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The role of ICEVs, HEVs, PHEVs, BEVs and FCVs in achieving stringent CO_2 targets: results from global energy systems modeling

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Abstract

A modified GET model version was used to investigate long-term, cost-effective fuel and vehicle technologies for global passenger transport. The aim was 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 450 ppm. In addition, the model was used to assess the sensitivity of future vehicle cost assumptions. For all cases investigated, there is no single technology and fuel that dominates throughout the century; instead a variety of fuels and vehicle technologies are important. The availability of CCS and CSP have a substantial impact on cost-effective fuel and technology choices, in general: (i) the introduction of CCS increases the use of coal in the energy system and conventional vehicle technology, (ii) the introduction of CSP reduces the relative cost of electricity in relation to hydrogen and tends to increase the use of electricity for transport, and (iii) the introduction of both CCS and CSP reduces the economic incentives to shift to more advanced vehicle technologies. Varying cost estimates for future vehicle technologies results in large differences in the cost-effective fuel and vehicle technology solutions. For instance, for low battery costs ($150/kWh), electrified powertrains dominate and for higher battery costs ($450/kWh), hydrogen-fueled vehicles dominate, regardless of CCS and CSP availability. The results highlight the importance of a multi-sector approach and the importance of pursuing research and development of multiple fuel and vehicle technologies.

Keywords: modeling, cost, alternative fuel, emissions, passenger car

1 Introduction

To facilitate further discussions of strategies to address climate change, the Global Energy Transition (GET) model [1-3], previously regionalized [4], was modified to include a more detailed description of passenger vehicle technology options (GET-RC 6.1) and was used to investigate connections between the transportation and other energy sectors.

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 that analyze the competition of electricity, hydrogen, and biofuels in the transportation sector [5-8]. Studies including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), e.g. Gül *et al.* [7], are neither global, nor meet atmospheric CO_2 concentrations below 550 ppm.

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 450 ppm. In the present work, CSP is both an energy technology and a proxy for other inexpensive, non-intermittent low-CO_2 electricity-generating technologies that may be developed in the future.

The model was used to address three questions: (i) what cost-effective fuel and vehicle technologies might dominate in a carbon-constrained world? (ii) to what degree is the answer to the first question affected by the introduction of CCS and/or CSP? and (iii) how sensitive are the results to future vehicle cost assumptions?

2 Method

The linear programming GET model constructed by Azar, Lindgren, and co-workers [1-4] covers the global energy system and is designed to meet exogenously-given energy demand levels, subject to a CO_2 constraint, at the lowest system cost.

2.1 Model structure

The world is treated as ten distinct regions with unimpeded movement of energy resources between regions (with the exception of electricity) with costs ascribed to such movement. Regional solutions were aggregated to give global results. The pattern of allowed global CO_2 emissions was constrained according to the emission profile leading to an atmospheric CO_2 concentration of 450 ppm, developed by Wigley and co-workers [9]. The model does not consider greenhouse gases other than CO_2.

The model is run for the period 2000-2130 with 10-year time steps presenting results from 2010-2100.

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.

2.2 Energy demand

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. Emphasis was given to personal transportation in the present study.

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) [10], assumptions regarding the activity demand (e.g., person-km, pkm, for personal transportation) associated with a given per capita income, for more details see Azar *et al.* [1].

2.3 Primary energy sources

In all areas except North America, Europe, and the Former Soviet Union, we assumed a biomass raw material cost of $2/GJ. In North America the cost was $3/GJ. In Europe and the Former Soviet Union the cost was $4/GJ. A detailed assessment of the biomass supply potential can be found in

Hoogwijk [11]. For four different scenarios and two biomass production cost levels (lower than 2 USD/GJ and lower than 4 USD/GJ), she estimates the global supply potential to lie in the range of 130-439 EJ/yr (with a mean value of 253 EJ/yr) by the year 2050. This is consistent with a recent OECD estimation of 244.6 EJ [12] and similar to Johansson *et al*. [13] where estimates on regional biomass supply potentials add up to a global maximum of 205 EJ per year, which we have chosen to follow in the present study.

For global supply potential of oil and natural gas we have chosen approximately twice their present proved recoverable reserves, i.e., 12,000 and 10,000 EJ, respectively [14-15] and assumed a regional distribution following Johansson *et al*. [13]. For coal we have chosen a global supply potential of approximately 260,000 EJ following the total resource estimates in Rogner [16]. In the model, CO_2 emission constraints limit the use of fossil fuels (generally less than 10% of the coal supply potential is used within this century when meeting 450 ppm).

Table 1: Cost and CO_2 data for transportation fuels

Primary energy	**Secon-dary energy**	**Invest-ment cost** $/kW$_{fuel}$	**Con-version effi-ciency**	**Life time** years	**Capa-city factor**	**Annual-ized [a] inv. cost** $/GJ$_{fuel}$	**O&M cost** $/GJ$_{fuel}$	**Distrib-ution cost** $/GJ$_{fuel}$	**Primary energy price [b]** $/GJ	**CO_2 emission[c]** kgC/GJ$_{fuel}$	**CO_2 storage cost [d]** $/GJ$_{fuel}$	**Total fuel cost [e]** $/GJ$_{fuel}$
Oil	Petro	900	0.9	25	0.8	2.74	1.66	2.00	3.00	22.78		9.73
NG	NG	-	1	-	-	-	-	6.40	2.50	15.40		8.90
Biomass	BTL	1000	0.6	25	0.8	3.05	1.84	3.47	2.00 [f]	0.00 [g]		11.69
NG	GTL	600	0.7	25	0.8	1.83	1.11	3.47	2.50	22.00		9.97
Coal	CTL	1000	0.6	25	0.8	3.05	1.84	3.47	1.00	41.17		10.02
Biomass	H_2	800	0.6	25	0.6	3.25	1.47	7.86	2.00 [f]	0.00 [g]		15.92
NG	H_2	300	0.8	25	0.6	1.22	0.55	7.86	2.50	19.25		12.76
Coal	H_2	700	0.65	25	0.6	2.84	1.29	7.86	1.00	38.00		13.53
Oil	H_2	400	0.75	25	0.6	1.62	0.74	7.86	3.00	27.33		14.22
Solar	H_2	2000	1	25	0.25	19.49	3.69	7.86	0.00	0.00 [g]		31.04
Bio-CCS	H_2	1000	0.55	25	0.6	4.06	1.84	8.36 [h]	2.00 [f]	-52.36	3.82	21.73
NG-CCS	H_2	500	0.75	25	0.6	2.03	0.92	7.86	2.50	2.05	0.68	14.83
Coal-CCS	H_2	900	0.6	25	0.6	3.66	1.66	7.86	1.00	4.12	1.37	16.21
Oil-CCS	H_2	600	0.7	25	0.6	2.44	1.11	7.86	3.00	2.93	0.98	16.71
Infra-structure[i]	BTL/ CTL/ GTL	500	1	50	0.7							
Infra-structure[i]	NG	1500	1	50	0.7							
Infra-structure[i]	H_2	2000	1	50	0.7							

a: Annualized investment cost C_I of energy conversion plant, calculated as

$$C_I = \frac{(1+r)^5 I}{10\alpha C_f}\left(1 - \frac{(1-1/T)^{10}}{(1+r)^{10}}\right),$$

where I is the investment cost, r is the discount rate (0.05/yr), T is the life time and C_f is the capacity factor. The constant α=31 Ms/yr is included to account for the conversion into GJ (remember 10 years per time step). The factor $(1+r)^5$ reflects that investments are made between two time steps.

b: Note that the stated primary energy costs do neither include scarcity rents (which are generated endogenously in the model) nor carbon taxes. To see the effect of an increasing carbon fee/tax, see Azar *et al*. [3].

c: The CO_2 emission factors we have used are: natural gas: 15.4, oil: 20.5, coal: 24.7 and biomass: 32 kgC/GJ [27].

d: The CO_2 storage cost is 10 $/t$CO_2$ (for CO_2 from fossil fuels) and 20 $/t$CO_2$ (for CO_2 from biomass). The reason for the higher cost for biomass CO_2 is that we assume that facilities capturing CO_2 from biomass will typically be smaller, see Azar *et al*. [3] for more details. We have assumed that 90% of the carbon can be captured.

e: The total fuel cost is derived as primary energy cost/conversion efficiency + C_I + O&M cost + distribution cost + CO_2 storage cost.

f: In the developing regions we have assumed a biomass feedstock cost of $2/GJ. In NAM and PAO the cost was set to $3/GJ. In EUR and FSU the cost was set to $4/GJ.

g: Future use of biomass and solar energy is assumed to contribute negligible CO_2 emissions.

h: Longer transportation distances of biomass to BioEnergy CCS plant adds $0.5/GJ to the distribution cost, since larger plants are desirable to capture economies of scale.

i: The incremental costs for investing in new infrastructure are based on the data presented in these three rows and are included for each fuel option in column 9. The cost for distribution of conventional petro is set to $2/GJ.

2.4 Cost data

Data for vehicle technology as well as conversion plants and infrastructure (e.g. investment costs, conversion efficiencies, lifetimes, and capacity factors) are held constant at their "mature levels", see Table 1 and Table 2. Technological change is exogenous in the GET model, i.e., the cost and performance, etc. are independent of how much they are used. We assume technology mature costs throughout the time period considered. We verified that this did not lead to an unduly rapid adoption of technologies. We further assume that technologies developed in one region are available for other regions. Global dissemination of technology is not seen as a limiting factor. All prices and costs are in real terms as future inflation is not considered. A global discount rate of 5% per year was used for the net present value calculations.

2.5 Constraints

Constraints on how fast changes can be made in the energy system have been added to the model to avoid solutions that are obviously unrealistic. This includes constraints on the maximum expansion rates of new technologies (in general, set so that it takes 50 years to change the entire energy system) as well as annual or total extraction limits on the different available energy sources.

The contribution of intermittent electricity sources (wind and solar PV) is limited to a maximum of 30% of total electricity use. To simulate the present situation in developing countries, a minimum of 30 EJ per year of the heat demand needs to be produced from biomass during the first decades. For CCS, we assumed a storage capacity of 600 GtC [17], a maximum rate of increase of CCS of 100 MtC/year and negligible leakage of stored CO2.

The future role of nuclear energy is primarily a political decision and will depend on several issues such as nuclear safety, waste disposal, questions of nuclear weapons proliferation and public acceptance. We assume that the contribution of nuclear power does not exceed the level we have today.

Table 2: Cost and CO_2 data for heat and electricity options

Primary energy	Invest-ment cost $/kWe	Con-version effi-ciency	Life time years	Capa-city factor	O&M cost $/GJe	Primary energy price [b] $/GJ	CO_2-emission[c] kgC/GJe	CO_2 storage cost [d] $/GJe	Total prod cost [e] $/GJe
Electricity									
Biomass	1200	0.5	25	0.7	2.21	2.00 [f]	0.00 [g]		10.39
Natural gas	500	0.55	25	0.7	0.92	2.50	28.00		7.21
Coal	1100	0.5	25	0.7	2.03	1.00	49.40		7.86
Oil	600	0.5	25	0.7	1.11	3.00	41.00		9.19
Solar PV	1200	1	25	0.25	2.21	0.00	0.00 [g]		13.91
Solar CSP	3200	1	30	0.6	2.06	0.00	0.00 [g]		14.42
Hydro	1000	1	40	0.7	1.84	0.00	0.00 [g]		4.92
Wind	600	1	25	0.25	1.11	0.00	0.00 [g]		6.95
Nuclear	2000	0.33	25	0.7	3.69	1.00	0.00 [g]		13.68
Bio-CCS	1700	0.3	25	0.7	3.13	2.00 [f]	-96.00	7.01	23.23 [h]
NG-CCS	900	0.45	25	0.7	1.66	2.50	3.42	1.14	11.49
Coal-CCS	1500	0.35	25	0.7	2.76	1.00	7.06	2.35	13.19
Oil-CCS	1000	0.4	25	0.7	1.84	3.00	5.13	1.71	14.53
Heat									
Biomass	300	0.9	25	0.7	0.55	2.00 [f]	0.00 [g]		3.82
Natural gas	100	0.9	25	0.7	0.18	2.50	17.11		3.31
Coal	300	0.9	25	0.7	0.55	1.00	27.44		2.71
Oil	100	0.9	25	0.7	0.18	3.00	22.78		3.87
Solar	400	0.9	25	0.25	0.74	0.00	0.00 [g]		4.64
Bio-CCS	500	0.8	25	0.7	0.92	2.00 [f]	-36.00	2.63	8.29 [h]
NG-CCS	300	0.8	25	0.7	0.55	2.50	1.93	0.64	5.36
Coal-CCS	500	0.8	25	0.7	0.92	1.00	3.09	1.03	4.94
Oil-CCS	300	0.8	25	0.7	0.553	3.00	2.56	0.85	6.20

For explanations, see footnotes to Table 1

Table 3: 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 2000 [c]	Year 2100	Base	Increment
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		8000-23000 [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 (HHV basis) used by Petro ICEV divided by that for alternative technology.
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. 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.
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.

2.6 Personal Transportation

Electricity and hydrogen are energy carriers; for simplicity we include these as "fuels". The model does not distinguish between gasoline and diesel fuels, which are lumped together as petroleum (petro). Five fuel options: petro, natural gas (NG), synthetic fuels (coal to liquid, CTL; gas to liquid, GTL; biomass to liquid, BTL), electricity, and hydrogen (H2) and five vehicle technologies: internal combustion engines (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs) were considered.

The efficiency and cost data were derived from published sources [1, 18-22]. 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 [23]. HEVs have a relatively short all-electric range (we assume 2 km). The all-electric range was set to 200 km for BEVs.

Model runs assessed the sensitivity to variation of the following: battery costs from $150/kWh (goal for long-term commercialization set by the US Advanced Battery Consortium [24]) 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 [21]); hydrogen storage costs from $1500/GJ (US Department of Energy target [25]) to $3500/GJ; and fuel cell stack cost from $65/kW (Ballard [26]) to $125/kW (CONCAWE [21]).

Table 3 provides the vehicle energy efficiency and cost data for the different combinations of fuel and vehicle technologies included in the model.

3 Results

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. Results on cost-effective fuels and drive train technologies, for the assumed global passenger vehicle fleet, in the four different scenarios are presented in Figure 1.

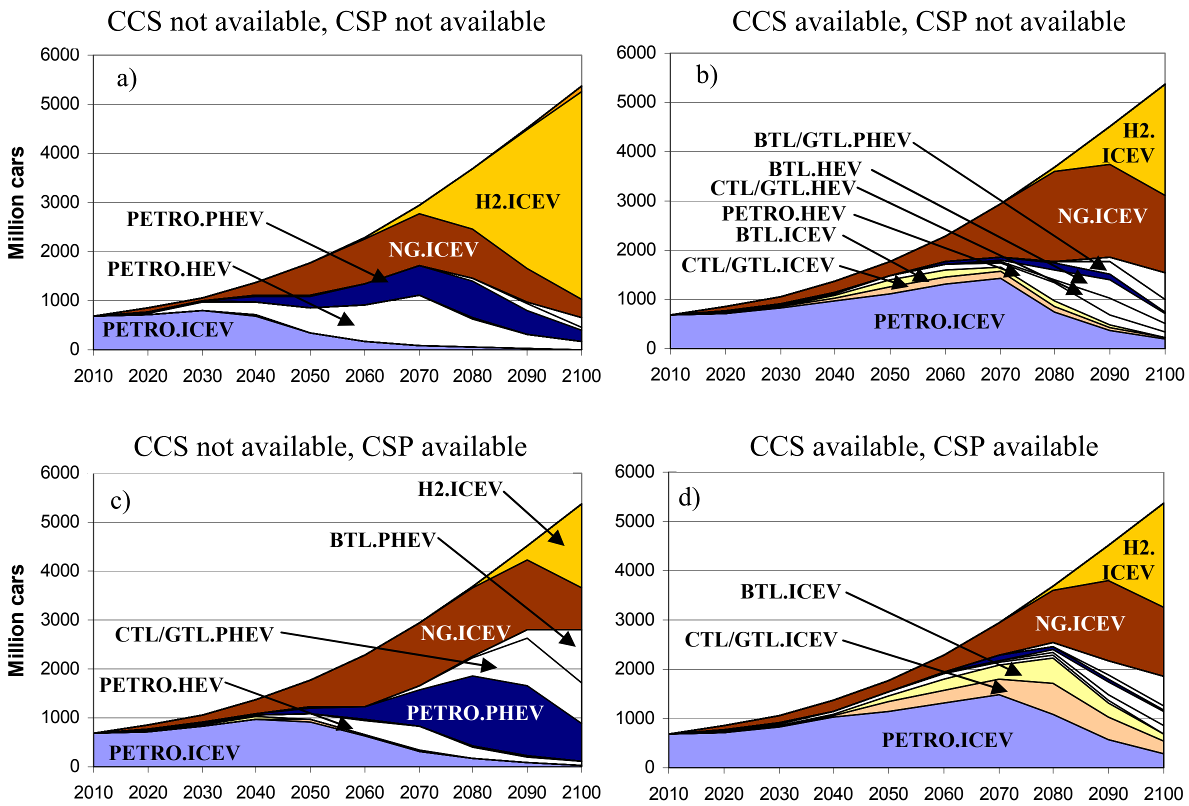

Figure 1: Global passenger vehicle fleet (millions) consistent with data assumed in case #1, i.e. a battery cost of \$300/kWh, a hydrogen storage cost of \$2500/GJ, a natural gas storage cost of \$1150/GJ, a FC stack cost of \$95/kW, and: (a) neither CCS nor CSP available, (b) only CCS available, (c) only CSP available, or (d) CCS and CSP both available.

Nine cases for vehicle costs were considered. Case #1 is based upon a battery cost of \$300/kWh, a hydrogen storage cost of \$2500 /GJ, a NG ICE storage cost of \$1150/GJ, and a fuel cell stack cost of \$95/kWh. Cases #2 and 3 explore the impact of changing the NG storage costs. Cases #4 and 5 explore the impact of changing the hydrogen storage cost assumptions. Cases #6 and 7 test the sensitivity to battery costs. Finally, cases #8 and 9 test the sensitivity to fuel cell stack cost. The results from cases # 2-9, assuming that both CCS and CSP are available, are presented in Figure 2.

3.1 Cost-effective fuel and vehicles

In all scenarios, there is no single vehicle technology and fuel that dominates throughout the century. The diversity of solutions reflects: (i) different regional resource availability and mobility demand, (ii) that relative cost-effectiveness between fuels and technology options, changes over time due to increased carbon constraints, and (iii) oil and natural gas supply potentials become scarcer with time and this alone drives the introduction of alternative fuels. In the figures, CTL and GTL (both from fossil sources) are combined for clarity.

3.2 Impact of CCS and CSP

The availability of CCS and CSP has a profound influence on the lowest cost passenger vehicle fuel and technology choice in a carbon-constrained world. 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).

The availability of CCS (compare Figure 1b with 1a) extends the use of conventional

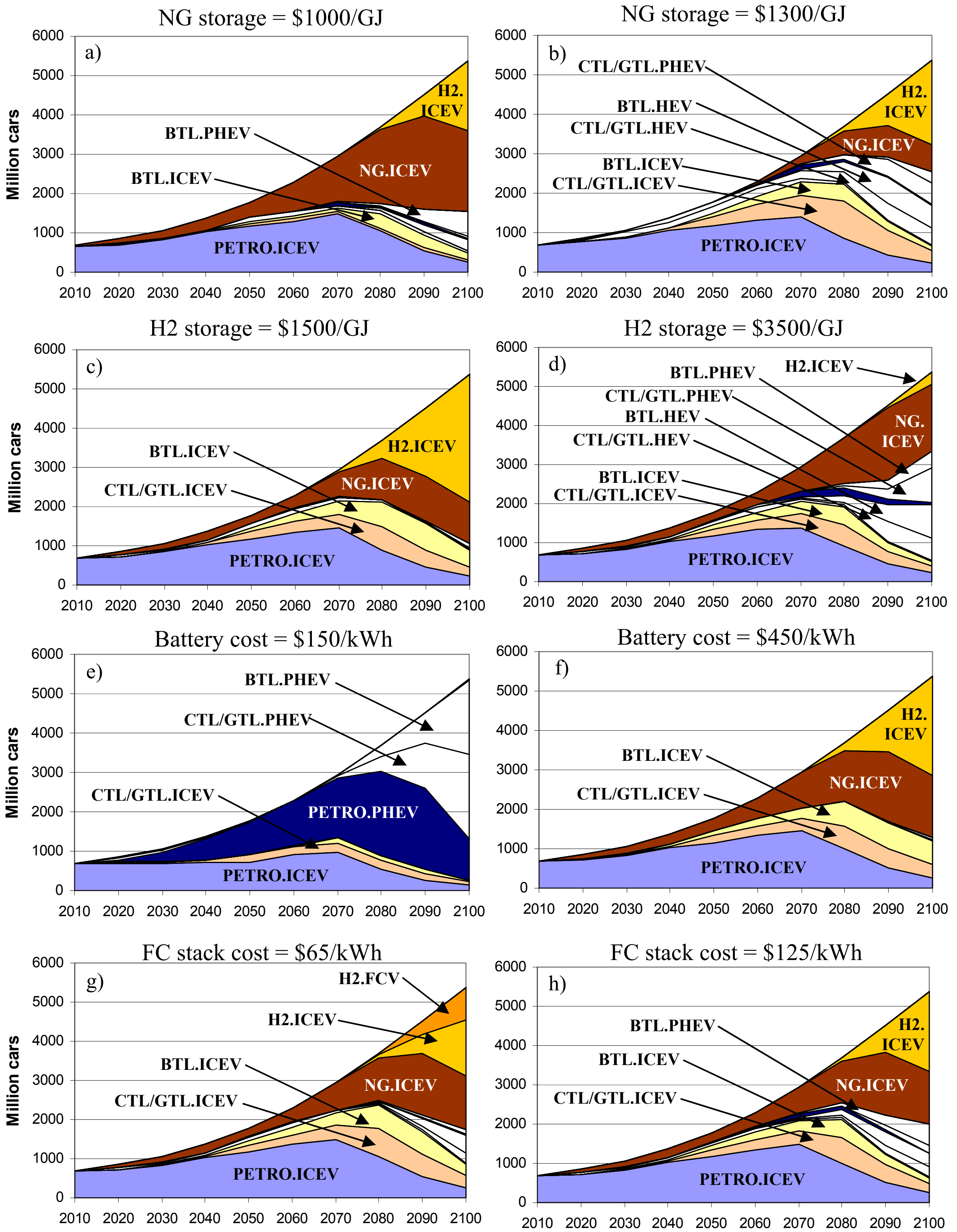

Figure 2: Global passenger vehicle fleet (millions) from the scenario assuming both CCS and CSP available consistent with data assumed in a) case #2 (lower NG storage cost, 1000 $/GJ), b) case #3 (higher NG storage cost, 1300 $/GJ), c) case #4 (lower H_2 storage cost, 1500 $/GJ), d) case #5 (higher H_2 storage cost, 3500 $/GJ), e) case #6 (lower battery cost, 150 $/kWh), f) case #7 (higher battery cost, 450 $/kWh), g) case #8 (lower FC stack cost, 65 $/kW), h) case #9 (higher FC stack cost, 125 $/kW).

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. The availability of CCS leads to coal displacing biomass in the heat sector which allows increased production of transportation fuel from biomass (when CCS is not available, biomass is used mostly to provide heat). 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 non-transport 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, when CSP is available, substantial volumes of PHEVs and HEVs fueled by petroleum and synthetic fuels (GTL and BTL) are used at the expense of ICEVs fueled by solar-based H2. The system dynamic at work is similar to that described above for CCS, but with 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.

3.3 Impact of vehicle technology cost

The impact from changing the assumptions on future vehicle technology costs are illustrated in Figure 2. The sensitivity to natural gas and hydrogen storage costs are shown in Figure 2a-d. Comparison of Figures 2b and 2d with 1d shows that a higher cost for on-board storage of natural gas or hydrogen increases the use of HEVs and PHEVs 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.

The sensitivity to variation of battery and fuel cell stack costs are shown in Figure 2e-h. Comparison of Figure 2e with 1d, 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 2f). Comparing Figure 3g with 1d shows that decreasing the fuel cell stack cost from $95 to $65/kW results in replacement of hydrogen ICE with hydrogen FC vehicle technology (more profound in the scenario assuming that neither CCS nor CSP are available – results not shown in this paper). Increasing the fuel cell stack to $125/kW (Figure 2h) removes the small number of H2 FCVs present in the $95/kW case. The impact of battery and fuel cell stack cost with both CCS and CSP available show the same trends illustrated above.

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). In an additional sensitivity analysis we ran the model assuming 100 km driving range for BEVs. Such cars are no longer directly comparable with the other car options in the model. Nevertheless, 100 km driving range might be an interesting option for city cars. As shown in Figure 3, BEVs enter the scenario when assuming this shorter driving range, first and foremost taking shares from PHEVs (compare with Figure 1).

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.

4 Discussion and conclusions

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

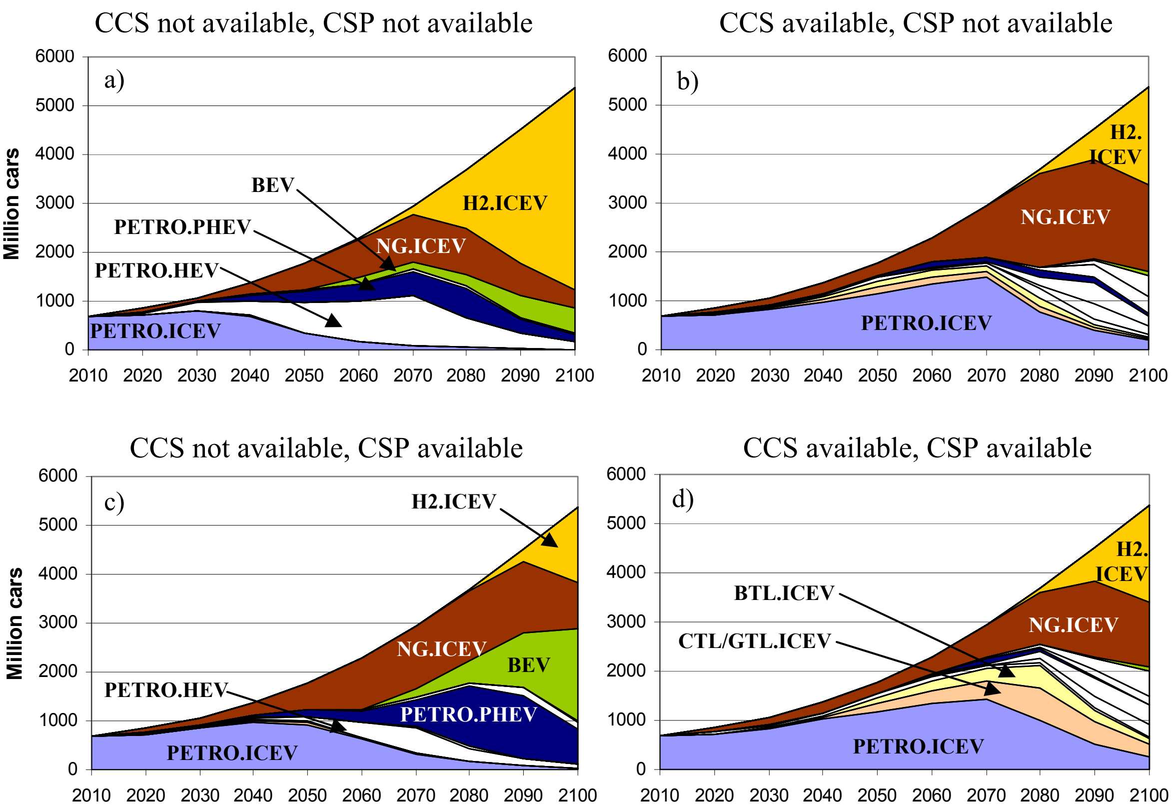

Figure 3: Global passenger vehicle fleet (millions) consistent with data assumed in case #1 and an assumed driving range of 100 km (instead of 200 km) for BEVs, in the scenarios: (a) neither CCS nor CSP available, (b) only CCS available, (c) only CSP available, or (d) CCS and CSP both available.

most important addition to earlier versions of the model was a more detailed description of light-duty vehicle technologies.

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 target of 450 ppm 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 remaining “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. For instance, for low battery costs ($150/kWh), electrified powertrains dominate and for higher battery costs ($450/kWh), hydrogen-fueled vehicles dominate, regardless of CCS and CSP availability. Thus, our results summarized above should not be interpreted to mean that the electricity production options alone will have a decisive impact on the cost-effective fuel and vehicle options chosen.

General results on cost-effective primary energy choices are that the use of coal increases substantially when CCS is available and that the use of solar energy (mainly solar-based hydrogen) increases when neither CCS nor CSP are available.

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.

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