Impact of Shale Gas on Energy Efficiency and Smart Manufacturing

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Shale Gas Monetization

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Outline

- U.S. energy/environment overview
- Energy efficiency and power production alternatives
- Smart manufacturing to reduce energy usage
- Next generation power systems(smart grids, combined heat and power)
- Thermal energy storage and process control

Perspective of this Paper

- Focuses on process operation and control (not design)
- Assumes use of existing infrastructure to maximize thermal efficiency
- Maximize efficiency ≡ minimize carbon footprint
- Most carbon dioxide currently comes from fossil fuel combustion
- Progress will require a systems approach

Reducing Carbon Footprint in Process Plants

- Reduce energy requirements
  - Use less energy-intensive chemistry/unit operations
  - Increase heat integration/cogeneration
  - Change the process to alter thermal vs. electro-mechanical energy
- Reduce carbon emissions (no major process changes)

CHP Energy and CO_2 Savings Potential (10 MW)

	10 MW CHP	10 MW PV	10 MW Wind	Combined Cycle (10 MW Portion)
Annual Capacity Factor	85%	22%	34%	70%
Annual Electricity	74,446 MWh	19,272 MWh	29,784 MWh	61,320 MWh
Annual Energy Savings	308,100 MMBtu	196,462 MMBtu	303,623 MMBtu	154,649 MMBtu
Annual CO_2 Savings	42,751 Tons	17,887 Tons	27,644 Tons	28,172 Tons
Annual NOx Savings	59.4 Tons	16.2 Tons	24.9 Tons	39.3 Tons

Source: U.S. Department of Energy

Impact of Shale (Natural) Gas in the U.S.

- Increasing supplies of domestic natural gas (+20%), $4/MSCF
- Increased usage in power generation(lower GHG)
- Makes U.S. industrial locations more globally competitive (feedstock, power)
- Changes regional industrial development options (e.g., NY-PA), subject to local environmental pressures

What is SMART Manufacturing?

The ability to take action, in real time, to OPTIMIZE your assets in the context of your business strategies and imperatives

SMLC

SMART MANUFACTURING
LEADERSHIP COALITION

The infusion of intelligence that transforms the way Industries conceptualize, design, and operate the manufacturing enterprise.

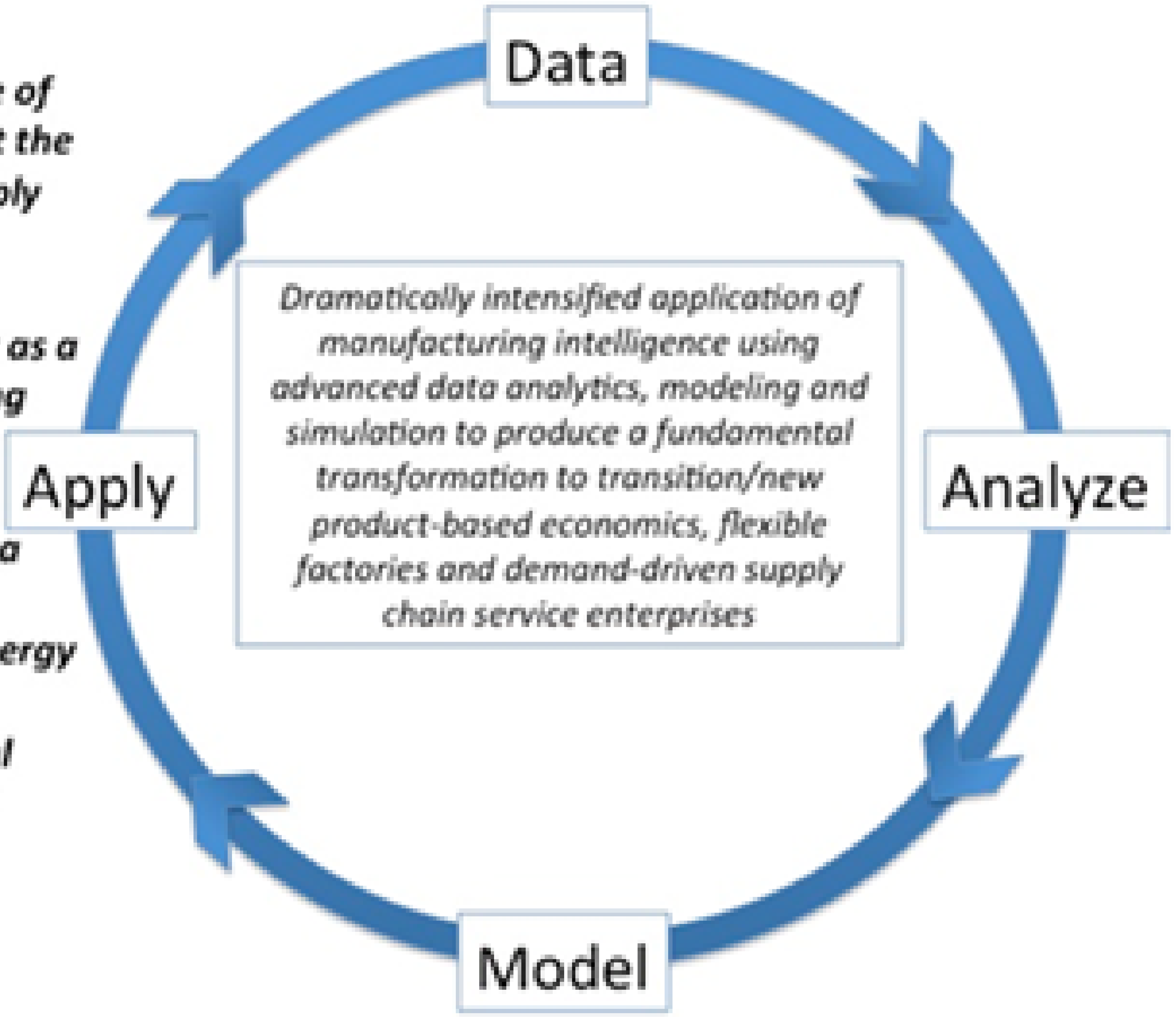
https://smartmanufacturingcoalition.org
http://smartmanufacturing.com

“Internet of Things” Deception

- Connect your smartphone to your digital scale
- Then you will lose weight
- You have to do something else?

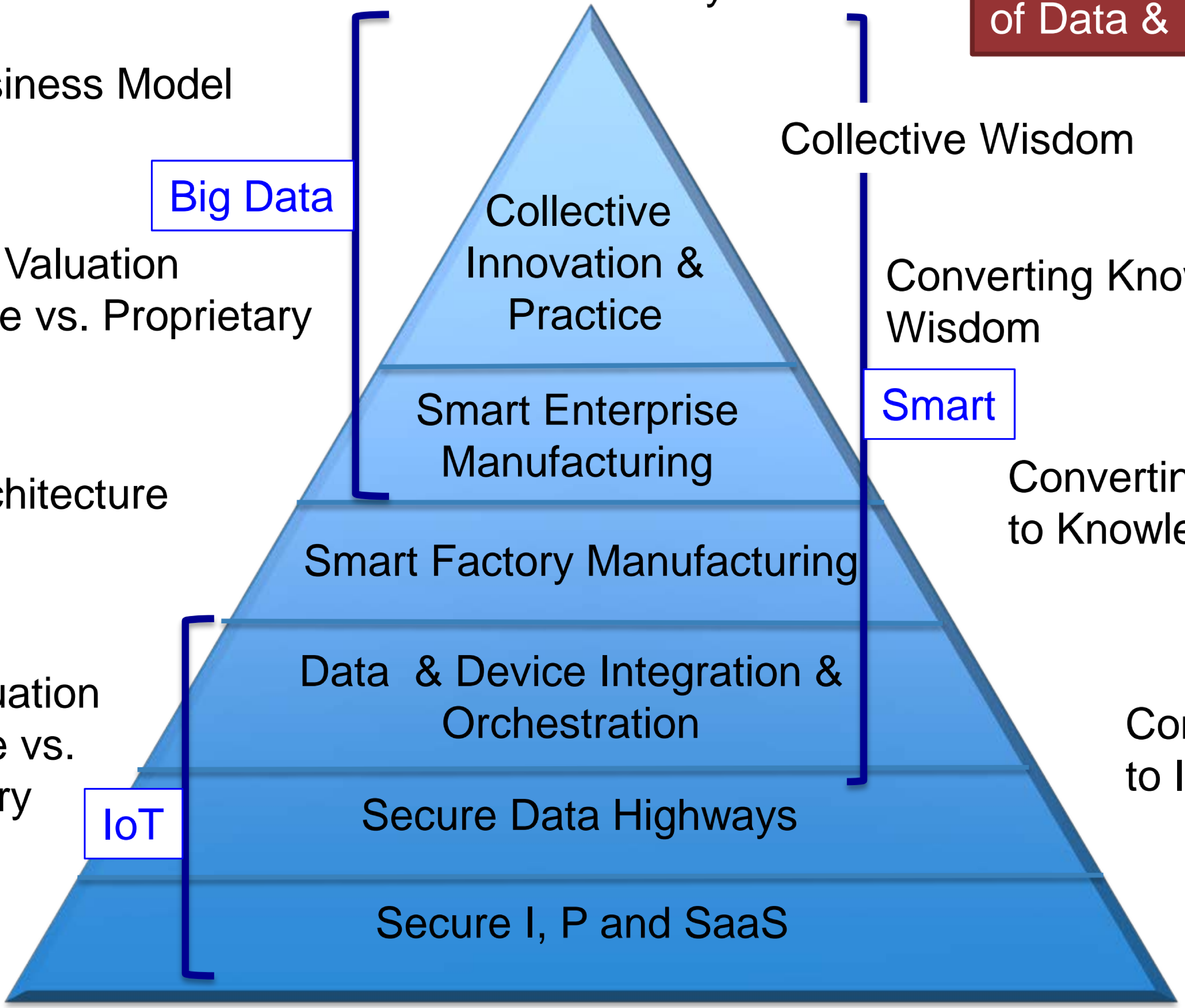
21st Century Smart Manufacturing

- ***Integrates the intelligence of the 'customer' throughout the entire manufacturing supply chain***
- ***Responds to the customer as a coordinated manufacturing enterprise***
- ***Responds to the public as a performance-oriented enterprise, minimizing energy and material usage and maximizing environmental sustainability, health and safety and economic competitiveness.***



Dramatically intensified application of manufacturing intelligence using advanced data analytics, modeling and simulation to produce a fundamental transformation to transition/new product-based economics, flexible factories and demand-driven supply chain service enterprises

The Business of Open Architecture Market, Valuation of Data & Innovation



Global Manufacturing Health & Sustainability

Collective Innovation & Practice

Smart Enterprise Manufacturing

Smart Factory Manufacturing

Data & Device Integration & Orchestration

Secure Data Highways

Secure I, P and SaaS

The Business Model of Data

Big Data

Practice Valuation Collective vs. Proprietary

Open Architecture

Data Valuation Collective vs. Proprietary

IoT

Collective Wisdom

Converting Knowledge to Wisdom

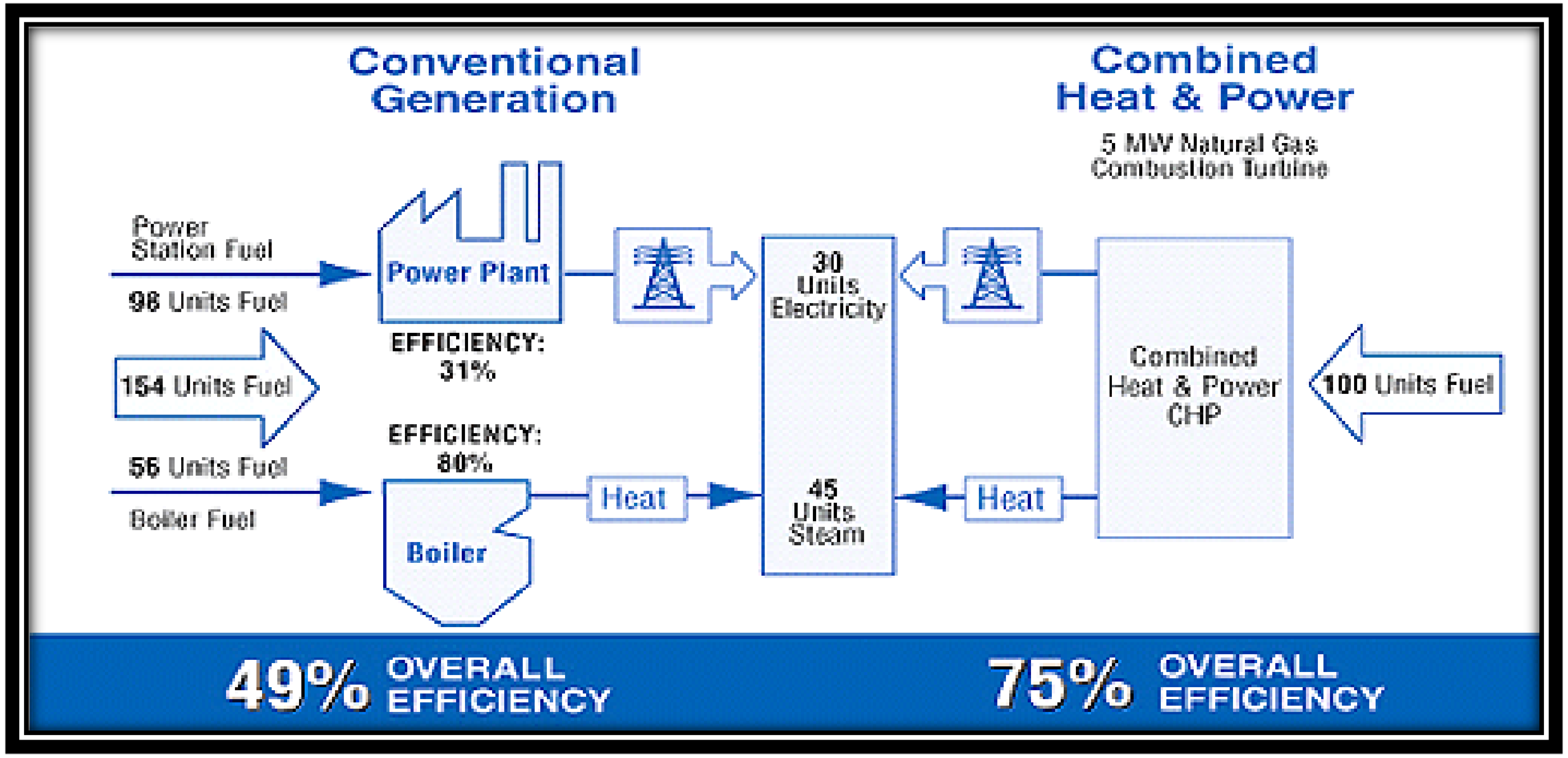
Smart

Converting Information to Knowledge

Converting Data to Information

Increased Generation Efficiency

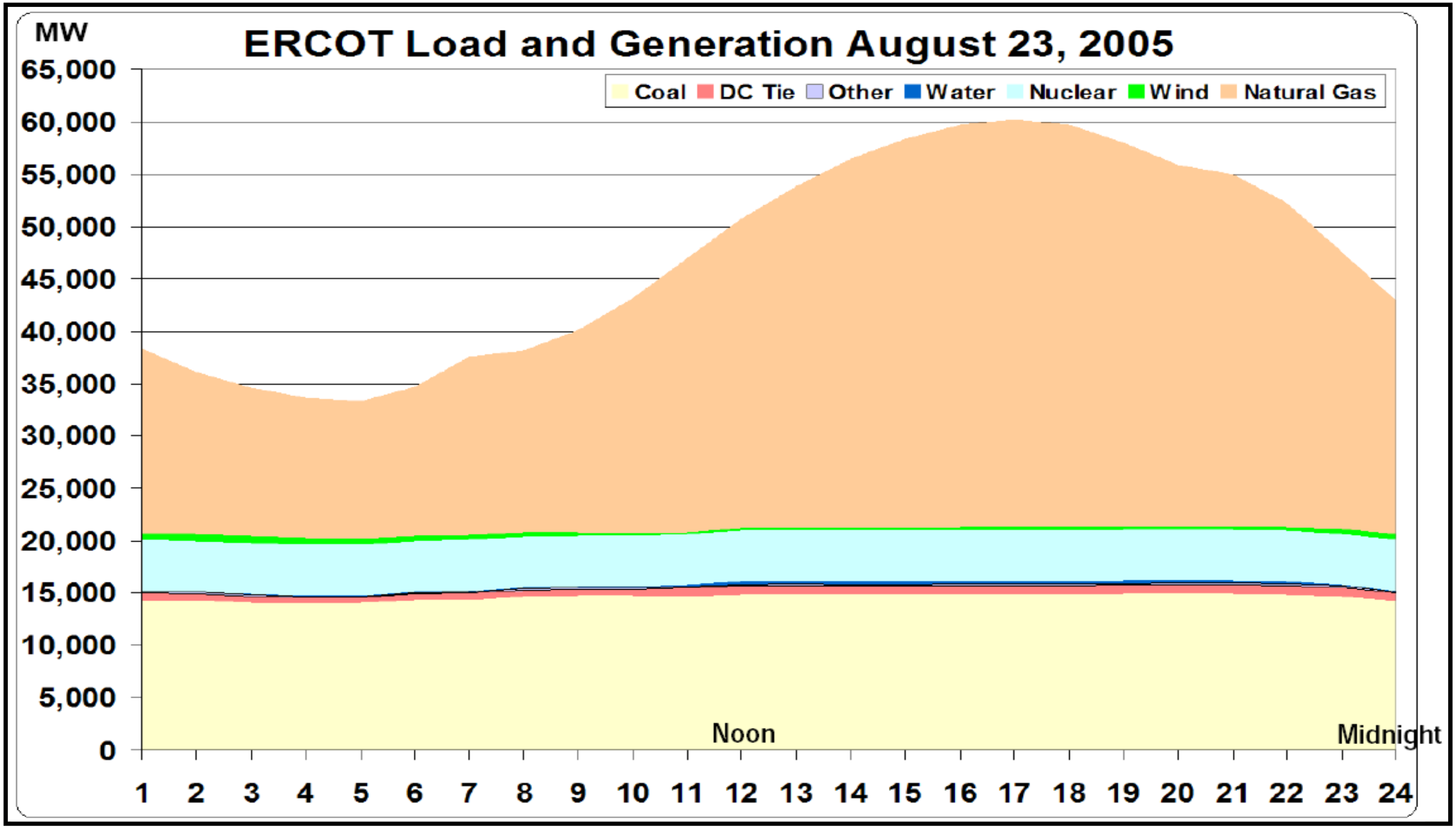
- Conventional efficiency: 40-55%
- Cogeneration efficiencies: 75-85%



Smart Power Grids

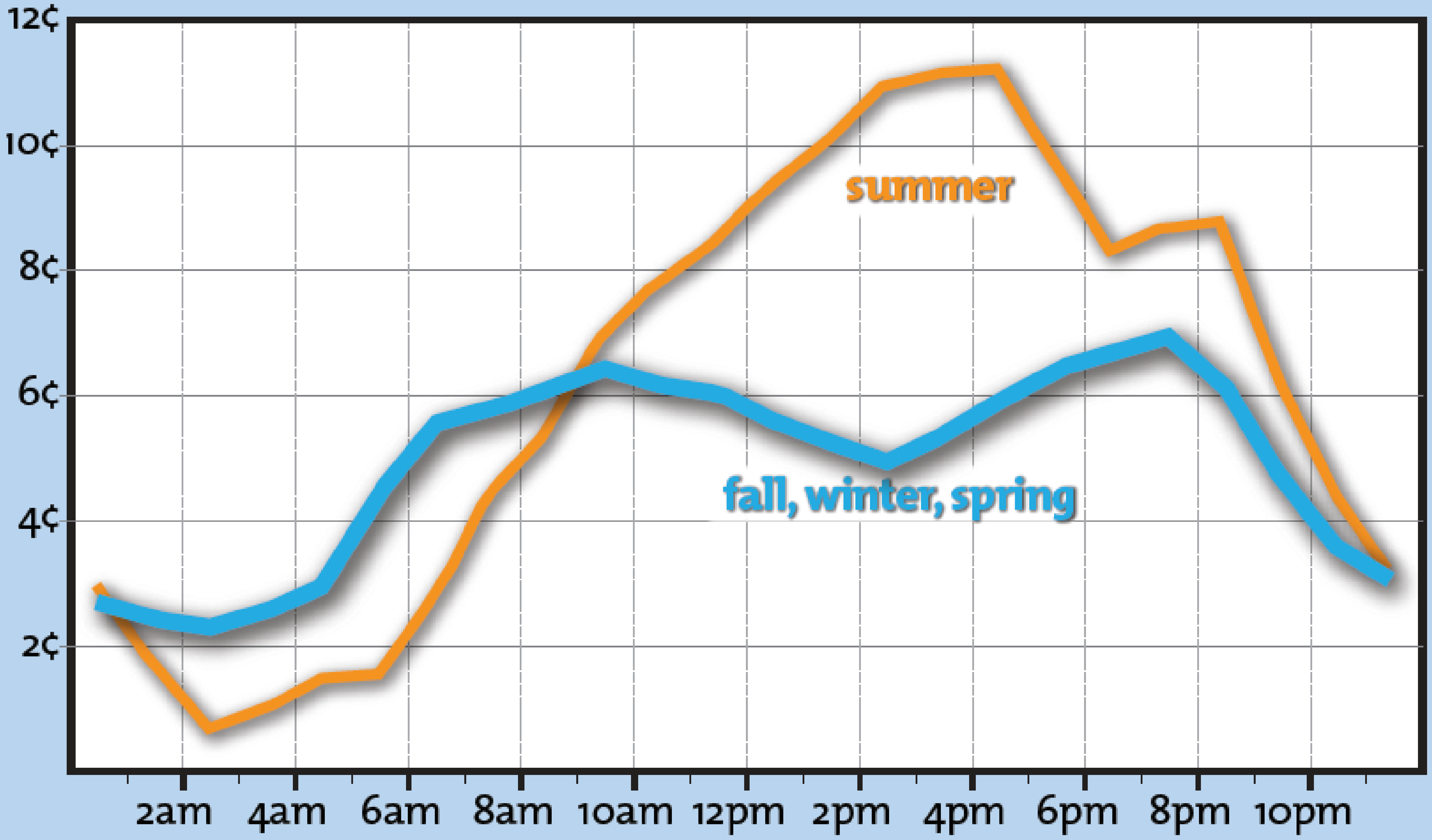
- Delivery of electric power using two-way digital technology and automation with a goal to save energy, reduce cost, and increase reliability.
- Power generated and distributed optimally for a wide range of conditions either centrally or at the customer site, with variable energy pricing based on time of day and power supply/demand.
- Increased use of intermittent renewable power sources such as solar or wind energy but increased need for energy storage.

Electricity Demand Varies throughout the Day



Source: ERCOT Reliability/Resource Update 2006

Average Real-Time Pricing Patterns for 2008*



*Summer prices are for June - August. Depending on market conditions, prices can vary signficantly from this typical pattern. Savings cannot be guaranteed.

Future Industrial Environment

- Stronger focus on energy use(corporate energy czars?)
- Increased energy efficiency and decreased carbon footprint
- Energy use measured and optimized for each unit operation
- Increased use of renewable energy(e.g., solar thermal and biomass) and energy storage
- Interface with smart grids and energy storage

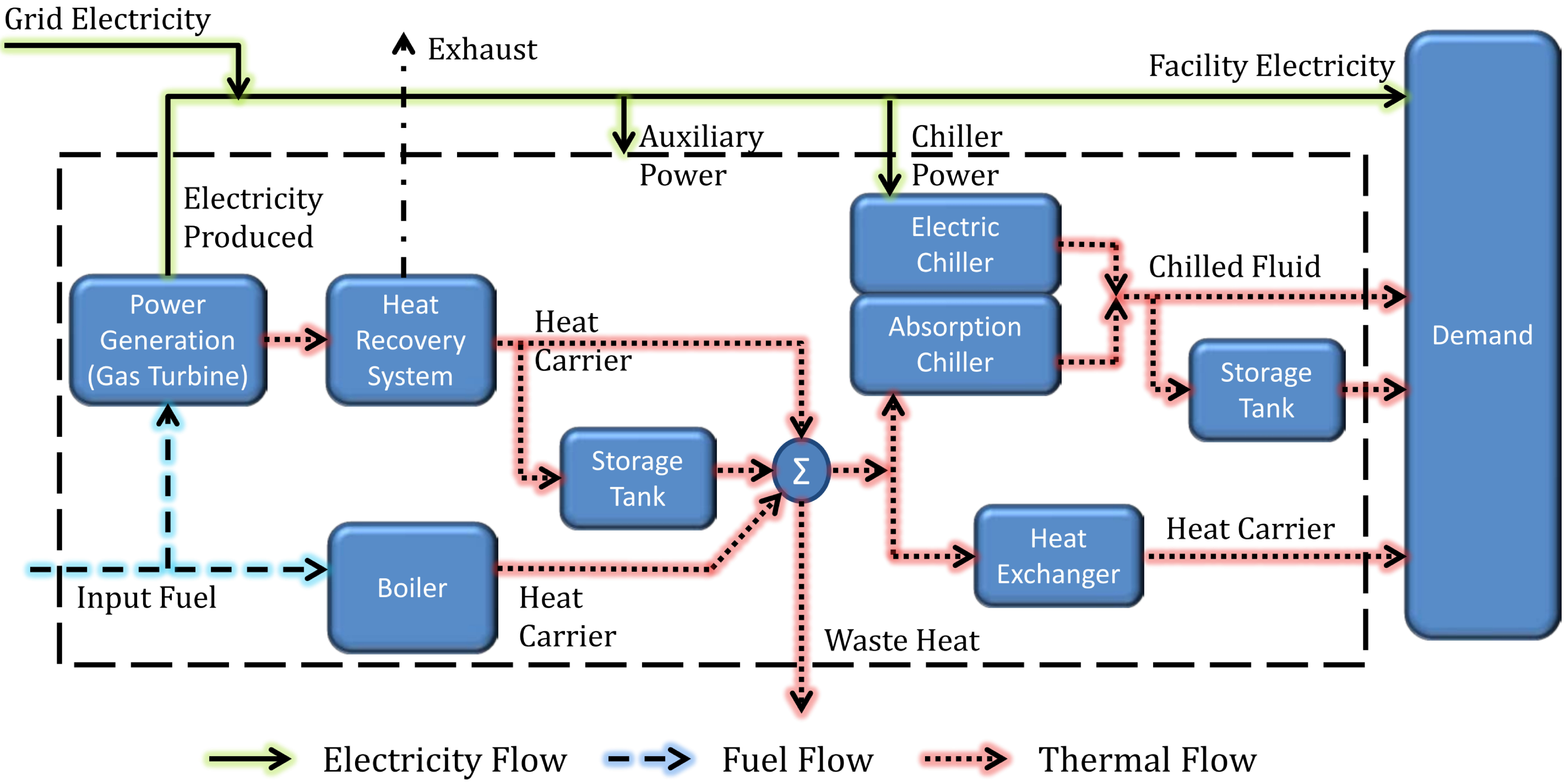
"FIRST, THE GOOD NEWS: WE'VE SHUT DOWN THE COAL-FIRED ELECTRIC POWER PLANT IN YOUR BACKYARD..."

Thermal Energy Storage

- Thermal energy storage (TES) systems heat or cool a storage medium and then use that hot or cold medium for heat transfer at a later point in time (steam, water, ice).

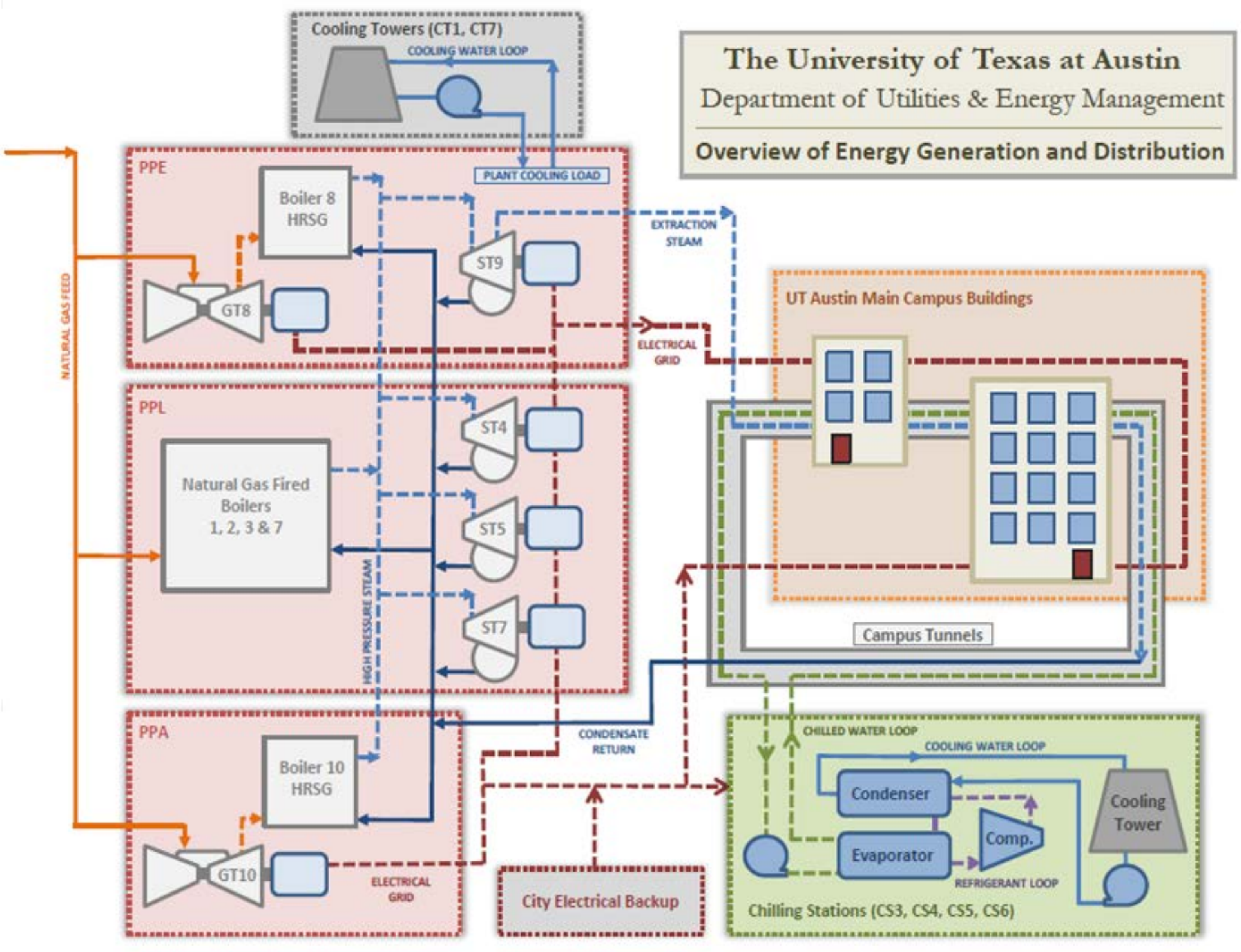
- Using thermal storage can reduce the size and initial cost of heating/cooling systems, lower energy costs, and reduce maintenance costs. If electricity costs more during the day than at night, thermal storage systems can reduce utility bills further.

- Incentive for thermal storage (NY Con Edison) for building or industrial users: $2,600/KW vs. $2,100/KW for battery storage



Energy flows in a combined heat and power system with thermal storage

UT Austin – A CHP plant (80+ % efficiency) with District Cooling Network



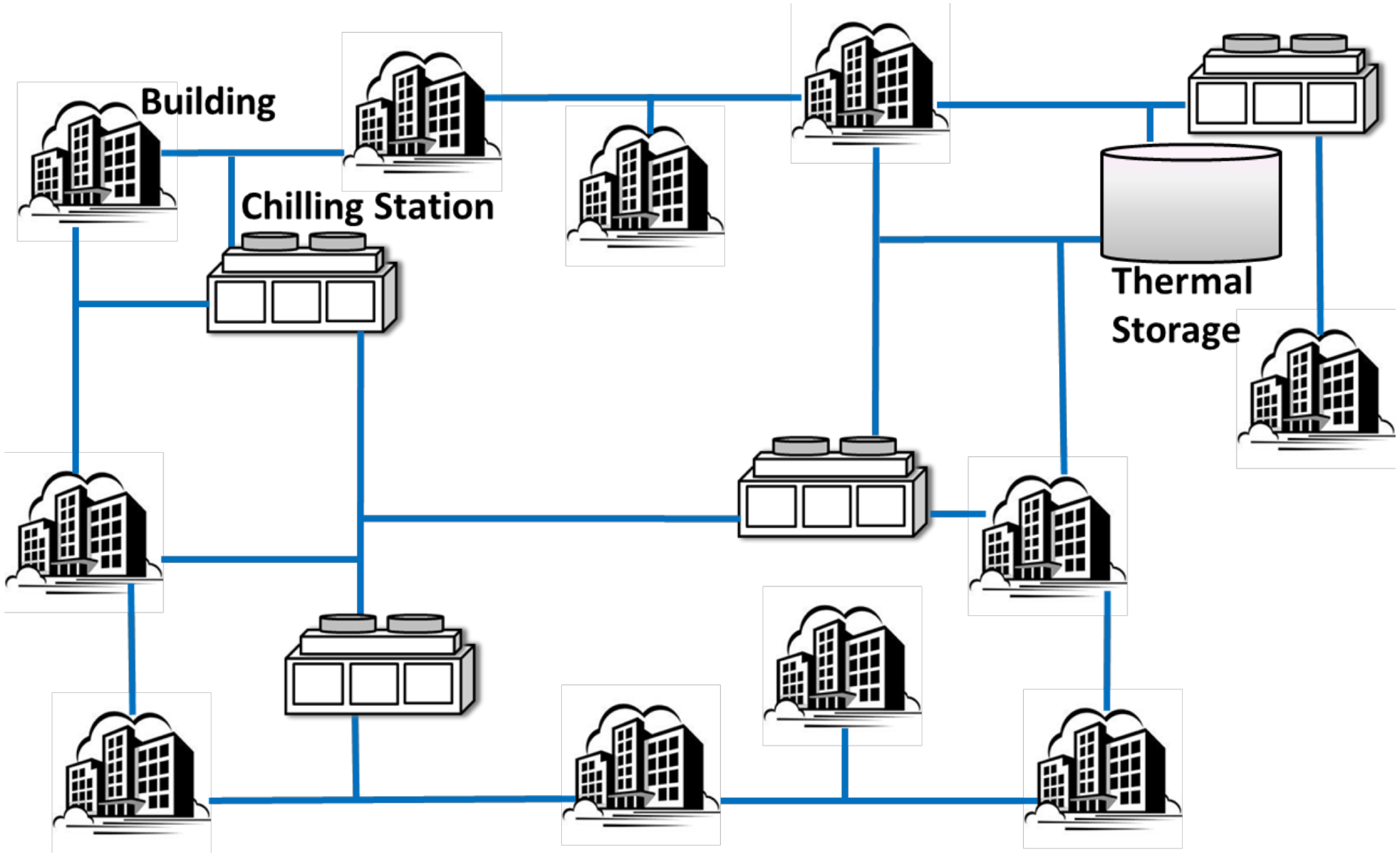
Hal C. Weaver Power Plant

- Kriti Kapoor
  - Modeling of the cooling system
- Kody Powell
  - Optimization with TES*
  - Load forecasting models
- Wesley Cole
  - Cooling load analysis
- Jong Kim
  - Selling electricity to grid

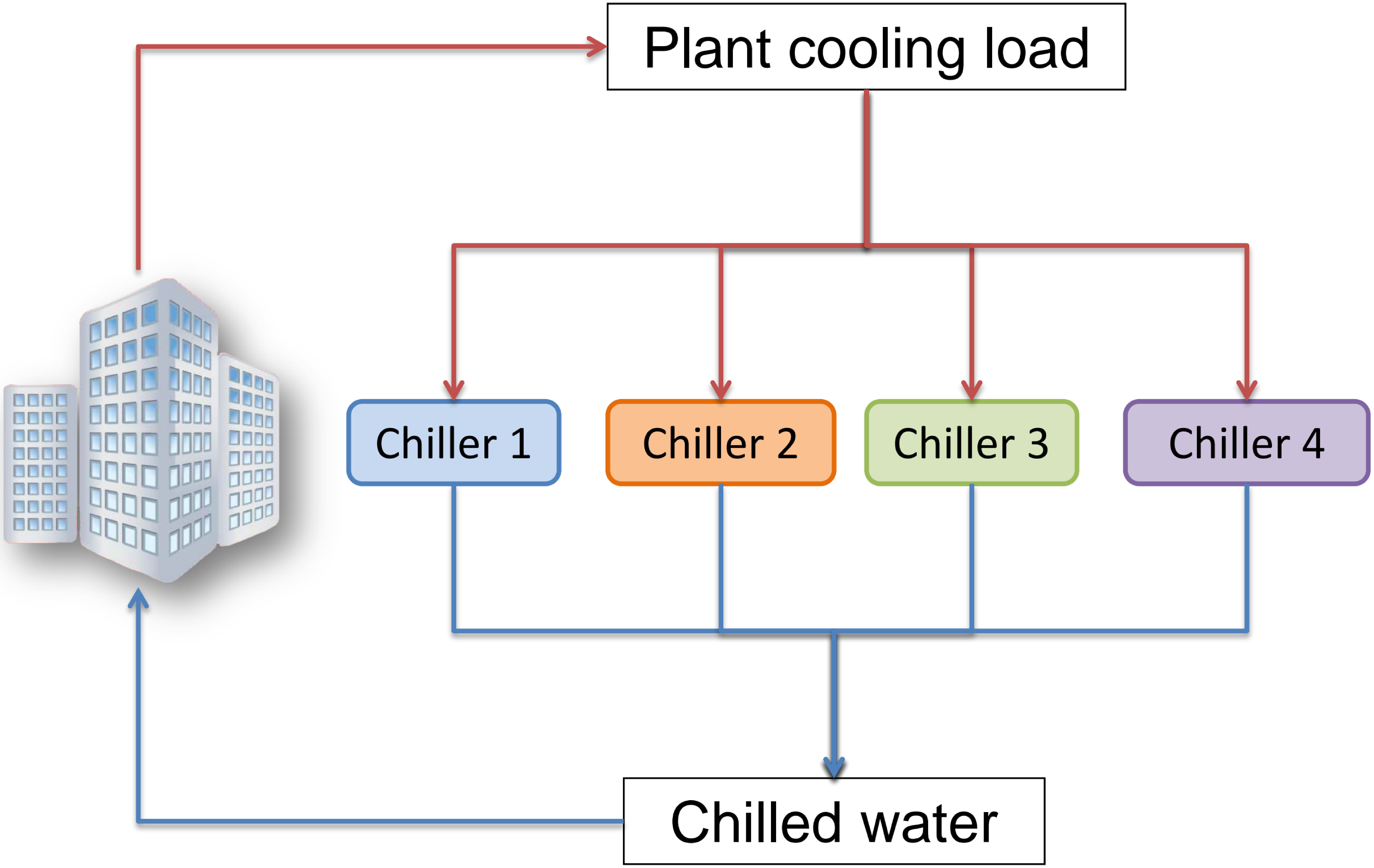
*TES – Thermal energy storage

District Cooling

- Chilled water network
- Economy of scale
  - Centralized chillers
  - Thermal energy storage
- Opportunity for optimal chiller loading



Optimal Chiller Loading to Save Energy



Plant cooling load

Chiller 1

Chiller 2

Chiller 3

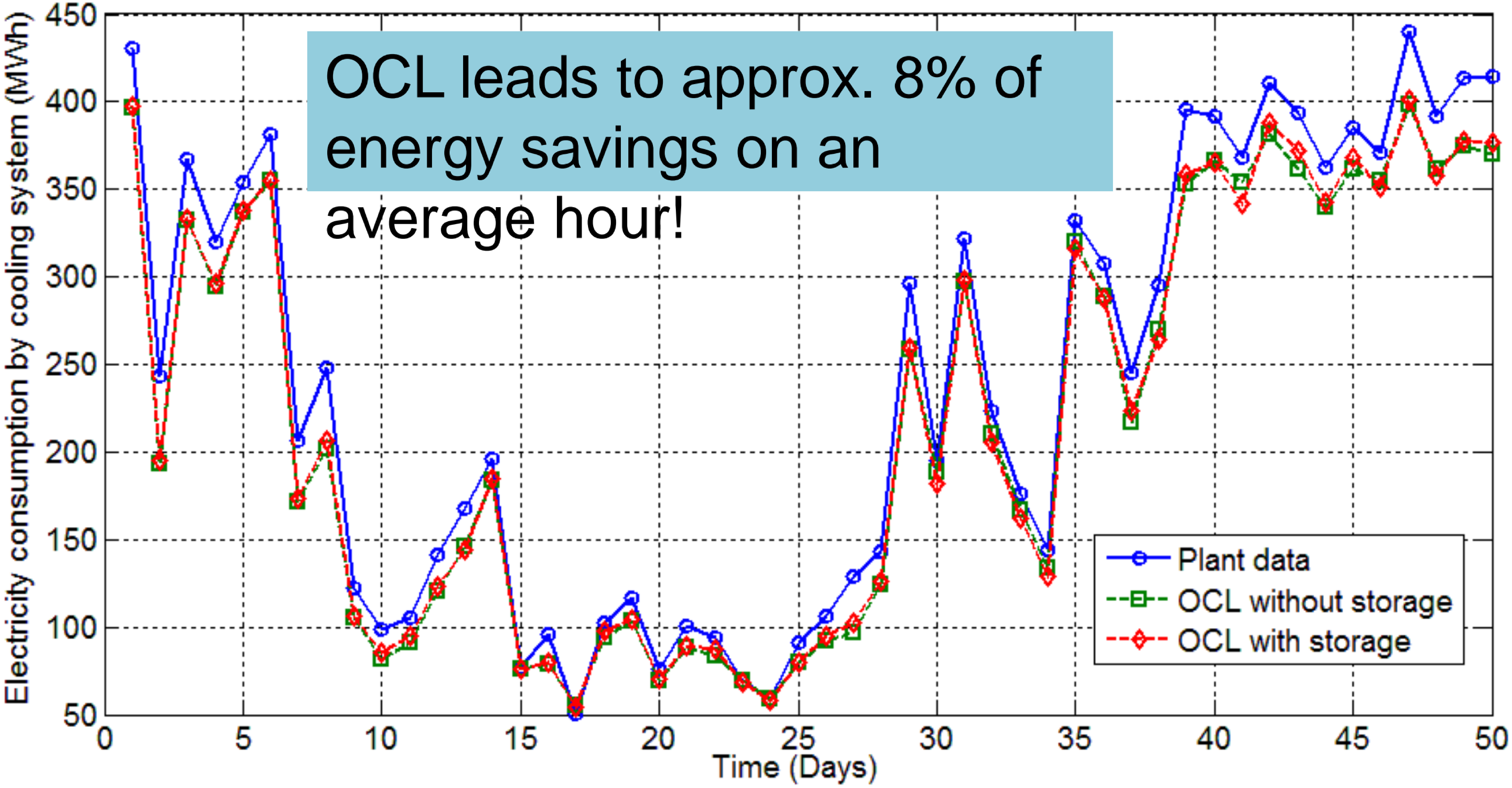
Chiller 4

Chilled water

Optimal Chiller Loading

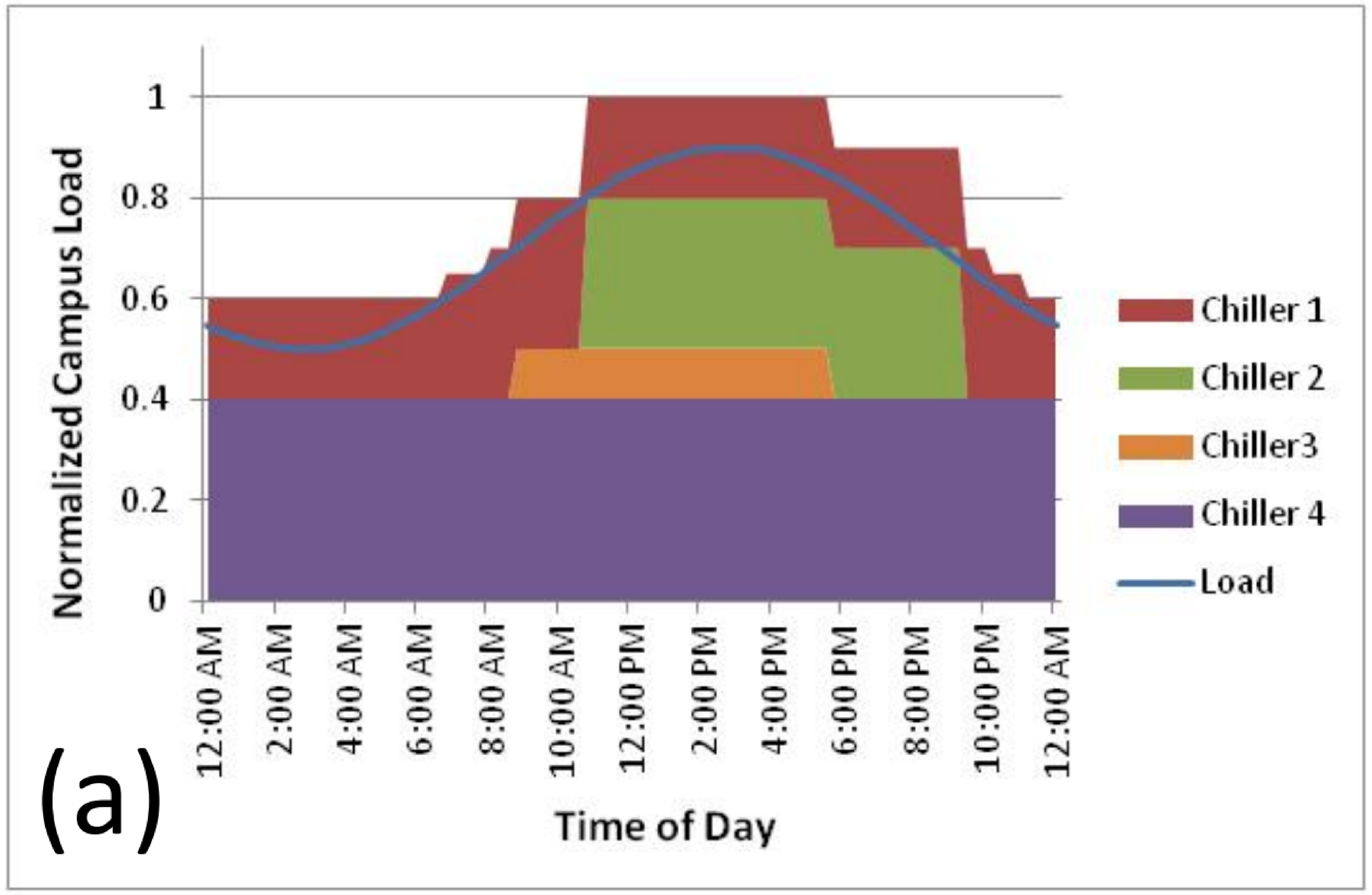
- A chiller cools the water for air conditioning
- Other energy consuming equipment in a chilling station are cooling towers and pumps
- Chillers are different from one another in terms of efficiency and/or capacity.
- Optimal chiller loading – best distribution of cooling load among chillers to minimize the power consumption
- Thermal energy storage – to store chilled water which can be used later

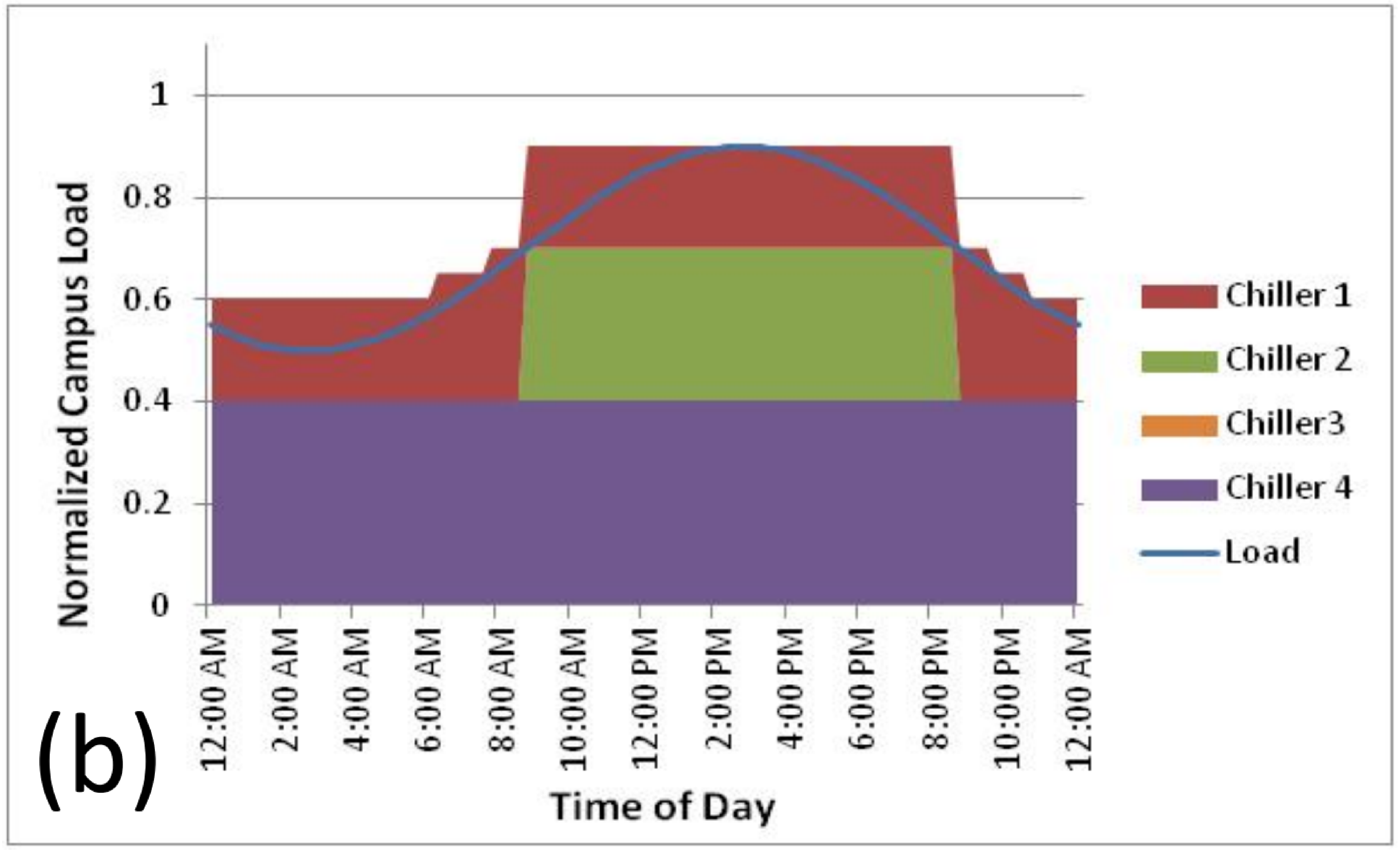
Optimization Results

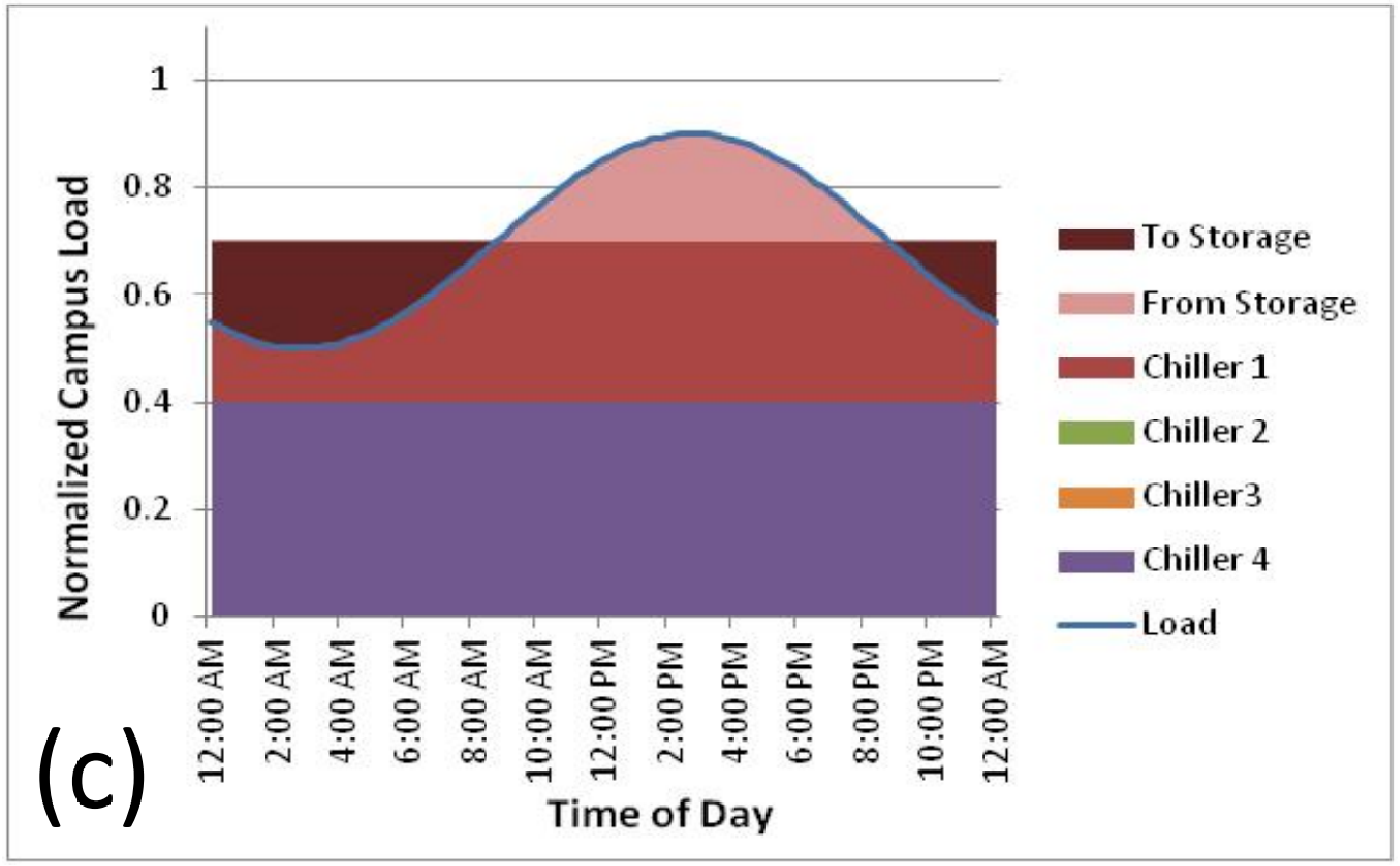


OCL leads to approx. 8% of energy savings on an average hour!

Thermal Energy Storage Operating Strategy with Four Chillers







-Chillers 1& 4 are most efficient, 3 is least efficient

-Chiller 1 is variable frequency

(a) Experience-based (operator-initiated)

  -No load forecasting

  -Uses least efficient chiller (Chiller 3)

(b) Load forecasting + optimization

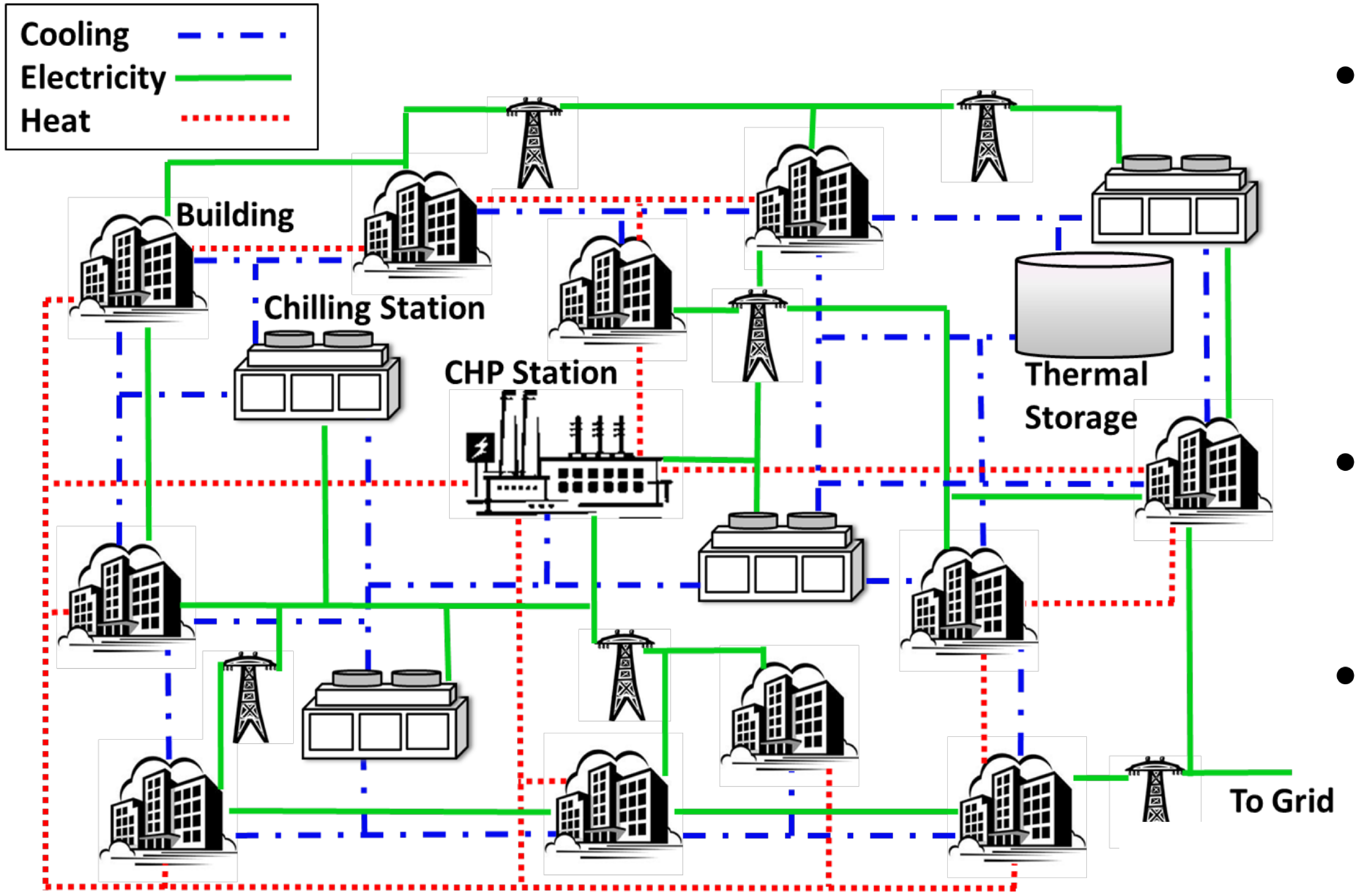
  -Uses most efficient chillers (avoids Chiller 3)

(c) Load forecasting + TES + optimization

  -Uses only two most efficient chillers

Energy System Optimization

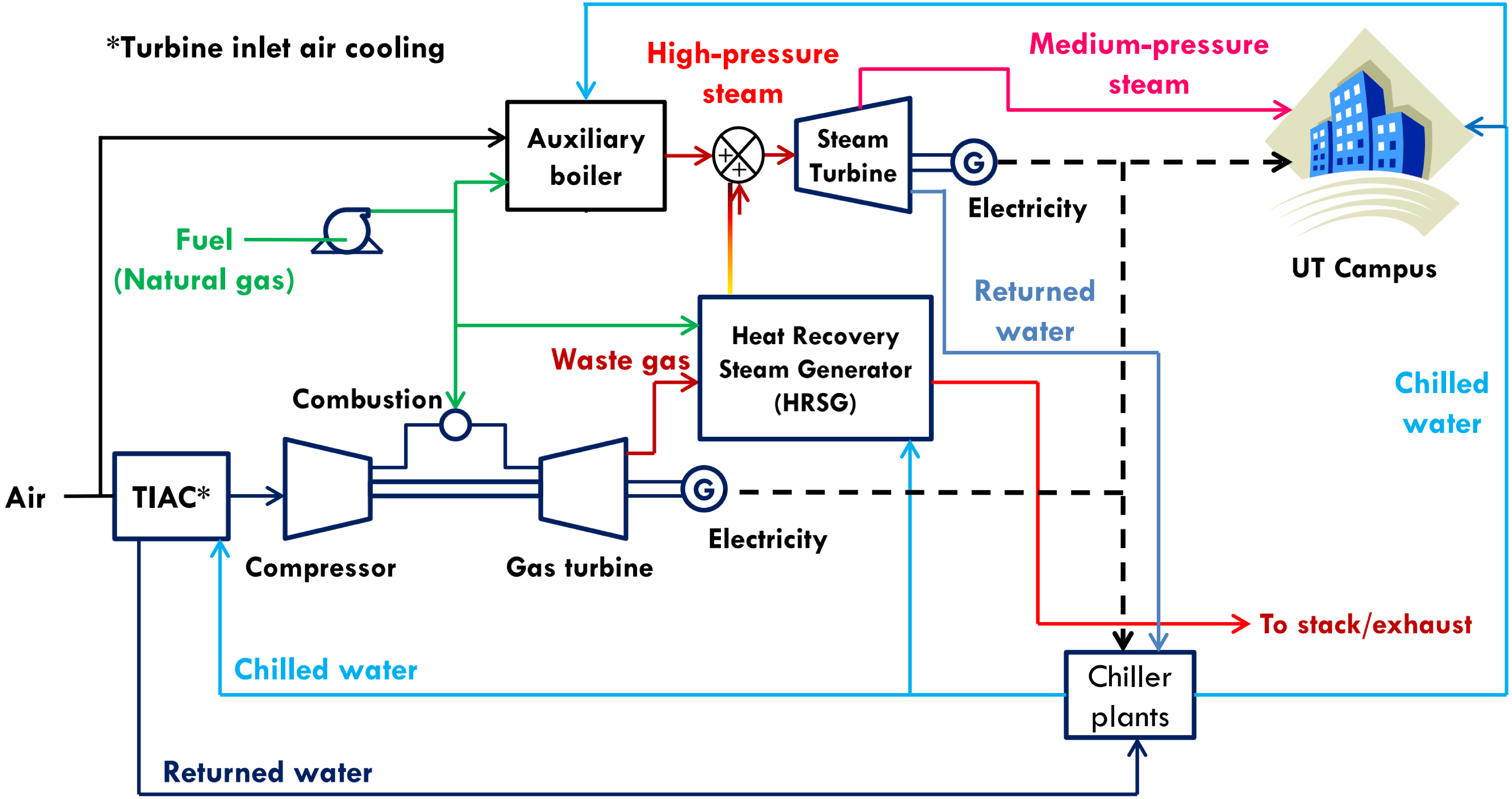
Smart electric grid operation



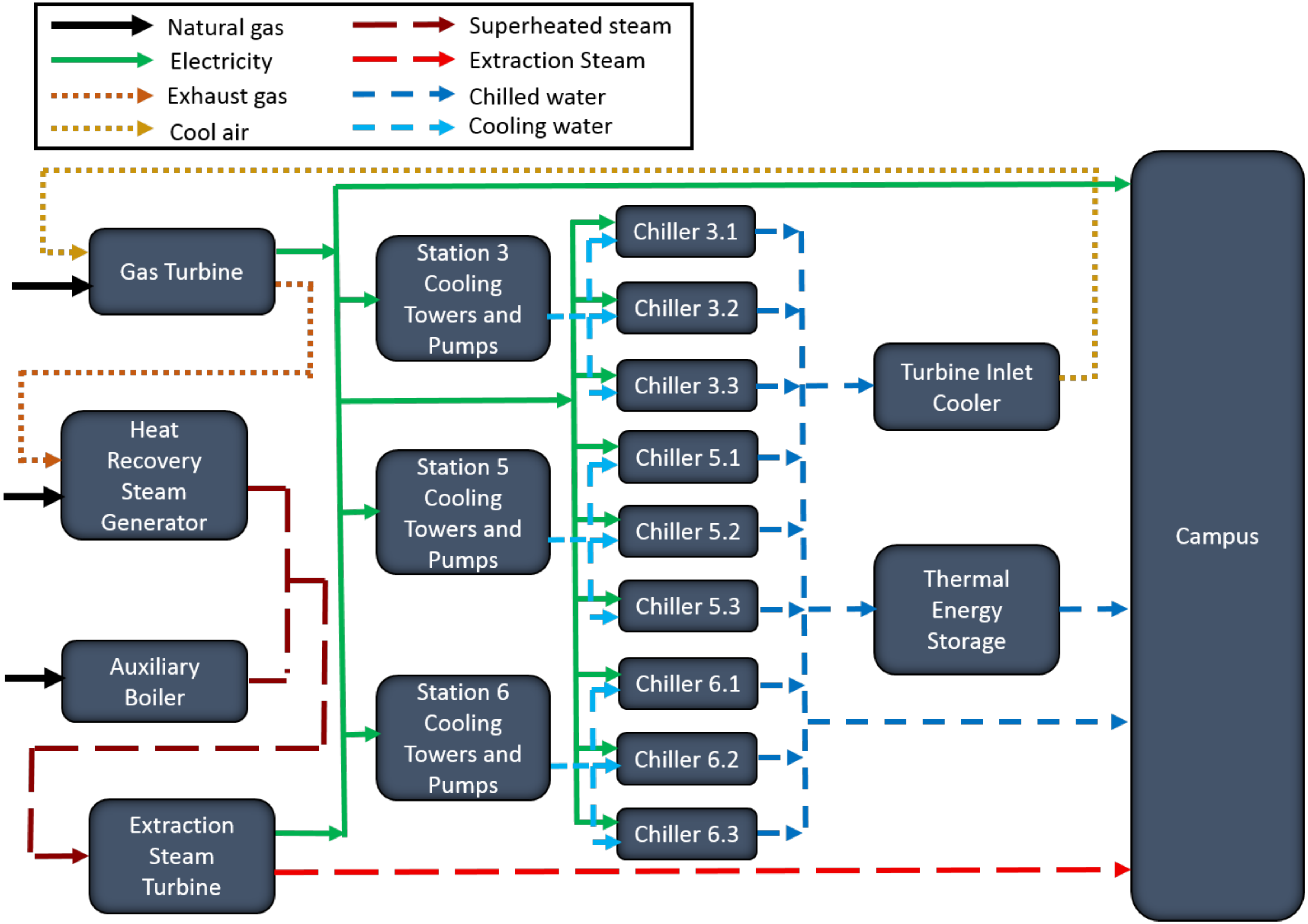
- The Campus is a microgrid and provides 100% of its
    - electrical
    - heating, and
    - cooling loads
- UT Austin does not participate in open electricity market
- Opportunity for interconnection with the external grid
    - economic benefit

Overview of the CHP Plant at UT Austin

Hal C. Weaver Power Plant (80+ % efficiency)



System Optimization



Mathematical Model

Model assumptions

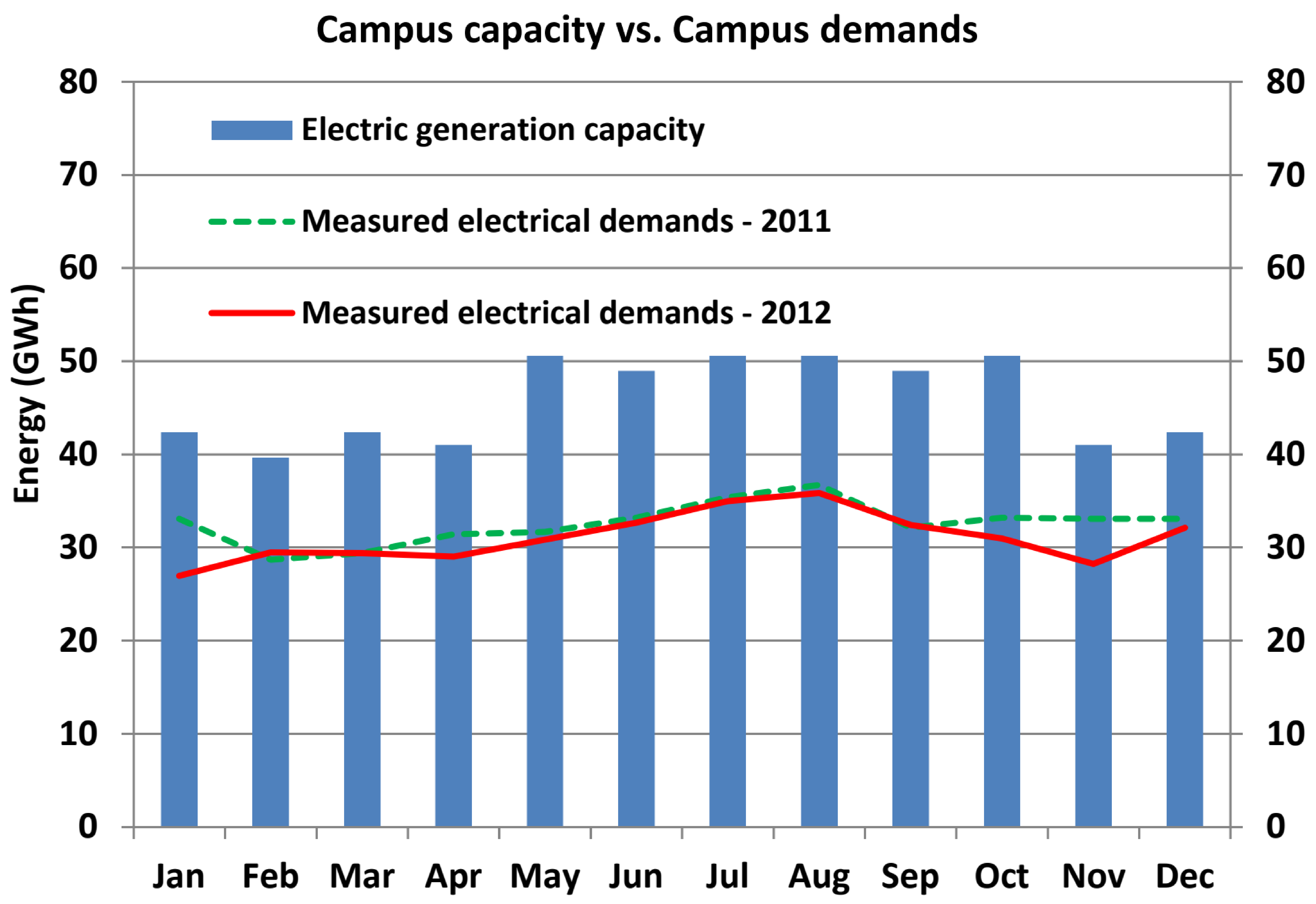
- Steady state
  - Sampling period Δt of 1 hour
- First principles models based on mass and energy balance
- Constant model parameters, i.e.,
  - Heat capacity C_p
  - Unit efficiency η
  - Lower heating value (LHV)
- Lumped parameter model

Units	# model parameters	# units
Gas turbine[a] (GT)	2	2
Heat recovery steam generator[a] (HRSG)	2	2
Boiler (BR)	1	2
Steam turbine[a] (ST)	1	2

a. There are two units of the same kind but only one unit operates at a time

Energy Consumption at UT Austin

Time period: 2011~2012



- UT could sell
  - 176 GWh to the grid in 2012
  - 157 GWh to the grid in 2011
- At an average electricity price of $ 0.02/kWh, potential revenue of
  - $ 3.53 million in 2012
  - $ 3.14 million in 2011

Economic Dispatch of a CHP Plant at UT Austin

Key assumptions

Economic Analysis

- Interconnection with ERCOT*
  - Case I
    - Sell/buy power to/from grid
    - $0 \leq P_m(k)$
    - $P_m(k) = 0$, standby mode
  - Case II
    - Only sell the extra power to grid
    - $P_I(k) \leq P_m(k)$
  - Case III
    - No power sales or purchases
    - Optimal turbine and boiler loading
    - $P_I(k) = P_m(k)$

- Type of Energy Market
  - Day-ahead energy market
- Time periods:
  - 2/1/2011 ~ 11/30/2011
  - 1/1/2012 ~ 12/31/2012
- Natural gas price: $5.12/MMBtu in 2011 or $3.96/MMBtu in 2012
  - 890,000 MMBTU/MSCF
  - Lower Heating Value (LHV) of 20,313 Btu/lbm
  - Natural gas density of 0.0438 lbm/SCF

*Electric Reliability Council of Texas

Economic Dispatch of a CHP Plant at UT Austin

Problem formulation – objective function to be minimized

Objective function

$$\min_{\substack{F^i_{d,GT},\ \theta^i_{IGV} \\ V^i_{W,TIAC},\ W^i_{f,HRSG} \\ W^i_{f,BR},\ W^i_{S,EXT}}} \quad J = \sum_{i=1}^{N} \left[\begin{array}{c} -C^i_{elec}\left(P^i_{m,GT} + P^i_{m,ST} - P_{I,i}\right) + C^i_{elec}\Delta H^i_{TIAC}\dfrac{1.1}{COP} \\ + \mathrm{C}_{fuel}\left(\mathrm{W}^i_{f,GT} + \mathrm{W}^i_{f,HRSG} + \mathrm{W}^i_{f,BR}\right) \end{array} \right] \Delta t, \quad N = \text{number of hours}$$

Solved using SQP algorithm

where

- $F_{d,\,GT}$ is the fuel demand signal in a gas turbine
- θ_{IGV} is an inlet guide vane angle
- $V_{W,\,TIAC}$ is the volumetric flow rate of cooling water
- $W_{f,\,HRSG}$ is the duct burner fuel flow in a HRSG
- $W_{f,\,BR}$ is the fuel flow in a boiler
- $W_{S,\,EXT}$ is extraction steam flow

Decision variables

- P_I is the electric load
- W_s is superheated steam flow rate
- C_{elec} is the price of electricity
- C_{fuel} is the price of natural gas
- COP is coefficient of performance

- Power production
- Cooling load in the TIAC system
- Total fuel consumption

$$\Delta H^i_{TIAC} = f\left(\theta_{IGV}, V_{W,\,TIAC}, T_a, P_a, RH, T_{wi,TIAC}\right)$$

Economic Dispatch of a CHP Plant at UT Austin

Problem formulation – constraints

Objective function

$$\min_{\substack{F^i_{d,\,GT},\ \theta^i_{IGV}\\ V^i_{W,\,TIAC},\ W^i_{f,\,HRSG}\\ W^i_{f,\,BR},\ W^i_{S,\,EXT}}} \quad \mathrm{J} = \sum_{i=1}^{N} \left[\begin{array}{c} -C^i_{elec}\left(P^i_{m,\,GT} + P^i_{m,\,ST} - P_{I,i}\right) + C^i_{elec}\Delta H^i_{TIAC}\dfrac{1.1}{COP} \\ + \mathrm{C}_{fuel}\left(\mathrm{W}^i_{f,\,GT} + \mathrm{W}^i_{f,\,HRSG} + \mathrm{W}^i_{f,\,BR}\right) \end{array} \right] \Delta t, \quad N = \text{number of hours}$$

Solved using SQP algorithm

subject to

$$F^-_{d,\,GT} \le F^i_{d,\,GT} \le F^+_{d,\,GT} \quad \text{for all } i$$

$$\theta^-_{IGV} \le \theta^i_{IGV} \le \theta^+_{IGV}$$

$$V^-_{W,\,TIAC} \le V_{W,\,TIAC} \le V^+_{W,\,TIAC}$$

$$W^-_{f,\,HRSG} \le W^i_{f,\,HSRG} \le W^+_{f,\,HRSG}$$

$$W^-_{f,\,BR} \le W^i_{f,\,BR} \le W^+_{f,\,BR}$$

$$W^{demand}_{S,\,EXT} \le W^i_{S,\,EXT} \le W_{S,\,THR}$$

$$T_{SH,\,HRSG} \le \Delta T_{min,\,HRSG} \le T^i_{e,\,HRSGi}$$

$$T^-_i \le T^i_i \qquad 0 \le P^i_{m,\,GT} \qquad 0 \le P^i_{m,\,ST} \le P^+_{m,\,ST}$$

$$T^i_e \le T^{ref}_e \qquad W^i_{SH,\,HRSG} \le W^+_{SH,\,HRSG}$$

$$T^i_f \le T^{ref}_f \qquad W^i_{SH,\,BR} \le W^+_{SH,\,BR}$$

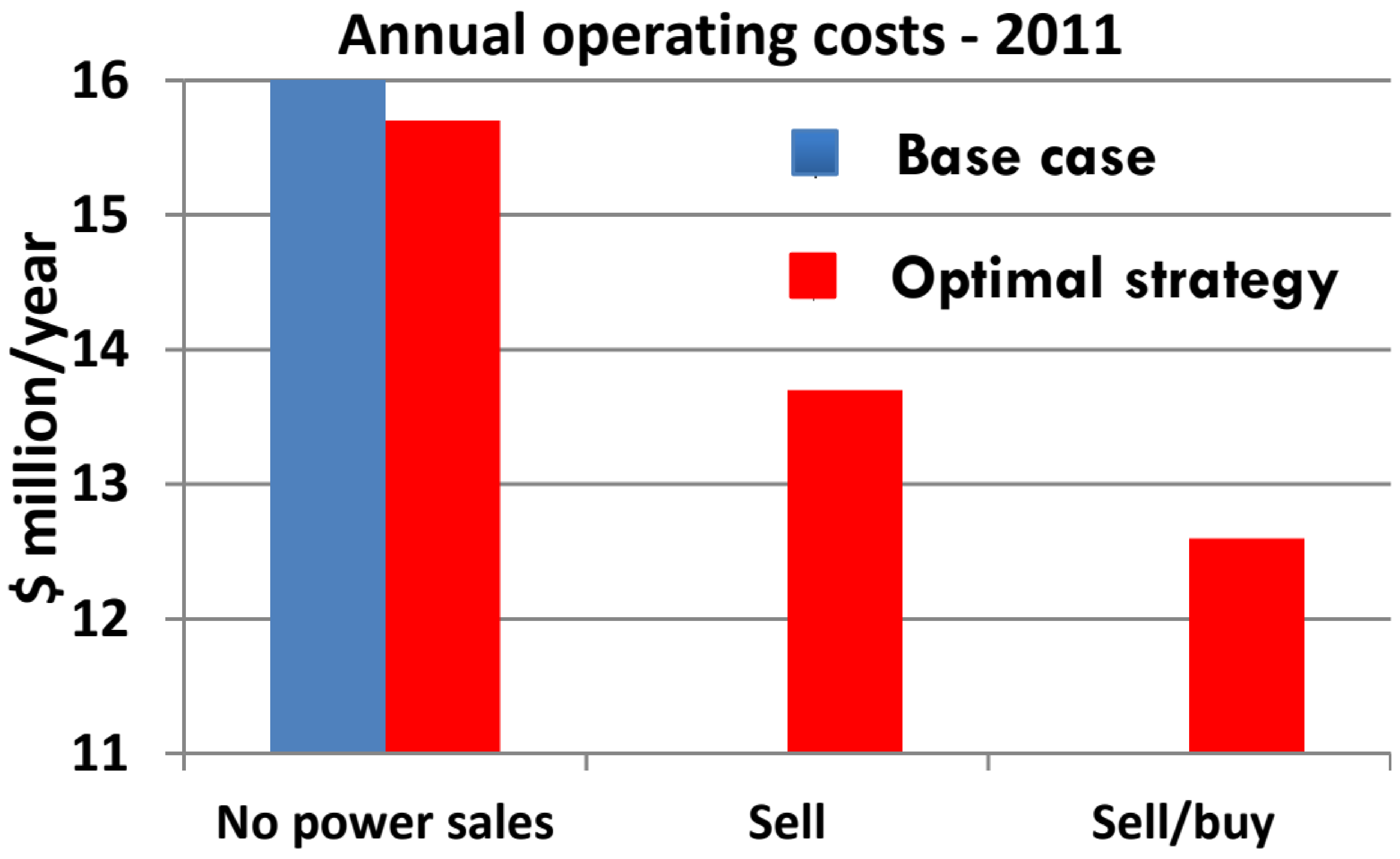
- $T_{SH,\,BR}$ is the temperature of steam produced from the boiler
- $T_{SH,\,HRSG}$ is the temperature of steam produced from the HRSG
- $W_{S,\,THR}$ is the throttle steam flow
- $W_{SH,\,BR}$ is the steam flow from the boiler
- $W_{SH,\,HRSG}$ is the steam flow from the HRSG
- T_f is the turbine's firing temperature
- T_i is the air temperature at compressor inlet

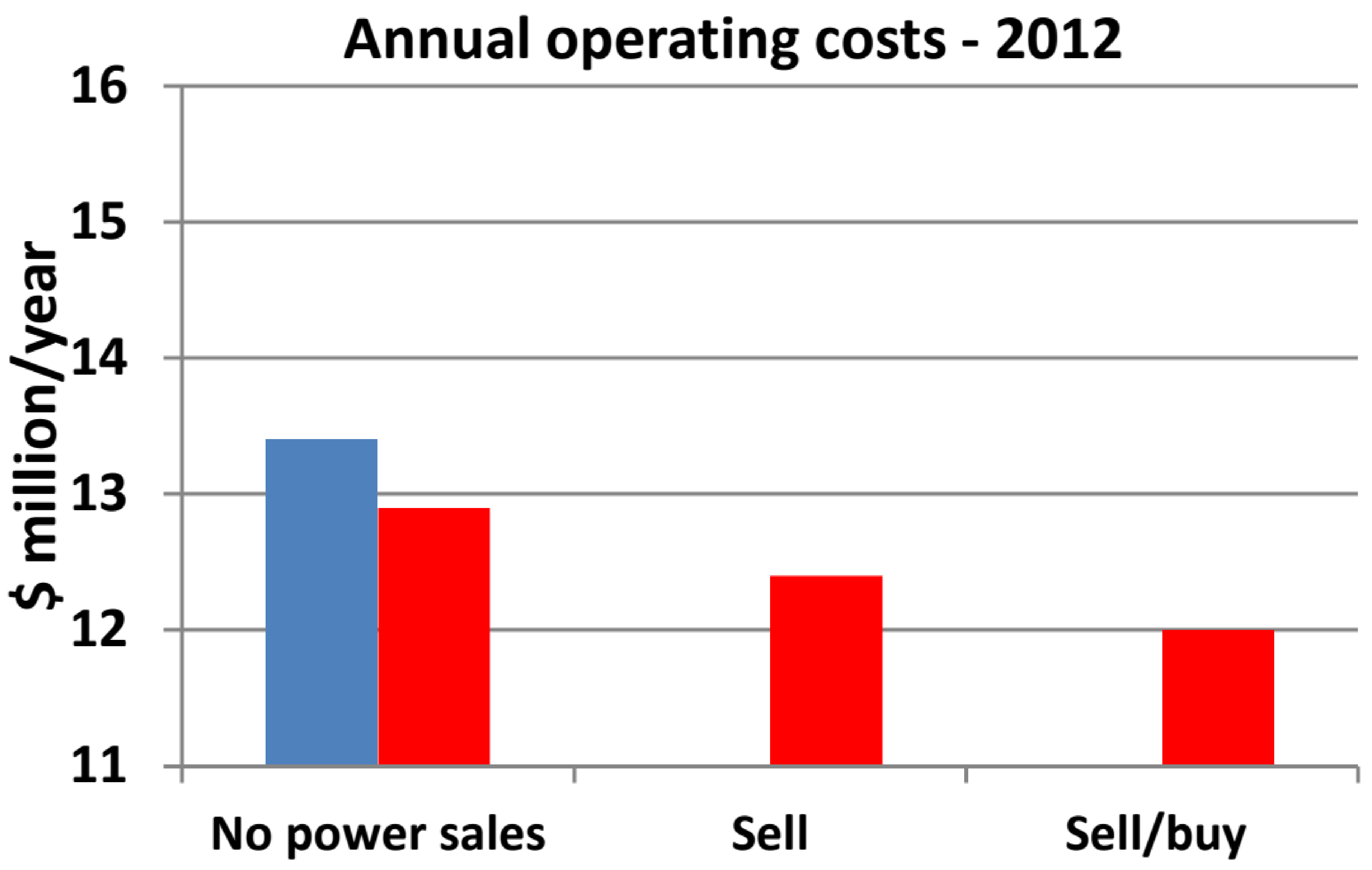
Economic Savings in Operating Costs

Summary

Year	Strategies	Scenarios	Operating costs ($ million)	Net income ($ million)	Net income (%)
2011 ($ 5.12 /MMBTU)	Base case		16.0	-	-
	Optimal strategy	Case I Sell/buy power	12.6	3.42 (2.23[a])	21.4 (14.0[a])
		Case II Sell power	13.7	2.34	14.6
		Case III No power sales	15.7	0.27	1.7
2012 ($ 3.96 /MMBTU)	Base case		13.4	-	-
	Optimal strategy	Case I Sell/buy power	12.0	1.4 (0.71[a])	10.8 (5.3[a])
		Case II Sell power	12.4	1.0	7.5
		Case III No power sales	12.9	0.5	3.7

[a] net income by selling power to the grid

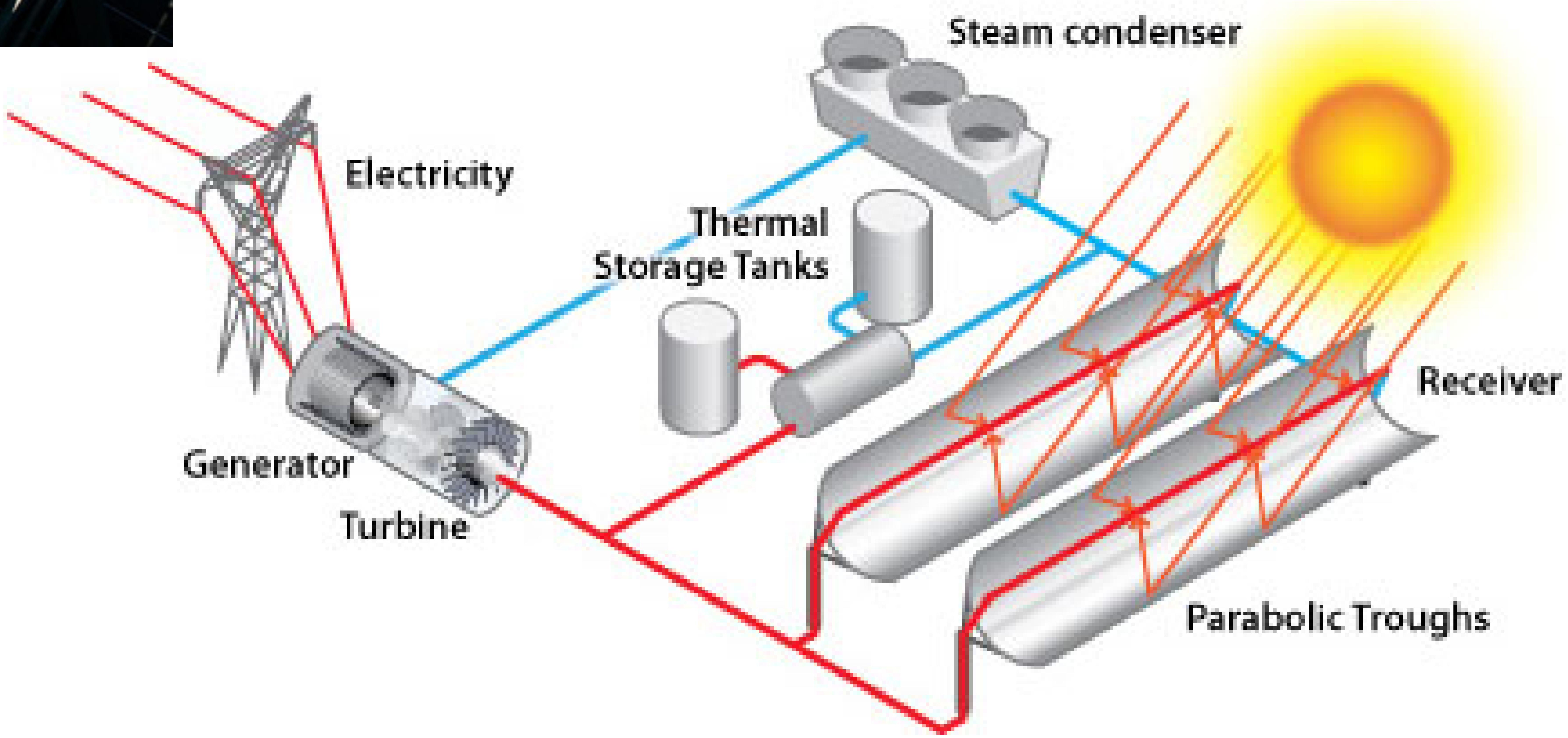




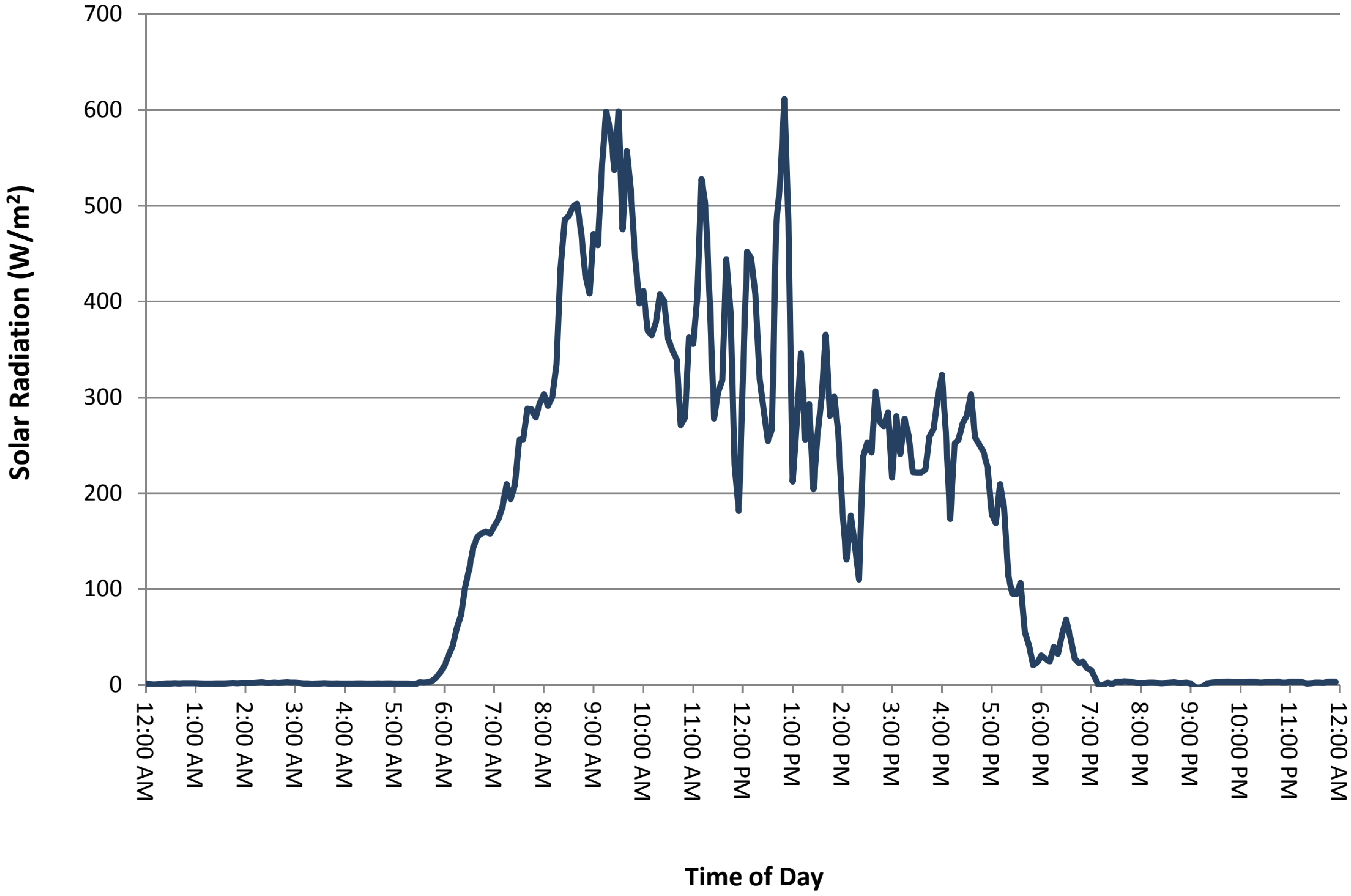
TES with Concentrated Solar Power (CSP)

- CSP technologies concentrate sunlight to heat a fluid and run a generator

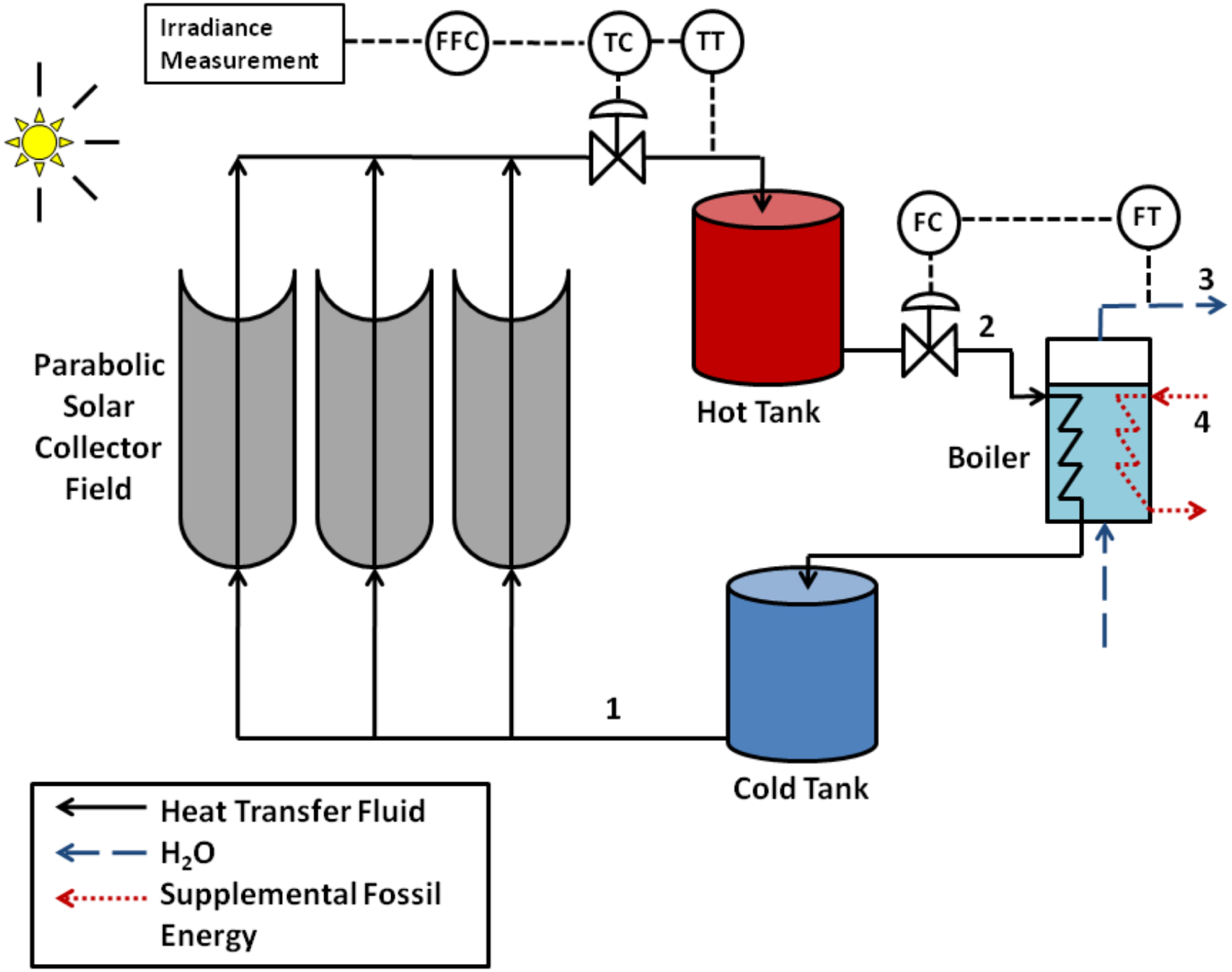
- By coupling CSP with TES, we can better control when the electricity is produced



Solar Energy and the Need for Storage



Solar Heating Augmented by Natural Gas Firing



- Feedforward + Feedback (PID) temperature control
  - Uses FF measurements of solar irradiance
  - Flow rate of stream 1 is manipulated variable
- Feedback control (PID) used for steam flow (power) control
- Supplemental gas used when solar energy is not sufficient (stream 4)

Summary of Results

	Sunny Day: System without Storage	Sunny Day: System with Storage	Cloudy Day: System without Storage	Cloudy Day: System with Storage
Solar Energy Delivered to Load	16.48	16.82	8.40	8.49
Supplemental Fuel Required (MWh)	12.58	7.18	15.78	15.51
Solar Share	47.6%	70.1%	34.3%	35.4%

- Solar Share increased by 47% on sunny day, 3% on Cloudy day
- Power quality much better with storage
- Dynamic optimization with weather forecasts can further improve solar share

Minimization of the nonrenewable energy consumption in bioethanol production processes using a solar-assisted steam generation system

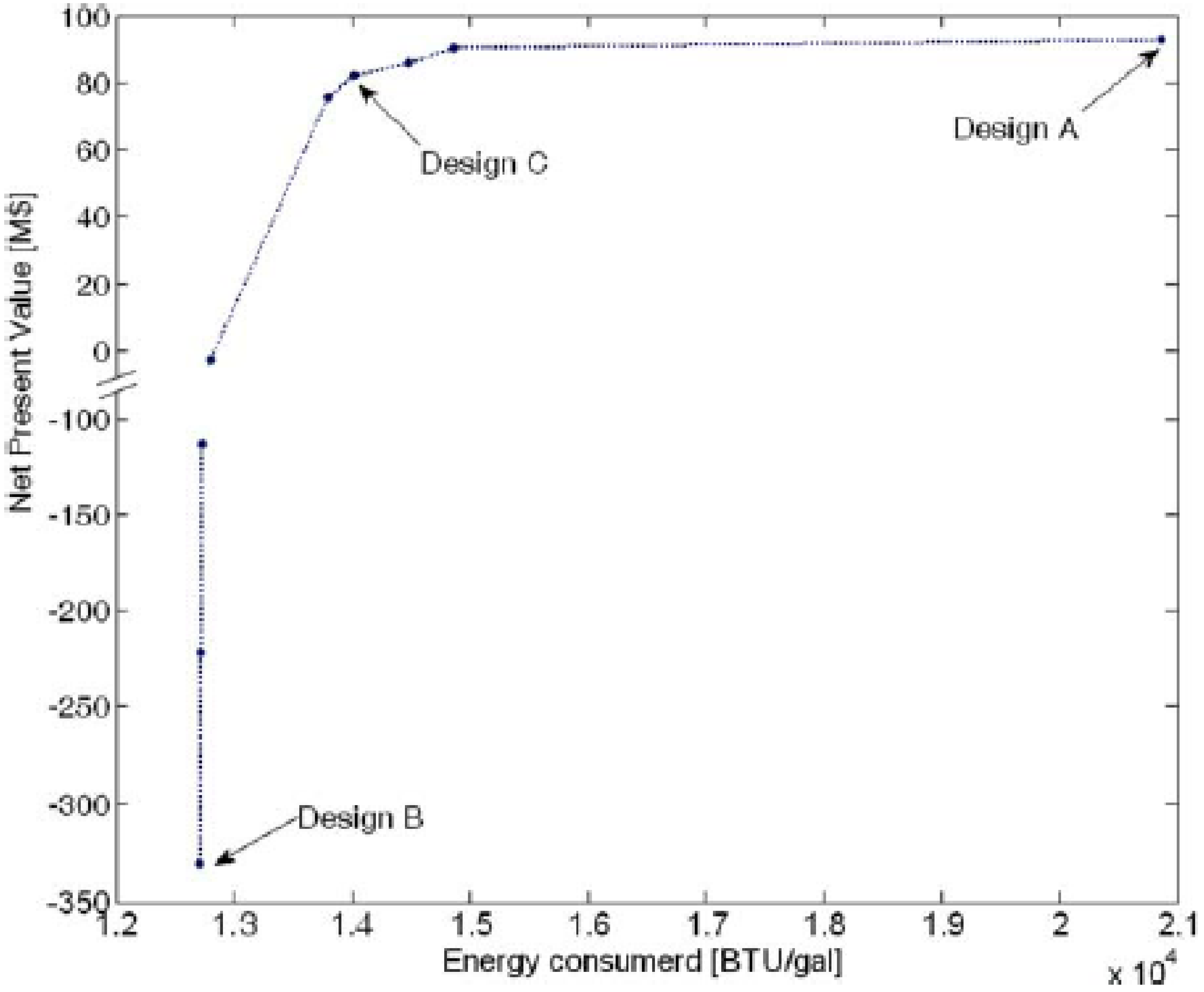
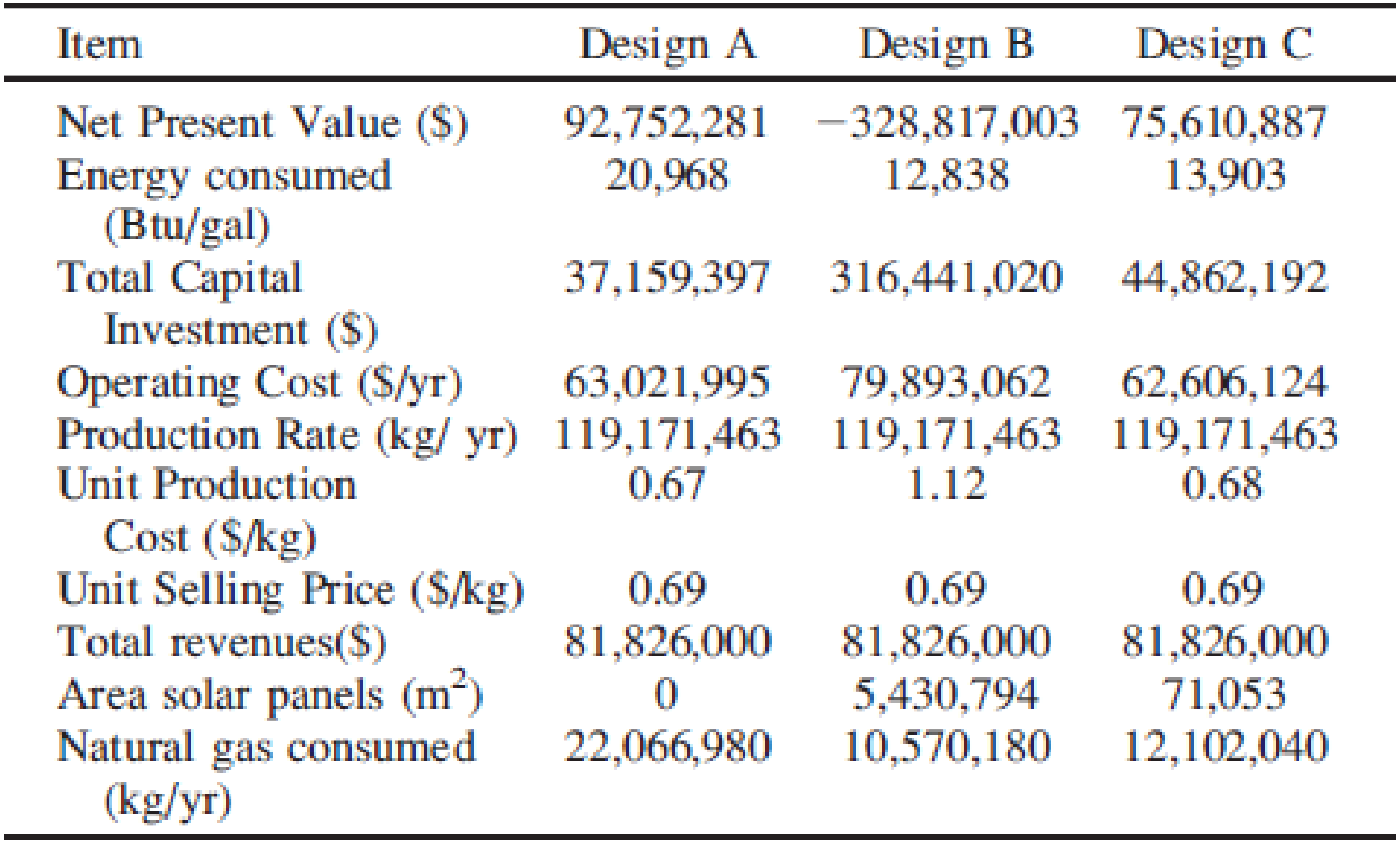


Figure 3. Pareto set of optimal solutions in the bioethanol production plant

AIChE Journal
Brunet, Robert, Gonzalo Guillén-Gosálbez, and Laureano Jiménez. "Minimization of the nonrenewable energy consumption in bioethanol production processes using a solar-assisted steam generation system." *AIChE Journal* 60.2 (2014): 500-506.

Table 5. Economic and Energetic Summary of the Bioethanol Process



Item	Design A	Design B	Design C
Net Present Value ($)	92,752,281	−328,817,003	75,610,887
Energy consumed (Btu/gal)	20,968	12,838	13,903
Total Capital Investment ($)	37,159,397	316,441,020	44,862,192
Operating Cost ($/yr)	63,021,995	79,893,062	62,606,124
Production Rate (kg/ yr)	119,171,463	119,171,463	119,171,463
Unit Production Cost ($/kg)	0.67	1.12	0.68
Unit Selling Price ($/kg)	0.69	0.69	0.69
Total revenues($)	81,826,000	81,826,000	81,826,000
Area solar panels (m^2)	0	5,430,794	71,053
Natural gas consumed (kg/yr)	22,066,980	10,570,180	12,102,040

AIChE Journal

Brunet, Robert, Gonzalo Guillén-Gosálbez, and Laureano Jiménez. "Minimization of the nonrenewable energy consumption in bioethanol production processes using a solar-assisted steam generation system." *AIChE Journal* 60.2 (2014): 500-506.

Conclusions

- Many opportunities to improve energy efficiency in the process industries by use of natural gas
- Energy efficiency ≡ sustainability (carbon footprint)
- Smart grids, cogeneration will change the power environment for manufacturing
- Competitive electricity market is a good match for CHP
- Energy storage plus PSE tools will be critical technologies to deal with this dynamic environment

Acknowledgments

- Texas Instruments
- UT Sustainability Fund
- CHEMSTATIONS
- UT Austin – Utilities and Energy Management