Preventing Climate Change with 100% Renewable Electricity and Transportation: Part I

What Does It Look Like?
What Would It Cost?
What Would It Do About CO_2?

Edwin Cox
OLLI

The Secret Sauce

All energy for electricity is generated by a combination of wind power and solar power

- Conventional generation by fossil fuels and nuclear power is phased out as plants meet end-of-life and are retired, not replaced

Storage spanning months is necessary to match time of use to time of generation, since these differ dramatically

- Hydrogen can be readily produced from electricity by hydrolysis of water, stored and used to generate electricity when needed by means of fuel cells
- Hydrogen is presently the only storage medium that can meet requirements, but is only in its infancy in energy storage applications

Why N.C.?

North Carolina is a useful test case for the adequacy of solar and wind resources to meet the demand, and determine the mix of wind, solar and storage that can meet the need

- N.C. climate, population, industry are reasonably representative of U.S. as a whole
- Utility electricity load data available
- Matching wind and solar data available

If N.C. results are projected globally, what could be the results in terms of CO_2 mitigation ? → Part II

The study

A research project to meet the requirements for my Master of Science in Mechanical Engineering degree at N.C. State

- Utility load data for Duke Energy Carolinas (DEC) and Progress Energy Carolinas (now Duke Energy Progress, or DEP) submitted to Federal Energy Regulatory Commission (FERC) - hourly
- Weather data (solar and wind) from the N.C. Climate Office and National Data Buoy Center – hourly
- Financial projections of costs for wind, solar and storage technologies from U.S. Department of Energy
- A custom simulation program written in the Python language

Wind turbines

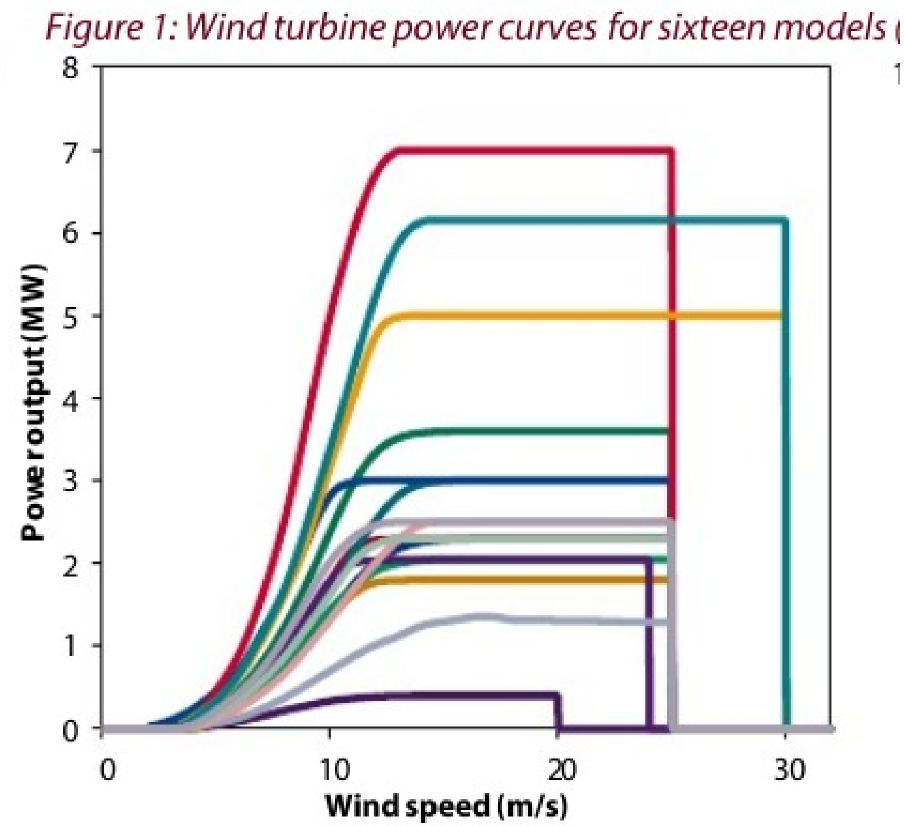
Vestas V112

- 3.0 MW maximum power
- Half-power at 8 m/s
- Full-power at 12 m/s
- Cutout at 25 m/s

Wind velocity V is at hub height (100 m), extrapolated from anemometer height

Power proportional to V^3

1 m/s = 2.2 mph



Photovoltaic system

1000 W array

- Nominal output at STC (1000 W/m^2, 25°C, AM1.5)
- β=-0.005%/°C
- NOCT 45°C
- System derate 15%
- Slope = latitude (35° in N.C.)
- South-facing
- Efficiency 15%

Solar and wind costs

Solar PV and Wind Turbine Financial Parameters				
	Wind		Solar	
	2008	2030	2008	2030
Capital	\$3000/kW	\$1418/kW	\$3000/kW	\$833/kW
O&M	\$94.0/kW-yr	\$94.0/kW-yr	\$12.3/kW-yr	\$6.2/kW-yr

Table 4. Wind and solar generation parameters

Grid-interactive storage (V2G)

Vehicle-to-Grid (Wikipedia article)

Lithium-ion batteries in EVs (electrical vehicles)

Intelligent controller charges vehicles but also reverses current flow from batteries to grid when needed to meet demand

Batteries drawn down only fractionally with limit set by driver

Can buffer mismatch between renewable generation and utility demand over hours to a few days at low cost

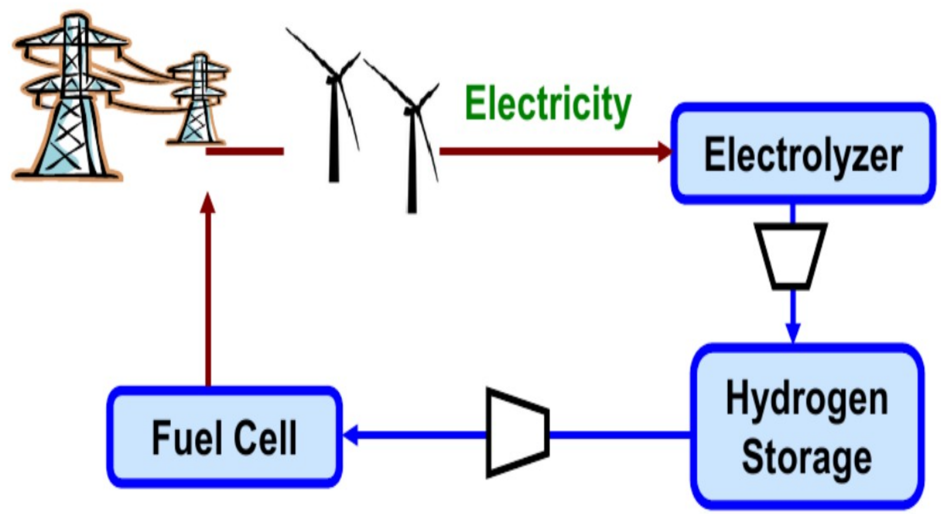
Minor part of project; won't spend time on it

Hydrogen storage

Excess electricity powers an electrolyzer, producing hydrogen

Hydrogen is stored under pressure in tanks (above-ground, below-ground)

During hours of deficit in generation vs. demand, hydrogen is withdrawn from tank and drives fuel cells to generate electricity



H_2 parameters

Hydrogen Generation, Storage and Use Financial Parameters						
	Electrolyzer		Storage		Fuel Cell	
Year	2008	2030	2008	2030	2008	2030
Capital	\$675/kW	\$300/kW	\$32.21/kWh	\$12.91/kWh	\$987/kW	\$428/kW
O&M	-	-	-	-	\$37/kW-yr	\$12/kW-yr
Efficiency	73%	87%	-	-	60%	70%

Table 5. Hydrogen generation, storage and use parameters

Source: US DOE NREL (Steward, 2009)

Utility-scale H_2 generation

ProtonOnsite M-series

- 2 MW input
- 1000 kg/d H_2 production
- PEM (proton exchange membrane) fuel cell run in reverse

Tailored to utility-scale applications

Pictured above: Proton OnSite's M Series megawatt platform, with the footprint of a 40' shipping container, is shown operating at more than 200 m^3 of hydrogen per hour. The modular design of the M Series enables solutions for an almost unlimited range of project sizes.

Hydrogen storage

Hydrogen at 273K, 170 bar (2500 psi) has density 15 kg/m^3

Typical tank 28600 kg, 1907 m^3

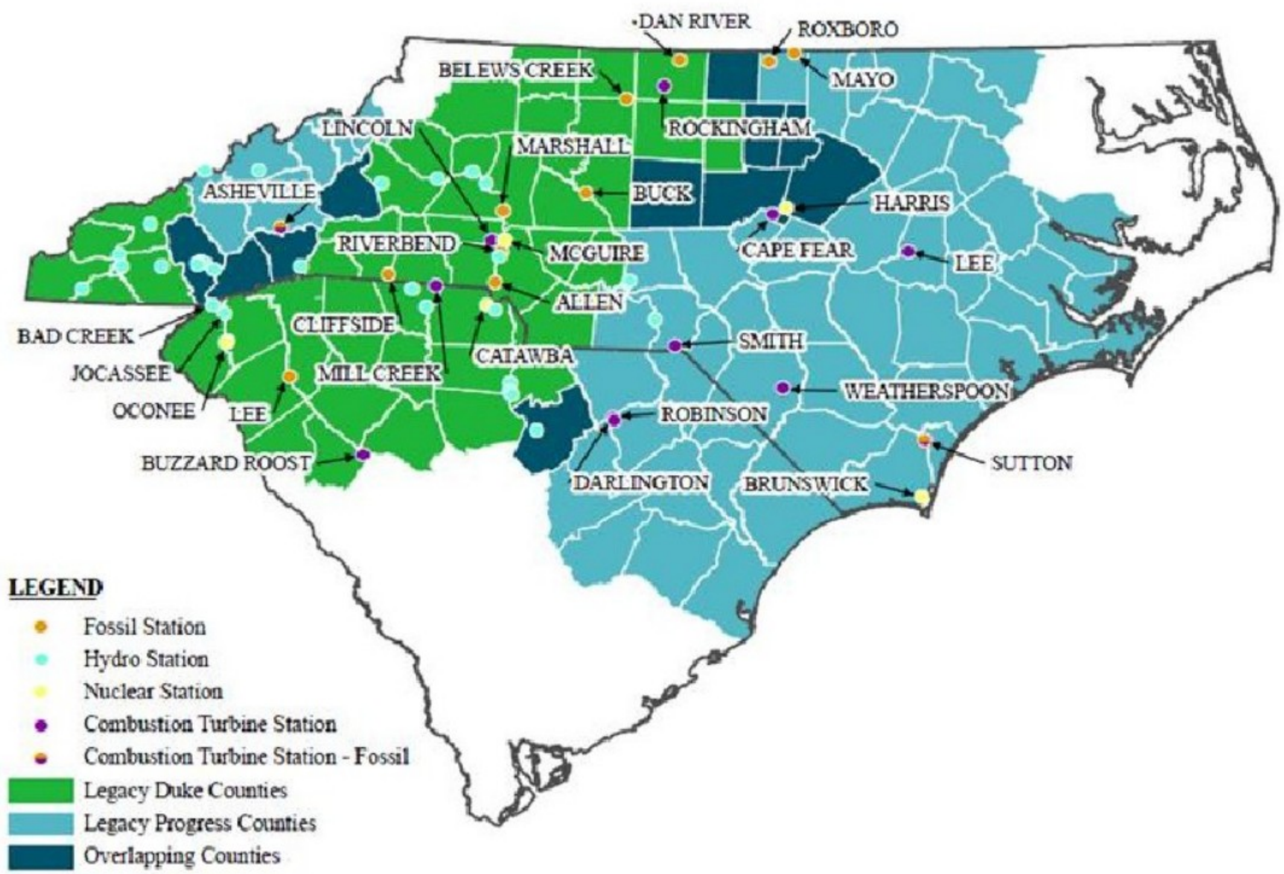
Cylindrical tank 10 m high, radius 7.8 m (2000 sq.ft. footprint)

Energy capacity 0.953 GWh (28600 kg x 120 MJ/kg x 1 kWh/3.6 MJ)

Peeking ahead, the required storage is 1500 GWh equivalent H_2; would be met by 1500 tanks distributed across N.C.

- Very small footprint!

DEC & DEP Territories



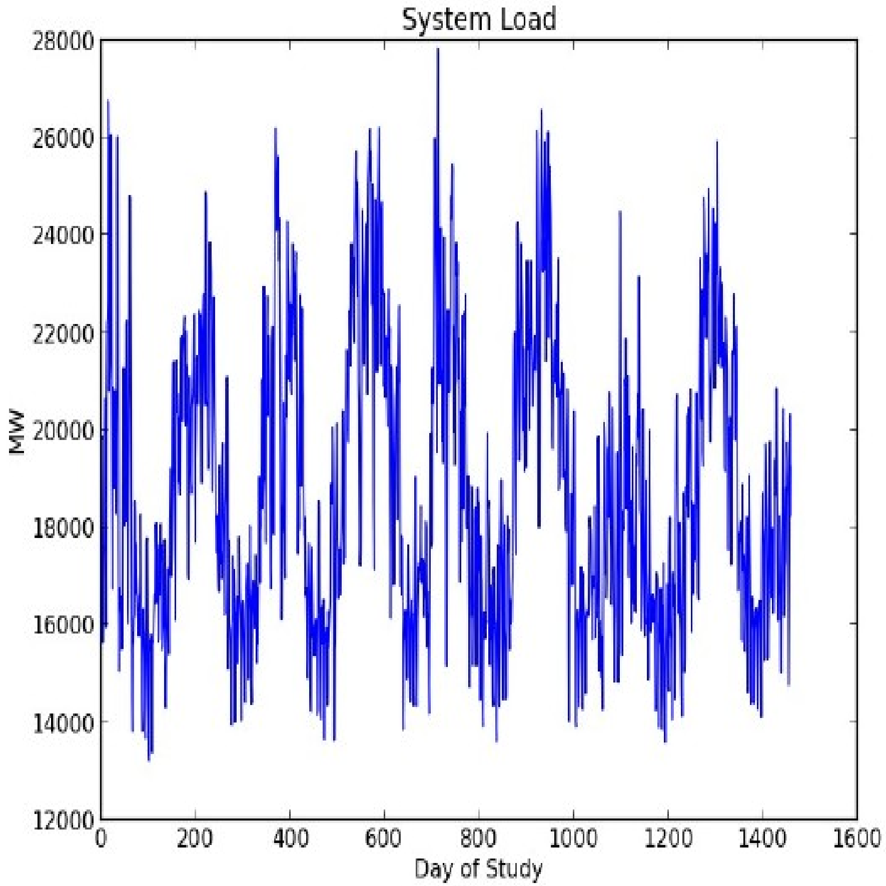
DEC/DEP system vs. N.C. load

Annual Energy Load (MWh) for DEC+DEP Compared with N.C. Electricity Sales Data				
Year	2009	2010	2011	2012
DEC+DEP	161,649	172,723	165,705	161,586
North Carolina	127,658	136,415	131,085	128,085
Ratio	1.27	1.27	1.26	1.26

Utilities cover parts of S.C. as well as N.C., but part of N.C. covered by other utilities

N.C. load (US EIA data) is less than DEC/DEP, but ratio consistent over the years, so hourly DEC/DEP should be a reasonable proxy for N.C.

System load



Highly season dependent

Low loads in Spring and Fall

Heavy Winter load for heating

Heavy Summer load for cooling

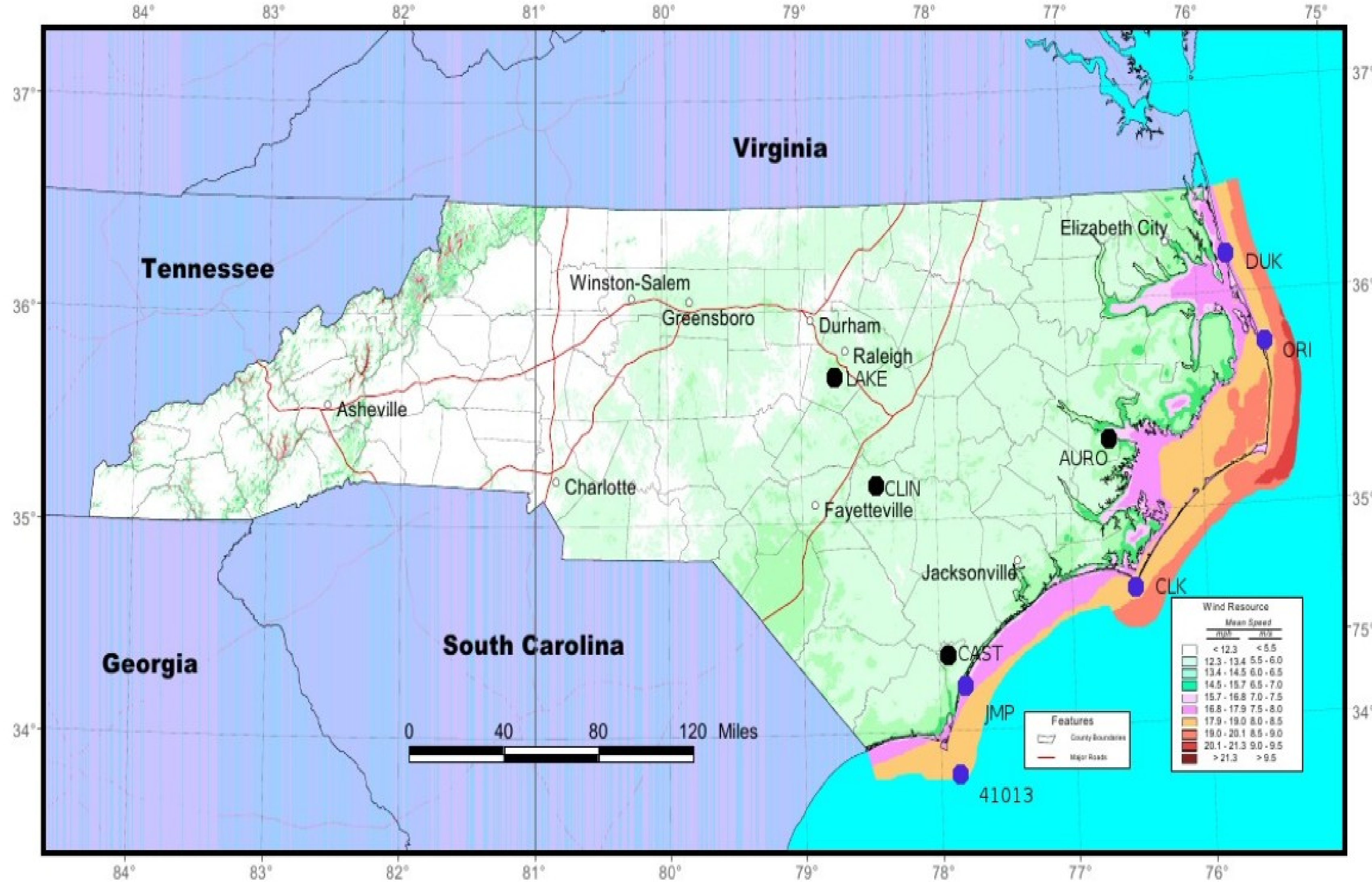


Fig. 2. North Carolina Monitoring Stations Used in Study

Solar Monitors

North Carolina ECONet Solar and Weather Monitoring Stations			
Station ID	Location	Latitude (°N)	Longitude (°W)
AURO	Aurora	35.562	76.716
CAST	Castle Hayne	34.321	77.916
CLIN	Clinton	35.022	78.282
LAKE	Raleigh	35.728	78.679

Wind Monitors

North Carolina Coastal Wind Monitoring Stations					
Stn ID	Station Name	Latitude (°N)	Longitude (°W)	Anem_Ht (m)	Water_Depth (m)
clkn7	Cape Lookout	34.622	76.525	14.4	On-shore
dukn7	Duck Pier	36.184	75.746	22.9	On-shore
orin7	Oregon Inlet Marina	35.796	75.548	7.6	On-shore
jmpn7	Johnny Mercer Pier	34.213	77.786	15.4	On-shore
41013	Frying Pan Shoals	33.436	77.743	5.0	23.5

Generation Calculation

Each hour, energy is calculated at each station from solar insolation or wind velocity

Total solar is average of all 4 solar locations

Total wind is average of all 5 wind locations

Total renewable energy is sum of solar and wind

SERENE Simulation

Simulation Engine for Renewable Energy in Python

Fancy name for automated hourly energy bookkeeping over 8760 hours

If energy generated is more than energy demand, excess is added to storage

If energy demand is more than energy generated, excess is drawn from storage

Energy being stored first goes to V2G until it is filled, then to hydrogen until it is filled, then used to generate methane to max capacity, then spilled

Energy retrieved from storage is first drawn from V2G, then H_2

If storage is empty, auxiliary generation (NG CT) is brought online

Run with various assumptions: amount of solar, amount of wind, amount of storage

Did it meet utility demand over the 4 year period?

What was the cost?

What was the corresponding cost of carbon for the avoided emissions?

Define 100% wind, solar

Assume unlimited amount of loss-less storage

- 30,000 GWh used

Wind turbine capacity (GW) to supply 100% of energy over the 4 years

- 43.5 GW = ~15,000 3 MW turbines

Solar PV capacity (GW) to supply 100% of energy over the 4 years

- 121.4 GW

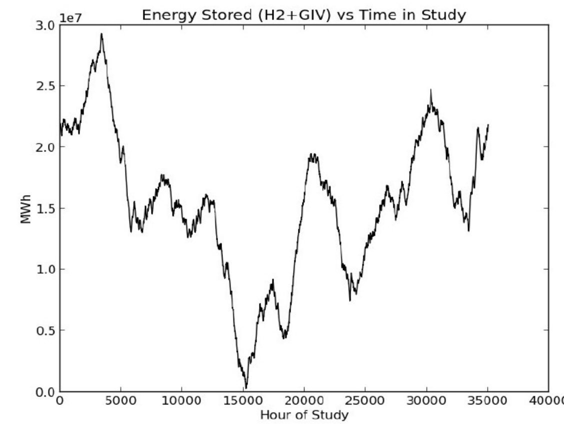


Fig. 4. Energy Stored vs. Study Day for 100% Wind Scenario

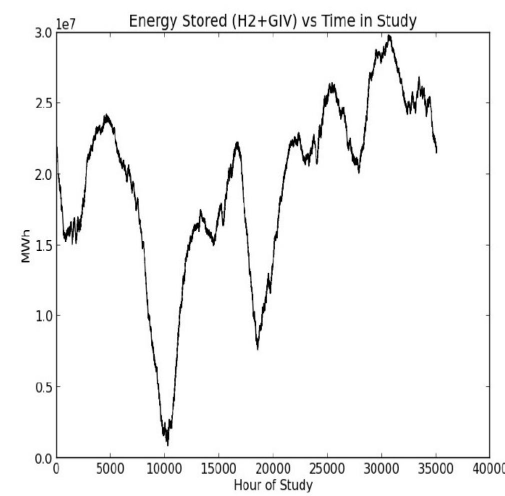


Fig. 5. Energy Stored vs. Study Day for 100% Solar Scenario

H_2 parameters

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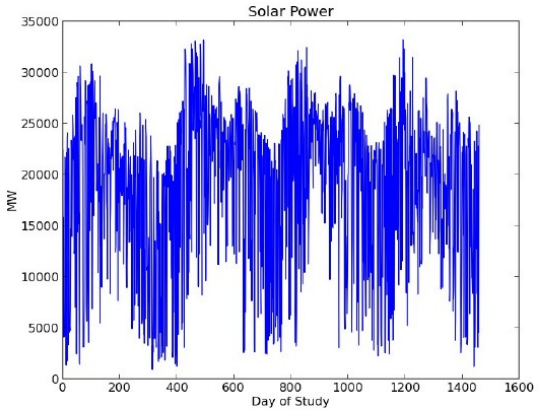
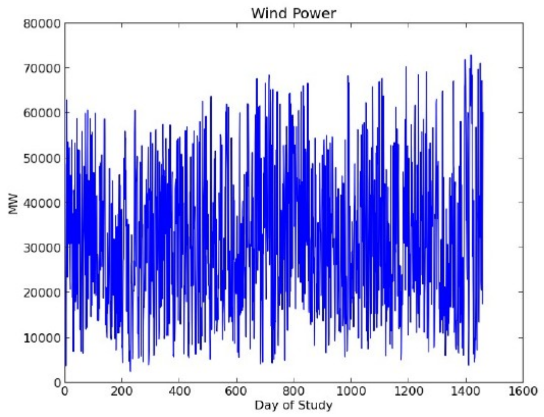
Seasonal generation patterns

Solar generation drops dramatically in Winter, peaks in Spring, and falls thereafter



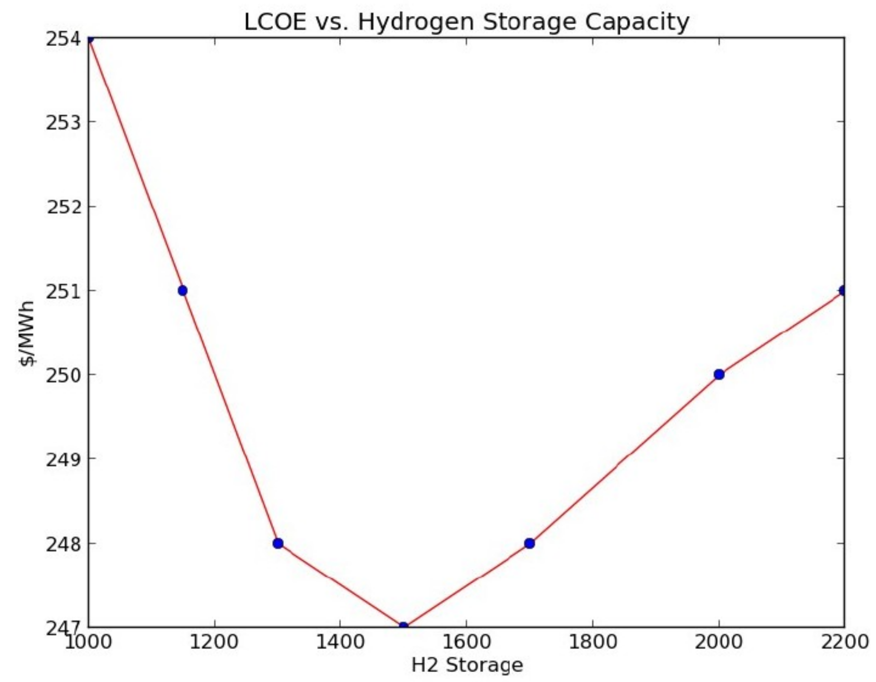
Wind pattern less obvious, but tends to higher Winter values and prolonged runs



Storage amount

Varied with generation held constant to find optimum cost

Distinct minimum about 1500 GWh equivalent H_2 storage, in both 2008 and 2030 cost structure



Parameters for simulation runs

Solar and wind

- Expressed as percentage of amount to provide 100% from each separately
- Run separately for 2008 actual and 2030 projected costs

Storage

- H_2 fixed at amount providing lowest cost/kWh, 1500 GWh
- V2G fixed at 100 GWh (7M vehicles x 15 kWh each)
- Optimum was similar for 2008 and 2030

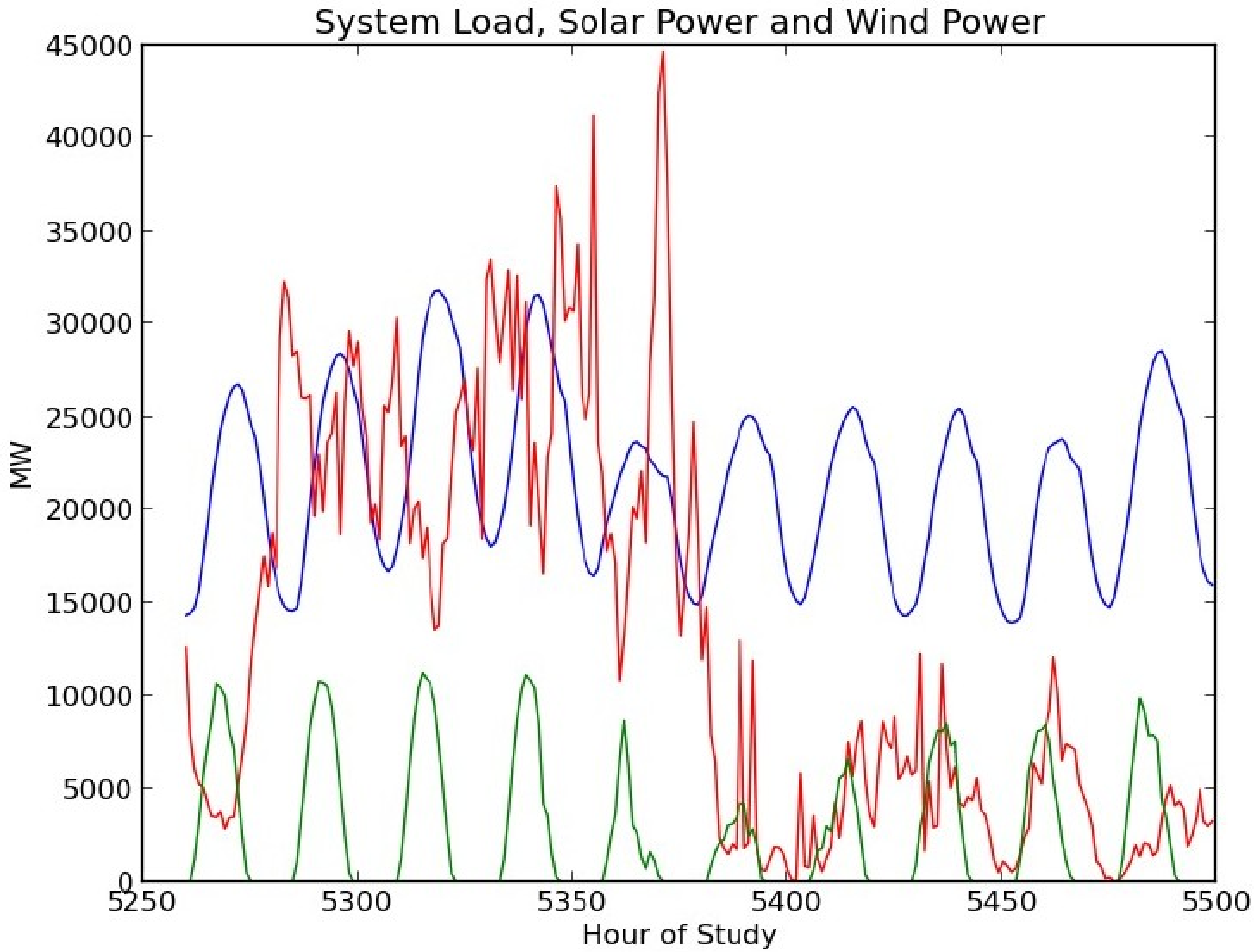
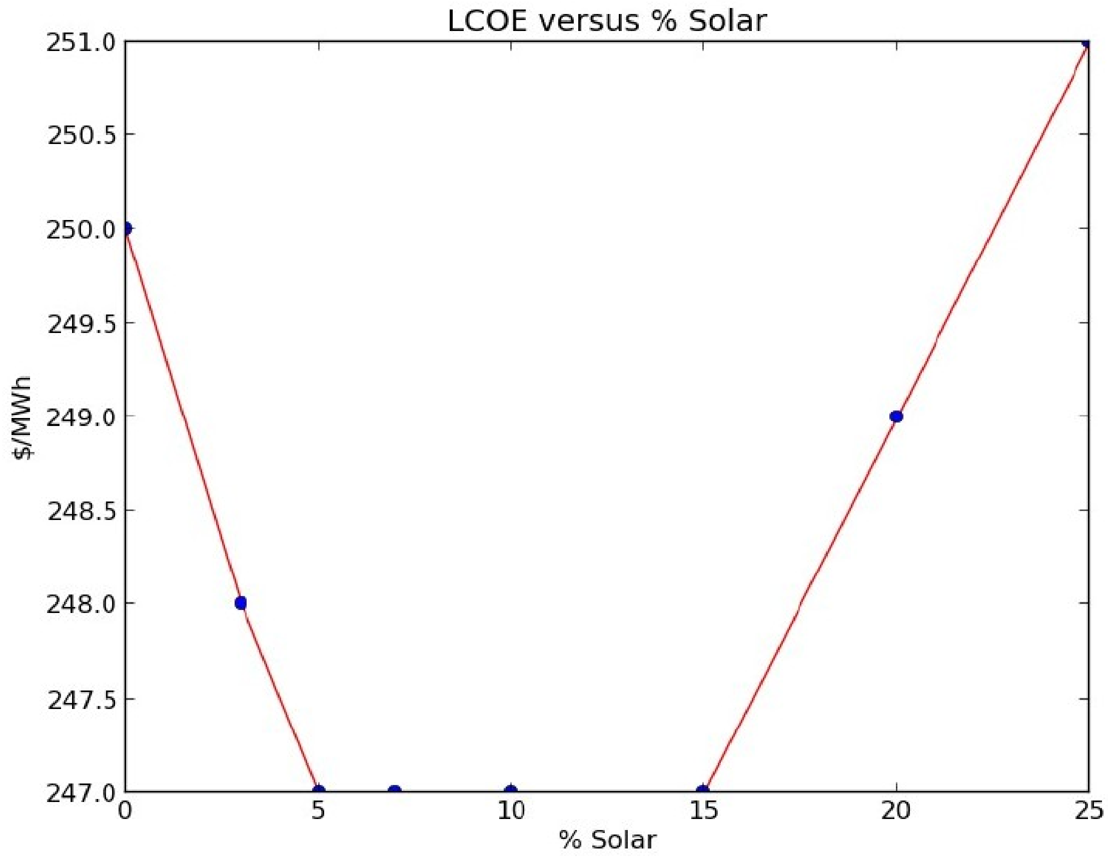


Fig. 9. Load (blue), Wind Generation (red) and Solar (green) Generation – mid July

LCOE vs % solar - 2008



Optimum solution - 2008

Electricity only

Solar of 10%

Wind 141%

LCOE $247/MWh ($0.247/kWh)

LCOE vs % solar - 2030

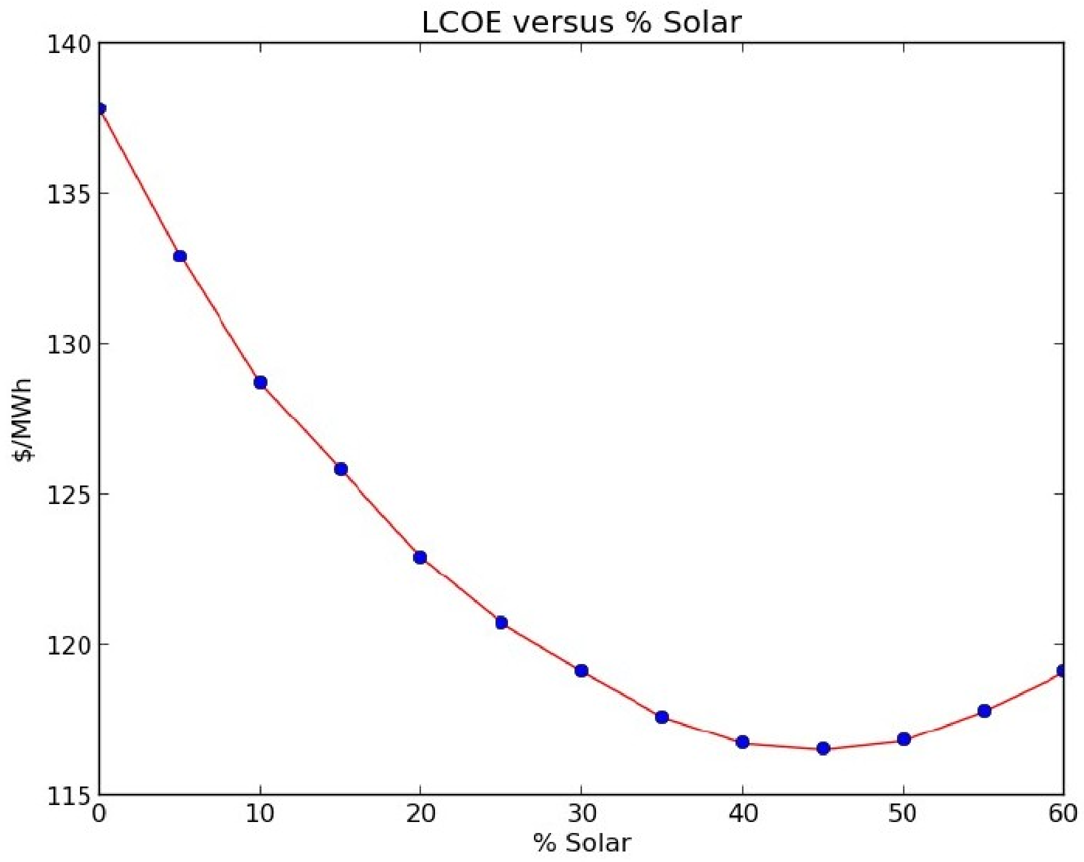


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Table 4. Wind and solar generation parameters

Optimum solutions - 2030

Electricity + transportation

- Lower cost of solar led to increased use of solar at optimum solution
- Solar 67 GW
- Wind 46 GW
- LCOE $116/MWh ($0.116/kWh)

Total Costs 2030

Total annual energy requirement

- 165537 GWh electricity
- 37040 GWh transportation (100% EV)

Total cost per year (2008$): $22.5 Billion

Costs by category

- Wind generation 48.6%
- Solar Generation 27.1%
- H2 storage 9.4%
- Fuel cell 6.2%
- Hydrolyzer 3.4%
- V2G 2.4%
- Auxiliary 1.9%

Sufficient resources: wind?

How much area would the required wind facilities occupy, and is it available in 2030?

Wind

- 100% is 43.5 GW = 14,500 3.0 GW turbines
- Turbine spacing is 660 m (six rotor diameters)
- Bureau of Ocean Energy Management (BOEM) has designated 2,800 square miles of potential wind development off N.C. coast (319 lease blocks each 9 sq.mi) at depth <50 m, distance < 50 mi. off coast
- At 49 turbines per block, total installed capacity is 55.9 GW (128%)
- Technology improvements should allow turbines in deeper water

Sufficient resources: solar?

How much area would the required solar facilities occupy, and is it available in 2030?

Solar

- 100% solar is 121.4 GW
- Area required: 850 km^2
- N.C. land area is 139,391 km^2
- Area required for 100% is 0.6% of total N.C. land area
- 7.5% solar could be achieved with just roof-top solar installations on residences
- Commercial rooftops, parking lots and other existing host sites could potentially be used in conjunction with existing uses

Mitigation of CO_2 emissions

Annual CO_2 emissions due to electricity in N.C. is 62.3 Mt CO_2/yr; due to transportation is 48.1 Mt CO_2/yr

An additional 3 Mt can be avoided by using excess generation to make CH_4 (natural gas)

Total abatement 113 Mt CO_2/yr

Revenue $12.6B

- Electricity: 202577 GWh @ $0.06/kWh → $12.2B
- Natural gas: $0.4B

Balance $12.6-$22.5 = -$9.9B

Mitigation cost = $9.9B / 113 Mt CO_2 = $88 / t$CO_2$