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Dynamic Optimization of Solar Thermal Energy Systems with Storage

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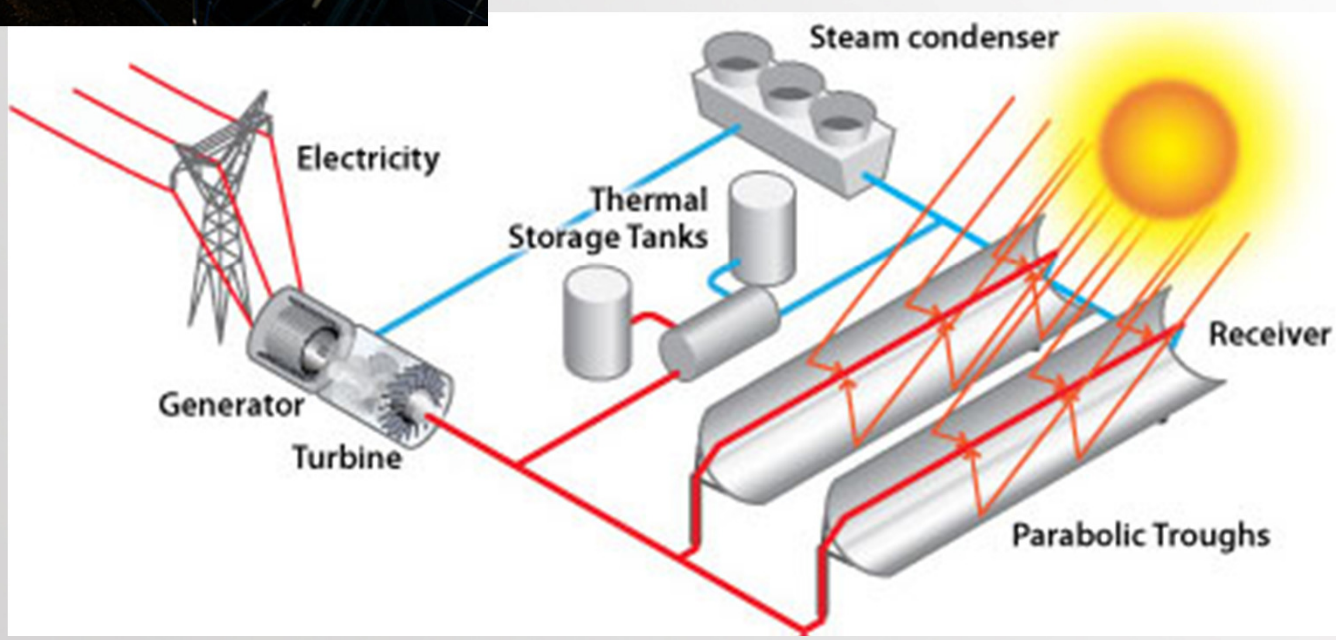
Overview of Solar Thermal Power

- Promising technology
- Systems approach – insight into plant design

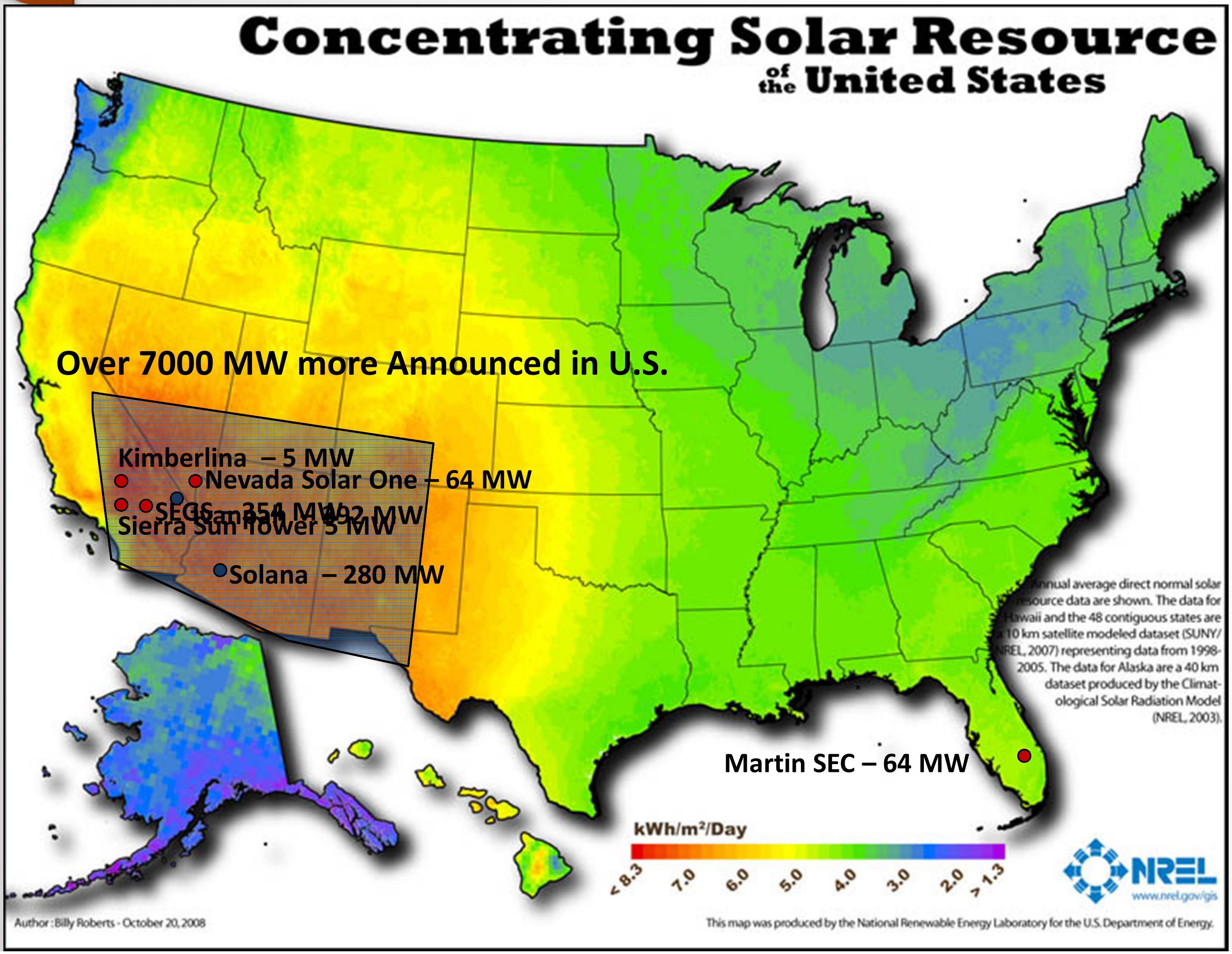


Solar Thermal vs Photovoltaic (PV)

	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	Large Scale & Distributed
Storage	Thermal Storage	Battery Storage
Dispatchable on a large scale	Yes	No
Impact on grid	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

The Potential of Solar Thermal Power



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Can Forecasts Help Solar Thermal?

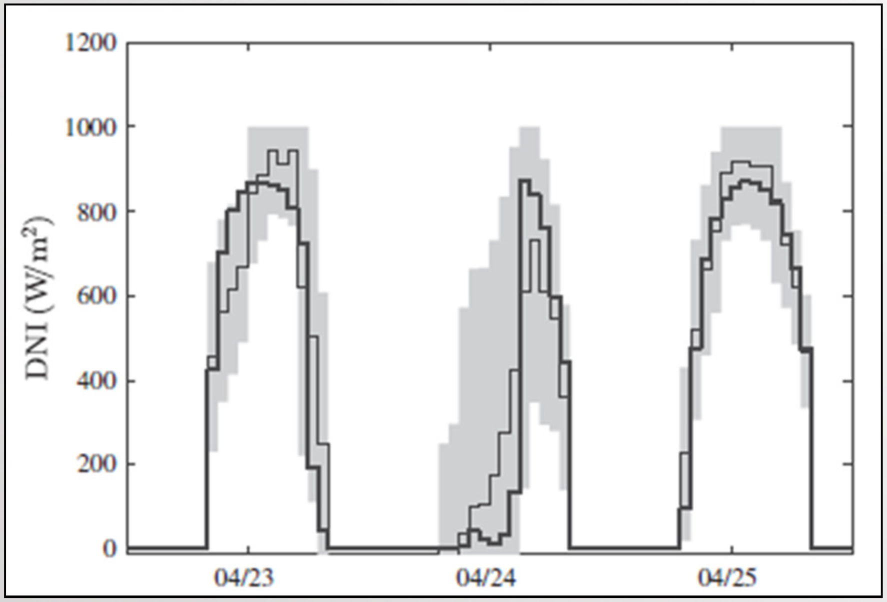
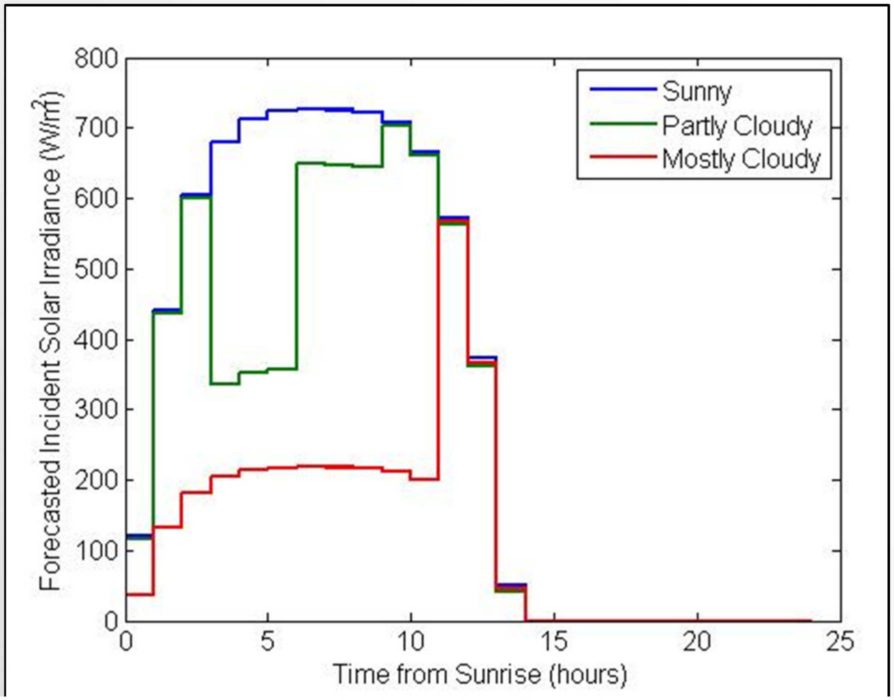


Image from: Marquez, R. and Coimbra, C. F. M., Forecasting of global and direct solar irradiance using stochastic learning methods, ground experiments and the NWS database, *Solar Energy*, Volume 85, 2011

- Forecasting technology advancing
- How do we take advantage?



- Look at extreme scenarios
- Compare Standard Control Approach to Dynamic Optimization

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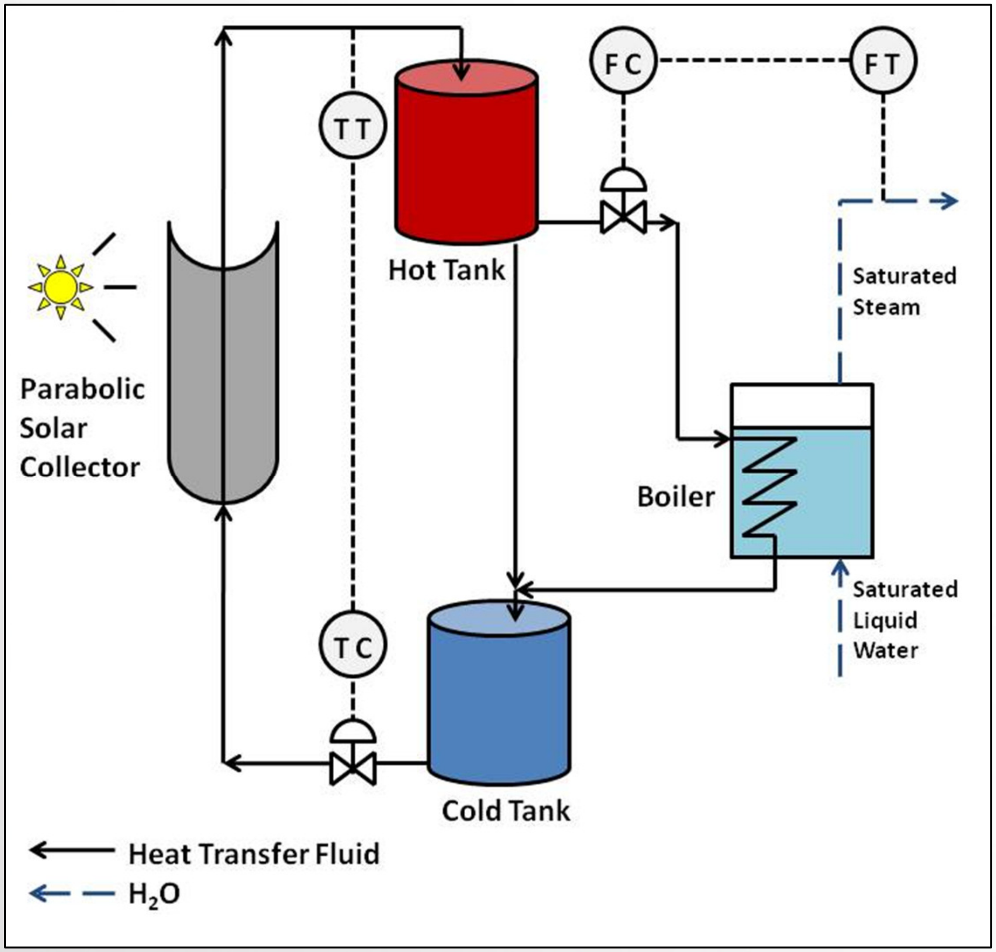
Constant Temperature and Constant Power Control

- NMPC approach
- Measure DNI, use as FF to plant
- Constant temperature, constant power
- Relief pipe used when hot tank fills

$$\min_{u(t)} \int_{t=0}^{t=T} \phi\left(\mathbf{x}(\tau),\mathbf{y}(\tau),\mathbf{u}(\tau),\mathbf{d}(\tau)\right) d\tau$$

$$\left.\begin{aligned}\dot{\mathbf{x}} &= \mathbf{f}\left(\mathbf{x}(\tau),\mathbf{y}(\tau),\mathbf{u}(\tau),\mathbf{d}(\tau)\right)\\ \mathbf{0} &= \mathbf{g}\left(\mathbf{x}(\tau),\mathbf{y}(\tau),\mathbf{u}(\tau),\mathbf{d}(\tau)\right)\\ \mathbf{0} &\geq \mathbf{h}\left(\mathbf{x}(\tau),\mathbf{y}(\tau),\mathbf{u}(\tau),\mathbf{d}(\tau)\right)\end{aligned}\right\}\tau\in\left[t=0,t=T\right]$$



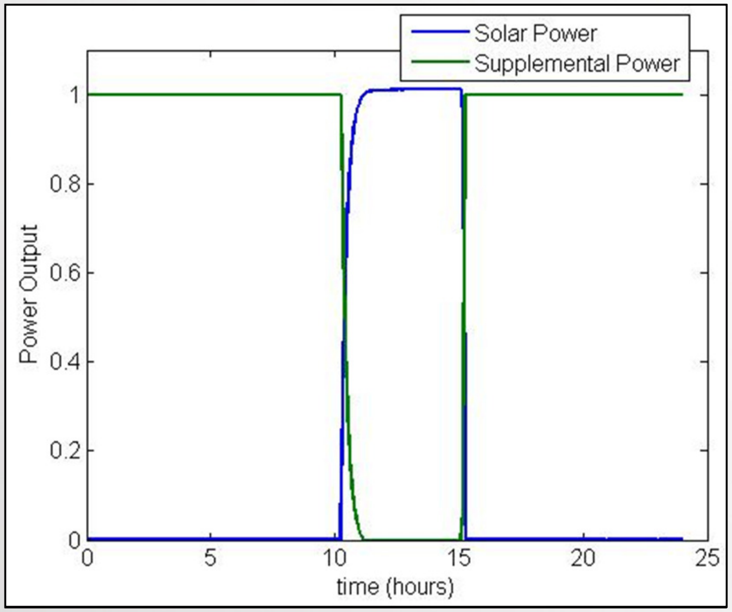
Constant T Constant Po Approach

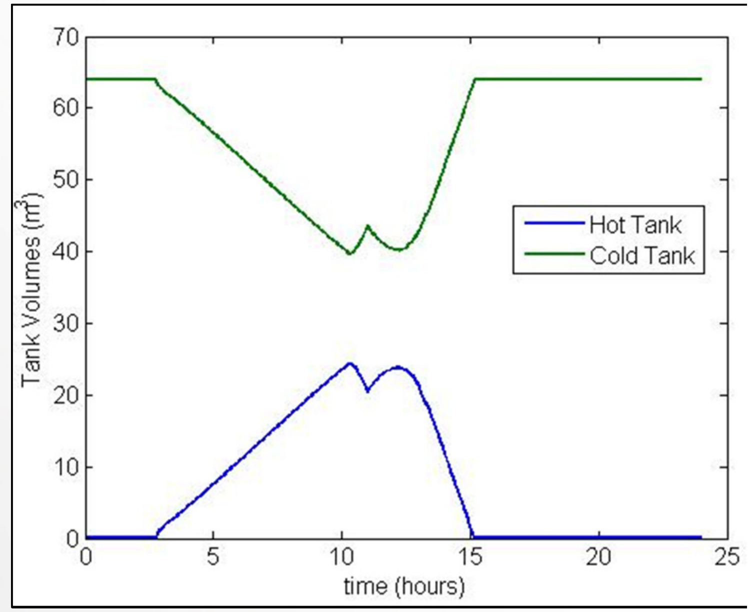
Performance Improved by:

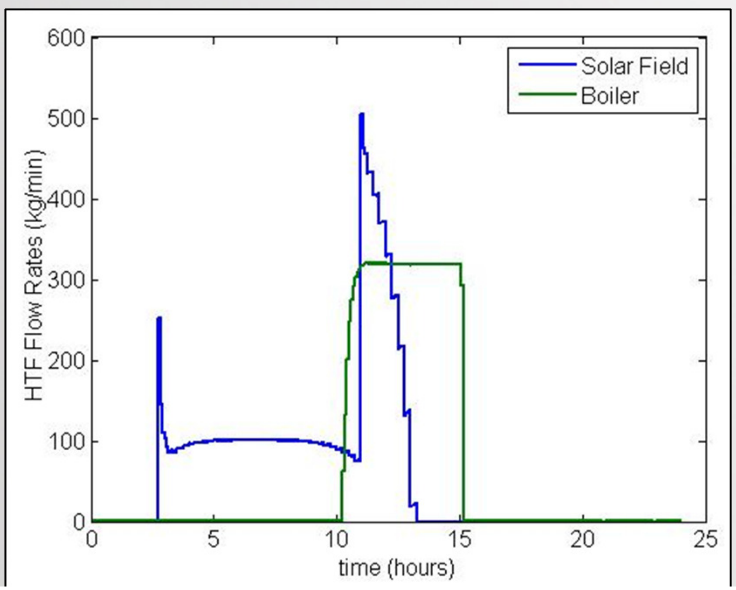
- Optimal temperature
- Hybrid Operation
- Storage Bypass

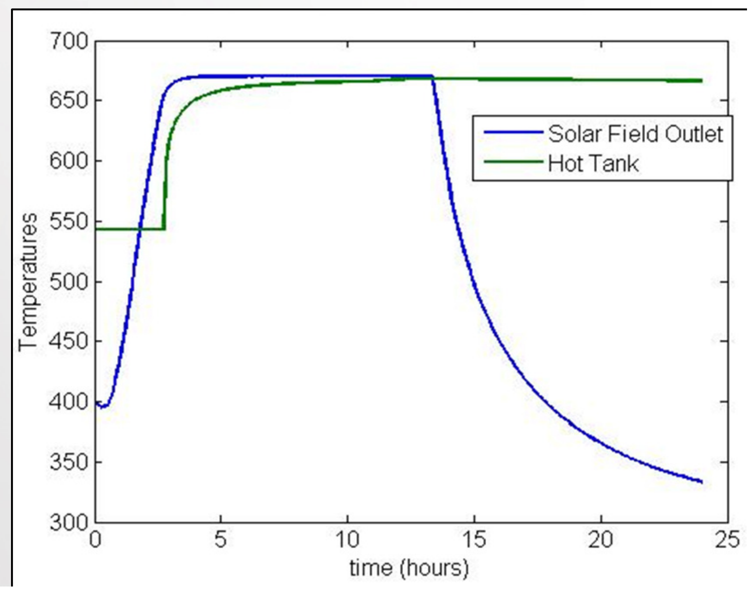
Further Improvements Needed:

- Strategy for more stable operation
- Consider stochastic problem









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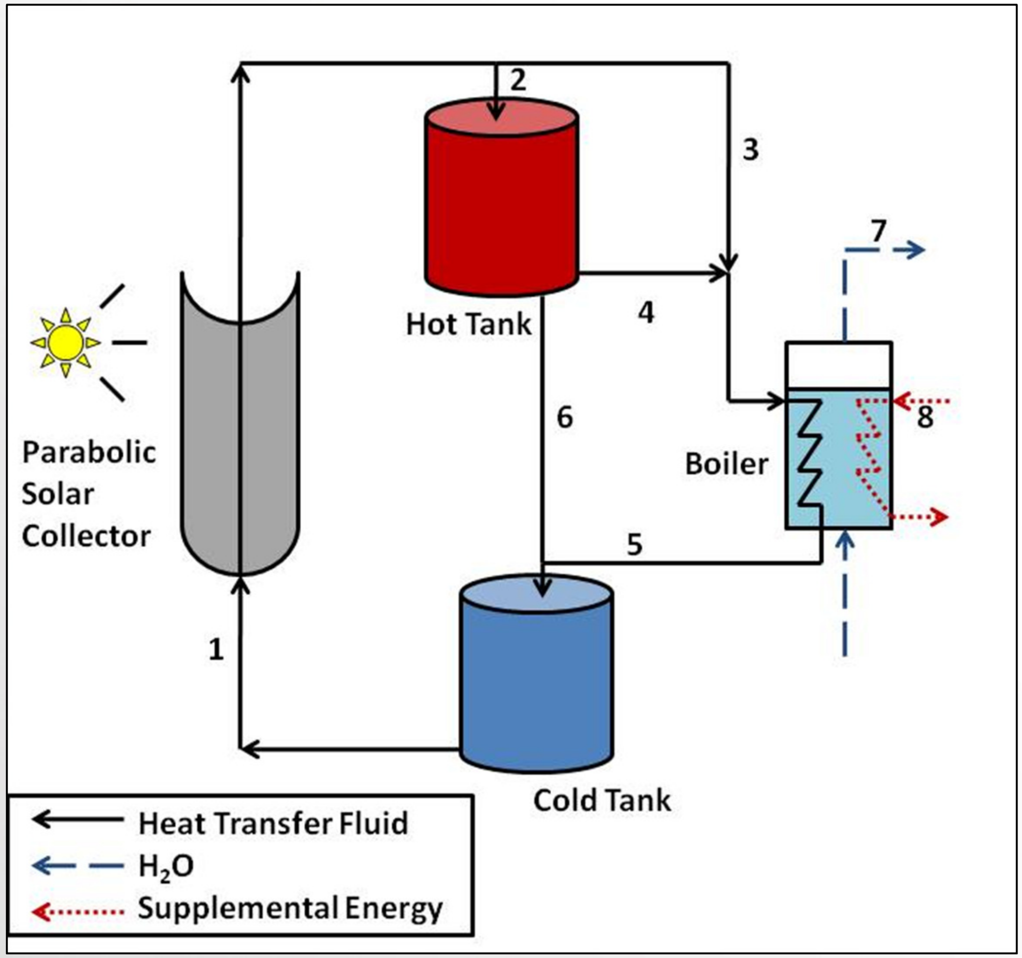
Dynamic Optimization w/ Forecasts

Hypothesis:

- Performance can be improved by:
  - Controlling to optimal temperatures
  - Hybrid operation
  - Ability to bypass storage
  - More DOFs

$$\min_{u(t)} \int_{t=0}^{t=T} \left(Po(\tau)\right) d\tau$$



Dynamic Optimization w/ Forecast

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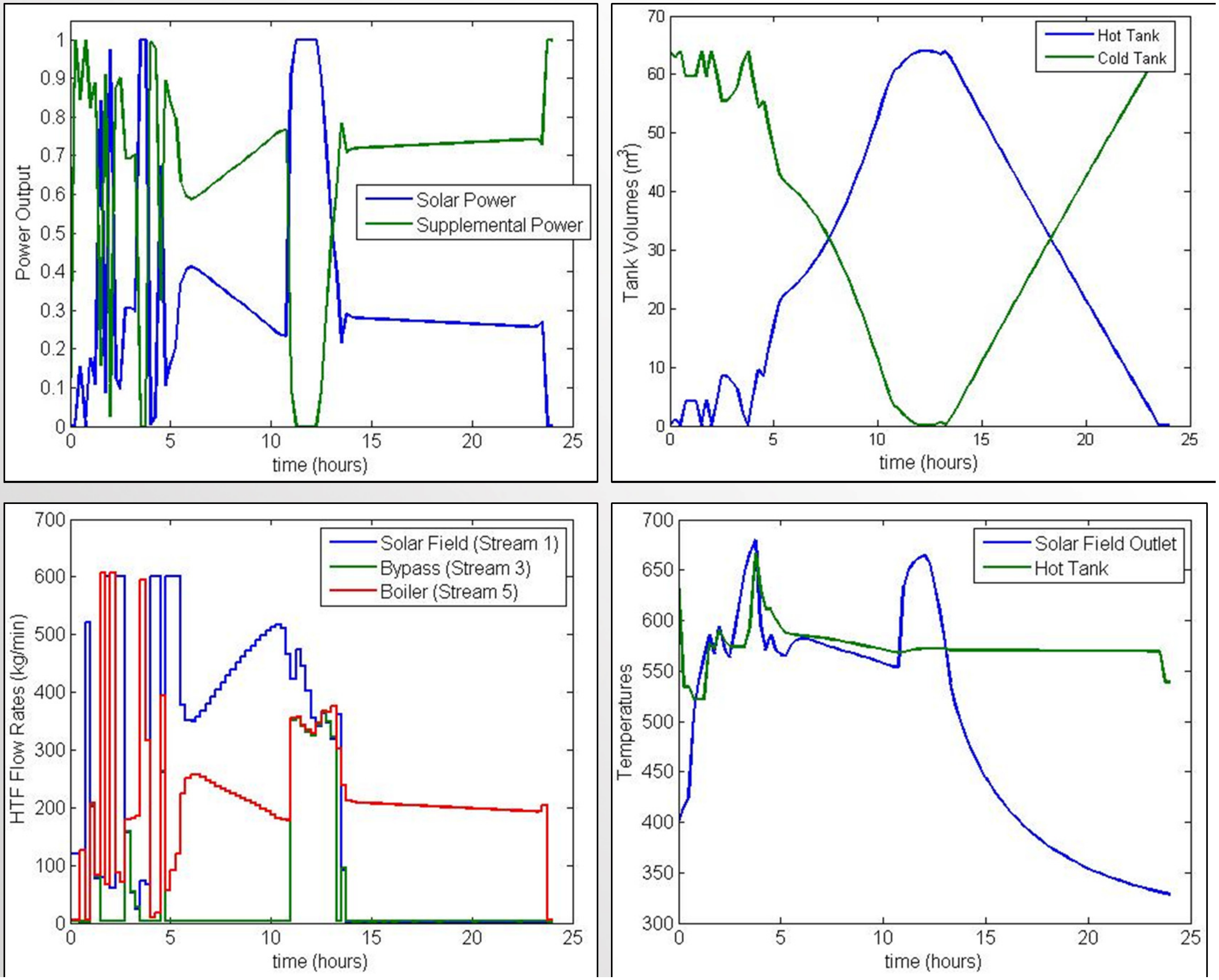
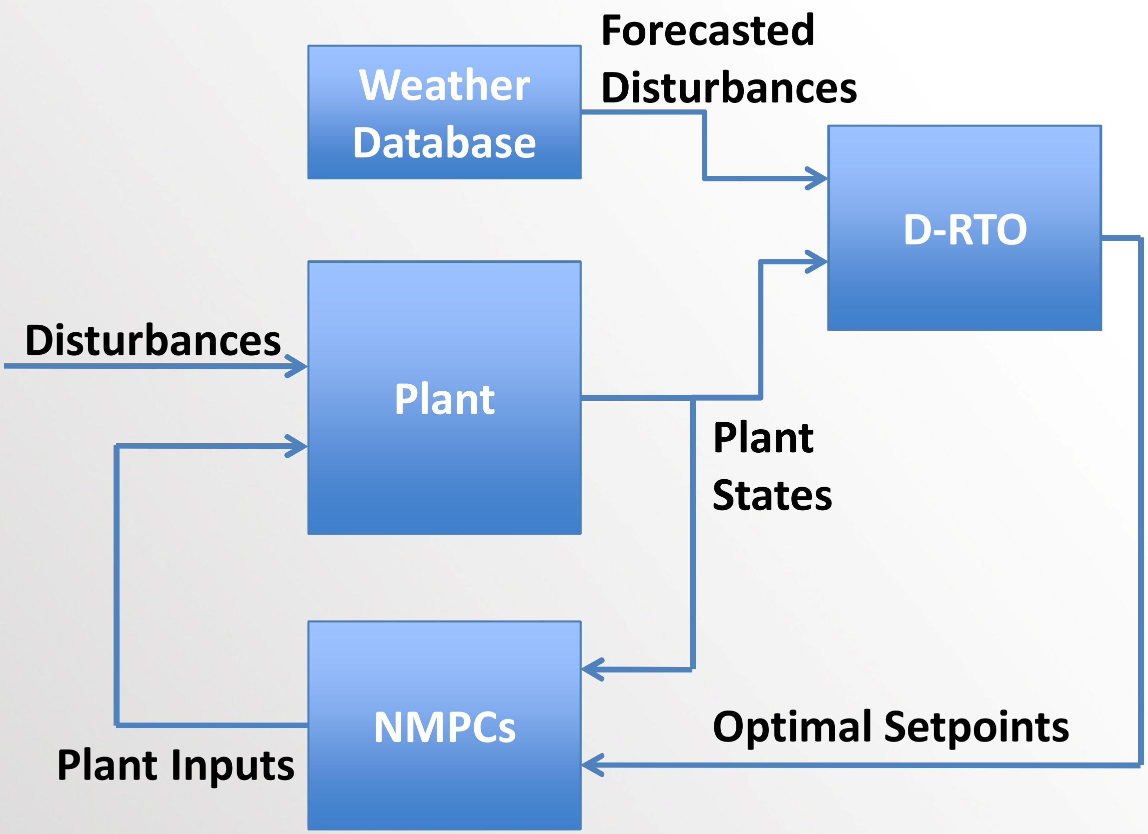


Dynamic Optimization Improves Performance

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

Proposed D-RTO Formulation

- Supervisory Control
- NMPC for stability (run every 2-5 minutes)
- D-RTO runs every 1-2 hours
  - Fewer variables may help solver find global min
- Forecast and plant states updated regularly



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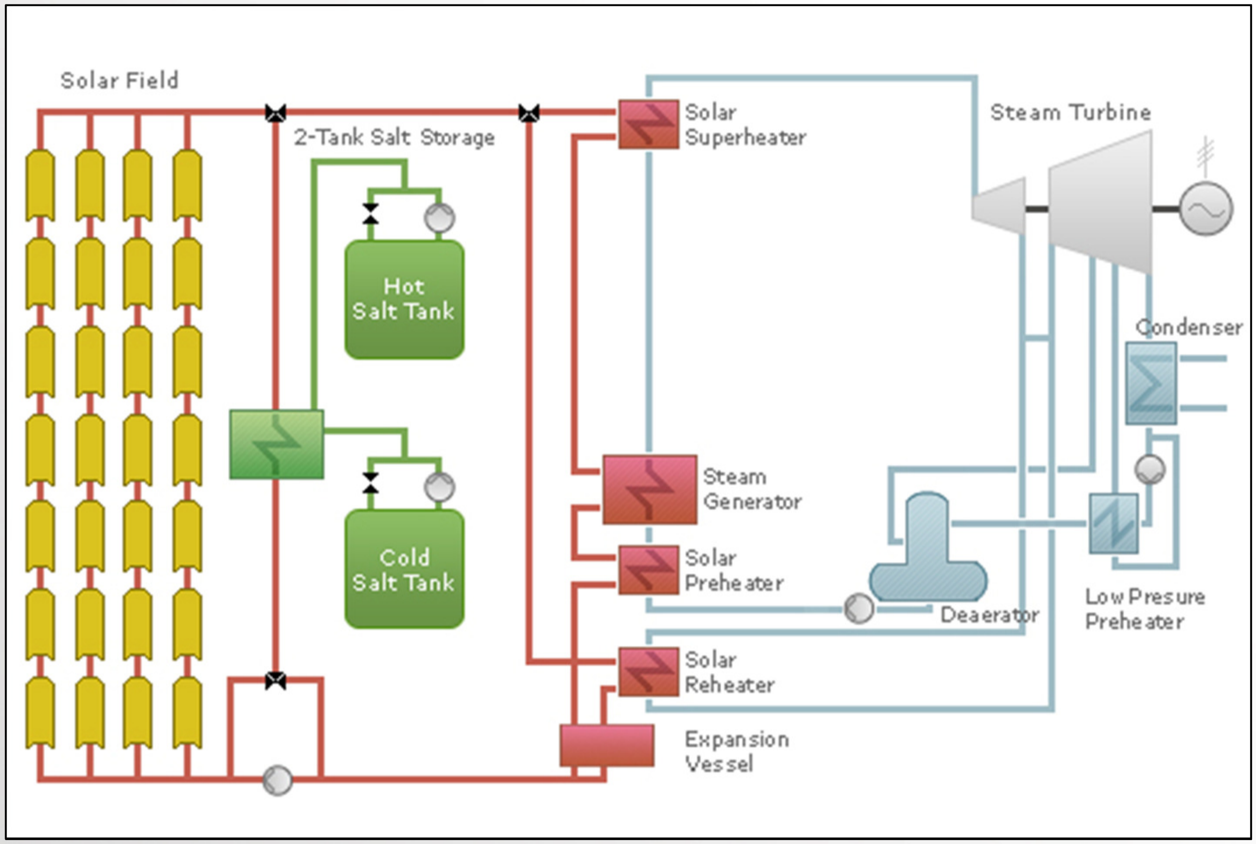
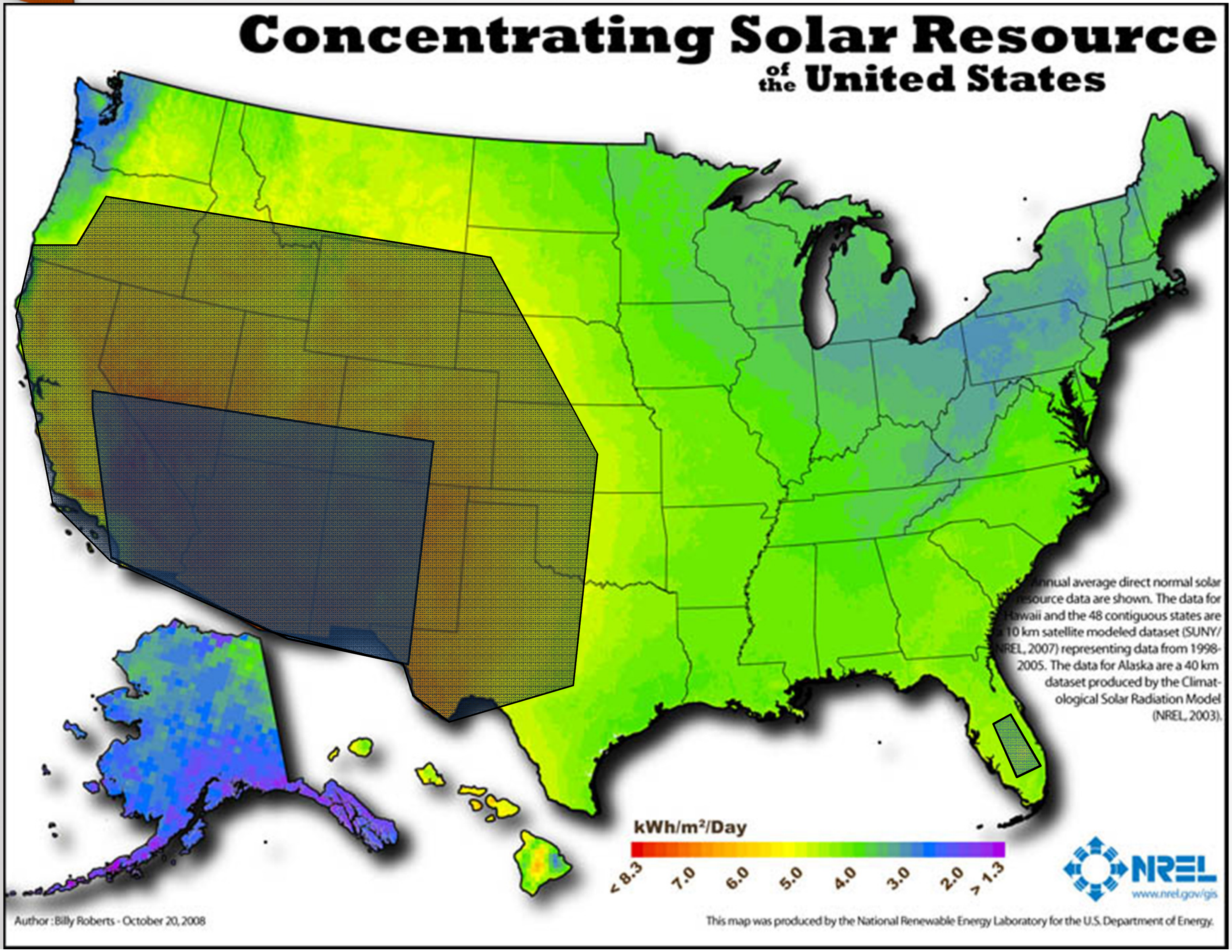
Opportunities for Further Improvement

- More DOFs → more optimal solutions
- Consider entire plant
- Include electric grid and demand forecasts
- Economic optimization
- Apply to other systems



Expanding the Potential of Solar Thermal Power



Conclusions

- Better utilization of renewable resources
  - Particularly on cloudy days
- Systems approach leads to design insights
- Hybridization can greatly expand solar thermal utilization
- Supervisory D-RTO needed
- Thanks to APMonitor, National Science Foundation, Cockrell School of Engineering, UT-Austin, Edgar Group