Review of Solutions to Global Warming, Air Pollution, and Energy Security

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Energy and Environmental Science

Supplementary Information
Appendix

Derivation of results used for this study.

Energy required for vehicles		Low case	High case
A1(S1)	2007 onroad vehicle miles traveled in the U.S. (mi/yr)	3.237E+12	3.237E+12
A2 (S2)	Total onroad vehicle fleet mileage (mpg)	1.711E+01	1.711E+01
A3=A1/A2	Gallons of fuel (gas+diesel) used (gal/yr)	1.892E+11	1.892E+11
A4	Lower heating value gasoline (MJ/kg)	4.400E+01	4.400E+01
A5	Gasoline density (kg/m3)	7.500E+02	7.500E+02
A6	Gallons per cubic meter (gal/m3)	2.642E+02	2.642E+02
A7=A4*A5/A6	Energy stored in gasoline (MJ/gal)	1.249E+02	1.249E+02
A8=A3*A7	Energy needed to power gasoline vehicles (MJ/yr)	2.363E+13	2.363E+13
A9 (S2)	Gasoline vehicle efficiency (fraction)	1.600E-01	1.800E-01
A10=A8*A9	Net energy to power U.S. onroad vehicles (MJ/yr)	3.781E+12	4.254E+12
A11	MJ per kWh	3.600E+00	3.600E+00
A12=A10/A11	Net energy to power U.S. onroad vehicles (kWh/yr)	1.050E+12	1.182E+12
U.S. and world CO2 emissions			
B1 (S3)	U.S. onroad vehicle CO2 2007 (MT-CO2/yr)	1.466E+03	1.466E+03
B2 (S3)	U.S. other-vehicle CO2 (MT-CO2/yr)	4.696E+02	4.696E+02
B3 (S4)	U.S. coal-electricity CO2 2007 (MT-CO2/yr)	1.958E+03	1.958E+03
B4 (S4)	U.S. natural gas-electricity CO2 (MT-CO2/yr)	3.618E+02	3.618E+02
B5 (S4)	U.S. oil electricity CO2 (MT-CO2/yr)	5.450E+01	5.450E+01
B5 (S4)	U.S. non-elect, non-transport. CO2 (MT-CO2/yr)	1.661E+03	1.661E+03
B6=B1+B2+B3+B4+B5	U.S. total fossil CO2 2007 (MT-CO2/yr)	5.971E+03	5.971E+03
B7 (S5)	World total CO2 2007 (MT-CO2/yr)	3.345E+04	3.345E+04
B8 (S6)	Fraction of upstream+combust onroad CO2 from combust	7.500E-01	7.500E-01
B9=B1/B8	U.S. onroad combust+fuel prod CO2 2007 (MT-CO2/yr)	1.955E+03	1.955E+03
U.S. CO2 emissions per kWh electricity generated			
C1 (S7)	US electricity CO2 (g-CO2e/kWH) (1998-2000 avg)	6.060E+02	6.060E+02
C2 (S7)	US electricity CH4 (g-CO2e/kWH) w/GWP 25	1.259E-01	1.259E-01
C3 (S7)	US electricity N2O (g-CO2e/kWH) GWP 298	2.595E+00	2.595E+00
C4=C1+C2+C3	Total US electricity CO2e (g-CO2e/kWh) (1998-2000)	6.087E+02	6.087E+02

Wind turbine characteristics			
D1(S8)	Mean annual wind speed (m/s)	8.500E+00	7.000E+00
D2 (S9)	Turbine rated power (kW)	5.000E+03	5.000E+03
D3 (S9)	Turbine rotor diameter (m)	1.260E+02	1.260E+02
D4=(0.087*D1-D2/D3^2) (S10)	Turbine capacity factor	4.246E-01	2.941E-01
D5	Hours per year (hrs)	8.760E+03	8.760E+03
D6=D2*D4*D5	Turbine energy output without losses (kWh/yr)	1.860E+07	1.288E+07
D7	Turbine effic. with transmission,conversion, array losses	9.000E-01	8.500E-01
D8=D6*D7	Turbine energy output with losses (kWh/yr)	1.674E+07	1.095E+07
D9=(4*D3)*(7*D3)/10^6 (S10)	Area for one turbine accounting for spacing (km2)	4.445E-01	4.445E-01
D10	Diameter of turbine tubular tower (m)	4.000E+00	5.000E+00
D11=PI*(D10/2)^2/10^6	Area of turbine tower touching ground (km^2)	1.257E-05	1.963E-05
D12	Lifetime of wind turbine (yr)	3.000E+01	3.000E+01
D13 (S11)	Energy to manufacture one turbine (kWh/MW)	4.277E+05	1.141E+06
D14=D13*D2/(D12*1000)	Energy to manufacture one turbine (kWh/yr)	7.128E+04	1.901E+05
D15=0.5*(D6a+D6b)	Avg turbine energy output before transmission (kWh/yr)	1.574E+07	1.574E+07
D16=D3*D2/D15	Energy payback time (yr) for given turbine and winds	1.359E-01	3.624E-01
D17=D14*C4	Single-turbine CO2 emissions (g-CO2e/yr)	4.339E+07	1.157E+08
D18=D17/D15	Single-turbine CO2 emissions (g-CO2e/kWh)	2.757E+00	7.352E+00
D19	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
D20	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
D21=C4*(D19+D20*(100yr/ D12))/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.247E+01	7.102E+01
D22=D21-D21	Wind minus wind time lag CO2 (g-CO2e/kWh)	0.000E+00	0.000E+00
Wind-powered battery-electric vehicles (wind-BEV)			
E1 (S12)	Battery effic. (delivered to input electricity ratio)	8.600E-01	7.500E-01
E2=A12/E1	Energy required for batteries for U.S. BEV (kWh/yr)	1.221E+12	1.576E+12
E3=E2/D8	Number of turbines required for U.S. wind-BEV	7.298E+04	1.439E+05
E4=E3*D9	Area to separate turbines for U.S. wind-BEV (km^2)	3.244E+04	6.397E+04
E5	Square km per square mile	2.590E+00	2.590E+00
E6	Land area of U.S. (50 states) (mi^2)	3.537E+06	3.537E+06
E7=E6*E5	Land area of U.S. (50 states) (km^2)	9.162E+06	9.162E+06
E8=E4/E7	Fraction of U.S. land turbine spacing for wind-BEV	3.541E-03	6.983E-03
E9	Land area of California (mi^2)	1.560E+05	1.560E+05
E10=E9*E5	Land area of California (km^2)	4.039E+05	4.039E+05
E11=E4/E10	California land fraction for spacing for U.S. wind-BEV	8.031E-02	1.584E-01
E12=E3*D11/E5	Footprint on ground U.S. wind-BEV (km^2)	9.170E-01	2.826E+00
E13=E12/E7	Fraction of U.S. land for footprint for all wind-BEV	1.001E-07	3.084E-07
E14=E3*D17/10^12	Wind-BEV onroad vehicles CO2(MT-CO2e/yr)	3.167E+00	1.665E+01
E15=(B9-E14)/B9	Percent reduction FFOV CO2 due to wind-BEV	9.984E+01	9.915E+01
E16=E15*B9/B6	Percent reduction US CO2 due to wind-BEV	3.268E+01	3.245E+01
E17 (AWEA, 2008S19)	Water for turbine manufacture (gal-H2O/kWh)	1.000E-03	1.000E-03
E18=E17*D6*E3	Gal-H2O/yr required to run U.S. wind-BEV	1.357E+09	1.854E+09
Wind-powered hydrogen fuel-cell vehicles (wind-HFCV)			
F1 (S2, S13)	hydrogen fuel cell efficiency (fraction)	5.000E-01	4.600E-01
F2=A10/F1	Energy required for U.S. HFCV (MJ/yr)	7.563E+12	9.248E+12
F3	Lower heating value of hydrogen (MJ/kg-H2)	1.200E+02	1.200E+02
F4=F2/F3	Mass of H2 required for fuel for HFCV (kg-H2/yr)	6.304E+10	7.709E+10
F5 (S2, S13)	Leakage rate hydrogen (fraction)	3.000E-02	3.000E-02

F6=F4/(1-F5)	Mass of H2 required with leakage (kg-H2/yr)	6.499E+10	7.947E+10
F7	Higher heating value of hydrogen (MJ/kg-H2)	1.418E+02	1.418E+02
F8 (S14)	Electrolyzer efficiency	7.380E-01	7.380E-01
F9=F7/(F8*F2)	Electrolyzer energy needed per kg-H2 (kWh/kg-H2)	5.337E+01	5.337E+01
F10 (S15)	Compressor Motor size (kW)	3.000E+01	3.000E+01
F11 (S15)	Electricity use as function of motor size (fraction)	6.500E-01	6.500E-01
F12 (S15)	Capacity of compressor (kg/year)	3.030E+04	3.030E+04
F13=D5*F10*F11/F12	Compressor energy needed per kg-H2 (kWh/kg-H2)	5.639E+00	5.639E+00
F14=F9+F13	Electrolyzer+compressor en req. (kWh/kg-H2)	5.901E+01	5.901E+01
F15=F6*F14	Electrolyzer+compressor Energy for all H2 (kWh/yr)	3.835E+12	4.690E+12
F16=F15/D8	Number of turbines required for wind-HFCV	2.292E+05	4.284E+05
F17=F16*D9	Separation area for turbines for wind-HFCV (km2)	1.019E+05	1.904E+05
F18=F17/E7	Fraction of U.S. land for spacing for wind-HFCV	1.112E-02	2.078E-02
F19=F17/E10	Fraction of California land for spacing for wind-HFCV	2.522E-01	4.714E-01
F20=D11*F16/E5	Turbine ground footprint for wind-HFCV (km^2)	2.880E+00	8.411E+00
F21=F16/E3	Ratio of turbines, wind-HFCV:wind-BEV	3.140E+00	2.977E+00
F22=F16*D17/10^12	Wind-HFCV CO2 from turbine lifecycle (MT-CO2e/yr)	9.944E+00	4.957E+01
F23=(B9-F22)/B9	Percent reduction FFOV CO2 due to wind-HFCV	9.949E+01	9.746E+01
F24=F23*B9/B6	Percent reduction US CO2 due to wind-HFCV	3.257E+01	3.190E+01
F25	H2 Molecular weight (g/mol)	2.01588	2.01588
F26	H2O molecular weight (g/mol)	18.01528	18.01528
F27=F26/F25	Water required for electrolyzer (kg-H2O/kg-H2)	8.936682739	8.936682739
F28	Density of liquid water (kg/m3)	1000	1000
F29=F27*A6/F28	Water required for electrolyzer (gal-H2O/kg-H2)	2.361E+00	2.361E+00
F30=F29*F6	Water required for wind HFCV (gal-H2O/yr)	1.534E+11	1.876E+11
F31=E18*F16/E3	Water for turbine manufacturing (gal-H2O/yr)	4.261E+09	5.517E+09
F32=F30+F31	Total water required (gal-H2O/yr)	1.577E+11	1.931E+11
Solar PV panel characteristics			
G1 (S16)	Sample solar panel rated power (W)	1.600E+02	1.600E+02
G2 (S16)	Mean capacity factor accounting for sunlight, PVs, inverter	2.000E-01	1.000E-01
G3=G1*G2*D5/1000	Single-panel energy output before transmis. loss (kWh/yr)	2.803E+02	1.402E+02
G4	Transmission efficiency	9.500E-01	9.000E-01
G5=G3*G4	Single-panel output w/ transmis. loss (kWh/yr)	2.663E+02	1.261E+02
G6 (S16)	Sample solar panel area (m2) plus walking space	1.888E+00	1.888E+00
G7 (S17)	Lifetime of solar panel (yr)	3.000E+01	3.000E+01
G8 (S17)	Single-panel CO2 emissions (g-CO2e/kWh)	1.900E+01	5.900E+01
G9=G8*G3	Single-panel CO2 emissions (g-CO2e/yr)	5.326E+03	8.269E+03
G10	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
G11	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
G12=C4*(G10+G11*100yr/ G7)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.247E+01	7.102E+01
G13=G12-D21	Solar PV minus wind time lag CO2 (g-CO2e/kWh)	0.000E+00	0.000E+00
Solar-PV powered battery-electric vehicles (PV-BEV)			
H1=E2/G5	Number of solar panels required for US PV-BEV	4.586E+09	1.249E+10
H2=H1*G6/10^6	Land+roof (km^2) for solar panels to power US PV-BEV	8.658E+03	2.358E+04
H3 (est.)	Fraction of solar panels on rooftops	3.000E-01	3.000E-01
H4=H2*(1-H3)	Land (km^2) for solar panels to power US PV-BEV	6.060E+03	1.650E+04
H5=H4/E7	Fraction of U.S. land for PV-BEV solar panels	6.615E-04	1.801E-03
H6=H4/E10	Fraction of California land for PV-BEV solar panels	1.500E-02	4.086E-02

H7=H4/E12	Ratio of solar-PV to wind land footprint for BEV	6.608E+03	5.841E+03
H8=H4/E4	Ratio of solar-PV to wind total spacing for BEV	1.868E-01	2.580E-01
H9=H1*(G9+G13)/10^12	PV-BEV CO2 emissions from solar panels (MT-CO2e/yr)	2.443E+01	1.033E+02
H10=100*(B9-H9)/B9	Percent reduction FFOV CO2 due to PV-BEV	9.875E+01	9.472E+01
H11=H109*B9/B6	Percent reduction US CO2 due to PV-BEV	3.232E+01	3.100E+01
H12 (S18,S19)	Water for building/cleaning panels (gal-H2O/kWh)	4.000E-02	4.000E-02
H13=H12*G3*H1	Gal-H2O/yr required to run U.S. PV-BEV	5.142E+10	7.002E+10
Corn Ethanol for E85 vehicles			
I1 (S20)	Efficiency of new E85 vehicles	3.200E-01	2.600E-01
I2=A10/I1	Energy required for new E85 vehicles 2007 (MJ/yr)	1.182E+13	1.636E+13
I3	Lower heating value of ETOH (MJ/kg)	2.680E+01	2.680E+01
I4	Density of ETOH (kg/m3)	7.870E+02	7.870E+02
I5=I3*I4/A6	Energy in ETOH (MJ/gal)	7.984E+01	7.984E+01
I6=I2/(0.2*A7+0.8*I5)	Gallons E85 for onroad vehicles (gal)	1.330E+11	1.841E+11
I7=I6*0.8	Gallons of ETOH in E85 for all U.S. onroad vehicles (gal)	1.064E+11	1.473E+11
I8=I6-I7	Gallons of gasoline in E85 for all U.S. onroad vehicles (gal)	2.660E+10	3.683E+10
I9 (S21)	kg-ETOH per bushel of corn	7.860E+00	7.860E+00
I10 (S21)	Bushels per acre on irrigated + nonirrigated land	1.810E+02	1.400E+02
I11	Square meters per acre	4.047E+03	4.047E+03
I12=I9*A6/I4	Gal-ETOH per bushel of corn	2.638E+00	2.638E+00
I13=I12*I10	Gal-ETOH per acre of dry corn	4.775E+02	3.694E+02
I14=I7/(I13*10^6)	Million acres of corn needed for all vehicles	2.228E+02	3.988E+02
I15=I14*I11	Square km of corn for all vehicles	9.016E+05	1.614E+06
I16=I15/E7	Fraction of U.S. land for corn-E85	9.840E-02	1.762E-01
I17=I15/E10	Fraction of California land for corn-E85	2.232E+00	3.995E+00
I18 (S22)	Total acres of harvested corn in U.S. 2003	7.350E+07	7.350E+07
I19 (S23)	Acres of irrigated corn U.S. 2003	9.750E+06	9.750E+06
I20=I19/I18	Fraction of harvested acres that are irrigated	1.327E-01	1.327E-01
I21 (S23)	Bushels per acre on irrigated land	1.780E+02	1.780E+02
I22=I21*I12	Gal-ETOH per acre of dry corn	4.696E+02	4.696E+02
I23 (S23)	Water required for corn (acre-feet-H2O/acre-land)	1.200E+00	1.200E+00
I24	U.S. gallons per acre-foot	3.259E+05	3.259E+05
I25=I23*I24/I22	Gal-H2O-irrigation/gal-ETOH	8.326E+02	8.326E+02
I26=I25*I20	Irrigated+nonirrigated gal-H2O/gal-ETOH	1.104E+02	1.104E+02
I27 (S24)	Gal-H2O-energy /gal-ETOH	1.100E-01	1.100E-01
I28 (S25)	Gal-H2O-factory/gal-ETOH	4.500E+00	4.500E+00
I29=I26+I27+I28	Total Gal-H2O/gal-ETOH	1.151E+02	1.151E+02
I30=I29*I7	Gal-H2O/yr required for all U.S. onroad vehicles	1.224E+13	1.695E+13
I31 (S26)	Total U.S. water use 2000 (gal/day)	4.080E+11	4.080E+11
I32=I31*365 days/yr	Total U.S. water use 2000 (gal/year)	1.489E+14	1.489E+14
I33=I30/I32	Fraction of U.S. water demand for corn-E85	8.220E-02	1.138E-01
I34=I15/E7	Ratio of corn-E85 to wind-BEV land footprint	9.831E+05	5.711E+05
I35 (S6, S28)	Percent change in FFOV CO2 with 100% corn-E85	-2.400E+00	9.300E+01
I36=I35*B9/B6	Percent change in US CO2 with 100% corn-E85	-7.856E-01	3.044E+01
I37=I36*0.30	Percent change in US CO2 with 30% corn-E85	-2.357E-01	9.133E+00
Cellulosic ethanol for E85 (cel-E85) vehicles			
J1 (S27, S29)	Tons dry matter/acre	1.000E+01	2.300E+00
J2 (S27)	Gallons-ETOH/ton-dry matter	1.000E+02	8.000E+01
J3=J1*J2	Gallons-ETOH/acre	1.000E+03	1.840E+02

J4=I7/(J3*10^6)	Million acres of switchgrass for all vehicles	1.064E+02	8.006E+02
J5=J4*I11	Square km of switchgrass for all cel-E85	4.305E+05	3.240E+06
J6=J5/E7	Fraction of U.S. land for cel-E85	4.699E-02	3.536E-01
J7=J5/E10	Fraction of California land for cel-E85	1.066E+00	8.021E+00
J8=J5/E12	Ratio of cel-E85 to wind-BEV land footprint	4.695E+05	1.147E+06
J9=J5/E4	Ratio of cel-E85 to wind-BEV total spacing	1.327E+01	5.064E+01
J10=0.5*I26	Irrigated+nonirrigated gal-H2O/gal-ETOH	5.522E+01	5.522E+01
J11=J10+I27+I28	Total Gal-H2O/gal-ETOH	5.983E+01	5.983E+01
J12=J11*I7	Gal-H2O/yr required for U.S. cel-E85	6.366E+12	8.814E+12
J13=J12/I32	Fraction of U.S. water demand for cel-E85	4.275E-02	5.919E-02
J14 (S6,S28)	Percent change FFOV CO2 with 100% cel-E85	-5.000E+01	5.000E+01
J15=J14*B9/B6	Percent change in US CO2 with 100% cel-E85	-1.637E+01	1.637E+01
J16=J15*0.30	Percent change in US CO2 with 30% cel-E85	-4.910E+00	+4.910E+00
Nuclear-powered battery-electric vehicles (nuclear-BEV)			
K1 (S30)	Average nuclear power plant size (MW)	8.470E+02	8.470E+02
K2 (S31)	Capacity factor globally 2005	8.590E-01	8.590E-01
K3=K1*K2*1000*D5	Energy per plant before transmission (kWh/yr)	6.374E+09	6.374E+09
K4=G4	Transmission efficiency	9.500E-01	9.000E-01
K5=K3*K4	Energy per plant after transmission (kWh/yr)	6.055E+09	5.736E+09
K6=E2/K5	Number nuclear plants to run U.S. nuclear-BEV	2.017E+02	2.747E+02
K7 (S32)	Nuclear CO2 lifecycle emissions (g-CO2e/kWh)	9.000E+00	7.000E+01
K8 (S33)	H2O evaporation nuclear (gal/kWh)	4.000E-01	7.200E-01
K9=K8*K3*K6	Gal-H2O/yr required to run U.S. nuclear-BEVs	5.142E+11	1.260E+12
K10=K9/I30	Fraction of U.S. water demand for nuclear-BEV	3.453E-03	8.464E-03
K11=K10*F16/E3	Fraction of U.S. water demand for nuclear-HFCV	1.084E-02	2.519E-02
K12 (S34)	Land required for mining uranium (ha-year/GWh)	6.000E-02	6.000E-02
K13 (S34)	Footprint+buffer for nuclear facility (ha-year/GWh)	2.600E-01	2.600E-01
K14 (S34)	Land for waste disposal for one plant (km^2)	8.000E-02	8.000E-02
K15	km^2 per hectare	1.000E-02	1.000E-02
K16=(K12+K13)*K15*K3/10^6+K14	Land (km^2) for one nuclear facility with buffer	2.048E+01	2.048E+01
K17 (S35)	Land (km^2) for nuclear facility buildings only	1.000E+00	4.000E+00
K18=K12*K3*K15/10^6+K14+K17	Footprint on ground (km^2) for one facility	4.904E+00	7.904E+00
K19=K16*K6	Land with buffer (km^2) to run US nuclear BEV	4.130E+03	5.624E+03
K20=K18*K6	Footprint on ground (km^2) to run US nuclear-BEV	9.892E+02	2.171E+03
K21=K19/E7	Fraction of US land for nuclear-BEV	4.508E-04	6.138E-04
K22=K21/E7	Fraction of US land for footprint of nuclear-BEV	1.080E-04	2.370E-04
K23=K20/E12	Ratio of nuclear to wind land footprint for BEV	1.079E+03	7.683E+02
K24=K19/E4	Ratio of nuclear to wind total spacing for BEV	1.273E-01	8.791E-02
K25	Lifetime of nuclear power plant (yr)	4.000E+01	4.000E+01
K26 (see text)	Time lag (yr) between planning and operation	1.000E+01	1.900E+01
K27	Time (yr) to refurbish after first lifetime	2.000E+00	4.000E+00
K28=C4*(K26+K27*100yr/K25)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	9.131E+01	1.765E+02
K29=K28-D21	Nuclear minus wind time lag CO2 (g-CO2e/kWh)	5.884E+01	1.055E+02
K30 (see text)	Nuclear emissions from war/terrorism (g-CO2e/kWh)	0.000E+00	4.100E+00
K31=(K7+K28+K30)*E2/10^12	Nuclear-BEV CO2 emissions (MT-CO2e/yr)	8.286E+01	2.830E+02
K32=100*(B9-K31)/B9	Percent reduction FFOV CO2 due to nuclear-BEVs.	9.576E+01	8.552E+01
K33=K32*B9/B6	Percent reduction US CO2 due to nuclear-BEVs	3.135E+01	2.799E+01

Hydroelectric powered battery-electric vehicles (hydro-BEV)			
L1 (S34)	Selected plant size (MW)	1.296E+03	1.296E+03
L2 (S36)	Capacity factor	4.240E-01	4.240E-01
L3=L1*L2*1000*D5	Energy per plant before transmission (kWh/yr)	4.814E+09	4.814E+09
L4=L3*G4	Energy per plant after transmission (kWh/yr)	4.573E+09	4.332E+09
L5=E2/L4	Number of hydro plants to run U.S. hydro-BEV	2.671E+02	3.637E+02
L6 (S34, S37)	Hydro CO2 emissions (g-CO2e/kWh)	1.700E+01	2.160E+01
L7 (S38, see text)	H2O evaporation hydroelectric (gal/kWh)	4.500E+00	7.560E+00
L8=L8*L3*L6	Gal-H2O/yr required to run U.S. BEVs	5.785E+12	1.323E+13
L9=L8/I31	Fraction of U.S. water demand for hydro-BEV	3.885E-02	8.887E-02
L10=L3*F15/E2	Fraction of U.S. water demand for hydro-HFCV	1.220E-01	2.645E-01
L11 (S34)	Area(km^2) required for single reservoir	6.531E+02	6.531E+02
L12=L11*L5	Area (km^2) required to run U.S. BEVs	1.744E+05	2.375E+05
L13=L12/E7	Fraction of US land for hydro-BEV	1.904E-02	2.592E-02
L14=L12/E12	Ratio of hydro to wind land footprint for BEV	1.902E+05	8.405E+04
L15=L12/E4	Ratio of hydro to wind total spacing for BEV	5.377E+00	3.713E+00
L16 (see text)	Lifetime of hydro power plant (yr)	8.000E+01	8.000E+01
L17 (see text)	Time lag (yr) between planning and operation	8.000E+00	1.600E+01
L18	Time (yr) to refurbish after first lifetime	2.000E+00	3.000E+00
L19=C4*(L17+L18*100yr/L16)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	6.392E+01	1.202E+02
L20=L19-D21	Hydro minus wind time lag CO2 (g-CO2e/kWh)	3.145E+01	4.920E+01
L21=(L6+L20)*E2/10^12	Hydro-BEV CO2 emissions (MT-CO2e/yr)	5.917E+01	1.116E+02
L22=100*(B9-L21)/B9	Percent reduction FFOV CO2 due to hydro-BEVs (%)	9.697E+01	9.429E+01
L23=L22*B9/B6	Percent reduction US CO2 due to hydro-BEVs (%)	3.174E+01	3.087E+01
Concentrated solar power powered battery electric vehicles (CSP-BEV) without storage			
M1	Typical plant size (MW)	1.000E+02	1.000E+02
M2 (S39)	Capacity factor without storage	2.500E-01	1.300E-01
M3=M1*M2*1000*D5	Energy per plant before transmission (kWh/yr)	2.190E+08	1.139E+08
M4=G4	Transmission efficiency	9.500E-01	9.000E-01
M5=M3*M4	Energy per plant after transmission (kWh/yr)	2.081E+08	1.025E+08
M6=E2/M5	Number CSP plants to run U.S. CSP-BEV	5.870E+03	1.537E+04
M7 (S40)	Lifetime of CSP plant (yr)	3.000E+01	3.000E+01
M8 (S40, S41)	Energy payback time (yr)	4.167E-01	5.583E-01
M9=0.5*(M3a+M3b)	Avg energy per plant before transmission (kWh/yr)	1.752E+08	1.664E+08
M10=M9*M8/M7	Energy to manufacture one CSP plant (kWh/yr)	2.433E+06	3.098E+06
M11=M10*C4	Single-CSP plant CO2 emissions (g-CO2e/yr)	1.148E+09	1.886E+09
M12=M11/M9	Single-CSP plant CO2 emissions (g-CO2e/kWh)	8.454E+00	1.133E+01
M13 (S42)	H2O consumption wet-cool parabolic trough (gal/kWh)	7.770E-01	7.770E-01
M14=M13*M3*M6	Gal-H2O/yr required to run U.S. CSP-BEV	9.989E+11	1.360E+12
M15=M14/I32	Fraction of U.S. water demand for wet-cool CSP BEV	6.708E-03	9.134E-03
M16=M14*F15/E2	Fraction of U.S. water demand for wet-cool CSP HFCV	2.106E-02	2.719E-02
M17 (S42)	Land area required (km^2) per installed MW CSP	1.900E-02	2.430E-02
M18=M17*M1	Land area required (km^2) for one 100 MW plant	1.900E+00	2.430E+00
M19=M18*M6	Land area (km^2) required to run U.S. CSP-BEV	1.115E+04	3.735E+04
M20=M19/E7	Fraction of U.S. land for CSP-BEV	1.217E-03	4.077E-03
M21=M19/E10	Fraction of California land for CSP-BEV	2.761E-02	9.248E-02
M22=M19/E12	Ratio of CSP to wind footprint area for BEV	1.216E+04	1.322E+04

M23=M19/E4	Ratio of CSP to wind spacing area for BEV	3.438E-01	5.839E-01
M24 (see text)	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
M25	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
M26=C4*(M24+M25*100yr /M7)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.247E+01	7.102E+01
M27=M26-D20	CSP minus wind time lag CO2 (g-CO2e/kWh)	0.000E+00	0.000E+00
M28=(M12+M27)*E2/10^{12}	CSP-BEV CO2 emissions (MT-CO2e/yr)	1.033E+01	1.785E+01
M29=100*(B9-M28)/B9	Percent reduction FFOV CO2 due to CSP-BEVs (%)	9.947E+01	9.909E+01
M30=M29*B9/B6	Percent reduction US CO2 due to CSP-BEVs (%)	3.256E+01	3.243E+01
Coal with CCS powering battery-electric vehicles (CCS-BEV)			
N1 (S34)	Typical plant size (MW)	4.250E+02	4.250E+02
N2 (S34, S43)	Capacity factor	8.500E-01	6.500E-01
N3=N1*N2*1000*D5	Energy per plant before transmission (kWh/yr)	3.165E+09	2.420E+09
N4 (S41)	Increase in energy required for CCS (fraction)	1.400E-01	4.000E-01
N5=N3/(1+N4)	Energy available for transmission (kWh/yr)	2.776E+09	1.729E+09
N6=N5*M4	Energy per plant after transmission (kWh/yr)	2.637E+09	1.556E+09
N7=E2/N6	Number of coal plants to run U.S. CCS-BEV	4.631E+02	1.013E+03
N8 (S44)	Coal CO2 direct emissions w/o CCS (g-CO2/kWh)	7.900E+02	1.017E+03
N9 (S43)	CCS CO2 reduction efficiency	9.000E-01	8.500E-01
N10=N8*(1-N9)	Coal CO2 direct emissions w/ CCS (g-CO2/kWh)	7.900E+01	1.526E+02
N11(S44)	Coal non-direct lifecycle CO2 (g-CO2e/kWh)	1.760E+02	2.890E+02
N12=N10+N11	Total lifecycle coal-CCS CO2 (g-CO2e/kWh)	2.550E+02	4.416E+02
N13 (S45)	H2O consumption from coal-fired power (gal/kWh)	4.900E-01	4.900E-01
N14=N13*N3*N7	Gal-H2O/yr required to run U.S. CCS-BEV	7.181E+11	1.201E+12
N15=N14/I32	Fraction of U.S. water demand for CCS-BEV	4.822E-03	8.064E-03
N16 (S34)	Land area for coal facility (km^2)	1.290E+00	1.290E+00
N17 (S34)	Land area for rail to transport coal (km^2)	8.600E-02	8.600E-02
N18 (S34)	Land area for coal mining (km^2)	3.800E+00	3.800E+00
N19=N16+N17+N18	Total land area for one coal plant (km^2)	5.176E+00	5.176E+00
N20=N19*N7	Land area (km^2) to run U.S. CCS-BEV	2.397E+03	5.242E+03
N21=N20/E7	Fraction of U.S. land for CCS-BEV	2.616E-04	5.722E-04
N22=N20/E12	Ratio of CCS to wind footprint area for BEV	2.614E+03	1.855E+03
N23=N20/E4	Ratio of CCS to wind spacing area for BEV	7.390E-02	8.194E-02
N24	Lifetime of coal-CCS power plant (yr)	3.500E+01	3.000E+01
N25 (see text)	Time lag (yr) between planning and operation	8.000E+00	1.600E+01
N26	Time (yr) to refurbish after first lifetime	2.000E+00	3.000E+00
N27=C4*(N25+N26*100yr/ N24)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	8.348E+01	1.583E+02
N28=N27-D21	Coal-CCS minus wind time lag CO2 (g-CO2e/kWh)	5.102E+01	8.725E+01
N29=N8-N10	CO2 injection rate into ground (g-CO2/kWh)	7.110E+02	8.645E+02
N30 (see text)	E-folding lifetime against leakage	1.000E+05	5.000E+03
N31=N29-N29*N30*(1-exp(-500yr/N30))/500yr	Average leakage over 500 years (g-CO2/kWh)	1.775E+00	4.182E+01
N32=(N11+N28+N31)*E2/10^12	CCS-BEV CO2 emissions (MT-CO2e/yr)	3.759E+02	8.990E+02
N33=100*(B9-N32)/B9	Percent reduction FFOV CO2 due to CCS-BEVs	8.077E+01	5.400E+01
N34=N33*B9/B6	Percent reduction US CO2 due to CCS-BEVs	2.644E+01	1.768E+01
Geothermal-powered battery-electric vehicles (geo-BEV)			
O1	Typical plant size (MW)	1.000E+02	1.000E+02

O2 (S46)	Capacity factor	9.700E-01	8.900E-01
O3=O1*O2*1000*D5	Energy per plant before transmission (kWh/yr)	8.497E+08	7.796E+08
O4=O3*G4	Energy per plant after transmission (kWh/yr)	8.072E+08	7.017E+08
O5=E2/M4	Number of geothermal plants to run U.S. geo-BEV	1.513E+03	2.245E+03
O6 (S46, S47)	Geothermal lifecycle CO2 (g-CO2e/kWh)	1.510E+01	5.500E+01
O7 (S46)	H2O consumption from geothermal (gal/kWh)	5.000E-03	5.000E-03
O8=O7*O3*O5	Gal-H2O/yr required to run U.S. geo-BEV	6.428E+09	8.753E+09
O9=O8/I32	Fraction of U.S. water demand for geo-BEV	4.316E-05	5.878E-05
O10 (S46)	Geothermal land requirement (m^2/GWh)	4.040E+02	4.040E+02
O11=O10*O3	Land area (km^2) for one plant	3.433E-01	3.150E-01
O12=O11*O5	Land area (km^2) to run U.S. geo-BEV	5.194E+02	7.072E+02
O13=O12/E7	Fraction of U.S. land for geo-BEV	5.669E-05	7.719E-05
O14=O12/E12	Ratio of geothermal to wind footprint area for BEV	5.664E+02	2.503E+02
O15=O12/E4	Ratio of geothermal to wind spacing area for BEV	1.601E-02	1.106E-02
O16	Lifetime of geothermal power plant (yr)	4.000E+01	3.000E+01
O17 (see text)	Time lag (yr) between planning and operation	3.000E+00	6.000E+00
O18	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
O19=C4*(O17+O18*100yr/O16)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.348E+01	7.710E+01
O20=O19-D21	Geothermal minus wind time lag CO2 (g-CO2e/kWh)	1.015E+00	6.087E+00
O21=(O6+O20)*E2/10^12	Geo-BEV CO2 emissions (MT-CO2e/yr)	1.968E+01	9.624E+01
O22=100*(B9-O21)/B9	Percent reduction FFOV CO2 due to geo-BEVs	9.899E+01	9.508E+01
O23=O22*B9/B6	Percent reduction US CO2 due to geo-BEVs	3.240E+01	3.112E+01
Wave-powered battery-electric vehicles (wave-BEV)			
P1 (S48)	Device size (MW)	7.500E-01	7.500E-01
P2 (S48)	Nominal wave power (kW/m)	5.500E+01	5.500E+01
P3 (S48)	Nominal energy per device before transmis. (kWh/yr)	2.700E+06	2.700E+06
P4 (S49)	Actual wave power (kW/m)	3.400E+01	2.800E+01
P5=(P7/P2)*P3/(P1*D5*1000)	Capacity factor	2.540E-01	2.092E-01
P6=P1*P5*1000*D5	Energy per device before transmission (kWh/yr)	1.669E+06	1.375E+06
P7=P6*G4	Energy per device after transmission (kWh/yr)	1.586E+06	1.237E+06
P8=E2/P7	Number of wave devices to run U.S. wave-BEV	7.703E+05	1.274E+06
P9 (S50)	Wave CO2 emissions (g-CO2e/kWh)	2.170E+01	2.170E+01
P10 (S48)	Width of wave device (m)	3.500E+00	3.500E+00
P11 (S48)	Length of wave device (m)	1.500E+02	1.500E+02
P12=P10*P11/10^6	Ocean surface footprint (km^2) for one wave device	5.250E-04	5.250E-04
P13=P12*P8	Ocean surface footprint (km^2) to run U.S. wave-BEV	4.044E+02	6.686E+02
P14 (S48)	Ocean surface array spacing (km^2) for one wave device	2.500E-02	2.500E-02
P15=P14*P8	Ocean surface array spacing (km^2) to run U.S. wave-BEV	1.926E+04	3.184E+04
P16=P15/E7	Fraction of U.S. land (over the ocean) for wave-BEV	2.102E-03	3.475E-03
P17=P13/E12	Ratio of wave to wind footprint area for BEV	4.410E+02	2.366E+02
P18=P15/E4	Ratio of wave to wind spacing area for BEV	5.936E-01	4.977E-01
P19 (S50)	Lifetime of wave device (yr)	1.500E+01	1.500E+01
P20 (see text)	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
P21	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
P22=C4*(P20+P21*100yr/P19)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	5.276E+01	1.116E+02
P23=P22-D20	Wave minus wind time lag CO2 (g-CO2e/kWh)	2.029E+01	4.058E+01
P24=(P9+P23)*E2/10^12	Wave-BEV CO2 emissions (MT-CO2e/yr)	5.129E+01	9.813E+01

P25=100*(B9-P24)/B9	Percent reduction FFOV CO2 due to wave-BEVs	9.738E+01	9.498E+01
P26=P25*B9/B6	Percent reduction US CO2 due to wave-BEVs	3.187E+01	3.109E+01
P27 (AWEA, 2008S19)	Water for device manufacture (gal-H2O/kWh)	1.000E-03	1.000E-03
P28=P27*P6*P8	Gal-H2O/yr required to run U.S. wave-BEV	1.286E+09	1.751E+09
Tidal-powered battery-electric vehicles (tidal-BEV)			
Q1 (S51)	Tidal turbine rated power (MW)	1.000E+00	1.000E+00
Q2 (S52)	Capacity factor	3.500E-01	2.000E-01
Q3=Q1*Q2*1000*D5	Energy per device before transmission (kWh/yr)	3.066E+06	1.752E+06
Q4=Q3*G4	Energy per device after transmission (kWh/yr)	2.913E+06	1.577E+06
Q5=E2/Q4	Number of tidal devices to run U.S. tidal-BEV	4.193E+05	9.992E+05
Q6 (S37)	Tidal CO2 emissions (g-CO2e/kWh)	1.400E+01	1.400E+01
Q7 (S51)	Turbine rotor diameter (m)	1.150E+01	1.150E+01
Q8 (S51)	Ocean floor footprint (km^2) for one tidal device	2.880E-04	2.880E-04
Q9=Q8*Q5	Ocean floor footprint (km^2) to run U.S. tidal-BEV	1.208E+02	2.878E+02
Q10=(4*Q7)*(7*Q7)/10^6 (S10)	Ocean floor array spacing (km^2) for one tidal device	3.703E-03	3.703E-03
Q11=Q10*Q5	Ocean floor array spacing (km^2) to run U.S. tidal-BEV	1.553E+03	3.700E+03
Q12=Q11/E7	Fraction of U.S. land (over ocean floor) for tidal-BEV	1.695E-04	4.038E-04
Q13=Q9/E12	Ratio of tidal to wind footprint area for BEV	1.317E+02	1.018E+02
Q14=Q11/E4	Ratio of tidal to wind spacing area for BEV	4.786E-02	5.784E-02
Q15 (same as wave)	Lifetime of tidal turbine (yr)	1.500E+01	1.500E+01
Q16 (see text)	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
Q17	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
Q18=C4*(Q16+Q17*100yr/Q15)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	5.276E+01	1.116E+02
Q19=Q18-D21	Tidal minus wind time lag CO2 (g-CO2e/kWh)	2.029E+01	4.058E+01
Q20=(Q6+Q19)*E2/10^12	Tidal-BEV CO2 emissions (MT-CO2e/yr)	4.188E+01	8.599E+01
Q21=100*(B9-Q20)/B9	Percent reduction FFOV CO2 due to tidal-BEVs	9.786E+01	9.560E+01
Q22=Q21*B9/B6	Percent reduction US CO2 due to tidal-BEVs	3.203E+01	3.129E+01
Q23 (S19)	Water for turbine manufacture (gal-H2O/kWh)	1.000E-03	1.000E-03
Q24=Q23*Q3*Q5	Gal-H2O/yr required to run U.S. tidal-BEV	1.286E+09	1.751E+09
U.S. energy consumption			
R1 (S53)	Coal electricity kWh/yr 2007	2.024E+12	2.024E+12
R2 (S53)	Oil electricity kWh/yr 2007	5.364E+10	5.364E+10
R3 (S53)	NatGas electricity kWh/yr 2007	8.815E+11	8.815E+11
R4=E2	WBEV Vehicles kWh/yr 2007	1.221E+12	1.576E+12
R5=(B2+B5)*(R1+R2+R3+R4)/(B6-B2-B5)	Other kWh/yr	2.320E+12	2.517E+12
Number of wind turbines required to displace CO2			
S1=R1/D8	Number of turbines to displace U.S. coal electricity	1.210E+05	1.849E+05
S2=R2/D8	Number of turbines to displace U.S. oil electricity	3.205E+03	4.900E+03
S3=R3/D8	Number of turbines to displace U.S. natgas electricity	5.267E+04	8.052E+04
S4=E3	Number of turbines to power U.S. BEVs	7.298E+04	1.439E+05
S5=R5/D8	Number of turbines to displace other U.S. sources	1.386E+05	2.299E+05
S6=S1+S2+S3+S4+S5	Number of turbines to displace all U.S. CO2	3.884E+05	6.441E+05
S7=B7*S6/B6	Number of turbines to displace world CO2	2.176E+06	3.608E+06

"Ref." refers to references in the main text.

S1. United States Department of Transportation (2008) www.fhwa.dot.gov/Environment/vmtext.htm

S2. Ref. 18
S3. Onroad-vehicle CO_2 was obtained by multiplying the 1999 rate of 1370 MT-CO_2/yr from Ref. 18 by the ratio of 2007 to 1999 total U.S. petroleum CO_2 emissions from Energy Information Administration (2008a) U.S. carbon dioxide emissions from energy sources 2007 flash estimate, www.eia.doe.gov/oiaf/1605/flash/flash.html. Other vehicle CO_2 was obtained by subtracting onroad-vehicle CO_2 and oil-electricity CO_2 (present table) from U.S. petroleum CO_2.
S4. 2007 U.S. coal, natural gas, and oil electricity CO_2 were estimated by scaling 2006 emissions from Energy Information Administration (EIA) (2007b) Emissions of greenhouse gases report, www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html by the 2007 to 2006 ratio of total energy-related CO_2 coal, natural gas, and petroleum from Energy Information Administration (2008a) U.S. carbon dioxide emissions from energy sources 2007 flash estimate, www.eia.doe.gov/oiaf/1605/flash/flash.html. Non-electricity, non-transportation CO_2 was calculated as the total 2007 CO_2 from the same source minus the electricity and transportation emissions from the present table.
S5. Marland, G., T.A. Boden, and R.J. Andres (2008) http://cdiac.ornl.gov/trends/emis/em_cont.htm. 2004 data extrapolated to 2007 using the slope of the carbon emission change per year.
S6. Ref. 58.
S6. Energy Information Administration (EIA) (2002) Updated state-level greenhouse gas emission coefficients for electricity generation 1998-2000, http://tonto.eia.doe.gov/ftproot/environment/e-supdoc-u.pdf. Global warming potentials of 25 and 298 were applied to methane and nitrous oxide, respectively to obtain CO_2e
S7. Ref. 23.
S9. Ref. 116.
S10. Refs. 11, 33.
S11. Ref. 37.
S12. Ref. 117.
S13. Schultz, M.G., T. Diehl, G.P. Brasseur, and W. Zittel (2003) Air pollution and climate-forcing impacts of a global hydrogen economy, Science, 302, 624-627.
S14. National Renewable Energy Laboratory (NREL) (2004) Technology brief: Analysis of current-day commercial electrolyzers, NREL/FS-560-36705, www.nrel.gov/docs/fy04osti/36705.pdf.
S15. Hydro-pac Inc. (2005) C03-40-70/140LX gas compressor for hydrogen specification sheet, www.hydropac.com/HTML/hydrogen-compressor.html.
S16. Table 1, footnote c.
S17. Refs. 40, 44-46,
S18. Ref. 86
S19. Ref. 85.
S20. The low and high range encompass a 2005 Honda gasoline-electric hybrid vehicle tank-to-wheel efficiency of 30% and are both higher than the 2005 Honda gasoline vehicle tank-to-wheel efficiency of about 22% (Fig. 7 of Ref. 18).
S21. Ref. 56. Also, in 2006, an average of 147.5 bushels of corn per harvested acre were produced in the U.S. (11,800 million bushels produced on 80 million acres).
S22. Ref. 77.
S23. Ref. 80.
S24. King, C.W. and M.E. Webber (2008) The water intensity of the plugged-in automotive economy, Environ. Sci. Technol., 42, 4305-4311.
S25. Ref. 81.
S26. Ref. 87.
S27. Ref. 78.
S28. Ref. 61.
S29. Ref. 79.
S30. European Nuclear Society (2008) Nuclear power plants, worldwide, http://www.euronuclear.org/info/npp-ww.htm.
S31. Ref. 20.
S32. Refs. 16, 49-51.
S33. Ref. 84.
S34. Ref. 31.
S35 American Nuclear Society (2008) http://www2.ans.org/pi/brochures/pdfs/power.pdf
S36 Energy Information Administration (EIA) (2006) Average capacity factors by energy source, www.eia.doe.gov/cneaf/electricity/epa/figes3.html, Table 1.

S37. Ref. 40.
S38. Ref. 83 for high value. The low value is estimated by attributing one-third of reservoir water to hydroelectric power.
S39. Low value from Ref. 16 and Table 1 for California solar; high value from Ref. 22.
S40. Ref. 39.
S41. Ref. 38.
S42. Ref. 86 gives CSP land area requirements 0.0203-0.0243 km^2/MW without storage (and 0.0324-0.047 km^2/MW with storage) (Table 3-1) and water requirements of 2.8 m^3/MWh consumption and 0.14 m^3/MWh for cleaning (Section A.1.3); Abengoa Solar (2008) Concentrated solar power, http://www.solucar.es/sites/solar/en/tec_ccp.jsp gives 0.019 km^2/MW without storage (and 0.038 km^2/MW with storage). Ref. 16 gives 0.02 km^2/MW without storage.
S43. Ref. 32.
S44. Ref. 49.
S45. Ref. 85.
S46. Ref. 27.
S47. Ref. 43.
S48. Pelamis Wave Power (2008) P-750 wave energy converter, http://www.pelamiswave.com/media/pelamisbrochure.pdf.
S49. Kane, M. (2005) California small hydropower and ocean wave energy resources, California Energy Commission, CEC-500-2005-075, www.energy.ca.gov/2005publications/CEC-500-2005-074/CEC-500-2005-074.PDF.
S50. Ref. 41.
S51. Ref. 97.
S52. Ref. 28.
S53. Energy Information Administration (2008b) Annual energy outlook 2008, http://www.eia.doe.gov/oiaf/aeo/electricity.html.