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Wind versus biofuels for addressing climate, health, and energy

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The favored approach today for addressing global warming is to promote a variety of options: biofuels, wind, solar thermal, solar photovoltaic, geothermal, and hydroelectric energy and to improve efficiency. However, by far, most emphasis has been on biofuels. Current-technology biofuels, though, cannot address global warming and may slightly increase death and illness due to air pollution. Future biofuels may theoretically slow global warming only slightly and with the cost of increased air pollution mortality. In both cases, the land required renders biofuels an impractical solution. Wind energy combined with the other options can substantially address global warming and health simultaneously.

First, lets look at biofuels, using ethanol as an example. E85 is a fuel containing 85 percent ethanol (which itself contains 5 percent gasoline as a denaturant) and 15 percent gasoline. If enough ethanol-E85 were produced from corn to power all U.S. onroad vehicles, 9.6-17.2 percent of U.S. land (2.2-3.9 Californias) would be needed to grow the corn (*1*). This E85 would reduce U.S. carbon emissions by only 0.6 percent (*2*), and would increase U.S. air-pollution deaths from vehicle exhaust by about 200 per year (*3*) over the current 10,000 per year.

A potential future source of ethanol is switchgrass. However, use of switchgrass for E85 in all U.S. onroad vehicles would require 4.6-16 percent of U.S. land (1-3.6 Californias) (*1*), reduce overall U.S. carbon emissions by at best 13.6 percent (*2*) and increase air-pollution deaths by about 200 per year (*3*). Because switchgrass-ethanol is land-limited and has upper-limit carbon benefits that, if realized, will be wiped out in 15 years by a natural population increase of 13.6 percent, switchgrass cannot solve global warming.

Stopping global warming while accounting for future economic growth requires an 80 percent reduction in current carbon emissions. Wind-energy can address global warming and air pollution health significantly on its own, while requiring relatively little land and providing energy security and minimizing the risk of terrorism. Over a 30-year lifetime, a wind turbine reduces carbon emissions by 97.8 percent (*4*). Since wind can (a) displace almost all carbon from fossil fuels, (b), provide electricity for light bulbs as well as vehicles (c) extract energy over ocean and land, and (d) leave a small footprint on the ground, it is an ideal solution to global warming.

How many current-technology five-megawatt turbines with 126-m diameter blades could run all U.S. onroad vehicles on batteries? About 71,000-122,000, with the low (high) estimates corresponding to 8.5 (7.5) m/s annually-averaged winds, a battery efficiency of 0.86 (0.75), and conversion/transmission/array losses of 10 (15) percent (*1*). This number is less than the 150,000-plus smaller turbines currently installed worldwide. Many of these turbines could be installed offshore, where the annually-averaged wind speed worldwide is 8.6 m/s (*5*).

Arrays of new turbines could reside over an ocean and land area equivalent to 0.35 (0.6) percent of U.S. land (*1*). Thus, wind for battery-electric vehicles would require 28-29 times less land than corn ethanol and 15-27 times less land than switchgrass ethanol for E85 vehicles. The footprint on the ground for all turbine towers to power onroad U.S. vehicles would be a trivial 1.1 (1.9) km^2 (*1*) Almost all the area between turbine towers could be used for farming, ranching, fishing, or open space.

Wind for hydrogen fuel cell vehicles would also eliminate carbon and air pollution but would require about three times the number of turbines and land area as for battery-electric vehicles (*1*) (much less than that for corn or switchgrass ethanol). Since onroad vehicles emit 26 percent of U.S. carbon (*1*), converting to wind for battery-electric or hydrogen fuel-cell vehicles would reduce U.S. carbon emissions by 25.4 percent. Another 120,000-160,000 large wind turbines could displace 29.8 percent more U.S. carbon from coal electricity (*1*). About 374,000-540,000 turbines could displace 97.8 percent of all U.S. carbon (*1*), simultaneously eliminating 50,000 annual air pollution deaths. Globally, wind could replace all fossil-fuel carbon with about 1.75-2.5 million large turbines (assuming use of new technologies, such as battery-electric vehicles) (*1*). Such a conversion would eliminate 800,000 annual outdoor air pollution-related deaths worldwide (*6*).

How much wind is available? From the latest studies, the world's entire energy needs can be satisfied many times over by wind over land and near shore (*5,7*).

Wind raises important issues, such as bird loss. However, if the world were powered on wind, bird loss would be less than 15 percent of the 50 million lost annually from U.S. communication towers alone (*8*) and would be offset by 800,000 human lives and millions of birds saved by eliminating fossil fuels.

Next, wind does not blow predictably. Yet, by interconnecting wind farms through the transmission grid, fast winds at one location compensate for slow winds at another. Other renewables, such as hydroelectric and solar, can also serve as backup, and wind energy stored in hydrogen or batteries does not need to be so predictable.

Finally, while wind turbines affect the scenery, so do all energy sources. Living near a wind farm would appear preferable to living near a power plant emitting chemicals.

In sum, use of biofuels, which do not reduce air pollution and have little climate benefit, at the expense of renewables that do, will cause certain damage as population, energy use, and emissions rise further. Current laws legislating increased renewables are too weak to reduce carbon emissions by 80 percent. Only a large-scale renewable and efficiency program can attain this goal. Because every dollar spent on an ineffective solution to global warming is one less dollar spent on a better solution, investment in all technologies in the hopes that one emerges the winner merely delays a real solution and provides a false sense of security.

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Appendix

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Table S1. Comparitive analysis of replacing U.S. onroad vehicles with wind-battery electric vehicles (WBEV), wind-hydrogen-fuel-cell vehicles (WHFCV), corn-E85 vehicles, and switchgrass-E85 vehicles, and estimates of the number of large wind turbines required to displace all U.S. and world carbon dioxide emissions.

Energy required for vehicles		Low case	High case
A (*S1*)	2006 onroad vehicle miles traveled in the U.S. (mi/yr)	3.160E+12	3.160E+12
B (*S2*)	Fleet mileage of all onroad vehicles (mpg)	1.711E+01	1.711E+01
C=A/B	Gallons of fuel to run all onroad vehicles (gal/yr)	1.847E+11	1.847E+11
D	Lower heating value of gasoline (MJ/kg)	4.400E+01	4.400E+01
E	Gasoline density (kg/m3)	7.500E+02	7.500E+02
F	Gallons per cubic meter (gal/m^3)	2.642E+02	2.642E+02
G=D*E/F	Energy stored in gasoline (MJ/gal)	1.249E+02	1.249E+02
H=C*G	Gross energy to power onroad vehicles (MJ/yr)	2.307E+13	2.307E+13
I (*S2*)	Fleet tank-to-wheel gasoline veh. efficiency (fract.)	1.600E-01	1.800E-01
J=H*I	Net energy to power U.S. onroad veh. 2006 (MJ/yr)	3.691E+12	4.153E+12
K	MJ per kWh	3.600E+00	3.600E+00
L=J/K	Net energy to power U.S. onroad veh. 2006 (kWh/yr)	1.025E+12	1.154E+12
Wind turbine characteristics			
M	Mean annual Rayleigh-distributed wind speed (m/s)	8.500E+00	7.500E+00
N (*S3*)	Turbine rated power (kW)	5.000E+03	5.000E+03
O (*S3*)	Turbine blade diameter (m)	1.260E+02	1.260E+02
P=(0.087*M-N/O^2) (*S4*)	Turbine capacity factor	4.246E-01	3.376E-01
Q	Hours per year (hrs)	8.760E+03	8.760E+03
R=N*Q*P	Turbine energy output without losses (kWh/yr)	1.860E+07	1.479E+07
S	Turbine efficiency (transmis./conversion/arrray losses)	9.000E-01	8.500E-01
T=R*S	Turbine energy output with losses (kWh)	1.674E+07	1.257E+07
U=(7*O)*(4*O)/10^6(*S4*)	Area for one turbine accounting for spacing (km^2)	4.445E-01	4.445E-01
V	Diameter of turbine tubular tower (m)	4.500E+00	4.500E+00
W=pi*(V/2)^2/10^6	Area touching ground of one turbine tower (km^2)	1.590E-05	1.590E-05
Wind-powered battery-electric vehicles (WBEV)			
X (*S5*)	Battery efficiency (delivered to input electricity ratio)	8.600E-01	7.500E-01
Y=L/X	Energy required for batteries for U.S. WBEV (kWh/yr)	1.192E+12	1.538E+12
Z=Y/T	Number of turbines required for U.S. WBEV	7.124E+04	1.224E+05
a=Z*U	Area needed to separate turbines for WBEV (km^2)	3.167E+04	5.440E+04
b	Square km per square mile	2.590E+00	2.590E+00
c	Land area of U.S. (mi^2)	3.537E+06	3.537E+06
d=c*b	Land area of U.S. (km^2)	9.162E+06	9.162E+06
e=a/d	Fraction of U.S. land for turbines for all WBEV	3.457E-03	5.938E-03
f	Land area of California (mi^2)	1.560E+05	1.560E+05
g=f*b	Land area of California (km^2)	4.039E+05	4.039E+05

h=a/g	Fraction of California land for turbines for U.S. WBEV	7.840E-02	1.347E-01
I=Z*W	Turbine tower area touching ground for WBEV (km^2)	1.133E+00	1.946E+00
Wind-powered hydrogen fuel-cell vehicles (WHFCV)			
J (*S2,S5*)	HFCV tank-to-wheel efficiency (fraction)	5.000E-01	4.600E-01
k=J/j	Energy required for U.S. HFCV (MJ/yr)	7.383E+12	9.028E+12
l	Lower heating value of hydrogen (MJ/kg-H_2)	1.200E+02	1.200E+02
m=k/l	Mass of H_2 required for fuel (kg-H2/yr)	6.154E+10	7.526E+10
n (*S6*,*S2*)	Hydrogen leakage rate (fraction)	3.000E-02	3.000E-02
o=m/(1-n)	Mass of H_2 required with leakage (kg-H_2/yr)	6.345E+10	7.758E+10
p	Higher heating value of hydrogen (MJ/kg-H_2)	1.418E+02	1.418E+02
q (*S7*)	Electrolyzer efficiency	7.380E-01	7.380E-01
r=p/(q*K)	Electrolyzer energy required per kg-H_2 (kWh/kg-H2)	5.337E+01	5.337E+01
s (*S8*)	Compressor motor size (kW)	3.000E+01	3.000E+01
t (*S8*)	Electricity use as a function of motor size (fraction)	6.500E-01	6.500E-01
u (*S8*)	Capacity of compressor (kg-H_2/yr)	3.030E+04	3.030E+04
v=Q*s*t/u	Compressor energy required per kg-H_2 (kWh/kg-H_2)	5.639E+00	5.639E+00
w=r+v	Electrolyzer+compressor en req. (kWh/kg-H_2)	5.901E+01	5.901E+01
x=o*w	Electrolyzer+compressor Energy for all H_2 (kWh/yr)	3.744E+12	4.578E+12
y=x/T	Number of turbines required for WHFCV	2.237E+05	3.643E+05
z=y*U	Separation area required for turbines for WHFCV (km^2)	9.944E+04	1.619E+05
AA=z/d	Fraction of U.S. land for turbines for WHFCV	1.085E-02	1.768E-02
BB=z/g	Fraction of California land for turbines for WHFCV	2.462E-01	4.009E-01
CC=W*y	Turbine tower area touching ground for WHFCV (km^2)	3.558E+00	5.794E+00
DD=y/Z	Ratio of turbines for WHFCV to turbines for WBEV	3.140E+00	2.977E+00
Corn Ethanol for vehicles			
EE (*S9*)	Fleet tank-to-wheel efficiency of new E85 vehicles	3.200E-01	2.600E-01
FF=J/EE	Energy required for new E85 vehicles 2006 (MJ/yr)	1.154E+13	1.597E+13
GG	Lower heating value of ethanol (MJ/kg)	2.680E+01	2.680E+01
HH	Density of ethanol (kg/m^3)	7.870E+02	7.870E+02
II=GG*HH/F	Energy in ethanol (MJ/gal)	7.984E+01	7.984E+01
JJ=FF/(0.2*G+0.8*II)	Gal-E85 for 2006 vehicles (gal)	1.298E+11	1.798E+11
KK=JJ*0.8	Gal-ethanol in E85 for U.S. onroad vehicles (gal)	1.039E+11	1.438E+11
LL=JJ-KK	Gal-gasoline in E85 for U.S. onroad vehicles (gal)	2.596E+10	3.595E+10
MM (*S10*)	kg-ethanol per bushel of corn	7.860E+00	7.860E+00
NN (*S10*)	Bushels of corn per acre	1.810E+02	1.400E+02
OO	Square meters per acre	4.047E+03	4.047E+03
PP=MM*F/HH	Gal-ethanol per bushel of corn	2.638E+00	2.638E+00
QQ=PP*NN	Gal-ethanol per acre of dry corn	4.775E+02	3.694E+02
RR=KK/(QQ*10^6)	Million acres of corn for U.S. onroad vehicles	2.175E+02	3.893E+02
SS=RR*OO	Square km of corn for U.S. onroad vehicles	8.801E+05	1.576E+06
TT=SS/d	Fraction of U.S. land for corn-E85 onroad vehicles	9.606E-02	1.720E-01
UU=SS/g	Fraction of California land for corn-E85 onroad veh.	2.179E+00	3.900E+00
Switchgrass ethanol for vehicles			
VV (*S11*)	Tons dry switchgrass/acre	1.000E+01	5.000E+00
WW (*S11*)	Gal-ethanol/ton-dry switchgrass	1.000E+02	8.000E+01
XX=VV*WW	Gal-ethanol/acre	1.000E+03	4.000E+02
YY=KK/(XX*10^6)	Million acres of switchgrass for U.S. onroad vehicles	1.039E+02	3.595E+02
ZZ=YY*OO	Square km of switchgrass for U.S. onroad vehicles	4.203E+05	1.455E+06
aa=ZZ/d	Fraction U.S. land for switchgrass-E85 onroad veh.	4.587E-02	1.588E-01
bb=ZZ/g	Fraction California land for switchgrass-E85 onr. veh.	1.041E+00	3.602E+00
U.S. and world CO2 emissions			
cc (*S12*)	U.S. total fossil-fuel CO_2 emiss. 2005 (MT-CO_2/yr)	6.270E+03	6.270E+03

dd (*S13*)	U.S. onroad vehicle CO_2 emission 2005 (MT-CO_2/yr)	1.620E+03	1.620E+03
ee (*S14*)	U.S. coal-elec. CO_2 emission 2005 (MT-CO_2/yr)	1.910E+03	1.910E+03
ff (*S14*)	U.S. oil-elec. CO_2 emission 2005 (MT-CO2/yr)	1.098E+02	1.098E+02
gg (*S14*)	U.S. nat. gas-elec. CO_2 emission 2005 (MT-CO_2/yr)	4.548E+02	4.548E+02
hh=cc-dd-ee-ff-gg (*S15*)	U.S. all other CO_2 emission 2005 (MT-CO_2/yr)	2.175E+03	2.175E+03
ii (*S12*)	World total fossil-fuel CO_2 emiss. 2005 (MT-CO_2/yr)	2.897E+04	2.897E+04
U.S. energy consumption			
jj (*S14*)	Coal-electricity 2005 (kWh/yr)	2.013E+12	2.013E+12
kk (*S14*)	Oil-electricity 2005 (kWh/yr)	1.230E+11	1.230E+11
ll (*S14*)	Natural gas-electricity 2005 (kWh/yr)	7.580E+11	7.580E+11
mm=Y	Onroad WBEV 2006 (kWh/yr)	1.192E+12	1.538E+12
nn=hh*(jj+kk+ll+mm)/(cc-hh)	All other fossil-fuel energy 2005 (kWh/yr)	2.171E+12	2.171E+12
Number of turbines required to displace CO2			
oo=jj/T	Turbines to displace U.S. coal electricity	1.203E+05	1.602E+05
pp=kk/T	Turbines to displace U.S. oil electricity	7.349E+03	9.787E+03
qq=ll/T	Turbines to displace U.S. natural gas electricity	4.529E+04	6.032E+04
rr=Z	Turbines to displace U.S. onroad vehicles with WBEV	7.124E+04	1.224E+05
ss=nn/T	Turbines to displace all other U.S. fossil-fuel energy	1.297E+05	1.874E+05
tt=oo+pp+qq+rr+ss	Turbines to displace all U.S. fossil-fuel CO_2	3.739E+05	5.400E+05
uu=ii*tt/cc	Turbines to displace world fossil-fuel CO_2	1.727E+06	2.495E+06

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