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

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Authors note

This research was made possible through support from the Electric Power Research Institute (EP-P26150C12608) and the Climate Decision Making Center (CDMC) at Carnegie Mellon University's Department of Engineering and Public Policy and 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, and Ed Rubin 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.

1. ABSTRACT

For low-carbon electricity generating technologies to play a significant role in the reduction of atmospheric CO_2 emissions, the public must accept their wide-spread deployment. This study asked members of the general public to rank ten technologies (e.g., wind, nuclear, coal with CCS, natural gas), and seven realistic low-carbon portfolios composed of these technologies. Participants received comprehensive and carefully balanced materials that systematically explained the costs and benefits of each. These materials were developed with input from domain experts to ensure correct information, and pilot-tested with members of the general public to ensure understanding. After ranking the technologies and the portfolios, participants also rated their overall opinion of CCS.

Participants' rankings of technologies suggest that they most favored energy efficiency, followed by nuclear, integrated gasification combined-cycle coal (IGCC) with CCS and wind. The most preferred portfolio included a mix of these four technologies. IGCC with CCS was preferred to pulverized coal with CCS, whether presented as a technology or within a portfolio. Coal technologies with CCS were preferred over those without CCS. Participants' *rankings* suggest acceptance of CCS, when presented in comparison to other technologies and within a low-carbon portfolio. However, when participants considered the technology in isolation, their *ratings* showed only slightly favorable opinions of CCS. This finding suggests a reluctant acceptance of CCS, given the alternatives. We conclude that the general public may be willing to reluctantly accept CCS, nuclear and other low-carbon technologies, once they fully understand the benefits, cost and limitations of the alternatives.

Keywords: public risk perception and communication; electricity generation; low-carbon; carbon capture and sequestration; CCS.

2. INTRODUCTION

Fossil fuel use by the electricity sector is the largest source of carbon dioxide (CO_2) emissions in the U.S. (1, 2) 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.(3) Achieving this reduction in the U.S. over the next half century will require an aggressive deployment of several advanced low-carbon technologies including wind, nuclear plants, natural gas plants and coal plants with technologies for carbon capture and deep geological sequestration (CCS), which separate CO_2 from the flue gas of electricity-generating plants and sequester it in deep geological formations.(4)

Renewable electricity sources, such as wind turbines, and perhaps solar thermal systems, will likely also play an important role in de-carbonizing the electricity grid, but are currently unable to meet baseload demand for electricity.(5) 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.(6, 7) Therefore, to ensure that electricity generation in the near future remains reliable 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.(5)

For any of these low-carbon technologies to become a viable option for reducing CO_2 emissions, the public must find them acceptable for wide-spread 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(8), nuclear power plants(9), pilot-scale CCS technologies(10, 11) and even wind farms(12). For example, ever since the reactor meltdown at Three Mile Island, people have been reluctant to accept new nuclear power plants (13-16), in part because they believe that they may emit dangerous levels of radiation.(15, 17, 18) In addition, public perceptions of CCS include the fear that CO_2 "burps" will be released from the ground and cause suffocation.(19, 20) Negative public sentiment also exists towards wind turbines, which some people perceive as noisy, aesthetically unappealing and a threat to birds and bats.(12, 21, 22) Yet, many members of the public 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.(20, 23)

Some proponents of CCS have suggested that people are reluctant to accept that technology because they lack information about how its costs and benefits compare to those of alternative technologies.(13, 20, 24) Low levels of understanding may also explain why surveys have found public perceptions of CCS to vary from negative(19, 25) to slightly positive(14, 26, 27). Some studies do suggest that people increase their support of CCS after they become more informed about the technology(10, 28), while others suggest that providing more information may lead to less favorable opinions of CCS(19, 29). Researchers have also stressed the need for better public education outreach regarding more familiar technologies such as wind turbines and nuclear reactors. (12, 15, 30)

Effective risk communication helps members of the general public to make more informed decisions about low-carbon technologies. The mental models approach(31) has been used to design risk communications about various topics including climate change(31), nuclear energy sources on spacecraft(32), and avian flu(33). Palmgren and colleagues(19) applied a modified mental models approach to explore initial public perceptions of CCS. In open-ended interviews, they asked lay people to describe their knowledge and beliefs about CCS, in their own words. Since most people had never heard of CCS(14), Palmgren and colleagues began by providing a brief written explanation of the technology before conducting their interviews. They found that respondents wanted to talk about CCS relative to other technologies that might be used in a future electricity-generating portfolio to reduce CO_2 emissions. These findings have been replicated in other public perception studies of CCS(24, 27), and nuclear plants(34). Accordingly, Palmgren et al.(19) asked 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% coal plants. The low-carbon portfolios that included “regular coal” with geographic or oceanic CCS were ranked below all other portfolios, while the portfolio with “regular coal” and nuclear was ranked as the next worst. Since then, other investigators have found that people may be less likely to accept any non-renewable technology when it is presented in isolation, compared to when it is included in a portfolio of possible options. (20, 35, 36)

Palmgren et al.’s (19) study had several limitations. First, while it provided modest detail about the risks and benefits for CCS, it did not provide similar information about other technologies. Second, no comparative cost data were provided. Third, the presented options did not differentiate between conventional coal-based technologies such as pulverized coal (PC) and more advanced technologies such as integrated gasification combined-cycle coal (IGCC). Finally, the presented portfolios were very simple, with many relying heavily on renewables, and may therefore have been infeasible. Several of the most preferred portfolios’ produced 50% of their electricity from a single intermittent renewable technology, such as solar photovoltaic (PV) or wind power. In reality, for the next few decades, the intermittency associated with these renewables will likely limit their potential contribution to a much smaller percentage, approximately 20% or less of the total electricity portfolio.(5)

The present study builds on Palmgren et al.(19), rectifying most of these limitations. Using the mental models approach, we developed informational materials about a set of low-carbon technologies and realistic portfolios designed to meet a specific CO_2 emissions limit. With the advice of domain experts, we developed *balanced* and *comparative* information about the costs, risks and benefits of each. The same set of attributes was described for each technology, adapting the presentation format from earlier work on risk ranking.(37-40) Materials used simple wording and were pilot-tested with members of the general public, using read-aloud protocols, to ensure correct understanding. Subsequently, we asked members of the general public to rank the technologies, as well as the portfolios, both individually and while participating in a group discussion. At the end of the study, we asked participants to rate their favorability of CCS, when presented in isolation, to examine whether their acceptance of this technology had changed from that observed using our standard portfolio representation. In short, our research aimed to examine well-informed participants' preferences for CCS and other low-carbon technologies, alone and as part of electricity portfolios designed to reduce CO_2 emissions.

3. METHODS

3.1. Materials

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

- four coal-based technologies (PC and the more advanced IGCC, both with and without CCS);

- natural gas combined cycle (which produce roughly half the CO_2 emissions of coal);
- advanced nuclear plants (generation III+ or IV);
- three renewable technologies - modern wind turbines, solar PV, and biomass using integrated gasification combined-cycle; and
- the reduction of electricity consumption through energy efficiency.

Each technology was described on a separate *Technology Description Sheet* (see Figure 1 for an example). To facilitate systematic comparisons(37, 39), these sheets used a standard format with a consistent set of entries and 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*.

To further facilitate comparisons between technologies, we developed additional sheets providing direct comparisons across all the technologies for several key attributes. For example, the *Cost Comparison* reported costs both in dollars per kilowatt-hour (kWh) as well as in terms of the monthly electricity bill that the median PA customer would receive. In addition to best estimates, uncertainty arising from variations in plant configuration, capacity factors, capital costs and fuel prices was conveyed using a simple graphical display.

Similarly, the *Pollution Comparison* addressed the emissions of five pollutants by each technology: CO_2, nitrogen oxides, sulfur dioxides, particulates and mercury. PC plants were chosen as the baseline for comparison because the study was conducted in PA, where a majority (56%) of the electricity generated in 2006 came from coal.(41) Values were displayed as a percent above or below the emissions of a PC plant without CCS. Additional text described exposure routes and the health and environmental consequences for each pollutant.

Because our study focused on electricity capacity expansion, we designed a set of seven low-carbon portfolios, representing realistic combinations of the ten technologies (Table I), each of which lead to 70% lower CO_2 emissions than if future expansion were achieved solely with PC plants. We chose portfolios that could realistically be constructed to reliably supply the estimated 25% increase in electricity demand in PA in the next 25 years.(42) To make the portfolios realistic, we limited the contribution of intermittent renewables to a small percentage (e.g. <7% for wind, <1% for solar PV) of the estimated total electricity capacity of PA in 2030.(42) These limits were closely aligned with the Tier 1 Alternative Energy Portfolio Standards for PA.(43)

As shown in Table I, four simple portfolios (i.e., A, B, C and G) relied on one technology for its baseload (i.e., reliable and non-intermittent) electricity source. The remaining three portfolios were modeled after the more diversified portfolios constructed by the EPRI PRISM Model(4), including the *limited* portfolio D, with predominantly renewables and increased efficiency efforts, using natural gas plants for baseload power and intermittency fill; the *semi-limited* portfolio E, with CCS, natural gas and renewables, but no nuclear power; and the *full* portfolio F, with CCS, nuclear, natural gas and renewables.

The portfolios were referred to as *Power Plant Combinations*. Each was first introduced using a pie chart, with additional details being provided in a packet including the *Technology Description Sheets* of the associated technologies. As with the individual technologies, we also provided comparisons of the portfolios in sheets entitled *Cost Comparison for Combinations* and *Pollution Comparison for Combinations*.

We developed all materials with input from subject-matters experts with knowledge in the relevant areas so as to ensure technical accuracy, and conducted pilot-tests with members of the general public to ensure comprehension, as is typical in the mental models approach.(31) To this end, we recruited a convenience sample of 11 participants who had non-technical backgrounds and at least a high-school education. They were asked to read all materials out loud and discuss anything that came to mind. These pilot-tests were intended to identify and resolve any confusion participants might have had about the presented materials, as have been observed in studies testing the effectiveness of cognitive interviewing.(44, 45) After every few interviews, materials were revised to address identified concerns, and double-checked by subject-matter experts. Despite the complexity of the materials, all were written at a 6th to 8th grade reading level, as measured using the Flesch-Kincaid Grade Level readability statistic.(46, 47) The complete set of the materials, including those described above, are available online at http://sds.hss.cmu.edu/risk/fleishman/LowCarbonPortfolioMaterials.html.

3.2. Participants

A diverse sample of 54 participants was recruited through community organizations in the Greater Pittsburgh Metropolitan Area. Participants were 18 to 73 years old (m=37.5). Thirty-five (65%) participants were female and 19 (35%) were male. Thirty-six (66%) classified their race as White, 16 (30%) as Black/African American, and two (4%) as American Indian/Alaska Native. All had graduated from high school. Thirty-four (63%) had completed at least a Bachelor's degree (in non-technical fields). The mean age of our sample compares well with that of the U.S. population (median=36.6).(48) However, our sample included more females (U.S. average is 51%), a greater percentage of Black/African Americans (U.S. is 13%), and was somewhat better educated than the U.S. general population (U.S. is 86% high school graduates and 28% with at least a Bachelor's degree).(49, 50)

3.3. Procedure

The procedures followed in this study are summarized in Figure 2. Before attending a group workshop, participants received "homework" study materials, including an *Introduction* about burning fossil fuels and climate change, a *Problem Question*, which provided context for the ranking exercise, as well as the *Technology Description Sheets, Cost Comparison* and *Pollution Comparison* for the individual technologies. The *Problem Question* read as follows:

> "PA 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 PA 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 materials, but prior to attending the group meeting, participants ranked the ten technologies to reflect how they would prefer to reduce CO_2 emissions from future electricity expansion in the next 25 years. We refer to these rankings as *pre-discussion technology rankings.* Participants were also asked to rate each information sheet and attribute in terms of "how hard or easy it was to understand the information provided" on a seven-point scale ranging from "very hard" to "very easy." We refer to these results as *pre-explanation* *comprehension ratings.* We also asked, "how important the information was when deciding upon your ranking," using a seven-point scale ranging from "not important at all" to "extremely important." We refer to these results as *pre-explanation importance ratings*. Participants then provided ratings on whether they believed: (1) "The continuing release of CO_2 into the earth's atmosphere during this century may result in serious climate change," (2) "Government regulation *should* begin to significantly limit the amount of CO_2 that is released into the earth's atmosphere" and (3) "Government regulation *will* begin to significantly limit the amount of CO_2 that is released into the earth's atmosphere at some time in the next 20 years." Each of these *viewpoints on climate change* were rated on a seven-point scale that ranged from "completely disagree" to "completely agree." In order to obtain participants' views of the relative importance of climate change when compared with other social issues such as education, crime, and health care, participants provided ratings of the *importance of 15 social and economic issues* using a seven-point scale that ranged from "not important" to "extremely important." Finally, participants answered 15 *true-or-false knowledge questions*, with each question testing participants' understanding of a specific information sheet or attribute. This set of questions was developed during the pilot-tests of the materials and addressed issues that had been most commonly misunderstood. These knowledge questions were pilot-tested to ensure that participants understood what was asked.

Eight workshops were conducted in total. Each involved four to nine participants, was conducted locally in the communities, lasted two to three hours, and followed a careful script adapted from a study with a similar methodology.(40) 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.

In each workshop, we first reviewed the "homework" materials and each of the *true-or-false knowledge questions* answered incorrectly by at least one participant in the group. After introducing the concept of a low-carbon electricity portfolio, or "Power Plant Combination," the experimenter provided the group with new materials that included *Power Plant Combinations*, *Cost Comparison for Combinations* and *Pollution Comparison for Combinations* and asked participants to study them individually. Additionally, participants received a *New Problem Question*, which amended the original *Problem Question* with the following language:

> "…the State of PA must change some of the power plant types that will be built here over the next 25 years. The PA Governor has suggested seven new power plant combinations. Each combination has a mix of two or more different power plant types that collectively release 70% 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 seven power plant combinations from best to worst."

After they had carefully studied all of these new materials, participants received a *Ranking Summary Sheet* to log each of the rankings they performed during the workshop. The personal *pre-discussion technology rankings* they had provided as part of their homework were included on these sheets. Participants were then asked to add their personal *pre-discussion portfolio ranking* onto the *Ranking Summary Sheet*. Next, they provided *post-explanation comprehension* and *importance ratings*, the same ratings as described above.

After these individual tasks were completed, participants worked together as a group to rank the portfolios in a sorting exercise facilitated by the experimenter and adapted from earlier risk ranking studies.(37, 38, 40) These risk ranking studies have shown that the group setting provides opportunities for participants to hear alternative perspectives held by their peers, before reconsidering their original rankings. When this group exercise had been completed, participants logged the *group portfolio rankings* onto their *Ranking Summary Sheets*. Working independently again, participants were given the opportunity to revise their individual rankings in the form of *post-discussion portfolio and technology rankings*.

At the end of the workshop, participants provided individual *post-discussion comprehension* and *importance ratings* and answered *group discussion ratings*, on a seven point scale from “completely disagree” to “completely agree,” which included the following statements: (1) “I am very satisfied with my group’s final ranking of the power plant combinations,” (2) “I feel that I made a significant contribution to the group discussion,” (3) “I feel that I influenced the group’s ranking of the power plant combinations,” and (4) “The group discussion influenced my own final ranking of the power plant combinations a great deal.” Finally, participants provided a *CCS favorability rating* to answer the question “do you oppose or favor putting CO_2 released by coal plants in deep rock formations?” Participants indicated their answer using a seven-point scale from “completely oppose” to “completely favor.” The survey then provided a list of issues that had been found to affect people’s favorability of CCS in Palmgren et al.(19). Participants indicated their agreement with these issues on a seven-point scale from “completely agree” to “completely disagree.” These *CCS-related concerns* and the *CCS favorability rating* were presented at the end of the workshop, so as not to attract special attention to CCS during the ranking exercises.

4. RESULTS

4.1. Analyses

We computed Kendall's coefficient of concordance (*W*) to examine the consistency of the rank-orders assigned to the technologies by the 54 participants. Wilcoxon paired-rank tests compared participants' rankings for each possible pair of technologies, as well as participants' *pre-* and *post-discussion technology rankings*. We conducted the same three analyses on portfolio rankings.

To further explore whether participants placed more importance on pollutant or cost information, we examined whether each participant's technology rankings were more strongly correlated to the pollutant information than to the cost information, as presented on the *Pollution Comparison* and *Cost Comparison* sheets, respectively. Specifically, we used the procedure proposed by Meng et al.(51) to test for differences between Fisher-transformed correlation coefficients. Doing so resulted in a separate *Z* value for each of the 54 participants, which were then averaged using the *Stouffer method*.(52) We performed the same analysis for portfolio rankings.

Subsequently, we used one-sample *t*-tests to examine whether *viewpoints on climate change* were strong enough to be significantly different from the scale midpoint. We further computed Pearson correlations between participants' ratings of *CCS-related concerns* and their *CCS favorability rating* to examine whether they are sensibly correlated. Finally, we computed Spearman rank-order correlations between participants *CCS favorability rating* and their rankings of the technologies and portfolios that include CCS.

To examine how well participants understood the materials, we conducted the following set of analyses. First, we performed a one-sample *t*-test to examine whether the percent of *true-or-false knowledge questions* answered correctly was significantly different from chance (50%). Second, we also conducted a one sample *t*-test to examine whether participants' *comprehension ratings*, provided on a seven-point Likert scale, were strong enough to be significantly different from the scale midpoint.

Finally, a one sample *t*-test examined whether participants' *group discussion ratings*, provided on a seven-point Likert scale, were significantly different from the scale midpoint. To validate participants' ratings of how much they perceived their technology rankings to be influenced by the group discussion, we computed Spearman rank-order correlations between participants' ratings and the mean absolute difference between their *pre-* and *post-discussion technology rankings*. We conducted the same analysis for the ratings of how much participants perceived their portfolio rankings to be influenced by the group discussion.

4.2. Technology Rankings

Kendall's coefficient of concordance showed a high degree of agreement between participants' *pre-discussion* rankings of the ten technologies, provided before the group discussion (W=0.36 p<0.001) as well as between their *post-discussion* rankings, provided after the group discussion (W=0.34, p<0.001). Figure 3 reports the mean *pre-discussion* (left) and *post-discussion* (right) technology rankings, where 1 is the "best" and 10 is the "worst". Wilcoxon paired-rank tests indicated that, for each technology, participants' *pre-discussion* rankings were not significantly different from *post-discussion* rankings (p>0.10).

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants' rankings between each possible pair of technologies. The superscripted letters in Figure 3 show, for each technology, the other technologies that were ranked as significantly "worse." Due to the large number of tests, we only report on results that are significant at $p<0.01$ for both the *pre-* and *post-discussion* rankings, unless noted otherwise.

Overall, energy efficiency received the best mean technology ranking and was significantly preferred to all other technologies. The second best mean ranking was for nuclear power, whose rankings were not significantly different from those for IGCC with CCS, and wind, which ranked, on average, as third and fourth, respectively. The other mean rankings in order, were for (5) biomass, (6) natural gas, (7) solar PV, (8) PC with CCS, (9) IGCC without CCS, and (10) PC without CCS. Perhaps most notably, rankings of IGCC and PC showed that participants preferred each technology with CCS rather than without it, and favored IGCC with CCS over PC with CCS.

4.3. Portfolio Rankings

Kendall's coefficient of concordance showed a high degree of agreement between participants' *pre-discussion* rankings ($W=0.31$, $p<0.001$) as well as between their *post-discussion* rankings of the seven portfolios ($W=0.45$, $p<0.001$). Figure 4 reports the mean *pre-discussion* (left) and *post-discussion* portfolio rankings (right), where 1 is the "best" and 7 is the "worst". Wilcoxon paired-rank tests indicated that, for each portfolio, participants' *pre-discussion* rankings were not significantly different from *post-discussion* rankings ($p>0.10$), except for portfolio B, the IGCC with CCS mix, which was ranked as better after the discussion compared to before it (Wilcoxon $z=-2.21$, $p=0.03$).

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants' rankings between each possible pair of portfolios. The superscripted letters in Figure 4 show, for each portfolio, the other portfolios that were ranked as significantly "worse." Due to the large number of tests, we only report on results that are significant at $p<0.01$ for both *pre-* and *post-discussion* rankings, unless noted otherwise.

Overall, portfolio F, which included IGCC with CCS and nuclear, was preferred the most, receiving the best mean ranking. Portfolio E, which included IGCC with CCS but no nuclear, received the second best mean *pre-discussion* ranking and third best *post-discussion* ranking. As the only two diverse portfolios including IGCC with CCS, both portfolios E and F were significantly preferred to all portfolios that did not include IGCC with CCS. Portfolio B, which included the less diverse IGCC with CCS mix, had the third best mean ranking *pre-discussion* and second best *post-discussion*. The other mean rankings in order were for (4) the *limited* portfolio D, with no CCS or nuclear, (5) portfolio G, with the natural gas and wind mix, (6) portfolio C with the nuclear mix, and (7) portfolio A with the simple PC with CCS mix. Similar to the pattern observed with the rankings of the technologies, rankings of the three portfolios that included IGCC with CCS (B, E, and F) were ranked as better than Portfolio A, the PC with CCS mix. In fact, all portfolios were ranked significantly better than Portfolio A.

4.4. Information and Attribute Importance

Tables II-IV show the *importance ratings* for the information materials, *Technology Description Sheet* attributes, and the pollutants in *Pollution Comparison*. These ratings suggest that participants placed relatively more importance on pollutant-related information, thus seeming to follow the experimental task presented in the *(New) Problem Question*. Indeed, on average, participants gave the highest *post-explanation* and *post-discussion* ratings to the *Pollution Comparison for Combinations* sheet. Participants' mean *pre-* and *post-explanation* importance ratings for different attributes suggest that CO_2 was seen as the most important, regardless of whether it was presented in qualitative (Table III) or quantitative (Table IV) format. While the CO_2 attribute did not receive the highest mean importance rating in the *Pollution Comparison for Combinations* (not shown), this was likely a result of all the portfolios having the same CO_2 emissions.

To further examine whether participants placed more importance on CO_2 emissions than on cost information, we tested, for each participant, whether that participant's technology rankings were more strongly correlated with the technologies' CO_2 emissions than their costs, as presented on the *Pollution Comparison* and *Cost Comparison* sheets, respectively.(51) Combined, the results across participants suggest that this was indeed the case (for *pre-discussion* rankings, mean Spearman's ρ=-0.40 for CO_2 emissions vs. mean Spearman's ρ=-0.03 for costs; z=5.86, p<0.001 and for *post-discussion* rankings, mean Spearman's ρ=-0.38 for CO_2 emissions vs. mean Spearman's ρ=-0.02 for costs; z=5.64, p<0.001).

We found the same pattern for all other pollutants listed on the *Pollution Comparison*. That is, both *pre*-and *post-discussion* technology rankings were more strongly correlated to each of the pollutant emissions levels listed for the technologies (i.e., nitrogen oxide, sulfur dioxide, particulates and mercury) than to the technologies' costs (p<0.001 for each). For portfolios, we repeated these analyses for pollutants other than CO_2, which, by design, was constant across all seven portfolios. For three of the four remaining pollutants (i.e., nitrogen oxide, particulates and mercury), participants' portfolio rankings were more highly correlated to the portfolios' emissions levels than to the portfolios' costs for *pre-discussion* portfolio rankings (p=0.04 for all three pollutants), but no significant differences were found with *post-discussion* portfolio rankings (*p*=0.11 for all three pollutants). Only when testing the latter pattern for the sulfur dioxide emissions variable, were participants' *post-discussion* portfolio rankings more highly correlated to the portfolios' costs than to the portfolios' emissions levels (mean Spearman's ρ=0.01 for sulfur dioxide emissions vs. mean Spearman's ρ=-0.22 for costs; *z*=-2.02, *p*=0.04). However, the result was not replicated for *pre-discussion* portfolio rankings (mean Spearman's ρ=-0.09 for sulfur dioxide emissions vs. mean Spearman's ρ=-0.09 for costs; *z*=-0.21, *p*=0.83).

4.5. Viewpoints on Climate Change and CCS

For all three *viewpoints on climate change*, participants' ratings were significantly higher than the midpoint, suggesting that participants showed moderate agreement. Thus, participants agreed that (1) carbon release leads to climate change (m=5.56, *t*=6.71, *p*<0.001) (2) the government should (m=5.73, *t*=8.20, *p*<0.001) and (3) will (m=4.73, *t*=3.43, *p*<0.01) regulate the amount of CO_2 released. Using the same questions, Palmgren et al.(19) reported slightly less agreement among respondents in that 2004 study. Mean ratings for the same three statements were between 4.0 and 4.7. Relative to the *importance of 15 social and economic issues*, participants in our study rated "improving education" and "improving health care" as, respectively, the first and second most important. The issue of "reducing climate change" was 10th most important out of 15. Education and health care were also the two most important issues in Palmgren and colleagues' study. Climate change was ranked as the least important of the 15.

We computed Pearson correlations between participants' 1-7 ratings of *CCS favorability* and *CCS-related concerns*. As in Palmgren et al., participants who were more opposed to CCS were more likely to agree with the following statements: "Sometime in the future enough CO_2

will leak out and may cause serious climate change after all" (*r*=-0.50, $p<0.001$); "Humans should not be using deep rock formations as a place to put waste of any kind" (*r*=-0.56, $p<0.001$); "Disposing of large volumes of CO_2 in deep rock formations may cause earthquakes" (*r*=-0.52, $p<0.001$); "Serious unintended consequences will show up many years from now suggesting that putting the CO_2 into the deep rock formations was not such a great idea" (*r*=-0.56, $p<0.001$); "CO_2 may gradually leak to the surface, and cause negative impacts on plants and animals" (*r*=-0.45, $p<0.001$); and more likely to disagree with: "Disposing of CO_2 in the deep rock formations can be made as safe as most other large industrial activities, such as current oil and gas production" (*r*=0.62, $p<0.001$). While the *CCS-related concerns* of "Once the CO_2 is put in the deep rock formations, it is not clear that it will stay where it should" and "CO_2 may have negative impacts on small animals that live in the very deep rock formations" also had a significant correlation coefficient in Palmgren et al., our results show no such correlation ($p>0.10$ for both) for these two statements. In contrast to Palmgren et al., participants in our study who were more favorable towards CCS, were also more likely to agree with the statement, "The government should spend large amounts of public money on research to find out how much CO_2 could be put in the deep rock formations, what the risks might be, and how to monitor and regulate this activity" (*r*=0.30, $p=0.03$). The non-significant results in Palmgren et al. were in the same direction.

Participants' mean ratings of CCS were slightly favorable, being significantly above the scale midpoint (m=4.72, $t=3.22$, $p<0.01$), where 1 is "completely oppose" and 7 is "completely favor". However, replicating other studies(16, 28, 34), ratings which treat CCS in isolation were not significantly correlated ($p>0.01$ using Spearman's rank-order correlation) to any of the rankings for technologies or portfolios that included CCS.

4.6. Participant Comprehension

Across the 15 *true-or-false knowledge questions* answered before the workshop, participants obtained an average score of 90% correct (sd=11%; range 60-100%). We found these scores to be significantly better (t=23.2, p<0.001) than chance (50% correct), suggesting a basic understanding of the materials. The most difficult questions were still answered correctly by the majority of participants (87%±34%[1] for the *Problem Question*, 87%±34% for the *Pollution Comparison* and 87%±34% for the *Technology Description Sheet* attribute of *How it works*).

Table V shows participants' mean *pre-* and *post-explanation comprehension ratings* of the information materials, provided before and after materials were explained by the experimenter, and *post-discussion ratings*, provided after group discussion. *Pre-explanation*, the *Cost Comparison*, *Pollution Comparison* and *Problem Question* received the lowest mean ratings, which were still significantly above the midpoint (m=5.23, t=5.53, p<0.001 for *Cost Comparison*; m=5.43, t=7.42, p<0.001 for *Pollution Comparison*; m=5.74, t=8.17, p<0.001 for the *Problem Question*) on a scale from 1 (very hard) to 7 (very easy), suggesting that the materials were relatively easy to understand.

4.7. Participant Satisfaction and Group Dynamics

Compared to the scale midpoint, where 1 is "completely disagree" and 7 is "completely agree," participants reported that they were satisfied with their group's portfolio ranking (m=5.69, t=9.32, p<0.001) and that they perceived to have contributed to the group discussion (m=5.46, t=7.48, p<0.001). Furthermore, participants indicated that they thought they had influenced the group's ranking (m=5.00, *t*=4.49, *p*<0.001), while also being influenced by the group discussion (m=5.09, *t*=5.16, *p*<0.001), suggesting positive group dynamics with a reciprocal discussion. Indeed, participants' perceptions of how much they were influenced by the group discussion are significantly correlated to the mean absolute difference between their *pre-* and *post-discussion technology rankings* (Spearman's ρ=0.34, *p*=0.01), with a marginal correlation shown for the mean absolute difference between *pre-* and *post-discussion portfolio rankings* (Spearman's ρ=0.26, *p*=0.06).

5. DISCUSSION

Participants favored improved energy efficiency over the other technologies. 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.

We found that coal technologies with CCS were preferred over those without CCS. That is, both the advanced coal-based technology, IGCC, and the more traditional coal-based technology, PC, were preferred with CCS to the same technologies without. This preference was consistent with participants rating CO_2 as the most important attribute in their ranking decisions. Moreover, IGCC was preferred over PC, with or without CCS. While IGCC with CCS ranked just below energy efficiency, participants ranked the less-advanced PC with CCS lower than wind, biomass, energy efficiency, nuclear and natural gas. 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 *post-discussion* for the simple IGCC with CCS mix, while the simple PC with

CCS portfolio 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 were able to infer 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(53,54), more neutral names may 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 was preferred to a similarly composed portfolio without nuclear. In part, this preference may be explained by the title we gave to nuclear ("Advanced Nuclear") which described next-generation technologies (i.e., Generation III+ and IV reactors), that are inherently safer than those in operation in the U.S. today. However, it is also possible that this preference simply reflects public attitudes having become less unfavorable toward nuclear since the Three Mile Island accident in 1979, as suggested in recent polls.(55,56)

Our study presented participants with realistic low-carbon portfolios. Previous studies have shown that members of the general public prefer such portfolios to CCS(10, 19, 20, 24, 27) or nuclear(15, 16) in isolation. This preference may explain why participants' *CCS favorability ratings*, in which CCS was treated in isolation, were not correlated with their rankings of technologies or portfolios that included CCS. While *CCS favorability ratings* show only slightly positive opinions, participants' rankings place portfolios that include CCS consistently in the 'best' status. This suggests that participants' preference for CCS may be a relative one. A similar "reluctant acceptance" has been reported in other CCS perception studies(28), as well as in nuclear perception studies(16, 34). While the results reported by Palmgren et al.(19) were likely influenced by the limited information provided to respondents, and its lack of balance, it is also likely that the reported lack of acceptance of CCS and nuclear resulted from the fact that diverse portfolios were not included.

In the present study, participants' technology rankings were more highly correlated with the technology pollutant emissions, as opposed to the technology costs. This finding suggests that participants relied on quantitative pollutant information when making decisions about the acceptability of low-carbon technologies. It may explain why solar PV, which was almost five time more expensive than the other technologies, had a mean ranking above three of the four cheaper coal technology options provided to participants. PV was still only ranked as *significantly* better than PC. This relationship, in which pollution information was more important to participants than cost, did weaken when participants were asked to rank portfolios. One possible explanation for this pattern of results may be that participants began to realize that their optimal portfolio would require some tradeoffs. That is, they may have recognized that the portfolio with the lowest emissions levels might contain a technology they favored less.

One limitation of our study is that it used a local convenience sample from the Pittsburgh Metropolitan area. Thus, firm conclusions cannot be drawn about public perceptions of these low-carbon technologies and portfolios in other locations or in areas surrounding a proposed energy infrastructure site. Another limitation concerns the presentation of a restricted set of portfolios. While these portfolios do represent a realistic and diverse set of the possible options for de-carbonizing future electricity expansion for the U.S. in the next few decades, we plan to allow respondents to construct their own internally consistent portfolios with the aid of a computer tool in future studies.

Our results contrast starkly with those of previous studies on public perceptions of CCS(19, 25) and nuclear(16, 34), in the sense that our participants seemed less reluctant to accept these technologies. The main difference between our study and previous ones is that our participants were given balanced and comparative information about the costs, risks, benefits and limitations of different low-carbon portfolios and technologies along with adequate time to study each and discuss them with other members of the general public.

As noted above, our materials were developed with elaborate input from both domain experts and members of the lay public, to ensure that the information given to participants was important and easy to understand. As a result, our participants probably made more informed decisions about their rankings than did participants in previous studies. Indeed, our participants appear to have understood the materials well, as indicated by their scores on knowledge questions about the materials, and by the fact that they rated them as easy to understand even before they were explained by the experimenter. Our participants placed high importance on CO_2-related information, showing that they understood the underlying objectives in the ranking exercise. Furthermore, the high degree of agreement between participants' rankings suggests that participants consistently interpreted these objectives in the same manner. Finally, participants seemed satisfied with the group discussion, reporting positive group dynamics and reciprocal interactions. These findings suggest that the format of our information materials and the procedure followed by participants, both based on insights gained from previous studies(37, 39), may work well both to educate the general public about the challenges of attaining a low-carbon energy future and, to elicit decision-relevant, informed public perceptions and preferences.

While members of the general public do not explicitly get to make decisions about U.S. energy policy such as those presented in this study, their understanding of the limitations and issues presented in achieving a low-carbon energy future is important to the timely and successful adoption of CO_2 emissions regulations in the U.S. The results of this study suggest that once they have understood the alternatives and their limitations, members of the general public will likely be more willing to accept CCS, nuclear and other low-carbon technologies as part of a low-carbon portfolio than previous research has suggested.

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[1] Statistics presented in this format denote (mean ± standard deviation).

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

Portfolio	Technology Composition
A: PC with CCS mix	81% PC Plants *with* CCS technologies 19% PC Plants
B: IGCC with CCS mix	83% IGCC Plants *with* CCS technologies 17% IGCC Plants
C: Nuclear mix	70% Advanced Nuclear Plants 30% PC Plants
D: EPRI PRISM *limited* portfolio, with no Nuclear or CCS	66% Natural Gas Plants 13% Energy Efficiency 10% Wind Power 6% Biomass Plants 5% Solar PV Power
E: EPRI PRISM *semi-limited* portfolio, 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: EPRI PRISM *full* portfolio, 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

Table II. Participants' mean importance ratings ± standard deviation for the information materials, on a scale from 1 (not important at all) to 7 (extremely important).

Information Materials	*Pre-explanation*	*Post-explanation*	*Post-discussion*
Pollution Comparison for Combinations	—	6.04 ± 1.12	5.98 ± 1.15
Pollution Comparison	6.02 ± 1.26	—	5.90 ± 1.24
Cost Comparison for Combinations	—	5.69 ± 1.38	5.78 ± 1.25
Technology Description Sheets	6.18 ± 0.92	5.50 ± 1.53***	5.57 ± 1.50
Cost Comparison	5.49 ± 1.35	—	5.54 ± 1.40

Notes: Those materials that were rated as significantly less important *post-explanation* and *post-discussion* are noted as such: *** for $p<0.001$; Ratings are ordered by *post-discussion* rating. *Pre-explanation* ratings were not reported for the portfolio materials and *post-explanation* were not reported for the quantitative technology comparisons.

Table III. Participants' mean importance ratings ± standard deviation for the *Technology Description Sheets'* attributes, on a scale from 1 (not important at all) to 7 (extremely important).

Attributes	*Pre-explanation*	*Post-explanation*	*Post-discussion*
CO_2 released	6.25 ± 1.02	$5.88 \pm 1.53^{+}$	5.44 ± 1.72*
Other Pollution/Waste	6.12 ± 1.03	5.83 ± 1.28	5.63 ± 1.50
Safety	5.78 ± 1.38	5.27 ± 1.56**	$4.96 \pm 1.79^{+}$
Limits of Use	5.59 ± 1.30	$5.10 \pm 1.54^{+}$	4.94 ± 1.66
Reliability	5.57 ± 1.25	5.35 ± 1.41	5.26 ± 1.64
How it Works	5.43 ± 1.63	5.12 ± 1.61	5.06 ± 1.69
Availability	5.39 ± 1.23	5.37 ± 1.27	5.26 ± 1.64
Cost	5.30 ± 1.39	5.53 ± 1.38	5.45 ± 1.60
Lifespan	5.25 ± 1.40	5.06 ± 1.70	$4.76 \pm 1.80^{+}$
Current Use	4.63 ± 1.52	4.62 ± 1.85	4.66 ± 1.73
Noise	3.92 ± 1.75	4.08 ± 2.00	4.09 ± 1.96

Note: Those attributes that were rated as significantly less important *post-explanation* and *post-discussion* are noted as such: ** for $p<0.01$, * for $p<0.05$ and $^{+}$ for $p<0.10$. Ratings for the attribute of *Land Use and Ecology* were not reported by participants.

Table IV. Participants' mean importance ratings ± standard deviation for the pollutants in the *Pollution Comparison*, on a scale from 1 (not important at all) to 7 (extremely important).

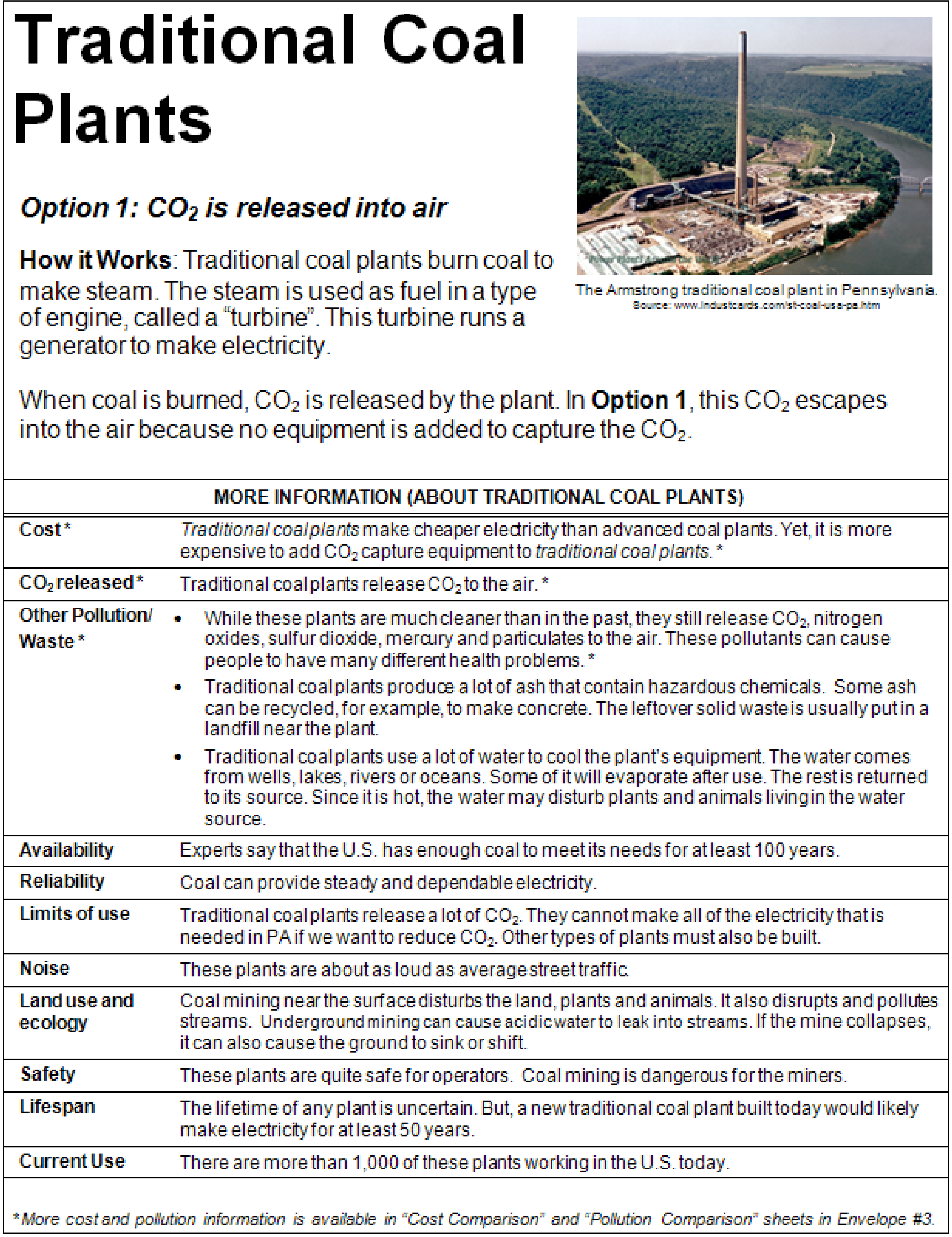
Pollutants	*Pre-explanation*	*Post-discussion*
CO_2	5.90 ± 1.50	5.63 ± 1.46
Nitrogen Oxide	5.76 ± 1.53	5.48 ± 1.34
Sulfur Dioxide	5.59 ± 1.51	5.46 ± 1.40
Mercury	5.47 ± 1.59	5.57 ± 1.51
Particulate Matter	5.33 ± 1.63	5.41 ± 1.52

Table V. Participants' mean comprehension ratings ± standard deviation for the information materials, on a scale from 1 (very hard) to 7 (very easy).

Technology Information Materials	*Pre-explanation*	*Post-explanation*	*Post-discussion*
Introduction	6.26 ± 1.20	6.02 ± 1.33	6.34 ± 0.94**
Technology Description Sheets	5.90 ± 1.15	6.16 ± 1.09^{+}	6.15 ± 1.03
Problem Question	5.74 ± 1.55	6.00 ± 1.25	6.06 ± 1.28
Pollution Comparison	5.43 ± 1.41	5.90 ± 1.19*	6.15 ± 0.91*
Cost Comparison	5.23 ± 1.60	5.82 ± 1.20**	6.23 ± 0.85**
Portfolio Information Materials	*Pre-explanation*	*Post-explanation*	*Post-discussion*
Cost Comparison for Combinations	—	6.00 ± 1.30	6.13 ± 1.00
Power Plant Combination Pie Charts	—	5.98 ± 1.26	6.17 ± 0.96
Pollution Comparison for Combinations	—	5.98 ± 1.16	6.13 ± 0.98
New Problem Question	—	5.84 ± 1.39	6.15 ± 1.10*

Note: Those materials that were rated as significantly easier *post-explanation* and *post-discussion* are noted as such: ** for $p<0.01$, * for $p<0.05$ and $^{+}$ for $p<0.10$; *Pre-explanation* ratings were not measured for the portfolio materials

Figure 1. One of the 10 *Technology Description Sheets* provided to participants on 8.5”x11” paper. This sheet is for pulverized coal without CCS, the baseline technology in the study. All other sheets adopted the same format and reported on the same set of attributes. The full set of materials used in the study is available at: http://sds.hss.cmu.edu/risk/fleishman/LowCarbonPortfolioMaterials.html



Traditional Coal Plants

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.

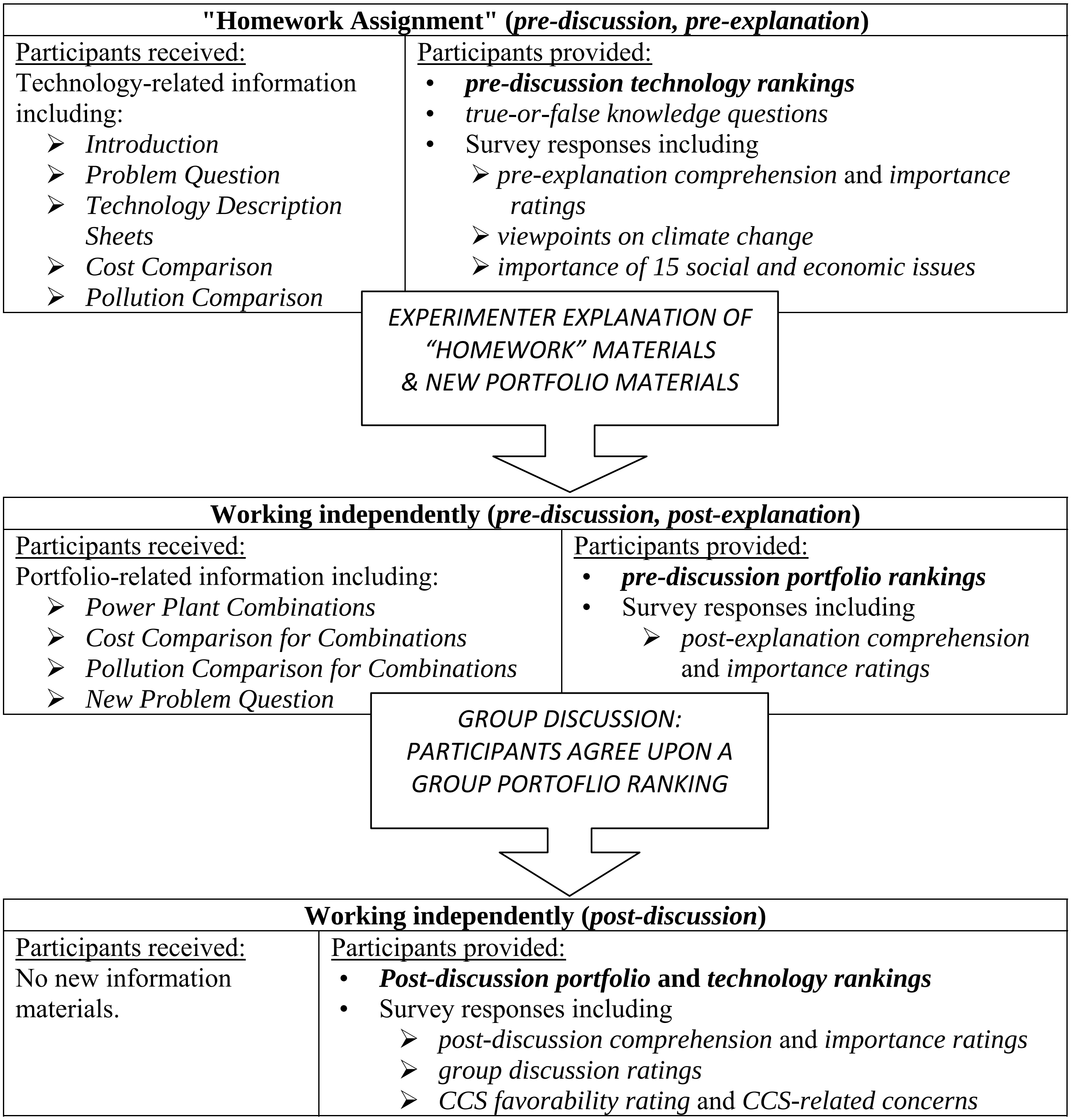
The Armstrong traditional coal plant in Pennsylvania.
Source: www.industcards.com/st-coal-usa-pa.htm

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.*

Figure 2. Summary of the experimental design and tasks completed by participants, beginning with individual homework and ending with a group workshop. Materials received by participants are listed in the left-hand boxes, tasks they performed are listed in the right-hand boxes.



"Homework Assignment" (*pre-discussion, pre-explanation*)

Participants received:
Technology-related information including:
- *Introduction*
- *Problem Question*
- *Technology Description Sheets*
- *Cost Comparison*
- *Pollution Comparison*

Participants provided:
- ***pre-discussion technology rankings***
- *true-or-false knowledge questions*
- Survey responses including
  - *pre-explanation comprehension* and *importance ratings*
  - *viewpoints on climate change*
  - *importance of 15 social and economic issues*

EXPERIMENTER EXPLANATION OF "HOMEWORK" MATERIALS & NEW PORTFOLIO MATERIALS

Working independently (*pre-discussion, post-explanation*)

Participants received:
Portfolio-related information including:
- *Power Plant Combinations*
- *Cost Comparison for Combinations*
- *Pollution Comparison for Combinations*
- *New Problem Question*

Participants provided:
- ***pre-discussion portfolio rankings***
- Survey responses including
  - *post-explanation comprehension* and *importance ratings*

GROUP DISCUSSION: PARTICIPANTS AGREE UPON A GROUP PORTOFLIO RANKING

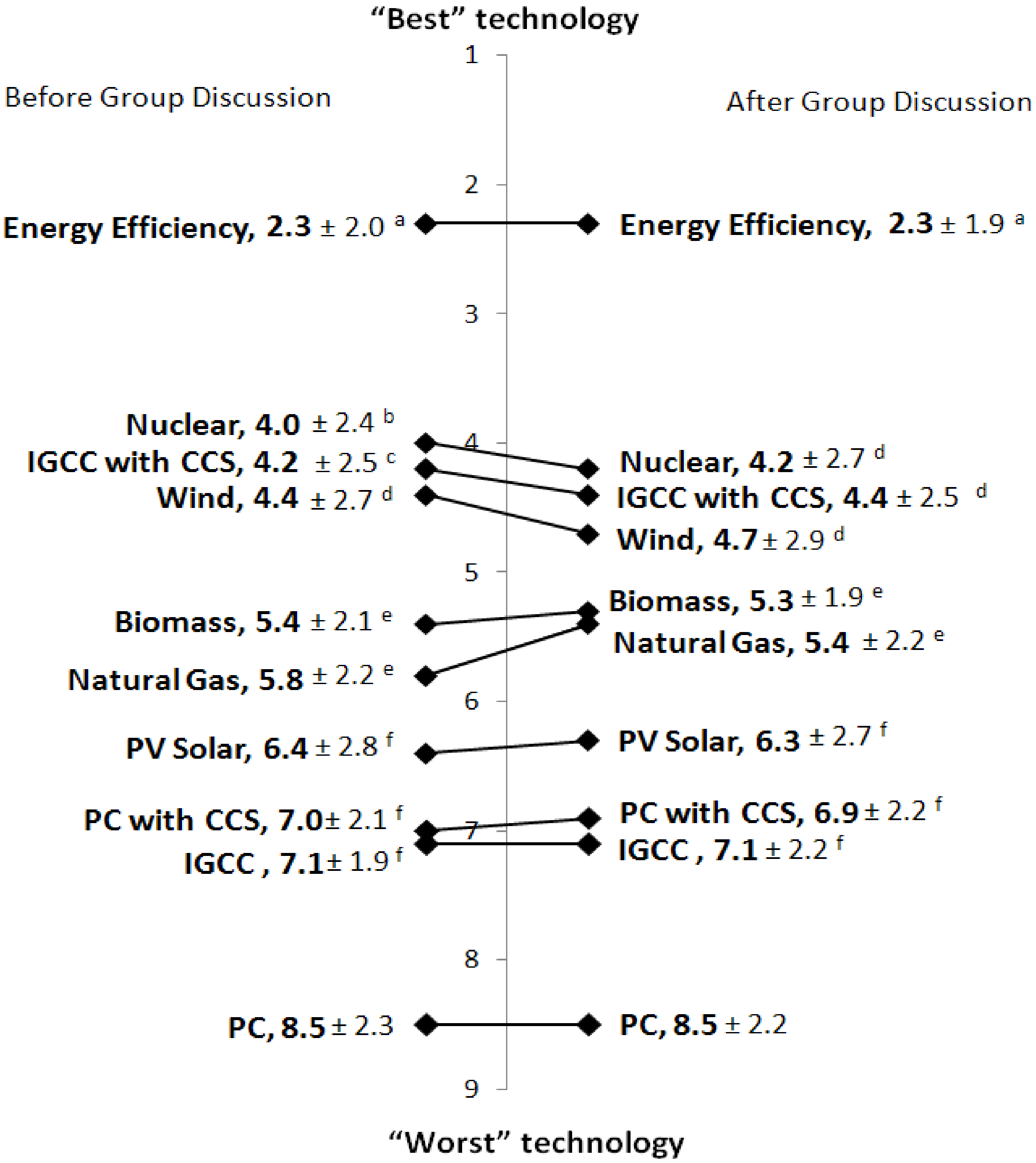
Working independently (*post-discussion*)

Participants received:
No new information materials.

Participants provided:
- ***Post-discussion portfolio* and *technology rankings***
- Survey responses including
  - *post-discussion comprehension* and *importance ratings*
  - *group discussion ratings*
  - *CCS favorability rating* and *CCS-related concerns*

Notes: Participants provided rankings before and after the group discussion (*pre-* and *post-discussion*, respectively). Participants provided ratings before and after the experimenter's explanation (*pre-* and *post-explanation,* respectively), and again after the group discussion (*post-discussion).*

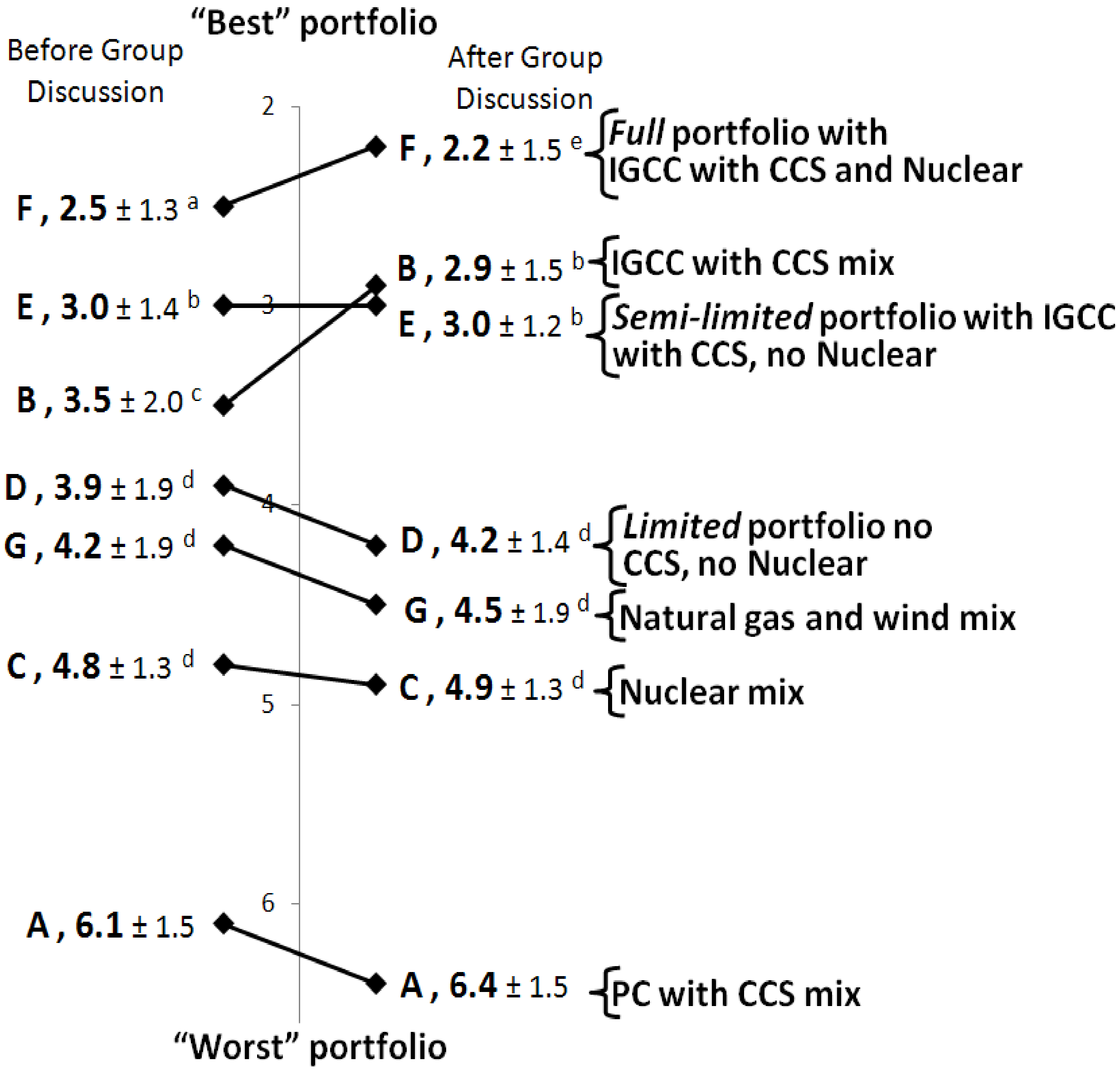
Figure 3. Participants' mean technology rankings ± standard deviation, *pre-* (left) and *post-discussion* (right), where 1 is the "best" and 10 is the "worst".



Note: Superscripted letters next to mean technology ranking indicate those technologies that ranked significantly worse at $p<0.01$, using a two-tailed Wilcoxon paired-rank test, where

a: all other technologies were ranked significantly worse
b: biomass, natural gas, PV, PC with CCS, IGCC and PC were ranked significantly worse
c: natural gas, PV, PC with CCS, IGCC and PC were ranked significantly worse
d: PV, PC with CCS, IGCC and PC were ranked significantly worse
e: PC with CCS, IGCC and PC were ranked significantly worse
f: PC was ranked significantly worse

Figure 4. Participants' mean portfolio rankings ± standard deviation, *pre*- (left) and *post*-discussion (right), where 1 is the "best" and 7 is the "worst".



Note: Superscripted letters next to mean portfolio ranking indicate those portfolios that ranked significantly worse at $p<0.01$, using a two-tailed Wilcoxon paired-rank test, where

a: portfolios B, D, G, C and A were ranked significantly worse
b: portfolios D, G, C and A were ranked significantly worse
c: portfolios C and A were ranked significantly worse
d: portfolio A was ranked significantly worse
e: portfolios E, D, G, C and A were ranked significantly worse