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Energy 2020

"Energy 2020 is an integrated, multi-region, multi-sector North American model that simulates the supply, price and demand for all fuels. The model can determine energy output and prices for each sector, both in regulated and unregulated markets. It simulates how such factors as energy prices and government measures affect the choices that consumers and businesses make when they buy and use energy. The model's outputs include changes in energy use, energy prices, greenhouse gas emissions, investment costs and possible cost savings from measures, which are used to identify the direct effects stemming from greenhouse gas reduction measures" (Environment Canada 2013).

Energy 2020 is based on a representation of all existing power plants in Canada and the US. It models Ontario, Québec and Alberta as well as their interconnections with US states and other Canadian provinces and territories. Its energy demand structure makes it possible to model data centers power demand independently of the rest of the energy demand. It models the future evolution of the Canadian energy sector based on economic assumptions and optimization rules. It has been used by many governmental agencies in the US and Canada (including the US EPA and Environment Canada) to analyze various energy and GHG emissions policies (Amlin 2015). There are several versions of the model with varying levels of regional detail. In this study, the version is regionally aggregated for the US and provincially disaggregated for Canada. This version is used by Environment Canada in its Energy, Emissions and Economy Model for Canada (E3MC).

Table S1: Business as usual scenario assumptions (adapted from Environment Canada, Canada's Emissions Trends. 2013. p. 1-80)

Parameter	Value
Annual Growth (2011-2020):	
Gross domestic product	2.1%
Price index (inflation)	1.8%
Population	1.1%
Household formation	1.3%
Labor force	0.8%
Labor productivity	1.2%
Price (2020):	
World crude oil price	102 (US)\$/barrel
Henry Hub natural gas price	5.30 (CAN)\$/GJ
Crude oil and natural gas production (2020):	
Crude and condensates	1,441×10 ³ barrels/day
Oil sands	3,315×10 ³ barrels/day
Natural gas (shale gas included)	4,861×10 ⁹ cubic feet
Electricity generation (2020):	
Coal and Petroleum Coke	58 TWh
Refined Petroleum Products	3 TWh
Natural Gas	40 TWh
Hydro	397 TWh
Nuclear	84 TWh
Other Renewables	28 TWh
Total generation	609 TWh

Table S2: Electric demand of extra data centres per year and scenario

Electricity (TWh)	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Sc1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sc2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Sc3	0.2	0.2	0.2	0.2	0.4	0.4	0.4	0.4	0.6	0.6	0.6	0.6	0.8	0.8	0.9	0.9
Sc4	0.2	0.2	0.4	0.4	0.6	0.6	0.8	0.8	1.0	1.0	1.3	1.3	1.5	1.5	1.7	1.7
Sc5	0.4	0.7	1.0	1.2	1.5	1.8	2.0	2.3	2.6	2.9	3.1	3.4	3.7	3.9	4.2	4.5

Note: while table S2 and totals in table S4 should be the same, some differences can be seen. These differences are due to the imperfect convergence of the solutions computed by Energy2020.

Table S4: Marginal electricity generated in US and Canada by source, by year and by scenario

Electricity (GWh)	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Biomass																
Sc1	0	0	36	39	2	0	0	0	0	0	0	0	0	0	0	0
Sc2	0	0	36	36	2	0	0	0	0	1	1	0	0	1	1	1
Sc3	0	0	30	30	6	0	0	0	0	1	1	1	1	2	2	2
Sc4	0	0	57	57	30	0	0	0	0	2	2	2	2	3	4	2
Sc5	0	0	130	164	146	0	0	38	0	5	4	3	3	310	10	8
Coal																
Sc1	38	91	35	52	78	89	97	96	99	99	85	82	82	79	87	87
Sc2	37	91	36	58	81	94	92	99	161	159	136	130	130	128	135	130
Sc3	35	79	30	52	132	164	164	173	247	252	204	200	272	267	269	266
Sc4	36	82	56	98	169	231	313	322	402	402	399	390	462	462	532	448
Sc5	66	242	131	316	348	693	798	892	841	1143	917	993	1089	873	1330	1149
Heavy Fuel Oil																
Sc1	1	7	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc2	2	7	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc3	2	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc4	2	7	6	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc5	3	20	17	0	0	0	0	2	0	0	0	0	0	0	0	0
Diesel-Gazoline																
Sc1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydro																
Sc1	0	0	12	0	0	0	0	0	0	0	0	0	0	12	13	12
Sc2	0	0	12	0	0	0	0	0	0	0	0	0	0	24	25	27
Sc3	0	0	15	0	0	0	0	0	0	0	0	0	0	57	57	59
Sc4	0	0	27	0	0	0	0	0	0	0	0	0	0	104	124	324
Sc5	0	0	67	0	0	0	0	0	281	0	281	281	281	484	304	523
Natural Gas																
Sc1	199	50	56	50	67	60	67	75	74	80	83	90	93	93	98	98
Sc2	204	58	70	61	78	70	76	81	182	184	188	192	194	196	200	201
Sc3	190	51	60	51	194	171	179	186	297	302	304	308	426	426	427	432
Sc4	199	59	178	158	274	244	362	367	488	491	614	615	741	743	859	753
Sc5	359	323	485	576	781	843	966	1059	1095	1374	1410	1559	1710	1861	2116	2343
Nuclear																
Sc1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind																
Sc1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Sc2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Sc3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	2
Sc4	0	0	1	0	0	0	0	0	0	0	0	0	0	4	5	2
Sc5	0	0	2	0	4	4	34	4	4	4	4	5	5	13	18	22
Total																
Sc1	239	148	144	141	147	149	163	171	173	179	168	172	175	185	199	198
Sc2	243	156	158	154	160	164	168	179	343	344	325	323	325	350	361	360
Sc3	227	137	139	133	332	335	342	358	544	555	510	509	699	755	757	762
Sc4	236	147	326	314	472	475	676	689	890	895	1016	1006	1205	1317	1525	1529
Sc5	428	585	831	1055	1279	1540	1799	1996	2221	2528	2617	2842	3088	3542	3778	4045

Table S5: ecoinvent processes used to model Energy 2020 electricity generation technologies

Energy2020	Ecoinvent	
Technology	Fraction	Process
US		
Coal	6.30%	{WECC, US only} electricity production, hard coal
	4.54%	{MRO, US only} electricity production, hard coal
	0.26%	{NPCC, US only} electricity production, hard coal
	15.42%	{RFC} electricity production, hard coal
	13.48%	{SERC} electricity production, hard coal
	1.81%	{SPP} electricity production, hard coal
	4.43%	{TRE} electricity production, hard coal
	1.40%	{FRCC} electricity production, hard coal
	6.93%	{WECC, US only} electricity production, lignite
	4.98%	{MRO, US only} electricity production, lignite
	0.29%	{NPCC, US only} electricity production, lignite
	16.95%	{RFC} electricity production, lignite
	14.82%	{SERC} electricity production, lignite
	1.98%	{SPP} electricity production, lignite
	4.87%	{TRE} electricity production, lignite
1.54%	{FRCC} electricity production, lignite	
Hydro	0.52%	{WECC, US only} electricity production, hydro, pumped storage
	0.82%	{NPCC, US only} electricity production, hydro, pumped storage
	1.57%	{RFC} electricity production, hydro, pumped storage
	3.63%	{SERC} electricity production, hydro, pumped storage
	0.13%	{SPP} electricity production, hydro, pumped storage
	12.98%	{WECC, US only} electricity production, hydro, reservoir, alpine region
	0.84%	{MRO, US only} electricity production, hydro, reservoir, alpine region
	2.15%	{NPCC, US only} electricity production, hydro, reservoir, alpine region
	0.47%	{RFC} electricity production, hydro, reservoir, alpine region
	1.98%	{SERC} electricity production, hydro, reservoir, alpine region
	0.08%	{SPP} electricity production, hydro, reservoir, non-alpine region
	0.04%	{TRE} electricity production, hydro, reservoir, non-alpine region
	0.55%	{FRCC} electricity production, hydro, reservoir, non-alpine region
	51.93%	{WECC, US only} electricity production, hydro, run-of-river
	3.37%	{MRO, US only} electricity production, hydro, run-of-river
	8.59%	{NPCC, US only} electricity production, hydro, run-of-river
	1.89%	{RFC} electricity production, hydro, run-of-river
	7.93%	{SERC} electricity production, hydro, run-of-river
0.32%	{SPP} electricity production, hydro, run-of-river	
0.16%	{TRE} electricity production, hydro, run-of-river	
0.04%	{FRCC} electricity production, hydro, run-of-river	
Natural Gas	6.22%	{WECC, US only} electricity production, natural gas, combined cycle power plant
	0.06%	{MRO, US only} electricity production, natural gas, combined cycle power plant
	3.56%	{NPCC, US only} electricity production, natural gas, combined cycle power plant
	4.80%	{RFC} electricity production, natural gas, combined cycle power plant
	7.85%	{SERC} electricity production, natural gas, combined cycle power plant
	1.26%	{SPP} electricity production, natural gas, combined cycle power plant
	5.32%	{TRE} electricity production, natural gas, combined cycle power plant
	4.48%	{FRCC} electricity production, natural gas, combined cycle power plant
	8.81%	{WECC, US only} electricity production, natural gas, conventional power plant
	0.90%	{MRO, US only} electricity production, natural gas, conventional power plant
	5.04%	{NPCC, US only} electricity production, natural gas, conventional power plant
	6.80%	{RFC} electricity production, natural gas, conventional power plant
	11.12%	{SERC} electricity production, natural gas, conventional power plant
	1.78%	{SPP} electricity production, natural gas, conventional power plant
	7.53%	{TRE} electricity production, natural gas, conventional power plant
	6.35%	{FRCC} electricity production, natural gas, conventional power plant
	1.23%	{WECC, US only} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
0.13%	{MRO, US only} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	

	0.71%	{NPCC, US only} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
	0.95%	{RFC} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
	1.56%	{SERC} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
	0.25%	{SPP} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
	1.05%	{TRE} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
	0.89%	{FRCC} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical
	2.07%	{WECC, US only} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	0.21%	{MRO, US only} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	1.18%	{NPCC, US only} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	1.60%	{RFC} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	2.61%	{SERC} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	0.42%	{SPP} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	1.77%	{TRE} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
	1.49%	{FRCC} heat and power co-generation, natural gas, conventional power plant, 100MW electrical
Nuclear	5.09%	{WECC, US only} electricity production, nuclear, boiling water reactor
	1.91%	{MRO, US only} electricity production, nuclear, boiling water reactor
	3.34%	{NPCC, US only} electricity production, nuclear, boiling water reactor
	11.45%	{RFC} electricity production, nuclear, boiling water reactor
	11.67%	{SERC} electricity production, nuclear, boiling water reactor
	0.36%	{SPP} electricity production, nuclear, boiling water reactor
	1.67%	{TRE} electricity production, nuclear, boiling water reactor
	0.78%	{FRCC} electricity production, nuclear, boiling water reactor
	2.60%	{WECC, US only} electricity production, nuclear, pressure water reactor
	3.76%	{MRO, US only} electricity production, nuclear, pressure water reactor
	6.55%	{NPCC, US only} electricity production, nuclear, pressure water reactor
	22.44%	{RFC} electricity production, nuclear, pressure water reactor
	22.86%	{SERC} electricity production, nuclear, pressure water reactor
	0.71%	{SPP} electricity production, nuclear, pressure water reactor
3.28%	{TRE} electricity production, nuclear, pressure water reactor	
1.52%	{FRCC} electricity production, nuclear, pressure water reactor	
Heavy Fuel Oil, Diesel and Gazoline	5.07%	{WECC, US only} electricity production, oil
	1.53%	{MRO, US only} electricity production, oil
	4.40%	{NPCC, US only} electricity production, oil
	16.57%	{RFC} electricity production, oil
	28.44%	{SERC} electricity production, oil
	0.25%	{SPP} electricity production, oil
	0.78%	{TRE} electricity production, oil
	7.21%	{FRCC} electricity production, oil
	2.71%	{WECC, US only} heat and power co-generation, oil
	0.86%	{MRO, US only} heat and power co-generation, oil
	2.45%	{NPCC, US only} heat and power co-generation, oil
	9.25%	{RFC} heat and power co-generation, oil
	15.87%	{SERC} heat and power co-generation, oil
	0.14%	{SPP} heat and power co-generation, oil
	0.44%	{TRE} heat and power co-generation, oil
	4.03%	{FRCC} heat and power co-generation, oil
	Wind and other	1.96%
1.61%		{MRO, US only} electricity production, wind, <1MW turbine, onshore
0.21%		{NPCC, US only} electricity production, wind, <1MW turbine, onshore
0.83%		{RFC} electricity production, wind, <1MW turbine, onshore
0.06%		{SERC} electricity production, wind, <1MW turbine, onshore
0.66%		{SPP} electricity production, wind, <1MW turbine, onshore
1.59%		{TRE} electricity production, wind, <1MW turbine, onshore
0.20%		{WECC, US only} electricity production, wind, >3MW turbine, onshore
0.17%		{MRO, US only} electricity production, wind, >3MW turbine, onshore
0.02%		{NPCC, US only} electricity production, wind, >3MW turbine, onshore
0.08%		{RFC} electricity production, wind, >3MW turbine, onshore
0.01%		{SERC} electricity production, wind, >3MW turbine, onshore
0.07%		{SPP} electricity production, wind, >3MW turbine, onshore
0.16%		{TRE} electricity production, wind, >3MW turbine, onshore

Biomass	23.39%	{WECC, US only} electricity production, wind, 1-3MW turbine, onshore
	19.20%	{MRO, US only} electricity production, wind, 1-3MW turbine, onshore
	2.51%	{NPCC, US only} electricity production, wind, 1-3MW turbine, onshore
	9.87%	{RFC} electricity production, wind, 1-3MW turbine, onshore
	0.76%	{SERC} electricity production, wind, 1-3MW turbine, onshore
	7.85%	{SPP} electricity production, wind, 1-3MW turbine, onshore
	18.95%	{TRE} electricity production, wind, 1-3MW turbine, onshore
	9.83%	{WECC, US only} electricity production, deep geothermal
	8.16%	{WECC, US only} heat and power co-generation, biogas, gas engine
	5.93%	{MRO, US only} heat and power co-generation, biogas, gas engine
	12.83%	{NPCC, US only} heat and power co-generation, biogas, gas engine
	17.94%	{RFC} heat and power co-generation, biogas, gas engine
	5.94%	{SERC} heat and power co-generation, biogas, gas engine
	0.21%	{SPP} heat and power co-generation, biogas, gas engine
	2.05%	{TRE} heat and power co-generation, biogas, gas engine
	6.90%	{FRCC} heat and power co-generation, biogas, gas engine
	13.02%	{WECC, US only} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
	3.12%	{MRO, US only} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
	11.41%	{NPCC, US only} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
	3.56%	{RFC} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
7.07%	{SERC} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	
0.46%	{TRE} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	
1.42%	{FRCC} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	
Canada		
Technology	Process	
Coal	{CA-X*} electricity production, lignite {CA-X} electricity production, hard coal	
Hydro	{CA-X} electricity production, hydro, pumped storage {CA-X} electricity production, hydro, reservoir, alpine region {CA-X} electricity production, hydro, reservoir, non-alpine region {CA-X} electricity production, hydro, run-of-river	
Natural gas	{CA-X} electricity production, natural gas, conventional power plant {CA-X} heat and power co-generation, natural gas, conventional power plant, 100MW electrical {CA-X} electricity production, natural gas, combined cycle power plant	
Nuclear	{CA-X} electricity production, nuclear, pressure water reactor, heavy water moderated	
Heavy Fuel Oil, Diesel and Gazoline	{CA-X} electricity production, oil	
Wind	{CA-X} electricity production, wind, <1MW turbine, onshore {CA-X} electricity production, wind, 1-3MW turbine, onshore {CA-X} electricity production, wind, >3MW turbine, onshore {CA-X} electricity production, wind, 2.3MW turbine, precast concrete tower, onshore	
Biomass	{CA-X} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	

*X refers to the abbreviation of the Canadian province in ecoinvent (e.g. QC for Quebec, ON for Ontario, etc.)

Note: since the electricity generation processes are modeled at the power plant level in ecoinvent, the electric losses and emissions occurring during the transport and distribution of electricity were added (based on regional data of ecoinvent) to each electric process so the transport and distribution is included.

Technology innovation

Finally, past tendencies observed in electricity generation were used to represent future evolution of technology efficiencies. The annual efficiencies of thermal power plants (coal, oil, natural gas and biomass) were computed on the basis of the amount of fuel burned and the electricity generated per fuel from 1996 to 2015. For that purpose, data have been collected from the US Energy Information Administration (EIA) database (US Energy Information Administration 2013b) for US thermal power plants. Then an extrapolation (linear regression) was made for 2015-2030 and the average annual change in efficiency was computed for each thermal technology. It was intended to follow the same approach for Canadian thermal power plants using data from Statistics Canada (Statistics Canada 2013). However, the too short period (nine years) covered by the Canadian database made the results quite uncertain. Therefore it was preferred to use US data to model the future efficiencies of the Canadian thermal technologies. Regarding nuclear power plants, the amounts of nuclear fuels consumed annually were not found, thus it was anticipated the future efficiency of Canadian nuclear power plants would follow the trend observed during 2003-2013 among the US nuclear power plants (US Energy Information Administration 2013a). The efficiency trend of wind power was computed with the annual electricity generation by wind farms and the installed capacity of wind power. The US EIA database (US Energy Information Administration 2013b) was used to compute the US wind farms efficiency trend but also for the Canadian one (due to the too short period covered by Statistics Canada). Then, following the same approach than for thermal technologies, the average annual change in efficiency of wind power technology was calculated for the 2015-2030 period. No efficiency trend data were found for hydropower. Therefore it was assumed this technology would not improve in the near future. Regarding this assumption, it should be noted that hydropower efficiency is already close to its theoretical limit (Liu et al. 2015) and is not expected to change significantly in the future. The annual efficiency changes of each technology are presented in table S7. Then, the substances inventory was computed based on the amount of electricity generated by each energy source, as modeled by Energy 2020 each year for each scenario. Finally, each data center deployment scenario was

compared to the BAU scenario to determine the differential energy sources used to power the additional Canadian data centers.

Table S7: Annual efficiency changes in US and Canada electricity generation anticipated for 2015-2030

Technology	Annual efficiency changes*
Coal	-0.48 %
Oil (heavy fuel oil and diesel)	-0.02 %
Natural gas	1.15 %
Biomass	-0.67 %
Nuclear	-0.03 %
Hydro	0.00 %
Wind	0.02 %

* Negative efficiency changes are interpreted as the aging of equipment and infrastructures.