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Fuel and Vehicle Technology Choices for Passenger Vehicles in Achieving Stringent CO_2 Targets: Connections between Transportation and Other Energy Sectors

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The regionalized Global Energy Transition (GET-R 6.0) model has been modified to include a detailed description of light-duty vehicle options and used to investigate the potential impact of carbon capture and storage (CCS) and concentrating solar power (CSP) on cost-effective fuel/vehicle technologies in a carbon-constrained world. Total CO_2 emissions were constrained to achieve stabilization at 400–550 ppm, by 2100, at lowest total system cost. The dominant fuel/vehicle technologies varied significantly depending on CO_2 constraint, future cost of vehicle technologies, and availability of CCS and CSP. For many cases, no one technology dominated on a global scale. CCS provides relatively inexpensive low-CO_2 electricity and heat which prolongs the use of traditional ICEVs. CSP displaces fossil fuel derived electricity, prolongs the use of traditional ICEVs, and promotes electrification of passenger vehicles. In all cases considered, CCS and CSP availability had a major impact on the lowest cost fuel/vehicle technologies, and alternative fuels are needed in response to expected dwindling oil and natural gas supply potential by the end of the century.

1. Introduction

Global climate change, caused by increasing levels of greenhouse gases in the Earth's atmosphere resulting from human activities (*1*), is a major issue that society is facing. CO_2 released during fossil fuel combustion and deforestation is the single largest contributor to the radiative forcing of climate change (*1*). The United Nations Framework Convention on Climate Change has been ratified by 192 countries and calls for stabilization of greenhouse gas concentrations in the atmosphere at a level that would "prevent dangerous anthropogenic interference with the climate system". There is no consensus on a precise level of CO_2 in the atmosphere that would prevent such interference. In the present work, we consider scenarios where CO_2 levels are stabilized in the range of 400–550 ppm. The current global average atmospheric CO_2 concentration is 385 ppm and is increasing by approximately 2 ppm per year (*2*). Substantial reductions in global CO_2 emissions over the rest of this century will be required to stabilize atmospheric CO_2 at 400–550 ppm. Efforts to stabilize atmospheric CO_2 levels are complicated by many considerations, not least of which being the fact that CO_2 emissions are spread across different economic sectors (e.g., industrial, residential, commercial, transportation) and geographic regions.

Transportation is a critical economic sector in modern society and a significant source of CO_2 emissions. In 2004, light-duty passenger vehicles were responsible for approximately 20, 17, and 11% of U.S., EU-15, and global fossil fuel CO_2 emissions, respectively (*3*). It is important to understand the fuel and vehicle technology choices available for passenger vehicles and how actions in other energy sectors might impact these choices. There have been few published energy systems studies using detailed transportation modules that analyze the competition of electricity, hydrogen, and biofuels in the transportation sector (*4*–*6*); studies where plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) are included, e.g., Gül et al. (*6*), are neither global, nor meet atmospheric CO_2 concentrations below 550 ppm. To facilitate future discussions of strategies to address climate change, the Global Energy Transition (GET) model (*7*–*9*), previously regionalized (*10*), was modified to include a more detailed description of passenger vehicle fuel and vehicle technology options (GET-RC 6.1).

The new GET-RC 6.1 model was used to quantify the potential impact of carbon capture and storage (CCS) technology and low CO_2 intensity electricity from renewable sources such as concentrating solar power (CSP) on cost-effective passenger vehicle fuel and technology options necessary to achieve stabilization of atmospheric CO_2 at 400–550 ppm. In the present work, CSP is both an energy technology and a proxy for other inexpensive low-CO_2 electricity-generating technologies that may be developed in the future. The model was used to address two questions: (i) what cost-effective fuel/vehicle technologies might dominate in a carbon-constrained world? and (ii) to what degree is the answer to the first question dependent on actions in other energy sectors?

2. Materials and Methods

The linear programming GET model constructed by Azar, Lindgren, and co-workers (*7*–*10*) covers the global energy system and is designed to meet exogenously given energy demand levels while stabilizing at a specific atmospheric CO_2 concentration at the lowest system cost. Regional energy demand in the GET model is derived by combining projections of global population (increasing to 10 billion in 2050 and 11.7 billion in 2100), World Energy Council estimates of the development of per capita income (IIASA/WEC scenario C1) (*11*), assumptions regarding the activity demand (e.g., person-km, pkm, for personal transportation) associated with a given per capita income (*7*), and energy intensity (e.g., MJ/pkm) for a given activity (*7*), for more details see the Supporting Information. The world is treated as 10 distinct regions with unimpeded movement of energy resources

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TABLE 1. Vehicle and Fuel Technology Combinations Included in the Model

	fuel technology						
vehicle technology	petro	BTL	GTL	CTL	NG	hydrogen [a]	electricity [b]
ICEV	yes	yes	yes	yes	yes	yes	
HEV	yes	yes	yes	yes	no	no	
PHEV	yes	yes	yes	yes	no	no	yes
BEV							yes
FCV	yes	yes	yes	yes	no	yes	

[a] Ten hydrogen production options including from coal, natural gas, oil, or biomass with, or without CCS, and solar (7), see Table S4 in the Supporting Information for details. [b] Thirteen different electricity production options considered, see Table S5 in the Supporting Information for details.

between regions (with the exception of electricity) with costs ascribed to such movement. Regional data were aggregated to give global results. The mobility demand assumptions are similar to those in the Sustainable Mobility Project (SMP) model developed by the World Business Council for Sustainable Development and the International Energy Agency (*12*). Stabilization of atmospheric CO_2 concentration at 400, 450, 500, or 550 ppm was investigated. The pattern of allowed global CO_2 emissions were constrained according to the emission profiles developed by Wigley and co-workers (*13*).

Energy demand is divided into three sectors: (i) electricity, (ii) transportation, and (iii) "heat" which comprises all stationary uses of energy except for those associated with generating electricity or transportation fuels. The model includes constraints on the expansion rates for different primary energy sources and energy technologies. Emphasis was given to personal transportation in the present study. Details concerning the treatment of personal transportation and energy sources, and modifications to the existing GET-R model made as part of this work are described below. Infrastructure costs are included in the model as presented in Table S4 in the Supporting Information.

The model is run for the period 2000−2130 with 10-year time steps presenting results from 2010−2100. Vehicle technology, CCS, and CSP costs were fixed throughout the model run at mature cost levels (see the Supporting Information). The description of the energy system in the model is a simplification of reality in at least four important respects: (i) consideration of limited number of technologies, (ii) assumption of price inelastic demand, (iii) selections made only on the basis of cost, and (iv) "perfect foresight" with no uncertainty of future costs, climate targets, or energy demand. The model does not predict the future and is not designed to forecast the future development of the energy system. The model does however provide a useful tool to understand the system behavior and the interactions and connections between energy technology options in different sectors in a future carbon-constrained world.

2.1. Personal Transportation. Five fuel options (petroleum, natural gas, synthetic fuels (coal to liquid, CTL; gas to liquid, GTL; biomass to liquid, BTL), electricity, and hydrogen) and five vehicle technologies (ICEV, HEV, BEV, PHEV, and FCV) were considered. Electricity and hydrogen are energy carriers; for simplicity we include these as "fuels". A total of 21 fuel and vehicle technology combinations were considered (see Table 1). If we include the 10 and 13 different possibilities considered for hydrogen and electricity production, respectively, the model has 63 technology combinations for light duty passenger vehicles and fuels. The model does not distinguish between gasoline and diesel fuels, which are lumped together as petroleum (petro), and the model does not consider greenhouse gases other than CO_2.

Table 2 provides the vehicle energy efficiency and cost data for the different combinations of fuel and vehicle technologies included in the model. The efficiency and cost data were derived from published sources (*7*, *14−18*) as discussed in the Supporting Information. An electric battery range of 65 km was adopted for PHEVs which enables approximately two-thirds of their daily driving distance to be powered by electricity from the grid on a single overnight charge (*19*). HEVs have a relatively short all-electric range (we assume 2 km). Initially we assumed that BEVs had the same range as other vehicles in the study (500 km) but we relaxed this to 200 km to make BEVs more cost competitive. Model runs assessed the sensitivity to variation of the following: battery costs from \$150/kWh (goal for long-term commercialization set by the U.S. Advanced Battery Consortium (*20*)) to \$450/kWh (above which the model results were insensitive to battery cost); natural gas storage cost from \$1000/GJ (as assumed in GET 1.0) to \$1300/GJ (consistent with estimation by CONCAWE (*17*)); hydrogen storage costs from \$1500/GJ (U.S. Department of Energy target (*21*)) to \$3500/GJ (above which the model results were insensitive to hydrogen storage cost); and fuel cell stack cost from \$65/kW (Ballard (*22*)) to \$125/kW (CONCAWE (*17*)).

2.2. Energy Sources. Primary energy sources in the GET-R model include fossil fuels (crude oil, natural gas, and coal), nonrenewable nonfossil sources (nuclear) and renewable sources (hydroelectric, wind, solar, and biomass). These energy sources can be converted to transportation fuels or used for generation of heat, electricity, or both (cogeneration). CCS is included as an option to decarbonize fuels derived from fossil sources and biomass as described below. The GET-R model allows solar energy to be used for generation of hydrogen from direct solar conversion, electricity from photovoltaic technology, solar heat and electricity from CSP as described below.

2.3. Carbon Capture and Storage (CCS). The capture and storage of CO_2 from combustion of fossil fuels and biomass is an important potential future technology option to address climate change. When applied to facilities fueled by biomass, CCS enables simultaneous removal of CO_2 from the atmosphere and provision of energy (e.g., heat, electricity, hydrogen) to society. Investment costs, annual O&M costs, economical lifetime and capacity factors were taken from GET 5.0 (*9*). We assume a storage capacity of 600 GtC, a maximum rate of increase of CCS of 100 MtC/year and negligible leakage of stored CO_2 (*9*). Further details are available in the Supporting Information.

2.4. Concentrating Solar Power (CSP). Unlike solar (photovoltaic) cells, which convert sunlight into electricity directly, CSP systems convert sunlight into electricity indirectly. CSP utilizes mirrors and lenses to concentrate sunlight onto a thermal receiver where heat is produced (*23*). The heat is then transported in a liquid medium to a steam generator where electricity is generated via turbines.

CSP technology has been demonstrated for the past 20 years in a 354 MW modular plant, consisting of nine CSP units, located in the Mojave Desert, California. Heat can be stored to allow for continuous electricity production and to

TABLE 2. Passenger (Light-Duty) Vehicle Energy Use and Cost Data in the Model

fuel-engine technology [b]	vehicle energy efficiency ratio (HHV) [a]		vehicle cost (USD)	
	year	year	base	increment
	2000[c]	2100		
Petro ICEV	1.0 [d]	1.0 [d]	20 000	
Synth ICEV	1.0	1.0		100
NG ICEV	1.0	1.0		1200−1600
H2 ICEV	1.15	1.15		1500−3500
HEV	1.3	1.3		1300−1900 [e]
BEV	3.75	2.85		8000−23 000 [e,f]
PHEV [g]	2.46	2.17		3000−8000 [e]
Petro FCV	1.2	1.2		4500−7500[e]
Synth FCV	1.3	1.3		4500−7500[e]
H2 FCV	1.8	1.8		4900−7900[e]

[a] Tank-to-wheels energy (higher heating value [HHV] basis) used by Petro ICEV divided by that for alternative technology. See Supporting Information for equivalent lower heating value (LHV) numbers and for more details. [b] Petro ICEV, Synth ICEV, NG ICEV, H2 ICEV = internal combustion engine vehicle fueled either by petroleum, synthetic fuel (CTL, GTL, or BTL), natural gas, or gaseous hydrogen; HEV = hybrid electric vehicle; BEV = battery electric vehicle, PHEV = plug-in hybrid electric vehicle; Petro FCV, Synth FCV, H2 FCV = fuel-cell vehicle fueled either by petroleum, synthetic fuel, or gaseous hydrogen. [c] While it is clearly not appropriate to use mature costs for advanced technology during the beginning of the time period, this assumption did not compromise the study since advanced technologies did not enter the scenarios until later in the time period studied. [d] By definition. Note that the overall energy consumption (MJ/km) by Petro ICEVs in 2100 is a factor of 2 less than that in 2000. [e] Battery cost of \$150−450/kWh, fuel cell stack cost of \$65−125/kW, hydrogen storage cost of \$1500−3500/GJ, natural gas storage cost of \$1000−1300/GJ assumed, see Supporting Information. [f] BEV cost based on 200-km driving range compared to 500 km range for the other technologies. [g] Efficiency shown assumes two-thirds of total distance traveled is powered via grid electricity. Synth HEV and Synth PHEV are also included in the model with efficiencies equal to Petro HEV and PHEV with \$100 additional incremental cost, see Supporting Information.

meet variable power needs on short notice. Depending on the system design, additional heat storage is not necessarily needed since the heat transfer fluid in the system can store heat for approximately 12 h (*24*, *25*). Costs for CSP are discussed in the Supporting Information.

3. Results

The GET-RC 6.1 model was used to investigate cost-effective fuel and vehicle technology options for passenger vehicles consistent with stabilization of atmospheric CO_2 levels at 400, 450, 500, or 550 ppm, with and without CCS and CSP, with vehicle costs varied over the ranges given in Table 2. Nine cases for vehicle costs were considered. Details concerning the impacts of battery cost, natural gas storage cost, hydrogen storage cost, and fuel cell stack cost are given in the Supporting Information.

3.1. Impact of CCS and CSP. Figure 1 shows plots of the light-duty passenger vehicle fleet from runs investigating CO_2 stabilization at 450 ppm (corresponding data for 400, 500, 550 ppm, and the no-constraint case (leading to approximately 700 ppm CO_2 in 2100) are given in the Supporting Information). Four scenarios are considered: (A) where neither CCS nor CSP are available, (B) where CCS is available but CSP is unavailable, (C) where CSP is available but CCS is unavailable, and (D) where both CSS *and* CSP are available.

The availability of CCS and CSP has a profound influence on the lowest cost passenger vehicle fuel and technology choice consistent with stabilization of atmospheric CO_2 levels. Without CCS or CSP (Figure 1A), personal transportation changes from petroleum-fueled ICEVs to a combination of mostly HEVs and PHEVs fueled by petroleum and ICEVs fueled by natural gas. Approaching 2100, these vehicles start to be replaced mostly by ICEVs fueled by hydrogen (produced via solar energy). In the figures, CTL and GTL (both from fossil sources) are combined for clarity.

The availability of CCS (compare Figure 1B with 1A) extends the use of conventional petroleum-fueled ICEVs by a few decades, results in the use of more ICEVs and HEVs fueled by biofuels and CTL/GTL, and delays the introduction of ICEVs fueled by hydrogen (produced from coal with CCS). The system dynamic at work is that CCS provides relatively inexpensive low-CO_2 electricity and heat from coal which prolongs the use of traditional ICEVs. When CCS is not available, biomass is used mostly to provide heat. The availability of CCS leads to coal displacing biomass in the heat sector which allows increased production of transportation fuel from biomass. While CCS enables the production of much cheaper hydrogen (from coal instead of solar), the overall importance of hydrogen decreases reflecting the fact that CCS enables nontransport sectors to realize more emission reductions at a lower cost than in the transport sector.

The availability of low-CO_2 electricity from CSP has somewhat different impacts. As seen by comparing Figure 1C with 1A (see Figures S11−S13 in the Supporting Information for 400, 500, and 550 ppm cases), when CSP is available, substantial volumes of PHEVs and HEVs fueled by petroleum and synthetic fuels (GTL and BTL) are used in lieu of ICEVs fueled by solar based H_2. The system dynamic at work is similar to that described above for CCS. There are two effects: (i) CSP displaces fossil fuel derived electricity and prolongs the use of petroleum-fueled ICEVs, and (ii) CSP provides low-CO_2 electricity and promotes the electrification of passenger vehicles.

When both CSP and CCS are available (see Figure 1D) cost-effective opportunities for CO_2 reduction in other sectors allow substantial use of ICEVs powered by petroleum, GTL, and BTL. As shown in Figures S2−S13 in the Supporting Information, the conclusion that CCS and CSP availability have a large impact was robust to variation of vehicle technology costs.

3.2. Vehicle-Fuel Technology Diversity. As indicated by the complexity of the plots in Figure 1 (and Supporting Information Figures S2−S13), in most cases petroleum, synthetic fuel (CTL/GTL and BTL), hydrogen, electricity, and natural gas all play important roles as fuels, and ICEVs, HEVs, and PHEVs all play significant roles as vehicle technologies. While the relative importance of the different fuel and vehicle technologies depends on the specifics of each case, usually no one technology dominates on a global scale. The diversity

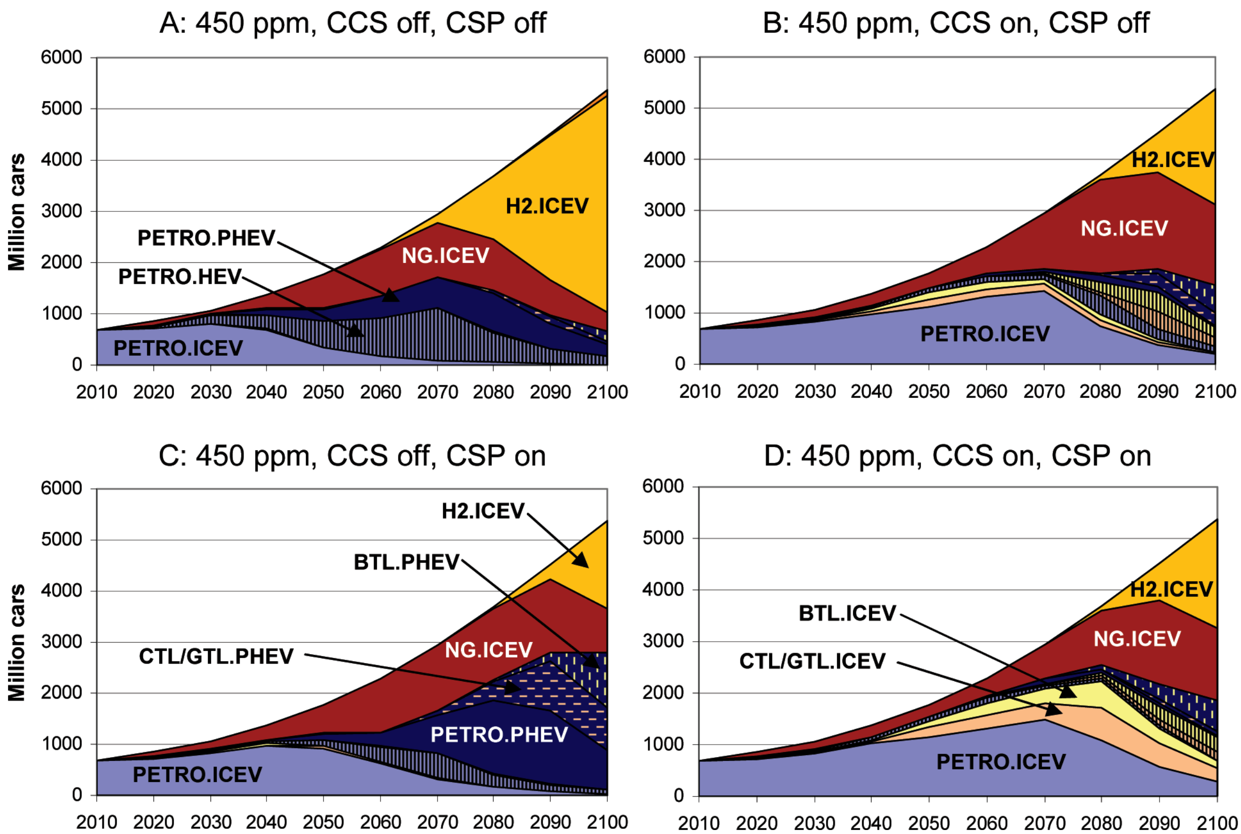

FIGURE 1. Global passenger vehicle fleet (millions) consistent with atmospheric CO_2 stabilization at 450 ppm, a battery cost of $300/kWh, a hydrogen storage cost of $2500/GJ, a natural gas storage cost of $1150/GJ, a FC stack cost of $95/kW (Case no. 1 vehicle costs, see Table 3 Supporting Information), and: (A) neither CCS nor CSP available, (B) only CCS available, (C) only CSP available, or (D) CCS and CSP both available.

of the results shown in Figure 1 (and Supporting Information Figures S2–S13) has three causes: (i) the carbon constraints increase over time which changes the relative cost-effectiveness between fuels and technology options over time, (ii) the oil and natural gas supply potentials become scarcer over time, and (iii) there are several technologies that have similar cost attributes and optimal solutions differ regionally depending on resource availability and regional differences in driving distances and vehicle occupancy which influence cost per passenger km.

3.3. CO_2 Constraint. As the CO_2 constraint is increased, actions to replace conventional petroleum ICEVs are required earlier. For example, moving from a CO_2 stabilization target of 450 ppm (Figure 1) to 400 ppm (Supporting Information Figure S13) brings forward by approximately 10–20 years the time when advanced vehicles and alternative fuels are introduced in large scale in the model.

3.4. Natural Gas and Hydrogen on-Board Storage Cost. Representative illustrations of the sensitivity to natural gas and hydrogen storage costs, are shown in Figure 2 for the case with 450 ppm CO_2 stabilization without CCS and CSP. Comparison of Figure 2A and B with Figure 1A, or Figure 2C and D with Figure 1A, shows that as the cost of on-board vehicle storage of natural gas or hydrogen increases, the penetration of HEVs and PHEVs increases at the expense of the gaseous-fuel-powered vehicles. This observation illustrates the competition between vehicles powered by gaseous fuels and electricity in a carbon-constrained world. Increased cost of storage of gaseous fuel favors the electricity-powered options in all four scenarios.

3.5. Battery and Fuel Cell Stack Cost. Representative illustrations of the sensitivity to variation of battery and fuel cell stack costs are shown in Figure 3 for the case with 450 ppm stabilization without CCS and CSP. Comparison of Figure 3A with Figure 1A, shows that PHEVs are an attractive solution for battery costs at the low end of the range investigated ($150/kWh). With increased battery price, and hence vehicle cost, PHEVs become less attractive. With battery costs at the high end of the range ($450/kWh), PHEVs are replaced by hydrogen-fueled vehicles (Figure 3B). Even at the lowest battery cost, BEVs were not found to be a cost-competitive, large-scale technology under any scenario investigated, even though BEVs were allowed to compete with reduced functionality (200 km driving range instead of 500 km for all other vehicles). Comparing Figure 3C with Figure 1A, shows that decreasing the fuel cell stack cost from $95 to $65/kW results in substantial replacement of hydrogen ICE with hydrogen FC vehicle technology. Increasing the fuel cell stack to $125/kW (Figure 3D) removes the small number of H2 FCVs present in the $95/kW case (Figure 1A). The impact of battery and fuel cell stack cost with CCS and CSP available are given in Figures S7–S10 in the Supporting Information and show the same trends illustrated above.

Gaseous fuels (natural gas and hydrogen) for HEVs and PHEVs were not explicitly considered here. As natural gas ICEVs and hydrogen ICEVs were competitive in certain cases, it is possible that the higher efficiencies associated with hybridization could make natural gas and hydrogen-fueled HEVs (and possibly PHEVs) competitive in those cases. Further work is needed to investigate this possibility.

3.6. Fossil Fuel Reserve Depletion. As described in the Supporting Information, the GET model assumes global supply potentials of oil, gas, and coal of approximately 12 000 EJ (approximately 2 trillion barrels), 11 000 EJ (approximately 300 trillion m^3), and 265 000 EJ (approximately equivalent to 10 trillion tonnes hard coal), respectively. The global biomass supply potential was 200 EJ/year. To account for reserve growth, the supply potentials for oil and natural gas are

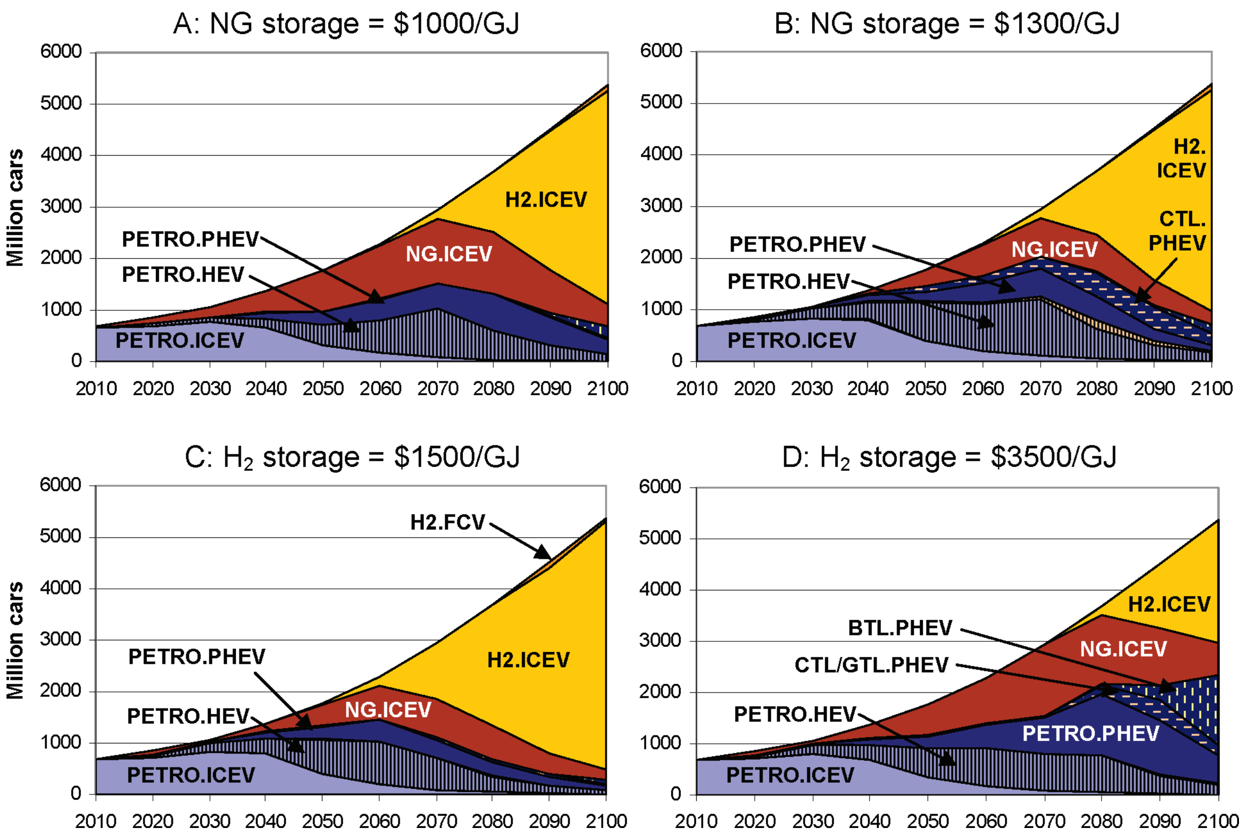

FIGURE 2. Global passenger vehicle fleet (millions) consistent with CO_2 stabilization at 450 ppm, with neither CCS nor CSP available, and: natural gas storage costs of either $1000/GJ (Case no. 2) (A), or $1300/GJ (Case no. 3) (B); hydrogen storage costs of either $1500/GJ (Case no. 4) (C), or $3500/GJ (Case no. 5) (D).

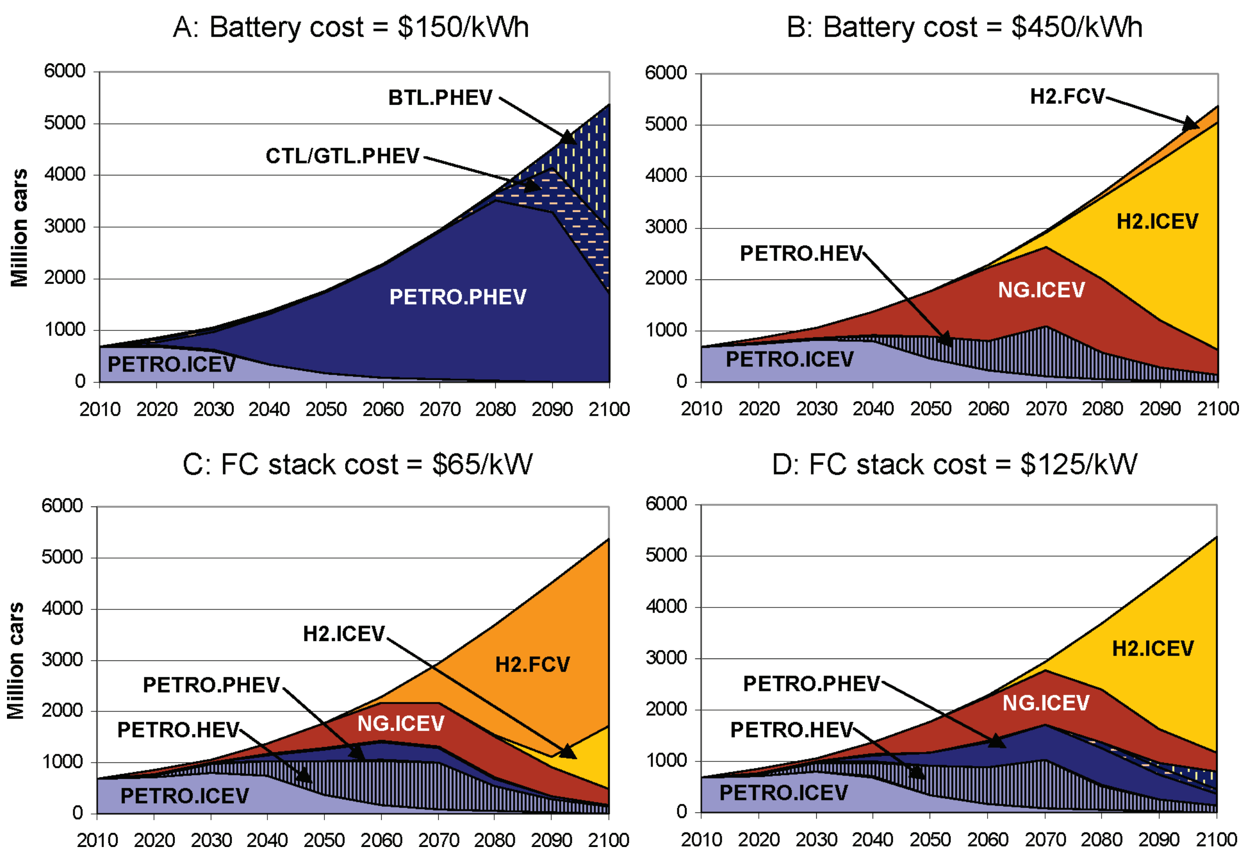

FIGURE 3. Global passenger vehicle fleet (millions) consistent with CO_2 stabilization at 450 ppm, with neither CCS nor CSP available, and: battery costs of either $150/kWh (Case no. 6) (A), or $450/kWh (Case no. 7) (B); fuel cell stack costs of either $65/kW (Case no. 8) (C), or $125/kW (Case no. 9) (D).

approximately twice the current estimates of economically recoverable, conventional reserves (*26*). In nearly all of the cases considered here, supply potentials of oil and natural gas are >90% depleted by 2100, whereas coal is only 5−10% depleted. As such, the phase-out of oil in the transport sector is ascribed in large part to its depletion. The emergence of alternative fuels is a necessary response even in the absence of CO_2 constraints.

3.7. Comparison with Previous Studies. Our finding that for a 550 ppm stabilization target, petroleum-fueled ICEV technology dominates for at least the 2010−2050 period (see Supporting Information Figure S11) is in agreement with the results from Turton and Barreto (*5*). Takeshita and Yamaji (*27*) ran a linear cost-minimizing energy model with a CO_2 stabilization target of 550 ppm by the year 2100 and with a "business as usual" (no CO_2 constraint) scenario. For the 550 ppm scenario, they reported substantial (approximately 25% in 2100) use of BTL technology, while for business as usual CTL/GTL was dominant in 2100. These results are consistent with our findings (see Supporting Information Figures S11 and S14). Gül et al. (*6*) used a MARKAL-based energy systems model to analyze competing energy carriers for Western Europe's transportation sector. In their CO_2 reduction scenario (reduction from 1990 of 50% by 2050 and 75% by 2100), the car sector is dominated by gasoline/diesel (first in ICEVs, then HEVs and to a small extent also PHEVs) with hydrogen-fueled FCVs becoming dominant by 2100. Our findings in many cases (e.g., Figures 1A, 2A and B, 3B−D) that petroleum-fueled ICEVs dominate initially and are replaced first by HEVs/PHEVs and then by hydrogen-fueled vehicles (ICEVs or FCVs) are consistent with those of Gül et al. (*6*). Finally, recognizing the updated estimates of the efficiency of hydrogen-fueled ICEVs, our results showing hydrogen use at the end of the century in almost all scenarios and gasoline/diesel dominating the passenger vehicle sector for the first half of the century are consistent with previous results from our group (*7, 8, 10*). We identified no previous studies of the impacts of CCS and CSP availability on vehicle-fuel technologies for comparison.

4. Discussion

The goal of this work was to investigate the connections between transportation and other energy sectors in a carbon-constrained world. In particular, we analyzed how CCS and CSP, technological options that have the potential to significantly reduce CO_2 emissions associated with electricity and heat generation, may affect optimal fuel and vehicle technologies for transport. This was done by further developing and running a global energy systems model (GET-R 6.0). The most important addition to earlier versions of the model was a more detailed description of light-duty vehicle technologies.

In all scenarios, there is no single technology and fuel that dominates throughout the century. The diversity of solutions reflects different regional resource availability and mobility demand as well as the fact that the relative cost-effectiveness between fuels and technology options changes over time due to increased carbon constraints. In addition, oil and natural gas supply potentials become scarcer with time and this alone drives the introduction of alternative fuels. This result holds in all scenarios studied.

Without either CCS or CSP, a substantial transition away from conventional gasoline and diesel to more efficient vehicle technologies or alternative "fuels" is cost-effective within the next few decades to meet stringent CO_2 stabilization targets (e.g., see Figure 1A). As for our key question, we find that the availability of CCS and CSP have substantial impacts on the fuel and technology options for passenger vehicles in meeting global CO_2 emission targets at lowest system cost. Four key findings emerge.

First, the introduction of CCS increases, in general, the use of coal (in the energy system) and ICEV (for transport). By providing relatively low-cost approaches to reducing CO_2 emissions associated with electricity and heat generation, CCS reduces the "CO_2 task" for the transportation sector, extends the time span of conventional petroleum-fueled ICEVs, and enables the use of liquid biofuels as well as GTL/CTL for transportation.

Second, the introduction of CSP reduces the relative cost of electricity in relation to hydrogen and tends to increase the use of electricity for transport (at the expense of hydrogen). Third, the introduction of CCS and CSP combined reduces the cost-effectiveness of shifting away from petroleum and ICEV. This era is prolonged. Advanced energy technologies (CCS and CSP) reduce the cost of carbon mitigation (in the model) and therefore the incentives to shift to more advanced vehicle technologies.

Fourth, the cost estimates for future vehicle technologies are very uncertain (for the time span considered) and therefore it is too early to express firm opinions about the future cost-effectiveness or optimality of different fuel and powertrain combinations. Extensive sensitivity analyses in which we varied these parameters over reasonable ranges result in large differences in the cost-effective fuel and vehicle technology solutions. Thus, our results summarized above should not be interpreted to mean that the energy system alone will have a decisive impact on the fuel and vehicle options chosen. For instance, for low battery costs ($150/kWh), electrified powertrains dominate regardless of the energy system. For higher battery costs ($450/kWh), hydrogen fueled vehicles dominate, regardless of CCS and CSP availability (see Figures S7 and S8 in the Supporting Information). In general, however, it is the combination of energy systems technologies (their cost and performance) with vehicle costs and performance that will determine the outcome for the transport sector.

Our findings have several policy and research implications. From a policy perspective, the findings highlight the need to recognize, and account for, the interaction between sectors in policy development. From a research perspective, the findings illustrate the importance of pursuing the research and development of multiple fuel and vehicle technology pathways.

As discussed in the introduction, the model is a simplification of reality in several important aspects. Important policy considerations such as energy security, agricultural support, and wealth distribution were not considered. Inherent uncertainties when constructing a model to 2100 also need to be recognized. The model is not intended to forecast the future but aims to provide insight into the importance of connections between energy sectors.

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Supporting Information Available

Further details of the model, efficiency and cost values for passenger vehicles, cost data for CSP, costs, and CO_2 data for transportation fuel and electricity options, biomass and fossil fuel cost and availability, passenger mobility demand, and impacts of vehicle technology costs. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) *IPCC, 2007: Climate Change 2007: the Physical Science Basis*; Cambridge University Press: New York, 2007.

(2) Tans, P. NOAA/ESRL, Trends in atmospheric carbon dioxide - Mauna Loa. www.esrl.noaa.gov/gmd/ccgg/trends/ (accessed December 2008).
(3) Wallington, T. J.; Sullivan, J. L.; Hurley, M. D. Emissions of CO_2, CO, NO_x, HC, PM, HFC-134a, N_2O and CH_4 from the global light duty vehicle fleet. *Meteorol. Z.* **2008**, *17*, 109–116.
(4) Endo, E. Market penetration analysis of fuel cell vehicles in Japan by using the energy system model MARKAL. *Int. J. Hydrogen Energy* **2007**, *32*, 1347–1354.
(5) Turton, H.; Barreto, L. Automobile technology, hydrogen and climate change: a long term modelling analysis. *Int. J. Altern. Propul.* **2007**, *1*, 397–426.
(6) Gül, T., Kypreos, S., Barreto, L. Hydrogen and biofuels - A modelling analysis of competing energy carriers for Western Europe. *Proceedings of the World Energy Congress "Energy Future in an Interdependent World*. Rome, Italy, November 11−15 2007.
(7) Azar, C.; Lindgren, K.; Andersson, B. A. Hydrogen or Methanol in the Transportation Sector?, KFB-Report 2000:35, Sweden, ISBN: 91−88371−90−5. www.kfb.se/pdfer/R-00−35.pdf.
(8) Azar, C.; Lindgren, K.; Andersson, B. A. Global energy scenarios meeting stringent CO_2 constraints−Cost effective fuel choices in the transportation sector. *Energy Policy* **2003**, *31*, 961–976.
(9) Azar, C.; Lindgren, K.; Larson, E.; Mollersten, K. Carbon capture and storage from fossil fuels and biomass−Costs and potential role in stabilizing the atmosphere. *Clim. Change* **2006**, *74*, 47–79.
(10) Grahn, M.; Azar, C.; Lindgren, K., The role of biofuels for transportation in CO_2 emission reduction scenarios with global versus regional carbon caps, *Biomass Bioenergy* **2009**, *33*, 360–371.
(11) IIASA/WEC, Global energy perspectives to 2050 and beyond, World Energy Council, London, 1995. http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py
(12) Mobility 2030: Meeting the Challenges to Sustainability, ISBN: 2-940240-57-42004; World Business Council for Sustainable Development: Geneva, Switzerland, 2004.
(13) Wigley, T. M. L. Model for the assessment of greenhouse-gas induced climate change. http://www.cgd.ucar.edu/cas/wigley/magicc/installation.html.
(14) EC Alternative Fuels (EUCAR). Market Development of Alternative Fuels, Report of the European Commission, alternative fuels contact group, December 2003.
(15) TIAX. Full Fuel Cycle Assessment Tank to Wheels Emissions and Energy Consumption, Report CEC-600-2007-003-D, February 2007.
(16) Choudhury, R. GM well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems - A European study, http://www.lbst.de/gm-wtw/, September 2002.
(17) CONCAWE EUCAR Report. Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context; European Commission: Luxembourg, 2006; available at http://ies.jrc.cec.eu.int/wtw.html.
(18) Wang, M. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, version 1.7, 2005. http://www.transportation.anl.gov/software/GREET/.
(19) Santini, D.; Wang, M. PHEV technology analysis at Argonne. http://www.transportation.anl.gov/pdfs/HV/548.pdf (accessed December 2008).
(20) U.S. Advanced Battery Consortium. http://www.uscar.org/ (accessed March 2008).
(21) U.S. Department of Energy, targets for on-board hydrogen storage systems, http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf, accessed March 2008.
(22) Ballard Inc. http://phx.corporate-ir.net/phoenix.zhtml?c=76046&p=irol-newsArticle&ID=985592&highlight (accessed March 2008).
(23) United States Department of Energy. Concentrating Solar Power: Energy from Mirrors, DOE/GO-102001−1147, FS 128, March 2001. http://www.nrel.gov/docs/fy01osti/28751.pdf (accessed March 2008).
(24) Shinnar, R.; Citro, F. A road map to U.S. decarbonization. *Science* **2006**, *313*, 1243.
(25) Shinnar, R.; Citro, F. Solar thermal energy: the forgotten energy source. *Technol. Soc.* **2007**, *29*, 261.
(26) British Petroleum, Statistical Guide of World Energy 2008. http://www.bp.com.
(27) Takeshita, T.; Yamaji, K. Important roles of Fischer−Tropsch synfuels in the global energy future. *Energy Policy* **2008**, *36*, 2791–2802.

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