Obstacles and Challenges to Integrating Renewable Energy in Electricity Grids

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Climate Change, Climate Science and Economics: Prospects for an Alternative Energy Future (Springer 2013)

Alberta-BC Power Grid

- Promise: Alberta and BC cooperation in the electricity sector could greatly reduce CO_2 emissions
  - Large rents from trade – Alberta's excess generation at night from wind and coal plants could be stored behind BC dams
  - BC buys Alberta power for pennies per kWh at night and sells it back at $s per kWh during peaks
  - Alberta has prevented further upgrades of intertie
- Problem: Alberta's electricity operations are open to the public; those of BC are a mystery

Things we have been studying:

1. Can electricity trade between Alberta and BC make wind energy more attractive?
   - Wind is intermittent → Gas and/or diesel plants are needed to compensate for intermittency.
   - Trade allows Alberta to use BC's hydro reservoirs and operation of dams to store excess wind generation.
2. How do varying levels of carbon taxes change Alberta's optimal generation mix?
3. Is nuclear power an attractive alternative energy source?

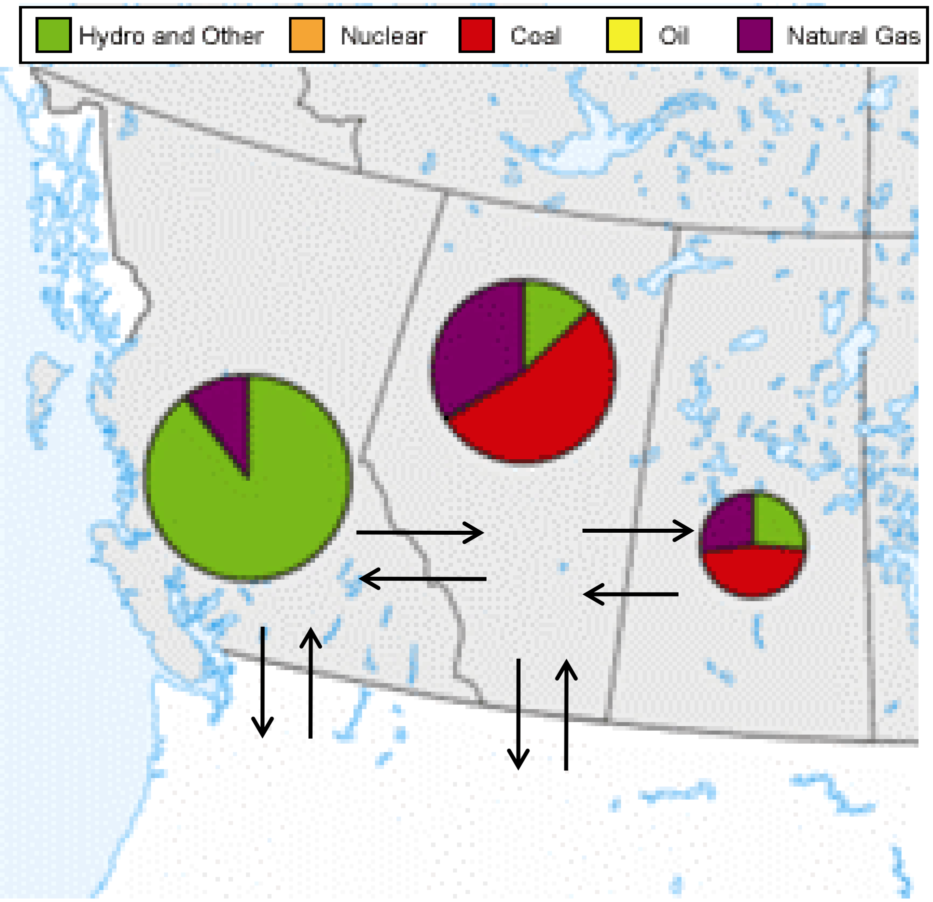
Additional Background

Alberta's Electricity System

- Deregulated market, transactions coordinated by AESO

-Trade based on price differentials: primarily reacts to the Mid-Columbia Electricity Price Index (MidC)

- Marginal fuel type: Coal, natural gas



BC's Electricity System

- Regulated market

- Dominated by hydroelectricity (~92-96%)

Saskatchewan's Electricity System

- Regulated market

- Dominated by coal and gas, some hydro & wind

MidC

- Marginal fuel type: hydro

Interties

- BC-Alberta intertie is rated at 1,000 MW into BC (but operates at only 650 MW) and rated at 1,200 MW into Alberta (but tends to operate below 750 MW)
  - We assume 750 MW and 1500 MW (both directions)
- BC has an intertie with the U.S. rated at 3,150 MW capacity (2,850 MW west side, 300 MW east side), while the import capability is 2,000 MW
- Alberta has an intertie with the U.S. rated at 300 MW in both directions, and an intertie with Saskatchewan rated in both directions at 153 MW

Comparison of generating mixes, 2015

ALBERTA

Generation type	Maximum capacity (MW)
Coal	6,271
Closed-cycle gas	1,716
Simple-cycle gas	944
Cogeneration gas	4,483
Hydro	894
Wind	1,434
Biomass & other	409
TOTAL	**16,151**

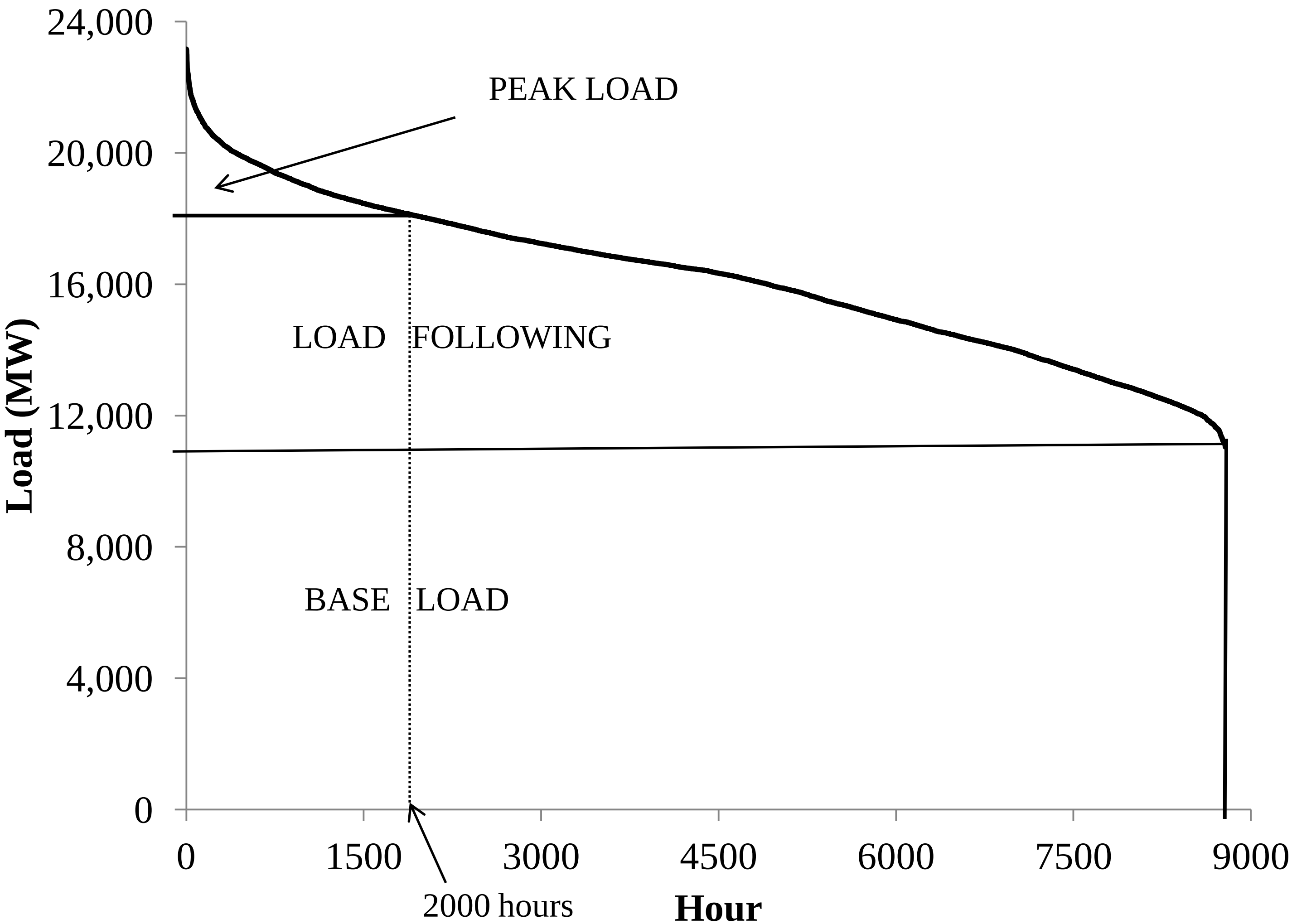
http://ets.aeso.ca/ets_web/ip/Market/Reports/CSDReportServlet
[accessed January 6, 2015]

British Columbia

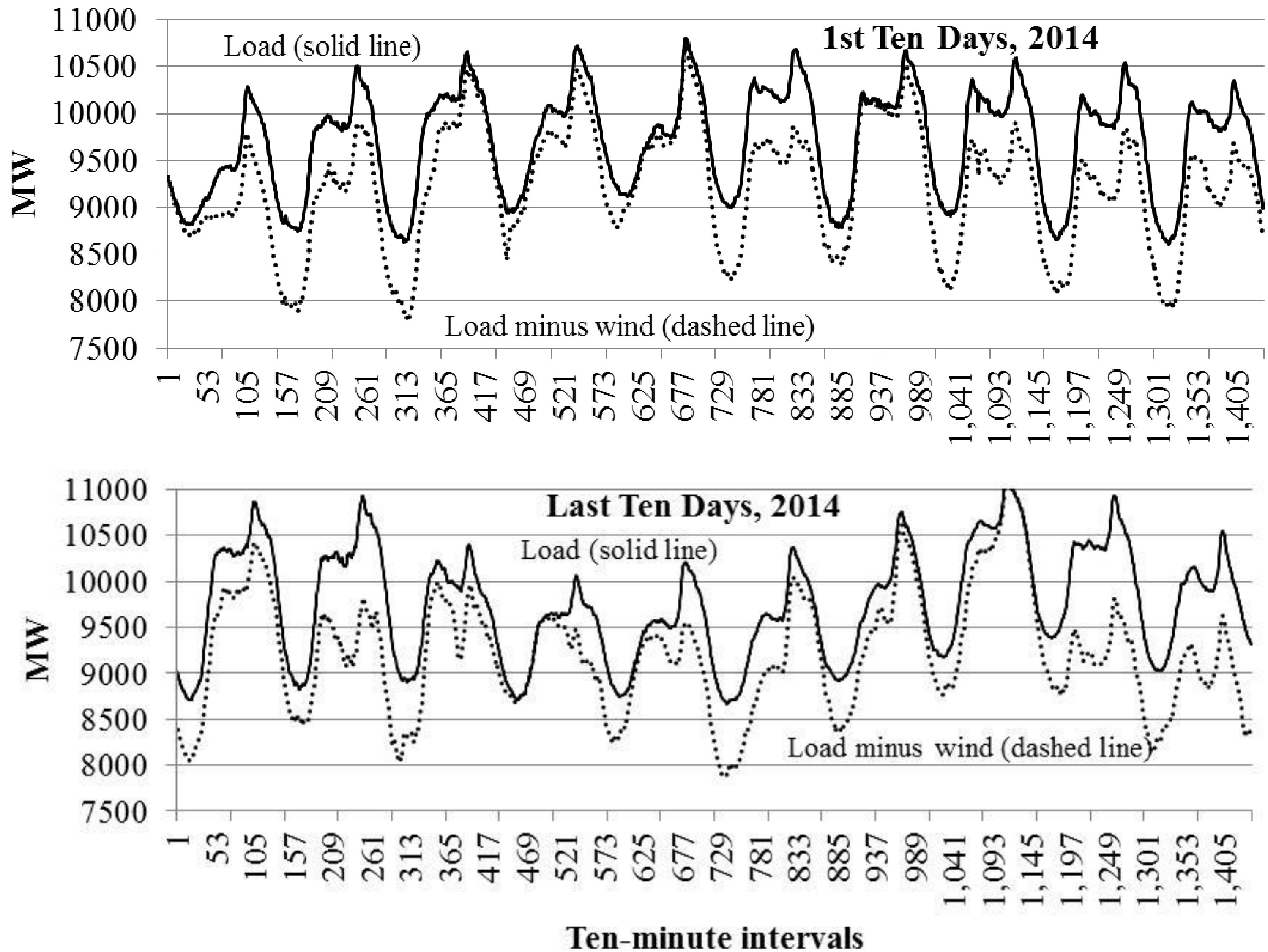
Generation type	Maximum capacity (MW)
Coal	-
Gas	1,464
Hydro	13,649
Wind	248
Biomass & waste heat	369
TOTAL	**15,730**

http://en.wikipedia.org/wiki/List_of_generating_stations_in_British_Columbia
[accessed January 12, 2015]

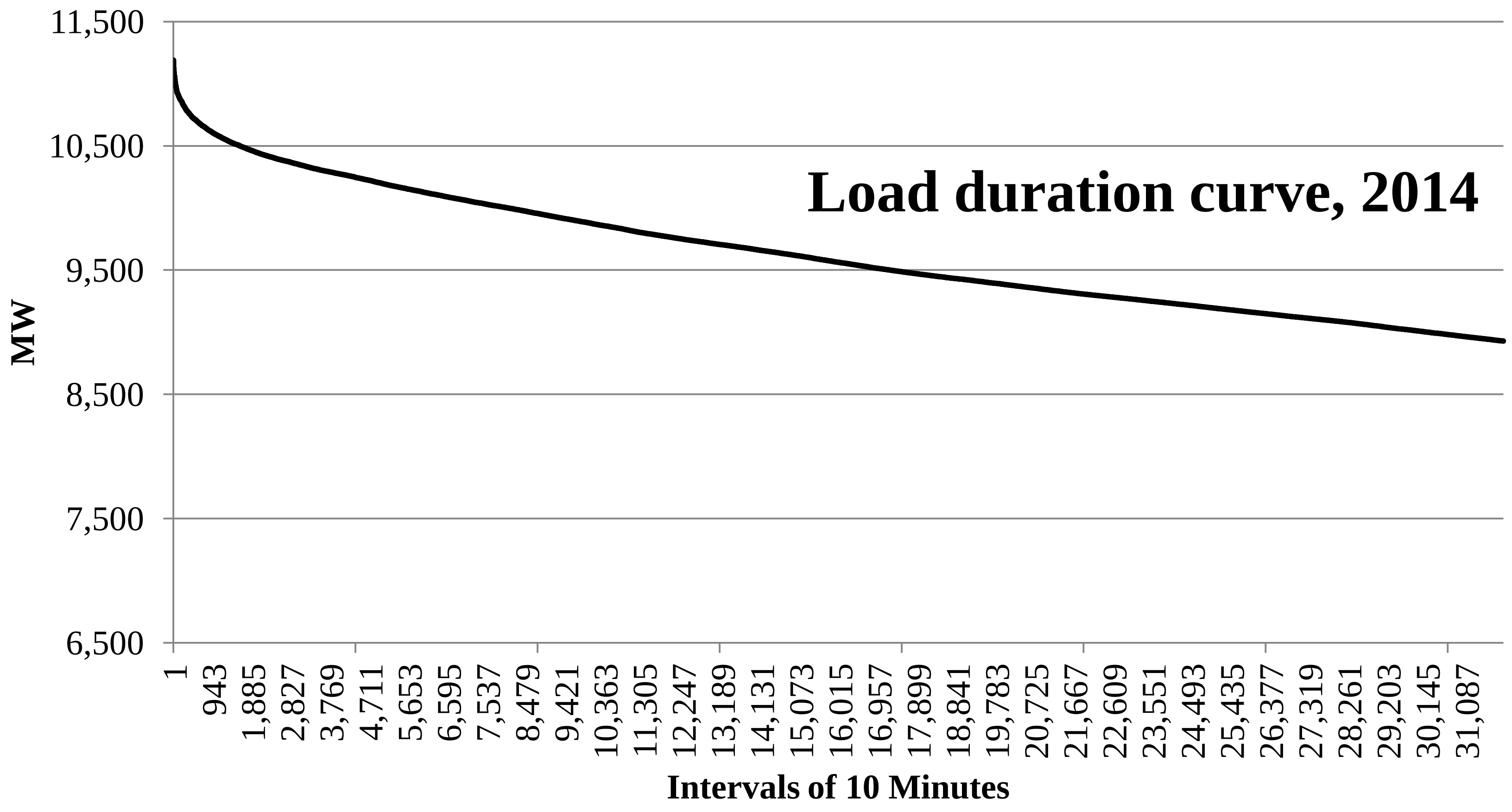
AB: 0 wind on January 6, 14:23, but
646 MW (45%) on January 12, 16:34



24,000
20,000
16,000
12,000
8,000
4,000
0
Load (MW)
PEAK LOAD
LOAD FOLLOWING
BASE LOAD
0
1500
3000
4500
6000
7500
9000
2000 hours
Hour

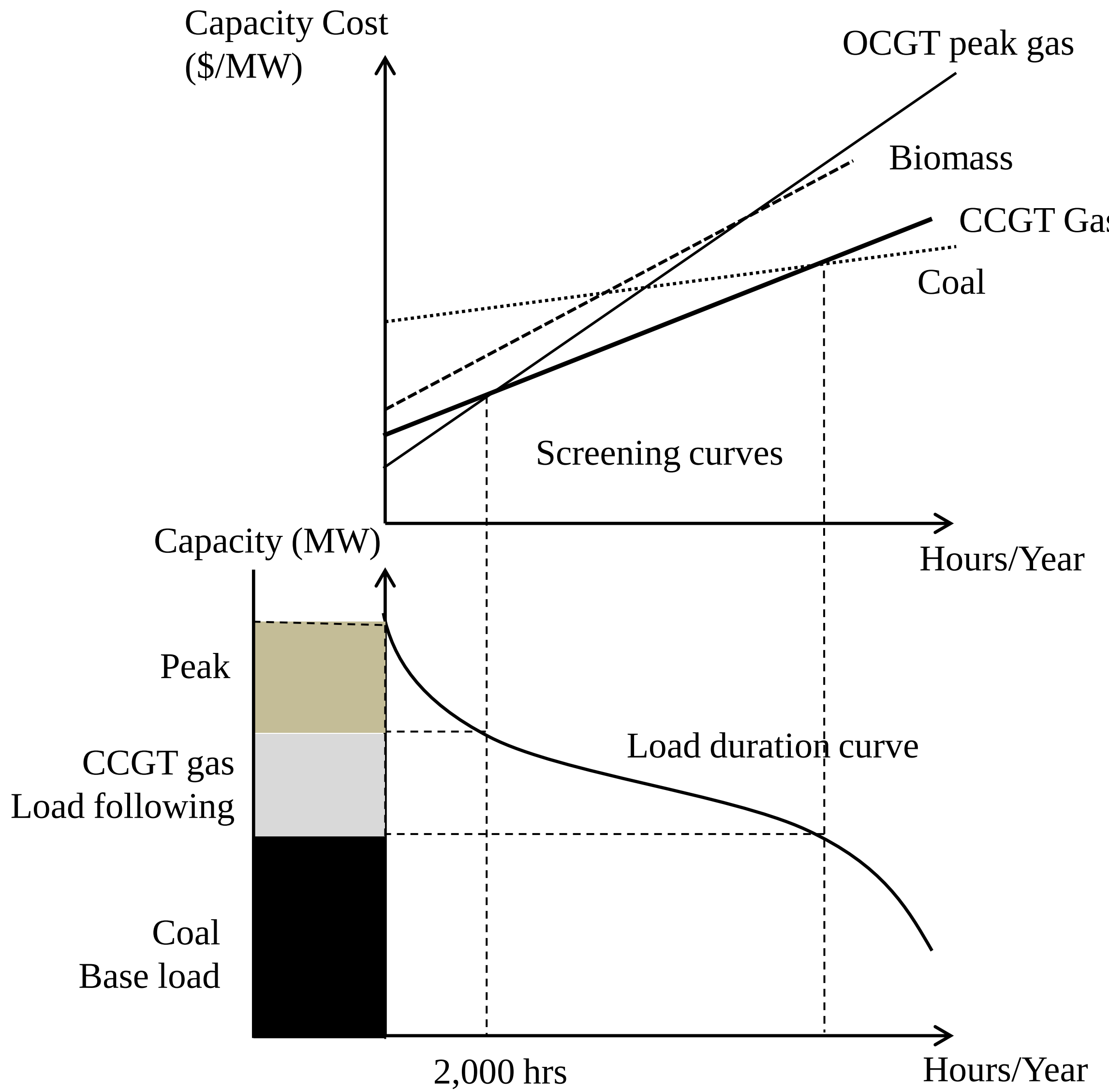


Alberta Load and Wind Generation at 10-minute Intervals, First and last 10 Days in 2014 (Wind below 100MW Jan 1, 3, 5, 7; Capacity factors = 33.5% and 38.1%)

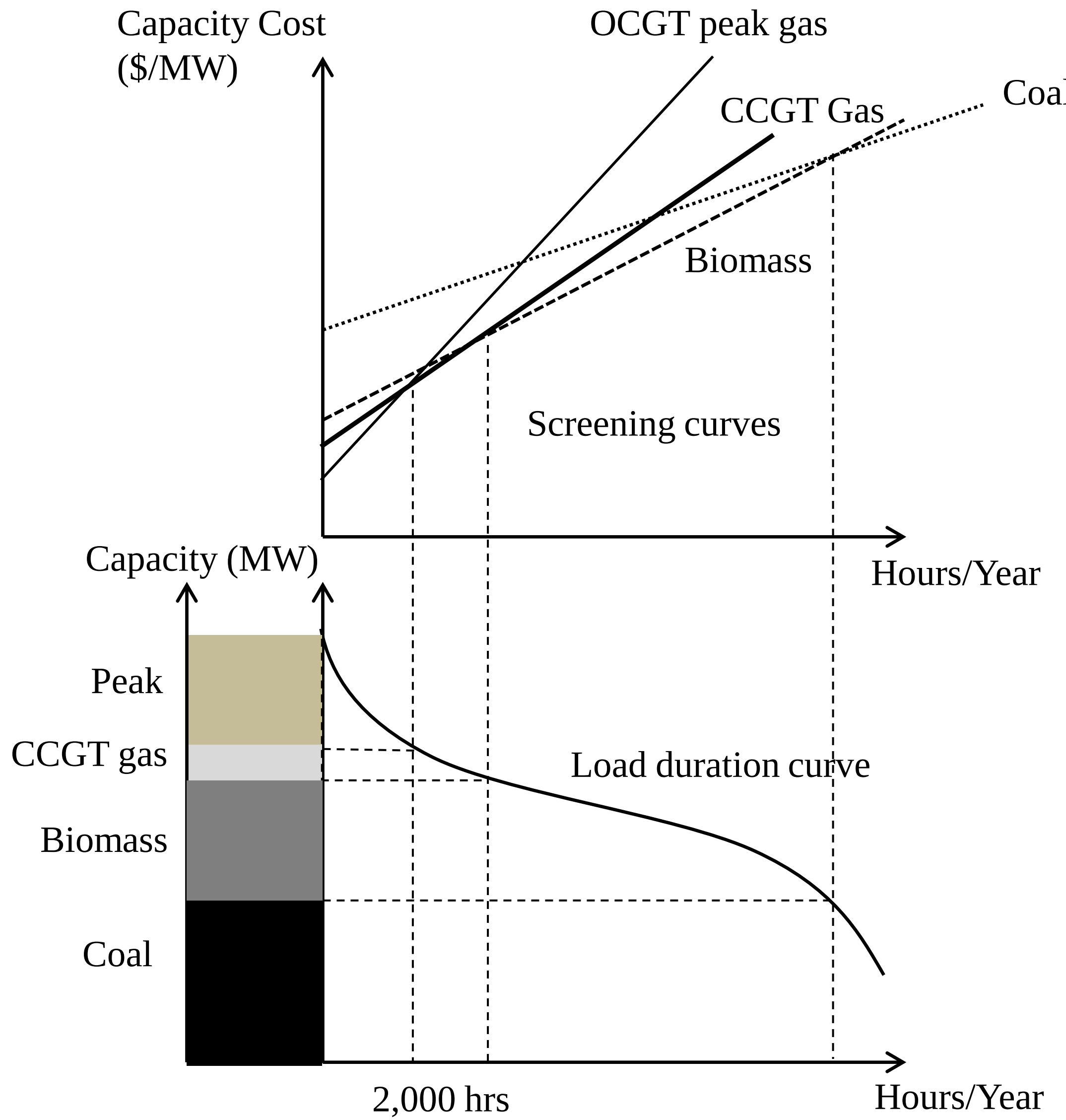


Load duration curve for Alberta, 2014 (Min = 4461 MW; Max = 11,192 MW)

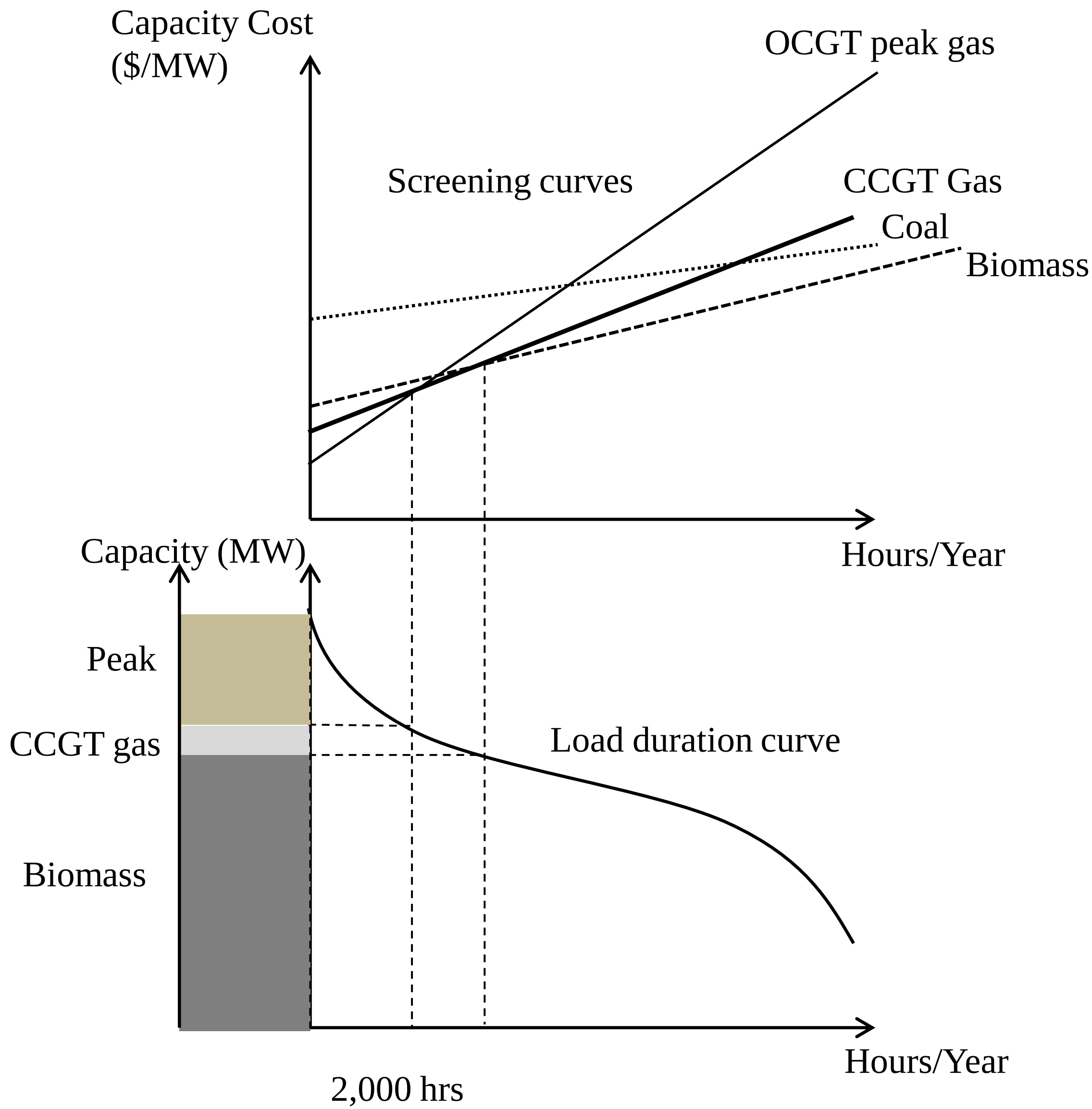
Base Scenario



Tax Scenario



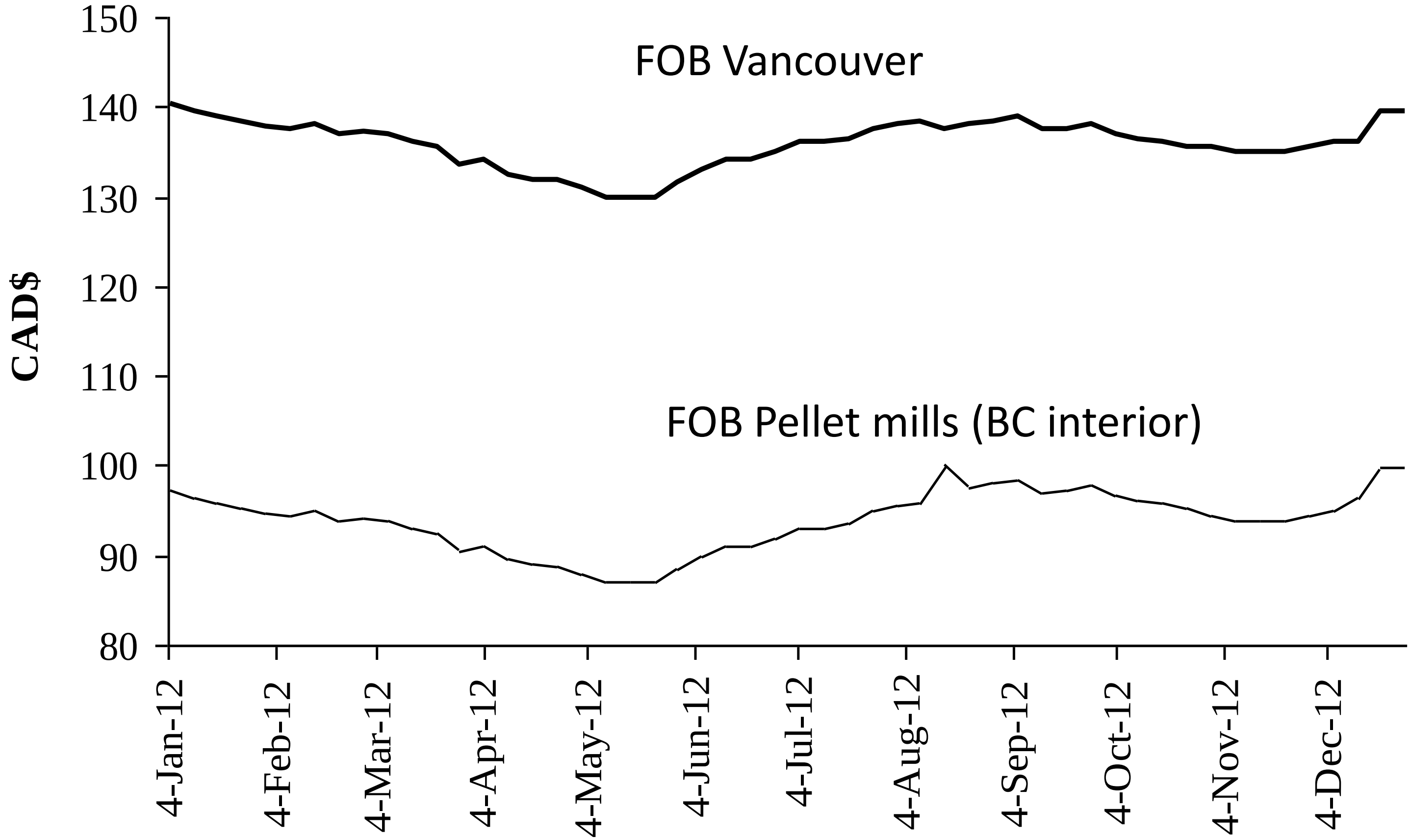
Feed-in Tariff



Co-firing Wood Pellets in Alberta Coal Plants

- BC has 1,875 Mt of wood pellet production capacity (2012), 65% of Canadian total selling mainly into Europe (840 Mt to UK; 240 Mt to NL)
- 2011 amendment to Canadian Environmental Protection Act (1999) lowered emissions intensity for new or refurbished thermal power plants to 375tCO_2/GWh, later raised to 420tCO_2/GWh (U.S. standard 500 tCO_2/GWh)
- Johnston & van Kooten (*Energy Economics* 2015) examined the costs

Wood pellet prices (C$ per tonne), Weekly 2012



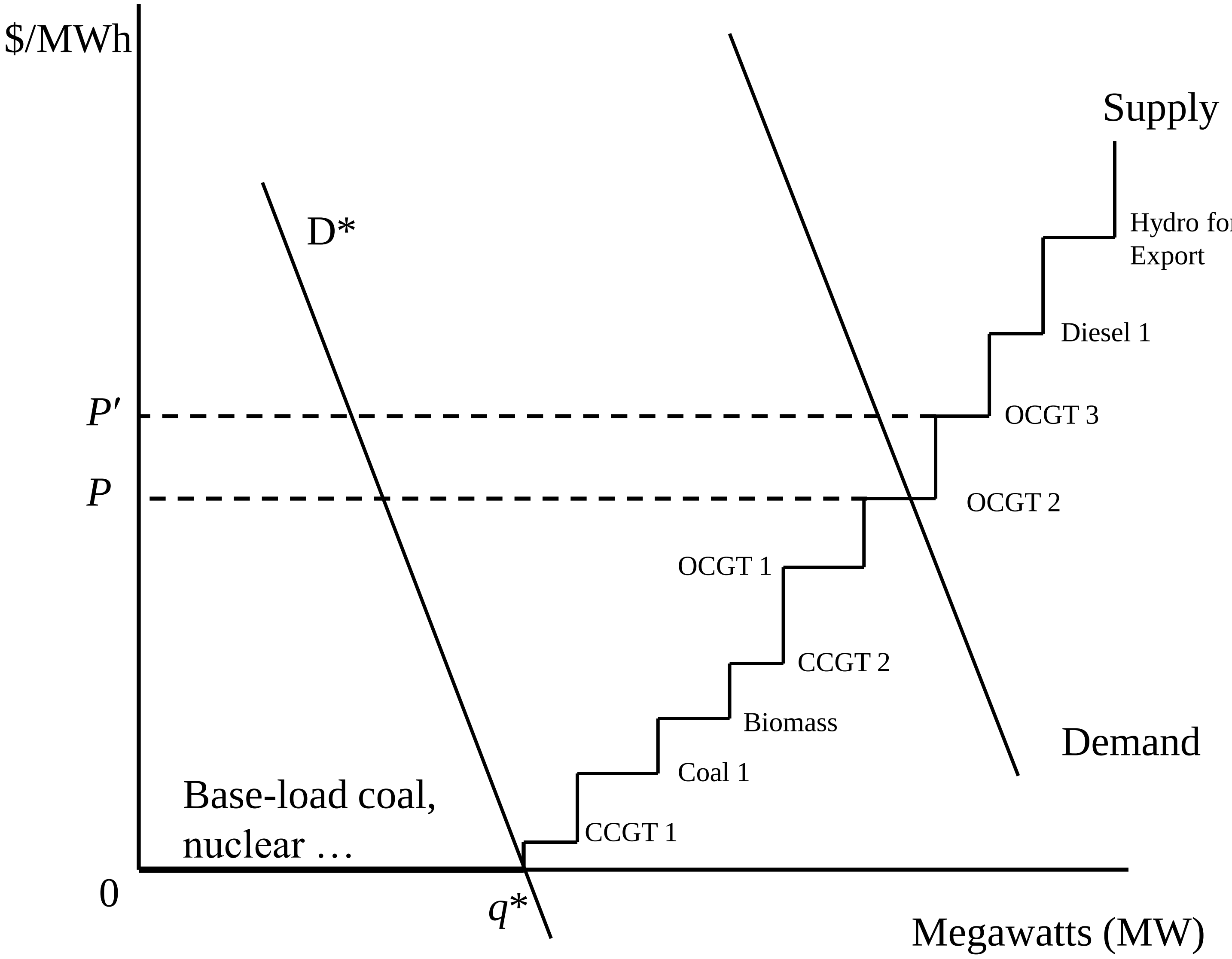
Installed coal-fired capacity in Alberta, 2012

Station		Capacity	Completed	CO_2	NOx	SO_2
Unit		(MW)	(Year)	(t/GWh)	(t/GWh)	(t/GWh)
Battle River						
	3	150	1969	931	1.9	5.5
	4	150	1975	882	1.8	5.4
	5	389	1981	1,176	2.4	5.0
Genesee						
	1	410	1989	980	2.0	2.0
	2	410	1994	980	2.0	2.0
	3	495	2005	676	0.7	0.9
HR Milner						
	1	158	1972	1,103	2.3	3.0
Keephills						
	1	396	1983	1,103	2.3	2.1
	2	396	1983	1,127	2.3	2.1
	3	495	2011	676	0.7	0.6
Sheerness						
	1	390	1986	1,127	2.3	6.4
	2	390	1990	1,127	2.3	6.4
Sundance						
	3	408	1976	980	2.0	1.8
	4	386	1977	931	1.9	1.8
	5	386	1978	833	1.7	2.0
	6	386	1980	784	1.6	2.0

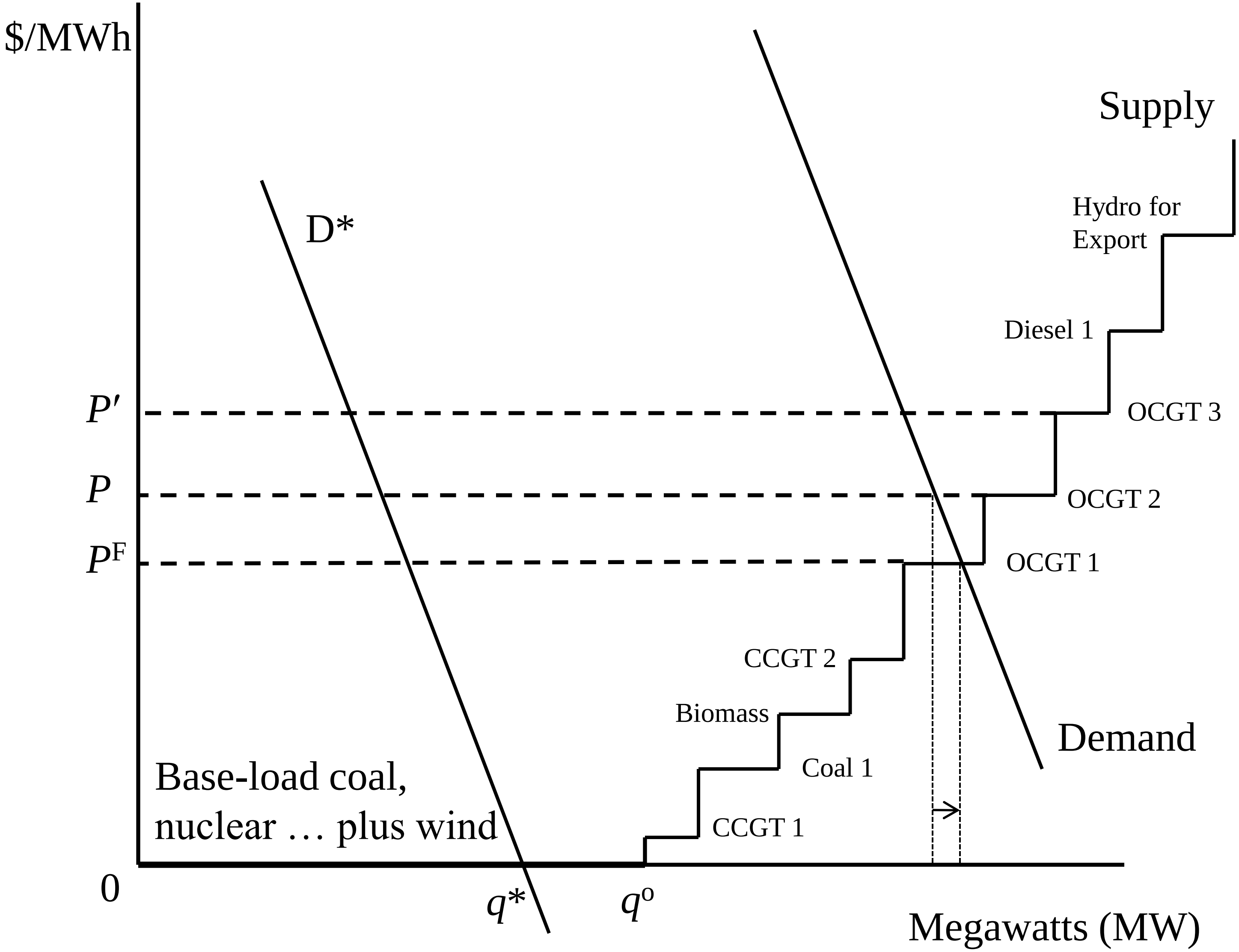
Total Emissions and Abatement Costs under 5% and 15% Co-fire Scenarios

Scenario		5% Co-fire			15% Co-fire	
	Policy	Emissions (Mt CO_2)	Average abatement cost ($/t$CO_2$)		Emissions (Mt CO_2)	Average abatement cost ($/t$CO_2$)
Carbon tax ($/t$CO_2$)						
	$0	56.5	n.a.		56.5	n.a.
	$50	45.6	262.18		42.6	253.06
	$100	32.2	323.30		33.5	318.08
	$150	29.9	348.41		29.9	348.41
	$200	29.9	410.99		29.9	410.99
Feed-in tariff ($/MWh)						
	$0	56.5	n.a.		56.5	n.a.
	$30	56.5	n.a.		56.4	240.33
	$60	56.5	n.a.		49.8	287.48
	$90	54.3	715.74		49.8	321.48
	$120	54.3	749.39		49.8	355.37

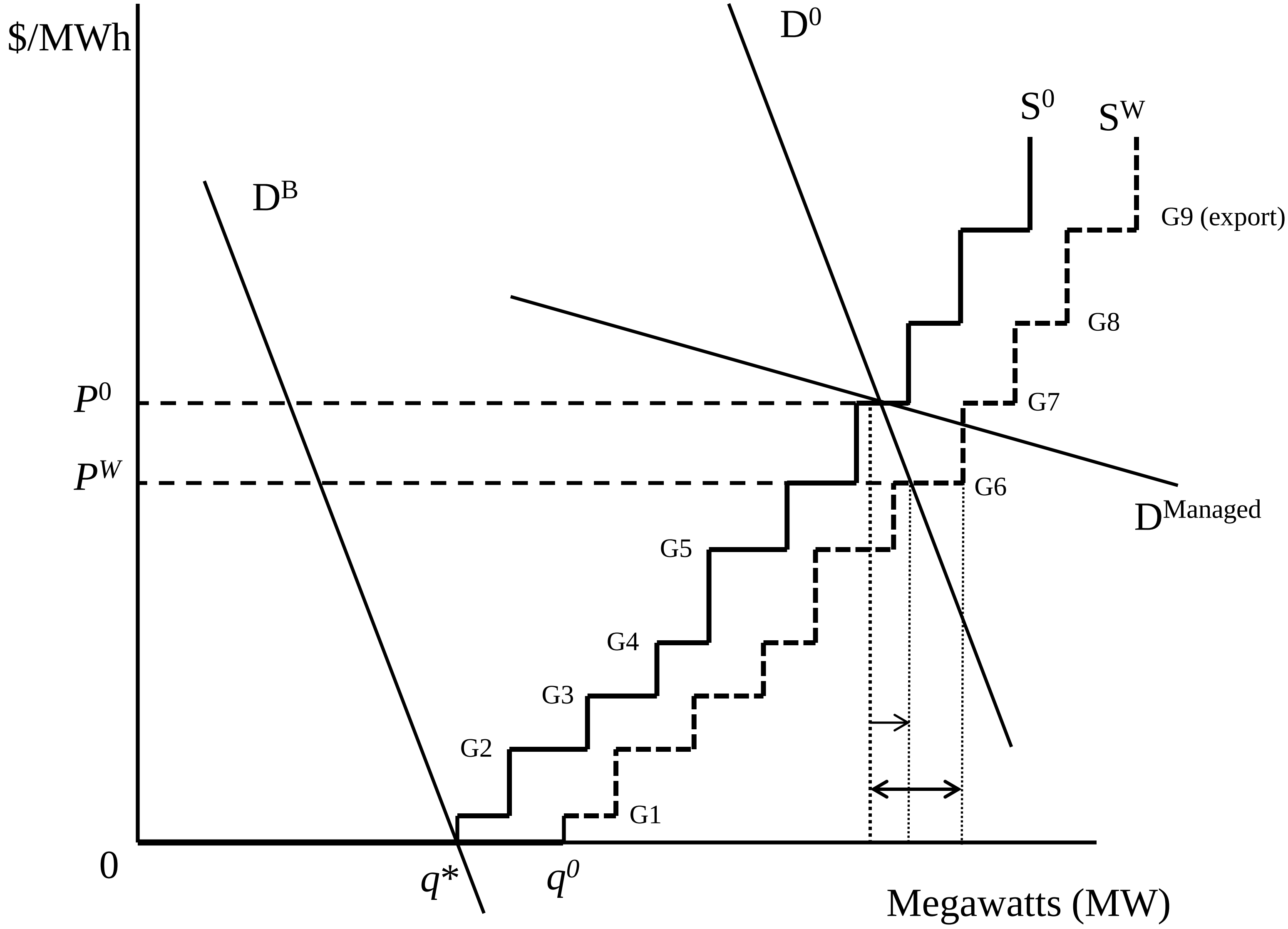
Market Merit Order (no wind)



Market Merit Order (with wind)



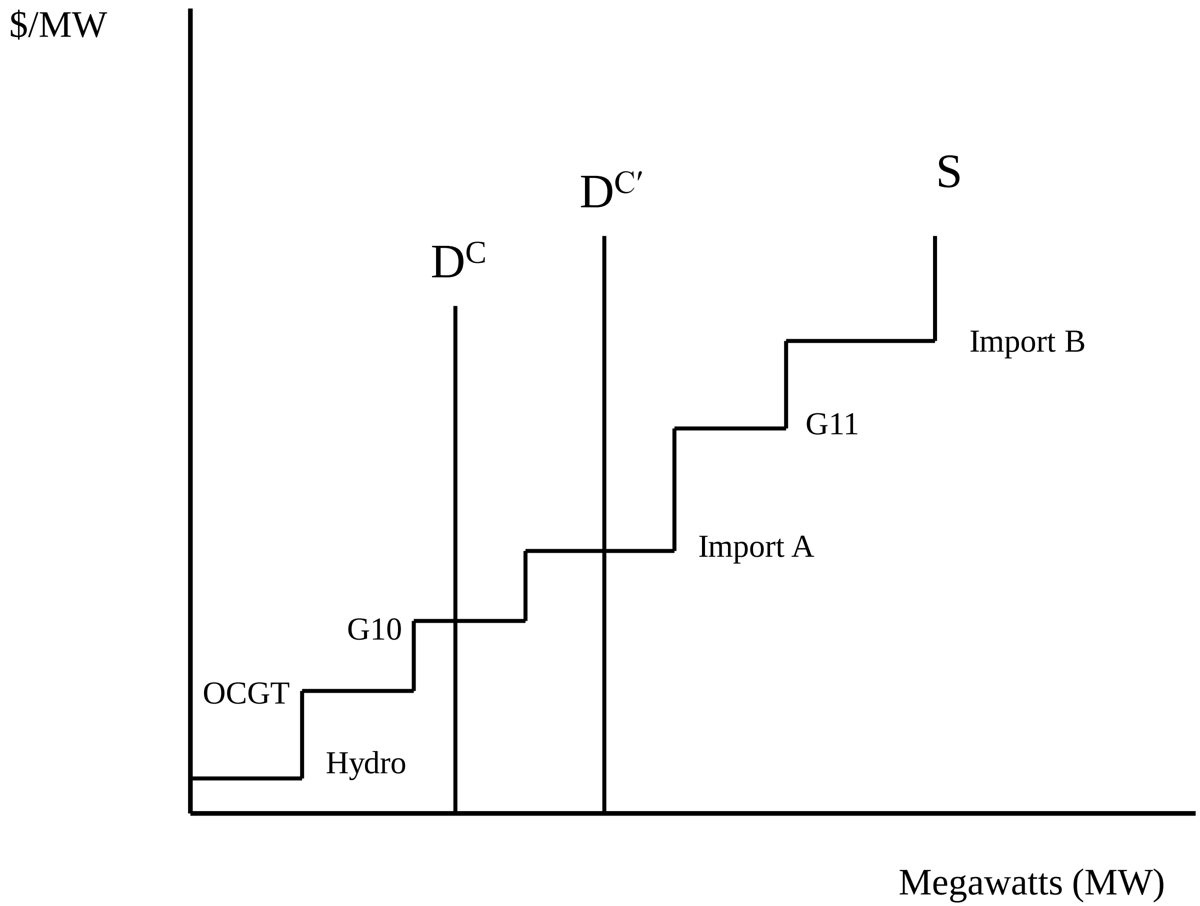
Market Merit Order (variable wind)



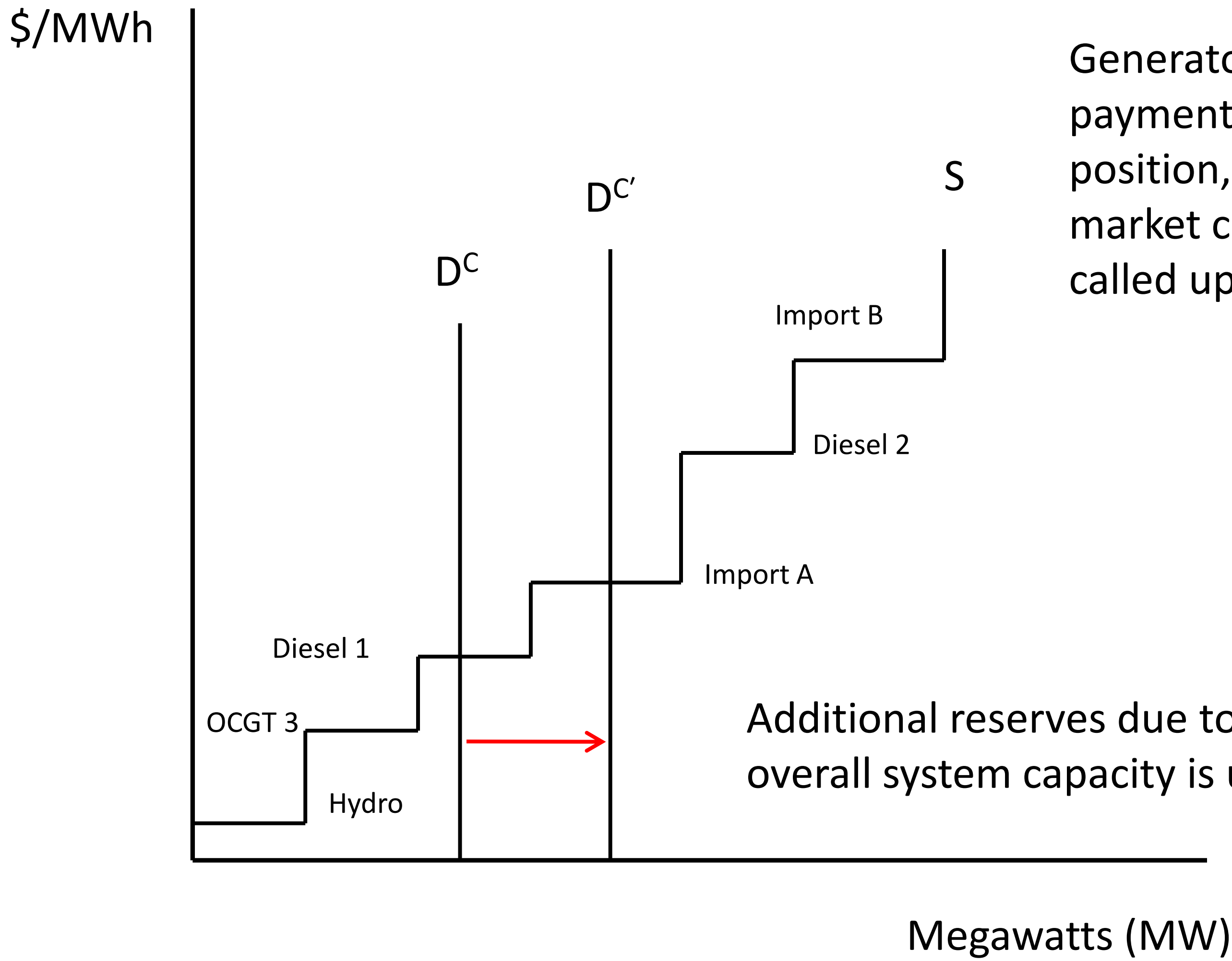
The Reserve Market

- Reserves consist of
  - Regulating reserves: deal with short-term (seconds up to 10 minute) fluctuations in load are met
    - Base-load plants have a little bit of wiggle room
    - Gas/diesel generators operating at part capacity
    - Standby reserves (spinning reserves)
  - Load following reserves deal with anticipated changes in load over an hour
  - Contingent reserves: Western Electrical Coordinating Council (WECC) rules require sufficient reserves to meet failure of largest unit on line plus some % of thermal generation
- Generators bid into the reserve market

Reserve Market



Market for Regulating and Contingent Reserves



Generators receive payment for reserve position, plus the market clearing price if called upon.

Additional reserves due to wind, even if overall system capacity is unchanged.

Managing Wind Resources

- Difficult to integrate wind into electricity grids
  – Wind is variable and intermittent
  – Too little or too much wind → output drops suddenly to zero.
- **Capacity Factor**:

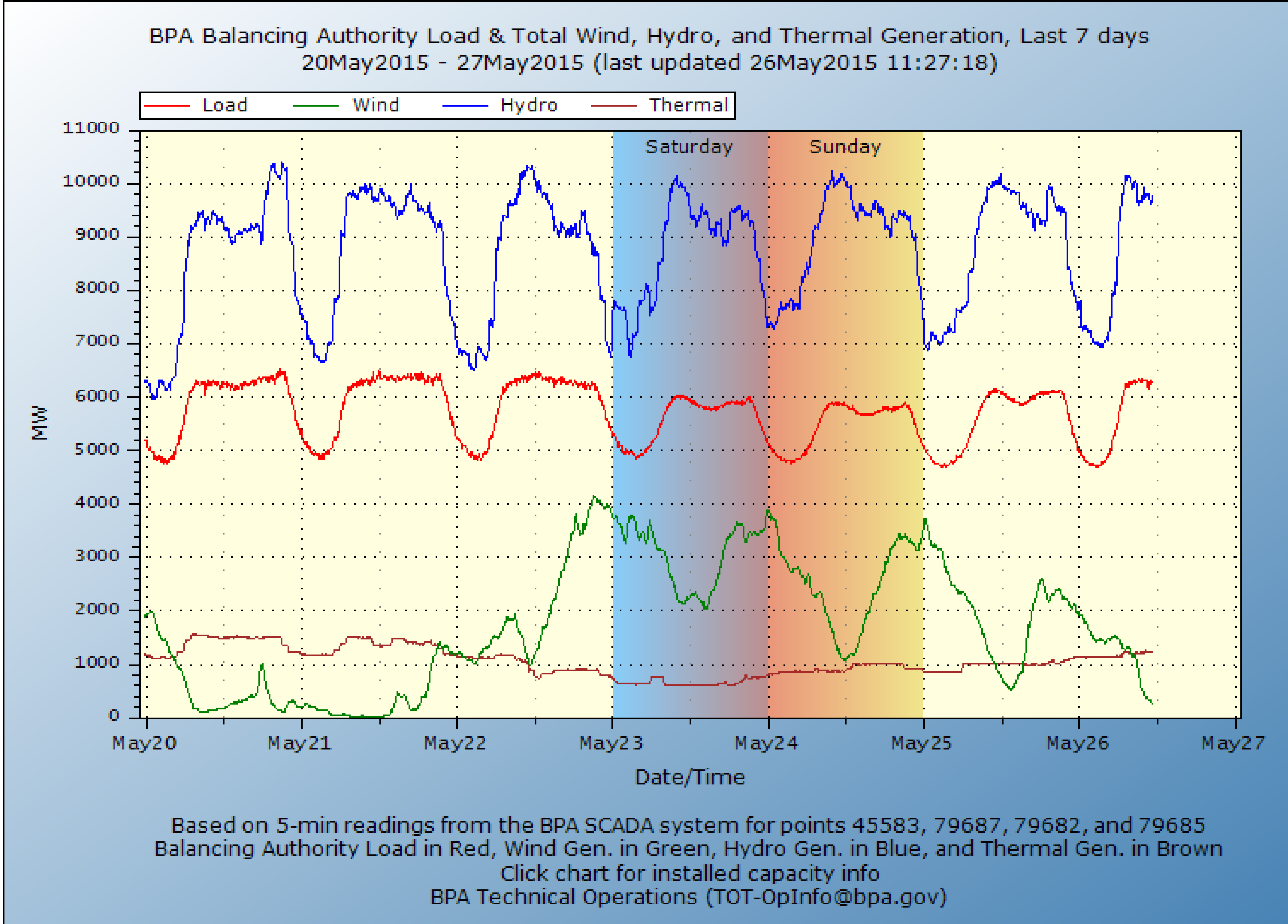
  CF = Actual generation in one year / (Rated Capacity × 8760 hrs)

  – Capacity factors for wind rarely exceed 20-25%
  – CFs for nuclear power = 95%
  – CFs for coal and CCGT = 85-90%

- **Wind penetration** = Wind capacity / Non-wind capacity

  Alternative definition:

  Wind penetration = Wind generation capacity / Peak load



Source: http://transmission.bpa.gov/business/operations/Wind/baltwg.aspx

Model

AESO maximizes profit subject to load, trade, economic and engineering constraints:

$$\Pi = \sum_{t=1}^{T}\left[\begin{array}{l} P_{A,t}D_t - \sum_i \left(OM_i + b_i + \tau\varphi_i\right)Q_{i,t} + \\ \qquad \sum_{k\in[BC,SK,MidC]}\left(\left(P_{A,t} - P_{k,t} - \delta_k\right)M_t + \left(P_{k,t} - P_{A,t} - \delta_k\right)X_t\right) \end{array}\right] - \sum_i \left(a_i - d_i\right)\Delta C_i$$

P = price, D = demand or load, OM = operating costs, b = fuel costs,
τ = carbon tax, φ = conversion factor (fuel into CO_2) on per MWh basis,
Q = power production (MWh),
M = imports, X = exports,
a = per unit cost of adding capacity (\$/MW),
d = per unit cost of decommissioning capacity (\$/MW),
C = capacity (MW)

Demand is met every hour:

$$\sum_i Q_{t,i} + \sum_{k \in [BC,SK,MID]} \left(M_{k,t} - X_{k,t}\right) \geq D_t, \forall t = 1,\dots,T$$

Ramping-up constraint:

$$Q_{t,i} - Q_{(t-1),i} \leq \frac{C_i}{R_i}, \forall i, t = 2,\dots,T$$

Ramping-down constraint:

$$Q_{t,i} - Q_{(t-1),i} \geq -\frac{C_i}{R_i}, \forall i, t = 2,\dots,T$$

Capacity constraints:

$$Q_{t,j} \leq C_i, \forall k, t$$

Import transmission constraint:

$$M_{k,t} \leq TRM_k, \forall k, t$$

Export transmission constraint:

$$M_{k,t} \leq TRK_k, \forall k, t$$

Non-negativity:

$$Q_{t,i}, M_{k,t}, X_{k,t} \geq 0, \forall t, i, k$$

Background Data

Asset	Years to build	Construction Costs ($/kWh) Overnight	Decommission as % of overnight	Variable Costs ($/MWh) O&M	Fuel	Emissions (tCO_2/MWh)	Ramp rate % of capacity per hour[c]
Nuclear	7	5000.0	42.8	3.1	14.0	0.020	0.010
Biomass	2	1280.0	22.2	6.6	92.7	0.250	0.025
Coal	4	1777.0	24.0	6.6	15.6	0.850	0.025
Wind	3	1300.0	n.a.	0.2	0.0	0.015	n.a.
Hydro	4	2100.0	n.a.	10.0	1.01	0.009	n.a.
CCGT	3	965.4	10.0	4.9	43.5	0.450	0.075
OCGT	2	694.8	10.0	14.7	48.2	0.450	0.125

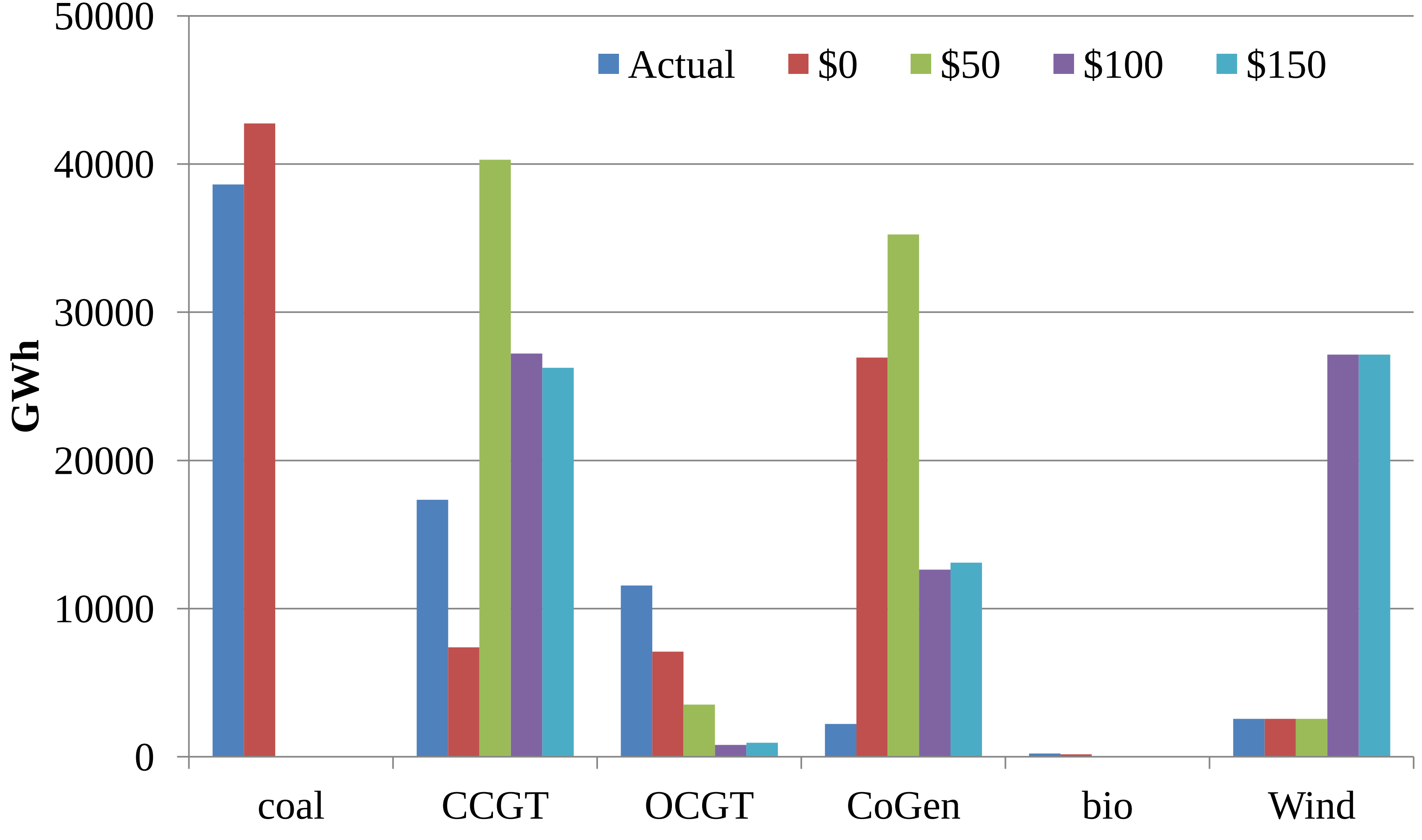
Source: Various including The Economist, Conrad Fox, AESO, etc.

Load and Price Data, 2014

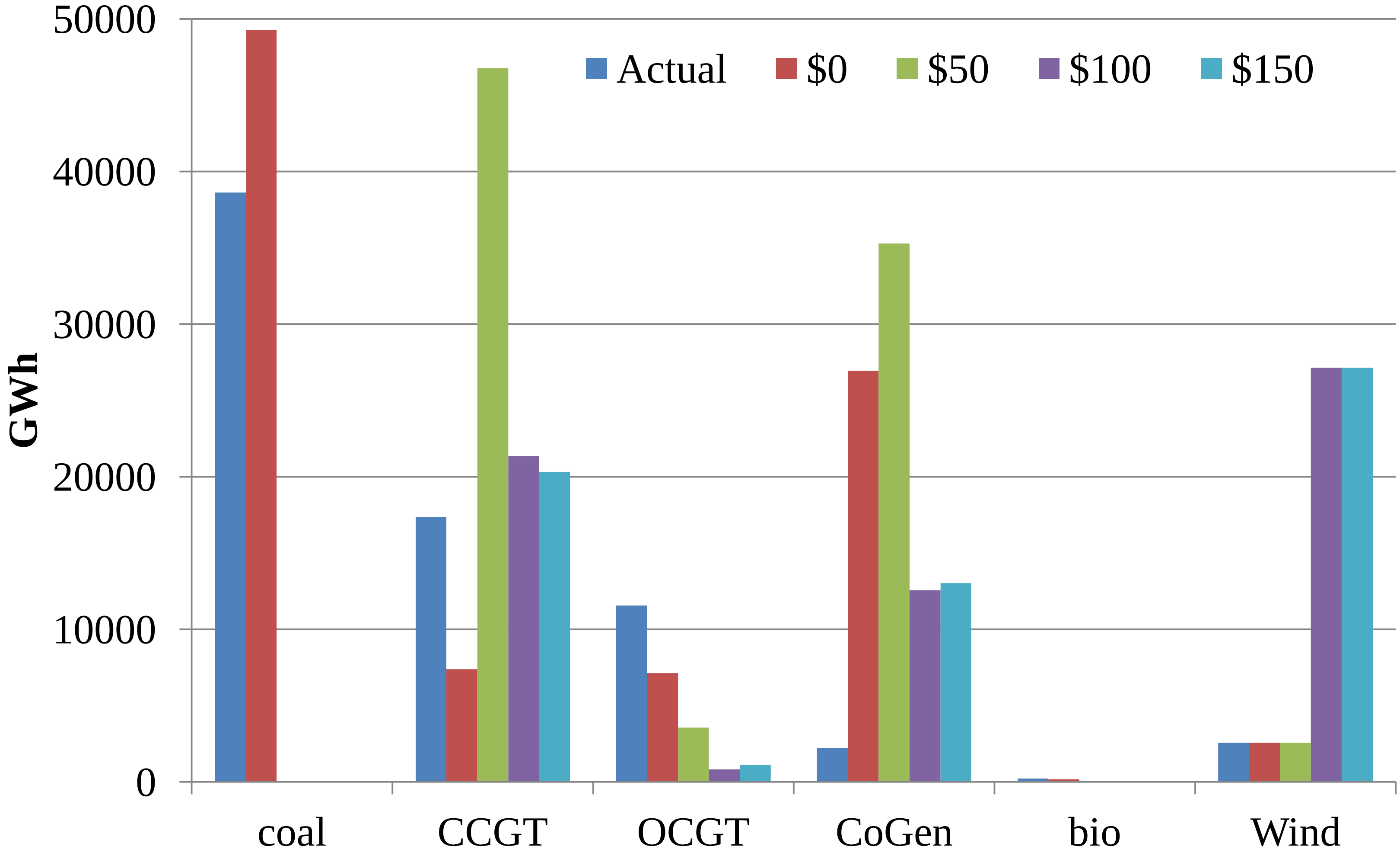
	Alberta	Saskatchewan	British Columbia	Mid-Columbia
	Load (MW)			
Average	9,128	–	7,061	21,940
Maximum	11,192	3,379(2013)	10,672	30,246
Minimum	4,461	–	4,817	13,453
	Generation (GWh)			
	79,962	22,129(2012)	61,850	192,195
	Energy Price ($/MWh)			
Average	49.41	55	50	38.82
Maximum	999.99	–	-–	216.32
Minimum	7.88	–	–	14.30

Alberta's system ramps at 600 MW per hour; BC 200 MW per minute!

AB-BC Intertie Capacity = 750 MW (no nuclear; wind maximized)

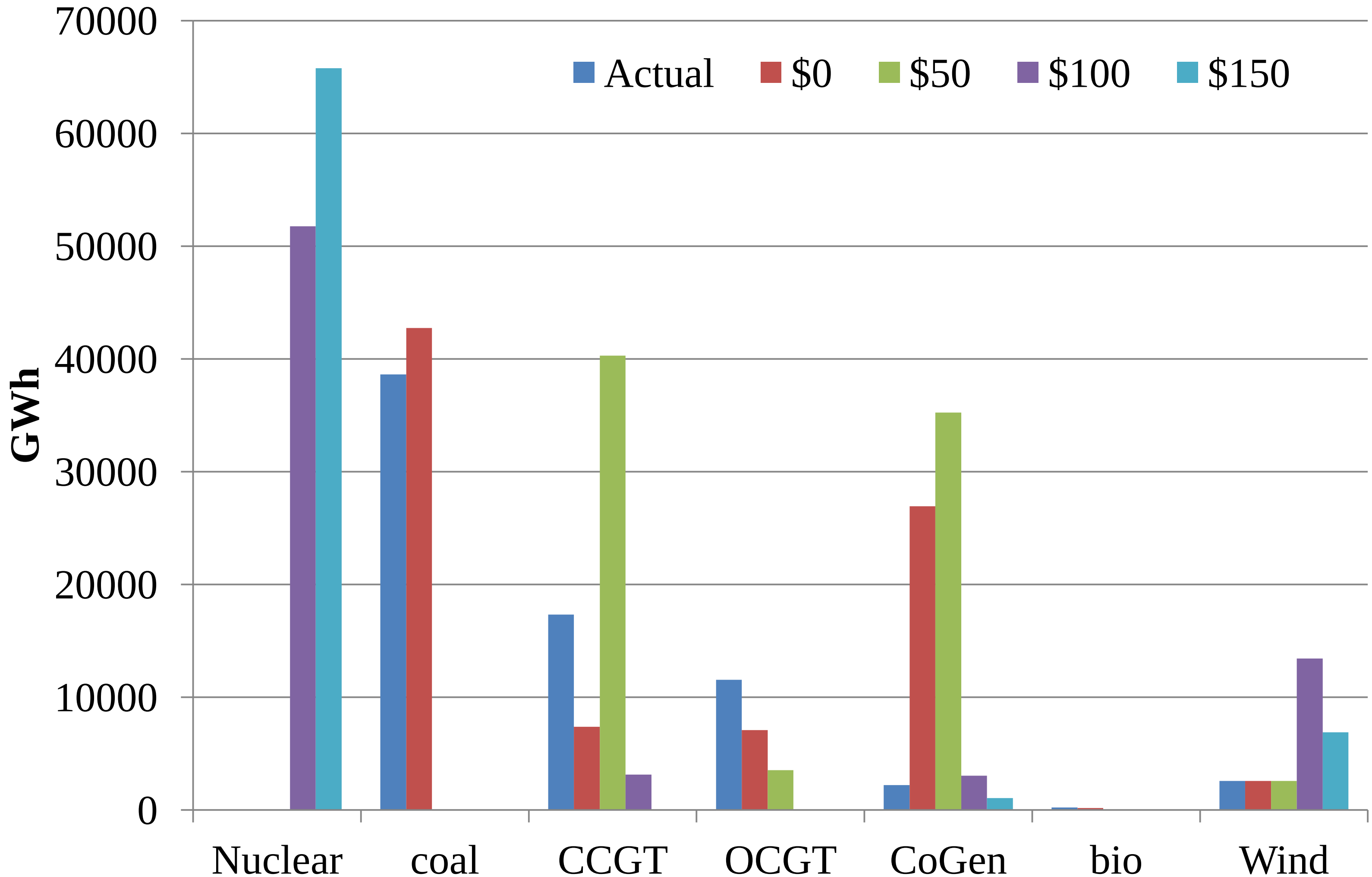


AB-BC Intertie Capacity = 1500 MW (no nuclear; wind maximized)

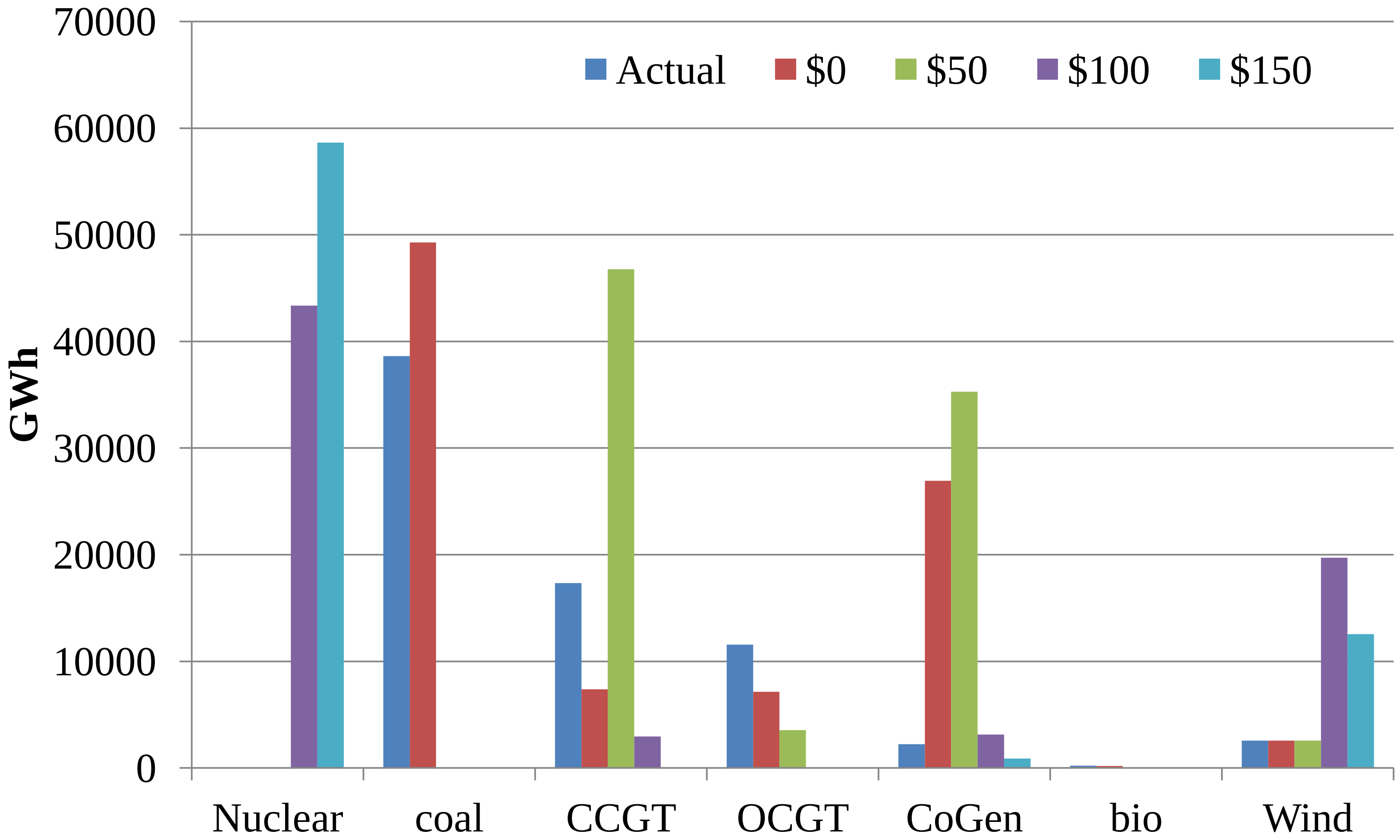


Notice higher use is made of the intertie to store base load generation at low carbon prices

AB-BC Intertie Capacity = 750 MW (nuclear)



AB-BC Intertie Capacity = 1500 MW (nuclear)



Wind is less than its maximum; intertie is used to regulate base load capacity

Annual Emissions (Mt CO_2)

Price of carbon	No nuclear Intertie capacity 750 MW	No nuclear Intertie capacity 1500 MW	Nuclear Intertie capacity 750 MW	Nuclear Intertie capacity 1500 MW
$0	66.74	73.00	66.74	73.00
$50	47.09	50.86	47.09	50.86
$100	24.32	20.91	4.88	4.78
$150	24.17	20.74	2.06	1.90

Wind and switching to natural gas can reduce emissions by two-thirds or more; nuclear power along with storage can reduce emissions by upwards of more than 95%

Movement along the Interties: Net Alberta Exports (GWh)

Price of carbon	No nuclear Intertie capacity			Nuclear Intertie capacity	
	750 MW	1500 MW		750 MW	1500 MW
$0	10,177	16,747		10,177	16,747
$50	4,910	11,448		4,910	11,448
$100	-8,948	-14,810		-5,409	-7,619
$150	-9,270	-15,189		-3,048	-4,698

Nuclear power comes into the optimal grid when price of carbon is $\$100/tCO_2$ or more; less power is imported with a higher capacity intertie as more nuclear and wind power is exported.

Optimal Capacity by Generator Type (MW)

	Nuclear	Coal	CCGT	OCGT	Wind
Initial	0	6550	3800	1500	805
No trade between Alberta and BC					
$0	0	4536	3800	1500	805
$50	0	0	7550	2290	805
$100	0	0	8020	1820	805
$150	0	0	7980	1855	6365
$200	0	0	8075	1765	11,380
150(Nuke)	5945	0	3800	90	805
$200(Nuke)	6910	0	3015	0	805
Alberta-BC trade along 1300MW-capacity intertie					
$0	0	4100	3800	1500	805
$50	0	0	7565	1500	805
$100	0	0	7970	265	805
$150	0	0	6370	1865	9940
$200	0	0	6630	1605	11,500
150(Nuke)	2810	0	3800	1630	805
$200(Nuke)	6330	0	1965	0	805

Source: van Kooten et al., 2013. *Am J of Agric Economics* 95(2)

Country	Projects	MW
China	1,522	84,232
India	830	14,517
Mexico	30	4,276
Brazil	68	5,519
Chile	19	1,653
Uruguay	15	707
South Africa	16	2,451
South Korea	13	377
Argentina	11	665
Morocco	7	603
Dominican Republic	6	230
Pakistan	8	405
Costa Rica	6	197
Cyprus	6	268
Philippines	5	321
Panama	5	674
Kenya	5	527
Vietnam	5	188
Sri Lanka	5	51
Thailand	3	267
22 other countries	43	2,363

TOTAL	2,628	120,751

CDM wind projects, May 1, 2015

Conclusions

- At low carbon prices, gas replaces coal
- Existence of an AB-BC intertie implies Alberta will try to export more base load at low carbon prices and import more hydroelectricity as price of carbon increases
- As the carbon price rises, large investments in wind are incentivized because of available wind sites with high capacity factors
  - Location of population, transmission, etc. imply it is not always optimal to choose on basis of highest CFs (McWilliam et al., 2012. *Renewable Energy* 48)
- Intertie capacity to BC facilitates intermittent wind because of storage capacity in BC hydro reservoirs

Conclusions (cont)

- Increased intertie capacity also facilities larger, cheaper base-load thermal plants that take advantage of BC storage to keep output above base load.
- Nuclear energy reduces need for wind
  - Nuclear takes advantage of storage in BC so capacity can exceed base load requirements depending on intertie capacity
  - With nuclear generation, emissions can be reduced by 95% or more; not possible with intermittent wind since reserves are needed when wind goes ‘missing’ for long periods
  - Canadian target of 30% reduction in CO_2 emissions from 2005 base by 2030 will require some wind but primarily nuclear energy, or alternatively carbon capture and storage (CCS)
    - Scott, D.S., 2007. *Smelling Land. The Hydrogen Defense against Climate Catastrophe*. Can Hydrogen Assoc & Natural Resources Canada.
    - Long, J.C.S. and J. Greenblatt, 2012. *Issues in Science & Tech.* Spring