Risk Analysis, Vol. 30, No. 9, 2010

DOI: 10.1111/j.1539-6924.2010.01436.x

Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies

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Public perceptions of carbon capture and sequestration (CCS) and other low-carbon electricity-generating technologies may affect the feasibility of their widespread deployment. We asked a diverse sample of 60 participants recruited from community groups in Pittsburgh, Pennsylvania to rank 10 technologies (e.g., coal with CCS, natural gas, nuclear, various renewables, and energy efficiency), and seven realistic low-carbon portfolios composed of these technologies, after receiving comprehensive and carefully balanced materials that explained the costs and benefits of each technology. Rankings were obtained in small group settings as well as individually before and after the group discussions. The ranking exercise asked participants to assume that the U.S. Congress had mandated a reduction in carbon dioxide emissions from power plants to be built in the future. Overall, rankings suggest that participants favored energy efficiency, followed by nuclear power, integrated gasification combined-cycle coal with CCS and wind. The most preferred portfolio also included these technologies. We find that these informed members of the general public preferred diverse portfolios that contained CCS and nuclear over alternatives once they fully understood the benefits, cost, and limitations of each. The materials and approach developed for this study may also have value in educating members of the general public about the challenges of achieving a low-carbon energy future.

KEY WORDS: Carbon capture and sequestration; CCS; electricity generation; low-carbon; public risk perception and communication

1. INTRODUCTION

Fossil fuel use by the electricity sector is the largest source of carbon dioxide (CO_2) emissions in the United States. To avoid the worst global warming scenarios, CO_2 emissions from the electricity sector must be reduced by 50–80% below today's levels by 2050.[(1)] Achieving this reduction in the United States over the next half century will require an aggressive deployment of several advanced low-carbon technologies including nuclear plants, natural gas plants, and coal plants with carbon capture and sequestration (CCS), which separates CO_2 from the flue gas of electricity-generating plants and sequesters it in deep geological formations.[(2)]

Renewable electricity sources, such as wind turbines, and perhaps solar thermal systems, will likely also play an important role in decarbonizing the electricity grid, but are currently unable to reliably meet demand for electricity.[(3)] The power generated by these technologies is too intermittent, requiring fossil-fuel powered plants or expensive energy storage systems to provide backup power when it is not windy or sunny.[(4)] Therefore, to ensure that electricity generation in the near future remains reliable

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and cost effective, with minimal risk of supply disruptions, any *significant* reductions in electricity sector CO_2 emissions will likely need to involve more reliable and available low-carbon technologies such as coal plants with CCS, natural gas, or nuclear power.[3]

For any of these low-carbon technologies to become a viable option for reducing CO_2 emissions, people must find them acceptable for widespread deployment. In the past, public acceptance has proven to be a major obstacle to the cost-effective development of new energy infrastructure, including oil refineries,[5] nuclear power plants,[6] pilot-scale CCS technologies,[7] and even wind farms.[8] For example, ever since the reactor meltdown at Three Mile Island, people have been reluctant to accept new nuclear power plants,[9,10] in part because they believe that nuclear plants may emit dangerous levels of radiation.[11,12] In addition, public perceptions of CCS include the fear that CO_2 "burps" will be released from the ground and cause suffocation.[13–15] Negative public sentiment also exists toward wind turbines, which some people perceive as noisy, aesthetically unappealing, and a threat to birds and bats.[8,16] Yet, many people believe that it is possible to rely on an electricity generation portfolio composed of 100% variable and intermittent renewables—even though technical experts raise serious doubts.[14]

In various surveys of large national samples, public perceptions of CCS ranged from negative[13,17] to slightly positive.[18,19] Low levels of awareness and understanding of CCS may explain some of this variation.[9,20,21] Indeed, people tend to provide "pseudo-opinions" even when they have limited or no information about the survey topic.[18,22] To combat this problem, survey researchers often provide some information about CCS before asking participants to report their perceptions. Doing so has increased support of the technology in some studies,[18,21] while decreasing it in others.[13,23] Possibly, this lack of consistency reflects the quality of the information that these surveys provided about CCS, which is often limited to only a few sentences. Many researchers question the ability of general population surveys to provide valid public opinion measures of relatively unknown topics, instead supporting the use of informative and deliberative measures to remedy stability and consistency problems.[24] Indeed, people's opinions are likely to become more stable, as well as more consistent with their values, as they receive more information and become better informed.[18] Here, we therefore examined *informed* public perceptions of CCS and other low-carbon technologies.

To make informed decisions about any low-carbon technology, people need proper information that is both technically accurate and understandable. However, a recent review suggests that most existing CCS communications are too technical and do not address people's informational needs.[25] Possibly, these communications were developed by technical experts with a limited understanding of their lay audience. Indeed, communication materials tend to be more effective when their development is based on input from the intended audience, to ensure that the information addresses their concerns in wording they understand.[e.g.,26–28] The mental models approach involves explicitly mapping the knowledge or "mental models" of both experts and lay people before developing a risk communication.[29] Content is then focused on information that experts deem relevant, and that is missing from lay people's "mental model"—in wording that is tested for lay people's understanding. This mental models approach has been used to design risk communications about various topics including climate change,[29] nuclear energy sources on spacecraft,[30] xenotransplantation,[31] sexually transmitted diseases,[32] and avian flu.[33]

Palmgren and colleagues[13] applied a modified mental models approach to explore initial public perceptions of CCS. In open-ended interviews, they examined lay people's knowledge and beliefs about CCS. They found that interviewees preferred not to evaluate CCS on its own, but rather in the context of other technologies that might be used to reduce CO_2 emissions. These findings have been replicated in public perception studies of CCS[14,19] and nuclear plants.[34] In a subsequent study, Palmgren *et al.*[13] therefore asked survey respondents to rank their willingness to pay for a set of electricity-generating portfolios, each reducing carbon emissions by 50% compared to a portfolio of 100% "regular" coal plants. The two low-carbon portfolios that included coal plants with CCS (combined with regular coal plants) were ranked below all other portfolios, while the portfolio that included nuclear (also combined with regular coal plants) was ranked as the next worst.

Yet, other studies have found that people are more likely to accept nonrenewable technologies, such as CCS and nuclear, when they are included in a portfolio of possible options, as compared to when they are presented in isolation.[14,35] Furthermore, some proponents of CCS have suggested that people would be more likely to accept that technology if they had information about how its costs and benefits compare to those of alternative technologies.[9,14] To make informed choices between low-carbon energy-generating technologies, people also need better communications about more familiar technologies such as wind turbines and nuclear reactors.[8,11,36]

In this study, we examined people's *informed* decisions about electricity-generating technologies by asking participants to rank 10 technologies and seven portfolios composed of those technologies that were designed to meet a specific CO_2 emissions limit. We built on the work by Palmgren *et al.*,[13] while rectifying four of its limitations. First, while Palmgren *et al*. presented simplified portfolios that relied too much on a single technology, we designed our seven portfolios to be realistic, reliable, and representative of possible portfolios for expanding future electricity capacity. Second, while Palmgren *et al*. provided only a few sentences to describe each technology, we presented comprehensive and balanced information sheets for each, using simple wording and a systematic presentation format.[37–39] Third, unlike Palmgren *et al*., we systematically covered the same set of attributes (including risks, benefits, and costs) in the presentation of each technology and portfolio. Fourth, in addition to providing their personal rankings (as in Palmgren *et al*.), our participants also ranked the portfolios in a group exercise, allowing them to hear alternative views, to improve their engagement and understanding, and revise their initial rankings.[37–39]

2. METHODS

2.1. Materials

We chose a set of 10 electricity-generating technologies that could realistically be constructed in Pennsylvania (where we recruited participants) over the next 25 years:

(1) four coal-based technologies, including pulverized coal (PC) and integrated gasification combined-cycle coal (IGCC), both with and without CCS;
(2) natural gas combined cycle;
(3) advanced nuclear plants (generation III+ or IV);
(4) three renewable technologies—modern wind turbines, solar photovoltaic (PV), and biomass using integrated gasification combined-cycle; and
(5) reducing electricity consumption through energy efficiency.

Each technology was described on a separate *Technology Sheet* (see Fig. 1 for an example). To facilitate comparisons,[37] each sheet systematically described the same attributes: *How it works*, *Cost*, *CO_2 released*, *Other pollution/waste*, *Availability*, *Reliability*, *Limits of use*, *Noise*, *Land use and ecology*, *Safety*, *Lifespan,* and *Current use*. Technologies were systematically compared on an additional *Cost Comparison* (presenting best estimates with uncertainty bars for electricity cost per kilowatt-hour and estimated monthly electricity bills for the median Pennsylvania customer) as well as on a *Pollution Comparison* (presenting a relative comparison of technology emission rates for CO_2, nitrogen oxides, sulfur dioxides, particulates, and mercury).

We also presented seven low-carbon portfolios, referred to as *Power Plant Combinations* (Table I), designed to emit 70% less CO_2 than a portfolio composed entirely of PC plants (the technology that currently generates a majority of the electricity in Pennsylvania). We chose portfolios that could reliably supply a 25% increase in electricity demand in Pennsylvania in the next 25 years, while limiting the contribution of intermittent renewables to a realistic amount (e.g., <7% for wind, <1% for solar PV[3]).[40] Four simple portfolios (i.e., A, B, C, and G) relied mostly on one reliable technology. Two portfolios were based on diverse combinations proposed by the Electric Power Research Institute.[2] The first (D) included predominantly renewables and increased efficiency efforts, using natural gas plants for baseload power and intermittency fill; and a second (F) had IGCC with CCS, nuclear, natural gas, and renewables. We also included a third diverse portfolio (E) that used IGCC with CCS, natural gas, and renewables, but no nuclear power. Portfolios were compared in sheets entitled *Cost Comparison for Combinations* and *Pollution Comparison for Combinations*.

We developed all materials with input from subject-matter experts with knowledge in the relevant areas to ensure balance and technical accuracy. Content was iteratively pilot-tested with members of the general public.[29,41] Subsequently, the materials were revised to improve identified concerns and misunderstandings, and double-checked by subject-matter experts. Despite the complexity of the

[3] Contribution of intermittent renewables was based on a percentage of the *total estimated capacity* of PA in 2030.

Traditional Coal Plants

The Armstrong traditional coal plant in Pennsylvania.
Source: www.industcards.com/st-coal-usa-pa.htm

Option 1: CO_2 is released into air

How it Works: Traditional coal plants burn coal to make steam. The steam is used as fuel in a type of engine, called a "turbine". This turbine runs a generator to make electricity.

When coal is burned, CO_2 is released by the plant. In **Option 1**, this CO_2 escapes into the air because no equipment is added to capture the CO_2.

MORE INFORMATION (ABOUT TRADITIONAL COAL PLANTS)	
Cost*	*Traditional coal plants* make cheaper electricity than advanced coal plants. Yet, it is more expensive to add CO_2 capture equipment to *traditional coal plants*.*
CO_2 released*	Traditional coal plants release CO_2 to the air.*
Other Pollution/ Waste*	• While these plants are much cleaner than in the past, they still release CO_2, nitrogen oxides, sulfur dioxide, mercury and particulates to the air. These pollutants can cause people to have many different health problems.* • Traditional coal plants produce a lot of ash that contain hazardous chemicals. Some ash can be recycled, for example, to make concrete. The leftover solid waste is usually put in a landfill near the plant. • Traditional coal plants use a lot of water to cool the plant's equipment. The water comes from wells, lakes, rivers or oceans. Some of it will evaporate after use. The rest is returned to its source. Since it is hot, the water may disturb plants and animals living in the water source.
Availability	Experts say that the U.S. has enough coal to meet its needs for at least 100 years.
Reliability	Coal can provide steady and dependable electricity.
Limits of use	Traditional coal plants release a lot of CO_2. They cannot make all of the electricity that is needed in PA if we want to reduce CO_2. Other types of plants must also be built.
Noise	These plants are about as loud as average street traffic.
Land use and ecology	Coal mining near the surface disturbs the land, plants and animals. It also disrupts and pollutes streams. Underground mining can cause acidic water to leak into streams. If the mine collapses, it can also cause the ground to sink or shift.
Safety	These plants are quite safe for operators. Coal mining is dangerous for the miners.
Lifespan	The lifetime of any plant is uncertain. But, a new traditional coal plant built today would likely make electricity for at least 50 years.
Current Use	There are more than 1,000 of these plants working in the U.S. today.

**More cost and pollution information is available in "Cost Comparison" and "Pollution Comparison" sheets in Envelope #3.*

Fig. 1. Example of one of the 10 technology sheets (online version in color).

Table I. The Low-Carbon Electricity Generation Portfolios Presented in this Study

Portfolio Description	Technology Composition
A: Mix of PC with CCS and PC	81% PC plants *with* CCS technologies 19% PC plants
B: Mix of IGCC with CCS and IGCC	83% IGCC plants *with* CCS technologies 17% IGCC plants
C: Nuclear and PC mix	70% advanced nuclear plants 30% PC plants
D: Diverse portfolio, including no nuclear or CCS	66% natural gas plants 13% energy efficiency 10% wind power 6% biomass plants 5% solar PV power
E: Diverse portfolio, including IGCC with CCS, but no nuclear	48% natural gas plants 20% IGCC plants *with* CCS technologies 13% wind power 13% energy efficiency 5% PC plants 1% solar PV power
F: Diverse portfolio, including IGCC with CCS and nuclear	25% IGCC plants *with* CCS technologies 21% advanced nuclear plants 20% natural gas plants 17% PC plants 10% wind power 7% energy efficiency
G: Natural gas and wind mix	66% natural gas plants 34% wind power

Note: Portfolio descriptions were not shown to participants.

materials, all were written at a 6th to 8th grade reading level, as reflected in the Flesch-Kincaid Grade Level readability statistic.[42,43] The complete set of the materials, including those described above, are available online at http://sds.hss.cmu.edu/risk/fleishman/InformationMaterials.html.

2.2. Participants

A diverse sample of 60 participants was recruited through community organizations in the Greater Pittsburgh Metropolitan Area. Participants were 18 to 73 years old ($M = 36.7$; Median = 36). Of these, 63% were female, and 33% nonwhite, almost all of whom were African American. All had graduated from high school, with 67% having completed at least a Bachelor's degree in a nontechnical field. By comparison, the U.S. population is similar in age (Median = 36.6), includes fewer females (51%) and African Americans (13%), while being less educated (86% with a high school diploma and 28% with at least a Bachelor's degree).[44]

2.3. Procedure

After signing up for the study, participants received "homework" materials by mail, including the *Technology Sheets*, the *Cost Comparison*, and the *Pollution Comparison*. They were presented with an introduction about climate change, and the following problem question:

> Pennsylvania will need more electricity in 25 years than the power plants it has now can make. . . . The original plan was to build all traditional coal plants [PC without CCS]. But, suppose that the U.S. Congress has just passed a law to reduce the CO_2 released by power plants built in the future. As a result of this law, the State of Pennsylvania must change some of the power plant types that will be built here over the next 25 years. These power plant types will collectively need to release less CO_2. Imagine that the Governor of Pennsylvania has asked you to serve on a Citizen's Advisory Panel to give advice on the kinds of plants to build. Your job is to rank the different power plant types from best to worst.

After reading the homework materials, but prior to attending the group meeting, participants provided *prediscussion technology rankings* ranging from best (=1) to worst (=10). They also provided *preexplanation comprehension ratings* of the five information sheets, on a scale anchored at very hard (=1) and very easy (=7). Participants then rated their agreement with the 15 environmental statements appearing on Dunlap *et al*.'s[45] *new ecological paradigm (NEP) scale,* with responses anchored at completely disagree (=1) and completely agree (=7). Finally, they answered 15 *true-or-false knowledge questions* about their homework materials, focusing on those issues that had been most commonly misunderstood in the pilot tests described above.

We conducted nine workshops, each involving four to nine participants, held in local communities, lasting two to three hours, and following a careful script adapted from a study with a similar methodology.[39] Each group first received a review of the homework materials, spending more time on topics for which related *true-or-false knowledge questions* were answered incorrectly by at least one participant. Participants then received the *Power Plant Combinations*, *Cost Comparison for Combinations*, and *Pollution Comparison for Combinations*, with a revised problem question focusing on portfolios. Subsequently, participants provided their *prediscussion* *portfolio ranking* ranging from best (=1) to worst (=7). Next, they provided *postexplanation comprehension ratings,* which were comparable to those completed preexplanation.

Subsequently, participants worked together as a group to rank the portfolios in a sorting exercise, which was facilitated by the experimenter and adapted from earlier risk ranking studies.[37–39] They then individually reviewed their personal rankings, and provided *postdiscussion portfolio and technology rankings*. They also provided individual *postdiscussion comprehension ratings*, which were similar to those provided prediscussion. Finally, questions about CCS were answered at the end, so as not to attract special attention to CCS during the ranking exercises. Participants provided a *CCS favorability rating* on a scale anchored at completely oppose (=1) to completely favor (=7). Upon completing the study, participants received \$95, with the option to donate part or all of it to the community organization through which they had been recruited.

3. RESULTS

3.1. Technology Rankings

We computed Kendall's coefficient of concordance (W) to examine the consistency of participants' personal rankings of the 10 technologies. It showed a high degree of agreement between *prediscussion rankings*, provided before the group discussion ($W = 0.38$, $p < 0.001$), as well as between *postdiscussion rankings*, provided after the group discussion ($W = 0.36$, $p < 0.001$). Fig. 2 reports the mean *prediscussion* (left) and *postdiscussion* (right) *technology rankings*, where 1 is the "best" and 10 is the "worst." Wilcoxon paired-rank tests indicated that, for each technology, participants' *prediscussion rankings* were not significantly different from *postdiscussion* rankings ($p > 0.05$). For each technology, we also examined the effect of group discussion on agreement, using Wilcoxon paired-rank tests to compare postdiscussion agreement (seen in the mean absolute deviation of individuals' *postdiscussion rankings* from the group mean *postdiscussion rankings* of that technology) with prediscussion agreement (seen in the mean absolute deviation of individuals' *prediscussion rankings* from the group mean *prediscussion rankings* of that technology). Setting $\alpha = 0.01$ to correct for the number of tests, we found that group discussion increased participants' agreement about energy efficiency, which had significantly higher postdiscussion agreement than prediscussion agreement (Wilcoxon $z = -2.54$, $p = 0.01$).

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants' rankings for each possible pair of technologies, as provided *pre-* and *postdiscussion*. The superscripted letters in Fig. 2 indicate, for each technology, the other technologies that were ranked as significantly "worse." Due to the large number of these comparisons, we only report those that are significant at $\alpha = 0.01$. Overall, energy efficiency was significantly preferred to all other alternatives, both *pre-* and *postdiscussion*. The second best mean ranking was for nuclear power, whose rankings were not significantly different from those for IGCC with CCS, wind, biomass *postdiscussion* and natural gas *postdiscussion*—which, respectively, ranked third through sixth, on average. The other mean rankings were, in order, (7) solar PV, (8) PC with CCS, (9) IGCC without CCS, and (10) PC without CCS. Perhaps, most notably, each coal technology (IGCC, PC) was significantly preferred with (vs. without) CCS. Furthermore, the more advanced coal technology (IGCC) was significantly preferred over the more conventional coal technology (PC)—whether with or without CCS.

3.2. Portfolio Rankings

Kendall's coefficient of concordance showed a high degree of agreement between participants' *prediscussion rankings* ($W = 0.31$, $p < 0.001$) and their *postdiscussion rankings* of the seven portfolios ($W = 0.46$, $p < 0.001$). Fig. 3 reports the mean *prediscussion* (left) and *postdiscussion portfolio rankings* (right), where 1 is the "best" and 7 is the "worst." Wilcoxon paired-rank tests indicated that, for each portfolio, participants' *prediscussion rankings* were not significantly different from *postdiscussion* rankings ($p > 0.05$). As with the technologies, we examined the effect of group discussion on participants' agreement about each portfolio, using Wilcoxon paired-rank tests to compare postdiscussion agreement (seen in the mean absolute deviation of individuals' *postdiscussion rankings* from the group mean *postdiscussion rankings* of that technology) with prediscussion agreement (seen in the mean absolute deviation of individuals' *prediscussion rankings* from the group mean *prediscussion rankings* of that technology). Postdiscussion agreement was significantly higher than prediscussion agreement for every portfolio (with each Wilcoxon $z < -3.31$, $p \leq 0.001$).

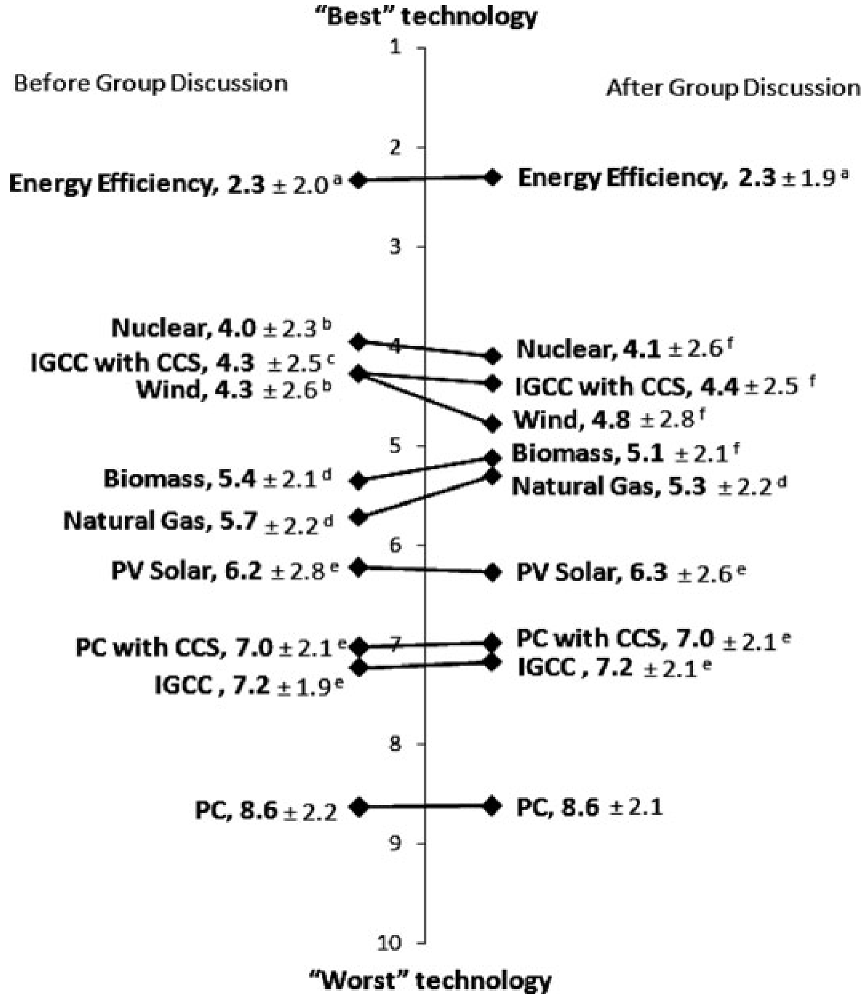

Fig. 2. Participants' mean technology rankings ± standard deviation, pre- (left) and postdiscussion (right).
Note: Superscripted letters next to mean technology rankings refer to Wilcoxon paired-rank tests results ($p < 0.01$), suggesting that:
a: all other technologies were ranked as significantly worse;
b: biomass, natural gas, PV, PC with CCS, IGCC, and PC were ranked as significantly worse;
c: natural gas, PV, PC with CCS, IGCC, and PC were ranked as significantly worse;
d: PC with CCS, IGCC, and PC were ranked as significantly worse;
e: PC was ranked as significantly worse;
f: PV, PC with CCS, IGCC, and PC were ranked as significantly worse.

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants' rankings between each possible pair of portfolios, as provided *pre-* and *postdiscussion*. The superscripted letters in Fig. 3 indicate, for each portfolio, which of the other portfolios were ranked as significantly "worse." Due to the large number of these comparisons, we only report those that are significant at $\alpha = 0.01$. Overall, portfolio F, which included a diverse portfolio with both IGCC with CCS and nuclear, received the best mean ranking. Portfolio E, which was similarly diverse but included only IGCC with CCS and no nuclear, received the second best mean ranking. The two diverse portfolios including IGCC with CCS (E and F) were significantly preferred to all portfolios that did not include IGCC with CCS. Portfolio B, which included the less diverse mix of IGCC with CCS and IGCC, had the third best mean ranking. The other mean rankings in order were (4) the diverse portfolio D, with no CCS or nuclear, (5) portfolio G, with the natural gas and wind mix, (6) portfolio C, with the nuclear and PC mix, and (7) portfolio A with the simple mix of PC with CCS and PC. Thus, the pattern of results was similar to that observed with the technologies, with rankings of the three portfolios including IGCC with CCS (B, E, and F) being preferred to portfolio A, the only mix including PC with CCS. In fact, all portfolios were ranked significantly better than portfolio A.

3.3. Viewpoints on Environmental Issues and CCS

Participants' responses to the 15 *NEP scale ratings* were scored such that higher ratings reflected stronger pro-environmental attitudes. Participants' mean *NEP scale ratings* ($M = 4.67$, $SD = 0.64$) had good internal consistency (Cronbach's $\alpha = 0.68$), and

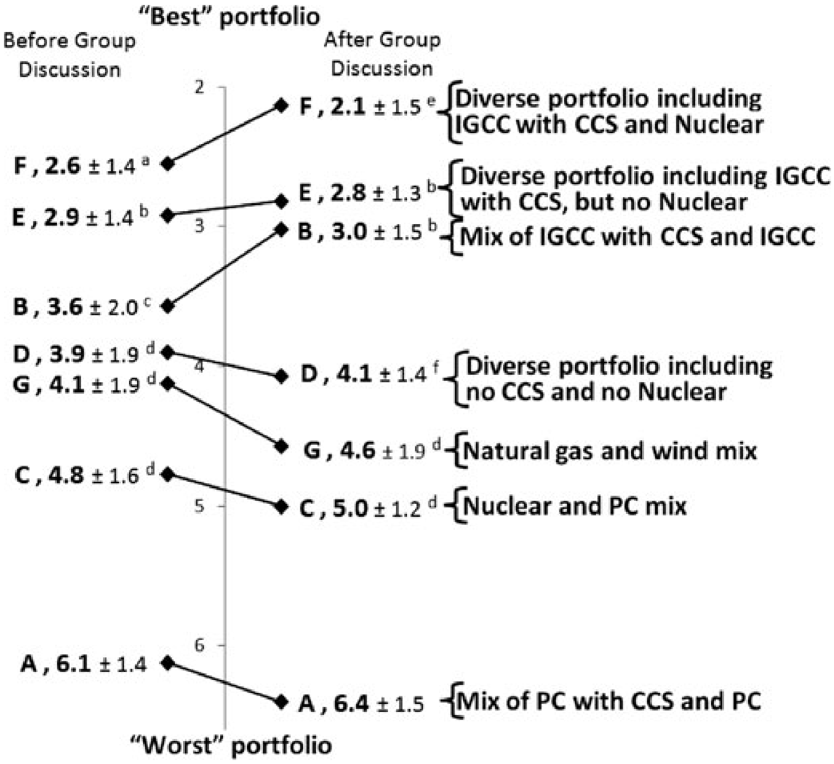

Fig. 3. Participants' mean portfolio rankings ± standard deviation, *pre-* (left) and *post*discussion (right).
Note: Superscripted letters next to mean portfolio rankings refer to Wilcoxon paired-rank tests results ($p < 0.01$), suggesting that
a: portfolios B, D, G, C, and A were ranked as significantly worse;
b: portfolios D, G, C, and A were ranked as significantly worse;
c: portfolios C and A were ranked as significantly worse;
d: portfolio A was ranked as significantly worse;
e: portfolios E, D, G, C, and A were ranked as significantly worse;
f: portfolios G, C, and A were ranked as significantly worse.

were significantly above the scale midpoint of 4 ($t = 8.14$, $p < 0.001$), suggesting pro-environmental attitudes. Spearman rank correlations between the mean *NEP scale ratings* and participants *postdiscussion rankings* (reverse coded for these analyses, such that higher numbers reflect a higher preference) suggest that participants who were more pro-environmental preferred wind ($r_s = 0.35$, $p = 0.01$), as well as two of the four portfolios including this technology ($r_s = 0.29$, $p = 0.02$ for portfolio D and $r_s = 0.30$, $p = 0.02$ for portfolio E). A negative correlation was also found between the mean *NEP scale ratings* and the portfolio that included IGCC with CCS and no wind ($r_s = -0.36$, $p = 0.01$ for portfolio B).

Participants' mean *CCS favorability ratings* ($M = 4.75$, $SD = 1.62$) were slightly favorable, being significantly above the scale midpoint of 4 ($t = 3.55$, $p < 0.001$). A marginally significant negative correlation between participants' *CCS favorability* and the mean *NEP scale rating* ($r = -0.27$, $p = 0.09$) suggests that the more pro-environmental participants were slightly more opposed to CCS. Furthermore, replicating other studies,[10,18,34] participants' *CCS favorability ratings*, which evaluated CCS in isolation, were not significantly correlated to the *postdiscussion* rankings of technologies or portfolios that included CCS ($p > 0.05$).

3.4. Participant Comprehension

Across the 15 *true-or-false knowledge questions* answered after the homework but before the group meetings, participants obtained an average score of 91% correct ($SD = 12\%$; range 60–100%). Using a one-sample *t*-test, we found these scores to be significantly better ($t = 25.7$, $p < 0.001$) than chance performance due to pure guessing (i.e., 50% correct, with true/false statements), suggesting a basic understanding of the materials. The most difficult question was still answered correctly by the majority of participants ($M = 83\%$, $SD = 38\%$).

Participants' *comprehension ratings* also suggest a basic understanding of the materials prior to receiving the experimenter's verbal explanation or group discussion. The *Cost Comparison* received the lowest mean *comprehension rating* ($M = 5.28$, $SD = 1.55$), which was still significantly above the midpoint of 4 ($t = 6.25$, $p < 0.001$). All other *comprehension ratings* for the information materials and attributes were also found to be significantly above the scale midpoint ($p < 0.001$ for each). A planned contrast, conducted in a repeated measures ANOVA examining all five *comprehension ratings* by their timing (*pre-explanation, postexplanation, postdiscussion comprehension*), showed a significant linear increase in ratings over time ($F(1, 48) = 9.41$, $p < 0.01$; with *preexplanation* $M = 5.75$, $SD = 1.07$, *postexplanation* $M = 6.00$, $SD = 0.93$, *postdiscussion* $M = 6.21$, $SD = 0.82$), thus suggesting that the group sessions helped to improve participants' comprehension of the information materials.

4. DISCUSSION

Our informed participants favored energy efficiency over the other low-carbon alternatives. Next, participants favored nuclear power, the advanced coal-based technology IGCC with CCS, and wind. This is also evident from their overall preference for portfolio F, which included a diverse mix of these four technologies.

Perhaps more notably the advanced coal-based technology, IGCC, and the more traditional coal-based technology, PC, were preferred with CCS to the same technologies without. Moreover, IGCC was preferred over PC, with or without CCS. In rankings of the portfolios, a similar pattern emerged. The two diverse portfolios including IGCC with CCS were ranked as better than every alternative portfolio that did not include IGCC with CCS. Participants also showed this preference *postdiscussion* for the simple mix of IGCC with CCS and IGCC, while the simple mix of PC with CCS and PC was ranked lower than every other portfolio. Thus, participants only preferred portfolios with CCS when included with the IGCC technology. While it is possible that participants inferred the relative benefits of IGCC over those for PC from the information we provided, it is also possible that this preference ordering simply resulted from the titles we gave to PC and IGCC ("Traditional Coal" and "Advanced Coal," respectively). Although these terms are accurate and have been commonly used to refer to these technologies,[46] other names might be perceived as more neutral and lead to different preferences.

Surprisingly, most of our participants seemed to have relatively favorable views of nuclear power. The technology received the second best ranking, and the diverse portfolio that included nuclear power was preferred *postdiscussion* to a similarly composed portfolio without nuclear. In part, this preference may be explained by the title we gave to nuclear power ("Advanced Nuclear"), which described next-generation technologies (i.e., Generation III+ and IV reactors), that are inherently safer than those in operation in the United States today. However, it is also possible that this preference simply reflects public attitudes having become less unfavorable toward nuclear power since the Three Mile Island accident in 1979, as suggested in recent polls.[47,48]

Although participants with stronger proenvironmental attitudes were more in favor of wind and somewhat less in favor of CCS, overall agreement of rankings was relatively high, even before group discussion. Group discussion increased agreement about every portfolio, as well as energy efficiency, but did not change agreement about the other low-carbon technologies, or the relative rankings of technologies and portfolios. That stability in preferences would be expected with well-informed participants. Indeed, we went through extensive efforts to inform our participants, presenting them with comprehensive and balanced information about low-carbon energy generation technologies, and using a group meeting procedure to further improve their understanding. After studying the homework materials, they already obtained good scores on the *true-or-false knowledge questions* scores. The improvement in their *comprehension ratings* suggests that they perceived themselves as becoming even better informed over the course of the group meeting.

Our results contrast starkly with those of previous studies, which suggest much lower public acceptance of CCS[13,21] and nuclear power,[10,34] as well as unstable preferences.[22] One potential explanation for that difference is that our participants made more informed decisions about these technologies. Their understanding of our comprehensive communication materials improved steadily during the course of the study, due to receiving carefully designed step-by-step instructions, and actively engaging in deliberative group discussions. Second, our study asked participants to consider these technologies as part of realistic low-carbon portfolios, which tend to be preferred over CCS [13,14,19] or nuclear power[10,11] in isolation. Third, our results asked participants to rank these technologies and portfolios relative to low-carbon alternatives, while previous studies asked participants to rate these technologies in isolation. Although people may be reluctant to accept specific technologies such as CCS[18] and nuclear power,[10,34] as seen in their individual ratings, they may nevertheless prefer them over other alternatives, which can be seen in rankings.

Moreover, while ratings may allow survey respondents to express the magnitude of their preferences between technologies, rankings reflect explicit comparisons between technologies, based on tradeoffs between their perceived gains and losses.

Perhaps as a result, *CCS favorability ratings*, in which CCS was treated in isolation, were not correlated with their rankings of technologies or portfolios that included CCS, suggesting that the two tasks reflect different thought processes. Rankings can provide decision-relevant results for policymakers who use risk-ranking methods to order priorities in government agencies.[49] Moreover, when these rankings are provided by a well-informed sample, they are more likely to be reliable (i.e., be consistent with people's values and remain stable over time).[18]

Our study used a local convenience sample from the greater Pittsburgh metropolitan area. Firm conclusions cannot be drawn about informed public preferences for these low-carbon technologies and portfolios in other locations. However, our results do suggest that our materials, which gave participants a stable basic understanding, and our group meeting procedure, which further improved understanding of the materials and resolved some disagreement, may be useful for helping members of the general public to make more informed decisions about which low-carbon technologies to support. The materials and the approach can easily be adapted for use in other settings, including classrooms and museums.

Although the materials and group meeting procedure may be useful to inform members of the general population about general public choices for low-carbon technologies, people living near specific energy infrastructure sites may have different informational needs. In such communities, there is often a complex interplay of political, social, environmental, and economic factors that influence people's perceptions, which otherwise do not play a role in the shaping of general public perceptions about technologies.[7] For example, community opposition is often influenced by issues of trust[7,20,50–52] and may not depend on the *type* of energy facility being sited, but rather on the decisionmakers who are involved in the siting process. Outside of our controlled setting, uninformed members of the general public will also likely be persuaded with biased messages from advocates. Thus, no assurance exists that public debates over energy policy will result in the informed preferences found in our study. Nevertheless, had our respondents not found diverse portfolios containing CCS and nuclear to be preferable to others, the tasks facing energy policy decisionmakers would be much more challenging. Policymakers and electricity utility or power companies could adapt the materials and approach to proactively engage communities in the energy infrastructure siting process, educating them and gauging their perceptions. Policymakers could find the materials especially helpful when communicating with their constituents about the tradeoffs between the costs, risks, and benefits of energy policy or siting decisions.

A final limitation of our study is that we used a discrete set of portfolios, in the ranking exercise. While the portfolios we presented represent a realistic and diverse set of the possible options for decarbonizing future U.S. electricity expansion, there are certainly other feasible technology combinations. In future work, we plan to allow respondents to construct their own portfolios with the aid of a computer tool that supports unlimited combinations within realistic constraints.

Overall, this study suggests that once people have understood the alternatives for low-carbon energy generation, and their limitations, they may show a reluctant preference for CCS and nuclear power, and diverse low-carbon portfolios including these technologies.

ACKNOWLEDGMENTS

This research was made possible through support from the Electric Power Research Institute (EP-P26150C12608) and the Climate Decision Making Center at Carnegie Mellon University's Department of Engineering and Public Policy, which is sponsored through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University.

We thank Jay Apt, Michael Berkenpas, Elizabeth Casman, Mandy Holbrook, Paul Fischbeck, Baruch Fischhoff, Sean McCoy, Ed Rubin, and Henry Willis for their advice and expert review, the many local community groups who participated in the study, and Charlotte Fitzgerald, Benjamin Mayer, and Oleg Trofimov for their valuable assistance.

REFERENCES

1. IPCC. Climate change 2007: Mitigation. Pp. 251–322 in Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds). Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York: Cambridge University Press, 2007.
2. James R, Richels R, Blanford G, Gehl, S. The Power to Reduce CO_2 Emissions: The Full Portfolio. Pala Alto, CA: EPRI Technology Assessment Center, Electric Power Research Institute Report, 1015461, 2007.
3. Apt J, Lave LB, Pattanariyankool S. A national renewable portfolio standard? Not practical. Issues in Science and Technology, 2008; 28(1):53–59.

4. Walawalker R, Apt J, Mancini R. Economics of electric energy storage for energy arbitrage and regulation in New York. Energy Policy, 2007; 35(4):2558–2568.
5. Mouward J. No new refineries in 29 years? There might well be a reason. New York Times, May 9, 2005. Available at: http://www.nytimes.com/2005/05/09/business/09refinery.html, accessed August 28, 2009.
6. Guigni M. Social Protest and Policy Change: Ecology, Antinuclear, and Peace Movements in Comparative Perspective. Lanham, MD: Rowman and Littlefield, 2004.
7. Bradbury J, Ray I, Peterson T, Wade S, Wong-Parodi G, Feldpausch A. The role of social factors in shaping public perceptions of CCS: Results of multi-state focus group interviews in the U.S. Energy Procedia, 2009; 1(1):4665–4672.
8. Firestone J, Kempton W. Public opinion about large offshore wind power: Underlying factors. Energy Policy, 2007; 35(3):1584–1598.
9. Curry TE, Ansolabehere S, Herzog HJ. A Survey of Public Attitudes Towards Climate Change and Climate Change Mitigation Technologies in the United States: Analyses of 2006 Results. Cambridge, MA: Massachusetts Institute of Technology, 2007.
10. Grove-White R, Kearnes M, Macnaghten P, Wynne B. Nuclear futures: Assessing public attitudes to new nuclear power. Political Quarterly, 2006; 77(2):238–246.
11. Poortinga W, Pidgeon NF, Lorenzoni I. Public Perceptions of Nuclear Power, Climate Change and Energy Options in Britain: Summary Findings of a Survey Conducted During October and November 2005. Norwich, UK: Centre for Environmental Risk, 2006.
12. Purvis-Roberts KL, Werner CA, Frank I. Perceived risks from radiation and nuclear testing near Semipalatinsk, Kazakhstan: A comparison between physicians, scientists, and the public. Risk Analysis, 2007; 27(2):291–302.
13. Palmgren CR, Morgan MG, Bruine de Bruin W, Keith DW. Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. Environmental Science and Technology, 2004; 38(24):6441–6450.
14. Ashworth P, Boughena N, Mayhew M, Millar F. An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond. Energy Procedia, 2009; 1(1):4749–4756.
15. Wallquist L, Visschers VHM, Siegrist M. Lay concepts on CCS deployment in Switzerland based on qualitative interviews. International Journal of Greenhouse Gas Control, 2009; 3:652–657.
16. Gross C. Community perspectives of wind energy in Australia: The application of a justice and community fairness framework to increase social acceptance. Energy Policy, 2007; 35(5):2727–2736.
17. Reiner D, Curry T, Figueredo M, Herzog H, Ansolabehere S, Itaoka K, Akai M, Johnsson F, Odenberger M. An international comparison of public attitudes towards carbon capture and storage technologies. Proceedings of the Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8). Trondheim, Norway. June 22, 2006.
18. de-Best Waldhober M., Daamen D, Faaij A. Informed and uninformed public opinions on CO_2 capture and storage technologies in the Netherlands. International Journal of Greenhouse Gas Control, 2009; 3(3):322–332.
19. Sharp J. Public Attitudes Towards Geological Disposal of Carbon Dioxide in Canada. British Columbia: Simon Frasier University, School of Resource and Environmental Management Report, 384, 2005.
20. Huijts NMA, Midden CJH, Meijnders AL. Social acceptance of carbon dioxide storage. Energy Policy, 2007; 35:2780–2789.
21. Reiner D, Curry T, Figueiredo M, Herzog H, Ansolabehere S, Itaoka K, Johnsson F, Odenbergeret M. American exceptionalism? Similarities and differences in national attitudes toward energy policy and global warming. Environmental Science and Technology, 2006; 40:2093–2098.
22. Fishkin J. Strategies of public consultation. Integrated Assessment Journal, 2006; 6(2):57–72.
23. Itaoka K, Okuda Y, Saito A, Akai M. Influential information and factors for social acceptance of CCS: The 2nd round survey of public opinion in Japan. Energy Procedia, 2009; 1(1):4803–4810.
24. Price V, Neijens PC. Opinion quality in public opinion research. International Journal of Public Opinion Research, 1997; 9(4):336–360.
25. Reiner DM. A Looming Rhetorical Gap: A Survey of Public Communications Activities for Carbon Dioxide Capture and Storage Technologies. Electricity Policy Research Group Working Papers, No. 0801. Cambridge, UK: University of Cambridge, 2008.
26. Morgan MG, Fischhoff B, Bostrom A, Lave L, Atman, CJ. Communicating risk to the public. Environmental Science and Technology, 1992; 26(11):2048–2056.
27. Fischhoff B, Slovic P, Lichtenstein S. Lay foibles and expert fables in judgments about risk. American Statistician, 1982; 36(3):240–255.
28. Bruine de Bruin W. Judgment and decision making in adolescents. In Dhami MK, Schlottmann A, Waldmann M (eds). Judgment and Decision Making as a Skill: Learning, Development, and Evolution. Cambridge, UK: Cambridge University Press, in press.
29. Morgan MG, Fischhoff B, Bostrom A, Atman CJ. Risk Communication: A Mental Models Approach. New York: Cambridge University Press, 2002.
30. Maharik M, Fischhoff B. The risks of using nuclear energy sources in space: Some lay activists' perceptions. Risk Analysis, 1992; 12(3):383–391.
31. Bruine de Bruin W, Fischhoff B, Güvenç Ü, Caruso D, Armstrong C. A model-based scenario approach to communicating the risks of xenotransplantation. Risk Analysis, 2009; 29: 1105–1115.
32. Downs JS, Murray PJ, Bruine de Bruin W, White JP, Palmgren C, Fischhoff B. Interactive video behavioral intervention to reduce adolescent females' STD risk: A randomized controlled trial. Social Science & Medicine, 2004; 59: 1561–1572.
33. Fischhoff B, Bruine de Bruin W, Güvenç U, Brilliant L, Caruso D Analyzing disaster risks and plans: An avian flu example. Journal of Risk and Uncertainty, 2006; 33:131–149.
34. Pidgeon NF, Lorenzoni I, Poortinga W. Climate change or nuclear power—No thanks! A quantitative study of public perceptions and risk framing in Britain. Global Environmental Change, 2008; 18(1):69–85.
35. Itaoka K, Saito A, Akai M. Public acceptance of CO_2 capture and storage technology: A survey of public opinion to explore influential factor. Proceedings of Seventh International Conference on Greenhouse Gas Control Technologies. Cheltenham, UK 2004.
36. Kaldellis JK. Social attitude towards wind energy applications in Greece. Energy Policy, 2005; 33:595–602.
37. Florig HK, Morgan MG, Morgan KM, Jenni KE, Fischhoff B, Fischbeck PS, DeKay ML. A deliberative method for ranking risks (I): Overview and test bed development. Risk Analysis, 2001; 21(5):913–921.
38. Morgan KM, DeKay ML, Fischbeck PS, Morgan MG, Fischhoff B, Florig HK. A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers. Risk Analysis, 2001; 21(5):923–937.
39. Willis HH, DeKay ML, Morgan MG, Florig HK, Fischbeck PS. Ecological risk ranking: Development and evaluation of a method for improving public participation in environmental decision making. Risk Analysis, 2004; 24(2):363–378.

40. PA General Assembly. Senate Bill No. 1030 (Printer's number 1419): Providing for the Sale of Electric Energy Generated from Renewable and Environmentally Beneficial Sources, for the Acquisition of Electric Distribution and Supply Companies and for the Powers and Duties of the Pennsylvania Public Utility Commission, March, 15, 2004. Available at: http://www.legis.state.pa.us/cfdocs/legis/home/session.cfm, accessed on January 5, 2009.
41. Presser S, Blair J. Survey pretesting: Do different methods produce different results? Chapter 2 in Marsden P (eds). Sociological Methodology. San Francisco, CA: Jossey-Bass, 1994.
42. Flesch R. A new readability yardstick. Journal of Applied Psychology, 1948; 32(2):221–233.
43. Kincaid JP, Fishburne RP, Rogers RL, Chissom BS. Derivation of New Readability Formulas (Automated Readability Index, Fog Count and Flesch Reading Ease Formula) for Navy Enlisted Personnel. Memphis, TN: Naval Technical Training, U.S. Naval Air Station, 1975.
44. U.S. Census Bureau. Generated by Fleishman LA using American FactFinder, 28 January 2010. Available at: http://factfinder.census.gov, accessed August 5, 2009.
45. Dunlap RE, Van Liere KD, Mertig AG, Jones RE. Measuring endorsement of the new ecological paradigm: A revised NEP scale. Journal of Social Issues, 2000; 56: 425–442.
46. Liu Q, Shi M, Jiang K. New power generation technology options under the greenhouse gases mitigation scenario in China. Energy Policy, 2009; 37(6):2440–2449.
47. CBS News New York Times. American Public Opinion: Today vs. 30 Years Ago. New York. January 11–15, 2009. Available at: http://www.cbsnews.com/htdocs/pdf/SunMo_poll_0209.pdf, accessed September 1, 2009..
48. Jones JM. Support for Nuclear Energy Inches Up to New High. Washington, DC: Gallup, 2009. Available at: http://www.gallup.com/poll/117025/support-nuclear-energy-inches-new-high.aspx, accessed September 1, 2009.
49. DeKay ML, Florig HK, Fischbeck PS, Morgan MG, Morgan KM, Fischhoff B, Jenni KE. The use of public risk ranking in regulatory development. Pp. 208–230 in Fischbeck PS, Farrow RS. (eds). Improving Regulation: Cases in Environment, Health, and Safety. Washington, DC: Resources for the Future.
50. Siegrist M, Cvetkovich G. Perception of hazards: The role of social trust and knowledge. Risk Analysis, 2000; 20(5):713–719.
51. Midden CJH, Huijts NMA. The role of trust in the affective evaluation of novel risks: The case of CO_2 storage. Risk Analysis, 2009; 29(5):743–751.
52. Terwel BW, Harinck F, Ellemers N, Daamen DDL. Competence-based and integrity-based trust as predictors of acceptance of carbon dioxide capture and storage (CCS). 2009; 29(8):1129–1140.