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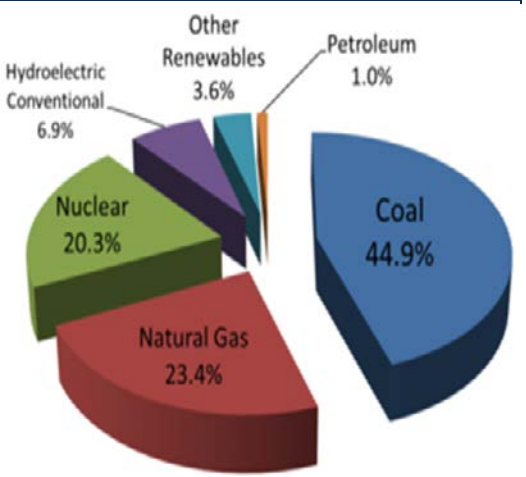

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Electricity Generation Portfolio Optimization

Ray Byrne (6113)
Nadine Miner (6114)
Denise Padilla (6133)

SANDIA REVIEW & APPROVAL NUMBER

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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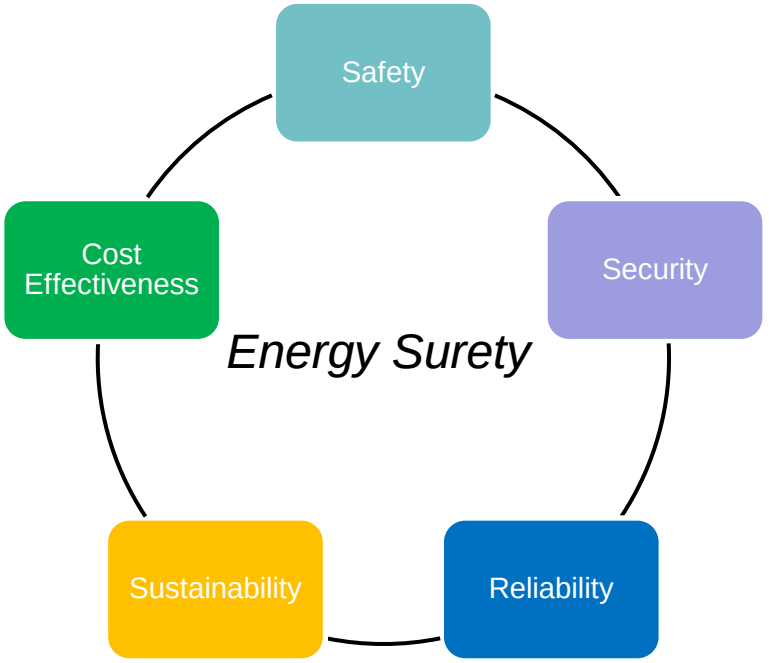
Problem Statement

- Identify the optimal electricity generation source mix based on the five Energy Surety performance metrics for the following generation sources:
  - Conventional Coal
  - Advanced Coal
  - Advanced Coal with Carbon Capture and Sequestration (CCS)
  - Natural Gas Conventional Combined Cycle (CC)
  - Natural Gas Advanced CC
  - Natural Gas Advanced CC with CCS
  - Natural Gas Conventional Combustion Turbine
  - Natural Gas Advanced Combustion Turbine
  - Advanced Nuclear
  - Wind
  - Wind (Offshore)
  - Solar PV
  - Concentrated Solar Thermal
  - Geothermal
  - Biomass
  - Hydro



Safety

- Sandia Definition
  - Supply safe supplies of energy to end user
- Problem Definition
  - Sum of injury data and fatality data for each generation type (per 100,000 workers)
  - Fatalities scaled by a criticality factor of 10
  - Cost function minimizes the sum of fatalities and injuries

Generation Type	Fatalities	Injuries
Conventional Coal	5.74	63
Advanced Coal	5.74	63
Advanced Coal with CCS	5.74	63
Natural Gas Conventional CC	4.3	18
Natural Gas Advanced CC	4.3	18
Natural Gas Advanced CC with CCS	4.3	18
Natural Gas Conventional Combustion Turbine	4.3	18
Natural Gas Advanced Combustion Turbine	4.3	18
Advanced Nuclear	3.1	3
Wind	3.1	3
Wind (Offshore)	6.3	12
Solar PV	3.1	3
Concentrated Solar Thermal	3.1	3
Geothermal	3.1	3
Biomass	7.6	17
Hydro	3.1	3

1. Bureau of Labor Statistics, U.S. Department of Labor, “Workplace injuries and illness – 2010”
2. Bureau of Labor Statistics, U.S. Department of Labor, “National census of fatal occupational injuries in 2010”

Security

- Sandia Definition
  - Protection of energy supply infrastructure
- Problem Definition
  - Heuristic security rating from 0-10 based on the following categories of risk
    - Initial cost risk
    - Fuel, O&M cost risk
    - New regulation risk
    - Carbon price risk
    - Water constraint risk
    - Capital shock risk
    - Planning risk
  - Risk is inversely proportional to security
  - Cost function minimizes risk

Generation Type	Security Rating
Conventional Coal	9
Advanced Coal	8
Advanced Coal with CCS	8.5
Natural Gas Conventional CC	7.5
Natural Gas Advanced CC	8
Natural Gas Advanced CC with CCS	7.5
Natural Gas Advanced Combustion Turbine	7.5
Advanced Nuclear	9.5
Wind	2
Wind (Offshore)	2
Solar PV	2
Concentrated Solar Thermal	5.5
Geothermal	5.5
Biomass	7.5
Hydro	8.5

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"Practicing Risk-Aware Electricity Regulation: What Every State Regulator Needs to Know", A Ceres Report, by R. Binz, R. Sedano, D. Furey, D. Mullen, April 2012. On-line source for article: http://www.ceres.org/resources/reports/practicing-risk-aware-electricity-regulation/view

Risk Categories used for Security Assessment

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- **Initial Cost**
  - Largest spending is in the building cycle therefore largest amount of risk to consumer and investor
  - Includes the cost to rebuild
- **Fuel and Operating Cost**
  - Fuel cost and availability
  - O&M cost and risks
- **New Regulation Risk**
  - Air and water quality regulations
  - Waste disposal
  - Land use and zoning
- **Carbon Price Risk**
  - State or federal limits on greenhouse gas emissions
- **Water Constraint Risk**
  - Availability and cost of cooling and process water
- **Capital Shock Risk**
  - Availability and cost of capital, and risk to firm due to project size
- **Planning Risk**
  - Risk of inaccurate load forecasts
  - Competitive pressure

Reliability

- Sandia Definition
  - Can provide energy when and where needed
- Problem Definition
  - Availability factor (%)
  - Cost function maximizes reliability

Generation Type	Availability (%)
Conventional Coal	80
Advanced Coal	80
Advanced Coal with CSS	80
NG conventional CC	85
NG advanced CC	85
NG advanced CC with CCS	85
NG conventional combustion turbine	85
NG Advanced combustion turbine	85
Advanced nuclear	90
Wind	20
Wind - offshore	40
Solar PV	15
Solar thermal	80
Geothermal	80
Biomass	80
Hydro	42

1. “Cost and performance baseline for fossil energy plants, Vol. 1,” DOE/NETL-2007/1281, May 2007
2. ”Availability factor,” http://en.wikipedia.org/wiki/Availability_factor
3. “Hydropower resources,” http://energyfuture.wikidot.com/hydropower-resources

Sustainability

- Sandia Definition
  - Can be maintained for long durations
- Problem Definition
  - Heuristic weighting from 0-10 based on US-wide energy source reserve data[1] with scaling by US-wide yearly energy use data[2]
  - Renewable energy assumed to have 100% sustainability
  - Cost function maximizes sustainability

Generation Type	Sustainability
Conventional Coal	6
Advanced Coal	6
Advanced Coal with CSS	6
NG conventional CC	2
NG advanced CC	2
NG advanced CC with CCS	2
NG conventional combustion turbine	2
NG Advanced combustion turbine	2
Advanced nuclear	9
Wind	10
Wind - offshore	10
Solar PV	10
Solar thermal	10
Geothermal	7
Biomass	8
Hydro	8

1. U.S Department of Energy, Energy Information Administration, Annual Energy Outlook 2005
http://www.world-nuclear.org/info/inf09.html(World Nuclear Association)
2. EPA.gov

Cost Effectiveness

- Sandia Definition
  - Provided at affordable cost
- Problem Definition
  - US-wide levelized cost of electricity, LCOE ($/MWh)[1]
  - Cost function minimizes cost

Generation Type	Cost
Conventional Coal	94.8
Advanced Coal	109.4
Advanced Coal with CSS	136.2
NG conventional CC	66.1
NG advanced CC	63.1
NG advanced CC with CCS	89.3
NG conventional combustion turbine	124.5
NG Advanced combustion turbine	103.5
Advanced nuclear	113.9
Wind	97
Wind - offshore	243.2
Solar PV	210.7
Solar thermal	311.8
Geothermal	101.7
Biomass	112.5
Hydro	86.4

1. U.S. Energy information administration, “Levelized cost of new generation resources in the annual energy outlook 2011,” http://www.eia.gov/oiaf/aeo/electricity_generation.html

Optimization Model Input Data Summary

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Generation Type	Safety	Security	Reliability	Sustainability	Cost
Conventional Coal	635.74	9	80	6	94.8
Advanced Coal	635.74	8	80	6	109.4
Advanced Coal with CSS	635.74	8.5	80	6	136.2
NG conventional CC	184.3	7.5	85	2	66.1
NG advanced CC	184.3	7.5	85	2	63.1
NG advanced CC with CCS	184.3	8	85	2	89.3
NG conventional combustion turbine	184.3	7.5	85	2	124.5
NG Advanced combustion turbine	184.3	7.5	85	2	103.5
Advanced nuclear	33.1	9.5	90	9	113.9
Wind	33.1	2	20	10	97
Wind - offshore	126.3	2	40	10	243.2
Solar PV	33.1	2	15	10	210.7
Solar thermal	33.1	5.5	80	10	311.8
Geothermal	33.1	5.5	80	7	101.7
Biomass	177.6	7.5	80	8	112.5
Hydro	33.1	8.5	42	8	86.4

Energy Surety Optimization Cost Function for Electricity Generation

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- Cost function implemented in Matlab using the Optimization toolbox (fmincon function)

$$f = \sum_{i=1}^{N} w_1 x_i C_i^{safety} + \sum_{i=1}^{N} w_2 x_i C_i^{security} - \sum_{i=1}^{N} w_3 x_i C_i^{reliability} - \sum_{i=1}^{N} w_4 x_i C_i^{sustainability} + \sum_{i=1}^{N} w_5 x_i C_i^{cost}$$

Term	Description
C_i^{safety}	injuries/100,000 workers + 10*fatalities/100,000 workers
$C_i^{security}$	heuristic rating 0-10
$C_i^{reliability}$	Availability factor (percent)
$C_i^{sustainability}$	heuristic rating 0-10
C_i^{cost}	Levelized cost of electricity (LCOE), $/MWh

w_i are weightings that sum to 100 percent

Each C_i is normalized by dividing by the $mean(C)$

Optimization Results

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SCENARIO	Today	1 - Safety	2 -Security	3 - Reliability	4 - Sustainability	5 - Cost	6 - Equal	7	8
Safety		100	0	0	0	0	20	10	0
Security		0	100	0	0	0	20	10	50
Reliability		0	0	100	0	0	20	60	50
Sustainability		0	0	0	100	0	20	10	0
Cost effectiveness		0	0	0	0	100	20	10	0
TECHNOLOGY									
Conventional coal	44.8								
Advanced coal									
Advanced coal with CSS									
NG conventional CC	23.9								
NG advanced CC						100			
NG Advanced CC with CCS									
NG conv comb turbine									
NG advanced comb turbine									
Advanced nuclear	19.6	16.7		100				100	
Wind	2.3	16.7			25		100		
Wind – Offshore			33.3		25				
Solar PV	0.03	16.7	33.3		25				
Solar thermal		16.7	33.3		25				50
Geothermal	0.37	16.7							50
Biomass	0.46								
Hydro	6.3	16.7							

Conclusions

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- Our model is vastly oversimplified for the complexity of the problem
- For an improved representation of reality, the following should be considered
  - Obtain more accurate input data for the optimization
  - Perform the optimization on a regional basis
  - Incorporate existing generation and optimize the incremental changes
  - Incorporate additional constraints
    - Transmission
    - Regulations (e.g. environmental, emissions, tax, etc.)

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BACKUP

Security

- Source: “Practicing Risk-Aware Electricity Regulation: What Every State Regulator Needs to Know”, A Ceres Report, by R. Binz, R. Sedano, D. Furey, D. Mullen, April 2012. On-line source for article: http://www.ceres.org/resources/reports/practicing-risk-aware-electricity-regulation/view
- Point Value: 0-4 (None – Very High), scaled to a Heuristic weighting of 0-10

RELATIVE RISK EXPOSURE OF NEW GENERATION RESOURCES

Resource	Initial Cost Risk	Fuel, O&M Cost Risk	New Regulation Risk	Carbon Price Risk	Water Constraint Risk	Capital Shock Risk	Planning Risk
Biomass	Medium	Medium	Medium	Medium	High	Medium	Medium
Biomass w/ incentives	Medium	Medium	Medium	Medium	High	Low	Medium
Biomass Co-firing	Low	Low	Medium	Low	High	Low	Low
Coal IGCC	High	Medium	Medium	Medium	High	Medium	Medium
Coal IGCC w/ incentives	High	Medium	Medium	Medium	High	Low	Medium
Coal IGCC-CCS	High	Medium	Medium	Low	High	High	High
Coal IGCC-CCS w/ incentives	High	Medium	Medium	Low	High	Medium	High
Efficiency	Low	None	Low	None	None	Low	None
Geothermal	Medium	None	Medium	None	High	Medium	Medium
Geothermal w/ incentives	Medium	None	Medium	None	High	Low	Medium
Large Solar PV	Low	None	Low	None	None	Medium	Low
Large Solar PV w/ incentives	Low	None	Low	None	None	Low	Low
Natural Gas CC	Medium	High	Medium	Medium	Medium	Medium	Medium
Natural Gas CC-CCS	High	Medium	Medium	Low	High	High	Medium
Nuclear	Very High	Medium	High	None	High	Very High	High
Nuclear w/ incentives	Very High	Medium	High	None	High	High	Medium
Onshore Wind	Low	None	Low	None	None	Low	Low
Onshore Wind w/ incentives	Low	None	Low	None	None	None	Low
Pulverized Coal	Medium	Medium	High	Very High	High	Medium	Medium
Solar - Distributed	Low	None	Low	None	None	Low	Low
Solar Thermal	Medium	None	Low	None	High	Medium	Medium
Solar Thermal w/ incentives	Medium	None	Low	None	High	Low	Medium

- Hydro | High | Med | Low | Low | Very High | High | High

Electricity Generation by Fuel Type over time in the US

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