Emergency Energy Plan

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1. Purpose

This is a plan to enable the United States to transition away from fossil fuel as fast as possible. Large increases in fuel prices have the potential to radically de-stabilize and perhaps even collapse the US economy if we don't take steps to counter them.

It turns out that many people in and out of government have been hard at work planning for this transition. It is now the time to hasten the implementation of those plans.

Note that we will not be able to convert away from fossil fuels in a short period of time, but we should be able to reduce out consumption of oil substantially in five years or less. This should reduce the demand for oil and bring the price down. Even before the reductions start taking effect, it should send a message that investing in oil futures is far from a "sure thing".

I am not claiming credit for most of these ideas. About the only significant contribution I have made is the idea of paying for this by surcharging certain automobile sales.

2. Assumptions

Fossil fuel prices, especially oil, will continue to rise because demand for oil is growing. This is caused by China, and to some extent India, becoming wealthy. China currently has the second largest superhighway system in the world and the Chinese market for new cars is second only to the United States. The projections from the Transportation Technology R&D Center (http://www.transportation.anl.gov/) of Argonne National Labs show that Chinese demand for oil will double roughly every ten years and will surpass US 2004 consumption levels sometime between 2030 and 2041 (http://www.transportation.anl.gov/pdfs/TA/398.pdf).

The US Government is not able to move fast enough to manage the rapidly changing technical environment needed to save our economy from a disaster. The role of government should be to set overall direction and provide incentives. Government cannot move fast enough to manage the details.

Neither the US Government, nor any other single entity in the United States has the resources necessary to make this happen. This has be an “all hands on deck” effort, a little like the mobilization for World War II.

A significant reduction in US oil consumption will drive oil prices down. In other words, whatever reductions we make in one area will drive down prices and take the pressure off making reductions in other areas. It’s possible that even the fact that the US government is providing serious incentives will bring prices down (by scaring away commodities speculators).

Technology roadmaps that make incremental changes to existing technology are much more likely to be successful than big bang projects that replace everything all at once.

One can’t wait for all the issues to be resolved in the fast moving technology area. One has to plan activities around the best estimate of where other parts of the project will be in a few years time.

3. The Plan

The goals of this plan are to encourage changes that will rapidly reduce consumption of petroleum fuels. This plan concentrates on motor vehicles and heating because I believe these industries are well on their way to producing results and this can be accelerated with a little economic incentive. We also need to make sure capital is available for all kinds of renewable energy projects.

3.1. Electric Automobile Incentives

The goals for these electric automobile incentives are threefold:

1. Reduce petroleum consumption.
2. No increase in carbon footprint.
3. Provide incentives for enough renewable electrical power generation to offset the increase in other pollutants that would otherwise result from the increased use of electric vehicles.

Encourage production of fully electric cars (not hybrids). We should do this by providing rebates to electric car purchasers that are funded by surcharges on gasoline only vehicles. Initially, the plan would provide a 50% rebate for Rebate Eligible Electric Vehicle (REEV) purchases. For every vehicle purchased, the plan would also make an Offset Contribution (OC) into a Renewable Electric Power Fund (REPF) to subsidize renewable electrical power generation. Vehicles that incorporate photovoltaic cells would also be eligible to receive some payment from the REPF fund. This plan would be paid for by surcharges on gasoline only vehicles (GVs). Once the sales of REEVs get to the point where the rebates produce a certain surcharge on GVs, the surcharges would be capped and the receipts divided proportionally between the REEV purchasers and the REPF. Once the rebates drop below $500, the program would automatically terminate. Simple hybrid vehicles (HEVs) would not be eligible for rebates, but would also not be surcharged. This plan would apply to ALL vehicles with an empty weight less than 6000 pounds (the intent being to ensure there is no way to make an SUV that isn't part of the plan).

The surcharges would be set by periodically defining a Master Surcharge Rate (MSR). The MSR is the surcharge on a GV that gets 1 mile per gallon on the combined EPA mileage test. The surcharge on any given vehicle would be the MSR divided by the combined EPA mileage rating for that vehicle. The MSR would be set periodically based on forecast REEV sales, but must be within the range of 15,000 and 150,000. The lower limit is intended to proved seed money for the rebate fund. The upper limit is intended to keep GV vehicle prices from exploding when sales of REEVs take off. When the upper limit on the MSR is reached, the rebates and OCs would be reduced to

keep expenditures as close to receipts as possible. The same proportion would be used to reduce the vehicle rebate and the OC.
The vehicle rebate would initially be the minimum of 50% of the actual selling price and $25,000.

The OC to the REPF for a REEV is to be determined by the DOE (using resources at the Transportation R&D Center of Argonne National Labs). The OC amount will be computed as if it were a grant to provide the incentive to install a residential Photo Voltaic Solar Collection system with enough average daily power to charge the REEV for a 30 mile trip. This theoretical grant should be enough to make the system pay for itself in 10 years. The system costs used should be those forecast for one to two years after the vehicle sale.

A GV would be defined as any vehicle that runs on carbon based fuel where the engine runs constantly during the period of time the vehicle is moving.

A REEV would be defined as any vehicle that is capable of traveling at least 40 miles on an internal power source without consuming any sort of carbon based fuel. The internal power source can be a battery charged from the power grid or the internal power source can be some other power source that has no derivation from fossil fuel. This category is intended to include plug-in hybrids (PHEVs) that are capable of traveling 40 miles or more on a charge. A REEV is not required to always operate by first depleting the battery for 40 miles, but it is required to be capable of operating that way. In order to be classified as a REEV, the battery technology used must not contain any hazardous wastes (i.e., no NiMH). In order to be classified as a REEV, the net energy consumption and net carbon production must be less than that of a HEV. Again, the intent here is to cover PHEVs, but we don't want to rule out other technologies that are just as effective. For example, fuel cell vehicles can be as effective, but that depends on how the hydrogen for the fuel cells is derived.

In order to be classified as a REEV, the vehicle must have a carbon footprint equal or better to an equivalently sized HEV. The DOE would be responsible to setting these requirements; however, the net efficiency (aka mileage) of the vehicle will need to meet something like the following performance goals for electric operation:

- 90% or better battery charging efficiency.
- An efficiency target scaled as appropriate for weight and aerodynamics from a baseline. The baseline shall be around 310wH/mi for a 3000 pound vehicle, measured at the wall outlet.

The assumption behind this plan is that we will start out with hybrid vehicles (which are widely available, now). The progression to plug-in hybrids is probably a year or two off when practical battery technology can be put into volume production. In the interim, excluding hybrids from any surcharges should encourage all manufacturers to develop the hybrid technology that is a necessary step to the full PHEV path. The cross-linking with a renewable electrical power generation fund is to compensate for the increased sulfur oxide emissions (aka acid rain) that will result because PHEVs will be charged off the power grid and a lot of that power will come from burning coal. The efficiency requirements for REEVs ensure that any new vehicles are carbon neutral with respect to HEVs.

The rebate approach is preferable to setting up specific timetables, because it gives the auto manufacturers more flexibility in terms of development schedules. If we simply set up incentives, the technology can be developed at the fastest pace possible without government getting in the way.

This plan would be implemented by auto manufacturers and possibly coordinated by the IRS (which already manages temporary financial professionals on a regular basis).

3.2. Heavy Truck Incentives

There should be a plan for heavy trucks, too. The plan for heavy trucks should be similar to the automobile plan; however, it should not emphasize plug-in hybrids. Plug-in hybrid technology won't have much benefit for commercial vehicles, because they are driven much more on a daily basis than personal vehicles. Depending on how the vehicle is being used, hybrid technology will result in 10-50% fuel savings with commercial vehicles. There should be two plans for trucks:

The first plan should provide something like a 25% rebate for hybrids that is paid for by surcharges.

The second plan should offer a 50% tax credit for a full EV (i.e., a vehicle that runs on fuel cells or one that has a large enough battery to run all day on one charge) and that doesn't result in increased pollution. I don't think either of these technologies will be practical in the short term, but I could be wrong (there are busses in service running on fuel cells, now).

3.3. Renewable Electricity Production Incentives

We need to increase renewable electricity production for two reasons:

1. The current electrical power infrastructure is supposed to be able to handle the addition of grid connected EVs in the short term, but in the long term, we are likely to need more capacity.
2. Charging EVs from the grid will increase pollution that causes acid rain if the additional load is taken up by coal-fired plants (which is likely to happen).

We must provide incentives to purchasers of renewable energy production products such as solar cells and wind generators. Right now, we see an American producer of solar cells selling all of their production to Germany because the German government is providing more support. We need to fix that situation. The German plan enacts a minimum price guarantee for all sellers of electric power. This strikes me as a windfall that the owners of coal and oil fired electric plants do not deserve.

A better plan would provide grants from the REPF to approved renewable power projects with the target of allowing those projects to break even on ROI in about ten years. For the most part, projects should be evaluated on a cost benefit basis; however, some preference should be given to projects that generate power close to where it will be consumed (like on garage roofs). When the REPF is exhausted we should continue incentives with tax credits (spread out over several years for large expenditures).

3.4. Solar Heating Incentives

Solar hot water heating technology is quite ubiquitous these days. It can be had from many suppliers. It can't completely replace the burning of fossil fuels in many areas, but it can reduce consumption just about everywhere. In many cases, this technology is cost effective without any help; however, the payback is pretty long-term and there needs to be more motivation to use it. We must restore the 30% tax credits for business and individuals.

We also need to make sure zoning laws and building codes don't inhibit the technology (see *Miscellaneous Enabling*).

3.5. Capital Gains Exemptions

We need to encourage investment in manufacturing capacity for the technologies needed for these conversions. We can do that by waiving all capital gains tax on stock purchased at IPO from American renewable energy companies (even short term capital gains). If logistically practical, this would include capital gains for the initial purchaser at IPO and the purchaser who buys it from the initial purchaser. This capital gains waiver should also apply to stock offerings from existing public companies that are expanding manufacturing capacity for renewable energy technologies.

3.6. Miscellaneous Enabling

There are some things we can do to enhance the adoption of some technologies, such as:

1. Forbid local zoning laws from prohibiting homeowners from installing renewable energy collectors.
2. Establish default building codes for renewable energy collectors that will apply in areas that haven't had time to incorporate this technology into their own building codes.
3. Forbid state governments from preventing municipal power generation.
4. Mandate net billing for electrical power in all states and territories.
5. Mandate that power companies pay for generated power (at premium wholesale rates) when a customer's net power consumption is negative (i.e., when a customer generates more power than they consume during a billing period).
6. Continue to support the Green Jobs Act and expand it if there aren't going to be enough tradesmen trained to implement the REPF grants.

3.7. Government Programs

The existing DOE research programs should be expanded where needed. The Transportation Technology R&D at Argonne National Labs has done a lot of the basic research on electric vehicles and has also been doing a lot of research into the environmental and economic effects of deploying them. The GREET program has been quite helpful in preparing this plan. Obviously, this work needs to be given priority in funding.

4. Technology Roadmap

4.1. Automobiles

I expect that the progression in automobile design will go from the current Hybrid Electric Vehicles to Plug-in Hybrid Electric Vehicles and then to Fuel Cell Electric Vehicles.

4.1.1. Hybrid Electric Vehicles

Hybrid electrical vehicles (HEVs) are vehicles that have a fossil fuel motor driven generator that charges a small battery. The battery acts to smooth out power consumption and, in some cases, allows the fossil fuel motor to shutdown periodically. This means that the fossil fuel motor runs at peak efficiency when turned on and doesn't run all the time. This results in substantial savings in stop and go traffic and modest savings at highway speeds. Most implementations also charge the batteries from braking energy. These have been in production for several years. The Toyota Prius is probably the most prolific. The motors and generators have been refined quite a bit and there are startup companies developing more efficient technologies in anticipation of the coming need (http://www.rasertech.com/technology.html for example). Hybrid vehicles use 30% less energy (30% less gas) than conventional gasoline vehicles. This also results in similar reductions of pollutants.

4.1.2. Plug-in Hybrid Electric Vehicles

Plug-in hybrid vehicles (PHEVs) add more battery capacity and a charger to a hybrid vehicle. The charger enables the battery to be charged from the power grid without using the vehicle's generator. This is quite inelegant, but it's very practical because most people don't drive long distances on a daily basis. That means one can charge the car overnight off the power grid (during non-peak hours) and only use the fossil fuel generator for long trips. For most people, this will result in using about one fourth the energy as a GV. The current technical issue with producing plug-in hybrids with enough range is battery technology. It's possible to do it with the lithium batteries used for computers, but this is somewhat expensive, now. It is pretty likely there will be practical Lithium batteries in the very near future. GM and Toyota are publicly claiming they will have plug-in hybrids available in 2010 (http://www.forbes.com/reuters/feeds/reuters/2008/06/16/2008-06-16T200331Z_01_N16273264_RTRIDST_0_GM-VOLT-UPDATE-1.html).

Note that PHEVs don't eliminate that use of fossil fuels altogether, but they shift consumption of petroleum fuels to electrical energy that is (for the most part) generated by burning coal and natural gas. Estimation of the energy usage of PHEVs is complicated by two factors:

1. The energy consumption varies depending on driving habits (and how diligent drivers are about plugging the car into the charger).
2. They don't exist, yet; so, one can't be as accurate on predictions.

If one never drives more than 40 miles per day, the PHEV can always run off the battery: This is called "Grid" mode, because the battery is charged from the grid and the gasoline engine remains turned off. The opposite of grid mode is when the internal combustion engine is running. This is known as ICE mode (Internal Combustion Engine mode).

I used a rather large spreadsheet from ANL called GREET 1.7 to analyze the efficiency and pollution generated by various auto configurations. The GREET model for PHEVs generates numbers based on what percentage of time the PHEV is operating in grid mode. My own driving habits will probably result in about 80% grid mode. Someone who drives their car for long trips on the weekend and doesn't commute to work would get 35% or lower grid usage. I ran numbers for 40%, 65% and 90%. The information in the GREET model was generated from simulations. There are several electric vehicles actually being produced by small companies, now, and the GREET model seems to slightly underestimate their efficiency. I have used both the numbers generated by the original GREET model and numbers from a slightly modified model that seems to predict the real implementations a little better.

The overall energy efficiency of PHEVs is almost the same as HEVs using the original GREET model. Using the updated model, they become slightly more efficient as the percentage of grid usage goes up. The reduction in petroleum usage for a PHEV runs from 58% to 90% as the grid percentage goes up (it is being supplanted by coal and natural gas, remember). This prediction is essentially the same whether one uses the original GREET model or the updated one.

4.1.2.1. Carbon Footprint of Plug-In Hybrids

The carbon footprint of plug-in hybrids is less than that of a convention gasoline vehicle no matter what model one applies. The improvement is not quite as good as HEVs using the original GREET simulation. Using the updated efficiencies, the carbon emissions improve slightly as the percentage of grid usage goes up. It would appear that recent incremental improvements have tipped the balance here. This implies that it is important to set efficiency requirements for REEVs in order to ensure the carbon footprint stays under that of HEVs.

4.1.2.2. Other Emissions

The increased burning of coal results in quite a bit more sulfur oxides being released and less improvement in nitrous oxides than one sees with HEVs. These are the compounds most responsible for acid rain. This is one reason we need to encourage renewable power generation at the same time we encourage use of new EV technology.

4.1.3. Battery Only Electric Vehicles

Battery only electric vehicles have large batteries that can be charged overnight. A company called Tesla Motors (http://www.teslamotors.com/) is currently shipping a battery-powered sports car with a range of 220 miles. The big problem with battery only electric vehicles is that recharging takes a long time and that makes them impractical for long trips.

4.1.4. Fuel Cell Electric Vehicles

Fuel cell powered vehicles replace the fossil fuel motor and generator in a hybrid with a fuel cell that consumes hydrogen and produces electricity directly. These still need a small battery to handle peak power demands. Ford has demonstrated a concept car called the Edge that has a larger battery that can be charged from the power grid (the same as a plug-in hybrid). Fuel cell powered vehicles are the holy grail of electric cars because they produce no pollution. The big problems with these are the lack of a hydrogen re-fueling network; the fact that fuel cells are relatively expensive; fuel cells haven't been mass produced before; and the technology for efficient production of hydrogen is still under development. That said, Ford and Honda have announced plans to start selling them in about 3 years.

4.2. Heavy Trucks

The same technologies that have been used in cars have been used in heavy trucks. At this point, hybrid busses have been in use for several years and there are some fuel cell busses in use. The army and an organization called CALSTART have been promoting the use of hybrid heavy trucks. According to a CALSTART presentation to Congress (CALSTART_Science_Comm_Testimony_June_2008.pdf), hybrids are just being introduced to selected markets and the result has been successful; however, things are proceeding slowly. They have seen fuel savings in the 10-50 percent range.

Note that the plug-in hybrid concept doesn't make much sense for a heavy truck, because most heavy trucks are used many more hours per day than personal vehicles. I would expect the truck fleet to go hybrid first and then transition to fuel cells. I don't think that battery technology will allow for a battery only commercial truck in the foreseeable future.

4.3. Electrical Power Generation

There are a number of technologies for electrical power generation (Photovoltaic Cells, Solar Collectors, Wind, Geo-Thermal, Hydro). These all have the common property of being hooked up to the power grid. All generating facilities in the United States (and Canada, I believe) are normally connected together in parallel in giant grids (which is why large parts of the country can black out if something goes wrong). The amount current flowing in the grid is controlled by how hard each generator drives the line. The most practical way to exploit new power generation technologies is to connect them into this grid. Historically, power companies in some areas have tried to keep third parties from connecting to the grid in order to maintain control over rates (that is not the reason they give, but it is the real reason). The new technologies, especially solar cells, are often implemented on a small scale and depend on everyone connected to the power grid being able to generate power (and get paid for it). This requires two things:

1. Net billing. This means that the power meter use to monitor a customer's power use runs in both directions. If they are using more power than they generate, the meter runs forward. When they generate more power than they use, the meter runs backward.
2. The power company must buy any customer generated surplus power generated in a billing period.

Transmitting power over long distances encounters some losses. ANL estimates the average losses at 8%. This means it is preferable to generate power near where it will be used.

4.4. Biofuels

4.4.1. Corn Ethanol

Bio-fuel technology based on corn is an all around bust and should not be encouraged. Not only is the net energy from producing corn from alcohol minimal, but also the net CO_2 production is worse than just burning coal or oil (http://seattletimes.nwsource.com/html/nationworld/2004171188_ethanol08.html). Here is another opinion from the New York Times (http://www.nytimes.com/2007/09/19/opinion/19wed1.html?ei=5090&en=3f365e624044ae12&ex=1347854400&adxnnl=1&partner=rssuserland&emc=rss&adxnnlx=1190213412-zHQdh/KF1ym+fXUTheqZBQ).

It is well documented that corn ethanol production is not very efficient. The most accurate estimate (2002) from the USDA (http://www.usda.gov/oce/reports/energy/aer-814.pdf) puts the energy ratio for ethanol production at 1.34. Other estimates have varied from .75 to 1.44. There is a new USDA paper that puts the ratio at 1.67. It does this by making unrealistic assumptions about something called "Energy credits for co-products". The short explanation is that the ethanol production process produces other useful byproducts and some of the energy used in the ethanol production is allocated to the byproducts. Without considering co-products at all, the energy ratio for ethanol production is 1.06. The 1.34 number is derived by considering the energy needed to produce substitutes for the byproducts. The 1.67 number is derived using "ASPEN Plus, a process simulation program, to allocate the energy used in the plants to ethanol and byproducts." Given that it's pretty unlikely that we would build ethanol distillation facilities for the sole purpose of generating these byproducts, this is total nonsense. The 1.34 number appears to be fairly accurate; although, it might be little high because it doesn't include the energy used to build the ethanol plants. Both of the USDA papers are quite enthusiastic about pointing out that ethanol production is not, as earlier papers claimed, a net energy loss. I do agree with the 2002 USDA paper's claim that the low energy ratios from earlier papers are based on old economic data and the 1.34 result is more in line with current farming and manufacturing efficiencies.

Now, let's take a look at what that 1.34 actually means. It means that if the ethanol production enterprise were to be entirely self-supporting, three quarters of the output would have to be used to support itself! Even using the wildly inflated 1.67 ratio, three fifths of the output would have to be used to support itself. This is pretty close to being a fool's errand. By comparison, producing Ethanol from sugar cane has an energy ratio pretty close to 8. That means that for sugar cane, only 1/8 of the fuel produced would need to be used to fuel the plant, harvest the cane and grow it.

4.4.2. Cellulosic Ethanol

Cellulosic ethanol might be a workable. There is one company out there that supposedly has it working (http://www.iogen.ca/), but they haven't started building the plant, yet. There also don't seem to be any positive changes on the web site other than they are trying to get money from the Canadian government and another plant they were supposedly planning on building seems to have mysteriously disappeared; so, this one does have a vaporware look to it.

Cellulosic processes involve using non-food agricultural products, waste agricultural products, and other waste products (i.e., paper). These processes generate the alcohol using enzymes and/or catalysts; so, they have the potential to have usable energy ratios. The carbon footprint for cellulosic ethanol is unknown. There is the claim that the tilling soil for planting things like switch grass results in a negative carbon footprint, but using waste cellulosic waste products that are around anyway seems pretty likely to be neutral (or an improvement over burning).

4.4.3. Other Biofuels

We have been latching onto Ethanol as a fuel because we know how to make it; however, there may actually be better biofuels that can be made using similar enzyme techniques as those used for cellulosic ethanol.

4.5. Battery Re-cycling

NiMH batteries are hazardous wastes. Lithium ion battery technology does not incorporate hazardous waste.

4.5.1. Recycling Lithium Ion Batteries

Lithium batteries don't contain any hazardous waste and can be disposed of; however, there is at least one company recycling them to reclaim the raw materials: http://www.kinsbursky.com/.

4.6. Recharging from the Power Grid

How efficient are electric cars (rechargeable hybrids will be similar)? The GM EV1 vehicle used 300-340 Wh/mi. The Tesla roadster uses round 230 Wh/mi. The Tesla is probably a lot more efficient than a high volume production car would be. OTOH, the EV1 vehicle is somewhat dated. This is going to be a rapidly moving target, but let's assume 280 Wh/mi. Assuming 280 Wh/mi, It will take 9.3kWh to charge batteries for 30 miles of driving. On the average, American cars travel about 30 miles per day. This is similar to the power draw of air conditioners and most recharging would be done overnight (when the AC load is lower).

The following table shows the equivalent gas mileage for electric cars of varying efficiencies. The first column is the claimed electrical efficiency (lower numbers are better). The 2nd column is the vehicle weight. The third column adjusts the vehicle efficiency to compensate for battery charger efficiency. This is assuming 90% efficiency for battery charging. The weight adjusted (Wt Adj) columns are adjusted to project the efficiency of a 3500 lb vehicle. The adjustment is done assuming 3/4 of the power consumption is proportional to the vehicle weight (the rest is overcoming wind drag). The "% Ref" column is relative to a 3500 lb reference gasoline vehicle that gets 23.2 mi/gal.

	Wh/mi	Weight	Chg Adj Wh/mi	Wt Adj Wh/mi	mi/gal	Wt Adj mi/gal	% Ref	30 mi kWh
EV1	**320**	**2910**	**355.6**	**409.6**	**84.6**	**73.9**	**319**	**10.7**
Tesla Roadster	**233**	**2690**	**258.9**	**317.4**	**116.3**	**96.1**	**414**	**7.8**
AC Propulsion tzero	**180**	**2293**	**200.0**	**279.0**	**150.5**	**111.6**	**481**	**6.0**
GM Volt	**280**	**3140**	**311.1**	**337.9**	**96.7**	**89.3**	**385**	**9.3**
AC Propulsion eBox	**260**	**3050**	**288.9**	**320.9**	**104.2**	**94.1**	**406**	**8.7**

5. GREET Model Results

5.1. Updated GREET Model Results (375% GC, 425% EV)

Gasoline Vehicle: CG and RFG

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	267	984	4,950	6,201
Fossil Fuels	259	883	4,847	5,989
Coal	39	163	0	202
Natural Gas	160	305	0	465
Petroleum	60	416	4,847	5,323
CO2	17	67	380	465
CH4	0.460	0.079	0.015	0.554
N2O	0.000	0.005	0.012	0.018
GHGs	29	71	384	484
VOC: Total	0.018	0.118	0.180	0.316
CO: Total	0.033	0.039	3.745	3.817
NOx: Total	0.122	0.116	0.141	0.379
PM10: Total	0.010	0.044	0.029	0.083
PM2.5: Total	0.005	0.016	0.015	0.036
SOx: Total	0.042	0.078	0.006	0.126
VOC: Urban	0.003	0.074	0.112	0.189
CO: Urban	0.001	0.018	2.329	2.348
NOx: Urban	0.005	0.046	0.088	0.140
PM10: Urban	0.000	0.009	0.018	0.027
PM2.5: Urban	0.000	0.005	0.009	0.015
SOx: Urban	0.004	0.033	0.004	0.040

Grid-Connected SI HEV: CG and RFG 40% Grid

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	157	1,214	2,535	3,905
Fossil Fuels	152	1,065	2,426	3,643
Coal	24	593	327	943
Natural Gas	88	283	111	482
Petroleum	41	190	1,988	2,219
CO2	11	140	154	304
CH4	0.341	0.034	0.004	0.379
N2O	0.000	0.004	0.007	0.011
GHGs	19	142	156	317
VOC: Total	0.016	0.050	0.074	0.140
CO: Total	0.019	0.041	2.247	2.307
NOx: Total	0.071	0.152	0.071	0.294
PM10: Total	0.150	0.025	0.025	0.201
PM2.5: Total	0.038	0.010	0.012	0.061
SOx: Total	0.028	0.299	0.003	0.329
VOC: Urban	0.001	0.031	0.046	0.078
CO: Urban	0.001	0.013	1.398	1.411
NOx: Urban	0.004	0.039	0.044	0.087
PM10: Urban	0.000	0.005	0.016	0.021
PM2.5: Urban	0.000	0.003	0.007	0.010
SOx: Urban	0.002	0.062	0.002	0.066

Grid-Connected SI HEV: CG and RFG 65% Grid

Item	Btu/mile or grams/mile Feedstock	Fuel	Vehicle Operation	Total
Total Energy	142	1,557	2,029	3,727
Fossil Fuels	138	1,358	1,896	3,391
Coal	22	894	531	1,447
Natural Gas	75	331	181	586
Petroleum	41	133	1,184	1,358
CO2	10	199	90	299
CH4	0.360	0.022	0.002	0.384
N2O	0.000	0.004	0.004	0.008
GHGs	19	200	91	311
VOC: Total	0.018	0.031	0.043	0.092
CO: Total	0.016	0.051	1.311	1.378
NOx: Total	0.064	0.198	0.041	0.304
PM10: Total	0.239	0.022	0.023	0.285
PM2.5: Total	0.060	0.010	0.010	0.080
SOx: Total	0.028	0.453	0.001	0.482
VOC: Urban	0.001	0.018	0.027	0.046
CO: Urban	0.001	0.014	0.815	0.830
NOx: Urban	0.003	0.044	0.026	0.074
PM10: Urban	0.000	0.004	0.015	0.019
PM2.5: Urban	0.000	0.002	0.006	0.009
SOx: Urban	0.002	0.087	0.001	0.090

Grid-Connected SI HEV: CG and RFG **90% Grid**

Item	Btu/mile or grams/mile Feedstock	Fuel	Vehicle Operation	Total
Total Energy	127	1,900	1,523	3,550
Fossil Fuels	123	1,651	1,365	3,139
Coal	20	1,196	735	1,951
Natural Gas	62	379	250	691
Petroleum	41	76	380	497
CO2	9	258	26	293
CH4	0.378	0.010	0.001	0.389
N2O	0.000	0.004	0.001	0.005
GHGs	19	259	26	304
VOC: Total	0.020	0.012	0.012	0.045
CO: Total	0.014	0.060	0.374	0.449
NOx: Total	0.056	0.245	0.012	0.313
PM10: Total	0.329	0.019	0.021	0.369
PM2.5: Total	0.082	0.010	0.008	0.100
SOx: Total	0.028	0.607	0.000	0.635
VOC: Urban	0.001	0.006	0.008	0.015
CO: Urban	0.001	0.014	0.233	0.248
NOx: Urban	0.003	0.049	0.007	0.060
PM10: Urban	0.000	0.003	0.013	0.017
PM2.5: Urban	0.000	0.002	0.005	0.007
SOx: Urban	0.002	0.112	0.000	0.114

Grid-Connected SI HEV: CG and RFG **100% Grid**

Item	Btu/mile or grams/mile Feedstock	Fuel	Vehicle Operation	Total
Total Energy	121	2,037	1,320	3,479

Fossil Fuels	118	1,768	1,153	3,038
Coal	19	1,316	817	2,153
Natural Gas	57	398	278	733
Petroleum	41	53	58	152
CO2	9	281	0	290
CH4	0.386	0.005	0.000	0.391
N2O	0.000	0.004	0.000	0.004
GHGs	19	282	0	301
VOC: Total	0.021	0.005	0.000	0.026
CO: Total	0.013	0.064	0.000	0.077
NOx: Total	0.053	0.263	0.000	0.317
PM10: Total	0.365	0.018	0.021	0.403
PM2.5: Total	0.091	0.010	0.007	0.108
SOx: Total	0.028	0.668	0.000	0.696
VOC: Urban	0.000	0.001	0.000	0.002
CO: Urban	0.001	0.015	0.000	0.015
NOx: Urban	0.003	0.051	0.000	0.055
PM10: Urban	0.000	0.003	0.013	0.016
PM2.5: Urban	0.000	0.002	0.005	0.007
SOx: Urban	0.002	0.121	0.000	0.123

Electric Vehicle

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	107	1,798	1,165	3,069
Fossil Fuels	104	1,560	1,017	2,681
Coal	17	1,162	721	1,900
Natural Gas	50	351	245	647
Petroleum	36	47	51	134
CO2	8	248	0	256
CH4	0.340	0.005	0.000	0.345
N2O	0.000	0.003	0.000	0.004
GHGs	17	249	0	266
VOC: Total	0.019	0.004	0.000	0.023
CO: Total	0.012	0.057	0.000	0.068
NOx: Total	0.047	0.232	0.000	0.279
PM10: Total	0.322	0.016	0.021	0.358
PM2.5: Total	0.080	0.008	0.007	0.096
SOx: Total	0.025	0.590	0.000	0.614
VOC: Urban	0.000	0.001	0.000	0.002
CO: Urban	0.001	0.013	0.000	0.014
NOx: Urban	0.003	0.045	0.000	0.048
PM10: Urban	0.000	0.003	0.013	0.016
PM2.5: Urban	0.000	0.002	0.005	0.006
SOx: Urban	0.002	0.107	0.000	0.109

Well-to-Wheels Energy and Emission Changes (%, relative to GVs Fueled with CG and RFG)

	Grid-Independent SI HEV: CG and RFG	**Grid-Connected SI HEV: CG and RFG – 40% Grid**	**Grid-Connected SI HEV: CG and RFG – 65% Grid**	**Grid-Connected SI HEV: CG and RFG – 90% Grid**	**Grid-Connected SI HEV: CG and RFG – 100% Grid**	**Electric Vehicle**
Total Energy	-32.4%	-37.0%	-39.9%	-42.8%	-43.9%	-50.5%
Fossil Fuels	-32.4%	-39.2%	-43.4%	-47.6%	-49.3%	-55.2%
Coal	-32.4%	367.7%	617.8%	867.9%	967.9%	842.3%
Natural Gas	-32.4%	3.6%	26.2%	48.7%	57.7%	39.2%

Petroleum	**-32.4%**	**-58.3%**	**-74.5%**	**-90.7%**	**-97.1%**	**-97.5%**
CO2	-32.4%	-34.5%	-35.7%	-37.0%	-37.5%	-44.9%
CH4	-33.0%	-31.6%	-30.7%	-29.8%	-29.4%	-37.7%
N2O	-10.3%	-36.8%	-53.4%	-69.9%	-76.6%	-79.3%
GHGs	-32.2%	-34.4%	-35.8%	-37.2%	-37.7%	-45.0%
VOC: Total	-31.7%	-55.7%	-70.7%	-85.7%	-91.8%	-92.7%
CO: Total	-0.6%	-39.6%	-63.9%	-88.2%	-98.0%	-98.2%
NOx: Total	-26.3%	-22.4%	-19.9%	-17.5%	-16.5%	-26.3%
PM10: Total	-21.3%	**140.6%**	**241.8%**	**343.0%**	**383.5%**	**329.5%**
PM2.5: Total	-19.1%	**68.3%**	**123.0%**	**177.7%**	**199.5%**	**166.7%**
SOx: Total	-32.4%	**162.1%**	**283.8%**	**405.4%**	**454.0%**	**388.8%**
VOC: Urban	-31.7%	-58.6%	-75.4%	-92.3%	-99.0%	-99.1%
CO: Urban	-0.3%	-39.9%	-64.7%	-89.4%	-99.3%	-99.4%
NOx: Urban	-22.1%	-37.6%	-47.2%	-56.9%	-60.7%	-65.3%
PM10: Urban	-11.0%	-22.6%	-29.9%	-37.2%	-40.1%	-41.6%
PM2.5: Urban	-11.9%	-29.1%	-39.9%	-50.6%	-54.9%	-56.6%
SOx: Urban	-32.4%	**62.7%**	**122.1%**	**181.6%**	**205.4%**	**169.4%**

Ratios of Vehicle Fuel Economy and Emissions by Advanced and Alternative-Fueled Vehicles (from the *Inputs* sheet),

(SI technologies are relative to GVs fueled with baseline gasoline.)

	Grid-Independent SI HEV: CG and RFG	Grid-Connected SI HEV: CG and RFG, ICE Mode	Grid-Independent SI ICE HEV: H2	Grid-Connected SI ICE HEV: H2, ICE Mode	Grid-Connected SI HEV: Low-Level EtOH Blend with Gasoline, Grid Mode	Grid-Connected SI ICE HEV: H2, Grid Mode	Electric Vehicle
MPG (per gasoline equivalent gallon)	148.0%	148.0%	160.0%	160.0%	500.0%	500.0%	550.0%
VOC: exhaust	54.0%	54.0%	20.0%	20.0%	0.0%	0.0%	0.0%
VOC: evaporative	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CO	100.0%	100.0%	20.0%	20.0%	0.0%	0.0%	0.0%
NOx	84.0%	84.0%	84.0%	84.0%	0.0%	0.0%	0.0%
PM10: exhaust	100.0%	100.0%	10.0%	10.0%	0.0%	0.0%	0.0%
PM10: brake and tire wear	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
PM2.5: exhaust	100.0%	100.0%	10.0%	10.0%	0.0%	0.0%	0.0%
PM2.5: brake and tire wear	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
CH4	47.0%	47.0%	10.0%	10.0%	0.0%	0.0%	0.0%
N2O	100.0%	100.0%	100.0%	100.0%	0.0%	0.0%	0.0%

5.2. Original GREET estimates (300% PHEV, 350% EV)

Grid-Connected SI HEV: CG and RFG **40% Grid**

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	169	1,418	2,667	4,253
Fossil Fuels	164	1,242	2,542	3,947
Coal	25	724	408	1,158

Natural Gas	93	322	139	555
Petroleum	45	195	1,994	2,234
CO2	12	168	154	334
CH4	0.380	0.035	0.004	0.418
N2O	0.000	0.004	0.007	0.012
GHGs	21	170	156	347
VOC: Total	0.018	0.050	0.074	0.142
CO: Total	0.020	0.048	2.247	2.315
NOx: Total	0.076	0.179	0.071	0.326
PM10: Total	0.187	0.027	0.025	0.239
PM2.5: Total	0.048	0.011	0.012	0.071
SOx: Total	0.031	0.366	0.003	0.399
VOC: Urban	0.001	0.031	0.046	0.078
CO: Urban	0.001	0.014	1.398	1.413
NOx: Urban	0.004	0.045	0.044	0.093
PM10: Urban	0.000	0.005	0.016	0.021
PM2.5: Urban	0.000	0.003	0.007	0.010
SOx: Urban	0.002	0.074	0.002	0.078

Grid-Connected SI HEV: CG and RFG **65% Grid**

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	161	1,888	2,243	4,293
Fossil Fuels	157	1,645	2,083	3,885
Coal	25	1,108	664	1,797
Natural Gas	84	395	226	706
Petroleum	48	142	1,193	1,383
CO2	12	244	90	346
CH4	0.422	0.023	0.002	0.448
N2O	0.000	0.004	0.004	0.009
GHGs	22	246	91	360
VOC: Total	0.021	0.032	0.043	0.097
CO: Total	0.018	0.061	1.311	1.390
NOx: Total	0.072	0.241	0.041	0.355
PM10: Total	0.299	0.025	0.023	0.347
PM2.5: Total	0.075	0.012	0.010	0.097
SOx: Total	0.032	0.561	0.001	0.595
VOC: Urban	0.001	0.019	0.027	0.047
CO: Urban	0.001	0.016	0.815	0.832
NOx: Urban	0.004	0.053	0.026	0.083
PM10: Urban	0.000	0.005	0.015	0.019
PM2.5: Urban	0.000	0.003	0.006	0.009
SOx: Urban	0.002	0.106	0.001	0.110

Grid-Connected SI HEV: CG and RFG **90% Grid**

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	154	2,359	1,820	4,332
Fossil Fuels	150	2,048	1,625	3,823
Coal	24	1,492	919	2,436
Natural Gas	75	468	313	856
Petroleum	50	88	393	531
CO2	12	321	26	358
CH4	0.465	0.011	0.001	0.477
N2O	0.000	0.005	0.001	0.006
GHGs	23	322	26	372
VOC: Total	0.025	0.013	0.012	0.051

CO: Total	0.017	0.075	0.374	0.466
NOx: Total	0.068	0.304	0.012	0.384
PM10: Total	0.411	0.023	0.021	0.455
PM2.5: Total	0.103	0.012	0.008	0.123
SOx: Total	0.034	0.757	0.000	0.792
VOC: Urban	0.001	0.007	0.008	0.015
CO: Urban	0.001	0.018	0.233	0.251
NOx: Urban	0.004	0.061	0.007	0.073
PM10: Urban	0.000	0.004	0.013	0.018
PM2.5: Urban	0.000	0.002	0.005	0.008
SOx: Urban	0.002	0.139	0.000	0.141

Grid-Connected SI HEV: CG and RFG **100% Grid**

	Btu/mile or grams/mile			
Item	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	151	2,547	1,650	4,348
Fossil Fuels	147	2,210	1,441	3,798
Coal	24	1,645	1,021	2,691
Natural Gas	71	497	348	916
Petroleum	51	67	72	190
CO2	12	351	0	363
CH4	0.482	0.007	0.000	0.489
N2O	0.000	0.005	0.000	0.005
GHGs	24	353	0	377
VOC: Total	0.026	0.006	0.000	0.033
CO: Total	0.016	0.080	0.000	0.097
NOx: Total	0.067	0.329	0.000	0.396
PM10: Total	0.456	0.022	0.021	0.499
PM2.5: Total	0.114	0.012	0.007	0.133
SOx: Total	0.035	0.835	0.000	0.870
VOC: Urban	0.001	0.002	0.000	0.002
CO: Urban	0.001	0.018	0.000	0.019
NOx: Urban	0.004	0.064	0.000	0.068
PM10: Urban	0.000	0.004	0.013	0.017
PM2.5: Urban	0.000	0.002	0.005	0.007
SOx: Urban	0.002	0.152	0.000	0.154

Electric Vehicle

	Btu/mile or grams/mile			
Item	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	130	2,183	1,414	3,727
Fossil Fuels	126	1,894	1,235	3,255
Coal	21	1,410	875	2,307
Natural Gas	61	426	298	785
Petroleum	44	57	62	163
CO2	10	301	0	311
CH4	0.413	0.006	0.000	0.419
N2O	0.000	0.004	0.000	0.004
GHGs	20	303	0	323
VOC: Total	0.023	0.005	0.000	0.028
CO: Total	0.014	0.069	0.000	0.083
NOx: Total	0.057	0.282	0.000	0.339
PM10: Total	0.391	0.019	0.021	0.430
PM2.5: Total	0.098	0.010	0.007	0.115
SOx: Total	0.030	0.716	0.000	0.746
VOC: Urban	0.001	0.001	0.000	0.002
CO: Urban	0.001	0.016	0.000	0.016
NOx: Urban	0.004	0.055	0.000	0.059

PM10: Urban	0.000	0.003	0.013	0.016
PM2.5: Urban	0.000	0.002	0.005	0.007
SOx: Urban	0.002	0.130	0.000	0.132

Well-to-Wheels Energy and Emission Changes (%, relative to GVs Fueled with CG and RFG)

	Grid-Independent SI HEV: CG and RFG	**Grid-Connected SI HEV: CG and RFG – 40% Grid**	**Grid-Connected SI HEV: CG and RFG – 65% Grid**	**Grid-Connected SI HEV: CG and RFG – 90% Grid**	**Grid-Connected SI HEV: CG and RFG – 100% Grid**	**Electric Vehicle**
Total Energy	-32.4%	-31.4%	-30.8%	-30.1%	-29.9%	-39.9%
Fossil Fuels	-32.4%	-34.1%	-35.1%	-36.2%	-36.6%	-45.7%
Coal	-32.4%	474.5%	791.3%	1108.1%	1234.9%	1044.2%
Natural Gas	-32.4%	19.4%	51.8%	84.2%	97.1%	69.0%
Petroleum	**-32.4%**	**-58.0%**	**-74.0%**	**-90.0%**	**-96.4%**	**-96.9%**
CO2	-32.4%	-28.2%	-25.6%	-22.9%	-21.9%	-33.0%
CH4	-33.0%	-24.5%	-19.2%	-13.9%	-11.8%	-24.4%
N2O	-10.3%	-34.4%	-49.6%	-64.7%	-70.7%	-74.9%
GHGs	-32.2%	-28.2%	-25.7%	-23.1%	-22.1%	-33.3%
VOC: Total	-31.7%	-54.9%	-69.4%	-83.9%	-89.7%	-91.2%
CO: Total	-0.6%	-39.4%	-63.6%	-87.8%	-97.5%	-97.8%
NOx: Total	-26.3%	-14.0%	-6.4%	**1.3%**	**4.4%**	-10.5%
PM10: Total	-21.3%	**186.5%**	**316.4%**	**446.3%**	**498.2%**	**416.3%**
PM2.5: Total	-19.1%	**96.3%**	**168.4%**	**240.5%**	**269.3%**	**219.5%**
SOx: Total	-32.4%	**217.5%**	**373.8%**	**530.0%**	**592.5%**	**493.6%**
VOC: Urban	-31.7%	-58.5%	-75.3%	-92.1%	-98.8%	-98.9%
CO: Urban	-0.3%	-39.8%	-64.6%	-89.3%	-99.2%	-99.3%
NOx: Urban	-22.1%	-33.6%	-40.8%	-48.0%	-50.9%	-57.9%
PM10: Urban	-11.0%	-21.4%	-27.9%	-34.4%	-37.0%	-39.2%
PM2.5: Urban	-11.9%	-27.7%	-37.6%	-47.5%	-51.5%	-54.0%
SOx: Urban	-32.4%	**93.2%**	**171.8%**	**250.3%**	**281.7%**	**227.2%**

Ratios of Vehicle Fuel Economy and Emissions by Advanced and Alternative-Fueled Vehicles (from the *Inputs* sheet),

(SI technologies are relative to GVs fueled with baseline gasoline.)

	Grid-Independent SI HEV: CG and RFG	**Grid-Connected SI HEV: CG and RFG, ICE Mode**	**Grid-Independent SI ICE HEV: H2**	**Grid-Connected SI ICE HEV: H2, ICE Mode**	**Grid-Connected SI HEV: Low-Level EtOH Blend with Gasoline, Grid Mode**	**Grid-Connected SI ICE HEV: H2, Grid Mode**	**Electric Vehicle**
MPG (per gasoline equivalent gallon)	148.0%	148.0%	160.0%	160.0%	300.0%	300.0%	350.0%
VOC: exhaust	54.0%	54.0%	20.0%	20.0%	0.0%	0.0%	0.0%
VOC: evaporative	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CO	100.0%	100.0%	20.0%	20.0%	0.0%	0.0%	0.0%
NOx	84.0%	84.0%	84.0%	84.0%	0.0%	0.0%	0.0%
PM10: exhaust	100.0%	100.0%	10.0%	10.0%	0.0%	0.0%	0.0%
PM10: brake and tire wear	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
PM2.5: exhaust	100.0%	100.0%	10.0%	10.0%	0.0%	0.0%	0.0%
PM2.5: brake and tire wear	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
CH4	47.0%	47.0%	10.0%	10.0%	0.0%	0.0%	0.0%
N2O	100.0%	100.0%	100.0%	100.0%	0.0%	0.0%	0.0%