Impacts of Water on the Electric Grid

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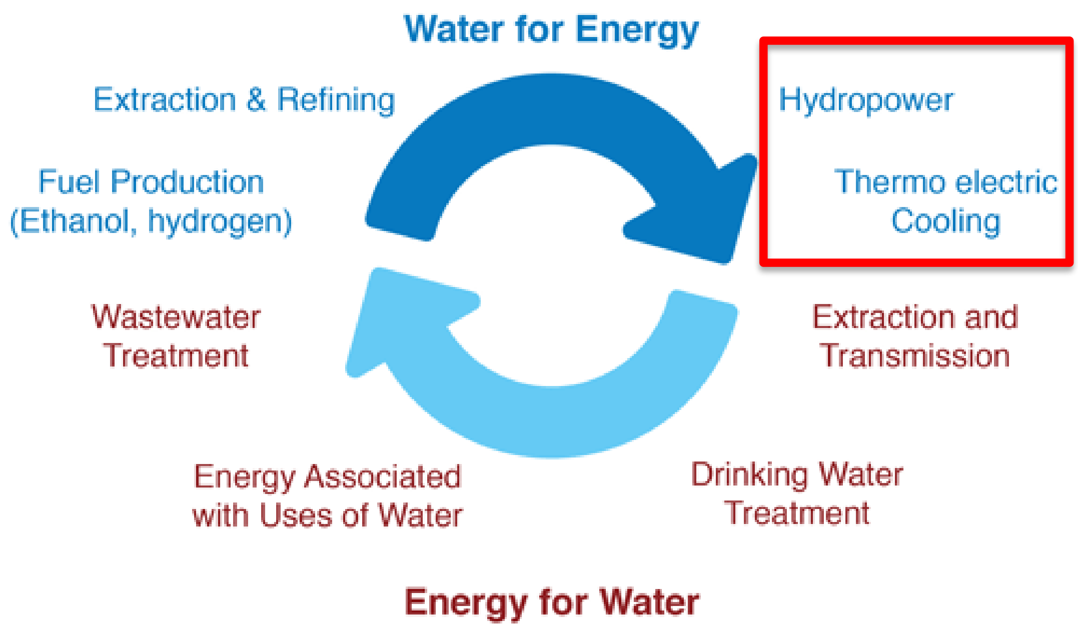
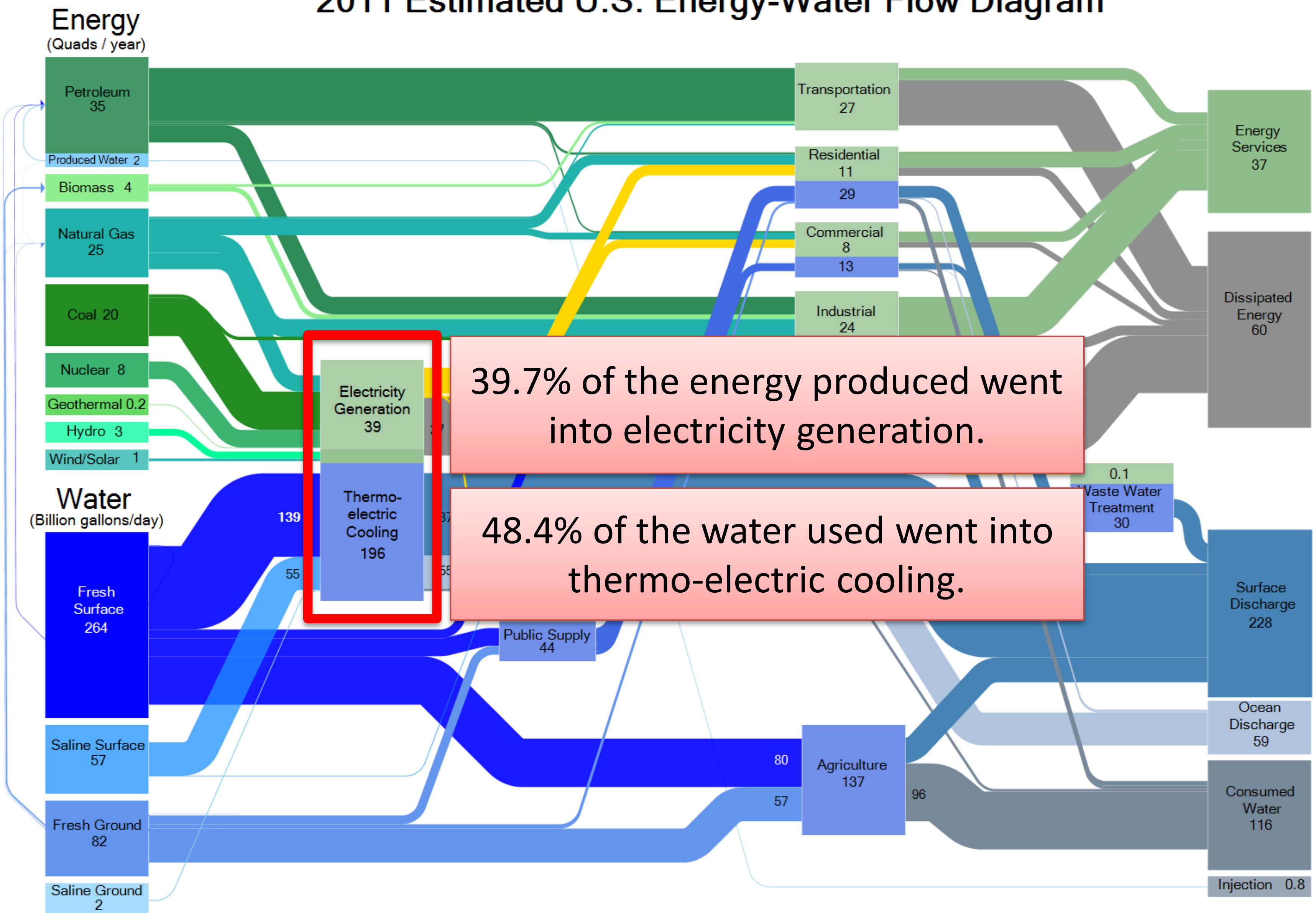
Water-Energy Nexus (WEN)

- The water-energy nexus is the relationship between how much water is used to generate and transmit energy, and how much energy it takes to collect, clean, move, store, and dispose of water.



http://voxglobal.com/wp-content/uploads/Energy-Water-blog.gif

2011 Estimated U.S. Energy-Water Flow Diagram



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

"The Water-Energy Nexus: Challenges and Opportunities" (Dept. of Energy)

WEN Working Groups

- There is a need for cross-sector real-time decision making and planning.
  - A more direct connection between water and energy databases, as well as ways to jointly analyze them.

How can I incorporate water constraints and effects into electric planning and operations analysis in order to facilitate these studies?

Game Theory

- *The mathematical study of interaction among independent, self-interested agents.*
- The goal is to find the game's “Nash Equilibria” (NE)
  - NE: Given the strategies of the other participants, no participant has incentive to change their own strategy.
  - Incentive is measured using a utility function, which calculates the participant’s payoff.

Prisoner's Dilemma

Two prisoners suspected of a crime

- Both confesses: 5-year sentence each.
- Both <u>S</u>ilent: 1-year sentence each.
- Only one <u>C</u>onfesses: confessor gets 0-year sentence, other prisoner gets 10-years.

strategy

P1 \ P2	S	C
S	-1 -1	-10 -0
C	0 -10	$\boxed{-5 \ -5}$

payoff

Nash Equilibrium

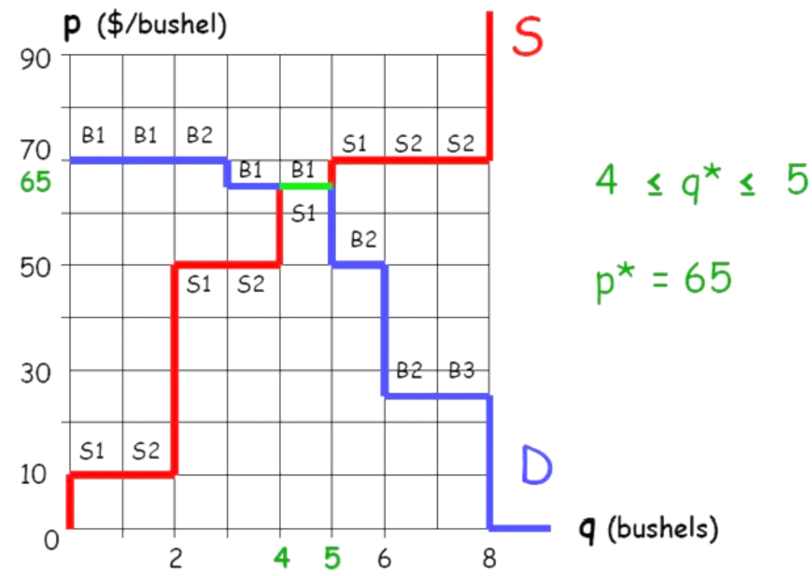
Electricity Market

- Growth in game-theoretical analysis due to electricity deregulation.
- “PoolCo” Model
  - A centralized marketplace that clears the market for buyers and sellers.
  - Electric power sellers/buyers submit bids to the pool for the amounts of power that they are willing to trade.
  - An ISO within a PoolCo would implement the economic dispatch and produce a single (spot) price for electricity.

Electricity Market

- Winning bidders are paid the spot price that is equal to the highest bid of the winners.
- Payoff = generation profit (revenue – cost).

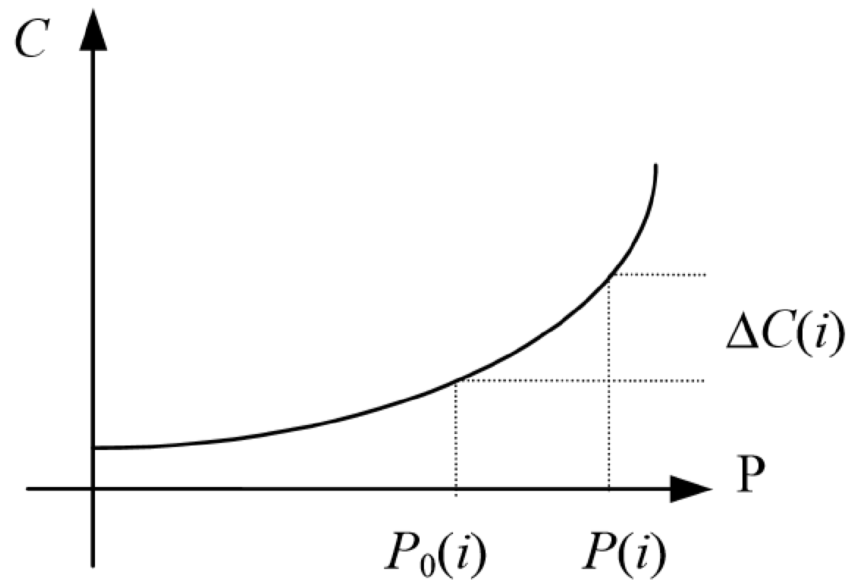
Bushels	S1	S2	B1	B2	B3
1	$10.00	$10.00	$70.00	$70.00	$25.00
2	$50.00	$50.00	$70.00	$50.00	0
3	$65.00	$70.00	$65.00	$25.00	0
4	$70.00	$70.00	$65.00	0	0
5	∞	∞	0	0	0
7	∞	∞	0	0	0
8	∞	∞	0	0	0



Generation Cost

- Generation and Operatio

$$C(P(i)) = a(i) + b(i)P(i) + c(i)P(i)^2$$



- Cost Increment Incurred

$$\Delta C(i) = C(P(i)) - C(P_0(i))$$
$$= b(i)\Delta P(i) + c(i)P(i)\Delta P(i) + c(i)P_0(i)\Delta P(i)$$

Generation Cost

- Incremental Cost

$$\pi(i) = \frac{\Delta C(i)}{\Delta P(i)} = b(i) + c(i)P(i) + c(i)P_0(i)$$

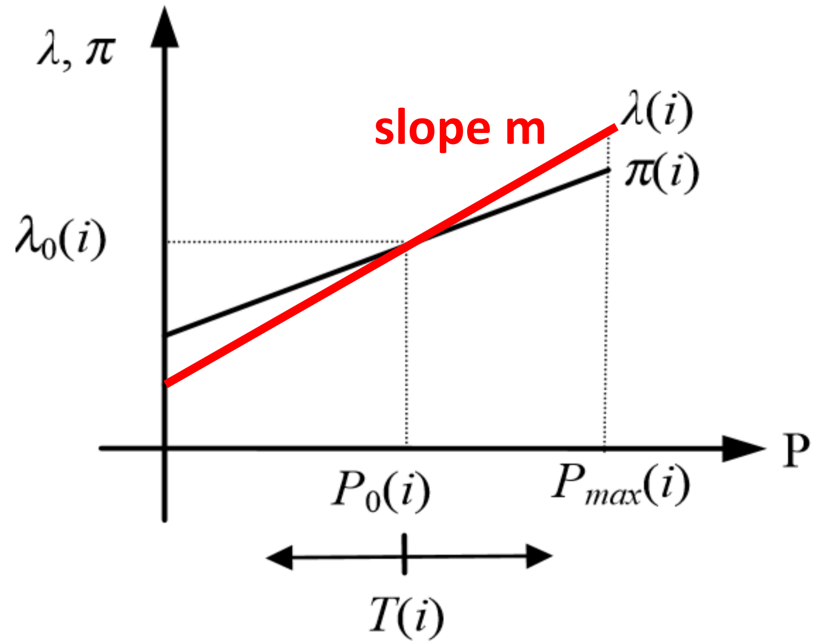
- Take the limit as ΔP→0 to get the marginal cost:

$$\lambda(i) = \frac{dC(i)}{dP(i)} = b(i) + 2c(i)P(i)$$

Buy or Sell Power?

- A utility will increase it's generation level beyond $P_0(i)$ if the selling price is greater than $\lambda_0(i)$.
- If the spot price (ρ) is lower, the utility will import power
- Payoff B(i)

$$B(i) = -\Delta C(i) + \rho T(i)$$



$$\lambda(i) = \lambda_0(i) + m(i)P(i)$$

Participant Strategies

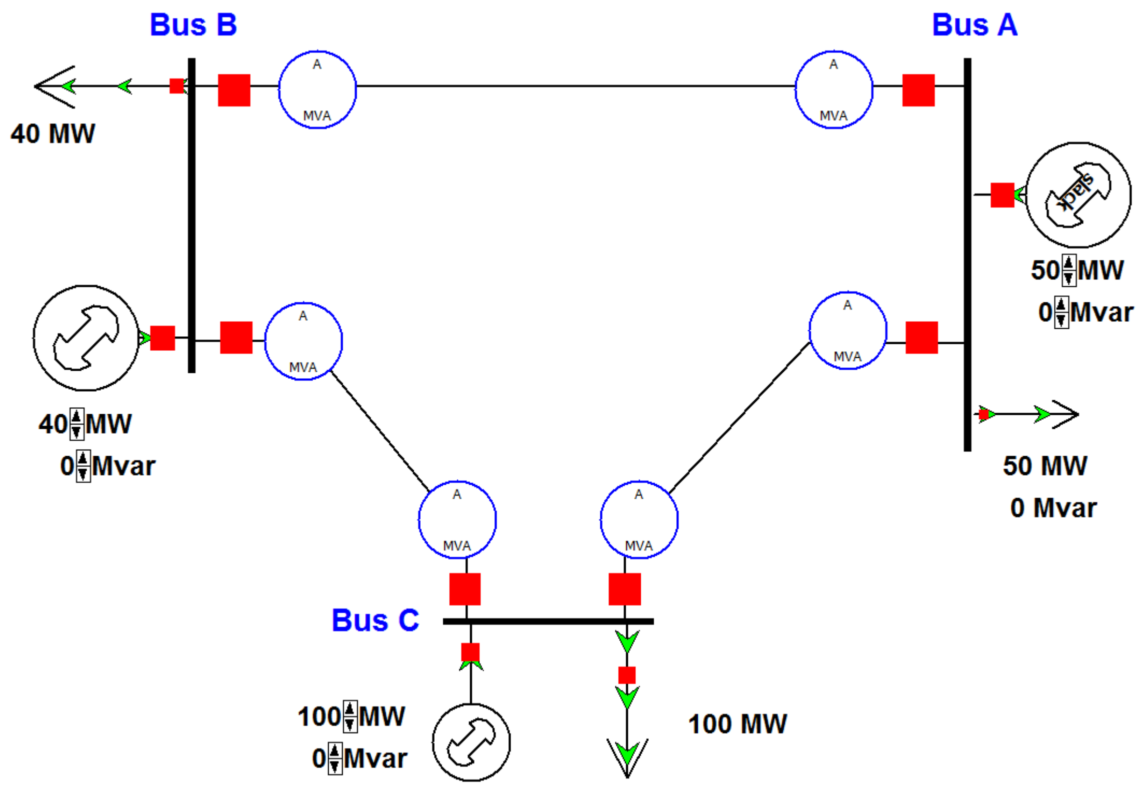
- Economic Dispatch: payoffs are maximized when utilities trade at $m_i = 2c_i$.
- Utilities are able to change their bids by adjusting the sl

$$\lambda(i) = \frac{dC(i)}{dP(i)} = b(i) + 2c(i)P(i)$$

$$\lambda(i) = \lambda_0(i) + m(i)P(i)$$

- Strategies (H, M, L):
  - H = Bid higher than MC ($m_i = 2.3c_i$)
  - M = Bid at MC ($m_i = 2c_i$)
  - L = Bid lower than MC ($m_i = 1.7c_i$)

Three-Utility Example



Utility	Load (MW)	P_{max} (MW)	Price Coefficients			λ_0 ($/MWh)
			a	b	c	
A	50	100	0	15	0.025	17.5
B	40	100	0	12	0.05	16
C	100	100	0	17	0.01	19

Three-Utility Example

$\{A,C\}\{B\}$ $\downarrow \quad \mapsto$	H	L	M
HH	13.40, 17.23	12.63, 21.05	11.43, 21.39
HL	10.70, 22.93	4.77, 28.20	6.34, 27.05
HM	11.67, 22.00	5.69, 27.15	7.28, 26.02
LH	19.05, 13.51	18.85, 11.90	14.50, 19.12
LL	14.85, 15.38	14.62, 16.14	11.41, 22.05
LM	15.58, 15.18	9.67, 24.04	11.94, 21.69
MH	18.04, 14.52	17.66, 14.40	13.57, 19.87
ML	14.00, 17.74	13.72, 18.34	9.90, 23.83
MM	14.78, 17.28	8.36, 25.17	10.55, 23.20

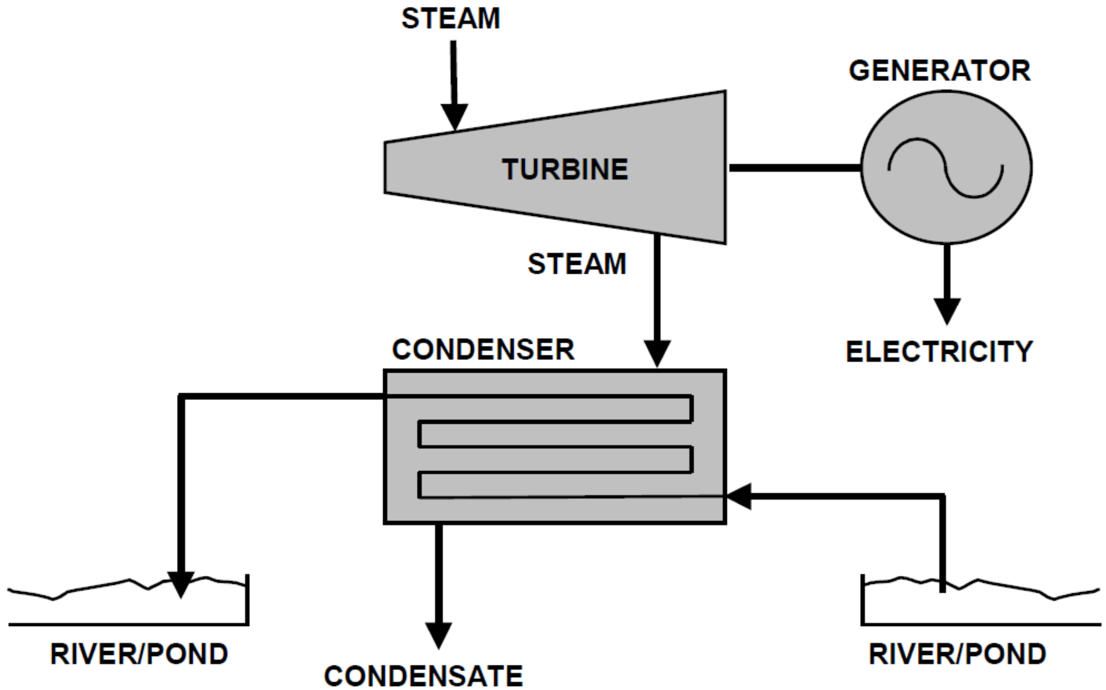
- First value is the sum of payoffs for A and C.
- Multiple equilibria exists, algorithms exist to calculate them.

How Can Water Be Added to This Analysis?

- As an "effective water cost"
  - Becomes imbedded into the generation fuel cost
  - Varies with plant configuration
    - Fuel type, cooling type, max MW
  - Use of water consumption/withdrawal factors
- As a MW constraint on the generation
  - Not as straightforward as the effective water cost
- In both cases, study the behavior/changes in the Nash Equilibrium.

Once-Through Cooling

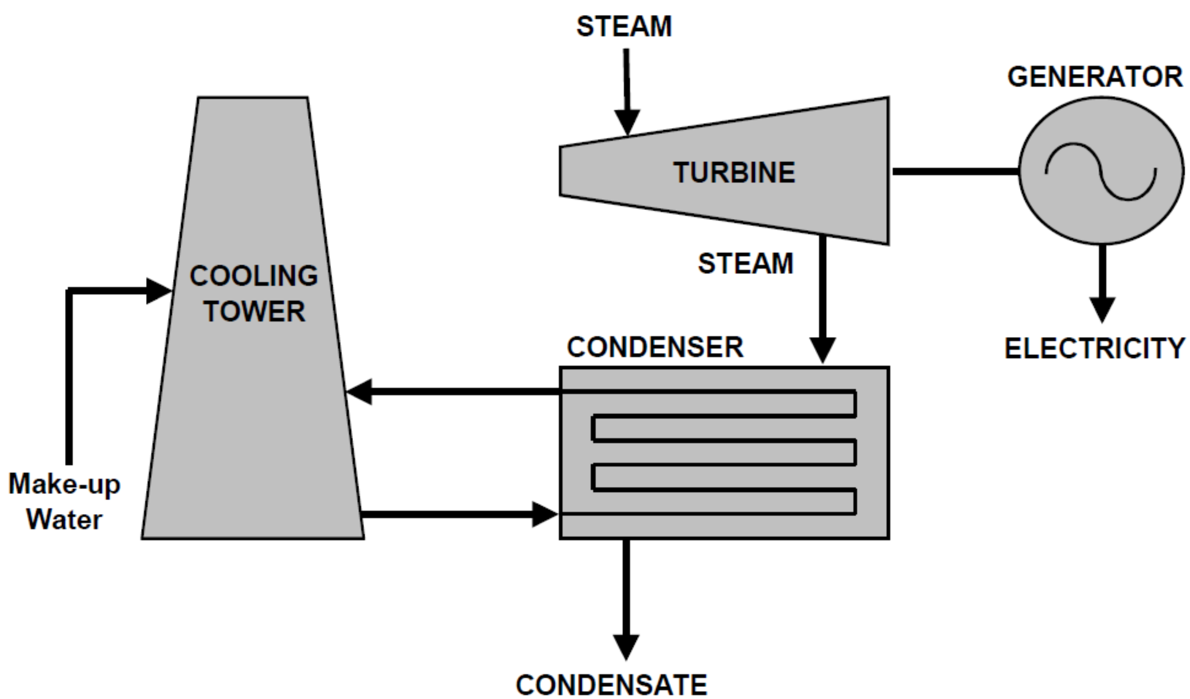
- Water is passed through a heat exchanger to condense the steam and returned back to the river.
  - Minimal consumption but significant withdrawals.



NREL Technical Report TP-6A20-50900, March 2011

Closed-Loop Cooling

- Cooling water is recycled in a cooling tower.
- A percentage of the cooling water is evaporated to cool it.
  - Re ion.



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Effective Water Cost

- An Analysis of the WEN in Illinois
  - Analyzed the capital costs in retrofitting once-through cooling technologies with recirculating technologies
  - Found an effective water cost of \$0.03-0.06 /m^3
- Water Withdrawal/Consumption Factors
  - NREL Report in 2011
  - EIA Data (publically available)
- (Water Factor)*(Effective Cost) ≈ "Water Fuel Cost"

Water Consumption/Withdrawal Factors

Fuel	Cooling	Technology	Consumption Min (gal/MWh)	Consumption Max (gal/MWh)	Withdrawal Min (gal/MWh)	Withdrawal Max (gal/MWh)
PV	N/A	Utility Scale	0	33	N/A	N/A
Wind	N/A	Turbine	0	1	N/A	N/A
Hydro	N/A	Aggregate	1,425	18,000	N/A	N/A
Nuclear	Once Through	Steam	100	400	25,000	60,000
N. Gas	Once-Thr.	Steam	95	291	10,000	60,000
N. Gas	Tower	Steam	662	1,170	950	1,460
Coal	Once-Thr.	Steam	100	317	20,000	50,000
Coal	Tower	Steam	480	1,100	500	1,200

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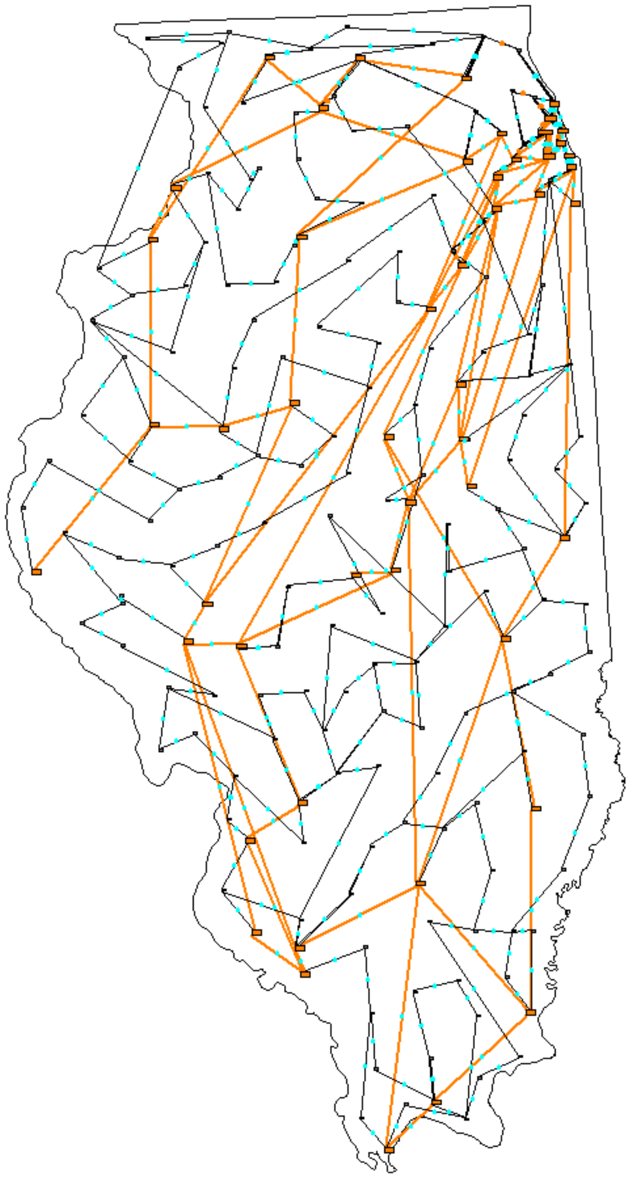
Water Factors into Cost ($/MWh)

Fuel	Fuel Cost	Water Cost	Open Con.	Open With.	Closed Con.	Closed With.	Open Total	Closed Total
Hydro	0	0.03	0.5105	0	0	0	0.5705	0
Nuclear	1	0.03	0.0305	5.04	0.0765	0.125	6.1305	1.2015
Wind	0	0.03	0	0	0	0	0.06	0
Natural Gas	2.59	0.03	0.027	3.977	0.0935	0.1365	6.654	2.82
Coal	2.16	0.03	0.0285	4.1305	0.078	0.114	6.379	2.352
Hydro	0	0.06	1.021	0	0	0	1.021	0
Nuclear	1	0.06	0.061	10.08	0.153	0.25	11.141	1.403
Wind	0	0.06	0	0	0	0	0	0
Natural Gas	2.59	0.06	0.054	7.954	0.187	0.273	10.598	3.05
Coal	2.16	0.06	0.057	8.261	0.156	0.228	10.478	2.544

IL-200 Synthetic Case

- Developed as part of a research project funded by ARPA-E.
- Characteristics
  - 200 Substations
  - 452 Buses
  - 202 Generators (50.6 GW)



Dealing With Incomplete Information

- Previously assumed there was competition with "complete" information.
  - Each utility knew not only it's own cost coefficients, but the coefficients of others.
  - Choosing a strategy was straightforward (Probability = 1).
- Realistically, they don't know exact values.
  - Each participant has "incomplete" generation information.
  - Plenty of ways to obtain relatively accurate guesses, however.

Mixed Strategies

- Pure vs Mixed Strategies
  - Pure: chooses a strategy with probability =1.
  - Mixed: assign probabilities to each of their own strategies
- Mixed Strategy Nash Equilibria
  - Participants develop probabilistic distributions based on market structure and participant behavior.
  - Instead of working with an exact payoff, *expected* payoff is used.
    - Average payoff, weighted by the strategy probabilities.

Future Work

- Use of mixed strategies
  - Methodology for creation of probability distributions
  - Better selection of bidding strategies
- Development of water scenarios
- Nash Equilibrium Analysis
  - Analysis of participant bidding behaviors/constraints
- Additional metrics associated with water vulnerabilities

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