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Strategies for cost-effective carbon reductions: a sensitivity analysis of alternative scenarios ☆

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Abstract

Analyses of alternative futures often present results for a limited set of scenarios, with little, if any, sensitivity analysis to identify the factors affecting the scenario results. This approach creates an artificial impression of certainty associated with the scenarios considered, and inhibits understanding of the underlying forces. This paper summarizes the economic and carbon savings sensitivity analysis completed for the *Scenarios for a Clean Energy Future* study (Interlaboratory Working Group, 2000). Its 19 sensitivity cases provide insight into the costs and carbon-reduction impacts of a carbon permit trading system, demand-side efficiency programs, and supply-side policies. Impacts under different natural gas and oil price trajectories are also examined. The results provide compelling evidence that policy opportunities exist in the United States to reduce carbon emissions and save society money. Published by Elsevier Science Ltd.

Keywords: Sensitivity analysis; Energy policy; Carbon emissions

1. Background and Purpose

The *Scenarios for a Clean Energy Future* (CEF) study is the most comprehensive assessment to date of policy- and technology-based opportunities to address the energy challenges facing the United States (Brown et al., 2001; Interlaboratory Working Group (IWG), 2000). This work builds on previous analysis such as the Five-Lab Study (Interlaboratory Working Group, 1997) and a previous analysis for the EPA using the LBNL NEMS framework (Koomey et al., 1998). It explores three policy scenarios using modified versions of the National Energy Modeling System (NEMS) model used for the Annual Energy Outlook 1999 (EIA, 1998a). The Business-as-Usual (BAU) scenario assumes a continuation of current energy policies and a steady, but modest pace of technological progress. In contrast, the Moderate and Advanced scenarios are defined by policies that are consistent with increasing levels of public commitment and political resolve to solve the nation's energy-related challenges.

This paper extends the CEF analysis by presenting an expanded range of policy scenarios composed of different subsets of policy interventions and different energy price forecasts. These analyses assess the consequences of futures other than those portrayed by the BAU, Moderate, and Advanced scenarios. This allows policy-makers and the public an opportunity to study the advantages and disadvantages of a wide array of different policy choices within the context of alternative energy price trajectories. Two key outcomes or metrics are presented for each of the "sensitivity" cases: carbon emissions and direct costs. By comparing and contrasting these metrics it is possible to identify important policy clusters and to assess the benefits and costs associated with a wide range of different policy approaches.

2. Methodology

To untangle the driving forces behind the CEF scenarios, we analyze different bundles of

☆ The Excel spreadsheets containing all scenario results are posted on the web at http://enduse.lbl.gov/projects/cef.html

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Table 1
Illustrative demand- and supply-side policies

Demand-side policies: Moderate scenario	Supply-side policies: Moderate scenario
–50% increase in cost-shared, federal R&D on energy efficiency technologies –Implement new efficiency standards for building equipment, beyond those already planned –Expand voluntary labeling and deployment programs by 50% –Voluntary agreements with individual industries and trade associations to reduce energy intensities of production by 0.5% per year over the BAU scenario –Mandate upgrades of all motors to standards set by the 1992 Energy Policy Act, by 2020 –Tax credits for the purchase of more fuel-efficient vehicles	–50% increase in cost-shared, federal R&D on clean electric supply technologies –Production tax credits of 1.5c/kWh (1992$) for the first 10 years of operation from wind and biomass power generation installed through 2004 –Full electric industry restructuring in 2008
Demand-side policies: Advanced scenario	**Supply-side policies: Advanced scenario**
–100% increase in cost-shared, federal R&D on energy efficiency technologies –More end-uses covered by building standards; another round of standards for some products –Expand voluntary labeling and deployment programs by 100% –Voluntary agreements with individual industries and trade associations to reduce energy intensities of production by 1.0% per year over the BAU scenario –Mandate upgrades of all motors to standards set by the Consortium for Energy Efficiency, by 2020 –Voluntary fuel economy agreements with auto manufacturers –"Pay-at-the-pump" auto insurance	–100% increase in cost-shared, federal R&D on clean electric supply technologies –Renewable energy portfolio standards mandating 7.5% of all electricity sales from wind, biomass, solar, and geothermal for the years 2010–2015 –SO_2 ceiling reduced in steps by 50% between 2010 and 2020 to represent tighter particulate matter standards

demand- and supply-side policies, as well as a range of domestic carbon permit trading programs.

The demand- and supply-side policies are divided into those that were modeled in the BAU, Moderate and Advanced scenarios. In the BAU forecast, current energy policies and programs are assumed to continue, resulting in a steady but modest pace of technological progress and improved efficiencies. In the Moderate scenario, policies were designed to reflect a modest shift in political will and public opinion. In the Advanced scenario, policies reflected the presumption of a nationwide sense of urgency to meet significant goals relative to energy productivity, oil supply vulnerability, air quality, and greenhouse gas mitigation. Table 1 illustrates these Moderate and Advanced policies.

The domestic carbon trading programs examined here differ only in terms of the assumed carbon permit trading price $0, $25, $50, or $100 per metric ton of carbon (in $1997). Emissions trading programs work by allocating allowances that permit the release of limited quantities of emissions during a specified period (e.g., annually). A firm's response will depend on its costs of control compared with the market price of carbon permits. We assume that the domestic carbon trading program is announced in 2002 and is implemented in 2005. Each year, beginning in 2005, permits are sold in a competitive auction run by the federal government. The federal government collects the carbon permit revenues and transfers them back to the public. The goal of the carbon permit rebate is to leave people's "incomes" intact while changing the relative price of carbon-based fuels.

We create 16 of the 19 sensitivity cases by combining the following policy options and carbon permit values in different ways:

1. Demand side policies—BAU, Moderate, or Advanced scenario
2. Supply side policies—BAU, Moderate, or Advanced scenario
3. Carbon permit trading price—$0, $25, $50, or $100 per metric ton of carbon

These 16 combinations are shown in Table 2. We define a policy implementation level as the combination of demand and supply policies. Five out of the possible nine levels are analyzed.

Each of these five policy implementation levels is examined with three different carbon trading prices ($0, $25, and $50). We only apply a $100 carbon permit price to the BAU implementation. The BAU $100 sensitivity is included so that this analysis can be compared with the Energy Information Agency's Impacts of Kyoto study (EIA, 1998b). The Impacts of Kyoto study evaluates six goals for 2010 carbon reductions, and meeting these goals require carbon prices between $67

Table 2
Sixteen incremental sensitivities used for examining CEF trends

Policy implementation level	Assumed carbon permit trading price: No. trading	$25/t	$50/t	$100/t
BAU	**BAU $0**[a]	BAU $25	BAU $50	BAU $100
Moderate	**Mod $0**[a]	Mod $25	Mod $50	
Advanced	Adv $0	Adv $25	**Adv $50**[a]	
Demand BAU, Supply Advanced	S-Adv $0	S-Adv $25	S-Adv $50	
Demand Advanced, Supply BAU	D-Adv $0	D-Adv $25	D-Adv $50	

[a] Bolded names correspond to the CEF study's main scenarios (BAU, Moderate, and Advanced)

and $348 per metric ton of carbon ($1996). The BAU $100 sensitivity shows carbon emissions reductions in line with the reductions seen in the Impacts of Kyoto report for a carbon permit trading fee of this approximate magnitude.

For clarity, every sensitivity name includes the policy implementation level as well as the carbon trading permit price. The CEF Advanced scenario is therefore called the "Adv $50" sensitivity in this article, the Moderate Scenario is called "Mod $0," and Business-as-Usual Scenario is called "BAU $0."

During the CEF study review, the authors were asked whether higher natural gas or oil prices would lead to different conclusions. Therefore, we modeled how more pessimistic assumptions affecting natural gas and oil prices might change the results for the Advanced scenario. Fig. 5 compares three new sensitivities with seven of the above sensitivities. Table 3 shows the ten sensitivities that are included in Fig. 5. The seven in the first three rows are identical to those in Table 2. The last three rows contain the last three of the nineteen sensitivities.

For these last three sensitivities, we limited the technological progress of natural gas drilling, exploration and recovery beyond the normal progress rate in NEMS. This change, called high-gas (HG), had varying impacts on natural gas prices depending on the policy levels that were assumed. When applied to the Adv $50 scenario, the HG impact was a 7% increase in average natural gas prices above the Advanced scenario in 2020. The impact of HG S-Adv $50 case was to increase natural gas prices 8% over the S-Adv $50 forecast for 2020. In the third sensitivity, the EIA's "High World Oil Prices" (EIA, 1998a) were added to the HG Adv $50 sensitivity. This leads to a 13% increase in the average petroleum prices in 2020, as well as a 7% increase in the average natural gas prices compared to Adv $50.

The two key outcomes or metrics for each of the "sensitivity" cases are carbon emissions and the direct costs for energy services. Carbon emissions are measured as annual emissions in million metric tons. Direct costs, explained below, are measured in $1997 and are presented in Tables 4 and 5. They include:

Table 3
Sensitivities used for analysis of higher prices in Fig. 5

	Assumed carbon permit trading price		
	No. trading	$25 /t	$50 /t
Policy implementation level:			
Business-As-Usual	**BAU $0**[a]		
Advanced	Adv $0	Adv $25	**Adv $50**[a]
Demand BAU, Supply Advanced	S-Adv $0	S-Adv $25	S-Adv $50
Fuel price variation:			
Advanced, high gas prices			HG Adv $50
Demand BAU, Supply Advanced, high gas price			HG S-Adv $50
Advanced, high oil and gas prices			HOG Adv $50

[a] Bolded names correspond to two of the CEF study's main scenarios (BAU and Advanced)

1. The incremental technology investment costs (i.e., the cost of efficiency improvements beyond the business-as-usual case). These are estimated by applying the cost of conserved energy to the annual energy savings.
2. Policy implementation and administration costs (including the cost of administering the public programs as well as the cost of production tax credits for renewable energy and the renewable portfolio standard). Administration costs for efficiency programs are estimated to be $0.6 per Mbtu of primary energy saved.
3. RD&D costs (both the federal investment and the private sector match). RD&D investment costs are split 50/50 between federal appropriations and matching private sector funds.
4. Consumers' electricity and fuel costs (energy bill minus the permit trading fee or carbon charge). The energy bill calculation is the sum of the product of energy consumption and energy price for each major fuel type within a sector. (Fuel prices increase when there is a carbon charge.) From society's perspective, a carbon charge is not a true cost. Therefore, the Carbon Transfer Payment is included as a benefit to balance out the portion of the energy bill that increases due to the carbon charge. In other words,

Table 4
2010 direct costs for sensitivities (billions of $1997)

Scenario	Total	Incremental cost beyond BAU $0: Technology	Program admin.	RD & D	Energy bill	Carbon transfer	Change in costs: Sum of increments
BAU $0[a]	651	—	—	—	—	—	—
BAU $25	649	3	1	0	37	(43)	(2)
BAU $50	653	7	1	0	77	(83)	3
BAU $100	662	13	3	0	151	(155)	12
Mod $0	611	11	3	1	(55)	0	(40)
Mod $25	613	15	3	1	(18)	(40)	(38)
Mod $50	618	19	4	1	20	(77)	(33)
S-Adv $0	639	(1)	0	2	(12)	0	(12)
S-Adv $25	639	2	0	2	26	(42)	(12)
S-Adv $50	643	5	1	2	64	(80)	(8)
HG S-Adv $50	657	6	1	3	76	(80)	7
D-Adv $0	603	23	4	1	(76)	0	(47)
D-Adv $25	605	27	6	1	(40)	(39)	(45)
D-Adv $50	610	31	6	1	(5)	(74)	(40)
Adv $0	591	22	4	3	(88)	0	(59)
Adv $25	594	26	5	3	(52)	(38)	(56)
Adv $50	605	32	9	3	(16)	(73)	(45)
HG Adv $50	605	30	6	3	(12)	(73)	(46)
HOG Adv $50	637	34	7	3	15	(72)	(13)

[a] Note: BAU $0 is the baseline. Incremental costs are estimated relative to BAU $0. Numbers in parentheses are negative costs (i.e. benefits).

Table 5
2020 direct costs for sensitivities (Billions of $1997)

Scenario	Total	Incremental cost beyond BAU $0: Technology	Program admin.	RD & D	Energy bill	Carbon transfer	Change in costs: Sum of increments
BAU $0[a]	694	—	—	—	—	—	—
BAU $25	690	4	1	0	37	(46)	(4)
BAU $50	692	8	2	0	75	(88)	(2)
BAU $100	702	17	3	0	148	(160)	8
Mod $0	632	31	6	1	(100)	0	(62)
Mod $25	630	34	7	1	(66)	(41)	(64)
Mod $50	626	38	8	1	(38)	(77)	(68)
S-Adv $0	691	0	0	2	(4)	0	(3)
S-Adv $25	681	5	1	2	24	(45)	(13)
S-Adv $50	691	8	2	2	68	(81)	(2)
HG S-Adv $50	703	8	2	3	79	(82)	9
D-Adv $0	578	59	11	1	(187)	0	(116)
D-Adv $25	584	63	12	1	(150)	(37)	(110)
D-Adv $50	587	67	13	1	(119)	(70)	(107)
Adv $0	582	59	11	3	(186)	0	(112)
Adv $25	582	63	12	3	(152)	(37)	(112)
Adv $50	589	69	13	3	(122)	(67)	(105)
HG Adv $50	595	67	13	3	(114)	(68)	(99)
HOG Adv $50	623	70	14	3	(91)	(67)	(71)

[a] Note: BAU $0 is the baseline. Incremental costs are estimated relative to BAU $0. Numbers in parentheses are negative costs (i.e. benefits).

fuel prices increase but additional revenue is generated. The amount of the transfer payment is the product of the carbon charge and the carbon emissions.

The direct costs of energy services do not include the indirect macroeconomic effects of a carbon permit trading system on the economy. We discuss the indirect effects below using conclusions from the analysis contained in Sanstad et al. (2001). In addition, the direct costs exclude a variety of externality and collateral costs and benefits. On the cost side of the ledger, we do not quantify amenity losses (e.g., from cars with lower horsepower) or opportunity costs. On the benefit side, we do not quantify reduced health care costs from cleaner air, the productivity benefits associated with upgraded technology investments, or the potential growth in export markets for energy technologies. While these effects may be large in some cases, the empirical foundation for including them in our numerical analysis is too limited.

3. Results

We show results in five graphs. Figs. 1 and 2 include the ten BAU, Moderate, and Advanced policy implementations. Figs. 3 and 4 include the thirteen sensitivities with some combination of BAU or Advanced supply and demand policies. Of these 13, six do not appear in Figs. 1 and 2 (the S-Adv and D-Adv implementations) and the other seven (BAU and Advanced implementations) are repeated from Figs. 1 and 2. Fig. 5 contains two of the policy implementations from Fig. 4, and three points representing higher fuel price trajectories.

On all five figures, the x-axis shows the absolute level of US carbon emissions in million metric tons of carbon (MtC). The y-axis shows total direct cost of energy services in 2010 or 2020, expressed on an annual basis.

This type of graph was first developed by Krause et al. (1995), and it is most useful when presenting results from many different sensitivities. Each point on the graph represents the direct costs and carbon emissions of an individual sensitivity case. Lines or arrows between sensitivities are used to relate sensitivities to each other. In this article, all of the lines start at the BAU \$0 case. The lines are drawn to represent groups of sensitivities that use the same set of non-price policies for both the supply side and the demand side, but with varying levels of carbon permit trading values. The arrows in Fig. 5 show the result of adding higher natural gas and oil prices to a given sensitivity case.

4. Discussion

We derive several important conclusions from the graphical results.

First, **application of the Moderate or Advanced sets of demand- and supply-side policies, in any combination, decreases the direct costs of energy services while at the**

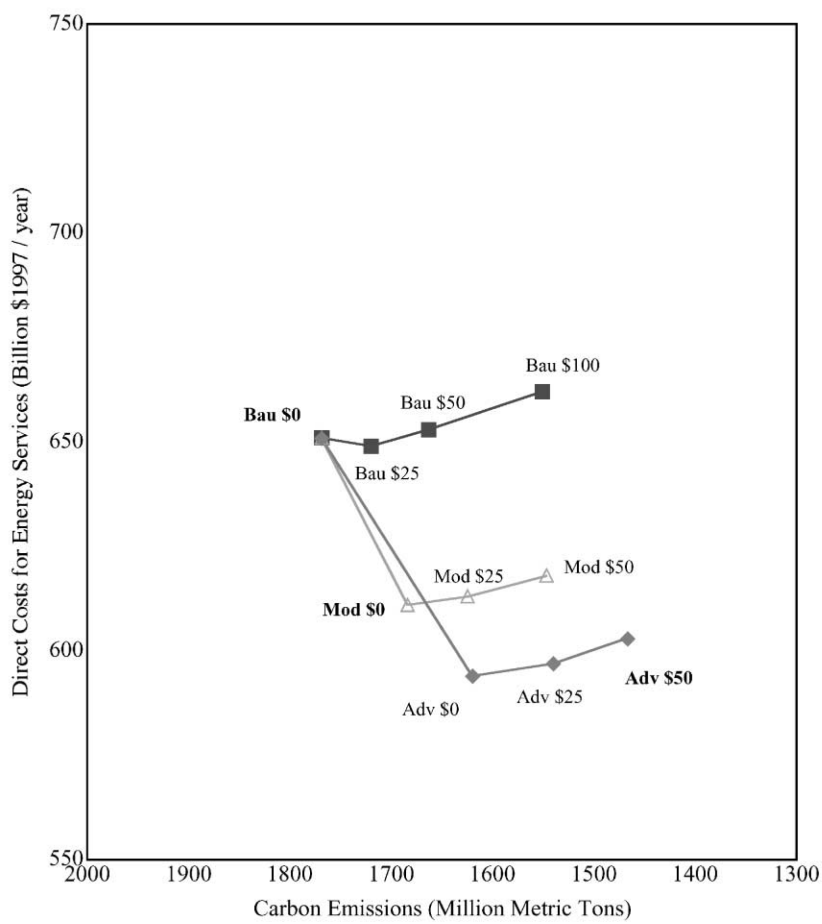

Fig. 1. CEF 2010 direct costs and carbon emissions (BAU, Moderate, and Advanced policy implementations).

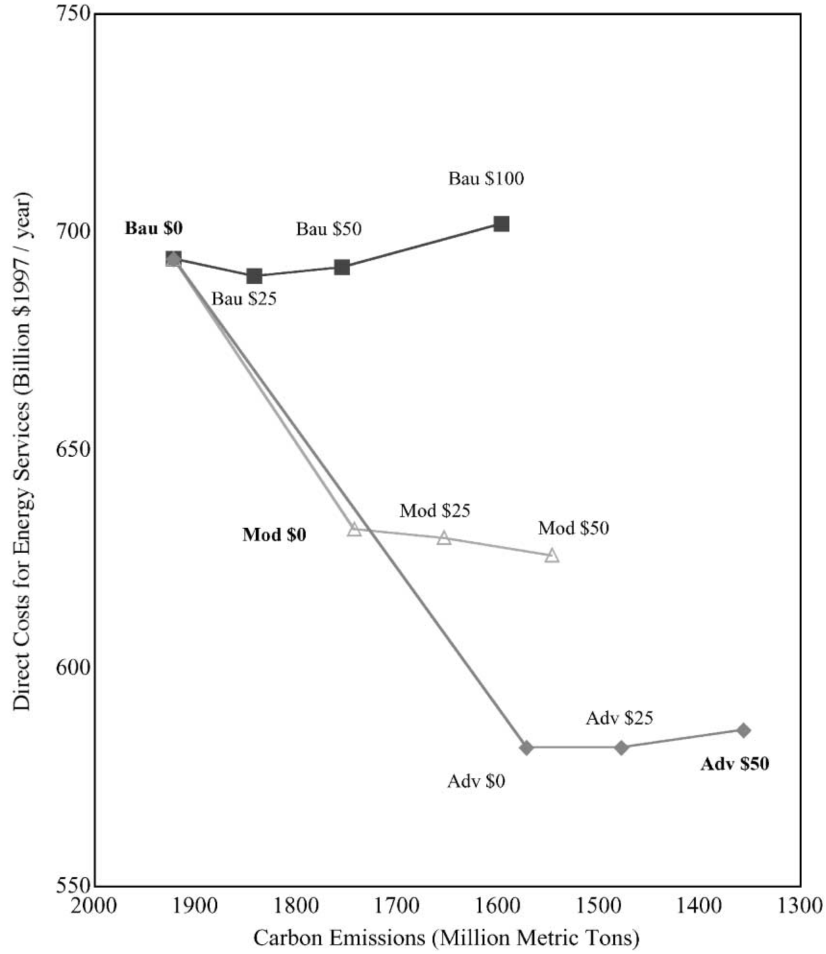

Fig. 2. CEF 2020 direct costs and carbon emissions (BAU, Moderate, and Advanced policy implementations).

same time reducing carbon emissions. Figs. 1 and 2 show that the direct costs of the Moderate demand- and supply-side policies are consistently 6% lower in cost than BAU in 2010 and 9% lower in cost in 2020, regardless of the level of carbon permit value. Similarly, the Advanced demand- and supply-side policies are 8% and 16% lower than BAU in 2010 and 2020, respectively. Thus, a corollary to this finding is that net savings in direct costs are greater, both in absolute and percent terms, in 2020 than in 2010. The extra ten years lead to additional savings due to stock turnover, and because some of the policies implemented are not fully effective until after 2010. Figs. 3 and 4 show that the same trend of direct cost and carbon reductions applies to the S-Adv and D-Adv sensitivity cases.

Second, **the demand-side policies by themselves have a much larger effect on reducing direct costs and carbon emissions than the supply-side policies by themselves.** The cost of carbon reductions were similarly found to be higher for supply-side technologies and policies than for demand-side approaches in studies by the National Academy of Sciences, Office of Technology Assessment, and Tellus Institute among others (Brown et al., 1998).

The demand-side policies dampen energy use and carbon emissions in approximately equal proportions. Supply-side policies, on the other hand, principally reduce carbon emissions in the electricity sector. Of the various combinations shown in Figs. 3 and 4, coupling demand-side policies with carbon trading at $50/t comes the closest to achieving the carbon reductions of the most aggressive case—the Advanced scenario.

Demand-side policies propel the introduction of more efficient technologies into the market. This, in turn, reduces the need for new electricity generation. Unlike the demand-side policies, supply-side policies hardly dampen future energy demand. Nonetheless, supply-side policies, such as renewable portfolio standards and sulfur dioxide emission limits, lead to more renewable generation and less coal generation, which results in lower carbon emissions.

Third, **the carbon emissions for all CEF policy implementations are reduced similarly by adding a carbon permit trading program, while direct costs generally increase.** A $25/t permit price reduces emissions by 3–5% in 2010 and 4–7% in 2020 (compared to the same $0 policy implementation). A $50/t permit price more or

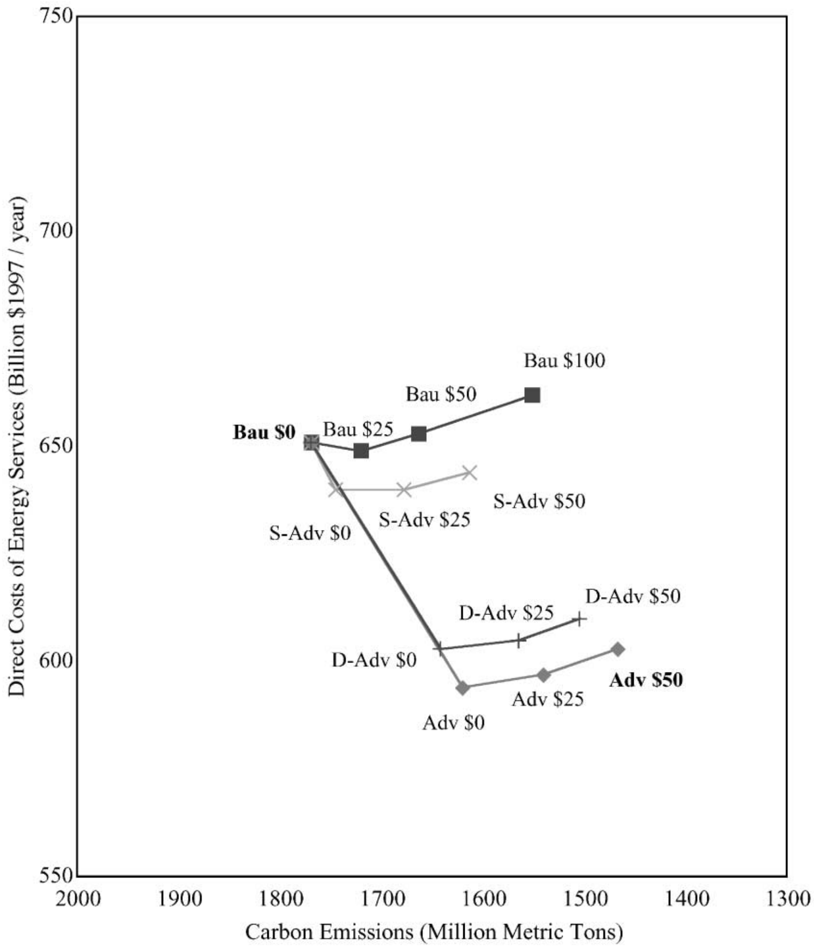

Fig. 3. CEF 2010 direct costs and carbon emissions (BAU, supply-only Advanced, demand-only Advanced, and Advanced policy implementations).

less doubles that effect, reducing emissions by between 6–9% in 2010 and 9–14% by 2020 in all policy implementations. These reductions occur primarily because in a carbon permit world (at least through the year 2020), there is less coal generation and more gas-fired generation. The carbon permit price adds a larger price increment to coal than natural gas because of coal's higher carbon content. If cost-effective carbon sequestration technologies were available for managing coal's carbon emissions, the impact of carbon trading on coal use would be smaller.

Fourth, **the carbon trading policy alone does not reduce carbon emissions as much as most of the non-price policy implementations, and it typically leads to higher direct costs.** The Mod $0 case makes further reductions than BAU $25 and Adv $0 goes beyond the reductions for BAU $50 in 2010. Ten years later the Mod $0 case beats BAU $50 and the Adv $0 surpasses BAU $100 reductions.

Compared with the demand- and supply-side cases, a trading case alone where carbon acquires a value of $25/t has the least impact on carbon emissions. At a value of $50/t, the carbon trading case still reduces carbon emissions less than the demand-side scenarios. Carbon emissions decrease by only 6% to 9% relative to BAU.

Finally, **the carbon emissions of the policy cases are essentially unaffected by 15–30% higher natural gas and oil prices.** The two higher gas price variations lead to similar effects: slightly higher carbon emissions and direct costs that are about $13 billion higher in 2020 (relative to the sensitivities that used standard price trajectories, S-Adv $50, and Adv $50). The higher carbon emissions are caused by a reduction in gas-fired electricity generation, most of which is replaced by coal generation. Biomass, geothermal, and wind also made up for some of the lost generation.

In contrast to these high gas price sensitivities, the higher oil and gas price variation leads to slightly lower carbon emissions and significantly higher direct costs (an increase of about $40 billion in 2020). The discrepancy between the effects of the HG Adv $50 and the HOG Adv $50 variations requires a deeper examination of the results. There are three major

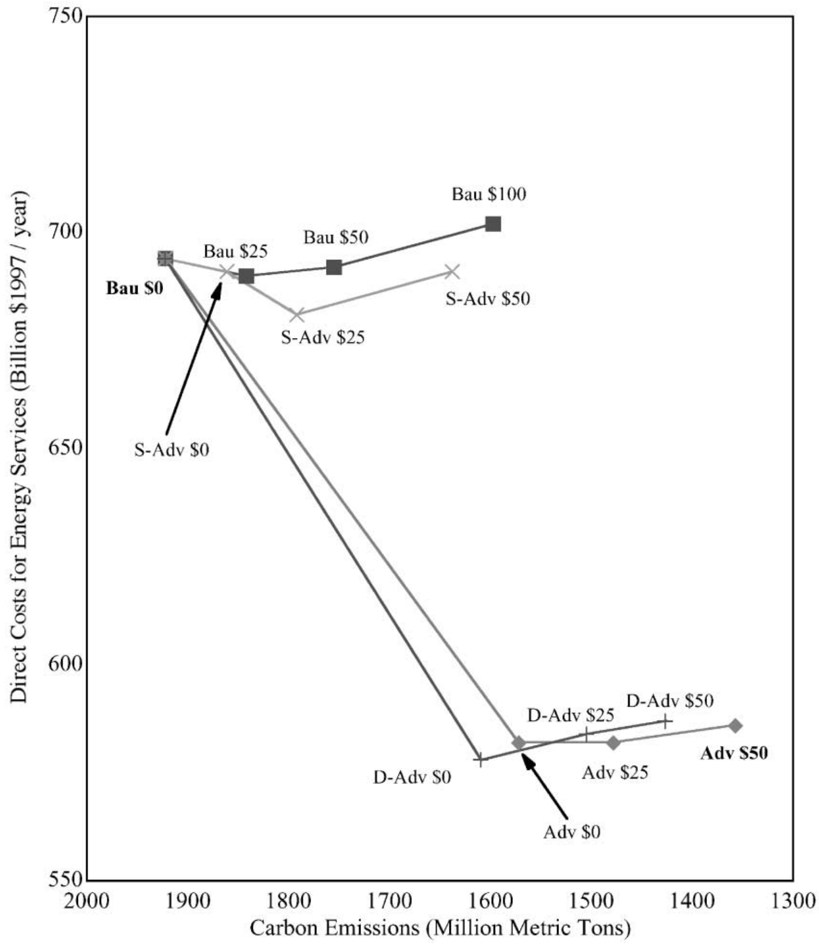

Fig. 4. CEF 2020 direct costs and carbon emissions (BAU, supply-only Advanced, demand-only Advanced, and Advanced policy implementations).

reasons why HG Adv $50 and HOG Adv $50 do not have similar effects when compared to the Adv $50 sensitivity.

1. The high oil price effect is stronger than the high natural gas price effect. HG Adv $50 increases the natural gas wellhead price by 20% in 2020, while the HOG Adv $50 leads to both a 14% natural gas wellhead price increase as well as a 29% petroleum price increase in 2020.
2. Oil makes up a larger share of domestic energy supply than natural gas, so changes in oil prices have larger repercussions than natural gas price increases. By 2020 petroleum accounts for 38% of primary energy consumed and natural gas accounts for 28% of the nation's energy use in the BAU forecast.
3. Carbon emissions drop in the HOG Adv $50 case because the overall energy consumption decreases. Energy use is the same in the Adv $50 and HG Adv $50 forecasts, but the HOG Adv $50 sensitivity consumes about 1% less energy due to higher prices. Most of this reduction comes from oil use in the transportation sector. These carbon emission reductions are offset slightly by an increase in carbon emissions in the electric sector caused by a shift from natural gas to coal generation resulting from the higher natural gas prices and fuel switching from oil to electricity in buildings and industry.

The direct costs discussed in this article do not include the indirect macroeconomic effects of a carbon permit trading system. As discussed in Sanstad et al. (2001), the possible negative economic impact of a $50/*t* carbon permit trading fee in 2010 is of the same order of magnitude as the net direct benefits in our Advanced scenario with $50/*t* carbon permit fee. By 2020, the net direct benefit, which grows over time, will likely be larger than these indirect costs (indirect costs would likely not increase if the carbon permit fee remains at $50/t over time).

These indirect costs are minimal for cases without a carbon charge (such as Mod $0 and Adv $0). Thus, we can conclude that the no-carbon-charge sensitivities both save money and reduce carbon emissions, but the

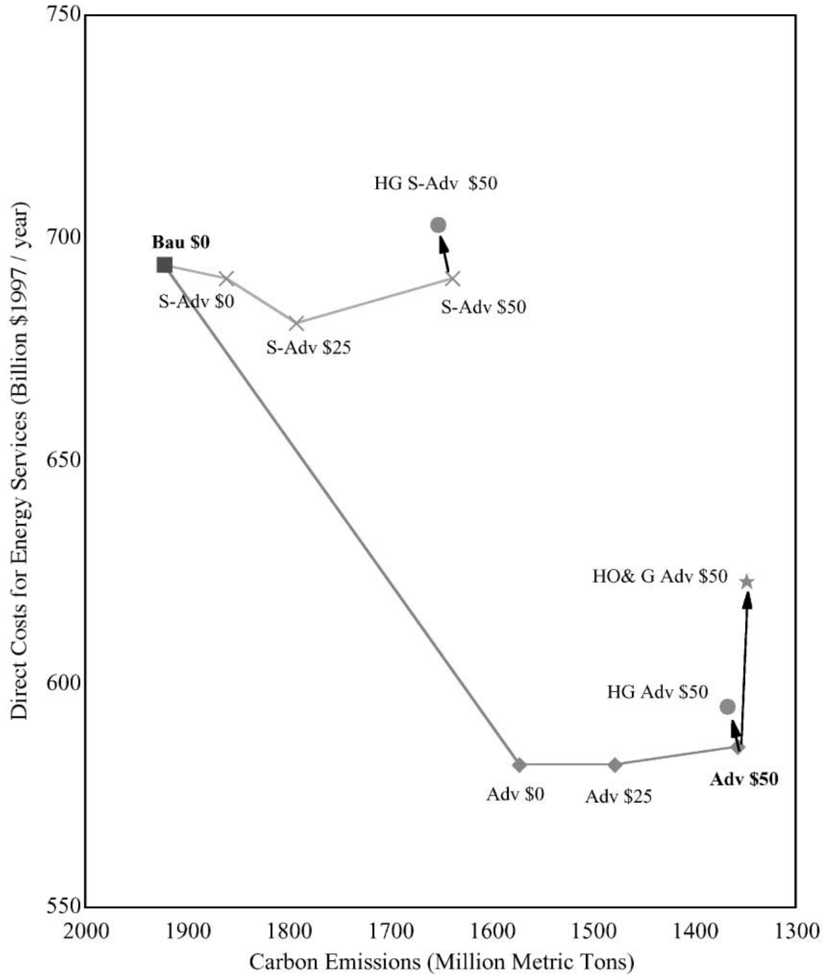

Fig. 5. High fuel price sensitivities relative to supply-only Advanced and Advanced forecasts, CEF 2020 direct costs and carbon emissions.

question becomes more complex when a carbon charge is involved (Sanstad et al., 2001). The sensitivities with carbon charges may also achieve net societal savings (depending on assumptions about how the permit revenues are recycled), but we have not conducted a comprehensive analysis of the indirect effects in 2010 or 2020 of the range of carbon charges considered here. IPSEP (2001) attempts to estimate the potential impacts of revenue recycling and other policy shifts on the CEF results.

These results, while largely consistent with the previous work in this area (NAS 1992, OTA 1991, IWG 1997, and Krause et al., 1999), directly contradict conventional wisdom in certain academic fields. Some analysts argue, on theoretical grounds, that it is impossible for society to reduce carbon emissions and save money at the same time. These assertions fail to recognize a growing body of research on program evaluation, transaction cost economics, behavioral economics, information economics, and institutional economics that show that environmental and economic goals can be compatible. We do not address these issues in detail here, but refer the reader to treatments of them by DeCanio (1993,1998), Brown (2001), Sanstad et al. (1995), Sanstad and Howarth (1994), Huntington et al. (1994), Koomey (1990), Koomey et al. (1996), Koomey and Sanstad (1994), Laitner et al. (2000), Greening et al. (1997), Krause (1996), and Krause et al. (1993). Conventional wisdom can often be misleading (Koomey, 2001), and in this case it has inhibited discussion of the data and evidence needed to resolve the debate over these issues.

5. Future research needs

As with most studies of important policy issues, many questions remain unanswered and there are areas where the analysis could be improved. Four key areas requiring additional research are highlighted below.

1. Further research is needed to explain the driving forces behind policy impacts. Such research would help to identify the interactions between specific policies and the dynamics of program impacts over

time. In some cases policies can produce positive synergies, resulting in greater carbon reductions than the sum of their individual impacts. In other instances, policies can have overlapping impacts, reducing the same carbon emissions. A better understanding of these interactions is needed. Many driving forces evolve over time, confounding the process of developing scenarios and forecasts. These forces include diminishing returns and free riders that would tend to reduce effectiveness over time. They also include learning, free drivers and spillovers, and economies of scale and scope that would all tend to increase effectiveness. These driving forces need to be better characterized and understood.
2. Estimates of indirect macroeconomic costs for domestic carbon trading programs with different carbon permit values and time frames are needed. In this paper, we were able to utilize a review of the modeling literature that produced an estimate of macroeconomic costs in 2010, for a system with permits that trade for \$50/t. Estimates for the \$25 and \$100/t cases are unavailable. In addition, projections over a longer time frame are needed in order to assess more fully the impacts of these programs. This research should include the potential for revenue recycling to reduce macroeconomic costs. These calculations would allow a more complete picture of societal costs for different policy scenarios and time frames.
3. Improved models and analysis tools are needed. It would be valuable to use a forecasting model other than CEF–NEMS to examine the same CEF policy scenarios that we explore here. A comparison of such results would yield important insights into the sensitivity of the results to the choice of modeling framework. This in turn would suggest areas where models need to be improved. There has been some work in this area (Hansen and Laitner, 2000), but more such work is urgently needed to advance available modeling tools.
4. New pilot programs are needed, along with evaluations of existing programs, to determine how best to promote the adoption of more energy-efficient, low-carbon products at the scale envisioned for the Moderate or Advanced scenarios. While the program experience upon which we based the scenarios is wide ranging and well understood, field testing and program evaluation are critical to develop the most effective implementation strategies in the current energy policy environment.

6. Conclusions

The sensitivity analyses explored in this article give important insights into the factors affecting the costs and potential carbon savings of a variety of programs and policies that could be implemented to reduce carbon emissions and address other energy-related challenges.

For instance, our sensitivity cases indicate that the application of the Moderate or Advanced sets of demand- and supply-side policies, in any combination, decreases the direct costs of energy services while at the same time reducing carbon emissions. Further, we show that the demand-side policies by themselves have a larger effect on reducing direct costs and carbon emissions than the supply-side policies by themselves. Similarly, the carbon trading policy (with carbon permits trading up to \$50/t), on its own, does not reduce carbon emissions as much as most of the non-price policy sets, and it typically increases the direct costs of energy services. While carbon permits are an obvious way to reduce carbon emissions, supply or demand policies by themselves can lead to larger carbon reductions and lower direct costs than a \$50 carbon permit value implemented in isolation.

Our results provide compelling evidence that policy opportunities exist to reduce carbon emissions and save society money. The exact extent of those opportunities is an issue about which reasonable people can disagree, but that such opportunities exist is clear. Their ultimate extent is an empirical question that can best be answered by implementing and monitoring pilot programs and by evaluating the impacts of current programs. Appeals to theory alone are inadequate in the debate over the costs of reducing carbon emissions in the United States. Real program evaluation data are needed to resolve this debate, and we should pursue such data with all due haste.

Acknowledgements

More information about the Scenarios for Clean Energy Future study can be found at <http://enduse.lbl.gov/Projects/CEF.html>. The complete set of output spreadsheets for this analysis can be downloaded at <http://enduse.lbl.gov/Projects/Sensitivities.html>. These spreadsheets contain detailed results for energy use, carbon emissions, and costs for all sectors and end-uses.

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