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Informed Public Choices for Low-Carbon Electricity Portfolios Using a Computer Decision Tool

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KEYWORDS: low-carbon energy, public decision-making, interactive decision tool

ABSTRACT

Reducing CO_2 emissions from the electricity sector will likely require policies that encourage the widespread deployment of a diverse mix of low-carbon electricity generation technologies. Public discourse informs such policies. To make informed decisions and to productively engage in public discourse, citizens need to understand the tradeoffs between electricity technologies proposed for widespread deployment. Building on previous paper-and-pencil studies, we developed a computer tool that aimed to help non-experts make informed decisions about the challenges faced in achieving a low-carbon energy future. We report on an initial usability study of this interactive computer tool. After providing participants with comparative and balanced information about ten electricity technologies, we asked them to design a low-carbon electricity portfolio. Participants used the interactive computer tool, which constrained portfolio designs to be realistic and yield low CO_2 emissions. As they changed their portfolios, the tool updated information about projected CO_2 emissions, electricity costs, and specific environmental impacts. As in the previous paper-and-pencil studies, most participants designed diverse portfolios that included energy efficiency, nuclear, coal with carbon capture and sequestration, natural gas and wind. Our results suggest that participants understood the tool and used it consistently. The tool may be downloaded from http://cedmcenter.org/tools-for-cedm/informing-the-public-about-low-carbon-technologies/.

Keywords: low-carbon energy, public decision-making, computer decision tool

1. INTRODUCTION

Reducing CO_2 emissions from the electricity sector will likely require policies that combine improved energy efficiency with the widespread deployment of a diverse mix of low-carbon electricity generation technologies such as natural gas, renewables, nuclear power, and coal with carbon capture and sequestration (CCS). In the United States, proposed policies have been much debated and subsequently stalled in the U.S. Congress.[1-3] Such debates tend to receive ample media attention, and become influenced by public opinion.[4] However, policy-makers need to know in somewhat greater detail which climate change mitigation policies have the most public support. Therefore, a great deal of public perception research aims to measure people's preferences for low-carbon alternatives, with the goal of informing climate policy.[5-8] To be effective, public discourse about low-carbon electricity policy should be based on informed public perceptions about low-carbon technologies.

Yet many non-experts remain relatively uninformed about the costs, benefits and limitations of low-carbon electricity generating technologies.[5,9-13] For example, many fail to recognize that wind and solar power have limited ability to meet electricity demand due to intermittency,[12,14] and dramatically underestimate the cost of solar power.[13] Lay people also mistakenly believe that nuclear plants emit CO_2 and contribute to climate change[5,9] and that CCS could result in "burps" of CO_2 from underground that could cause suffocation.[11,15,16] These misconceptions and knowledge gaps are problematic because studies show that uninformed participants tend to report technology preferences that are unrealistic (i.e., not consistent with the capabilities of current electricity generation systems)[7,16] and unstable (i.e., based on labile opinions that are inconsistent with a person's full set of values).[6,17] Informed participants could be expected to provide preferences that are more realistic, more representative of their values, and, therefore, more useful to policy-makers.[15,17-19]

In order to improve people's understanding and promote more informed public debate, researchers have called for a move from public perception surveys to more deliberative studies that provide participants with more detailed information.[17,20] This has been shown to help study participants form more informed preferences.[8] However, most studies have provided this information using static text, tables and figures that do not allow them to engage in a 'learning-by-doing' exercise. In contrast, interactive decision tools allow people to actively explore how different choices in the tool's input variables affect a number of outcomes of interest. These types of interactive decision tools have been shown to improve knowledge,[21,22] reduce decisional conflict (i.e., feeling uninformed, unclear about values, and unsupported in decision-making),[23,24] improve aspects of decision-making[25] such as confidence and stability,[26] engage attention and transmit information better[27,28] and improve agreement between people's values and their choices.[22]

In a previous paper-and-pencil study,[8] we provided comprehensive and carefully balanced materials that explained the costs and benefits of a set of technologies (e.g., coal with CCS, natural gas, nuclear, various renewables and energy efficiency) to lay participants and subsequently asked them to rank the technologies as well as a restricted set of seven realistic low-carbon portfolios composed of these technologies. Although this study suggested the feasibility of providing comprehensible information about low-carbon technologies, participants were not able to interact with the information so as to reveal the explicit association between different technologies and their risks, costs and benefits. In addition, the seven portfolio choices available to participants represented a restricted subset of possible technology combinations – thus limiting participants' choices. In the study reported here, we rectified these limitations by developing a computer decision tool that allowed lay respondents to interact with the technology information by constructing electricity portfolios and choosing their preferred low-carbon electricity portfolio. As participants changed their portfolios, the tool updated information about projected CO_2 emissions, electricity costs, and health, land, and water impacts. This study builds upon our initial work by elucidating public low-carbon portfolio preferences from a realistic set of choices, constrained only by physical feasibility. Perhaps more importantly, the work illustrates that the computer tool may have value in educating the general public about the challenges we face in achieving a low-carbon energy future, as well as in supporting public debate about the most promising portfolios.

The design of the computer tool, as well as supplementary materials provided to participants were informed by previous research,[8] using the mental models approach for designing communications.[29] The mental models approach uses four systematic steps with the goal of developing communication materials that provide relevant information in understandable terms: (1) identify what people should know about the topic under consideration, through an interdisciplinary literature review and input from diverse experts (expert model), (2) identify what people already know and the wording they choose to describe what they know, through open-ended interviews (lay model), (3) design communication materials to address key gaps and misconceptions in people's knowledge, as identified by a comparison of lay and expert knowledge characterized in the previous steps, as well as any additional decision-relevant concerns that interviewees shared, in wording borrowed from the interview transcripts and (4) iteratively refining the content based on domain expert evaluations to ensure balance and accuracy, as well as input from intended audience members, to ensure their understanding.[29] The mental models methodology has been applied to understand people's decision-making and information needs about a wide variety of topics including climate change,[9,29-31] hurricane modification,[32] smart meters for their homes,[33] avian flu,[34,35] sexually transmitted diseases,[25,36] and vaccines.[37]

In our previous work, we used the mental models approach to develop detailed communication materials to inform public preferences about ten technologies (e.g., coal with and without CCS, natural gas, nuclear, renewables, and energy efficiency), and seven restricted low-carbon portfolios that were constructed for Pennsylvania (where we recruited participants) to meet the state's increasing future electricity demands.[8] After being asked to assume that the U.S. Congress had mandated a 50% reduction in CO_2 emissions from power plants built in the future, the participants in our previous study[8] used paper-and-pencil methods to rank the technologies and several pre-specified portfolios. Participants displayed a basic understanding of the materials, which improved further over the course of the study. Overall, these informed participants preferred, in order: energy efficiency, nuclear, integrated gasification combined-cycle coal (IGCC) with CCS and wind. Their rankings of the seven portfolios showed consistency with these technology preferences, and reflected a preference for diversity.

Here, we present the findings of an initial study that tested the usefulness of the computer-based tool that allowed participants to design their own low-carbon portfolios, restricted only by technology-specific physical and engineering limitations. Participants first received systematic information based on available data through July 2010, about ten electricity technologies. As a “homework” exercise, participants ranked the technologies. Subsequently, they attended small group meetings held in their community in February and March of 2011. Before and after group discussions, they used an interactive portfolio-building computer tool (Figure 1) to build multiple portfolios that could meet an electricity goal of generating 60 terawatt-hours of electricity per year for Pennsylvania while reducing CO_2 emissions by 50% relative to a status quo scenario. The computer tool and information materials are available for download at http://cedmcenter.org/tools-for-cedm/informing-the-public-about-low-carbon-technologies/.

To assess people’s preferences for low-carbon electricity generation technologies, we analyzed participants' (1) technology rankings and the composition of the low-carbon portfolios they designed. To assess whether people could use the tool productively, we examined (2) whether their portfolio preferences were consistent with their degree of pro-environmental attitudes; (3) whether their portfolio preferences were consistent with their technology preferences, and over time; and (4) their comprehension of and satisfaction with the materials and computer tool.

2. METHODS

2.1. Materials

Our informational materials described ten electricity-generating technologies that could realistically be constructed in Pennsylvania (where we recruited participants) to meet increased electricity demand over the next 25 years: (1) five coal-based technologies, including pulverized coal (PC) and integrated gasification combined-cycle coal (IGCC), both with and without CCS, as well as pulverized coal co-fired with 10% biomass (switchgrass); (2) natural gas combined cycle; (3) nuclear plants (generation III+ or IV); (4) two renewable technologies—modern wind turbines, and utility-scale photovoltaic (PV) solar; and (5) reduced electricity consumption through the promotion of greater energy efficiency. Each technology was described on a separate Technology Sheet (see Supporting Information). To facilitate comparisons between these technologies, each sheet systematically described the same attributes: How it works, Availability, Reliability, Limits of use, Current Use, Safety and Environmental Impacts.

Technologies were also systematically compared on 11"x17" comparison sheets that presented graphs and text describing their Pennsylvania-specific respective CO_2 emissions and annual electricity generation, Health, Water and Land Impacts, and estimated residential electricity cost (see Supporting Information). Direct CO_2 emissions for fossil fuel plants were obtained using the Integrated Environmental Control Model (IECM),[38-40] augmented by assumptions from Mann and Spath.[41] Presenting direct CO_2 emissions was chosen over lifecycle emissions to simplify the already complex information presented to participants. Health costs were calculated using direct NO_x, SO_2 and PM values from IECM[38] and health damage data (dollars per ton of NO_x, SO_2 and PM emissions) obtained from the National Research Council report The Hidden Cost of Energy.[42] Water and land use values were obtained from Fthenakis and Kim.[43,44] Finally, residential electricity costs were calculated as levelized cost of electricity in 2008 $USD using values from Lazard Ltd.,[45] the U.S. Energy Information Administration,[46,47] and data from many other sources,[39,48-50] which are based on the current fixed and variable costs of technologies and do not account for potential cost efficiencies in the future. See the Supporting Information for details of all calculations and assumptions.

We used the mental models approach to design our informational materials.[29] A technical literature review identified the information that engineering, environmental science and energy policy experts deemed most relevant for evaluating these technologies. An additional literature review of public perception research helped us to identify the topics about which people have misconceptions and knowledge gaps. The multi-attribute descriptions of the technologies therefore targeted the information that the lay public most need to know about low-carbon electricity technologies. Materials were iteratively reviewed by lay participants to assure that they were understandable and were revised with subject-matter and energy policy experts to ensure accuracy and balance.[29,51,52] For the latter, we asked experts for individual feedback on the materials, as well as by convening a group of experts who have published extensively in the areas of fossil fuel technologies, CCS, renewables and energy efficiency to discuss the calculations and assumptions used to generate the quantitative information. Expert comments were reflected in the materials if feasible; when disagreement occurred between experts, this was noted. Any remaining errors are those of the authors. All information was written at a 6th to 8th grade reading level, as reflected in the Flesch-Kincaid Grade Level readability statistic.[53,54]

Participants were also presented with a MS Excel-based portfolio-building computer decision tool that they could manipulate with the use of sliders on a user interface (see Figure 1). This tool was designed to build upon the information materials and was pilot-tested in a similar manner.[29, 51,52] Portfolio designs were limited by two constraints. First, the tool required direct CO_2 emissions to be at least 50% less than emissions from the status quo scenario, which described Pennsylvania as increasing capacity in a similar ratio to what exists today (i.e., approximately 50% of electricity generation from PC plants, 35% from nuclear plants, 14% from natural gas plants and 1% from wind farms). Second, the tool required the design of low-carbon portfolios that could annually generate an additional 60 terawatt-hours of electricity for Pennsylvania (i.e., to meet the expected 1% annual increase in electricity demand for the next 25 years).[55] Electricity reliability (i.e., a non-intermittent, predictable electricity supply) was achieved by following every watt of an intermittent renewable technology (i.e., wind and PV solar) included in the portfolio with an automatic addition of a watt of natural gas plant capacity.[56] Energy efficiency was also constrained to 20% of a participants' portfolio,[49] while PC plants co-fired with biomass were limited to 18% due to limitations on growing switch-grass in Pennsylvania.[57] The inclusion of all other technologies was only limited by the CO_2 emissions constraint.

As participants varied the percent of technologies in their portfolio (using the Build Center in Figure 1), they could observe the resulting changes in (1) CO_2 emissions and electricity generated (both in the Goal Center in Figure 1), (2) Annual Health Costs, Land Use and Annual Water Use (in the Impacts area in Figure 1) and (3) the increased cost in monthly electric bill and energy-driven increased cost-of-living (in the Cost area in Figure 1). Participants could then compare up to three self-selected portfolios on a separate screen (see Supporting Information), which presented a comparison across their CO_2 emissions, increased cost in monthly electric bill, annual health costs, land use and annual water use.

2.2. Participants

Our initial study of the computer tool was conducted with a diverse sample of 69 participants who were recruited through community organizations in the Greater Pittsburgh Metropolitan Area. Participants were 22 to 85 years old (mean = 53.9, median=58). Of these, 70% were female, and 13% nonwhite, almost all of whom were African American. All had graduated from high school, and 58% had completed at least a Bachelor’s degree. Sixty-five percent of our participants were registered Democrats, 22% were Republicans and 8% were Independents. The median annual household income of these participants was in the range of \$40,000–\$60,000. By comparison, the general Pittsburgh population is younger (median=33.2), less female (51.6%), has a larger nonwhite population (34%), has less education (34.4% with a Bachelor’s degree or higher) and has a lower median income (\$37,161).[58]

2.3. Procedure

After signing up for our initial computer-tool evaluation study, participants received “homework” materials by mail. They were presented with an introduction about climate change, the summary sheets on the various technologies (see Supporting Information), and the following problem question: “Today, the power plants in Pennsylvania (PA) make about 225 terawatt-hours (TWh) of electricity each year… In 25 years, the power plants in PA will need to make about 285 TWh of electricity each year to keep up with [increasing energy] demands. So, new plants will need to be built. These new power plants will make the additional 60 TWh of electricity that PA needs each year…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 … power plants [built in PA over the next 25 years] will collectively need to release 50% less CO_2 [than a status quo scenario]. 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 power plant types from best to worst."

After ranking the technologies from best (=1) to worst (=10), participants answered 24 true-or-false knowledge questions about these homework materials, focusing on those issues that had been most commonly misunderstood in the pilot tests described previously. Participants then rated their agreement with the 15 environmental statements appearing on Dunlap et al.'s[59] new ecological paradigm (NEP) scale, with responses anchored at completely disagree (=1) and completely agree (=7). Subsequently, participants attended small group meetings, which were held in their community. We conducted ten of these meetings, each lasting 2.5 to 3.5 hours and involving four to nine participants. The sessions carefully followed a script adapted from previous research.[8,60,61] 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 were introduced to the computer tool (Figure 1) through an initial presentation and a subsequent step-by-step exercise. Prior to using the computer tool on their own, participants answered a computer knowledge test, which measured their understanding of the computer tool by asking them to follow instructions to use the computer tool and then to report on the resulting output values (e.g., CO_2 emissions, electricity cost, annual water use, etc.) on the computer screen.

Finally, participants were provided with an updated user task to “build a combination of new power plants that you think is the best. The combination must make 60 TWh of electricity per year, but release 50% of the CO_2 that would have been released [under the status quo scenario presented previously in this paper].” Subsequently, participants used the computer tool to build three portfolios. After comparing these portfolios, they selected one most preferred portfolio, based on which we determined their pre-discussion technology percentages.

Next, participants engaged in a group discussion, sharing their chosen portfolio, and their opinions about the technologies. The experimenter created each participant’s portfolio on a computer tool that was projected onto a screen. A comparison of all participants’ portfolios in the group was then shown on the projected screen.

Subsequently, participants were given the opportunity to review and revise their personal portfolios, which provided our measure of their post-discussion technology percentages. Finally, they completed satisfaction ratings (e.g., “using the computer tool was an enjoyable experience,” “I learned a great deal about different electricity options from this study,” etc.) to indicate what they thought of the computer tool and the overall study, anchored on a scale from completely disagree (=1) to completely agree (=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

Below, we assess people's responses to communication materials about low-carbon technologies by first reporting on (1) people's preferences for low-carbon electricity generation technologies, as expressed as part of the 'homework' ranking exercise and with the computer tool. To assess whether people could use the tool productively, we examined (2) whether their expressed preferences were consistent with their pro-environmental attitudes; (3) whether their expressed preferences were consistent with their technology preferences and over time; (4) their comprehension of and satisfaction with the materials and computer tool

3.1. Preferences for Low-Carbon Electricity Generation Technologies

First, we examined participants' preferences for electricity generation technologies. As displayed in Figure 2, participants' mean technology rankings suggest that on average, they most preferred energy efficiency, nuclear, integrated gasification combined-cycle coal (IGCC) with CCS and natural gas. We used Wilcoxon paired-rank tests, a non-parametric version of the paired-sample t-test designed for use with rankings,[63] to examine whether there was a significant difference in participants' rankings for each possible pair of technologies. The superscripted letters in Figure 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 α=0.01. The tests suggested that preferences among the four most preferred technologies (i.e., energy efficiency, nuclear, IGGC with CCS and natural gas) were not significantly different from one another, but all these technologies were preferred to PV solar, IGCC, PC with biomass and PC. Perhaps most notably, three of the four low-carbon baseload technologies (i.e., nuclear, IGCC with CCS, and natural gas) were preferred significantly to the renewable technology photovoltaic (PV) solar. By comparison, coal technologies without CCS (i.e., IGCC, pulverized coal (PC), and PC with biomass) ranked as the three least preferred.

Next, we examined participants' preferences for low-carbon electricity portfolios composed of the ten technologies. We evaluated participants' portfolio designs by computing the percent of each technology included in their portfolio (i.e., technology percentage), as part of the maximum percent allowable for that technology. These maximums were constrained in the computer tool by an enforced policy to limit CO_2 emissions or by realistic technical limitations of the specific technology. The resulting standardized technology percentages had a possible range between 0 and 100, where 0 represents the exclusion of that technology from the portfolio and 100 represents the maximum allowable inclusion of that technology in the portfolio. Figure 3 shows participants' mean standardized technology percentages, as reported pre-discussion (left) and post-discussion (right). The superscripted letters in Figure 3 indicate, for each technology, the other technologies with significantly less standardized technology percentages. Due to the large number of these comparisons, we only report those that are significant at $\alpha=0.01$. The overall pattern of portfolio preferences was in line with the technology rankings shown in Figure 2, with energy efficiency being included most in portfolios, both pre- and post-discussion. This inclusion was significantly larger than that of all other alternatives post-discussion, while the standardized technology percentages for energy efficiency and nuclear were not significantly different from one another in the pre-discussion portfolios. The second largest standardized technology percentage was nuclear power, followed by natural gas, IGCC with CCS, wind and PC with CCS — which, respectively, had the third through sixth largest standardized technology percentages, on average, both pre- and post-discussion. The remaining four technologies (PC, solar PV, IGCC and PC with biomass) had the smallest standardized technology percentages and were not significantly different from one another.

Portfolio designs showed relatively good agreement across participants, as seen in Kendall's coefficient of concordance (W) across the rank-orderings of the ten technology percentages (pre-discussion, $W=0.57$, $p<0.001$; post-discussion, $W=0.61$, $p<0.001$). The most frequently chosen portfolio included a diverse combination of energy efficiency, nuclear, natural gas, coal with CCS and wind (31% of participants chose it pre-discussion, 38% chose it post-discussion). Although participants' portfolios could only meet the CO_2 emissions and electricity generation goals of the computer tool if they included one of the low-carbon baseload technologies in their portfolio (i.e., coal [IGCC or PC] with CCS, nuclear or natural gas), it is notable that a majority of participants (58.2% pre-discussion and 60.3% post-discussion) actually included all three. These results are in line with their technology rankings, which also showed strong preferences for these low-carbon baseload technologies.

3.2 Consistency of Preferences with Environmental Attitudes

Participants' responses to the 15 NEP scale ratings were scored such that higher ratings reflected stronger pro-environmental attitudes. Participants' mean NEP scale ratings ($M=5.00$, $SD=0.83$) had high internal consistency (Cronbach's $\alpha=0.83$), and were significantly above the scale midpoint of 4 (t=9.70, p<0.001), suggesting pro-environmental attitudes. Spearman rank correlation between NEP scale ratings and participants' technology rankings (reverse coded for these analyses, such that higher numbers reflect higher preference) suggest that participants who were more pro-environmental preferred PV solar (r_s=0.29, p=0.02), while less pro-environmental participants preferred PC with CCS (r_s=0.28, p=0.02). NEP scale ratings, however, were not significantly correlated to participants' technology percentages (Pears*on's r*<0.20, p>0.10, both pre- and post-discussion).

3.3. Consistency of Portfolio Designs with Technology Preferences and Over Time

Our results suggest that participants' portfolio designs were consistent with their technology preferences, and remained stable over time. Participants' portfolios were consistently aligned with their technology preferences, as seen in significant positive Spearman rank-order correlations between participants' technology rankings (reverse-coded for these analyses, such that higher numbers reflect a higher preference) and their technology percentages in their pre-discussion portfolios (all r_s>=0.26, p<=0.04), with the exception of PC with biomass (r_s=0.09, p=0.46), PC with CCS (r_s=0.22, p=0.08) and IGCC (r_s=0.09, p=0.46), which had correlations in the same direction.

Participants were able to use the computer tool consistently over time, creating similar portfolios across the two design exercises held in this study. Indeed, we found significant Pearson correlations between pre-discussion and post-discussion technology percentages (r>=0.56, p<0.001 for each of the ten technologies, with the exception of r=-0.003, p=0.78 for IGCC). Paired t-tests between participants' pre- and post-discussion technology percentages show no significant differences (all $p>0.10$), except for energy efficiency, which was included significantly more in post-discussion portfolio designs than in pre-discussion designs ($t=-3.10$, $p<0.01$).

3.4. Participant Comprehension and Satisfaction

Even before the group discussion, participants were found to understand the study materials. After completing the homework materials, participants answered 24 true-or-false knowledge questions that focused on issues that had been most commonly misunderstood in our formative research on low-carbon technologies. They obtained an average score of 90% correct (SD=11%; range 46–100%), scoring significantly better ($t=28.2$, $p<0.001$) than chance performance due to pure guessing (i.e., 50% correct, with true/false statements). After the experimenter's explanation of the computer tool, participants answered a 13-question computer knowledge test, in which we measured their understanding of the computer tool by asking them to follow instructions to use the computer tool and then to report on the resulting output values (e.g., CO_2 emissions, electricity cost, annual water use, etc.) on the computer screen. They obtained an average score of 93% correct (SD=10%; range 62-100%) on this test, suggesting that they could correctly use the tool and understand its output. Participants also reported being satisfied with the computer tool. Their satisfaction ratings indicated that using the computer tool was "an enjoyable experience" (M=6.5, SD=1.0) on a scale from 1 (completely disagree) to 7 (completely agree), with the mean rating being significantly above the scale midpoint of 4 ($t=20.3$, $p<0.001$). Similarly, they reported that the tool was "a valuable use of [their] time" (M=6.3, SD=1.1, $t=17.9$, $p<0.001$), that they "learned a great deal about the different electricity options from the study" (M=6.4, SD=1.2, t=16.3, p<0.001), and that the information (1) covered the topics that they felt were "important about the electricity options," (M=6.1, SD=1.2, t=13.6, p<0.001), (2) "corrected some of [their] misconceptions about the electricity options" (M=5.3, SD=1.8, t=5.8, p<0.001) and (3) "filled in many of the gaps in [their] knowledge about the electricity options" (M=5.7, SD=1.7, t=8.3, p<0.001). For each of these assessments, t-tests showed that their mean was significantly above the scale midpoint, suggesting that participants felt generally favorable.

4. DISCUSSION

In this initial evaluation study of an interactive computer decision tool, our lay participants engaged in a 'learning-by-doing' exercise that apparently allowed them to make informed, deliberate, and internally consistent decisions about their portfolio designs. Indeed, participants scored very well on the knowledge tests of the paper materials and computer tool. After systematically comparing individual technologies and portfolios across costs, risks, benefits and limitations, our informed lay participants preferred energy efficiency, nuclear, IGCC with CCS, natural gas and wind, and designed diverse portfolios including these technologies. Their portfolio designs were consistent with their technology preferences and remained stable over the course of the study. These findings suggest that the computer tool and procedure elicited participants' informed opinions.[19] Moreover, participants' tended to be in agreement with each other about their portfolio designs. Similar to studies that show improved knowledge and reduced decisional conflict through use of interactive decision tools,[21-24] our participants' selfevaluations confirm that they believed they had learned a great deal from the study and that using the computer tool was an enjoyable and valuable use of their time. The overall comprehension and satisfaction reported by our participants suggest that the computer tool and supplemental materials may have value in educating the general public about the challenges we face in achieving a low-carbon energy future. The tool, which is available online at http://cedmcenter.org/tools-for-cedm/informing-the-public-about-low-carbon-technologies/, could easily be adapted for other educational settings, such as a science classroom or museum, or for web-based applications, and has been an active part of Carnegie Mellon University's Summer Center for Climate, Energy, and Environmental Decision-Making and Green Design Apprenticeship programs.

The finding that our participants were able to use the supplemental materials and computer tool productively to inform their decisions about low-carbon portfolios is indicative of the grounding of the underlying mental models methods used to develop both sets of communications. These methods are based on the foundations of prescriptive analysis, which aims to teach people how to make more informed decisions by comparing a normative model[62, 63] (how people should make decisions) to a descriptive model[64, 65] (how people actually make decisions), much in the same way that the mental models approach compares the expert and lay models.[29,63,64] In our previous work,[8] the expert model suggested that people should be evaluating low-carbon electricity technologies based on relevant attributes, while the lay models suggested, for example, that it was difficult and undesirable for them to evaluate a single technology in isolation. A prescriptive analysis of such findings led to our development of the computer tool and supplemental materials that considered both sets of decision models.

One limitation of our study is the infeasibility of presenting all relevant information about the technologies to our participants. By attempting to keep the materials succinct, we had to make judgments about the information to prioritize and the assumptions used. Thus, while we strove to present a balanced account of the costs, benefits and limitations of each electricity technology, some potential subjectivity was likely reflected in the development of the materials.

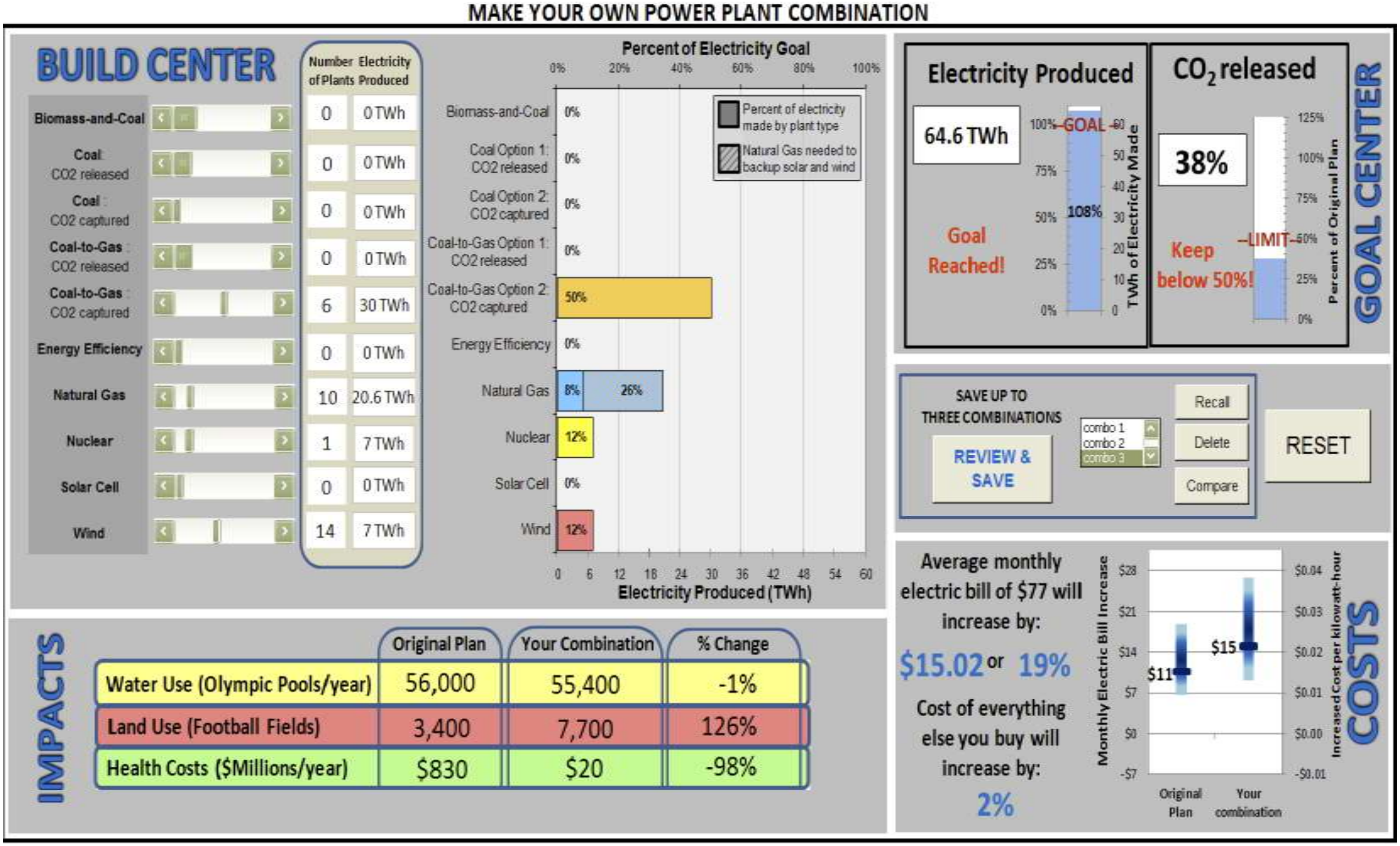
Another limitation is the use of a local convenience sample from the Pittsburgh Metropolitan area. Thus, our technology and portfolio preference results may not generalize to individuals recruited from other locations. While attaining generalizability would require randomly sampling from the Pittsburgh population or attempting to align sample demographics to that of the city, the results of the initial evaluation study presented here do suggest that our computer tool and materials gave participants a stable basic understanding, and may be useful for helping members of the lay public to make more informed decisions about which technologies to support for inclusion in a low-carbon electricity generation portfolio to be constructed in Pennsylvania in the next 25 years. The computer tool and materials may also be useful to inform policy-makers and other electricity decision-makers about general public choices for low-carbon technologies. However, the tool and materials are time and location-dependent. That is, the information presented was accurate for electricity generation in Pennsylvania in 2011. To be useful for education and decision support at the national scale, information would need to be adapted accordingly. Thus, caution should be taken when using the tool in its current form.

The tool's location dependency may also be relevant when informing people who live near specific energy infrastructure sites and may have different preferences and informational needs. This is possibly why our participants seemed to prefer nuclear and IGCC with CCS to many of the technology alternatives, while some local public perception studies suggest that people may not be as favorable to these technologies being developed in their backyard.[11,65,66] Another possible explanation for this preference over the other low-carbon alternatives of natural gas and renewables may be related to participants' attitudes toward Marcellus Shale natural gas drilling, which was becoming widespread during the time of our study.[67,68] Negative perceptions toward shale drilling in the Pittsburgh region may have led to natural gas, as well as the renewables that required the addition of natural gas in our model, to be less preferred. Finally, the preference of nuclear and IGCC with CCS may also be a result of our participants' showing a reluctant preference for these technologies. That is, while some of our participants may not have favorable opinions of nuclear or CCS when presented individually, they may still prefer low-carbon portfolios with a small amount of these technologies.[5,6,8]

Even after having learned from our homework materials, participants who held more pro-environmental attitudes ranked PV solar as better and PC with CCS as worse. That is appropriate given that they were well-informed about the technologies. Moreover, making good decisions (e.g., about which technologies to support) involves considering the tradeoffs of each alternative -- in light of one's own preferences.[69-71] Our materials and computer tool aim to improve recipients' knowledge and to facilitate more informed decisions, rather than influencing their preferences. That said, participants' portfolio designs showed no such pro-environmental attitude bias.

Furthermore, our participants' technology preferences were similar to those we found in our previous paper-based study that presented participants with only seven pre-determined portfolios.[8] In both studies, energy efficiency, nuclear and IGCC with CCS were the three most preferred technologies, while PC was consistently the least preferred. The most frequently designed portfolio by our participants includes a similar set of technologies (i.e., energy efficiency, nuclear, coal with CCS, natural gas and wind) to the most preferred portfolio in our previous study (i.e., a diverse portfolio with energy efficiency, nuclear, IGCC with CCS, natural gas, wind and PC).[8] While approximately two years elapsed between these two studies, both showed that informed participants preferred energy efficiency, nuclear, IGCC with CCS, natural gas and wind, and diverse portfolios including these technologies. These realistic portfolios are very similar to those recommended by most electricity and energy policy experts, who attest that there is no one silver bullet low-carbon electricity technology.[72,73] Instead, these experts recommend that achieving a 50-80% reduction in CO_2 emissions over the next few decades is going to take a combination of all available low-carbon technologies. Our participants were able to come to similar conclusions once they were given adequate information, time and the proper tools to inform their low-carbon energy policy decision.

FIGURES



MAKE YOUR OWN POWER PLANT COMBINATION

BUILD CENTER

	Number of Plants	Electricity Produced
Biomass-and-Coal	0	0 TWh
Coal: CO2 released	0	0 TWh
Coal: CO2 captured	0	0 TWh
Coal-to-Gas: CO2 released	0	0 TWh
Coal-to-Gas: CO2 captured	6	30 TWh
Energy Efficiency	0	0 TWh
Natural Gas	10	20.6 TWh
Nuclear	1	7 TWh
Solar Cell	0	0 TWh
Wind	14	7 TWh

IMPACTS

	Original Plan	Your Combination	% Change
Water Use (Olympic Pools/year)	56,000	55,400	-1%
Land Use (Football Fields)	3,400	7,700	126%
Health Costs ($Millions/year)	$830	$20	-98%

GOAL CENTER

Electricity Produced: 64.6 TWh

Goal Reached!

CO_2 released: 38%

Keep below 50%!

SAVE UP TO THREE COMBINATIONS

COSTS

Average monthly electric bill of $77 will increase by:

$15.02 or 19%

Cost of everything else you buy will increase by:

2%

Figure 1. Screen shot of the Portfolio-Building Computer Decision Tool, designed in Microsoft Excel. Participants designed electricity generation portfolios for state of Pennsylvania by using the slider bars in the “Build Center.” The computer tool provided immediate feedback about the annual electricity generation and CO_2 emissions relative to a status quo scenario (in the “Goal Center”), the annual water use, land use and health costs from air pollution (in the “Impacts” center) and the increased cost of electricity in \$/kilowatt-hour and average monthly electric bill, and the increase in cost-of-living (in the “Costs” center). Users could choose to “Reset” their portfolio at any time. Up to three portfolios that met the goal of generating 60 terawatt-hours of electricity per year while reducing CO_2 emission by 50% relative to a status quo scenario could be selected for “Review and Save.” Once saved, users could “Recall,” “Delete,” and “Compare” these portfolios.

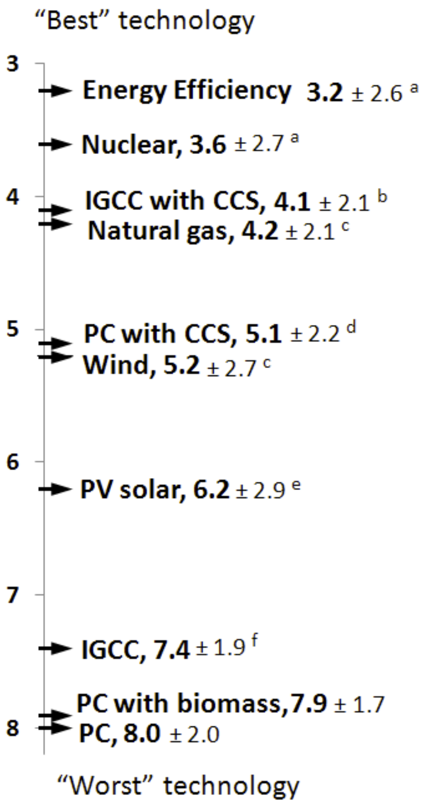


Figure 2. Participants' mean technology ranking ± standard deviation, on a scale from 1 (best) to 10 (worst). Superscripted letters next to mean technology rankings refer to Wilcoxon paired-rank tests results ($p < 0.01$), suggesting that: (a) PC with CCS, Wind, PV Solar, IGCC, PC with biomass and PC were ranked significantly worse, (b) PC with CCS, PV Solar, IGCC, PC with biomass and PC were ranked significantly worse, (c) PV Solar, IGCC, PC with biomass and PC were ranked significantly worse, (d) IGCC, PC with biomass and PC were ranked significantly worse, (e) PC with biomass and PC were ranked significantly worse, and (f) PC was ranked significantly worse.

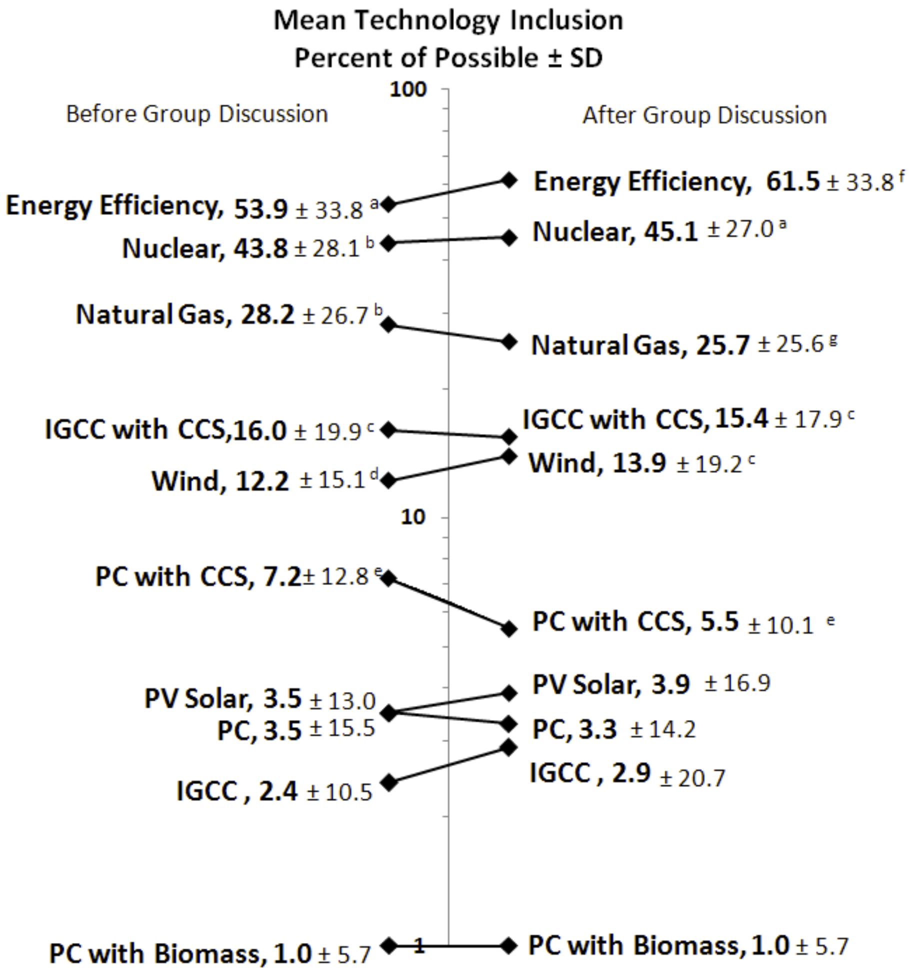


Figure 3. Participants' mean standardized technology percentages ± standard deviation, where 0 is no inclusion of that technology in a portfolio and 100 is maximum allowable inclusion of the technology in a portfolio, pre- (left) and post-discussion (right). Standardized technology percentages represent the percent of each technology included in participants' portfolio designs, as part of the maximum percent allowable for that technology. Superscripted letters next to mean standardized technology percentages refer to t-test results ($p < 0.01$) suggesting that standardized technology percentages of: (a) natural gas, IGCC with CCS, wind, PC with CCS, PV solar, PC, IGCC, and PC with biomass were significantly less, (b) IGCC with CCS, wind, PC with CCS, PV solar, PC, IGCC, and PC with biomass were

significantly less, (c) PC with CCS, PV solar, PC, IGCC, and PC with biomass were significantly less, (d) PV solar, PC, IGCC, and PC with biomass were significantly less, (e) PC with biomass was significantly less, and (f) all other technologies were significantly less, and (g) wind, PC with CCS, PV Solar, PC, IGCC, and PC with biomass were significantly less.

ASSOCIATED CONTENT

A screen shot of the computer tool's portfolio comparison screen, technology information sheets and calculations/assumptions used in the computer tool. This material is available free of charge via the Internet at http://pubs.acs.org.

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