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COSTS OF CARBON DIOXIDE ABATEMENT IN THE UNITED STATES

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ABSTRACT

We present an analysis of the costs of reducing CO2 emissions in the US in the near-term (the next ten years), by taking a bottom-up engineering-economic approach and covering a broad spectrum of technology-based abatement measures. In this meta-study technology cost-performance data are extracted from publicly available literature and "normalized" to a standard set of economic parameters and assumptions to assure consistency. Although the normalization is most complete for electric power and vehicles, the work covers buildings and industry as well. Costs of CO2 transport and sequestration are also discussed, but we have not considered emission reductions achievable by changes in the management of forest and agricultural land. Abatement costs are calculated with respect to a baseline, for which we have chosen the EIA forecast of the Annual Energy Outlook 2005. The emissions data are expressed as equivalent CO2, including CH4 and N2O; they also include upstream emissions, e.g. for fuel production. We also estimate the potential near-term emission reductions, as well as the uncertainties in abatement cost and reduction potential. The results are used to derive a supply curve, along with confidence intervals.

1. INTRODUCTION

The objective of this paper is to provide estimates of the costs of CO2 reduction and abatement options in the USA, based on a systematic survey and critical review of recent (1995 to present) national and international CO2 abatement studies (about 25% of the worldwide fossil fuel CO2 emissions come from the USA). The abatement strategies are analyzed for the major CO2 emitting sectors: power, vehicles, buildings, and industry. Various sequestration options are reviewed as well. The costs are normalized as much as possible to correspond to a consistent set of assumptions. The abatement options for the near-term (roughly the next ten years) are ranked in terms of their cost effectiveness, i.e. $/tonne of CO2 avoided (or CO2,eq including induced changes in emission of CH4 and N2O). The cost estimates are based on engineering studies of technologies and assume no change in the delivered product or service. Emission reductions from changes in consumer preferences or behavior, such as simply driving less, are not included. We also provide an estimate of the potential of emission reductions in the near term and plot a supply curve, i.e. the cumulative reductions as a function of a cost cutoff.

2. METHODOLOGY

2.1. Literature Review

We reviewed about 250 studies that derived and presented estimates of the cost of avoiding CO2 emissions. Of these more than 25 were studied closely and provided the basis for our calculations. Needless to say, the numbers in the different reports can and do differ, sometimes significantly. The assumptions for the economic analysis and the normalization methodology are described below. The results for the vehicle sector are based on our own calculations [Spadaro and Rabl 2006].

2.2. Perspective of Society

Since this paper presents the perspective of society, the economic analysis is very different from that of a private investor or consumer; the cost calculations and cash flows differ markedly between social and private perspective. In particular we use constant currency and the social discount rate (taken as 5%, except for some measures in buildings and industry where we could not recalculate the costs because the referenced studies did not provide sufficient detail). As an indication of what the costs might be for private investors, we also present some results for electric power at a discount rate of 15%. Taxes are not included because the net cost to society is zero: resources are merely transferred rather than consumed.

For insurance the basic considerations are the same. Namely, several vehicle technologies cost more than the ones they replace, for instance the hybrid vehicle costs more than a conventional one and if it is damaged in an accident, the repair may cost more as well. In this paper we include the incremental collision insurance due to higher vehicle price, as a proxy for higher repair costs. For the other technologies we assume that such changes in insurance costs are already included in the annual costs reported by the respective studies. Since we include only part of the insurance and no taxes on vehicle or fuel, the cost per ton of avoided CO2 may be radically different from what a private owner would pay. The difference may be further accentuated by our use of 5% as social discount rate.

2.3. Fuel Costs

Energy costs have to be based on the cost to society rather than energy prices paid by private consumers. Ideally they should include external costs, although we have neglected them and merely note in passing that the external costs of energy have been evaluated by the ExternE project series of the European Commission (see www.externe.info); they are very significant but their uncertainties are large (typically about a factor of three about the mean damage cost estimate). Since we neglect external costs, we take wholesale prices without taxes as a proxy for social cost of energy. Apart from external costs, differences between private prices and social costs represent transfers rather than real costs.

Choosing the cost of oil and natural gas is difficult at the present time of escalating/fluctuating and uncertain prices of crude oil. For the vehicle sector we have taken a cost of $ 1.50/gallon of gasoline and of diesel fuel, without taxes. For natural gas we assume $5.0/MBTU ($4.74/GJ) and for coal $1.3/MBTU ($1.23/GJ).

2.4. Other Greenhouse Gases and Upstream Impacts

Many of the technological options change not only the CO2 emissions of a process itself but also upstream emissions, for instance from the production of biofuels. Furthermore, some options involve changes in the emission of other greenhouse gases, especially CH4 and N2O. Such induced effects must be taken into account. They are particularly important for the production of fuels for vehicles. We have treated upstream impacts by using results from life cycle analyses (LCA). Our results account for changes in CH4 and N2O; they are reported in terms of CO2eq, using the commonly accepted values of global warming potential of these two gases.

2.5. Normalization

Since different studies are based on different sources, different data and different assumptions, their results can be quite different. Here we present a single cost estimate for each technology, by normalizing the different studies as much as possible. If the studies for a specific technology used the same assumptions and methodologies, they would all yield the same result. Therefore, there is no point in trying to normalize each individual study. Instead, for each technology we choose what we believe to be the most plausible set of assumptions and input parameters, including their uncertainty range. Then we calculate the corresponding cost per tonne of CO2. The most critical parameters are:

- Discount rate (which together with equipment life determines the annual charge rate[1]);
- Rates of CO2 emission;
- Capital costs; and
- Energy costs.

Learning rates are crucial for estimating future costs, especially of new or rapidly evolving technologies such as carbon capture. We account for learning, although the effect is not very important since our time horizon is relatively short, with negligible implementation of carbon capture.

Where appropriate, the costs for carbon capture include a nominal cost for transport and storage, specifically $6.7 (+2.3/-2.5)/tCO2,captured. This value is based on the data shown in Section 8 and is representative of geological storage with a transport distance of 100 miles. Note that the cost of transport and storage is proportional to the quantity of captured CO2 rather than the quantity of avoided CO2. Therefore, to obtain the total cost, the cost of transport and storage was multiplied by the tonnage[2] ratio tCO2,captured/tCO2,avoided before adding it to the cost of capture. That ratio is approximately 1.25 to 1.35 for coal and gas fired power plant technologies compared in this paper and in the range of 1 to 1.35 for large industries; these are the only sectors where carbon capture is relevant.

2.6. Uncertainties

To obtain an estimate of the uncertainty range, we started with the general observation that, because of the quadratic combination of standard deviations, the uncertainty is dominated by the terms that make the largest contribution to the result and that have the highest uncertainty; the uncertainty of the other terms can be neglected. According to this criterion, by far the most important parameters are cost and emission. In particular for the CCS options of electric power we have taken the low (high) CCS cost and low (high) CCS emission for the low (high) estimate.

[1] The annual charge rates sometimes called the fixed charge rate (FCR) includes not only the cost of money embodied in the discount rate but also all other recurring annualized charges including maintenance, taxes, insurance, replacements and others. We treat these items explicitly rather than combining them into the FCR.

[2] In this paper the mass basis is a metric ton (aka tonne) of CO_2 denoted by tCO2.

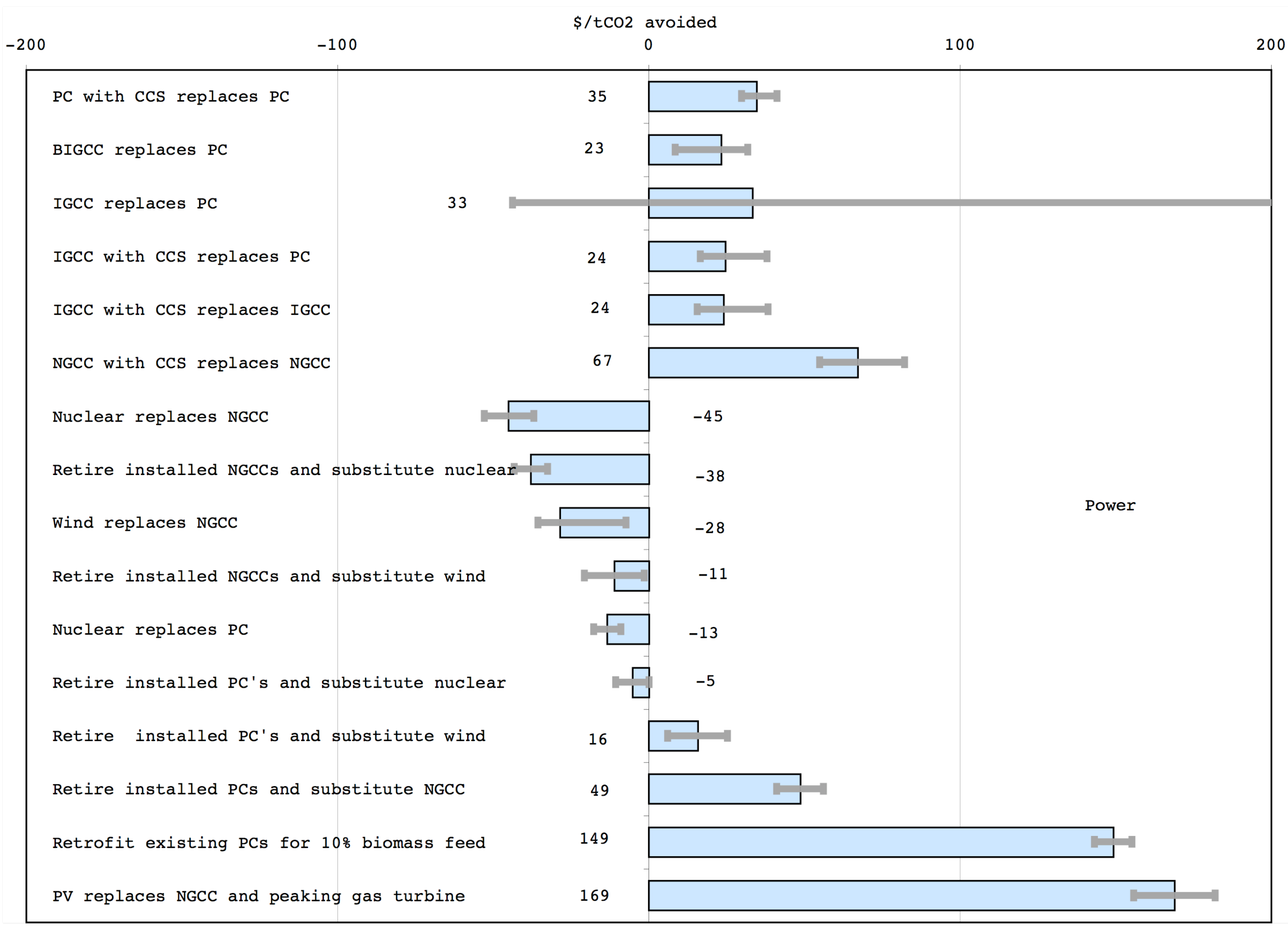
2.7. Limitations

The task of estimating costs and potential of options for reducing CO2 emissions is challenging, to say the least, and within the very limited means of a small team we have not been able to address all important issues. Our study suffers from two limitations. Firstly, many studies do not provide sufficient detail to allow us to standardize the results; for instance, some do not indicate the discount rate.

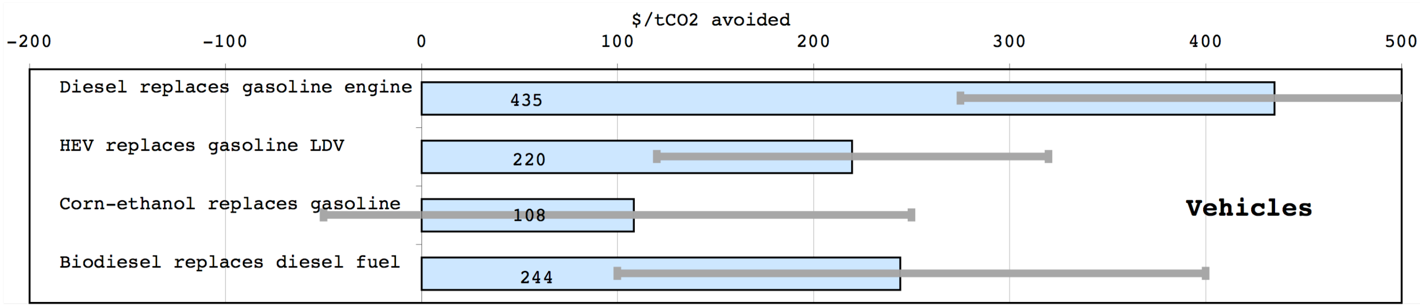
Secondly, many of the options entail collateral benefits or costs (e.g. reduced emission of other air pollutants due to energy conservation), but they have not been accounted for, even though, if an option decreases (increases) the emission of other pollutants, their damage cost should be subtracted (added) from the CO2 abatement cost. That is especially important for energy conservation and for improvements in process efficiencies. However, it would be not only a major undertaking to determine such emission changes and their costs, but the estimation of the damage costs of pollution (also called external costs) is very uncertain [Rabl and Spadaro 1999]. Furthermore, some air pollutants (e.g. tropospheric ozone and aerosols) have also important global warming impacts and should be included in a more comprehensive analysis. We have, however, included induced changes in the emission of CH4 and N2O, as CO2,eq using their GWP.

3. OVERVIEW OF THE RESULTS

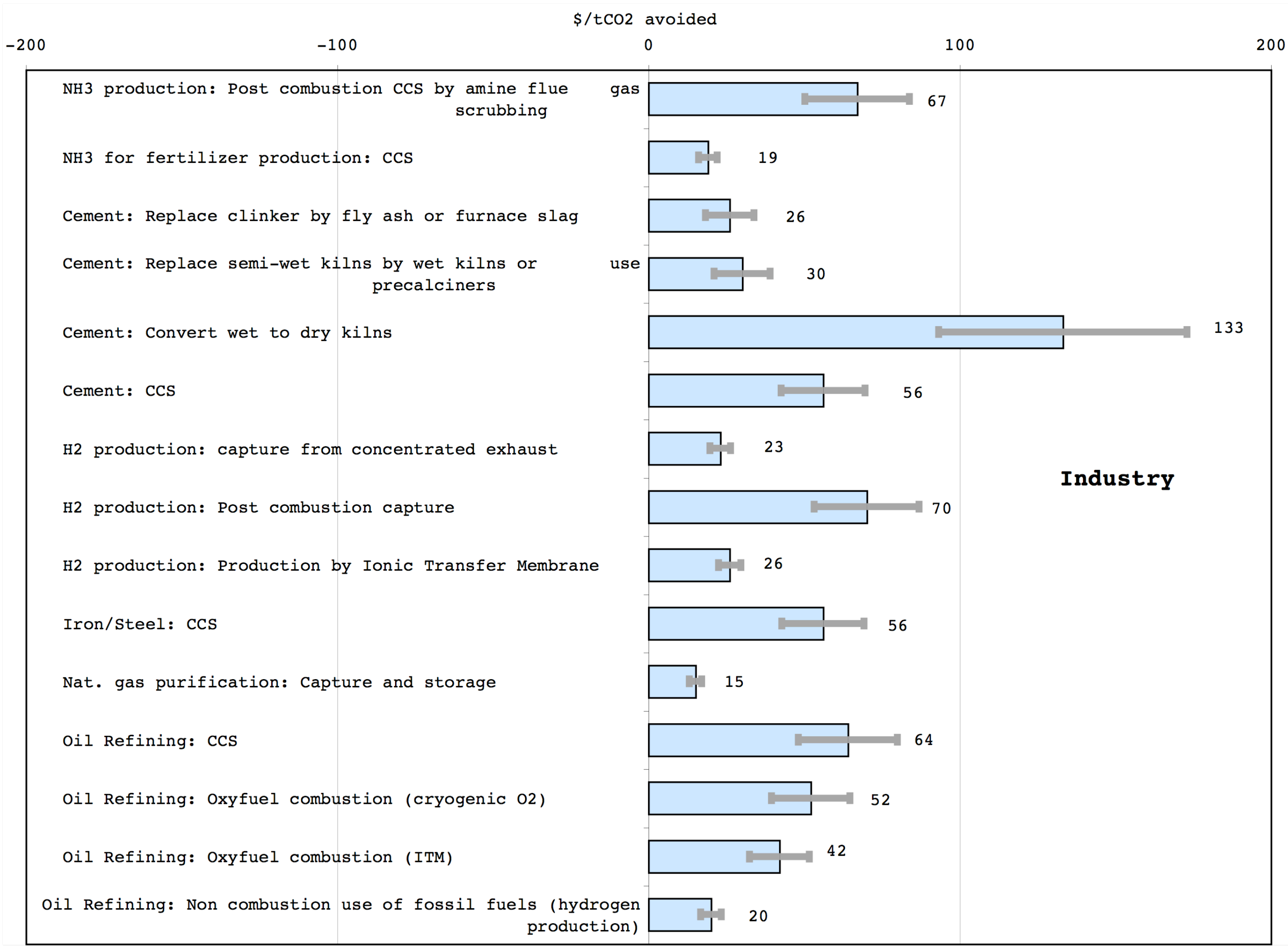
In Fig.1 we show the ranges of the costs per tonne of CO2 avoided in each of the four sectors that we have considered, for the 5% discount rate. Unfortunately the numbers across sectors are not entirely comparable because higher discount rates have been used in some of the studies of industry (10%) and buildings (7%). Only for the power and vehicle sectors have we been able to derive consistent results for 5%. The individual sectors are discussed in the following sections, followed by a discussion of CO2 sequestration.



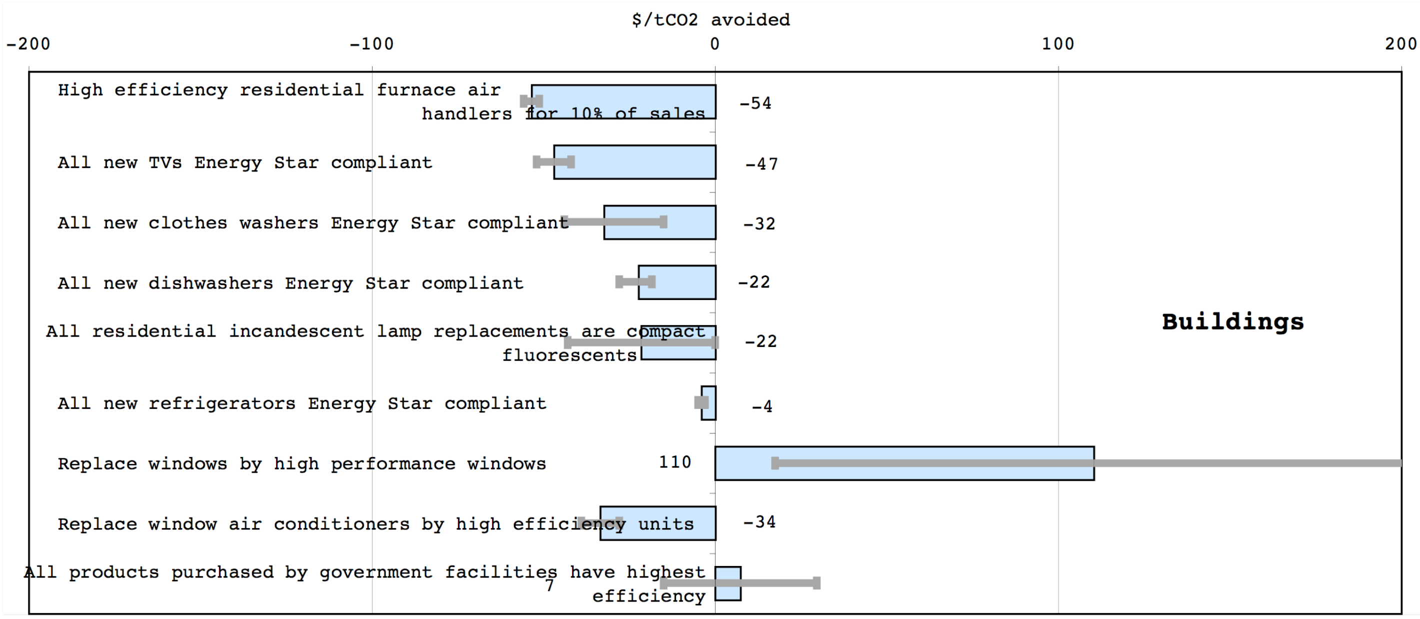
a) Power



b) Vehicles (note different scale)



c) Industry



d) Buildings

Fig.1. Abatement costs results for $/tCO2,eq avoided, with upper and lower bounds, for the technologies considered in this paper.

4. ELECTRIC POWER SECTOR

The total US CO2 emissions from fossil power plants were about 2.3 GtCO2 in 2003 [EPA 2005] and are expected to grow to 2.6 GtCO2 and 3.3 GtCO2 by 2010 and 2025, respectively [EIA 2005]. There are essentially two approaches for reducing CO2 emissions from this sector:

- The use of technologies such as wind, PV, biomass, nuclear, and natural gas plants that have lower or no CO_2 emissions and
- Carbon capture and sequestration (CCS)[3], for plants that burn fossil fuels.

We have considered the following technologies:

- CCS from standard pulverized coal (PC) plants
- Integrated gasification combined cycle (IGCC) with and without CCS
- Natural gas combined cycle (NGCC) with CCS
- Biomass-fueled integrated gasification combined cycle (BIGCC)
- Biomass fuel substitution
- wind
- photovoltaics (PV)
- nuclear power.

The costs per tonne of avoided CO2 account for changes in efficiency or performance due to the abatement measure; they have been calculated as follows:

$$(COE_{low} - COE_{ref})/[(CO_2/MWh)_{ref} - (CO_2/MWh)_{low}],$$

where

COE_{ref} = cost of electricity of the reference plant (in \$/MWh),
COE_{low} = cost of electricity of the plant with lower CO_2 emissions (e.g. by CCS),
$(CO_2/MWh)_{ref}$ = unit CO_2 emission of reference plant (in t_{CO2}/MWh),
$(CO_2/MWh)_{low}$ = unit CO_2 emissions of the plant with lower CO_2 emissions.

As an indication of approximate private costs per tonne of CO2 avoided we show in Table 1 the results with 15% discount rate next to the ones for 5%. The results for 5% have been plotted above in Fig.1; the uncertainties include only the uncertainties of the cleaner plant, the parameters of the reference plant being kept fixed. In Fig.1 we also show the cost of some technologies when used by retiring some of the existing plants (including their sunk costs).

[3] Abbreviations used in this paper include
BIGCC = biomass-fired integrated gasification combined cycle
CCS = carbon capture and storage
IGCC = integrated gasification combined cycle
LDV = light duty vehicle
NGCC = natural gas combined cycle (gas turbine Brayton cycle + Rankine bottoming cycle)
PC = pulverized coal

Table 1. Some $/tCO2 results for power, with discount rates 5% and 15%.

Discount rate	5%	15%
PC with CCS replaces PC	35	48
IGCC replaces PC	33	103
IGCC with CCS replaces PC	25	40
IGCC with CCS replaces IGCC	24	36
NGCC with CCS replaces NGCC	67	88
Nuclear replaces fossil generation mix	-22	-15
Wind replaces fossil generation mix	-11	8
BIGCC replaces PC	23	28
PV replaces peak and intermediate generation mix	166	431

The very low cost of CO2 avoidance by nuclear power may appear surprising. Let us therefore emphasize that ours is an engineering analysis, without any consideration of institutional or social conditions (but we have included decommissioning costs of $350 million according to the cited studies). In France nuclear is indeed the technology with the lowest cost for base load power. The basic reasons are (i) acceptance of nuclear power by the French population, and (ii) a single electricity company (EdF) for an entire country of 60 million.

Once CCS is implemented on a large scale, the cost of carbon capture should decrease, perhaps at a learning rate similar to what has been observed for other flue gas treatments. Let us consider the case where the incremental capital cost of carbon capture will be 50% lower than what we have assumed for Fig.1a. The relative decrease in the cost per tonne of avoided CO2 turns out to be much smaller because the cost of carbon capture is only one of several components in the calculation. For example, transport and storage of the captured CO2 contribute about $9/tCO2 for PC and $10/tCO2 for NGCC. We find that for PC with CCS the total cost per tonne of avoided CO2 decreases from $34.6/tCO2 to $28.3/tCO2 if the incremental capital cost of carbon capture decreases by 50%; for NGCC with CCS the analogous result is a decrease from $67.1/tCO2 to $57.6/tCO2 (the decrease is linear in the cost of carbon capture). Improvements in all components of the cost calculation (efficiency, operating cost, etc of CCS) are needed to bring about a dramatic gain for the cost per tonne of avoided CO2.

5. LIGHT VEHICLE SECTOR

In this sector we have focused on light duty vehicles, i.e. passenger cars and light trucks. For heavy trucks and buses we have only examined the option of replacing ordinary diesel fuel by biodiesel. The methods of carbon emission reduction include:

- fuel substitution (biofuels, hydrogen, etc.)
- vehicle efficiency improvements (e.g. weight reduction)
- motor improvements (advanced internal combustion engines, hybridization)
- new motors (fuel cells, electric vehicles)

For this sector there are relatively few studies, and most of them only evaluate the emissions of future technologies (usually as part of a life cycle assessment) without providing cost data. We had to combine the results of different studies and carry out our own calculations in order to determine the cost of CO2 that can be avoided by the various technological options. We average the vehicle costs over passenger cars and trucks, assuming that 40% of HEVs and 20% of advanced diesels are passenger cars.

For light duty vehicles (LDV) we assume that in the USA the only technology options for CO2 avoidance in the near-term time frame are corn ethanol (as E10) and a replacement of conventional LDVs by diesels or by hybrid electric vehicles (HEV). For biofuels we have considered Quirin et al. [2004] as the primary source with others for details. Of the options considered by these studies, only ethanol from corn and biodiesel from soy seem appropriate for USA in the near term. Our results include upstream emissions, calculated with the well-to-wheel software GREET [ANL 2005].

In view of the large and rapid fluctuations in the price of oil at the present time, it is difficult to foresee the price of fuel for LDVs even in the near future. Since the cost per ton of avoided CO2 for the LDV options varies strongly with the assumed fuel cost, it is instructive to show the sensitivity to this parameter in Fig.2. Likewise the incremental vehicle cost for the HEV and diesel options is very uncertain, especially for the latter because of environmental regulations that necessitate expensive abatement of PM and NOx emissions. The PM emissions of the diesel can be reduced by more than 90% by means of the particle filter (for which we estimate an extra cost of about $1000), a technology that is being used for the most recent diesel cars in Europe where diesels account for an increasing share of new LDV sales, over 50% in some countries. NOx emissions pose a problem in states like California and New York where selective catalytic reduction would be necessary (which we estimate to add about $2000). Since a diesel engine by itself costs about $1000 to $2000 more than a gasoline engine, we estimate an incremental vehicle cost of about $4600 for the replacement of gasoline by diesel engines in the USA. Our incremental vehicle costs are averages over passenger cars and light trucks, and so are the results shown here (although we have calculated them with separate numbers for each of these types). Note that the retail rice of vehicles can be a very misleading indicator of the true costs because manufacturers tend to sell below their costs when that is in the interest of creating a market for a new product. Our estimates of increased vehicle costs are based on a wide range of estimates.

To show several interesting variations in the same graph, namely fuel cost and incremental vehicle cost, these parameters are plotted in dimensionless form as ratio x/x_{base}. As base case values for the input parameters for Fig.2 we have chosen:

for replacement of conventional LDV by HEV:

x_{base} = *\$1.50/gal for fuel cost (excluding taxes) and* x_{base} = *\$4200 for incremental vehicle cost*;

for replacement of gasoline engine by diesel engine:

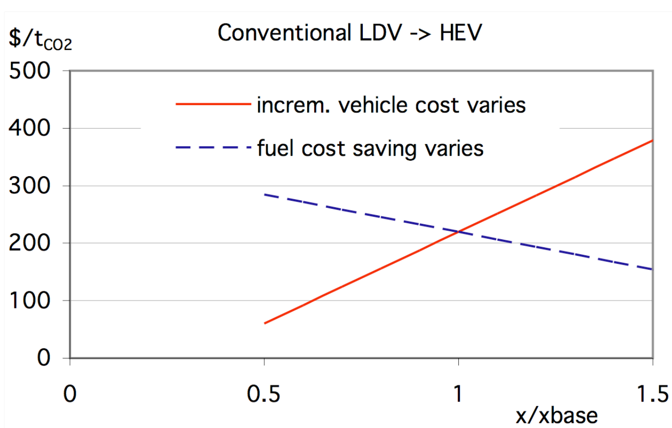
x_{base} = *\$1.50/gal for fuel cost and* x_{base} = *\$4600 for incremental vehicle cost;*

for replacement of gasoline by corn ethanol:

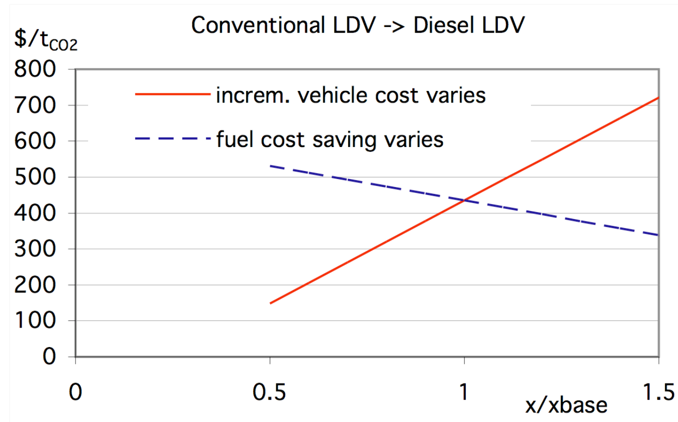
x_{base} = *\$1.50/gal for gasoline cost and* x_{base} = *\$1.20/gal for ethanol (gasoline equivalent \$1.80/gal);*

for replacement of diesel fuel by biodiesel:

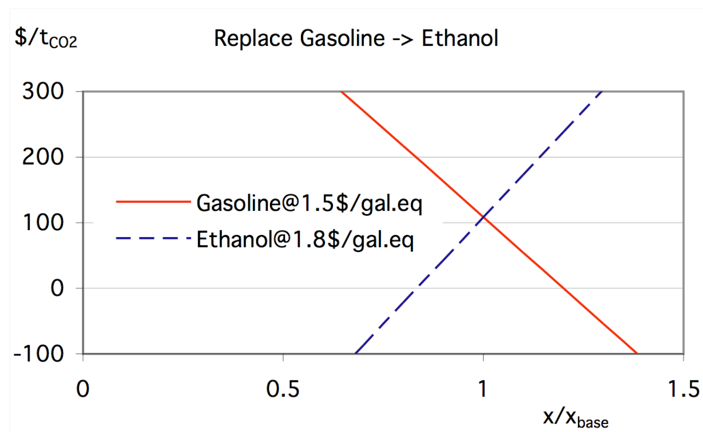
x_{base} = *\$1.50/gal for diesel cost and* x_{base} = *\$3.00/gal for biodiesel (essentially same performance as ordinary diesel).*



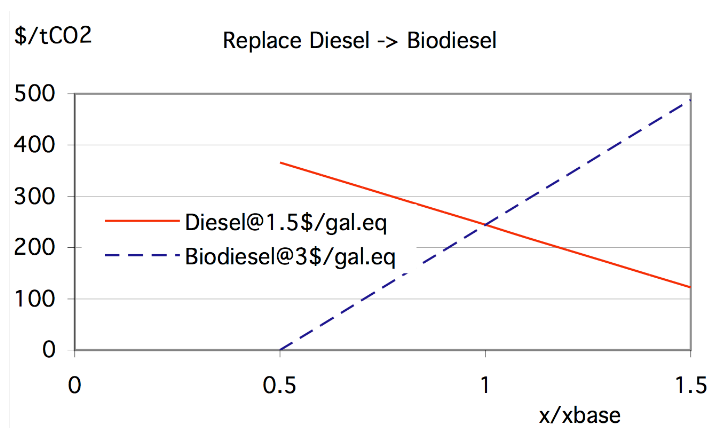
a) replacement of conventional LDV by HEV



b) replacement of gasoline engine by diesel engine



c) replacement of gasoline by corn ethanol (as E10)



d) replacement of diesel fuel by biodiesel

Fig.2. Sensitivity of abatement cost to fuel cost and incremental vehicle cost for four options (x-axis shows fuel cost and incremental vehicle cost as ratio relative to base value).

6. INDUSTRY SECTOR

Buildings and industry consume more than 50% of all energy used in the US. Therefore, they offer a significant potential CO_2 abatement potential. Information for this sector is, however, incomplete and cost estimation is more problematical than for electricity generation.

The technologies which appear to have the most significant potential for cost effective abatement include:

- modifications to ammonia production processes
- fuel switching, cement blending, and technical process upgrades in the cement industry
- carbon capture measures in the hydrogen production and steel production industries
- carbon capture in the gas and petroleum industries

Carbon capture technologies are essentially the same for industry and electric power plants, although there are some differences in $/t$CO_2$ because the composition of the flue gases is different.

Improvements in energy efficiency and process modifications, by contrast, are highly specific to each industry and technology and cover a wide variety of different options. Therefore it is difficult to get broadly-applicable cost estimates. Further, we have not been able to find all the input parameters assumed by the studies for improvements in energy efficiency and process modifications, and therefore we have not been able to normalize these costs according to the same ground rules as for power generation and carbon capture. This is perhaps not a serious limitation because in the industrial sector the potential reductions with such measures, that we found in the literature, are small compared to the reductions achievable by carbon capture.

The costs for carbon capture are based on the meta-analysis of Anderson and Newell [2003] who normalized their data; their discount rate is 10% but since no breakdown between capital and operating costs is provided, we are not able to recalculate the corresponding numbers for other discount rates.

7. BUILDINGS SECTOR

There are numerous energy efficiency measures in residential, institutional and commercial buildings. We cite some results for energy efficiency improvements in the building sector, based on studies by the national laboratories and other sources, such as ACEEE (American Council for an Energy Efficient Economy). They involve such measures as replacing appliances (lights, refrigerators, dishwashers, etc) by more efficient models, improvements in heating and cooling systems, and installation of high performance windows. The cost estimates for 2016 are typically in the range of about -$50 to about +$100 per tonne of CO_2 avoided, most of the central estimates being negative.

In terms of life cycle savings most of these measures look like very attractive investments. However, the quoted results are pure engineering estimates that do not take into account any transaction costs or particular circumstances that so often prevent the implementation of these measures. Energy cost is just one of many considerations that influence purchase decisions, such as considerations of comfort, convenience or esthetics. The very fact that most people have not implemented all of these measures proves that such considerations and transaction costs are crucial in practice. For these reasons the engineering estimates of $/t$CO_2$ in these studies can be considered optimistic, and it is difficult to estimate a realistic reduction potential.

8. SEQUESTRATION OF CO2

The methods of carbon sequestration include:

- geologic storage in deep saline aquifers, depleted oil fields, depleted natural gas fields and, deep unmineable coal seams
- storage in biomass, primarily forests
- soil-based approaches including reduced tillage, crop management and afforestation
- mineral carbonation
- deep ocean sequestration.

CO_2 transport is mostly by pipelines.

Geological storage appears to be the most economical option in the near term, particularly when the costs are reduced by credits from enhanced oil recovery (EOR). However, while the potential geologic storage capacity is very large compared to the CO_2 emissions, the storage supply curve may rise much faster than expected. For example, US on-shore geologic storage capacity is estimated to be about 3,800 GtCO_2 [Dooley 2004]. Of this, only about 13 GtCO_2 is associated with EOR and can benefit from the corresponding credits. Furthermore, the total emissions from point sources located within 250 miles of suitable reservoirs are only little over 3GtCO_2/yr, which would indicate a practical limit for geological sequestration. Note that any geologic reservoir can leak. Although some claim a leakage rate of 0.001%, based on industrial experience, a leakage rate of 0.1% is mentioned as “a general consensus” figure. We believe that the costs quoted in the literature do not fully reflect the exploration, drilling, and injection costs. This is in part because most of the capital and operating costs are embedded in the EOR operation, and not charged to sequestration.

Table 2 lists the cost estimates that we have been able to find. We have not shown them in Fig.1 because the cost of transport and the cost of sequestration in soil are functions rather than simple numbers. Transport cost depends on distance in approximately linear fashion, so we show the cost per mile. Sequestration in forests is an approximately linear function of the annual amount sequestered; we show it as an equation and estimate its uncertainty range as ±50%. Soil sequestration depends on the cumulative amount that is stored this way and we show several values.

Table 2. Cost estimates for transport and storage.

	Units	Central	Low	High
Transport				
@ pipeline capacity 0.5 $MtCO_2$/yr	$/t$CO_2$/mile	0.06	0.055	0.065
@pipeline capacity 1.0 $MtCO_2$/yr	$/t$CO_2$/mile	0.032	0.022	0.040
Geologic sequestration	$/t$CO_2$	3.5	2.0	5.0
Forests	$/t$CO_2$, with Annual amount in $MtCO_2$/yr	Cost = 3.0 + 0.0113* Annual amount	-50%	+50%
Mineralization	$/t$CO_2$	80	60	100
Soils				
@ 2.7 $MtCO_2$ sequestered	$/t$CO_2$	163		
@ 5.5 $MtCO_2$ sequestered	$/t$CO_2$	209		
@ 13.6 $MtCO_2$ sequestered	$/t$CO_2$	259		
Oceans (iron fertilization)	$/t$CO_2$	1.5	1	2

9. POTENTIAL REDUCTION OF EMISSIONS AND SUPPLY CURVE

9.1. Our Data for the Supply Curve

Finally we have combined the data for avoidance cost for electricity, buildings, industry and vehicles in the near term (~2016) to derive, at least approximately, a cumulative supply curve. Note that the estimation of supply curves is a challenging task and requires a major research effort, far beyond the scope of the present project. We searched the literature for data on the reduction potential of the various technologies but found that such data are currently available only for a subset of the technologies in Fig.1.

A major difficulty arises from the choice of the time frame because the potential reductions depend crucially on the rate at which the respective abatement measures can be implemented. Most of the possible measures require significant lead time for their implementation, for example retooling to change the production from conventional to hybrid LDVs. Note that once massive deployment of the technology begins, that would in turn lower the cost per avoided tonne of CO2, and this gradual cost decrease would also have to be taken into account in the supply curve – in other words, there are dynamic effects that complicate the construction of a meaningful supply curve for CO2.

In trying to estimate a plausible near-term technical potential for the technologies identified in the literature, we have taken into account technological progress and lead-times required to implement the abatement measures. As a result, the supply curve is based on the following assumptions:

- We have not included carbon capture and sequestration, except for certain industries where current processes (e.g. natural gas purification) already yield a CO_2 stream that could be sequestered instead of being vented to the atmosphere;
- For electric power we have estimated the incremental changes with respect to the 2010 forecast (EIA 2005), namely substitutions for new power plants and replacement of existing plants that could be retired without excessive cost and within reasonable duty cycle constraints;
- For LDVs we have estimated the market potential for HEVs and diesels, and we have assumed that the corn ethanol to be produced according to the latest legislation (Energy Policy Act of 2005) will be used as E10 (10% additive to gasoline);
- For buildings we have estimated plausible rates for replacements or new purchases.

9.2. A Smoothed Supply Curve to Account for Uncertainties

Of course the uncertainties of predicting costs and reduction potential are very large. That poses a problem for the construction of the supply curve because the order in which two options A and B appear in the curve depends on their relative cost. Since the costs are uncertain, the order of the options in the curve is uncertain as well. To deal with this difficulty we have considered probability distributions for both the cost and the reduction potential of each technology. For the costs we assume Gaussian distributions with the means indicated in Fig.1. For the potential we assume triangular probability distributions with the Min, Central and Max parameters in Table 3. Each particular set of costs and potentials corresponds to a particular supply curve. By means of a Monte Carlo calculation we have obtained 10000 supply curves by calculating, for each particular set of costs and potentials, the cumulative reductions achievable below cost cutoffs chosen in

100 equal increments from -\$100 to \$400 per tonne of CO2. By plotting, at each value of the cost cutoff, the mean cumulative potential together with its one-standard deviation confidence interval, we obtain the smoothed supply curve in Fig.3.

Table 3. Data for supply curve in the electricity, buildings, industry and vehicle sectors. This table and the supply curve include only those options of Fig.1 for which we have been able to estimate significant implementation rates.

Sector: Technology	$\$/t_{CO2}$	Mt_{CO2}/yr Min	Central	Max	Cumul. Mt_{CO2}/yr
High efficiency residential furnace air handlers capture 10% of sales	-53.5	0	0.9	1.8	0.9
All new TVs Energy Star compliant	-47.0	0	0.5	1	1.4
Substitute nuclear for 20% of new NGCCs	-45.0	0	19	38	20.4
Retire 5% of installed NGCCs and substitute nuclear	-37.9	0	14.5	29	34.9
Replace window air conditioners by high efficiency units	-33.5	0.2	0.6	1	35.5
All new clothes washers Energy Star compliant	-32.4	0.4	0.7	1	36.2
Substitute wind for 10% of new NGCCs	-28.5	0	9.5	19	45.7
All new dishwashers Energy Star compliant	-22.3	0.03	0.1	0.2	45.8
All residential incandescent lamp replacements are compact fluorescents	-21.5	10	17	25	62.8
Substitute nuclear for all new PCs	-13.4	0	11	22	74.0
Retire 5% of installed NGCCs and substitute wind	-11.1	0	14.5	29	88.5
Retire 5% of installed PC's and substitute nuclear	-5.2	0	90	181	178.8
All new refrigerators Energy Star compliant	-4.0	0.1	0.3	0.5	179.1
Cement: replace coal by lower carbon waste	0.0	2	4	6	183.1
All equipm't bought for government buildings has max efficiency	7.3	10	18	26	201.1
Nat. gas purification: Capture and storage	15.0	1.1	1.8	2.5	202.9
Retire 5% of installed PC's and substitute wind	15.7	0	90	181	293.2
NH_3 production: store CO_2	23.0	2	4	6	297.2
Cement: Replace clinker by fly ash or furnace slag	26.0	1	3	5	300.2
Cement: Replace semi-wet kilns by wet kilns or use precalciners	30.0	0	0.25	0.5	300.5
Retire 10% of installed PCs and substitute NGCC	48.6	0	82	163	382.1
Corn-ethanol (E10) replaces gasoline	108.0	10	20	30	402.1
Replace windows by high performance windows	110.3	2	5	7	407.1
Cement: convert wet to dry kilns	133.0	0	1	2	408.1
Retrofit 20% of existing PCs for 10% biomass feed	149.2	0	27	53	434.7
HEV replaces gasoline LDV	220.0	5	9	13	443.7
Biodiesel replaces diesel fuel	244.0	3	4	5	447.7
Diesel replaces gasoline engine	435.0	0	0.6	1	448.3

Obviously the reductions by 2016 are only a small fraction of the total emissions in each sector, as shown by Table 4.

Table 4. Near term reductions compared to the total emissions in each sector.

Sector	*Total emissions*	*Near term reductions*	
	Mt_{CO2}/yr	*Mt_{CO2}/yr*	*% of total*
Power	2,619	358	14%
Industry	755	14.1	2%
Vehicles	745	33.6	5%
Buildings	2,553	40	2%
Total	6,672	446	7%

10. CONCLUSIONS

For the first time in the published literature, we have reviewed CO2 abatement options in the USA and provided, as much as possible, standardized results for the cost per tonne of avoided CO2 in the near term, roughly the next ten years. The analysis covers power generation, buildings, industry and vehicles, but we have not considered emission reductions achievable by changes in the management of forest and agricultural land. We have also tried to estimate the potential emission reductions that could be expected during this time frame. Combining costs and potential reductions we have drawn a supply curve that indicates the total reduction below a specified cost per tonne. To account for uncertainties in both cost and reduction potential, we have performed a Monte Carlo calculation to obtain a smoothed supply curve with confidence intervals.

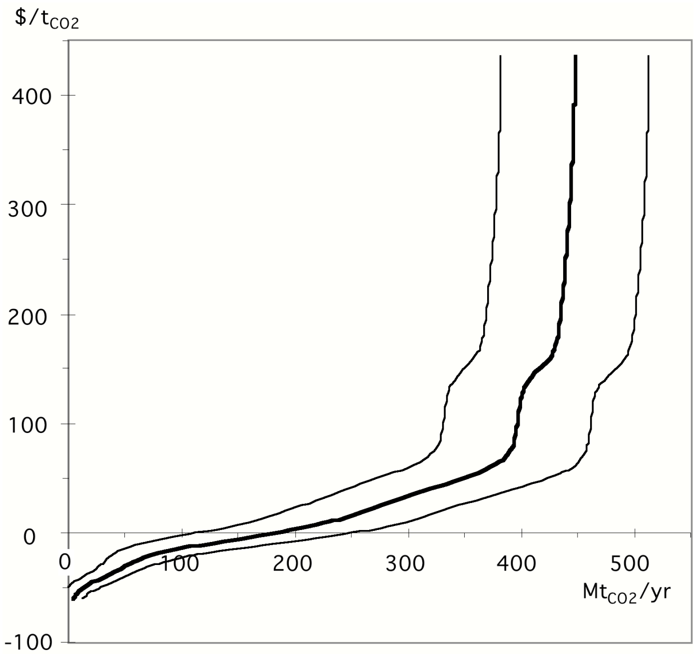


Fig.3. Smoothed supply curve for 2016 time frame, for the technologies and probability distributions in Table 3, plotted as maximum abatement cost vs. cumulative emission reduction. The upper and lower thin lines show the one-standard deviation confidence interval.

The technology options we have considered span a wide range of abatement costs, from about -\$50 to well over \$400 per tonne of avoided CO2. Generally the options in the vehicle sector are much more expensive than those in buildings and power. We emphasize that our numbers for costs and reduction potential achievable by energy conservation in buildings and of nuclear power are based on engineering estimates, without taking into account obstacles to implementation such as cost of information (for energy conservation) or siting problems (for nuclear). The total near term reductions add up to only a small fraction of the total emissions in the sectors we have reviewed. One of the reasons is the assumption that carbon capture and sequestration (CCS), a most promising option for the more distant future, will not make a significant contribution in the near term.

Some of the results can be applied to other countries. In particular, the cost of technologies such as power plants and hybrid vehicles are determined by a world wide market and essentially the same everywhere. For other options, especially biofuels, the costs are highly dependent on specific local conditions. The potential reductions, as percentage of the sectoral emissions, should be a fair indication for countries with similar industrial base.

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