Slow storage dynamics
- Hypothesis: Storage provides extra DOFs that can be exploited to enhance system performance.



Background

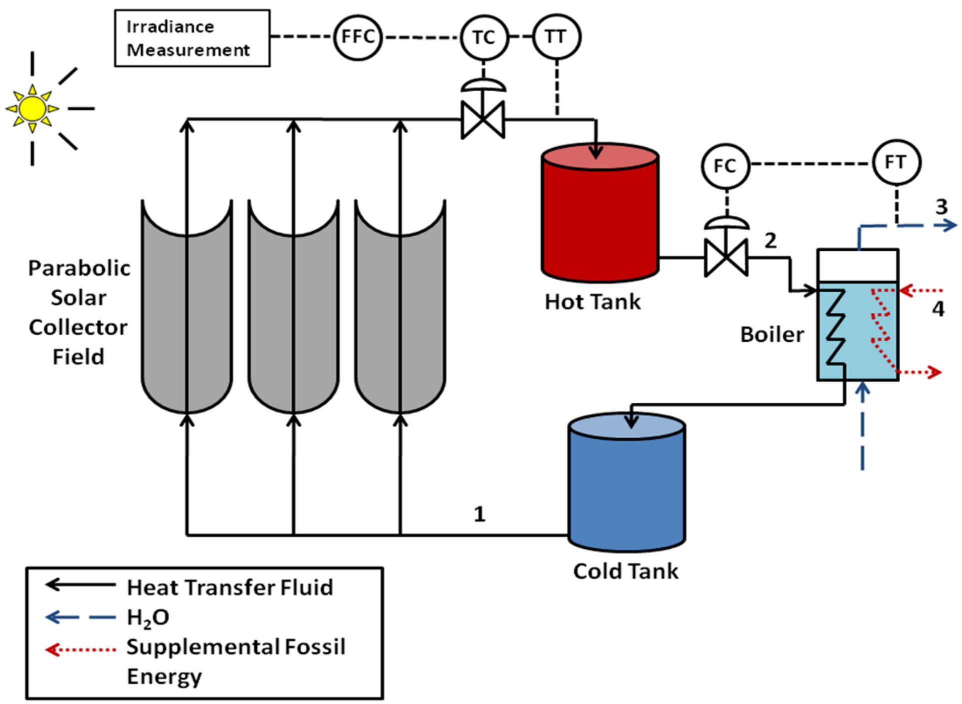
Thermal Energy Storage

- Energy stored as heat or cooling
- Low cost
- Niche but high impact applications
- Many types and configurations
  - Sensible, latent, chemical
  - Direct, indirect, two-tank, thermocline, etc.

Solar Thermal Energy Storage

Modeling and Control

- Solar thermal vs PV
- Storage is critical



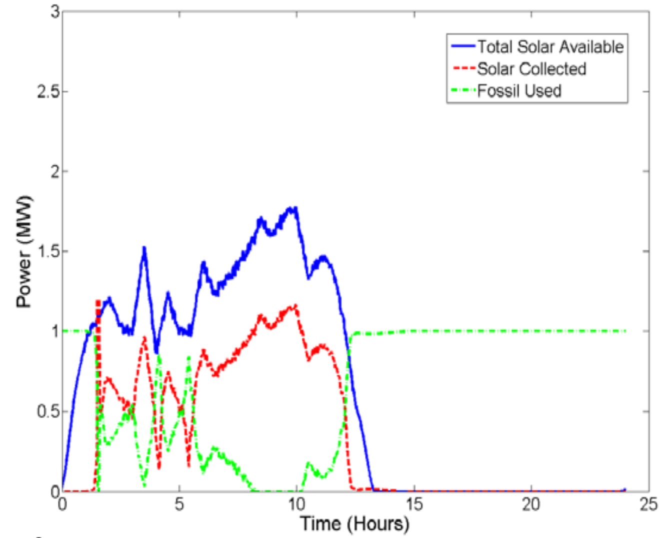
- First principles model
- Feedforward + feedback control

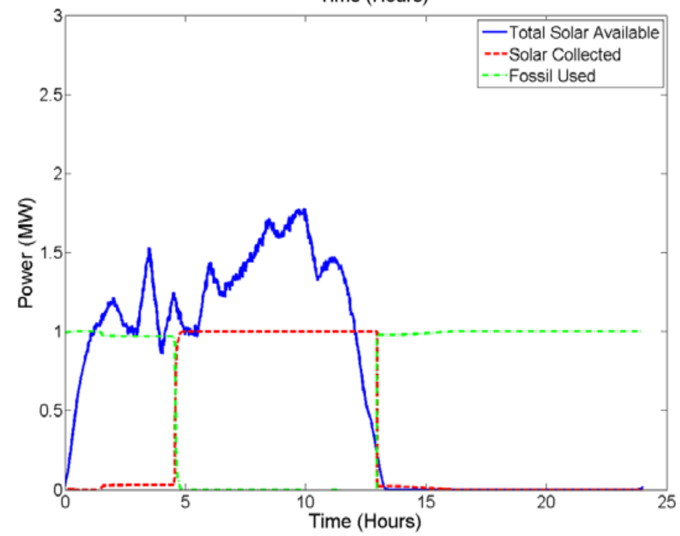
Solar Thermal Energy Storage

Modeling and Control: Results

- Mitigates intermittency problems
- Provides dispatchable power
- Increases solar share

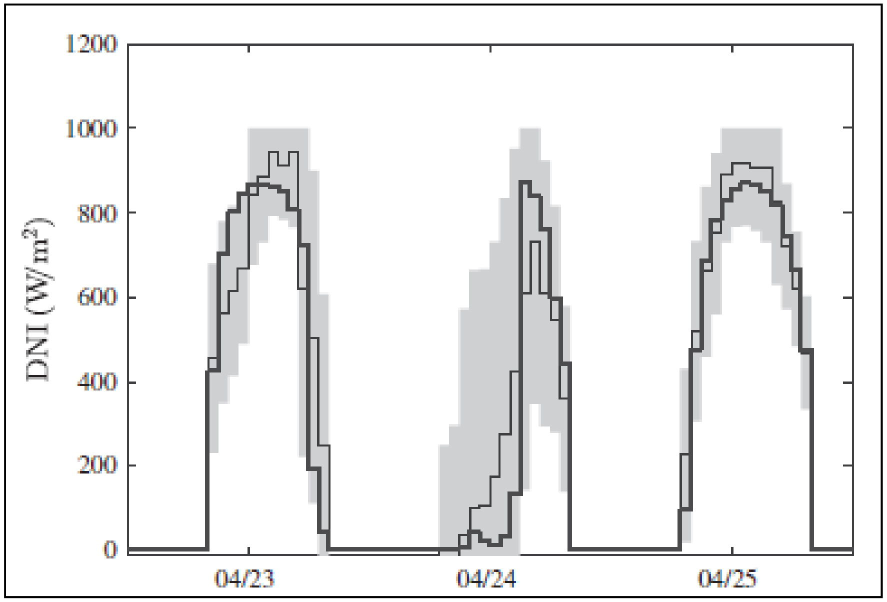
	Clear Day: w/o Storage	Clear Day: w/ Storage	Cloudy Day: w/o Storage	Cloudy Day: w/ Storage
Solar (MWh)	16.48	16.82	8.40	8.49
Supplemental (MWh)	12.58	7.18	15.78	15.51
Solar Share	47.6%	70.1%	34.3%	35.4%





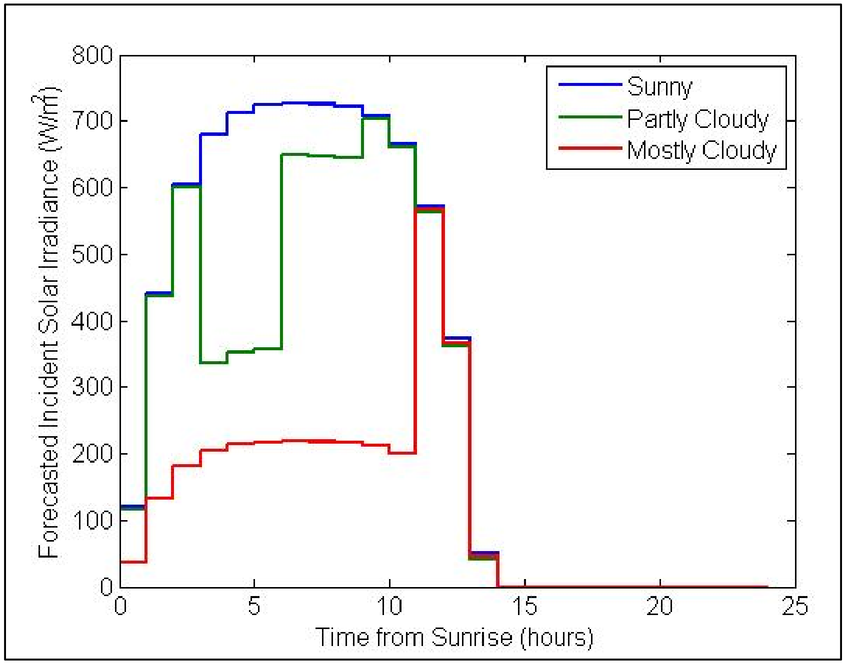
Solar Thermal Energy Storage

Incorporating DNI Forecasts



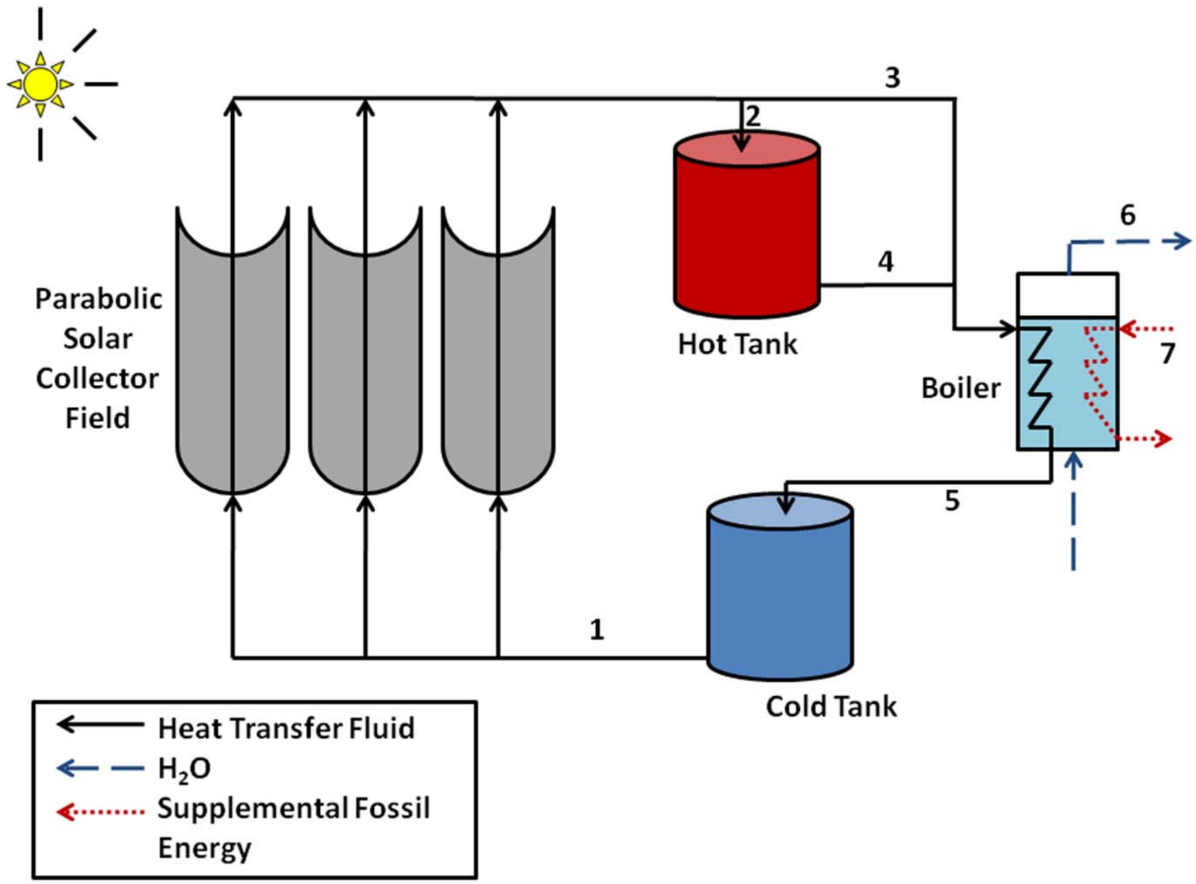
- Nonlinear DAE Model (APMonitor)
- Simultaneous solution method (IPOPT)

- Include forecast
- Some information is better than none



Solar Thermal Energy Storage

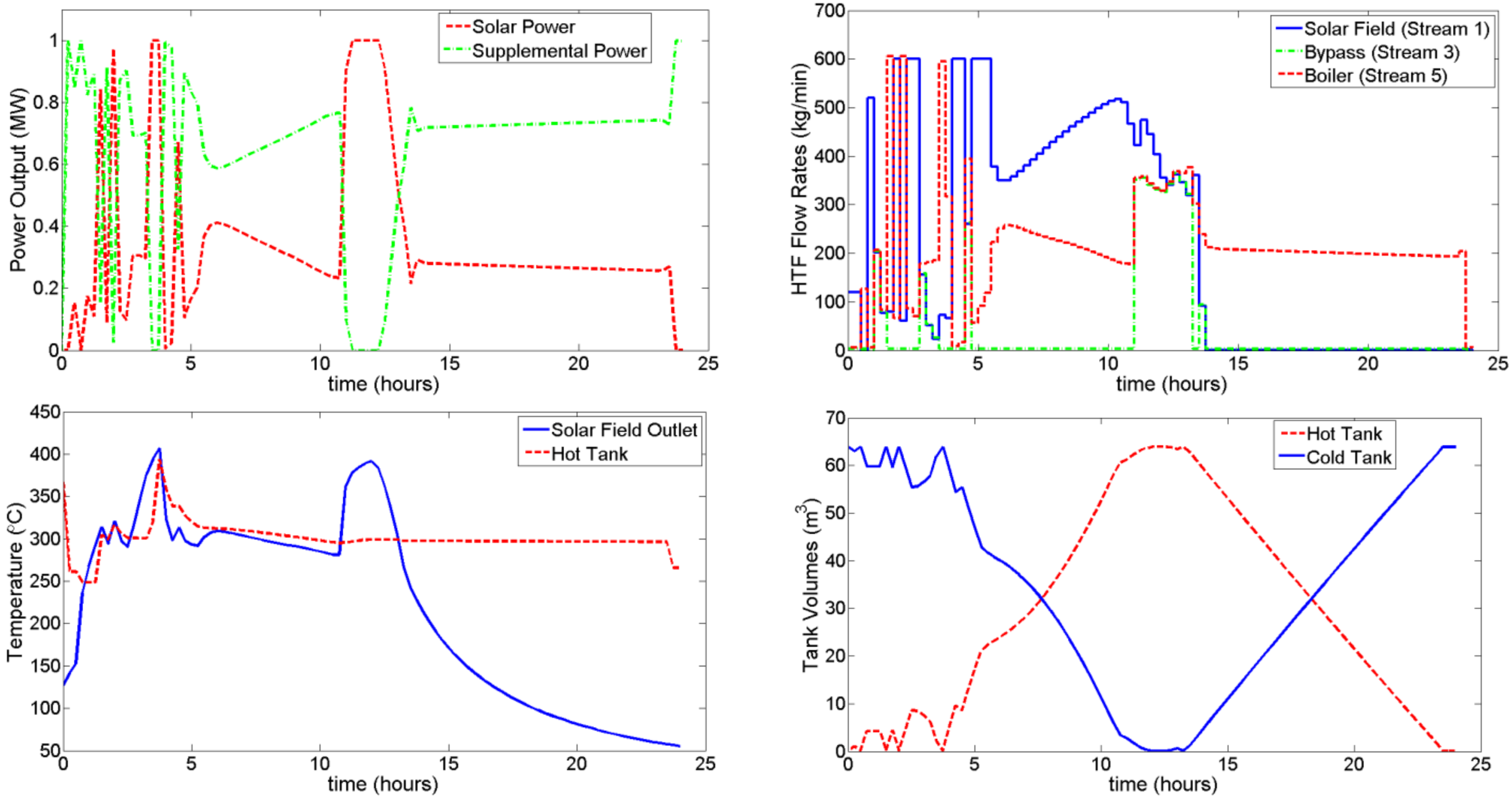
Intelligent Storage: Dynamic Optmization



- Storage bypass
- Optimal temperature control
- Hybrid operation

Solar Thermal Energy Storage

Dynamic Optimization: Results



Solar Thermal Energy Storage

Dynamic Optimization: Summary

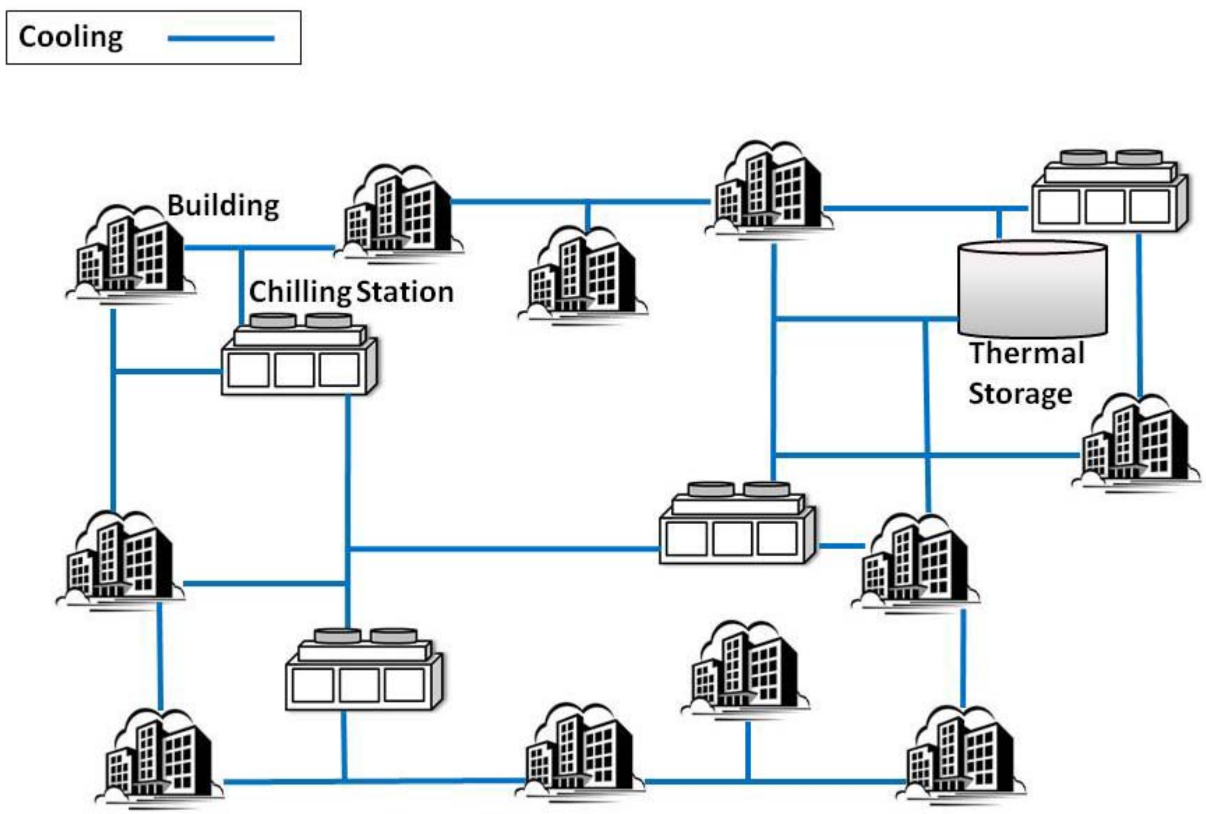
	Solar Energy Collected (MWh)	Energy Collected/ Total Incident Energy (%)
Sunny		
Standard Control	18.02	76.8%
Dynamic Optimization	18.59	79.2%
Partly Cloudy		
Standard Control	14.60	75.8%
Dynamic Optimization	15.83	81.1%
Mostly Cloudy		
Standard Control	4.75	52.1%
Dynamic Optimization	7.80	85.4%

- Most effective on cloudy day
- Could expand solar thermal footprint
- Future Work:
  - Stochastic problem
  - D-RTO

Proposed Future Work

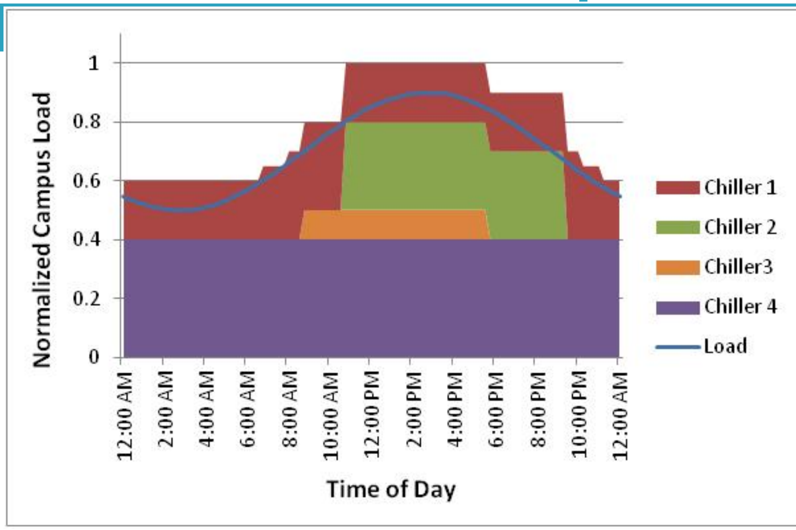
Phase 1: Campus Cooling w/ TES

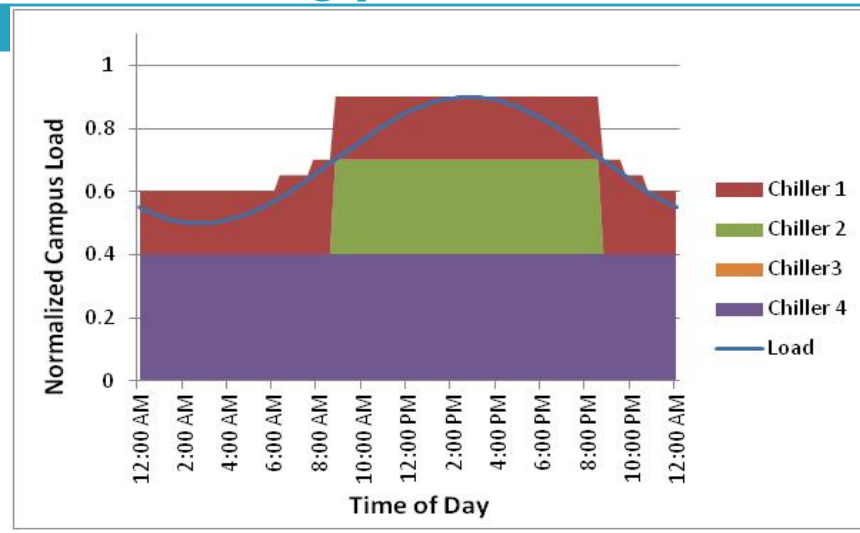
- Objectives:
  - Cooling system modeling
  - Empirical cooling load forecasting
  - Analytical analysis of economics and energy savings
  - Solve dynamic optimization
  - Test operation strategy
  - Recommendations by May 2012



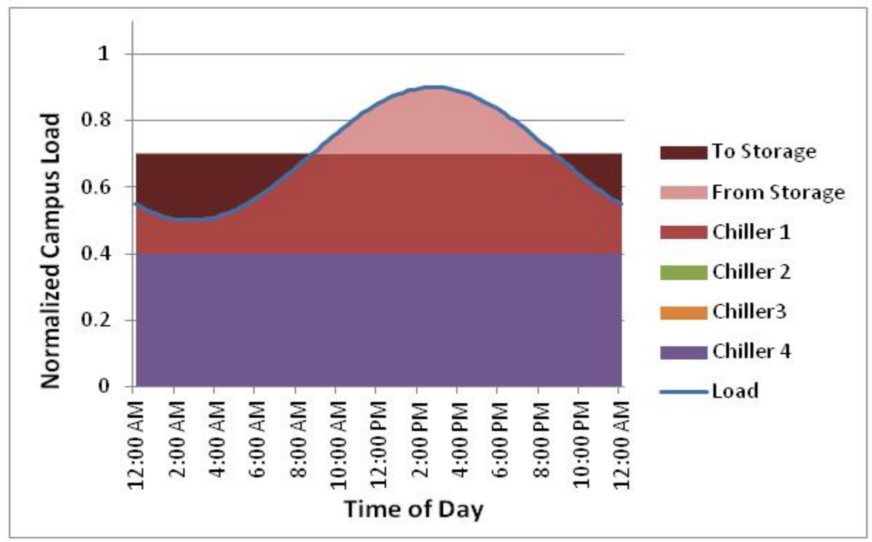
Proposed Future Work

Phase 1: TES Operation Strategy





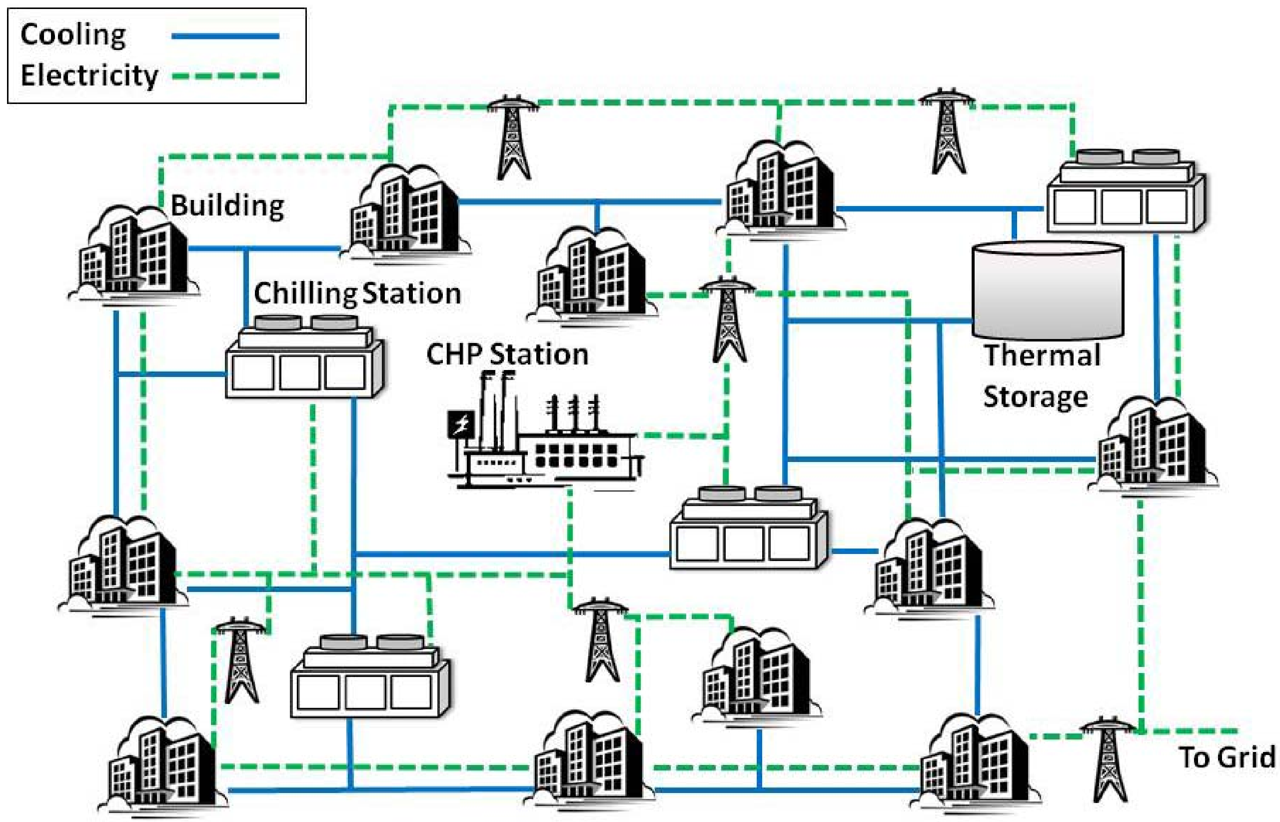
- Forecasting + operator
  - Prescient operation
- Forecasting + optimization
  - Improved operation
- Forecasting + TES + optimization
  - Utilizes all DOFs
  - Harness full potential of system



Proposed Future Work

Phase 2: Smart Electric Grid Operation

- UT is a microgrid
- TES → electric storage
- Free up peak generation capacity
  - Explore scenarios to sell/buy power to/from grid
- New opportunities for interconnection with ERCOT*
  - Accepting bids for ERS
  - $3000/MWh

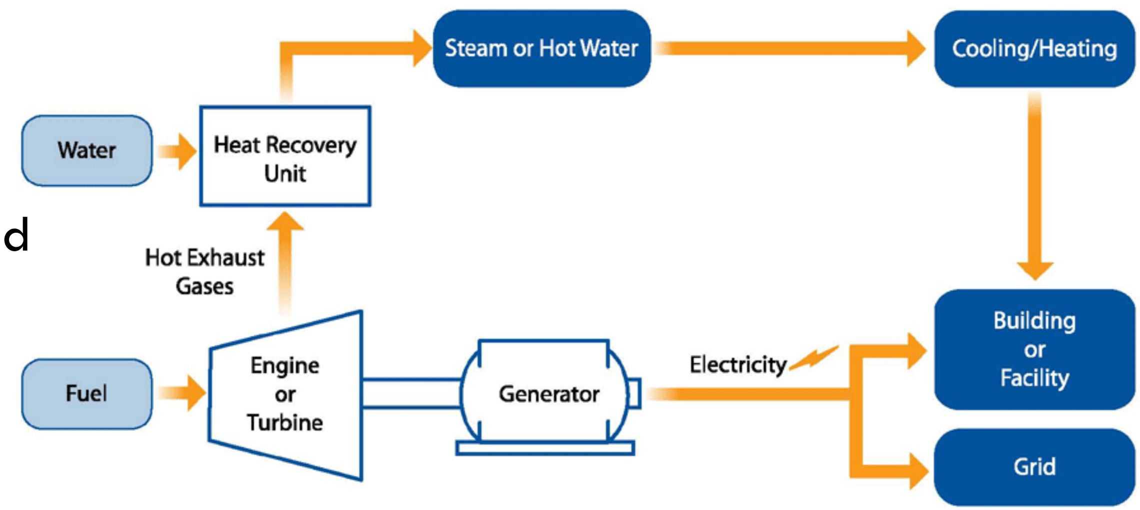


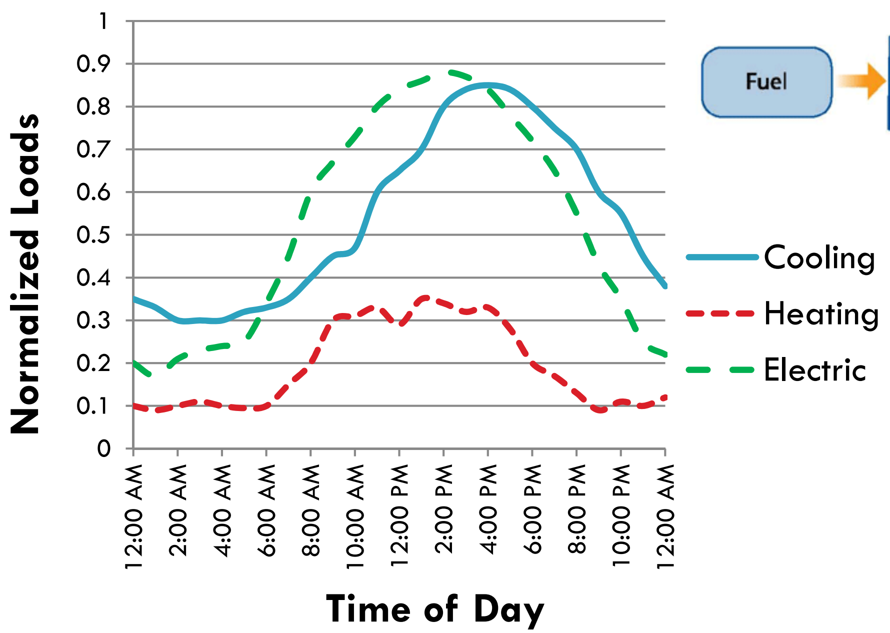
* http://files.harc.edu/sites/GulfCoastCHP/CHP2011/Patterson_EILS_CHP2011.pdf

Proposed Future Work

Combined Heat and Power + Cooling

- Combined Heat and Power
  - Coupled System
  - Independent Loads
- Multi-variable control needed



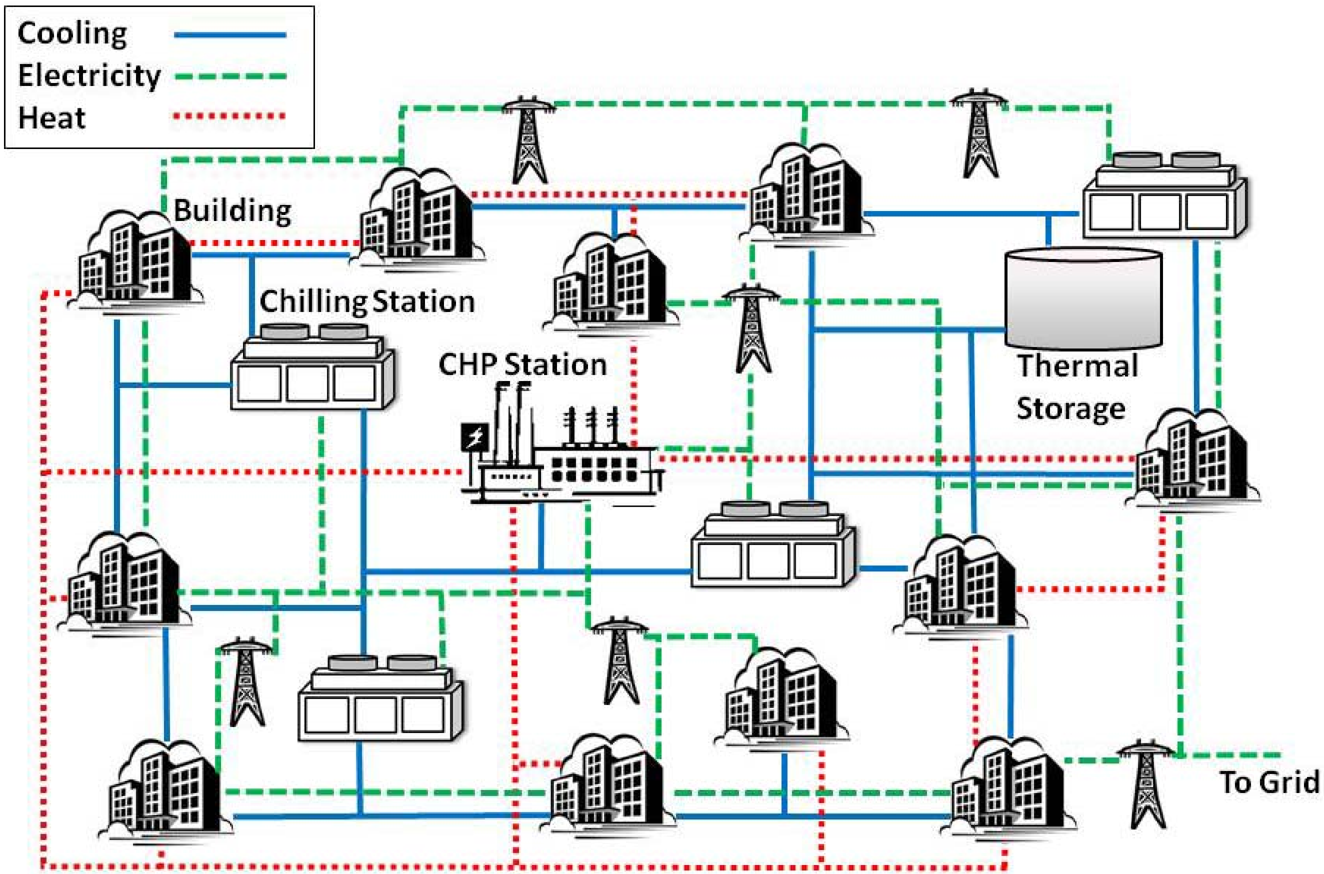


- 3 Loads to Forecast
  - Power
  - Cooling
  - Heat
- Energy Grid Optimization

Proposed Future Work

Phase 2: Dynamic Energy Grid Optimization

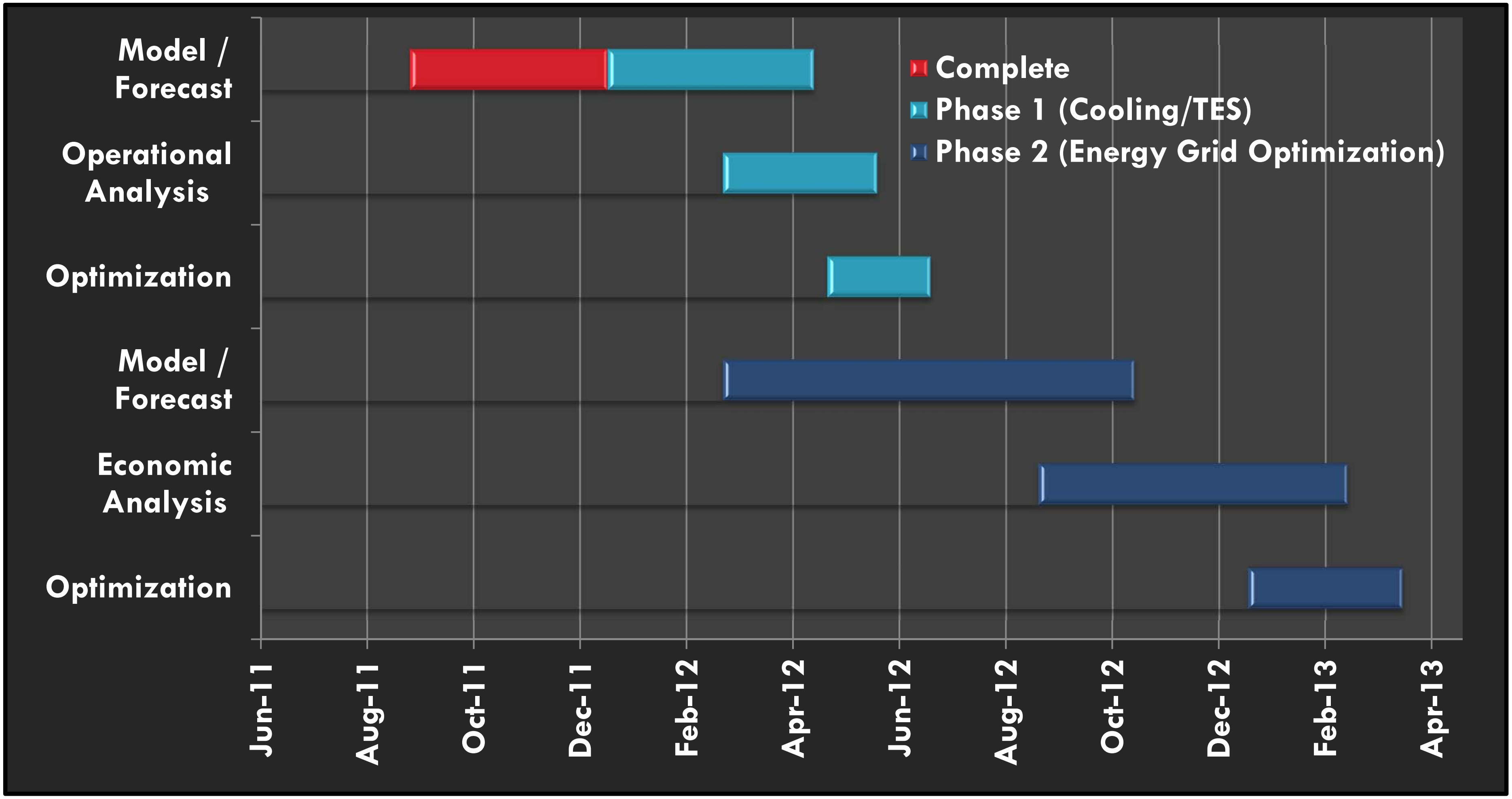
- Electric, Cooling, and Heating Networks
- Forecasts
  - Loads
  - Ambient Conditions
  - Electric and gas prices
- Dynamic optimization of large & complex energy network
- Evaluation of long-term economics for UT



Smart Grid Research
Collaboration Opportunities

Researcher	Component Modeling	Steady State & Dynamic Optimization	Economic/ Energy Analysis	Load/Pricing Forecasting	Multi-variable Control
Wesley Cole (PSP)	√	√	√		
Jongsuk Kim (Chemstations)	√		√		√
Kriti Kapoor (TI)	√	√	√		
Akshay Sriprisad (IGERT)			√	√	
Other IGERT/PSP	√	√	√	√	
BYU Chem E	√	√	√		√
UT CHP Facility			√	√	
Undergrad	√		√	√	

Project Timeline



Conclusions

- Optimization & Energy Storage Vital for Smart Grid
  - TES is a low cost option
  - Forecasting required
  - Proof of concept shown with solar thermal
- Large & Ambitious Project
  - Many collaboration opportunities
  - Opportunity for original, high-impact research
  - Fundamental
    - Solving large scale optimization problems
    - Incorporating energy storage and forecasting
  - Applied
    - Work with real system
    - Potential to save energy and money for UT

My Goals and Accomplishments
Career, Publications, Teaching

- Targeting Faculty Position
- Publications
  - Modeling and Control of Solar Thermal Plant w/ TES
    - Chem Eng Science – Accepted for Publication
    - American Control Conference 2011
  - Dynamic Optimization of Solar Thermal System w/ TES
    - American Control Conference 2012
  - Optimization and Control of TES Systems
    - Reviews in Chemical Engineering, submitted
  - 2012-2013 Goal: 6 total 1st Author Peer-Reviewed Publications
    - In progress: Novel TES model, Dynamic optimization of solar thermal plant
    - Possible future work: Load forecasting, Large campus microgrid optimization, multi-variable CHP control, Dynamic optimization of energy systems with storage, etc.
- Other Work
  - ExxonMobil Chemical Company Internship: Summer 2011 (Nonlinear control and Dynamic Optimization)
  - Re-formulated Distillation Lab for CHE 264

Acknowledgements

- Edgar Research Group
- National Science Foundation
- Cockrell School of Engineering
- AP Monitor
- Pecan Street, Inc.
- UT Austin – Utilities and Energy Management
- My Family

Appendix

- Solar Thermal First Principles Modeling
- Solar thermal vs photovoltaic
- Standard control approach results
- Dynamic real-time optimization

Parabolic Trough Solar Collector Model

Heat Transfer Fluid

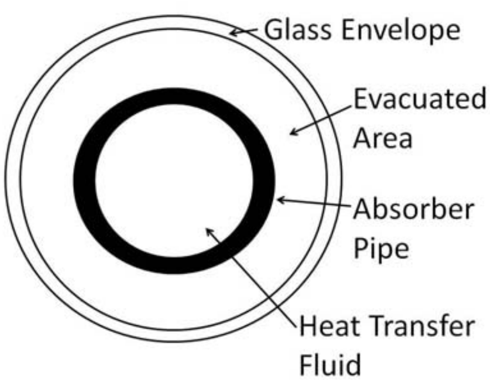
$$\rho_{HTF} C_{HTF} A_{ABS,i} \frac{\partial T_{HTF}}{\partial t} = \dot{m} C_{HTF} \frac{\partial T_{HTF}}{\partial x} + h_{pipe} P_{ABS,i} \left(T_{ABS} - T_{HTF} \right)$$

Absorber Pipe

$$\rho_{ABS} C_{ABS} A_{ABS} \frac{\partial T_{ABS}}{\partial t} = h_{pipe} P_{ABS,i} \left(T_{HTF} - T_{ABS} \right) - \frac{\sigma}{\frac{1}{\varepsilon_{ABS}} + \frac{1-\varepsilon_{ENV}}{\varepsilon_{ENV}} \left(\frac{r_{ABS,o}}{r_{ENV,i}} \right)} P_{ABS,i} \left(T_{ABS}{}^{4} - T_{ENV}{}^{4} \right) + q''_{absorbed}\, w$$

Glass Envelope

$$\rho_{ENV} C_{ENV} A_{ENV} \frac{\partial T_{ENV}}{\partial t} = \frac{\sigma}{\frac{1}{\varepsilon_{ABS}} + \frac{1-\varepsilon_{ENV}}{\varepsilon_{ENV}} \left(\frac{r_{ABS,o}}{r_{ENV,i}} \right)} P_{ABS,i} \left(T_{ABS}{}^{4} - T_{ENV}{}^{4} \right) - \sigma \varepsilon_{ENV} P_{env,o} \left(T_{ENV}{}^{4} - T_{AIR}{}^{4} \right) - h_{air} P_{ENV,o} \left(T_{ENV} - T_{AIR} \right)$$



$$T_{HTF}\left(t, x=0\right) = T_{in}$$

$$T_{HTF}\left(t=0, x\right) = T_{HTF,0}$$

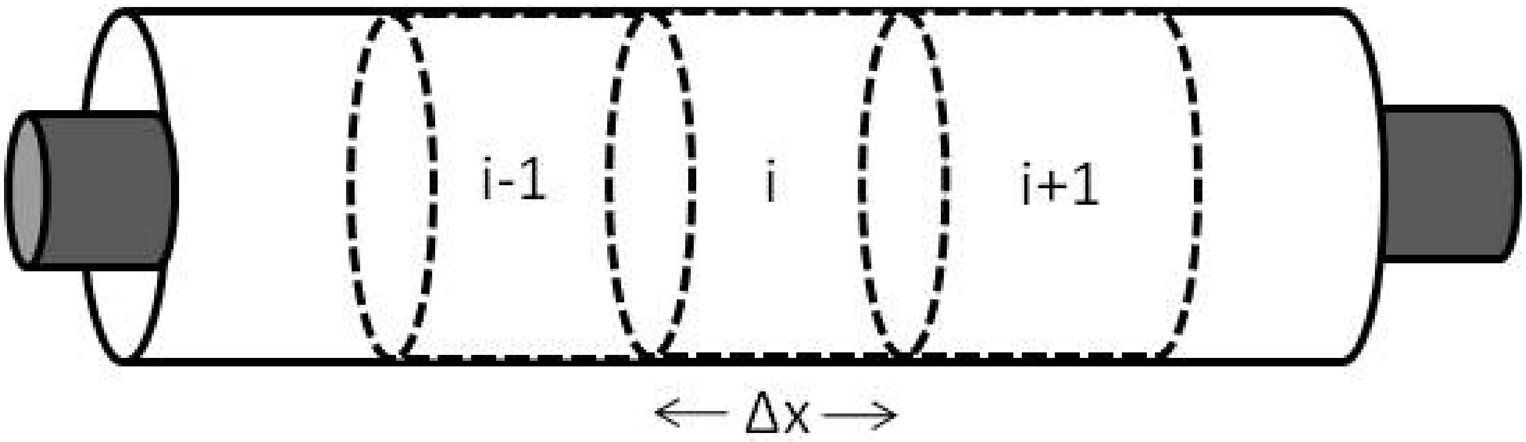
$$T_{ABS}\left(t=0, x\right) = T_{ABS,0}$$

$$T_{ENV}\left(t=0, x\right) = T_{ENV,0}$$

$$h_{pipe} = f(\dot{m})$$

$$h_{air} = f(V_w)$$

Spatial Discretization



- System divided into n segments: $\Delta x = L/n$
- Energy balance computed in each segment for fluid, absorber pipe and glass envelope
- Converts 3 coupled PDEs to 3n ODEs
- Backward difference method used to approximate spatial derivatives $\frac{dT}{dx} \approx \frac{\left(T(i) - T(i-1)\right)}{\Delta x}$

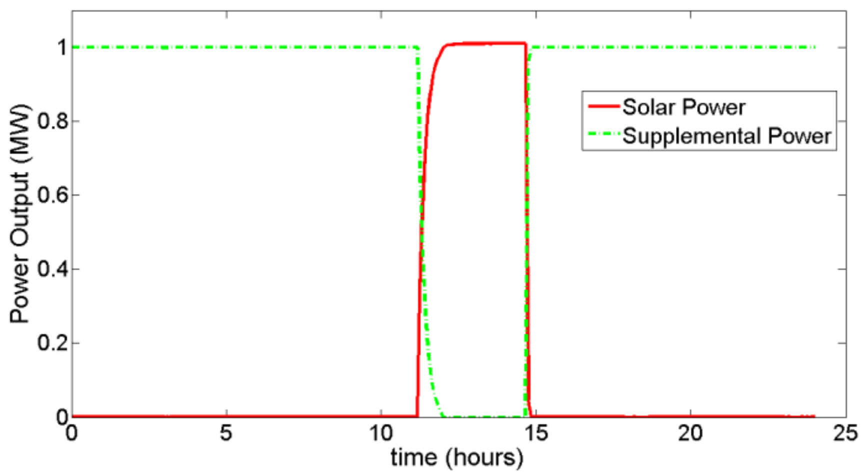
Solar Thermal vs Photovoltaic (PV)

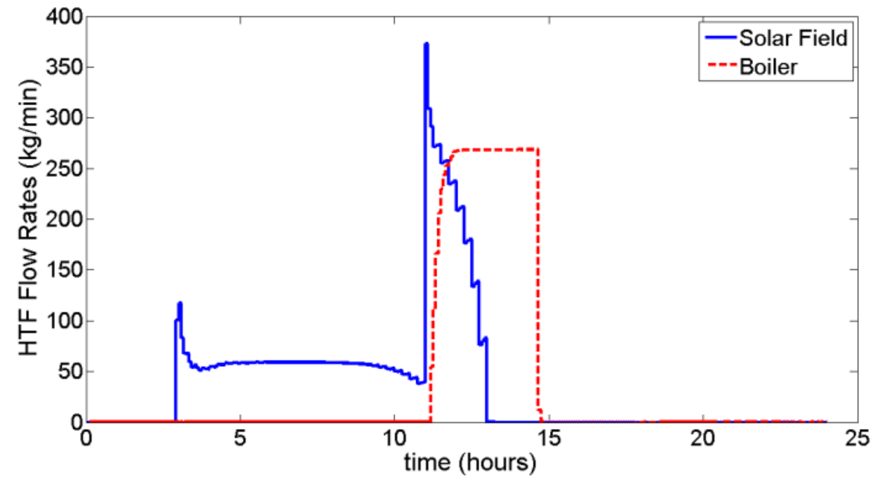
	Solar Thermal	Photovoltaic
Energy Conversion	Sunlight → Heat → Mechanical → Electricity	Sunlight → Electricity
Cost ($/kWh)	0.12[1] (0.06 Projected)[2]	0.18-0.23[1]
Efficiency[3]	~18%	~12%
Solar Irradiance Used	Direct Normal Irradiance (DNI)	Global Horizontal (GHI)
Scale	Large Scale	Distributed to large scale
Storage	Thermal Storage	Battery Storage
Dispatchable on a large scale	Yes	No
Impact on grid stability	Small	Large

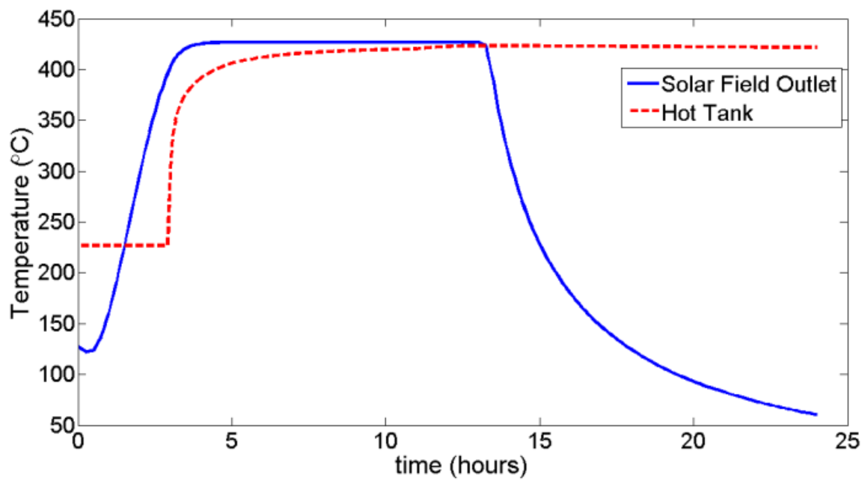
[1] http://www.window.state.tx.us/specialrpt/energy/exec/solar.html
[2] http://www.reuters.com/article/2009/08/24/us-energy-maghreb-desertec-sb-idUSTRE57N01720090824?sp=true
[3] http://solarbuzz.com/facts-and-figures/markets-growth/cost-competitiveness

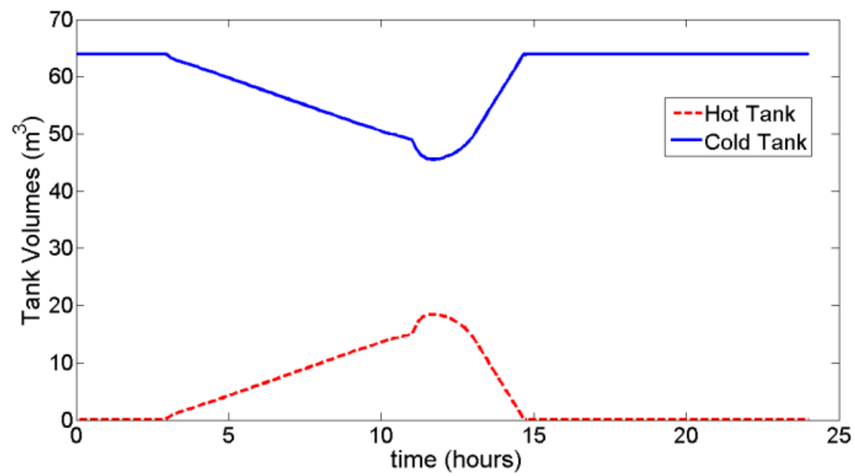
Solar Thermal Energy Storage

Standard Control: Results









Dynamic Real-Time Optimization