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Environmental Efficiency of Automobile Energy Choices

Peter V. Schwartz, *California Polytechnic State University, San Luis Obispo*
Chiweng Kam, *California Polytechnic State University - San Luis Obispo*
John Ross, Dr, *California Polytechnic State University, San Luis Obispo*

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Chiweng Kam[1], *John Ross, Peter V. Schwartz*,*

Physics Department, California Polytechnic State University, San Luis Obispo

We introduce three efficiency metrics to compare two alternative transportation energy technologies: internal combustion engines (ICE) using bioethanol versus battery electric vehicles (BEV) charged from solar thermal electric (STE) generation. Both technologies require the use of the land surface area, consume water, and emit CO_2. Travel efficiencies are measured in km/m^2 of land used annually, km/L of water used, and km/kg of emitted CO_2. Solar-electrical transportation utilizes land more than 200 times as efficiently, water more than 100 times as efficiently (when dry cooling of turbines is used), and emits less than 1/60th of the CO_2 per kilometer traveled as does bioethanol combustion.

Introduction

In recent years, there has been a trend to investigate nonpetroleum liquid fuels for internal combustion engines. Patzek and Pimentel (1), Hill (2), Shapouri (3) and many others have written on the topic of the net energy balance (NEB) of corn grain ethanol, indicating an NEB roughly equal to unity. NEB adds the energy value of any coproduct and subtracts off energy inputs required over the production life cycle.

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[1] Electrical Engineering Department, University of Notre Dame

[1]* Corresponding author phone: 805-756-1220; e-mail: pschwart@calpoly.edu

Farrell et al. (4) compiled the results of several papers into a single database (the ERG Biofuel Analysis Meta Model, EBAMM (5)). Several metrics have been used throughout this body of research, but all focus exclusively on energy and emissions rather than on use of natural resources. As observed at the conclusion of Farrell's paper, new metrics are needed to facilitate policy discussion and decisions pertaining to biofuels. Herein, we present metrics for kilometers traveled per "natural capital" used (land, water, and CO_2 emissions) (6).

Measuring transportation efficiency in miles per gallon (MPG) of fuel is limiting for two reasons. First, MPG doesn't reflect associated costs for embodied energy, pollution, and use of land and water. Second, it doesn't allow comparison with other transportation technologies, such as solar electricity. With three metrics described here, we compare efficiency of bioethanol vehicles with internal combustion engines (ICE) to solar thermal electric (STE) charged Battery Electric Vehicles (BEV). First, we compare energy production efficiencies for corn grain ethanol (CGE), switchgrass ethanol (SE), and STE, with respect to:

Gross Energy per land surface area, annually: MJ/(m^2yr),

NEB per surface area, annually: MJ/(m^2yr),

Gross Energy per water used: MJ/liter, and

Gross Energy CO_2 emitted: MJ/kg(CO_2).

Using the known mileage of BEVs and ethanol burning ICE vehicles, we are able to compare bioethanol to solar electric transportation in terms of kilometers driven: per surface area used annually: km/(m^2yr), per water used: (km/liter), and per kilogram of CO_2 emitted: (km/kg(CO_2)).

Previous analysis examined the land, water and CO_2 consumption for various renewable energy scenarios individually. One metric is power density (W/m^2 of earth's surface) (7). Mulder et al. performed a comparative analysis on Energy Return on Water Invested (EROWI, L/MJ) for several technologies (8). King and Webber discussed the water usage per mile driven for light-duty vehicles

(LDVs) and found that Plug-in Hybrid electric vehicles (PHEV) powered by the U.S grid consume 1/117th and withdraw 1/5th the water consumed by LDVs for fuel that is 85% ethanol (from corn grain in irrigated fields) and 15% gasoline (E85) (9-10). A life-cycle assessment (LCA) of greenhouse gases (GHG) emissions by Samaras and Meisterling indicates that current U.S-gridded PHEV could emit more CO_2/km than a fuel-efficient E85 fueled ICE, pointing out that the carbon intensity of electricity generation strongly influences PHEV emissions (11). Huang and Zhang perform a biomass-to-wheel energy efficiency analysis (12). Gifford and Brown performed well-to-wheels (WTW) analysis for water usage, CO_2 emissions, and primary energy consumption for 30 automotive transportation scenarios (13). There is overlap between our study and previous studies. However, BEVs powered by solar energy is a new scenario, which may be more sustainable.

When multiple data points are available for a single measurement, we report the average and standard deviation. This analysis considers three components of "natural capital" use: harvesting and farming of the feedstock, processing and refining of feedstock to fuel, and fuel efficiency of the vehicle. We do not consider the resources consumed in transportation of fuel and feedstock, nor those in the construction of ethanol facilities. These facilities often have other purposes and last many years. Since STE plants are single purpose, we include resources used in the plants' life-cycle (manufacture and dismantle).

Annual Produced Energy per Area of Land Used

Bioethanols

In this section, we analyze production and refining of CGE and SE, panicum virgatum – claimed twice as efficient an ethanol crop as corn per unit area and able to grow on marginal crop land (14). We consider both gross energy and NEB. Gross energy production considers only the chemical potential energy of the ethanol output, where NEB considers energy of coproducts as well as energy inputs required over the production life cycle. For instance, DDGS (Distiller's Dry Grains with Solubles), coproduct of ethanol, is cattle feed (14). The embodied energy of displaced cattle feed is credited to ethanol's NEB but not its gross energy. Additionally, the NEB calculation of the SE ethanol includes the recycled biomass energy (RBE) (4) produced from burning the lignin coproduct.

We consulted each paper (1-4, 15-17) for input and output energies, coproduction credit, and annual fuel production per square meter. We calculated means and standard deviation for gross energy output and NEB for both CGE and SE. In the case of papers covered by the EBAMM v1.1 database (18), the adjusted values were used when available. In the case of non-EBAMM papers, unavailable data were replaced with the mean values of the papers in EBAMM. Farrell et al. define the 'adjusted' EBAMM values as "adjusted for commensurate system boundaries" by "adding missing parameters (e.g., effluent processing energy) and dropping extraneous ones (e.g., laborer food energy)".

STE

Table I displays land use efficiency of the Solar Energy Generating Systems (SEGS) thermal plants, consisting of nine parabolic trough facilities in California's Mojave Desert with turbine capacities ranging from 14 MW – 80 MW). All plants in Table 1 are currently operational. Using the geospatial data provided by the CaSIL (California Spatial Information Library) database (19), a geographic information software, ArcGIS (20), was used to measure the total land footprints. Performance data are provided by NREL (21) and the facilities themselves (22).

TABLE 1. California Solar Thermal Plants

Plant	Total Solar Field (ha) (21)	Total footprint (ha) (20)	Net Turbine Capacity (MW_e) (21)	Total Solar Electricity Output (GWh/yr) (22)	MJ_e/ (m^2yr)	Power Density (W/m^2)
SEGS I & II	25	100	43.8	49	176	11.2
SEGS III – VII	108	400	150	343	308	19.6
SEGS VIII & IX	95	383	160	263	247	15.7

The total footprint in Table 1 accounts for the usable space occupied by the SEGS plants. The annual solar electricity output for each plant is obtained from their performance data between 1998 and 2002 (22) as shown in Table 1. The electricity generated by the dispatch system (e.g. gas boiler) is not included. The SEGS plants produce 244±66 MJ_e/m^2 solar electricity annually on average, consistent with Mackay's rough estimate for yearly time-averaged electric power density of concentrating solar power (desert) of 15 W_e/m^2 (23). The NEB for the SEGS STE plants is calculated based on the energy input of 0.14-0.16 MJ_e/kWh of electricity energy to build and dismantle the power plant (24). A recent LCA by NREL proposes a reference parabolic Trough Concentrating Solar Power plant (103 MW net capacity) with cumulative energy demand of 0.40 and 0.43 MJ_{eq}/kWh for wet-cooled design and dry-cooled design, respectively (25). A value of 0.42 MJ_{eq}/kWh is adopted for this analysis, corresponding to parasitic losses of about 12%. We are not evaluating the use of rooftop photovoltaic systems, which would have infinite energy production per surface area because the solar panels do not require usable space.

Figure 1 compares the annual energy produced in MJ/m^2 for bioethanol and STE. The uncertainty intervals represent one standard derivation among data collected. The uncertainty intervals for CGE NEB drop below zero representing net energy loss due to large energy input in ethanol production.

Meanwhile, the net energy for the solar technologies is very close to the gross energy output due to STE's low input energy requirements.

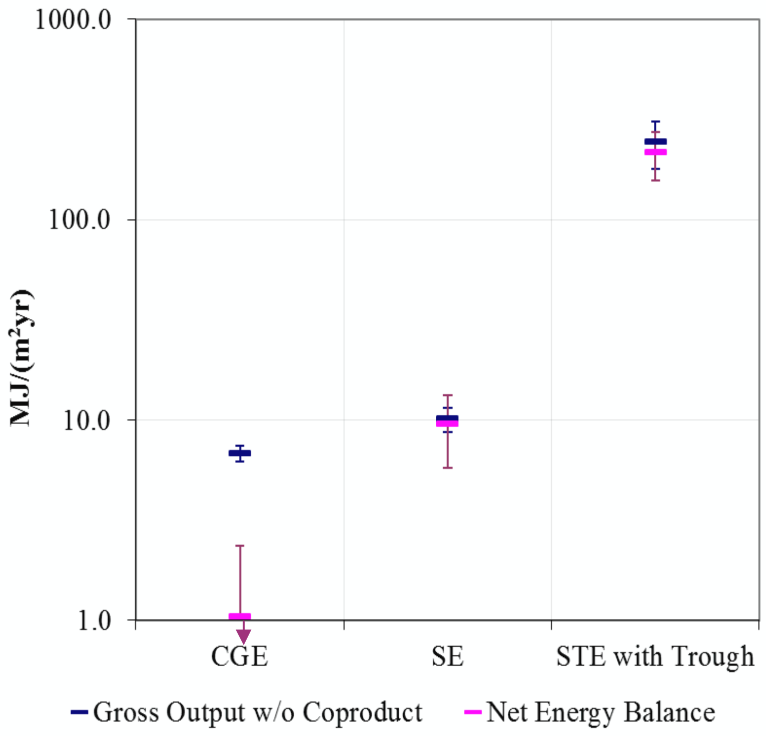

Figure 1 Annual Energy Produced per Square Meter of Land Used for Corn Grain Ethanol (CGE), Switchgrass Ethanol (SE) and Solar Thermal Electric (STE)

Annual Produced Energy per Liter of Water Used

Bioethanol

Previous studies in water use make a distinction between consumption and withdrawal (8-10, 26). Water consumption refers to water extracted from the source and not returned (e.g. evaporated water in the cooling tower) whereas cooling water may be withdrawn and returned to the source (8). In the context of STE plants studied herein, water consumption and withdrawal are the same because plants are located in deserts, away from large water bodies, and use evaporative cooling. For parity, only water consumption is considered for biofuel analysis.

Water is used to grow crops as well as to process ethanol from biomass. Processing corn grain consumes 4.5±0.7 liters of water per liter of ethanol produced (L/L) (27). An Argonne National Labs (ANL) study reports that water consumption has declined from 6.8 L/L to 3.0 L/L in the past ten years through production of wet distillers grain (WDG) as co-products instead of DDGS in dry mill plants (28). We use a value of 4.7 liters/liters.

The ANL report calculates total water consumed including irrigation with data from the US Department of Agriculture (USDA). Water consumption ranges from 7 L/L to 320.6 L/L due to different regional irrigation requirements. For cellulosic ethanol (from switchgrass), water consumption is less than 10 L/L because swtichgrass should require no irrigation (28). Chiu et al. reference several studies placing total water consumption between 263 and 784 L/L. Their own analysis yields 5 to 2000 L/L (26). By taking the average values from available references, CGE has a value of 540±340 L/L and SE: 5.9±5.6 L/L. The biofuel energy produced per liter of water used is shown in Figure 2. The first entry for bioethanol includes the irrigation water used for growing corn, whereas the second entry only accounts for water used in refining.

STE

A number of existing solar thermal plants use 'wet' cooling where water is evaporated to increase plant efficiency. For a wet-cooled STE plant, plant operation typically accounts for 90% of water consumption (25,29) with 10% for plant construction and dismantling, etc. During operation, water required for cooling alone accounts for 2600 - 3400 L/MWh_e (30-31), with an additional 10% used for maintenance such as washing the mirrors. The resulting operational water consumption is 2900 - 3800 liters per MWh, matching the value of 3585 L/MWh from a recent publication by NREL (32). Data from SEGS plants (III-VII) in 1995 place the water used for the wet cooling system 3100 - 3800 L/MWh (33). The NREL paper also compares a dry-cooling system and a wet-cooling system. Dry-cooling systems force air over a network of heat exchangers, known as an air-cooled condenser (ACC), and reduce water consumption by 93% (32) during operation. Another study (25) provides a complete lifecycle comparison showing that a dry-cooling system uses 77% less water, has 6% lower output (34), and has 8% greater cumulative energy demand (CED) and GHG emission (25). Thus, the life-cycle water consumption of a dry-cooled STE plant can be calculated to be 660 - 870 L/MWh$_e$. Water data from two hypothetical parabolic trough plants shows 3700 liters and 4700 liters per MWh$_e$ for wet-cooling, 300 liters and 1100 liters per MWh$_e$ for dry-cooling, respectively (25,35). Converting units yields 1.1±0.15 MJ/L (wet-cooled), and 10.3±1.4 MJ/L (dry-cooled).

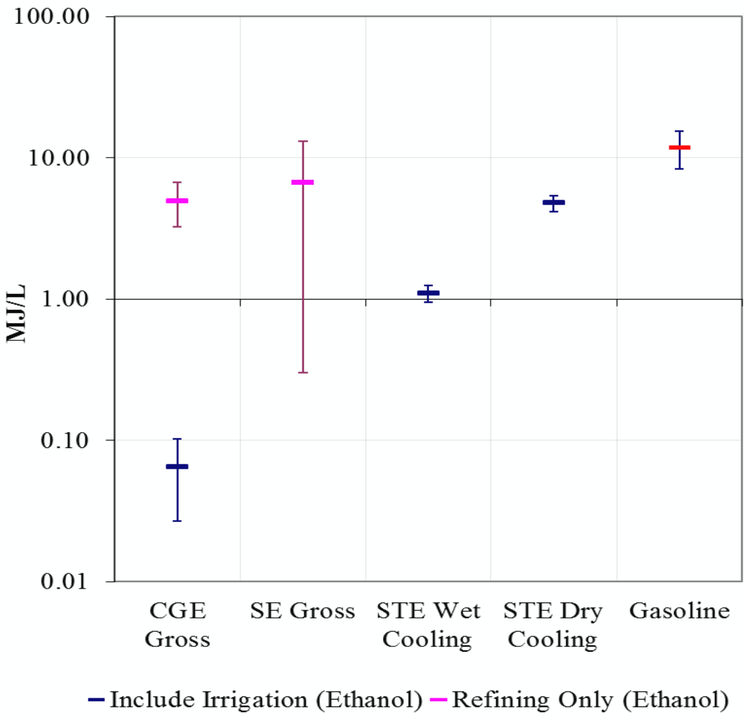

Figure 2 Annual Energy Produced (MJ) per liter of Water Used

Figure 2 compares bioethanol and STE for annual energy produced per amount of water used (MJ/L). Gasoline data are added for comparison; it takes approximately 3.9 gallons of water to produce one gallon of gasoline (28).

Energy Produced per Emitted CO_2

Bioethanol

To determine the greenhouse gas emissions of bioethanols, we averaged values from EBAMM and the California Air Resources Board (CARB) (36) in Figure 3. We included coproduction credited in some EBAMM source papers and gasoline for comparison (37).

STE

The data for STE GHG emissions include both the embodied emissions of the physical plant levelized over the projected project lifetime (typically 25 years) and emissions associated with operations and maintenance (31). We separately consider central receiver and parabolic trough STE due to a statistically significant difference. The original data in Lenzen (1999) estimates GHG Cost (GGC) at 60 gCO_2/kWh_e for central receiver and 90 gCO_2/kWh_e for parabolic tough (31). More recently, a literature review (24) places the range for central receiver STE between 11 and 48 gCO_2/kWh_e and parabolic trough STE between 10 gCO_2/kWh_e and 80 gCO_2/kWh_e. Figure 3 displays the net energy produced per emitted kg of CO_2.

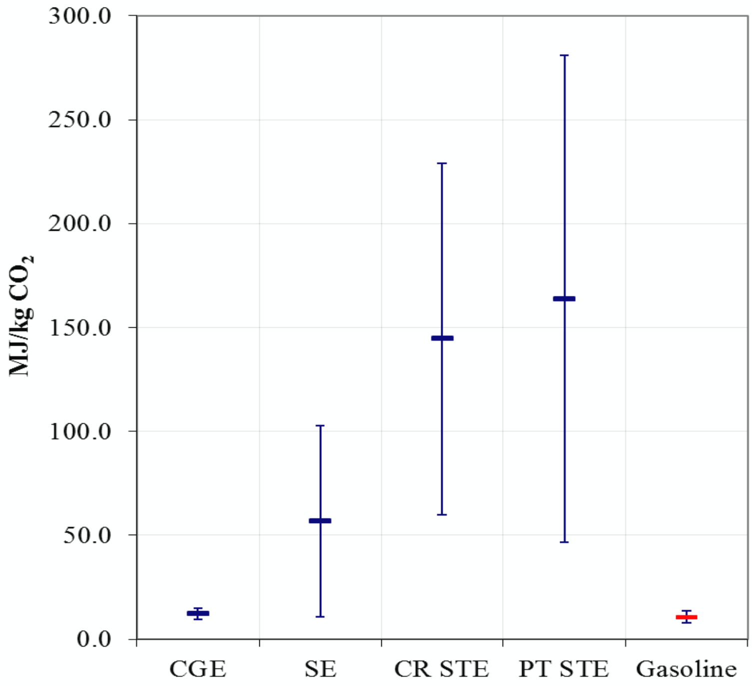

Figure 3 Energy Produced (MJ) per kilogram of CO_2 Emitted. CR: Central Receiver, PT: Parabolic Trough.

Mileage Efficiency

Bioethanols

In a recent study, we compared Environmental Protection Agency (EPA) mileage estimates between BEVs and similar gasoline vehicles, finding that electricity converts to motion 4 to 6.5 times more efficiently than does the chemical energy of gasoline (38). The same study also reports the fuel efficiencies for two BEVs, Tesla Roadster and Ebox, are 6.68 km/kWh and 5.56 km/kWh. With electrical transmission line losses of 8%, the travel efficiencies for the BEVs are 1.68 to 2.01 km/MJ. A CARB study (39) reports that in an ICE, E85 converts to 3-9% more mechanical energy than does the same amount of gasoline energy; we use 5%.

The average fuel economy of 2009 US domestically sold manual transmission sedans is 23.2 miles per gallon (40), or about 0.283 km/MJ of chemical energy in gasoline.

According to an LCA of ICE and BEV, the only difference in embodied vehicle CO_2 is due to the BEV's Li-ion battery (41). Along with two other studies (11,42), the average CO_2 emissions due to the battery alone are 0.7 g CO_2 per km traveled, which we account for. These estimates correspond to 0.22 km/MJ of chemical energy in ethanol and 1.8 km/MJ of electricity used. We combine these transportation efficiencies with the energy production efficiencies expressed above to yield the travel efficiencies with respect to land used (Figure 4), water used (Figure 5) and CO_2 emitted (Figure 6).

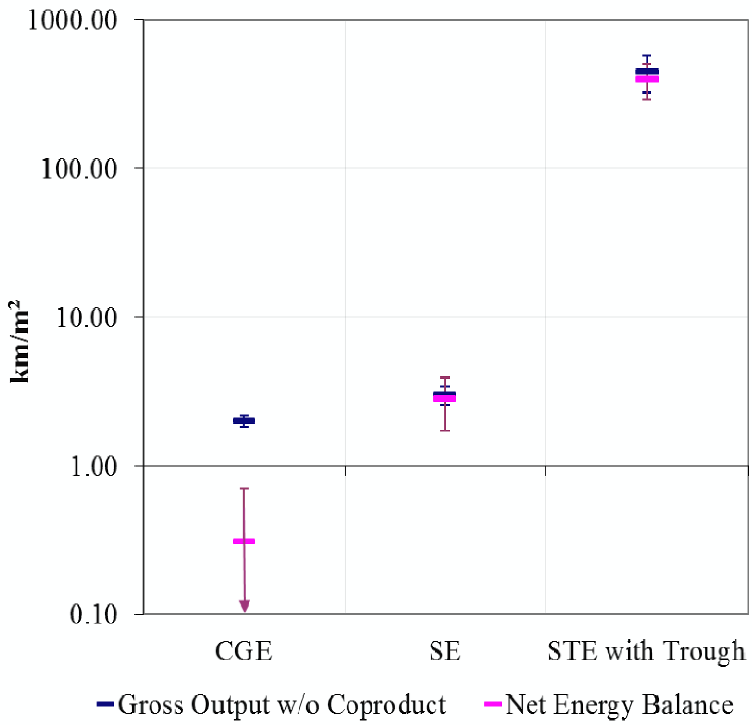

Figure 4 Distance Traveled per square meter of land used annually

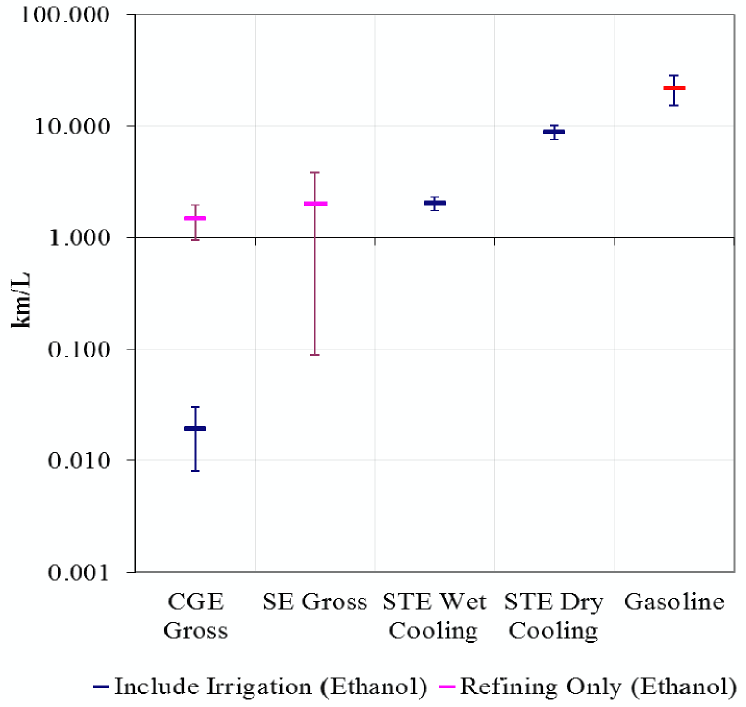

Figure 5 Distance Traveled per liter of Water Use

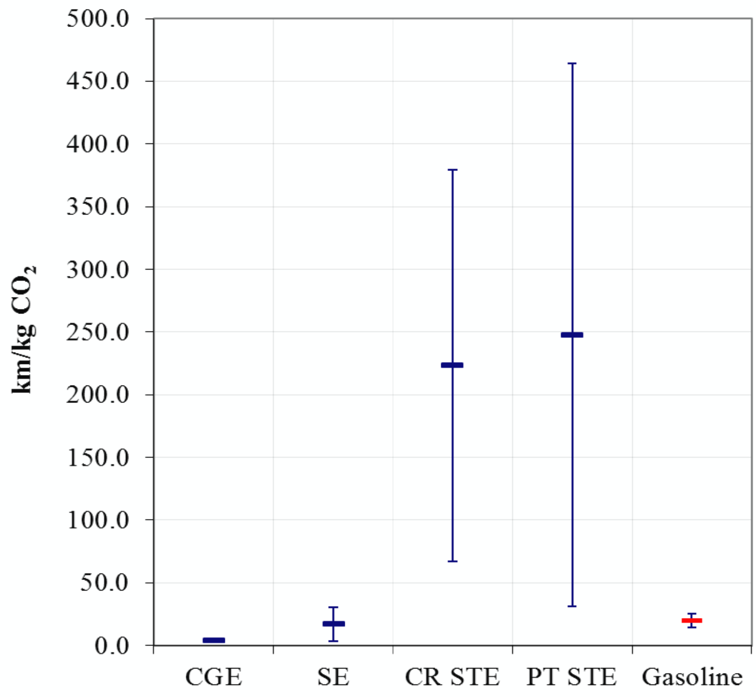

Figure 6 Distance Traveled per kilogram of CO_2 Emitted

Discussion

Compared to combined solar electric / BEV transportation, the combustion of biofuels is an inefficient use of land, water and atmosphere. Furthermore, recent data show that when corn is burned to generate electricity for a BEV, the distance travelled is 22 times more than when corn ethanol is consumed in an ICE vehicle from the same amount of corn (43). This is can be largely explained by comparing the efficiencies of photosynthesis to solar electrical conversion. Compared to the 15% efficiency commonly achieved in solar electric conversion, photosynthesis is very inefficient at producing biomass, only a portion of which is harvestable, rendering a photosynthetic conversion efficiency of well under 1% (44). Additionally, while electric motors (with battery charging losses) are about 75% efficient, combustion to motion is less than 20% efficient under typical driving scenarios.

We have only ***quantified*** the amount of land and water used, with the assumption that less is better. Comparing the importance of which ecosystems will be disturbed or what happens to the water afterwards is more difficult. Not all land and water are equal. Corn, and to a lesser extent switchgrass, require the use of arable land, displacing either vibrant ecosystems or crops which could otherwise be used to supply foodstuffs and fiber; STE facilities are optimally positioned in non-arable areas of the US. However, water is much more readily available in locations traditionally associated with agriculture than in the non-arable regions best suited for STE. While one can go much farther per liter of water using STE than biofuels, transporting the water to STE sites is difficult, and often agricultural water is supplied by rainfall (although using this water for crop growth is not necessarily "free of charge" to society). Added to this is the problem of releasing water vapor into the desert biosphere. The need for water – and the environmental impacts of its use – can be mitigated in part by implementing and improving dry cooling solutions for STE.

We have set forth new metrics, which we hope will improve transportation resource decision-making. Our land, air, and water have great value and we must account for them. Other important and more difficult metrics might be kilometers driven per kg of topsoil eroded, or kilometers per kg of algae resulting in nearby bodies of water (or biological oxygen demand) resulting from soil and fertilizer runoff. Our intention is to begin to measure the value of the "natural capital" that is used - or used up - in energy conversion (6).

Conclusion

We have introduced new efficiency metrics to compare two transportation energy technologies: internal combustion engines using ethanol and battery electric vehicles (BEV) charged from solar thermal electric (STE) generation. Both technologies require the use of land surface area and water, and produce CO_2 emissions. Our efficiency metrics are km/ m^2 of land used annually, km/L of water used, and km/kg of emitted CO_2. STE - BEV is more efficient than ICE with either switchgrass or corn ethanol. The absolute values are also worth noting: in order to fuel the 3 trillion vehicle miles traveled annually in the USA with corn ethanol, we would need to plant corn on about a fourth of the land surface area of continental USA (of which only 18% is arable). On the basis of the disparity in performance between biofuels and a combined STE – BEV program, if we are to shift from petroleum-based transportation and desire to retain our societal emphasis on transportation for personal and commercial pursuits, we should deemphasize biofuels and instead move our emphasis to developing technologies and infrastructure for both renewable electric power generation and battery electric vehicles.

Supporting Information Available

Details on data analysis are available in the supplied Microsoft Excel spreadsheet

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