

# **Public Decision-making about Low-Carbon Electricity Generation**

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## **Abstract**

To mitigate the effects of climate change, the U.S. will need a widespread deployment of energy efficiency efforts and low-carbon electricity generating technologies including nuclear, wind, natural gas, and coal with carbon capture and sequestration (CCS), technologies that separate CO<sub>2</sub> emissions from the flue-gas of fossil fuel power plants and sequester it in deep underground geological formations. The feasibility of this strategy will partially depend on public acceptance of these technologies as part of a national energy policy. To varying degrees, public misconceptions and knowledge gaps exist for each of these low-carbon technologies. Thus, people need balanced and comparative information to make informed decisions about which low-carbon electricity technologies and portfolios to support.

In this thesis, we describe paper-based and computer-based communications presenting multi-attribute descriptions about the costs, benefits, risks and limitations of ten electricity technologies and low-carbon portfolios composed of those technologies. Participants are first asked to rank the technologies under a hypothetical scenario where future power plant construction in Pennsylvania must meet a CO<sub>2</sub> emissions constraint. Next, participants attend small group meetings where they rank seven portfolios that meet a specific CO<sub>2</sub> emission limit. In a subsequent study, participants instead construct their own low-carbon portfolio using a computer decision tool that restricts portfolio designs to realistic technology combinations. We find that our participants could understand and consistently use our communications to help inform their decisions about low-carbon technologies. We conclude that our informed participants preferred energy efficiency, nuclear, and coal (gasification) with CCS, as well as diverse portfolios including these technologies.

The thesis continues with a retrospective view for the value of research that elicits general public opinions of CCS and that develops communications to educate people about low-carbon electricity generation. In the latter, we find that the knowledge of science teachers may be insufficient to correct common public misconceptions about low-carbon technologies among their students. Thus, the communications we developed for this thesis could also benefit science teachers.

Overall, we conclude that the computer tool, supplemental materials and procedure developed for this thesis may be valuable for educating the general public about low-carbon electricity generation.

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## Abbreviations

BTU	British thermal units
CCS	Carbon capture and sequestration
CO <sub>2</sub>	Carbon dioxide
EPRI	Electric Power Research Institute
FGD	Flue gas desulfurization
GE	General Electric
GWh	Gigawatt-hour
IECM	Integrated Environmental Control Model
IGCC	Integrated gasification combined-cycle coal
kg	Kilogram
kWh	Kilowatt-hour
L	Liter
m	Meter
MMBTu	Million British thermal units
MW	Megawatt
MWh	Megawatt-hour
NAS	National Academy of Sciences
NEMS	National Energy Modeling System
NEP	New ecological paradigm
NETL	National Energy Technology Laboratory
NO <sub>x</sub>	Nitrogen oxides
PA	Pennsylvania
PC	Pulverized Coal
PM	Particulate matter
PV	Photovoltaic
SCR	Selective catalytic reduction
SO <sub>2</sub>	Sulfur dioxide
TWh	Terawatt-hour

## **Chapter 1. Introduction**

### **1.1. Public perceptions of low-carbon electricity generation technologies**

To mitigate the effects of climate change, the U.S. will need a widespread deployment of energy efficiency efforts and low-carbon electricity generating technologies including nuclear, wind, natural gas, and coal with carbon capture and sequestration (CCS), technologies that separate CO<sub>2</sub> emissions from the flue-gas of fossil fuel power plants and sequester it in deep underground geological rock formations (e.g., 1, 2). The feasibility of this strategy will partially depend on public acceptance of these technologies as a part of a national energy policy, and on local community acceptance of their local infrastructure development.

To varying degrees, public misconceptions exist for each of these low-carbon electricity generation technologies. For example, ever since the reactor meltdown at Three Mile Island, people have been reluctant to accept new nuclear power plants (3-5), in part because they believe that they may emit dangerous levels of radiation (4, 6, 7). In addition, it is a common misconception that emissions from nuclear power plants increase the amount of CO<sub>2</sub> in the atmosphere (8) or are a source of global warming (9-11).

Negative public sentiment also exists towards renewable energy technologies. For example, some people perceive wind turbines as noisy, aesthetically unappealing and a threat to birds and bats (12-14). 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 most technical experts argue that this is not feasible (15, 16). This could partially be a result of people overestimating the current potential for solar power to meet rising demand in energy (17) or thinking photovoltaic (PV) solar power is ‘higher quality’ than conventional electricity (18). These beliefs could also be why people tend to overestimate the costs of non-

intermittent sources of electricity such as coal power, while underestimating the costs of solar and wind power (19).

Of all low-carbon electricity generation technologies, people tend to be most unfamiliar with carbon capture and sequestration (e.g., 3, 8, 20). Those who have heard of CCS may fear the unlikely event that CO<sub>2</sub> “burps” will be released from the ground and cause suffocation (15, 21), as well as the incorrect concern that CO<sub>2</sub> is flammable and may cause explosions (22, 23). Hence, to make informed decisions about which low-carbon electricity generation technologies to support, people will need more information upon which to make judgments and correct their misconceptions about the possible alternatives – especially CCS.

As CCS became a more realistic option for climate change mitigation in the past decade (e.g., 2, 24), researchers began to conduct surveys to examine initial public perceptions of the technology. These survey studies found that most members of the general public had never heard of CCS, and experienced difficulty answering survey questions about it (8, 25). To combat that problem, surveys eliciting CCS perceptions would provide a few informational sentences about the technology before asking for people’s opinion (8, 26). Since providing a few sentences is not sufficient to teach people about CCS, they remained relatively uninformed about the technology, leaving their opinions unstable and highly variable (25, 27, 28). People need more information about CCS to be able to provide reliable opinions about it.

In 2004, Palmgren et al. (21) sought to understand what information people needed to know about CCS in order to evaluate it. The authors conducted open-ended interviews and found that people wanted to know about the risks and benefits of CCS. Additionally, the interview results suggested that people did not want to evaluate CCS in isolation. Rather, they wanted to consider it in comparison to other low-carbon technologies and as a part of a low-carbon

electricity generation portfolio. Thus, in a follow-up survey, Palmgren asked members of the general public to rank a set of ten low-carbon portfolios, each consisting mainly of one technology (e.g., coal with CCS, one renewable technology, or nuclear power) after providing detailed information about the risks and benefits of CCS, and a sentence or two about the other, more familiar, low-carbon technologies in the portfolios. Overall, the portfolios with CCS were the least preferred, even significantly less than those portfolios including nuclear power.

This thesis builds on the work by Palmgren et al. (21), while rectifying four of its limitations. First, while Palmgren et al. presented simplified portfolios that relied too much on a single technology, our studies provide participants with realistic and reliable portfolio options for expanding future electricity capacity. In two studies, we provide pre-determined portfolios to participants, while in another we allow participants to build their own use a computer decision tool. Second, while Palmgren et al. provided only a few sentences to describe each technology, we presented comprehensive and balanced information sheets for each, using simple wording and a systematic presentation format (29-31). Third, unlike Palmgren et al., we systematically covered the same set of attributes (including risks, benefits, limitations, and costs) in the presentation of each technology and portfolio. Fourth, in addition to providing their personal rankings (as in Palmgren et al.), our participants also discussed their portfolio rankings and computer designs in a group exercise, allowing them to hear alternative views, to improve their engagement and understanding, and revise their initial rankings and choices (29-31).

## **1.2. Overview of this thesis**

This thesis is divided into eight chapters. First, this chapter provides a brief literature review of public misconceptions about CCS and other low-carbon electricity generation

technologies. The second chapter then describes the development of paper-based communications and an interactive computer tool aiming to elicit informed preferences for portfolios of low-carbon electricity generation technologies from members of the general public. Chapter three describes a study that evaluated the feasibility of using the paper-based materials to educate non-technical members of the general public, and has been published in the journal *Risk Analysis* (32). Chapter four repeats this study with science and math teachers. Next, chapter five describes a study that examines the feasibility of using the interactive computer tool to allow members of the general public to build low-carbon portfolios. Chapter six reports on a study that examines whether science teachers are prone to the same misconceptions as members of the general public. Chapter seven presents a letter to the editor that we have submitted to the *International Journal of Greenhouse Gas Control*, about the strengths of different methodologies for eliciting public perceptions of CCS. Finally, the eighth chapter briefly describes plans for future work and concludes this thesis.

## References

1. Pacala S & Socolow R (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science* 305(5686):968-972.
2. James R, Richels R, Blanford G, & Gehl S (2007) The Power to Reduce CO<sub>2</sub> Emissions: The Full Portfolio. (The EPRI Technology Assessment Center, Electric Power Research Institute, Palo Alto, CA.).
3. Curry TE, Ansolabehere S, & Herzog H (2007) A survey of public attitudes towards climate change and climate change mitigation technologies in the United States: Analyses of 2006 results. (Massachusetts Institute of Technology, Cambridge, Massachusetts).
4. Grove-White R, Kearnes M, Macnaghten P, & Wynne B (2006) Nuclear Futures: Assessing public attitudes to new nuclear power. *The Political Quarterly* 77(2):238-246.
5. Poortinga W, Pidgeon NF, & Lorenzoni I (2006) Public Perceptions of Nuclear Power, Climate Change and Energy Options in Britain: Summary Findings of a Survey Conducted during October and November 2005. Technical Report. (Centre for Environmental Risk, Norwich).

6. Slovic P (2000) *The perception of risk* (Earthscan Publications, London ; Sterling, VA) p 473.
7. Purvis-Roberts KL, Werner CA, & Frank I (2007) Perceived Risks from Radiation and Nuclear Testing Near Semipalatinsk, Kazakhstan: A Comparison Between Physicians, Scientists, and the Public. *Risk Analysis* 27(2):291-302.
8. Reiner D, *et al.* (2006) American Exceptionalism? Similarities and Differences in National Attitudes Toward Energy Policy and Global Warming. *Environ Sci Technol* 40:2093-2098.
9. Bostrom A, Morgan MG, Fischhoff B, & Read D (1994) What Do People Know About Global Climate Change? 1. Mental Models. *Risk Analysis* 14(6):959-970.
10. Read D, Bostrom A, Morgan MG, Fischhoff B, & Smuts T (1994) What Do People Know About Global Climate Change? 2. Survey Studies of Educated Laypeople. *Risk Analysis* 14(6):971-982.
11. Reynolds TW, Bostrom A, Read D, & Morgan MG (2010) Now What Do People Know About Global Climate Change? Survey Studies of Educated Laypeople. *Risk Analysis* 30(10):1520-1538.
12. Firestone J & Kempton W (2007) Public opinion about large offshore wind power: Underlying factors. *Energy Policy* 35(3):1584-1598.
13. Wolsink M (2007) Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives' *Renewable and Sustainable Energy Reviews* 11(6):1188-1207.
14. Gross C (2007) Community perspectives of wind energy in Australia: The application of a justice and community fairness framework to increase social acceptance. *Energy Policy* 35(5):2727-2736.
15. Ashworth P, Boughen N, Mayhew M, & Millar F (2009) An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond. *Energy Procedia* 1(1):4749-4756.
16. Broder JM (July 18, 2008) Gore Urges Change to Dodge an Energy Crisis. *The New York Times*.
17. Plate R, Monroe M, & Oxarart A (2010) Public Perceptions of Using Woody Biomass as a Renewable Energy Source. *Journal of Extension* 48(3):1-15.
18. Farhar B & Buhrmann J (1998) Public Response to Residential Grid-Tied PV Systems in Colorado: A Qualitative Market Assessment A Qualitative Market Assessment. (National Renewable Energy Laboratory, Golden, CO).

19. Ansolabehere S (2007) Public attitudes toward American's energy options : report of the 2007 MIT Energy Survey. (Massachusetts Institute of Technology. Center for Energy and Environmental Policy Research., Cambridge, MA).
20. Huijts NMA, Midden CJH, & Meijnders AL (2007) Social acceptance of carbon dioxide storage. *Energy Policy* 35(5):2780-2789.
21. Palmgren CR, Morgan MG, Bruine de Bruin W, & Keith DW (2004) Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. *Environ Sci Technol* 38(24):6441-6450.
22. McCoy S & Fleishman L (November 29, 2009) CO2 Misinformation. Pittsburgh Post-Gazette.
23. Shackley S, Mander S, & Reiche A (2006) Public perceptions of underground coal gasification in the United Kingdom. *Energy Policy* 34(18):3423-3433.
24. IPCC (2005) Carbon Dioxide Capture and Storage. eds Metz B, Davidson O, de Coninck H, Loos M, & Meyer L (Cambridge, UK), p 431.
25. de Best-Waldhober M, Daamen D, & Faaij A (2009) Informed and uninformed public opinions of CO2 capture and storage technologies in the Netherlands. *International Journal of Greenhouse Gas Control* 3(3):322-332.
26. Itaoka K, Okuda Y, Saito A, & Akai M (2009) Influential information and factors for social acceptance of CCS: The 2nd round survey of public opinion in Japan. *Energy Procedia* 1(1):4803-4810.
27. Fishkin J (2006) Strategies of Public Consultation. *Integrated Assessment* 6(2):57-72.
28. Malone EL, Dooley JJ, & Bradbury JA (2010) Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement. *International Journal of Greenhouse Gas Control* 4(2):419-425.
29. Florig KH, *et al.* (2001) A deliberative method for ranking risks (I): Overview and test bed development. *Risk Analysis* 21(5):913-821.
30. Morgan KM, *et al.* (2001) A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers. *Risk Analysis* 21(5):923-937.
31. Willis HH, DeKay ML, Morgan MG, Florig HK, & Fischbeck PS (2004) Ecological Risk Ranking: Development and Evaluation of a Method for Improving Public Participation in Environmental Decision Making. *Risk Analysis* 24(2):363-378.
32. Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.

## **Chapter 2. Development of Paper-based and Computer-based Communications**

To reap the benefits of emerging technologies, people must accept the related risks. Risk communication materials aim to explain those risks and benefits, allowing members of the general public to make informed decisions about whether or not to support emerging technologies. The mental models approach (1) aims to develop well-grounded risk communications that lay people understand, by: (1) identifying what people should know about the risk through an interdisciplinary literature review and expert input, (2) identifying what lay people already know, as to include relevant lay wording and decision contexts of the risk, (3) developing communication materials to address key gaps and misconceptions in lay knowledge, as identified by a comparison of lay and expert knowledge and (4) iteratively refining the content based on domain expert evaluations to ensure balance and accuracy, as well as lay evaluation, to ensure their understanding (1). This approach has been used to inform risk communications about various topics including climate change (1), nuclear energy sources on spacecraft (2), and avian flu (3). In this chapter, we describe how we applied a *modified* mental models approach to develop communication materials (paper-based and computer-based) about CCS and other low-carbon technologies. Specifically, we will describe the process for communication development (step 3) and refinement (step 4)

### **2.1. Paper-based communication materials**


As described in chapter 1, we set out to describe the electricity technologies to facilitate systematic comparisons. To do this, we drew upon an extensive literature review about CCS and alternative technologies. First, a technical literature review identified the information experts in engineering and environmental science deemed most relevant for evaluating these technologies.



An additional literature review of public perception research, previously described in Chapter 1, helped us to identify the topics about which people needed more information.

# Wind

**How it Works:** Modern wind machines are much larger than the old windmills in Holland, or the metal windmills that pumped water for cattle in the American West. They are often between 100 and 300 feet high. That is about as tall as a 10 to 30 story building. The machines have blades that look like an airplane propeller. The wind turns the blades, and this runs a generator to make electricity.



Modern wind turbines in Somerset, PA  
Source: www.solutions-site.org/

<b>Availability</b>	Wind farms work well when built in windy areas. PA has lots of wind on hilltops in the center of the state. However, even the best wind farms in PA only make 28% of the power that would be possible if the wind was always blowing. They cannot make 100% because sometimes the wind is not blowing. Wind farms are often located far away from where people live, since this is where it is the windiest. It is expensive to transmit the wind electricity across long distances.
<b>Reliability</b>	<ul style="list-style-type: none"> <li>Wind varies in strength, which can make it less dependable for making electricity. Because of this, wind farms cannot consistently make electricity. Natural gas plants must be built to "back up" or fill in electricity during times when it is not windy. In the future, we might use very large batteries to store electricity from wind, but that is very costly to do today.</li> <li>On average, a newly built wind farm in PA can make about 0.5 TWh of electricity over the course of the year. The natural gas plant built to fill in electricity when it is not windy will have to make about 1.2 TWh over the course of the year.</li> </ul>
<b>Limits to Use</b>	If many wind farms are built, there will be a lot of CO <sub>2</sub> released by the "back-up" natural gas plants. The more wind farms you build, the more indirect CO <sub>2</sub> that is released to the air. So wind farms can only be used to make up 28% of the additional electricity needed for PA if we want to reduce the CO <sub>2</sub> released from all new plants by 50%. This would be about 16.5 TWh of the 60 TWh.
<b>Current Use</b>	There are more than 100 wind farms working in the U.S. today.
<b>Environmental Impacts</b> (*Read Note Below)	<ul style="list-style-type: none"> <li>There is almost no solid waste from wind farms.</li> <li>Wind farms with many machines require hundreds of acres. If the machines are built on farm land, most of it can still be used for farming. In forests, trees must be cleared to build the machines. This can disturb the plants and animals. On mountain ridges, wind farms can be very visible.</li> <li>Wind farms make some low noise. It is less than the noise from most other power plants. But, since wind farms are in the country, the noise is often more noticeable.</li> <li>The blades of wind machines sometimes strike and kill birds and bats. New wind machines are being located away from bird (migration) flight paths. Less is known about how to prevent bat deaths.</li> </ul>
<b>Safety</b>	Wind farms present very few risks to people.

\* Note: Health, Water and Land Impacts are shown on a Separate Sheet

**Figure 2.1. Example *Technology Sheet***

To facilitate systematic comparisons across technologies, and across portfolios of these technologies, the communication materials used a multi-attribute presentation format similar to that employed in previous risk ranking exercises (e.g., 4, 5). The resulting materials systematically compared the costs, risks, benefits and limitations of each electricity technology

and low-carbon portfolio using a systematic multi-attribute format. Figure 2.1 shows an example *Technology Sheet*, with qualitative attributes of *How it works*, *Availability*, *Reliability*, *Limits of use*, *Current Use*, *Safety*, and *Environmental Impacts*.

Additionally, as in the risk ranking studies, we developed a hypothetical scenario to motivate participants' comparison of the technologies. This scenario, or *Problem Question*, asked participants to assume that U.S. Congress had mandated a reduction in CO<sub>2</sub> emissions from power plants to be built in the future. Further, participants were asked to assume that they had been chosen for a citizen's advisory panel to provide advice to the Pennsylvania (PA) Governor about which types of power plants to build. Figure 2.2 displays the full context of this "problem question."

To allow our participants adequate time to study the communication materials, we designed the materials to be read by participants on their own (i.e., as "homework"). As with previous risk ranking studies (e.g., 4, 5), participants read the communication materials prior to joining a group meeting where they could discuss the technologies among a small group of their peers. The complexity of the subject matter and the fact that participants read the materials without a facilitator present (i.e., they had little ability to ask questions if confused) required that we focus materials development and iterative refinement on (1) correcting knowledge gaps and misconceptions about the different technologies, (2) simplifying the readability of materials, and (3) using read aloud studies to ensure that participants could use the materials at home as we intended and would understand the information.

### ***2.1.1. Correcting misconceptions and knowledge gaps***

We explicitly tried to add information to the materials that would correct many of the common public misconceptions identified during the comprehensive literature review, as well as during read aloud studies (see section 2.1.3 for details). A few examples, including the misconceptions/knowledge gap and how we addressed it in the materials, are provided below:

- To address common misconceptions about the chemical-physical properties of CO<sub>2</sub> (6) and the relation to CCS, our information about CCS states, “Unlike oil or gas, CO<sub>2</sub> cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of CO<sub>2</sub> did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the CO<sub>2</sub> could build up for a while. In this case, people and animals could suffocate if the leak was large enough.”
- To address the lack of knowledge about the intermittency issues of wind and solar (7-9), our information about wind states, “even the best wind farms in PA only make 28% of the power that would be possible if the wind was always blowing. They cannot make 100% because sometimes the wind is not blowing... Wind varies in strength, which can make it less dependable for making electricity. Because of this, wind farms cannot consistently make electricity. Natural gas plants must be built to “back up” or fill in electricity during times when it is not windy. In the future, we might use very large batteries to store electricity from wind, but that is very costly to do today.”
- To address common misconceptions about nuclear plants (10-12), our information about nuclear states, “Nuclear plants release almost no radiation into the air, ground or water. So, a person who lives near a plant gets almost no radiation...The chance of a nuclear accident is very small. Nuclear material might leak into the air and water if there is an

accident. But, nuclear plants cannot explode like an atomic bomb. Unlike older plants in some parts of the world (Russia), all U.S. plants are built inside strong concrete buildings. These prevent leaks if there is an accident. There has been one accident at a U.S. commercial nuclear plant. It was in 1979 at the Three Mile Island plant in Central PA. The plant's concrete building kept the radiation from leaking. No plant workers or people living near the plant were harmed. Plants have been fixed to be much safer since the accident."

### **Problem Question**

#### The Current Situation

Today, the power plants in PA make about 225 terawatt-hours (TWh) of electricity each year. A TWh is a measure of electricity use. One TWh is a lot of electricity. In comparison, an average household in PA uses less than 0.001% of one TWh of electricity per year. Much of PA's 225 TWh of electricity comes from coal plants. Coal plants release CO<sub>2</sub> (carbon dioxide) into the air.

#### The Future Situation

The demand for electricity in PA increases every year. In 25 years, the power plants in PA will need to make about 285 TWh of electricity each year to keep up with demand. 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. The original plan was to build all coal plants. But, suppose that the U.S. Congress has just passed a law to reduce the CO<sub>2</sub> released by power plants built in the future. As a result of this law, the State of PA must rethink what power plant types will be built here over the next 25 years. These power plants will collectively need to release 50% less CO<sub>2</sub>. 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 Task

Your job is to rank the power plant types from best to worst. This will help to inform the Governor about which plants should be built in PA to make the additional 60 TWh of electricity needed each year.

**Figure 2.2. The Hypothetical Scenario for the Paper-based Communication Materials**

### 2.1.2. Simplify readability of materials

Survey researchers have shown that when survey content requires great effort to understand, respondents tend to become frustrated, which can influence their survey responses (13). Thus, researchers employ a number of strategies to simplify complex information. Here, we describe how we used some of these strategies to simplify the readability of our text- and graph-based information.

First, we simplified text readability by ensuring the materials were written at the 6<sup>th</sup>-8<sup>th</sup> grade reading level, as measured by the Flesch-Kincaid readability scale (14, 15). This scale, which accounts for the number of words in each sentence and number of syllables per word, is commonly applied to measure the understandability of survey items (16) and can be accessed in Microsoft Word's standard spelling and grammar proofing menu (under readability statistics). The scale is approximately equivalent to grade level. Thus, a Flesch-Kincaid score of 7.2 is about the 7<sup>th</sup> to 8<sup>th</sup> grade level. In the same way that including shorter sentences and words can reduce reader processing time, including words that are more frequent in common lay language can decrease processing time. While less-frequently used words may be understandable to readers, they may still require more processing time to understand. For example, in our materials, we state that CO<sub>2</sub> is *released* into the air, rather than the less frequently used word of *emitted*. As sentences become longer, and words become more rare (e.g., technical terms, abbreviations, etc.), the reader is required to remember lots of information at the same time. This can cause working memory to be overloaded and the content of the communications may be lost by the reader (e.g., 17).

We also strived to present quantitative information to participants in a usable and accessible format. Recommendations for presenting quantitative information, especially related

to risk information, are widely available (e.g., 18, 19, 20). However, the performance of a display method depends greatly on the information that a reader is trying to extract (21, 22). In our graphical materials, we aimed to create graphs that were easy to understand and could facilitate participants' comparison of technologies. We provided text with each graphical display (Figure 2.3) and directed participants to read the text prior to deciphering the graph. All quantitative information was presented using familiar units (e.g., monthly electric bill, football fields, etc.). When familiar units were not an option, text explanations were added to provide context for the units (e.g., the difference in size between a kilowatt-hour (kWh) and terawatt-hour (TWh)). Finally, participants only had to learn how to decipher two types of graphs to obtain all the quantitative information for the study. That is, the simple bar graph format (Figure 2.4) was used for all quantitative comparisons with the exception of the cost graph (Figure 2.5), which conveyed uncertainty as well as point estimates. While the cost graph was considerably more advanced than the others, pilot tests with the materials show that the main takeaway message (i.e., the relative differences in electricity prices and their ranges) was understandable.

### ***2.1.3 Read aloud studies***

To ensure that participants could understand the information and would use the materials as intended, we conducted read-aloud interviews, or pilot tests, in which lay participants were asked to read all of the materials out loud and say anything that came to mind. The read-aloud interviews each took about 2 hours, and were conducted with a convenience sample of members of the high-school educated, non-technical lay public. In return for their participation, we paid people \$25. After every few interviews, we gained enough insights to iterate through another revision of materials and expert review.

### 2.1.3.1 Ensure Participants Use Materials as Intended

Our interviews suggested that even after our simplification of the materials using strategies explained above, pilot participants tended to be overwhelmed by the amount of information and the task asked of them. Thus, we employed a number of strategies to reduce the cognitive capacity required (i.e., “cognitive load” (23)) by our participants to process the information.

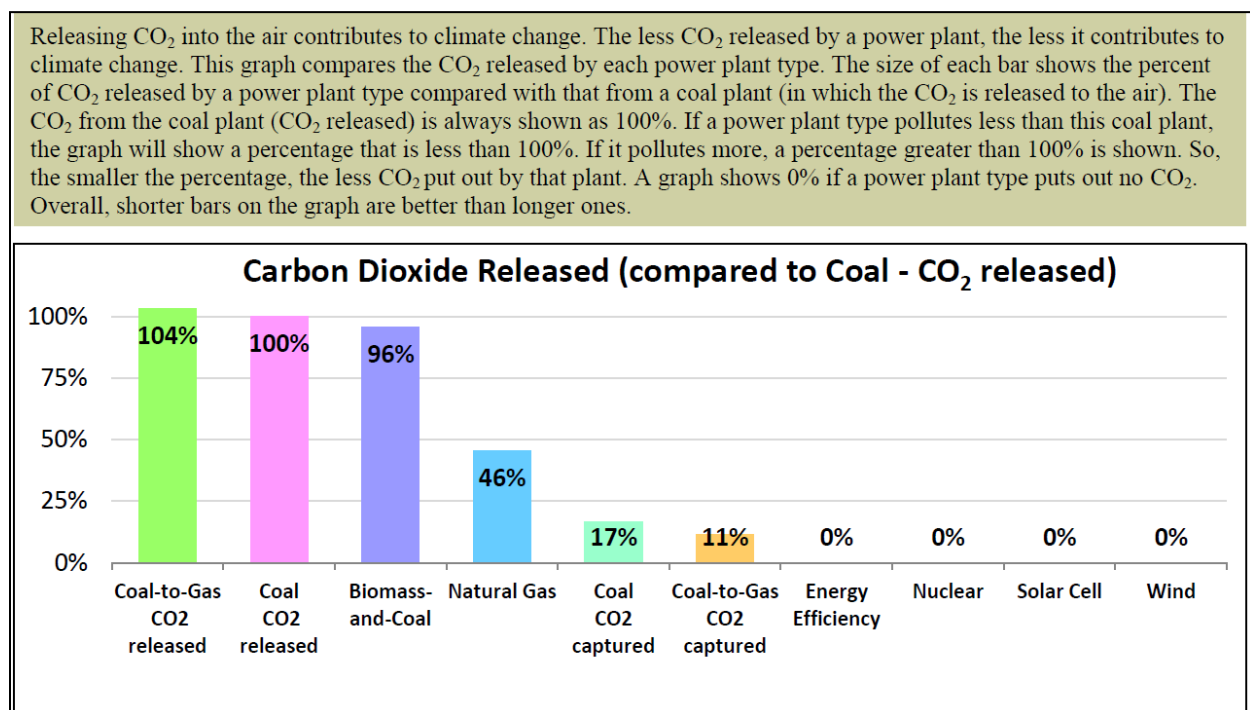


Figure 2.3. CO<sub>2</sub> released graph, with text to help participants decipher the graph

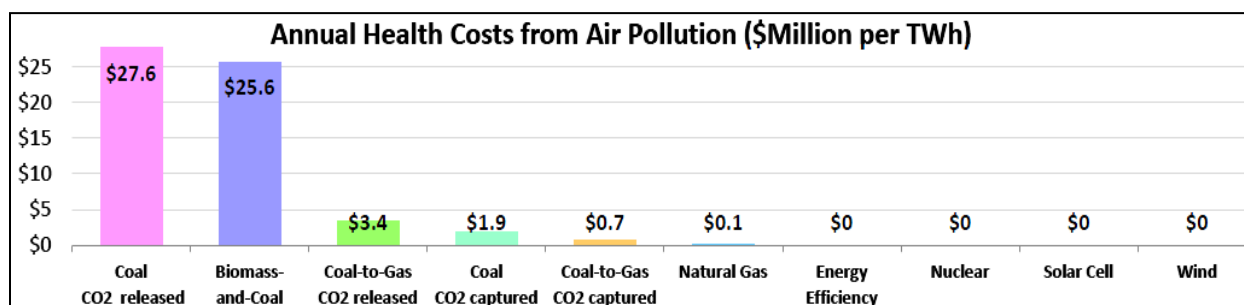


Figure 2.4. Simple bar graph format shown on the *Annual Health Costs* Graph

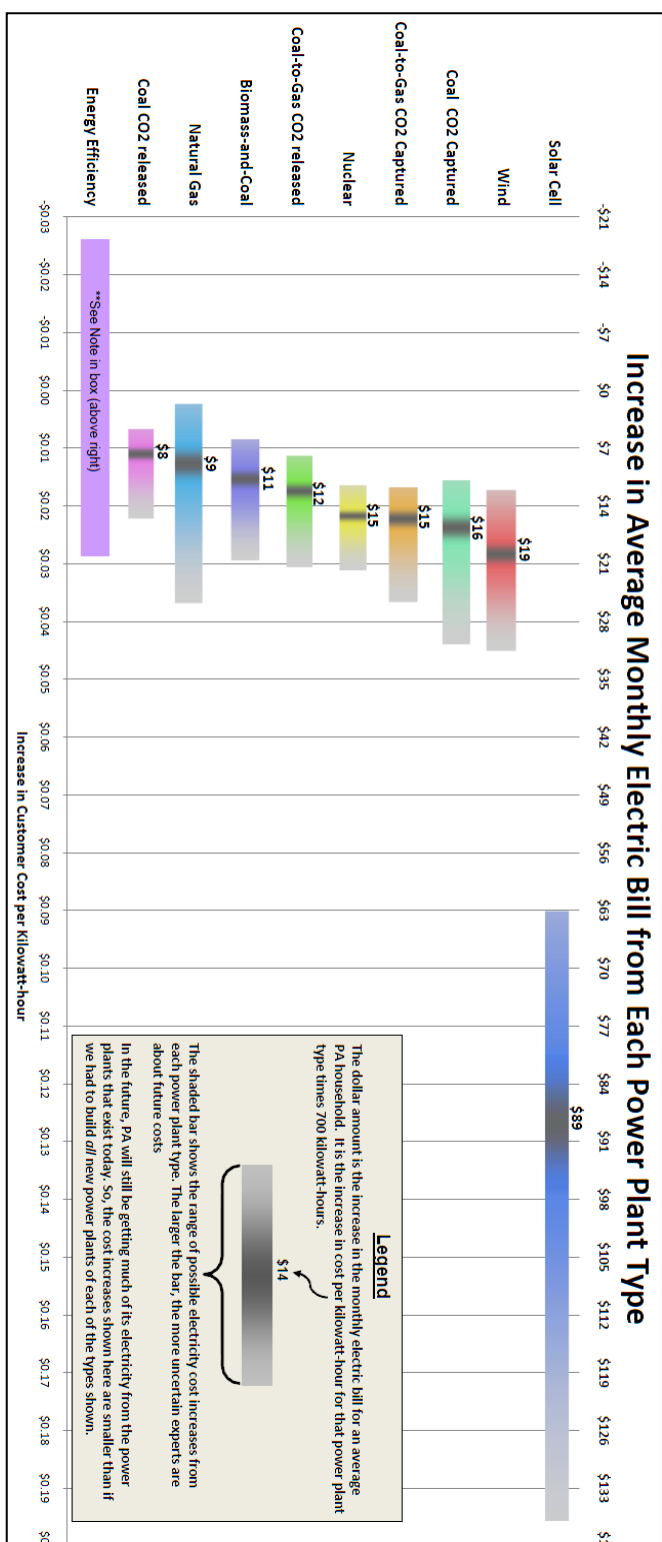


Figure 2.5. Cost Comparison Graph, showing most likely cost with a range for uncertainty



Mayer and Moreno (24) recommend segmenting the information, which allows learners to “digest intellectually one chunk of [information] before moving onto the next.” We employed segmentation methods at all steps in the procedure. We had originally intended to provide participants with information about technologies, and low-carbon portfolios composed of those technologies, for the “homework” portion of our studies. However, our interviews suggested that participants had difficulty processing the concept of an electricity portfolio, while learning about the individual technologies in parallel. Thus, we decided not to mention the portfolio concept to participants until they met for the group meeting. This allowed participants to focus solely on the individual technologies and their comparison. Further segmentation included separating participant tasks and information materials into multiple envelopes that were numbered in the order in which they were to be opened. The envelopes seemed to allow participants to remain on task by keeping them from becoming overwhelmed and from not looking ahead.

To further reduce the cognitive load of our participants, we eliminated information (with expert consent) that our pilot testers found to be extraneous during their read aloud studies. Extraneous information that is not decision-relevant to study participants nevertheless requires cognitive processing, leaving less cognitive capacity for essential information. Furthermore, information that did not correctly address the knowledge gaps of our intended audience could have left our readers confused. During the read-aloud protocol, we asked participants which information was missing and which was not important to them or to the decision at hand. If a few pilot testers agreed that a certain topic was extraneous, this would be grounds for its elimination.

Another strategy we employed was a color-coding of the technologies. The border of each technology sheet, as well as the colored bars in each graph was consistent across the technologies from sheet to sheet. If our participants chose not to read the technology names, they

could simply match up the colors. Finally, we explicitly provided our participants with a large blank sheet of paper for note taking while reading the materials. Read aloud studies confirmed that this helped participants to organize their thoughts, both by highlighting the items they found to be important, as well as freeing their working memory for new concepts.

#### *2.1.3.2 Ensure Participant Comprehension*

Another goal of our read-aloud studies was to assess our participants' comprehension of the overall task and communication materials. We employed a number of strategies to examine the understandability of our materials. First, we asked our pilot-testers to read the information aloud. In this way, we were able to hear which content caused them to pause or re-read the material. At these cues, we would ask them why they were confused and ask them to recommend wording that would better reflect the language and thought process of our intended audience. For instance, the concept of a payback period on energy efficient products was confusing to our participants until one pilot-tester suggested that we use the phrase "recoup the costs." Other strategies to assess comprehension during read-alouds included asking the participant to explain the content they read "in their own words," or quizzing them with knowledge-based questions about graphs (e.g., "which power plant releases the most carbon dioxide?").

## **2.2. Computer-based Communications: The Portfolio-Building Computer Tool**

While our initial studies were conducted with paper and pencil, for a later round of studies we developed a computer tool that was designed to allow users to construct their own portfolio by choosing the technologies to include, and their percentage penetration. As the user increases or decreases the technology percentages, the interactive tool provides immediate output

on the cost, health and environmental externalities of their designed portfolio. Using a similar method to that in the homework materials, we provided our participants with a realistic decision-context to motivate their use of the computer tool. Figure 2.6 displays the full context of this “problem question,” which tasks participants to, “...use the computer tool to...build a combination of new power plants that...must make 60 TWh of electricity per year, but release 50% of the CO<sub>2</sub> that would have been released [by a status quo scenario, in which Pennsylvania increases capacity in a similar ratio to what exists today].”

### Problem Question

#### The Current Situation

Right now, the power plants in PA make about 225 terawatt-hours (TWh) of electricity each year. A TWh is a measure of electricity use. One TWh is a lot of electricity. In comparison, an average household in PA uses less than 0.001% of one TWh of electricity per year.

#### The Future Situation

PA will need more electricity in 25 years than the power plants it has now can make. The power plants in PA will need to make about 285 TWh of electricity each year to keep up with demand. 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.

**The original plan was to build the following power plants in PA: 6 coal power plants (in which the CO<sub>2</sub> is released into the air), 4 natural gas power plants, 3 nuclear power plants and 1 wind farm.** But, suppose that the U.S. Congress has just passed a law to reduce the CO<sub>2</sub> 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 plants will collectively need to release 50% less CO<sub>2</sub> than the original plan. **A different combination of power plants will need to be built.** Imagine that the Governor of Pennsylvania has asked you to serve on a Citizen’s Advisory Panel **to give advice on how many of each plant type should be built in PA.**

#### Your Task

Your job is to use the computer tool to provide this advice. You will **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<sub>2</sub> that would have been released using the original plan.**

**Figure 2.6. The Hypothetical Scenario for Computer Tool User**

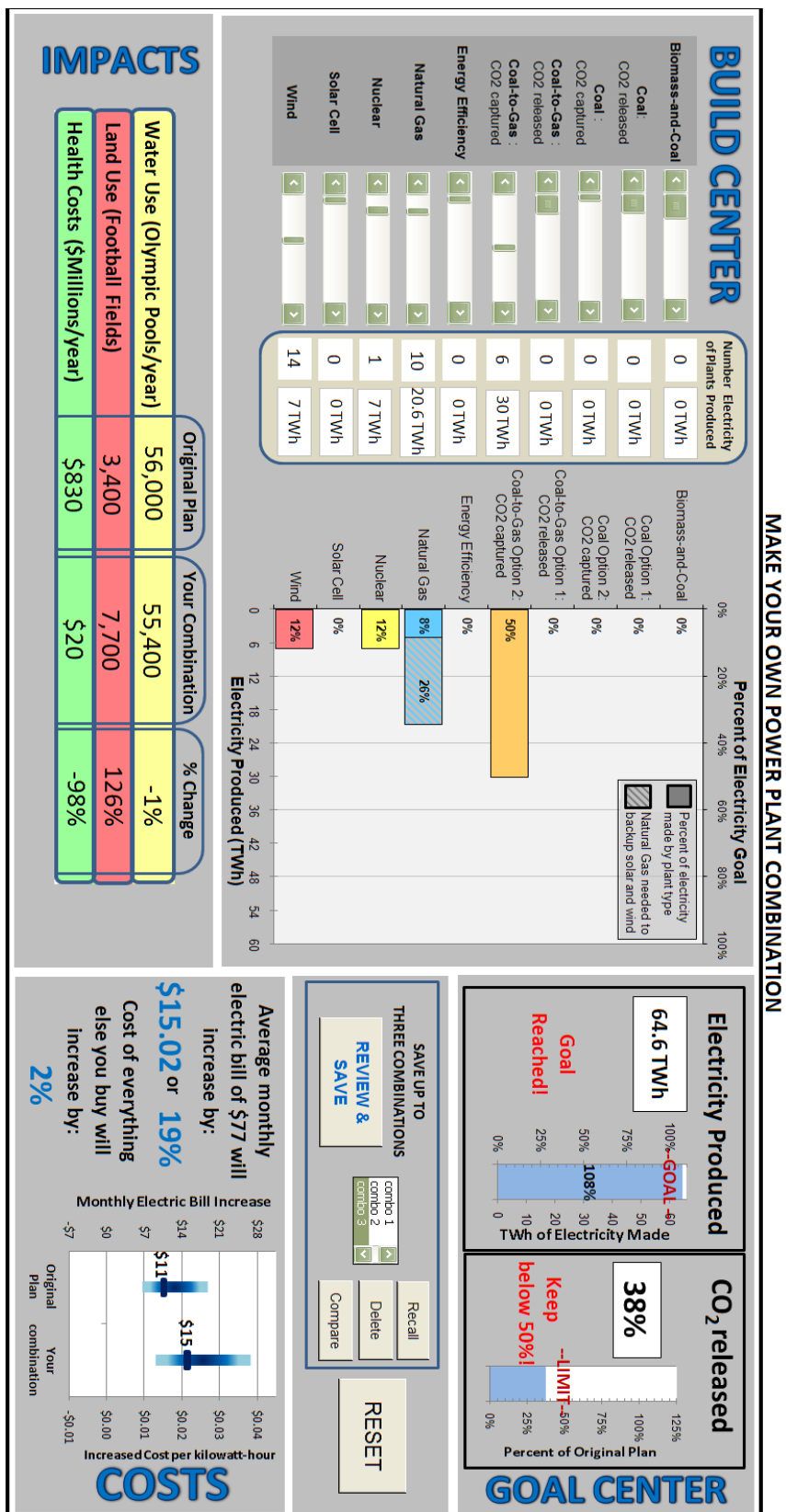


Figure 2.7. Screen shot of the Portfolio-Building Computer Decision

The computer tool was designed to constrain portfolio design to reliable and realistic technology combinations that could meet the CO<sub>2</sub> and electricity generation constraints. Thus, the tool elicits public preferences for low-carbon energy policy alternatives for PA (in the form of power plant construction plans), while presenting attributes that have been found to be important to the public when making decisions about which generation portfolios to support (25). In this way, our decision tool is able to facilitate informed decision-making about the challenges the U.S. faces in achieving a widespread deployment of low-carbon energy infrastructure by allowing users to “learn-by-doing”.

We specifically designed the computer tool for non-technical members of the general public who have taken adequate time to read and process the supplemental homework materials. The graphical displays, units of measurement, user decision-context and user instructions were designed to provide a seamless transition for the user into the dynamic computer tool environment. The initial design of the computer tool was iteratively refined based on input from lay pilot participants and subject-matter experts. The section below explains the design and functionality of the computer tool. Figure 2.7 shows a screen shot of the Excel-based computer tool with a realistic portfolio built on its screen.

### ***2.2.1. Design of the Computer Tool***

To make users’ decision scenario realistic, the computer tool allows users to build their portfolio at the power plant level. For instance, participants are told that a status quo scenario for PA would include the construction of 6 new coal plants, 4 new natural gas plants, 3 new nuclear plants and 1 new wind farm in the next 25 years. The ‘power plant construction’ occurs in the *Build Center* (Figure 2.8), where participants can use slider bars to build power plants. The tool

provides output showing the electricity produced by those plants (See Appendix A for calculation details) to the right of the slider bars. The bar graph on the right side of the *Build Center* represents the electricity generation by each technology as a percent of the electricity goal (i.e., 60 TWh). The bar for natural gas is separated in two to represent (1) the amount of natural gas controlled by the user (shown as a solid blue bar) and (2) the natural gas that is automatically added when a user includes solar or wind farms (shown as a striped bar). Natural gas capacity is added automatically at a ratio of 1 Watt of natural gas to 1 Watt of intermittent renewables (26). Thus, the user will see approximately 1 natural gas plant added to back up every 2 large-scale wind farms or every 3 large-scale solar plants (see Appendix A for more details).

The two constraints that users must adhere to are shown in the *Goal Center* (Figure 2.9). The bars on the two graphs increase as “CO<sub>2</sub> released” and “electricity produced” from the built portfolio increases. Users are warned if the direct CO<sub>2</sub> emissions from their portfolio increases beyond the 50% limit. They are permitted to create a portfolio that generates between 60 and 70 TWh, receiving a notice when their portfolio meets the 60 TWh goal and a warning when it increases beyond 70 TWh. This 10 TWh cushion is provided to users because it may be difficult for them to create a portfolio that generates exactly 60 TWh.

The interactive tool provides environmental indicators in the *Impacts center* (Figure 2.10). We chose Olympic-sized swimming pools per year and football fields as the units for water use and land use, respectively. Read aloud studies with the tool indicated that these units were preferred to units of gallons or acres. Each environmental indicator presented to participants includes its value under the status quo scenario, its value for the user’s portfolio and the percent change from the status quo. The rows are color-coded, such that values much greater

than the status quo are highlighted in red, values close to those of the status quo are highlighted yellow and those much less are in green.

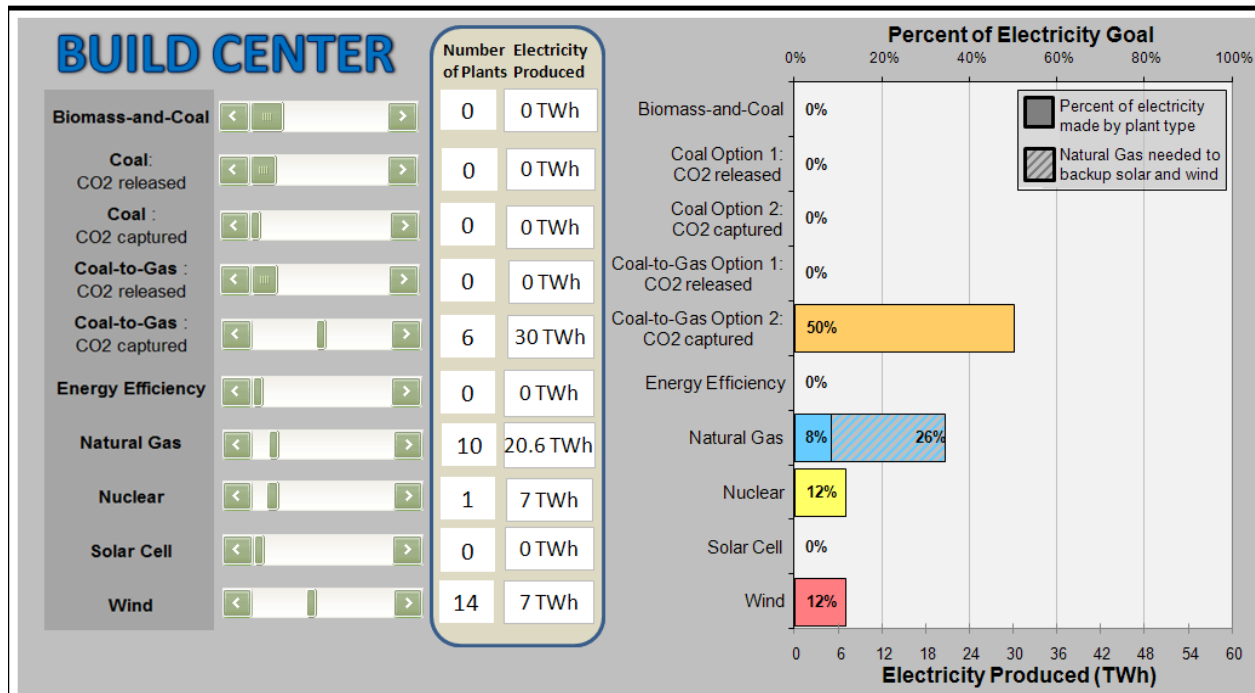


Figure 2.8. The *Build Center* of the computer tool

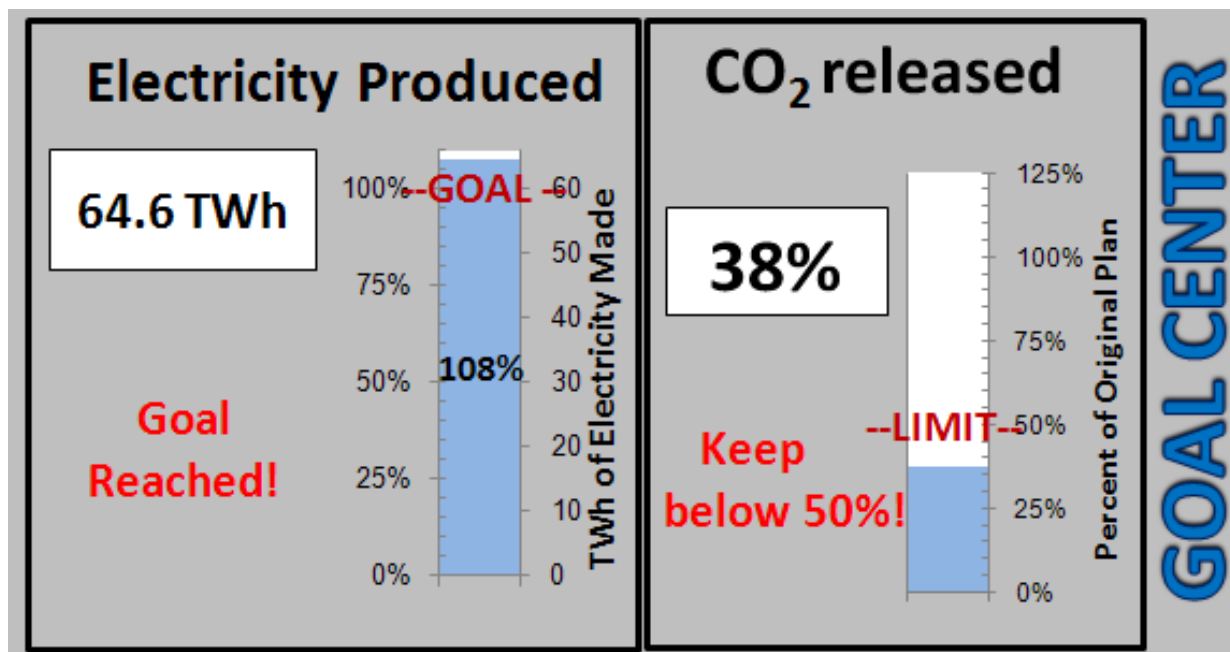


Figure 2.9. The *Goal Center* of the computer tool

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%

Figure 2.10 The *Impacts* center of the computer tool

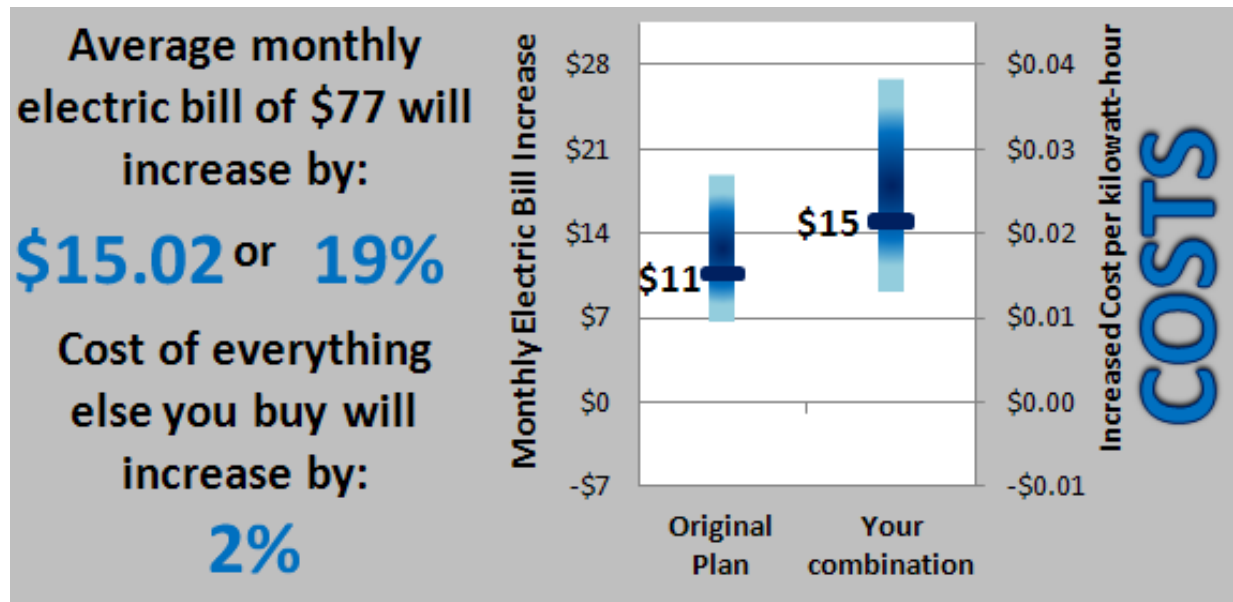


Figure 2.11. The *Costs* center of the computer tool

Additionally, the interactive tool includes a *Cost* Center (Figure 2.11), which presents a graph with uncertainty bars showing the increased cost in the monthly bill (left side y-axis) and in \$/kWh (right side y-axis) for the median PA household, for both the status quo scenario and the user's portfolio. The most likely increase in monthly electric bill is also presented as text, both as a dollar value and as a percent increase relative to the "average PA monthly electric bill" of \$77 (i.e., the product of \$0.11/kWh and 700 kWh/month). Additionally, to emphasize that an increase in electricity cost will affect more than simply the residential electricity bill, we presented a cost-of-living indicator. We assumed that energy costs account for 10% of the



consumer's cost of living (27). For every 10% increase in electricity bill cost then, the user would see a 1% increase in the "cost of everything else you buy."

After building a portfolio, users can save it by pressing the "review and save" button, which was programmed only to save portfolios that met the two constraints of CO<sub>2</sub> emissions and electricity generated. Users can save up to three portfolios and each would appear in the selection box next to the "review and save" button. Users can then recall these save portfolios to the screen. Once a user has identified three proposed portfolios, they can press the "compare" button that changes the user view to a *Compare* screen (Figure 2.12). Here, users can compare the three portfolios across the attributes of CO<sub>2</sub>, increased monthly costs, health costs, land use and water use.

Results of the study in which we elicit low-carbon portfolio preferences with the computer tool are reported on in Chapter 5. Chapters 3 and 4 present results from elicitations with the paper-based materials. For more information about the assumptions and calculations that were used in the paper materials and computer tool, see Appendix A.

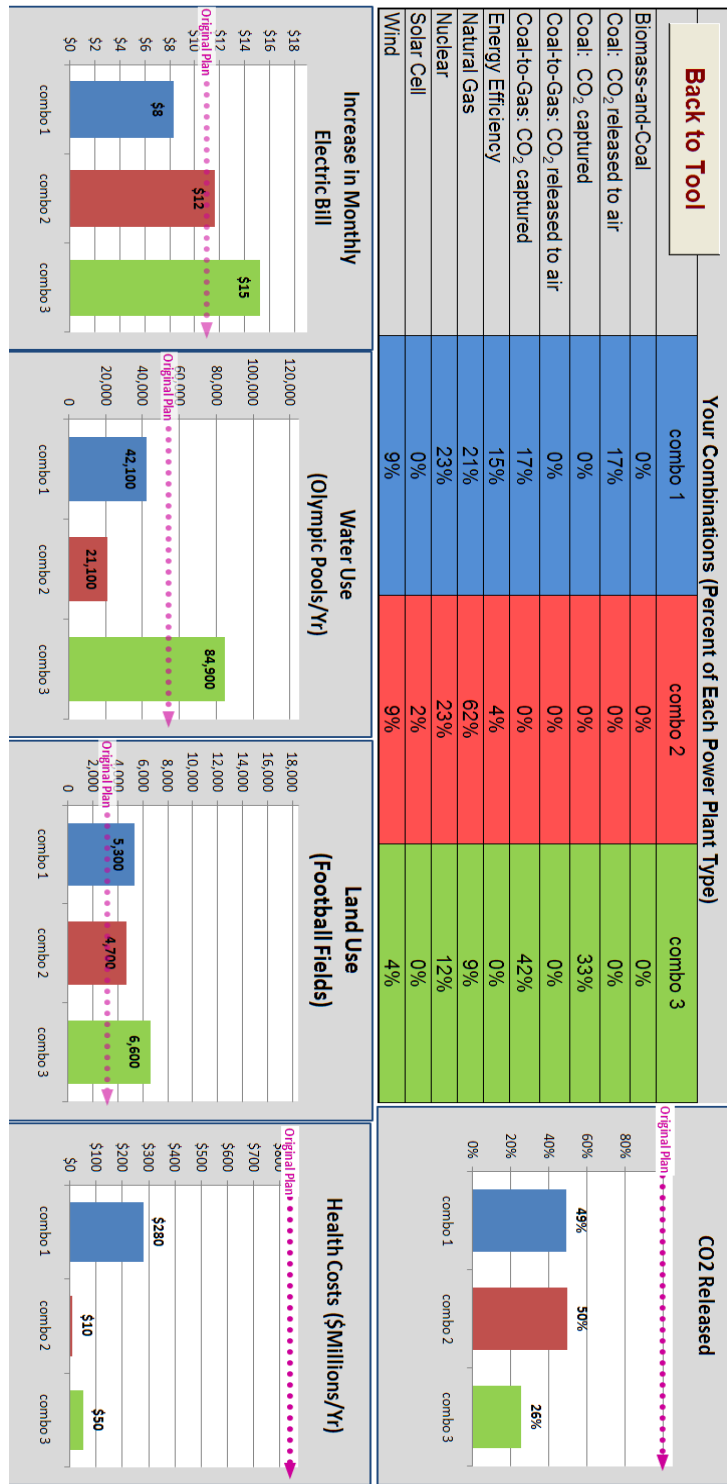


Figure 2.12. Screen shot of *Compare* screen of the Portfolio-Building Computer Decision Tool

## References

1. Morgan MG, Fischhoff B, Bostrom A, & Atman CJ (2002) *Risk Communication: A Mental Models Approach* (Cambridge University Press, New York).
2. Maharik M & Fischhoff B (1992) The risks of using nuclear energy sources in space: some lay activists' perceptions. *Risk Analysis* 12(3):383-391.
3. Fischhoff B, Bruine de Bruin W, Güvenç U, Brilliant L, & Caruso D (2006) Analyzing disaster risks and plans: An Avian Flu Example. *Journal of Risk and Uncertainty* 33:131-149.
4. Morgan KM, *et al.* (2001) A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers. *Risk Analysis* 21(5):923-937.
5. Florig KH, *et al.* (2001) A deliberative method for ranking risks (I): Overview and test bed development. *Risk Analysis* 21(5):913-921.
6. Wallquist L, Visschers VHM, & Siegrist M (2009) Lay concepts on CCS deployment in Switzerland based on qualitative interviews. *International Journal of Greenhouse Gas Control* 3(5):652-657.
7. Plate R, Monroe M, & Oxarart A (2010) Public Perceptions of Using Woody Biomass as a Renewable Energy Source. *Journal of Extension* 48(3):1-15.
8. Ansolabehere S (2007) Public attitudes toward American's energy options : report of the 2007 MIT Energy Survey. (Massachusetts Institute of Technology. Center for Energy and Environmental Policy Research., Cambridge, MA).
9. Farhar B & Buhrmann J (1998) Public Response to Residential Grid-Tied PV Systems in Colorado: A Qualitative Market Assessment A Qualitative Market Assessment. (National Renewable Energy Laboratory, Golden, CO).
10. Grove-White R, Kearnes M, Macnaghten P, & Wynne B (2006) Nuclear Futures: Assessing public attitudes to new nuclear power. *The Political Quarterly* 77(2):238-246.
11. Poortinga W, Pidgeon NF, & Lorenzoni I (2006) Public Perceptions of Nuclear Power, Climate Change and Energy Options in Britain: Summary Findings of a Survey Conducted during October and November 2005. Technical Report. (Centre for Environmental Risk, Norwich).
12. Purvis-Roberts KL, Werner CA, & Frank I (2007) Perceived Risks from Radiation and Nuclear Testing Near Semipalatinsk, Kazakhstan: A Comparison Between Physicians, Scientists, and the Public. *Risk Analysis* 27(2):291-302.
13. Razek JR & Cone RE (1981) Readability of Business Communication Textbooks-An Empirical Study. *Journal of Business Communication* 18(2):33-40.

14. Kincaid JP, Fishburne RP, Rogers RL, & Chissom BS (1975) Derivation of new readability formulas (Automated Readability Index, Fog Count and Flesch Reading Ease Formula) for Navy enlisted personnel. (Naval Technical Training, U.S. Naval Air Station Memphis, TN).
15. Flesch R (1948) A new readability yardstick. *Journal of Applied Psychology* 32(2):221-233.
16. Velez P & Ashworth SD (2007) The Impact of Item Readability on the Endorsement of the Midpoint Response in Surveys. *Survey Research Methods* 1(2):69-74.
17. Just MA & Carpenter PA (1980) A theory of reading: From eye fixations to comprehension. *Psychological Review* 87(4):329-354.
18. Lipkus IM (2007) Numeric, Verbal, and Visual Formats of Conveying Health Risks: Suggested Best Practices and Future Recommendations. *Medical Decision Making* 27(5):696-713.
19. Schirillo J & Stone E (2005) The greater ability of graphical versus numerical displays to increase risk avoidance involves a common mechanism. *Risk Analysis* 25(3):555-566.
20. Bostrom A, Anselin L, & Farris J (2008) Visualizing Seismic Risk and Uncertainty. *Annals of the New York Academy of Sciences* 1128(1):29-40.
21. Ibrek H & Morgan MG (1987) Graphical Communication of Uncertain Quantities to Nontechnical People. *Risk Analysis* 7(4):519-529.
22. Larkin JH & Simon HA (1987) Why a Diagram is (Sometimes) Worth Ten Thousand Words. *Cognitive Science* 11(1):65-100.
23. Chandler P & Sweller J (1991) Cognitive Load Theory and the Format of Instruction. *Cognition and Instruction* 8(4):293 - 332.
24. Mayer RE & Moreno R (2003) Nine Ways to Reduce Cognitive Load in Multimedia Learning. *Educational Psychologist* 38(1):43 - 52.
25. Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.
26. Katzenstein W & Apt J (2009) Response to Comment on “Air Emissions Due to Wind and Solar Power”. *Environmental Science & Technology* 43(15):6108-6109.
27. Bureau of Labor Statistics (2010) Consumer Price Index for All Urban Consumers

### **Chapter 3. Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies<sup>1</sup>**

#### **Abstract**

Public perceptions of carbon capture and sequestration (CCS) and other low-carbon electricity generating technologies may affect the feasibility of their widespread deployment. We asked a diverse sample of 60 participants recruited from community groups in Pittsburgh, PA to rank ten technologies (e.g., coal with CCS, natural gas, nuclear, various renewables, and energy efficiency), and seven realistic low-carbon portfolios composed of these technologies, after receiving comprehensive and carefully balanced materials that explained the costs and benefits of each technology. Rankings were obtained in small group settings as well as individually before and after the group discussions. The ranking exercise asked participants to assume that the U.S. Congress had mandated a reduction in CO<sub>2</sub> emissions from power plants to be built in the future. Overall, rankings suggest that participants favored energy efficiency, followed by nuclear, integrated gasification combined-cycle coal (IGCC) with CCS and wind. The most preferred portfolio also included these technologies. We find that these informed members of the general public preferred diverse portfolios that contained CCS and nuclear over alternatives once they fully understood the benefits, cost and limitations of each. The materials and approach developed for this study may also have value in educating members of the general public about the challenges of achieving a low-carbon energy future.

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<sup>1</sup> This chapter has been published as: Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.

### 3.1. Introduction

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

Renewable electricity sources, such as wind turbines, and perhaps solar thermal systems, will likely also play an important role in de-carbonizing the electricity grid, but are currently unable to reliably meet demand for electricity (3). The power generated by these technologies is too intermittent, requiring fossil-fuel powered plants or expensive energy storage systems to provide backup power when it is not windy or sunny (4). Therefore, to ensure that electricity generation in the near future remains reliable and cost-effective, with minimal risk of supply disruptions, any *significant* reductions in electricity sector CO<sub>2</sub> emissions will likely need to involve more reliable and available low-carbon technologies such as coal plants with CCS, natural gas, or nuclear power (3).

For any of these low-carbon technologies to become a viable option for reducing CO<sub>2</sub> emissions, people must find them acceptable for widespread deployment. In the past, public acceptance has proven to be a major obstacle to the cost-effective development of new energy infrastructure, including oil refineries (5), nuclear power plants (6), pilot-scale CCS technologies (7) and even wind farms (8). For example, ever since the reactor meltdown at Three Mile Island, people have been reluctant to accept new nuclear power plants (9, 10), in part because they

believe that they may emit dangerous levels of radiation (11, 12). In addition, public perceptions of CCS include the fear that CO<sub>2</sub> “burps” will be released from the ground and cause suffocation (13-15). Negative public sentiment also exists towards wind turbines, which some people perceive as noisy, aesthetically unappealing and a threat to birds and bats (8, 16). Yet, many people believe that it is possible to rely on an electricity generation portfolio composed of 100% variable and intermittent renewables (14) – even though technical experts raise serious doubts (3).

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

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

Palmgren and colleagues (13) applied a modified mental models approach to explore initial public perceptions of CCS. In open-ended interviews, they examined lay people's knowledge and beliefs about CCS. They found that interviewees preferred not to evaluate CCS on its own, but rather in the context of other technologies that might be used to reduce CO<sub>2</sub> emissions. These findings have been replicated in public perception studies of CCS (14, 19), and nuclear plants (34). In a subsequent study, Palmgren et al. (13) therefore asked survey respondents to rank their willingness to pay for a set of electricity-generating portfolios, each reducing carbon emissions by 50% compared to a portfolio of 100% "regular" coal plants. The two low-carbon portfolios that included coal plants with CCS (combined with regular coal



plants) were ranked below all other portfolios, while the portfolio that included nuclear (also combined with regular coal plants) was ranked as the next worst.

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

In the present study, we examined people's *informed* decisions about electricity generating technologies by asking participants to rank ten technologies and seven portfolios composed of those technologies that were designed to meet a specific CO<sub>2</sub> emissions limit. We built on the work by Palmgren et al. (13), while rectifying four of its limitations. First, while Palmgren et al. presented simplified portfolios that relied too much on single technologies, we designed our seven portfolios to be realistic, reliable and representative of possible portfolios for expanding future electricity capacity. Second, while Palmgren et al. provided only a few sentences to describe each technology, we presented comprehensive and balanced information sheets for each, using simple wording and a systematic presentation format (37-39). Third, unlike Palmgren et al., we systematically covered the same set of attributes (including risks, benefits, and costs) in the presentation of each technology and portfolio. Fourth, in addition to providing their personal rankings (as in Palmgren et al.), our participants also ranked the

portfolios in a group exercise, allowing them to hear alternative views, to improve their engagement and understanding, and possibly revise their initial rankings (37-39).

## **3.2. Methods**

### **3.2.1. 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:

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

Each technology was described on a separate *Technology Sheet* (see Figure 3.1 for an example). To facilitate comparisons (37), each sheet systematically described the same attributes: *How it works*, *Cost*, *CO<sub>2</sub> released*, *Other pollution/waste*, *Availability*, *Reliability*, *Limits of use*, *Noise*, *Land use and ecology*, *Safety*, *Lifespan* and *Current use*. Technologies were systematically compared on an additional *Cost Comparison* (presenting best estimates with uncertainty bars for electricity cost per kilowatt-hour and estimated monthly electricity bills for the median Pennsylvania customer) as well as on a *Pollution Comparison* (presenting a relative comparison of technology emission rates for CO<sub>2</sub>, nitrogen oxides, sulfur dioxides, particulates and mercury).

# Traditional Coal Plants

## Option 1: CO<sub>2</sub> 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-use-pa.htm](http://www.industcards.com/st-coal-use-pa.htm)

When coal is burned, CO<sub>2</sub> is released by the plant. In **Option 1**, this CO<sub>2</sub> escapes into the air because no equipment is added to capture the CO<sub>2</sub>.

### MORE INFORMATION (ABOUT TRADITIONAL COAL PLANTS)

<b>Cost*</b>	Traditional coal plants make cheaper electricity than advanced coal plants. Yet, it is more expensive to add CO <sub>2</sub> capture equipment to traditional coal plants.*
<b>CO<sub>2</sub> released*</b>	Traditional coal plants release CO <sub>2</sub> to the air.*
<b>Other Pollution/Waste*</b>	<ul style="list-style-type: none"> <li>While these plants are much cleaner than in the past, they still release CO<sub>2</sub>, nitrogen oxides, sulfur dioxide, mercury and particulates to the air. These pollutants can cause people to have many different health problems.*</li> <li>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.</li> <li>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.</li> </ul>
<b>Availability</b>	Experts say that the U.S. has enough coal to meet its needs for at least 100 years.
<b>Reliability</b>	Coal can provide steady and dependable electricity.
<b>Limits of use</b>	Traditional coal plants release a lot of CO <sub>2</sub> . They cannot make all of the electricity that is needed in PA if we want to reduce CO <sub>2</sub> . Other types of plants must also be built.
<b>Noise</b>	These plants are about as loud as average street traffic.
<b>Land use and ecology</b>	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.
<b>Safety</b>	These plants are quite safe for operators. Coal mining is dangerous for the miners.
<b>Lifespan</b>	The lifetime of any plant is uncertain. But, a new traditional coal plant built today would likely make electricity for at least 50 years.
<b>Current Use</b>	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 3.1 Example of one of the ten technology sheets

**Table 3.1. The Low-Carbon Electricity Generation Portfolios Presented in this Study**

<b>Portfolio</b>	<b>Technology Composition</b>
<b>A:</b> Mix of PC with CCS and PC	81% PC Plants <i>with</i> CCS technologies 19% PC Plants
<b>B:</b> Mix of IGCC with CCS and IGCC	83% IGCC Plants <i>with</i> CCS technologies 17% IGCC Plants
<b>C:</b> Nuclear and PC mix	70% Advanced Nuclear Plants 30% PC Plants
<b>D:</b> Diverse EPRI portfolio, with no Nuclear or CCS	66% Natural Gas Plants 13% Energy Efficiency 10% Wind Power 6% Biomass Plants 5% Solar PV Power
<b>E:</b> Diverse portfolio, with IGCC with CCS, but no Nuclear	48% Natural Gas Plants 20% IGCC Plants <i>with</i> CCS technologies 13% Wind Power 13% Energy Efficiency 5% PC Plants 1% Solar PV Power
<b>F:</b> Diverse EPRI portfolio, with IGCC with CCS and Nuclear	25% IGCC Plants <i>with</i> CCS technologies 21% Advanced Nuclear Plants 20% Natural Gas Plants 17% PC Plants 10% Wind Power 7% Energy Efficiency
<b>G:</b> Natural Gas and Wind mix	66% Natural Gas Plants 34% Wind Power

We also presented seven low-carbon portfolios, referred to as *Power Plant Combinations* (Table 3.1), designed to emit 70% less CO<sub>2</sub> than a portfolio composed entirely of PC plants (the technology that currently generates a majority of the electricity in Pennsylvania). We chose portfolios that could reliably supply a 25% increase in electricity demand in PA in the next 25 years, while limiting the contribution of intermittent renewables to a realistic amount (e.g. <7%

for wind, <1% for solar PV<sup>2</sup>) (40). Four simple portfolios (i.e., A, B, C and G) relied mostly on one reliable technology. Two portfolios were based on diverse combinations proposed by the Electric Power Research Institute (2). The first (D) included predominantly renewables and increased efficiency efforts, using natural gas plants for baseload power and intermittency fill; and a second (F) had IGCC with CCS, nuclear, natural gas and renewables. We also included a third diverse portfolio (E) that used IGCC with CCS, natural gas and renewables, but no nuclear power. Portfolios were compared in sheets entitled *Cost Comparison for Combinations* and *Pollution Comparison for Combinations*.

We developed all materials with input from subject-matter experts with knowledge in the relevant areas to ensure balance and technical accuracy. Content was iteratively pilot-tested with members of the general public (29, 41). Subsequently, the materials were revised to improve identified concerns and misunderstandings, and double-checked by subject-matter experts. Despite the complexity of the materials, all were written at a 6<sup>th</sup> to 8<sup>th</sup> grade reading level, as reflected in the Flesch-Kincaid Grade Level readability statistic (42, 43). The complete set of the materials, including those described above, are available online at <http://sds.hss.cmu.edu/risk/fleishman/InformationMaterials.html>.

### **3.2.2. Participants**

A diverse sample of 60 participants was recruited through community organizations in the Greater Pittsburgh Metropolitan Area. Participants were 18 to 73 years old (M=36.7; Median=36). Of these, 63% were female, and 33% nonwhite, almost all of whom were African-American. All had graduated from high school, with 67% having completed at least a

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<sup>2</sup> Contribution of intermittent renewables was based on a percentage of the *total estimated capacity* of PA in 2030

Bachelor's degree in a non-technical field. By comparison, the U.S. population, is similar in age (Median=36.6), includes fewer females (51%) and African-Americans (13%), while being less educated (86% with a high school diploma and 28% with at least a Bachelor's degree) (44).

### **3.2.3. Procedure**

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

“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<sub>2</sub> 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<sub>2</sub>. Imagine that the Governor of PA has asked you to serve on a Citizen's Advisory Panel to give advice on the kinds of plants to build. Your job is to rank the different power plant types from best to worst.”

After reading the homework materials, but prior to attending the group meeting, participants provided *pre-discussion technology rankings* ranging from best (=1) to worst (=10). They also provided *pre-explanation comprehension ratings* of the 5 information sheets, on a scale anchored at very hard (=1) and very easy (=7). Participants then rated their agreement with the 15 environmental statements appearing on Dunlap et al.'s (45) *New Ecological Paradigm*

(NEP) scale, with responses anchored at completely disagree (=1) and completely agree (=7). Finally, they answered 15 *true-or-false knowledge questions* about their homework materials, focusing on those issues that had been most commonly misunderstood in the pilot tests described above.

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

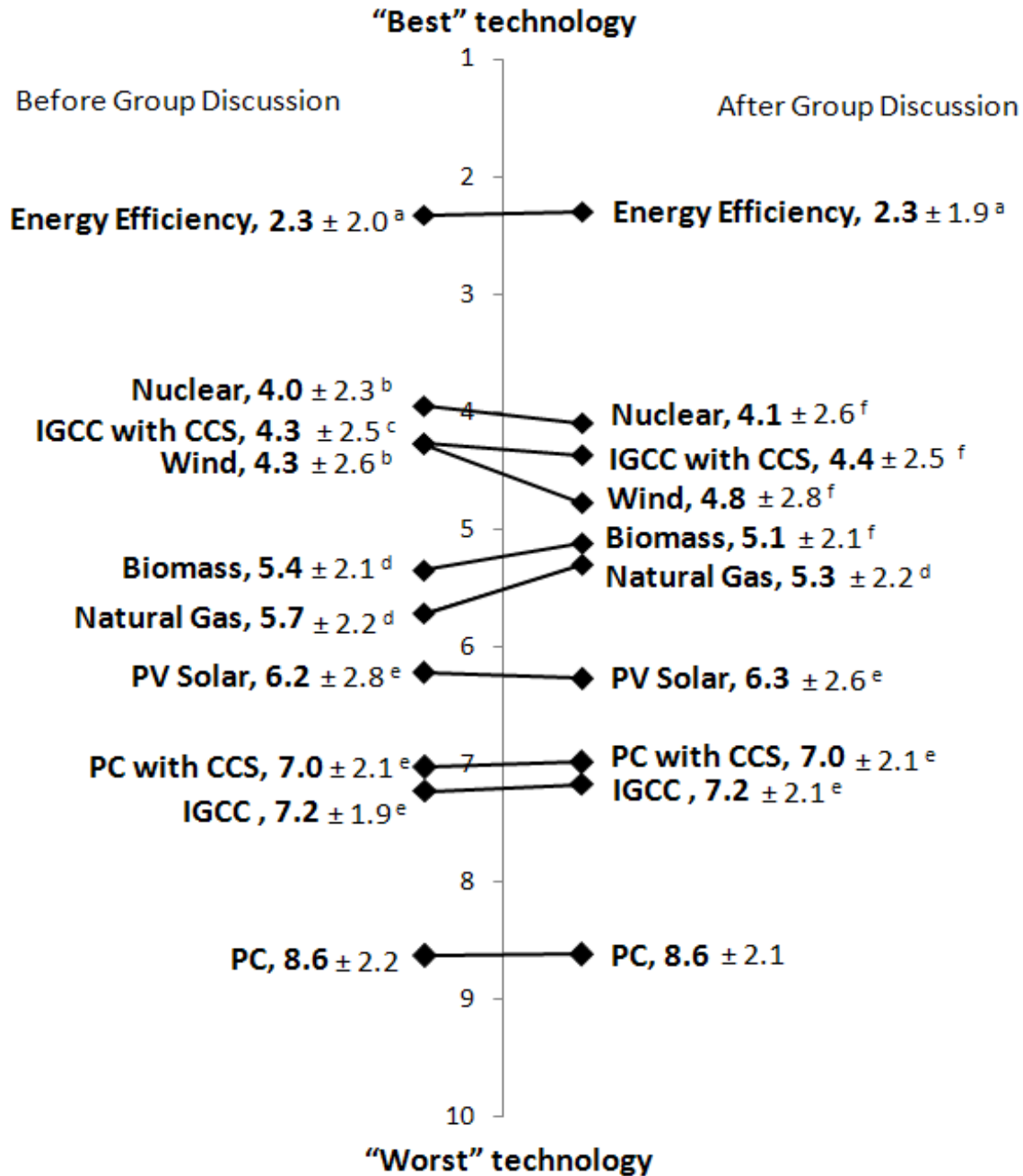
Next, participants worked together as a group to rank the portfolios in a sorting exercise, which was facilitated by the experimenter and adapted from earlier risk ranking studies (37-39). They then individually reviewed their personal rankings, and provided *post-discussion portfolio and technology rankings*. They also provided individual *post-discussion comprehension ratings*, which were similar to those provided pre-discussion. Finally, questions about CCS were answered at the end, so as not to attract special attention to CCS during the ranking exercises. Participants provided a *CCS favorability rating* on a scale anchored at completely oppose (=1) to completely favor (7) CCS. 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.

### 3.3. Results

#### 3.2.1. Technology Rankings

We computed Kendall's coefficient of concordance ( $W$ ) to examine the consistency of participants' personal rankings of the ten technologies. It showed a high degree of agreement between *pre-discussion rankings*, provided before the group discussion ( $W=0.38$   $p<0.001$ ), as well as between *post-discussion rankings*, provided after the group discussion ( $W=0.36$ ,  $p<0.001$ ). Figure 3.2 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* ( $p>0.05$ ). For each technology, we also examined the effect of group discussion on agreement, using Wilcoxon paired-rank tests to compare post-discussion agreement (seen in the mean absolute deviation of individuals' *post-discussion rankings* from the group mean *post-discussion rankings* of that technology) with pre-discussion agreement (seen in the mean absolute deviation of individuals' *pre-discussion rankings* from the group mean *pre-discussion rankings* of that technology). Setting  $\alpha=0.01$  to correct for the number of tests, we found that group discussion increased participant's agreement about energy efficiency, which had significantly higher post-discussion agreement than pre-discussion agreement (Wilcoxon  $z=-2.54$ ,  $p=0.01$ ).





**Figure 3.2. Participants' mean technology rankings  $\pm$  standard deviation, pre- (left) and post-discussion (right).**

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: PC with CCS, IGCC and PC were ranked significantly worse
- e: PC was ranked significantly worse
- f: PV, PC with CCS, IGCC and PC were ranked significantly worse

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants' rankings for each possible pair of technologies, as provided *pre-* and *post-discussion*. The superscripted letters in Figure 3.2 indicate, for each technology, the other technologies that were ranked as significantly “worse”. Due to the large number of these comparisons, we only report those that are significant at  $\alpha=0.01$ . Overall, energy efficiency was significantly preferred to all other alternatives, both *pre-* and *post-discussion*. The second best mean ranking was for nuclear power, whose rankings were not significantly different from those for IGCC with CCS, wind, biomass *post-discussion* and natural gas *post-discussion* -- which, respectively, ranked third through sixth, on average. The other mean rankings were, in order, (7) solar PV, (8) PC with CCS, (9) IGCC without CCS, and (10) PC without CCS. Perhaps most notably, each coal technology (IGCC, PC) was significantly preferred with (vs. without) CCS. Further, the more advanced coal technology (IGCC) was significantly preferred over the more conventional coal technology (PC) – whether with or without CCS.

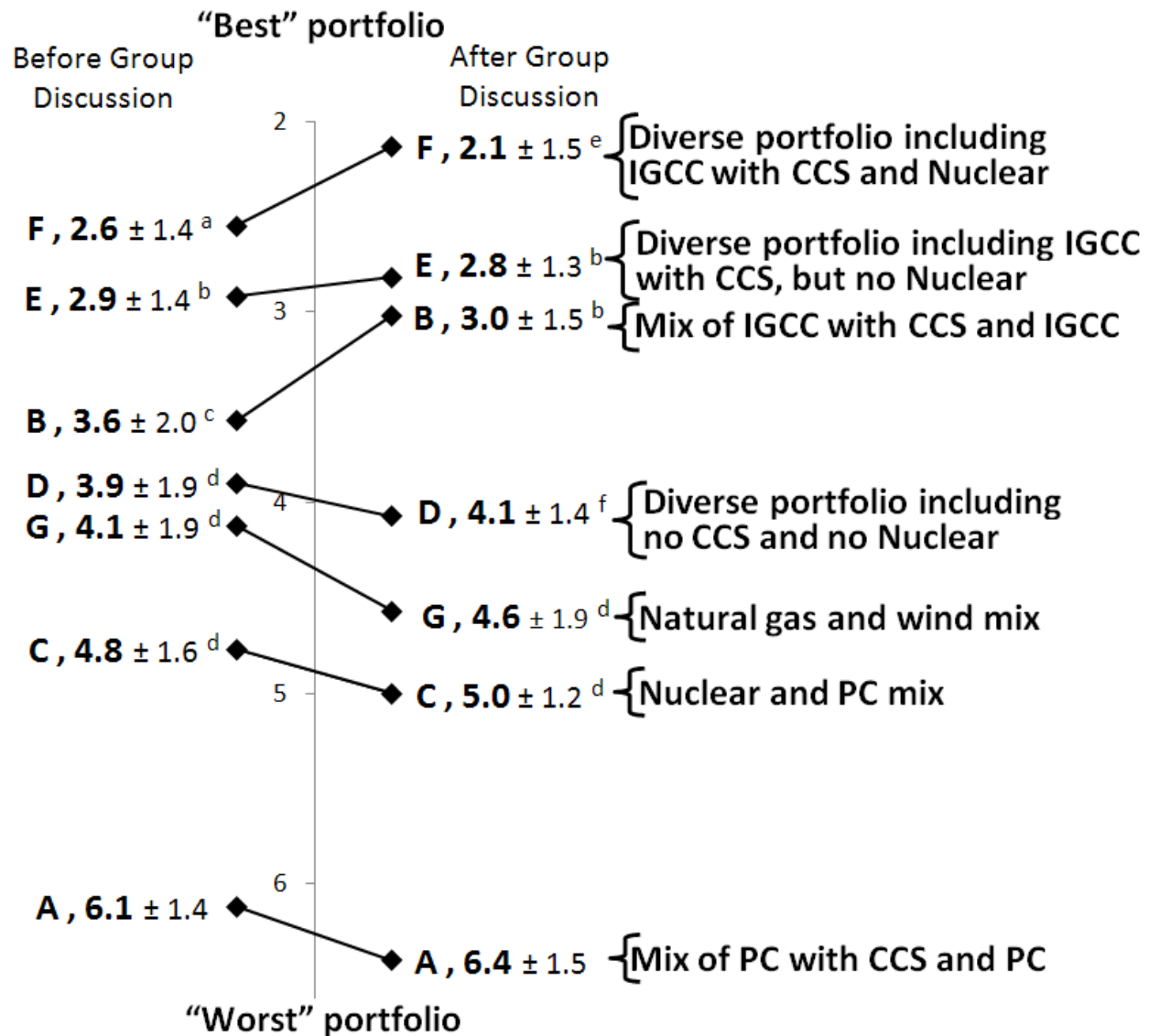
### **3.3.2. Portfolio Rankings**

Kendall's coefficient of concordance showed a high degree of agreement between participants' *pre-discussion rankings* ( $W=0.31, p<0.001$ ) and their *post-discussion rankings* of the seven portfolios ( $W=0.46, p<0.001$ ). Figure 3.3 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* ( $p>0.05$ ). As with the technologies, we examined the effect of group discussion on participants' agreement about each portfolio, using

Wilcoxon paired-rank tests to compare post-discussion agreement (seen in the mean absolute deviation of individuals' *post-discussion rankings* from the group mean *post-discussion rankings* of that technology) with pre-discussion agreement (seen in the mean absolute deviation of individuals' *pre-discussion rankings* from the group mean *pre-discussion rankings* of that technology). Post-discussion agreement was significantly higher than pre-discussion agreement for every portfolio (with all Wilcoxon  $z < -3.31$ ,  $p < 0.001$ ).

### ***3.3.3. Viewpoints on Environmental Issues and CCS***

Participants' responses to the 15 *NEP scale ratings* were scored such that higher ratings reflected stronger pro-environmental attitudes, and had good internal consistency (Cronbach's  $\alpha=0.68$ ). Participants' mean *NEP scale ratings* ( $M=4.67$ ,  $SD=0.64$ ) were significantly above the scale midpoint of 4 ( $t=8.14$ ,  $p<0.001$ ), suggesting pro-environmental attitudes. Spearman correlations between the mean *NEP scale ratings* and participants *post-discussion rankings* (reverse-coded for these analyses, such that higher numbers reflect a higher preference) suggest that participants who were more pro-environmental preferred wind ( $r_s=0.35$ ,  $p=0.01$ ), as well as two of the four portfolios including this technology ( $r_s=0.29$ ,  $p=0.02$  for portfolio D and  $r_s=0.30$ ,  $p=0.02$  for portfolio E). A negative correlation was also found between the mean *NEP scale ratings* and the portfolio that included IGCC with CCS and no wind ( $r_s=-0.36$ ,  $p=0.01$  for portfolio B).



**Figure 3.3. Participants’ mean portfolio rankings ± standard deviation, *pre-* (left) and *post-* discussion (right)**

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
- f: portfolios G, C and A were ranked significantly worse

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

#### **3.3.4. Participant Comprehension**

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

Participants' *comprehension ratings* also suggest a basic understanding of the materials prior to receiving the experimenter's verbal explanation or group discussion. The *Cost Comparison* received the lowest mean *comprehension rating* ( $M=5.28$ ,  $SD=1.55$ ), which was still significantly above the midpoint of 4 ( $t=6.25$ ,  $p<0.001$ ). All other *comprehension ratings* for the information materials and attributes were also found to be significantly above the scale midpoint ( $p<0.001$  for each). A planned contrast, conducted in a repeated measures ANOVA examining all 5 *comprehension ratings* by their timing (*pre-explanation*, *post-explanation*, *post-discussion comprehension*) showed a significant linear increase in ratings over time ( $F(1$ ,

48)=9.41,  $p<0.01$ ; with *pre-explanation*  $M=5.75$ ,  $SD=1.07$ , *post-explanation*  $M=6.00$ ,  $SD=0.93$ , *post-discussion*  $M=6.21$ ,  $SD=0.82$ ), thus suggesting that the group sessions helped to improve participants' comprehension of the information materials.

### **3.4. Discussion**

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

Surprisingly, most of our participants seemed to have relatively favorable views of nuclear power. The technology received the second best ranking, and the diverse portfolio that included nuclear was preferred *post-discussion* 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 (47, 48).

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

Our results contrast starkly with those of previous studies, which suggest much lower public acceptance of CCS (13, 20) and nuclear (10, 34), as well as unstable preferences (18). One potential explanation for that difference is that our participants made more informed

decisions about these technologies. Their understanding of our comprehensive communication materials improved steadily during the course of the study, due to receiving carefully designed step-by-step instructions, and actively engaging in deliberative group discussions. Second, our study asked participants to consider these technologies as part of realistic low-carbon portfolios, which tend to be preferred over CCS (13, 14, 19) or nuclear (10, 11) in isolation. Third, our results asked participants to rank these technologies and portfolios relative to low-carbon alternatives, while previous studies asked participants to rate these technologies in isolation. Although people may be reluctant to accept specific technologies such as CCS (18) and nuclear (10, 34), as seen in their individual ratings, they may nevertheless prefer them over other alternatives, which can be seen in rankings.

Moreover, while ratings may allow survey respondents to express the magnitude of their preferences between technologies, rankings reflect explicit comparisons between technologies, based on tradeoffs between their perceived gains and losses. Perhaps as a result, CCS *favorability ratings*, in which CCS was treated in isolation, were not correlated with their rankings of technologies or portfolios that included CCS, suggesting that the two tasks reflect different thought processes. Rankings can provide decision-relevant results for policy-makers who use risk-ranking methods to order priorities in government agencies (49). Moreover, when these rankings are provided by a well-informed sample, they are more likely to be reliable (i.e., be consistent with people's values and remain stable over time) (18).

Our study used a local convenience sample from the Pittsburgh Metropolitan area. Firm conclusions cannot be drawn about informed public preferences for these low-carbon technologies and portfolios in other locations. However, our results do suggest that our materials, which gave participants a stable basic understanding, and our group meeting



procedure, which further improved understanding of the materials and resolved some disagreement, may be useful for helping members of the general public to make more informed decisions about which low-carbon technologies to support. The materials and the approach can easily be adapted for use in other settings including classrooms and museums.

Although the materials and group meeting procedure may be useful to inform members of the general population about general public choices for low-carbon technologies, people living near specific energy infrastructure sites may have different informational needs. In such communities, there is often a complex interplay of political, social, environmental and economic factors that influence people's perceptions, which otherwise do not play a role in the shaping of general public perceptions about technologies (7). For example, community opposition is often influenced by issues of trust (7, 21, 50-52) and may not depend on the *type* of energy facility being sited, but rather on the decision-makers who are involved in the siting process. Outside of our controlled setting, uninformed members of the general public will also likely be persuaded with biased messages from advocates. Thus, no assurance exists that public debates over energy policy will result in the informed preferences found in our study. Nevertheless, had our respondents not found diverse portfolios containing CCS and nuclear to be preferable to others, the tasks facing energy policy decision-makers would be much more challenging. Policy-makers and electricity utility or power companies could adapt the materials and approach to pro-actively engage communities in the energy infrastructure siting process, educating them and gauging their perceptions. Policy-makers could find the materials especially helpful when communicating with their constituents about the tradeoffs between the costs, risks and benefits of energy policy or siting decisions.

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

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

## References

1. IPCC (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. ed B. Metz ORD, P.R. Bosch, R. Dave, L.A. Meyer (Cambridge, United Kingdom and New York, NY).
2. James R, Richels R, Blanford G, & Gohl S (2007) The Power to Reduce CO<sub>2</sub> Emissions: The Full Portfolio. (The EPRI Technology Assessment Center, Electric Power Research Institute, Palo Alto, CA.).
3. Apt J, Lave LB, & Pattanariyankool S (2008) A National Renewable Portfolio Standard? Not Practical. *Issues in Science and Technology* (Fall).
4. Walawalker R, Apt J, & Mancini R (2007) Economics of electric energy storage for energy arbitrage and regulation in New York. *Energy Policy* 35(4):2558-2568.
5. Mouward J (May 9, 2005) No New Refineries in 29 Years? There Might Well Be a Reason. New York Times.
6. Guigni M (2004) *Social protest and policy change: ecology, antinuclear, and peace movements in comparative perspective* (Rowman and Littlefield, Lanham, MD).
7. Bradbury J, *et al.* (2009) The Role of Social Factors in Shaping Public Perceptions of CCS: Results of Multi-State Focus Group Interviews in the U.S. *Energy Procedia* 1(1):4665-4672.

8. Firestone J & Kempton W (2007) Public opinion about large offshore wind power: Underlying factors. *Energy Policy* 35(3):1584-1598.
9. Curry TE, Ansolabehere S, & Herzog H (2007) A survey of public attitudes towards climate change and climate change mitigation technologies in the United State: Analyses of 2006 results. (Massachusetts Institute of Technology, Cambridge, Massachusetts).
10. Grove-White R, Kearnes M, Macnaghten P, & Wynne B (2006) Nuclear Futures: Assessing public attitudes to new nuclear power. *The Political Quarterly* 77(2):238-246.
11. Poortinga W, Pidgeon NF, & Lorenzoni I (2006) Public Perceptions of Nuclear Power, Climate Change and Energy Options in Britain: Summary Findings of a Survey Conducted during October and November 2005. Technical Report. (Centre for Environmental Risk, Norwich).
12. Purvis-Roberts KL, Werner CA, & Frank I (2007) Perceived Risks from Radiation and Nuclear Testing Near Semipalatinsk, Kazakhstan: A Comparison Between Physicians, Scientists, and the Public. *Risk Analysis* 27(2):291-302.
13. Palmgren CR, Morgan MG, Bruine de Bruin W, & Keith DW (2004) Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. *Environ Sci Technol* 38(24):6441-6450.
14. Ashworth P, Boughen N, Mayhew M, & Millar F (2009) An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond. *Energy Procedia* 1(1):4749-4756.
15. Wallquist L, Visschers VHM, & Siegrist M (2009) Lay concepts on CCS deployment in Switzerland based on qualitative interviews. *International Journal of Greenhouse Gas Control* 3(5):652-657.
16. Gross C (2007) Community perspectives of wind energy in Australia: The application of a justice and community fairness framework to increase social acceptance. *Energy Policy* 35(5):2727-2736.
17. Reiner D, *et al.* (2006) An international comparison of public attitudes towards carbon capture and storage technologies. *Proceedings of the 8th international conference on greenhouse gas control technologies.*, eds JJ G, N R, P Z, & H S (Elsevier, London, UK).
18. de Best-Waldhober M, Daamen D, & Faaij A (2009) Informed and uninformed public opinions of CO<sub>2</sub> capture and storage technologies in the Netherlands. *International Journal of Greenhouse Gas Control* 3(3):322-332.
19. Sharp J (2005) Public Attitudes towards Geological Disposal of Carbon Dioxide in Canada,. (School of Resource and Environmental Management, Simon Frasier University).

20. Reiner D, *et al.* (2006) American Exceptionalism? Similarities and Differences in National Attitudes Toward Energy Policy and Global Warming. *Environ Sci Technol* 40:2093-2098.
21. Huijts NMA, Midden CJH, & Meijnders AL (2007) Social acceptance of carbon dioxide storage. *Energy Policy* 35(5):2780-2789.
22. Fishkin J (2006) Strategies of Public Consultation. *Integrated Assessment* 6(2):57-72.
23. Itaoka K, Okuda Y, Saito A, & Akai M (2009) Influential information and factors for social acceptance of CCS: The 2nd round survey of public opinion in Japan. *Energy Procedia* 1(1):4803-4810.
24. Price V & Neijens P (1997) OPINION QUALITY IN PUBLIC OPINION RESEARCH. *International Journal of Public Opinion Research* 9(4):336-360.
25. Reiner D (2008) A looming rhetorical gap: A survey of public communication activities for carbon dioxide capture and storage technologies. in *Electricity Policy Research Group Working Papers* (University of Cambridge, Cambridge, UK).
26. Morgan MG, Fischhoff B, Bostrom A, Lave LB, & Atman C (1992) Communicating risk to the public. *Environmental Science & Technology* 26(11):2048-2056.
27. Fischhoff B, Slovic P, & Lichtenstein S (1982) Lay foibles and expert fables in judgments about risk. *The American Statistician* 36(3):240-255.
28. Bruin de Bruine W (2009) Judgment and decision making in adolescents. *Judgment and decision making as a skill: Learning, development, and evolution*, eds Dhimi M, Schlottmann A, & Waldmann M (Cambridge University Press, Cambridge).
29. Morgan MG, Fischhoff B, Bostrom A, & Atman CJ (2002) *Risk Communication: A Mental Models Approach* (Cambridge University Press, New York).
30. Maharik M & Fischhoff B (1992) The risks of using nuclear energy sources in space: some lay activists' perceptions. *Risk Analysis* 12(3):383-391.
31. Bruin de Bruine W, Fischhoff B, Guvenc U, Caruso D, & Armstrong CM (2009) A model-based scenario approach to communicating the risks of xenotransplantation. *Risk Analysis* 29:1105-1115.
32. Downs JS, *et al.* (2004) Interactive video behavioral intervention to reduce adolescent females' STD risk: a randomized controlled trial. *Social Science & Medicine* 59(8):1561-1572.
33. Fischhoff B, Bruine de Bruin W, Güvenç U, Brilliant L, & Caruso D (2006) Analyzing disaster risks and plans: An Avian Flu Example. *Journal of Risk and Uncertainty* 33:131-149.

34. Pidgeon NF, Lorenzoni I, & Poortinga W (2008) Climate change or nuclear power—No thanks! A quantitative study of public perceptions and risk framing in Britain. *Global Environmental Change* 18(1):69-85.
35. Itaoka K, Saito A, & Akai M (2004) Public acceptance of CO<sub>2</sub> capture and storage technology: A Survey of public opinion to explore influential factor. *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies*, eds Rubin ES, Keith DW, & Gilboy CF.
36. Kaldellis JK (2005) Social attitude towards wind energy applications in Greece. *Energy Policy* 33:595-602.
37. Florig KH, *et al.* (2001) A deliberative method for ranking risks (I): Overview and test bed development. *Risk Analysis* 21(5):913-821.
38. Morgan KM, *et al.* (2001) A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers. *Risk Analysis* 21(5):923-937.
39. Willis HH, DeKay ML, Morgan MG, Florig HK, & Fischbeck PS (2004) Ecological Risk Ranking: Development and Evaluation of a Method for Improving Public Participation in Environmental Decision Making. *Risk Analysis* 24(2):363-378.
40. Assembly PG (2004) Senate Bill No. 1030: Providing for the sale of electric energy generated from renewable and environmentally beneficial sources, for the acquisition of electric energy generated from renewable and environmentally beneficial sources by electric distribution and supply companies and for the powers and duties of the Pennsylvania Public Utility Commission.
41. Presser S & Blair J (1994) Survey Pretesting: Do Different Methods Produce Different Results? *Sociological Methodology*, ed Marsden P (Jossey-Bass, San Francisco, CA), pp 73-104.
42. Flesch R (1948) A new readability yardstick. *Journal of Applied Psychology* 32(2):221-233.
43. Kincaid JP, Fishburne RP, Rogers RL, & Chissom BS (1975) Derivation of new readability formulas (Automated Readability Index, Fog Count and Flesch Reading Ease Formula) for Navy enlisted personnel. (Naval Technical Training, U.S. Naval Air Station Memphis, TN).
44. Bureau USC (2010) Generated by Fleishman LA using American FactFinder.
45. Dunlap RE, Van Liere KD, Mertig AG, & Jones RE (2000) New Trends in Measuring Environmental Attitudes: Measuring Endorsement of the New Ecological Paradigm: A Revised NEP Scale. *Journal of Social Issues* 56(3):425-442.
46. Liu Q, Shi M, & Jiang K (2009) New power generation technology options under the greenhouse gases mitigation scenario in China. *Energy Policy* 37(6):2440-2449.

47. CBS News New York Times (2009) American Public Opinion: Today vs. 30 Years Ago. (New York).
48. Jones JM (2009) Support for Nuclear Energy Inches Up to New High. *Gallup Poll*.
49. Dekay M, *et al.* (The use of public risk ranking in regulatory development. *Improving Regulation: Cases in Environment, Health, and Safety*, eds Fischbeck P & Farrow R (Resources for the Future, Washington, DC).
50. Midden CJH & Huijts NMA (2009) The Role of Trust in the Affective Evaluation of Novel Risks: The Case of CO<sub>2</sub> Storage. *Risk Analysis* 29(5):743-751.
51. Siegrist M & Cvetkovich G (2000) Perception of Hazards: The Role of Social Trust and Knowledge. *Risk Analysis* 20(5):713-720.
52. Terwel B, Harinck F, Ellemers N, & Daamen DD (2009) Competence-Based and Integrity-Based Trust as Predictors of Acceptance of Carbon Dioxide Capture and Storage (CCS). *Risk Analysis* 29(8):1129-1140.

## **Chapter 4. Informing Teacher Preferences for Low-Carbon Technologies and Portfolios**

### **Abstract**

The drastic changes needed to mitigate climate change have created an urgent need to prepare an innovative scientific and technical workforce that can advance our knowledge of and develop solutions for a sustainable low-carbon energy future. However, past studies suggest that many teachers may lack the basic knowledge to effectively teach their students about climate change mitigation. Magnifying this problem is the fact that the climate change mitigation information available to teachers may be insufficient for providing them with detailed, comparative and balanced information about the mitigation options. In this study, we provided 6<sup>th</sup>-12<sup>th</sup> grade science and math teachers with comprehensive information about the costs, risks, benefits and limitations of a set of electricity generating technologies and low-carbon portfolios composed of those technologies. Since educators' knowledge and perceptions of low-carbon technologies may influence their students' decision-making related to these technologies, we also surveyed these teachers about their preferences for the low-carbon alternatives using methods developed for our previous study (Chapter 3). Our informed teachers favored energy efficiency, IGCC with CCS, nuclear and wind, and diverse portfolios including those technologies. These ranking results are strikingly similar to those elicited in our previous study with members of the general public. Overall, our teachers thought that they had learned new information about the low-carbon technologies, correcting some of their misconceptions and knowledge gaps. They further thought the materials and procedure would be easy to adapt for a high school classroom and would help students master the content that is required by two sets of the PA science

education standards. We conclude that the information we developed for a previous study (Chapter 3) could also benefit science teachers.

#### **4.1. Introduction**

The drastic changes needed to mitigate climate change have created an urgent need to prepare an innovative scientific and technical workforce that can advance our knowledge of and develop solutions for a low-carbon energy future. The study of climate change mitigation options such as low-carbon electricity technologies is a highly interdisciplinary, pedagogically challenging subject that does not fit easily into discipline-based science curricula or assessments. Indeed, the Pennsylvania Educational Standards do not explicitly cover climate science or mitigation strategies (1) and the National Science Foundation has recently awarded \$20 million in grants for climate change education to, in part, create an inventory of existing curricular and information resources and to develop new resources to address any curricular gaps that are found (2).

If educators are to effectively teach their students about climate change mitigation, though, they must first have the correct knowledge to do so. However, past studies suggest that many pre-service and elementary school teachers in various countries lack a basic understanding of the causes of climate change (3-8). It is no wonder, then, that many are uninformed about climate change mitigation strategies. For instance, studies show that these teachers have low levels of awareness of biomass technologies (6, 9), confusion about the ability of nuclear and wind to reduce climate change (7) and are unsure whether natural gas is a renewable energy source (9, 10). A survey of 6<sup>th</sup>-12<sup>th</sup> grade science teachers that we recently conducted (See Chapter 6) suggests that many may lack knowledge about some of the most critical issues related



to the low-carbon electricity technologies of nuclear, wind, solar and coal with carbon capture and sequestration (CCS) (11). Magnifying this problem is the fact that the climate change mitigation information available to teachers may either be too simplistic, biased toward one or more technologies, or so scattered among different sources that it is difficult to aggregate (12).

In this study, we provided 6<sup>th</sup>-12<sup>th</sup> grade science and math teachers with comprehensive information about the costs, risks, benefits and limitations of a set of electricity generating technologies and low-carbon portfolios composed of those technologies. The information was originally developed for non-technical members of the general public (13), and was thus written at the 6<sup>th</sup>-8<sup>th</sup> grade reading level. After using the information as part of our study, teachers were provided with the information to use in their classrooms. In this way, we were able to both educate teachers about low-carbon technologies, as well as provide them with the tools (e.g., curriculum) necessary to educate their students.

Since educators' knowledge and perceptions of low-carbon technologies could certainly influence their students' attitudes and decision-making related to these technologies, we also surveyed these teachers about their preferences for the low-carbon alternatives using methods developed for our previous study (13). That is, we asked teachers to rank ten technologies (e.g., coal with CCS, natural gas, nuclear, various renewables, and energy efficiency), and seven realistic low-carbon portfolios composed of these technologies, after receiving the comprehensive and balanced information described previously. Our teachers provided these rankings in group settings as well as individually before and after the group discussions.

## 4.2. Methods

### 4.2.1 Materials

We developed the information materials used to inform our teachers about low-carbon electricity generating technologies and portfolios from the study exploring informed preferences of non-technical members of the general public (See Chapter 3 and (13)). Teachers were presented with systematic, comparative and balanced information about a set of nine electricity generating technologies that could be realistically be constructed in Pennsylvania (where we recruited participants) over the next 25 years (i.e., pulverized coal (PC) and integrated gasification combined-cycle coal (IGCC), both with and without CCS, natural gas combined cycle, advanced nuclear plants, modern wind turbines, solar photovoltaic (PV) and biomass integrated gasification combined-cycle) and an option to reduce electricity consumption through energy efficiency. Each technology was described qualitatively, using a multi-attribute format, on a separate *Technology Sheet* and quantitatively compared to one another on a *Cost Comparison* and *Pollution Comparison*.

Teachers were also presented with seven low-carbon portfolios, referred to as *Power Plant Combinations* (Table 4.1), designed to emit 70% less CO<sub>2</sub> than a portfolio composed entirely of PC plants (the technology that currently generates a majority of the electricity in Pennsylvania). Four simple portfolios (i.e., A, B, C, and G) relied mostly on one reliable technology. Two portfolios were based on diverse combinations proposed by the Electric Power Research Institute (2). The first (D) included predominantly renewables and increased efficiency efforts, using natural gas plants for baseload power and intermittency fill; and a second (F) had IGCC with CCS, nuclear, natural gas, and renewables. We also included a third diverse portfolio (E) that used IGCC with CCS, natural gas, and renewables, but no nuclear power. Portfolios

were compared in sheets entitled *Cost Comparison for Combinations* and *Pollution Comparison for Combinations*.

**Table 4.1. The Low-Carbon Electricity Generation Portfolios Presented in this Study**

<b>Portfolio</b>	<b>Technology Composition</b>
<b>A:</b> Mix of PC with CCS and PC	81% PC with CCS 19% PC
<b>B:</b> Mix of IGCC with CCS and IGCC	83% IGCC with CCS 17% IGCC
<b>C:</b> Nuclear and PC mix	70% Nuclear 30% PC
<b>D:</b> Diverse portfolio, with no nuclear, IGCC with CCS or PC	66% Natural gas 13% Energy efficiency 10% Wind 6% Biomass 5% Solar PV
<b>E:</b> Diverse portfolio, with IGCC with CCS, but no nuclear	48% Natural gas 20% IGCC with CCS 13% Wind 13% Energy efficiency 5% PC 1% Solar PV
<b>F:</b> Diverse portfolio, with IGCC with CCS and nuclear	25% IGCC with CCS 21% Nuclear 20% Natural gas 17% PC 10% Wind 7% Energy efficiency
<b>G:</b> Natural gas and wind mix	66% Natural gas 34% Wind

Note: “Diverse portfolio” refers to the inclusion of the following technologies, unless otherwise noted: nuclear, IGCC with CCS, natural gas, PC, energy efficiency and wind

We developed all materials with input from subject-matter experts with knowledge in the relevant areas to ensure balance and technical accuracy. Content was iteratively pilot-tested with members of the general public. Despite the complexity of the materials, all were written at a 6<sup>th</sup> to 8<sup>th</sup> grade reading level, as reflected in the Flesch-Kincaid Grade Level readability statistic (14,

15). A more detailed review of the content and format of the materials, including technical considerations, can be found in Fleishman et al. (13). The complete set of the materials, including those described above, are available online at <http://cedm.epp.cmu.edu/tool-public-lowcarbon.php>

#### **4.2.2 Participants**

Sixty-eight 6<sup>th</sup>-12<sup>th</sup> grade science and math teachers were recruited from Western Pennsylvania. Forty of these teachers responded to requests for participants that were sent via email using pre-existing distribution lists held by the researchers and Carnegie Mellon University's Leonard Gelfand Center for Service Learning and Outreach. Twenty-eight teachers participated as part of a three-day teacher continuing education workshop coordinated by the Gelfand Center, entitled "What is Research?" Teachers were 23 to 64 years old ( $M = 41.1$ ). Of these, 63% were female, and 94% white. All had a Bachelor's degree in a technical field, such as math or science, with 76% of teachers having completed a Master's degree or higher (most in an education discipline). Thirteen percent of participants taught both math and science, with 72% teaching science exclusively and the remaining 15% teaching only math. More than 50% of the teachers had experience teaching 10<sup>th</sup>, 11<sup>th</sup> or 12<sup>th</sup> grade.

#### **4.2.3 Procedure**

The procedure and surveys as described in Fleishman et al. (13) were adapted for a larger group setting and for the teacher-specific audience. As in the previous study, teachers received "homework" materials by mail, including *Technology Sheets*, the *Cost Comparison*, *Pollution Comparison*, and an *Introduction* about climate change. After reading the "homework" materials,

teachers were asked to consider a hypothetical scenario in which they were chosen to advise the PA governor on power plant construction under a congress-mandated CO<sub>2</sub> emissions limit. Teachers provided this advice as a *pre-discussion technology ranking* ranging from best (=1) to worst (=10). Teachers then provided a *homework adaptability rating*, on a scale anchored at “very hard or adapt” for the classroom setting (=1) to “very easy to adapt” (=7). Subsequently, they indicated the grade level(s) (i.e., 6<sup>th</sup>-12<sup>th</sup> grade) for which the four types of the information sheets would be most appropriate. Finally, teachers rated their agreement with the 15 environmental statements appearing on the Dunlap et al.’s (16) *new ecological paradigm (NEP) scale*, with responses anchored at completely disagree (=1) and completely agree (=7).

We conducted three workshops, each taking 2 – 3 hours and held on the Carnegie Mellon University campus. The first workshop included 28 teachers who were enrolled in the “What is Research?” workshop. The second and third workshops included 25 and 15 teacher participants, respectively. As in our previous study, each group first received a review of the homework materials, as well as new materials including *Power Plant Combinations*, *Cost Comparison for Combinations*, and *Pollution Comparison for Combinations*. Teachers were again asked to consider a similar hypothetical situation, this time focusing on portfolios. Subsequently, teachers provided *pre-discussion portfolio rankings* ranging from best (=1) to worst (=7).

Next teachers engaged in a group discussion following a modified procedure to that used in Chapter 3 and in Fleishman et al. (2010). First, teachers were separated into sub-groups of three to seven people. Within each subgroup, teachers were asked to come to an agreement on a ranking of the portfolios, using a procedure of their choice. One teacher from each sub-group then presented their group’s ranking results, including the group’s reasons behind their rankings,

to the larger group. After each sub-group presentation, an experimenter led a group discussion to reflect on any differences, similarities or patterns in each of the sub-groups rankings.

Teachers then rated their agreement with statements about the group ranking process, with responses anchored at completely disagree (=1) and completely agree (=7). They also provided a *group ranking adaptability rating*, on a scale anchored at “very hard to adapt” for the classroom setting (=1) to “very easy to adapt” (=7). They then individually reviewed their personal rankings, and provided *post-discussion portfolio* and *technology rankings*.

Subsequently, teachers provided a *workshop adaptability rating*, on a scale anchored at “very hard to adapt” for the classroom setting (=1) to “very easy to adapt” (=7). They then indicated the grade level(s) (i.e., 6<sup>th</sup>-12<sup>th</sup> grade) for which the four types of portfolio information sheets would be most appropriate.

Upon completing the study, the teachers who participated in the “What is Research?” workshop received \$25/hour and one Act 48 continuing education credit (from the PA Department of Education) per hour for their participation. The remaining teachers received \$95 and three Act 48 continuing education hours. All teachers were provided with the website address to access the study’s information materials for use in their classrooms.

## **4.3. Results**

### ***4.3.1 Technology Rankings***

We computed Kendall’s coefficient of concordance ( $W$ ) to examine the consistency of participants’ personal rankings of the ten technologies. It showed significant agreement between *pre-discussion rankings*, provided before the group discussion ( $W=0.36$   $p<0.001$ ), as well as between *post-discussion rankings*, provided after the group discussion ( $W=0.37$ ,  $p<0.001$ ).

Figure 4.1 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* ( $p>0.05$ ) except for IGCC with CCS, which was ranked significantly better *post-discussion*.

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants’ rankings for each possible pair of technologies, as provided *pre-* and *post-discussion*. The superscripted letters in Figure 4.1 indicate, for each technology, the other technologies that were ranked as significantly “worse”. Due to the large number of these comparisons, we only report those that are significant at  $\alpha=0.01$ . Overall, energy efficiency was significantly preferred to every alternative except IGCC with CCS, both *pre-* and *post-discussion*. The second and third best mean rankings were for IGCC with CCS and nuclear power, respectively, whose rankings were not significantly different from each other. However, these technologies were ranked better than biomass, IGCC, NGCC, PC with CCS, PV solar and PC -- which, respectively, ranked fourth through tenth, on average. Perhaps most notably, each coal technology (IGCC, PC) was significantly preferred with (vs. without) CCS. Further, the more advanced coal technology (IGCC) was significantly preferred over the more conventional coal technology (PC) – whether with or without CCS.

#### **4.3.2 Portfolio Rankings**

We computed Kendall’s coefficient of concordance ( $W$ ) to examine the consistency of participants’ personal rankings of the seven portfolios. It showed significant agreement between *pre-discussion rankings*, provided before the group discussion ( $W=0.33$   $p<0.001$ ), as well as

between *post-discussion rankings*, provided after the group discussion ( $W=0.53$ ,  $p<0.001$ ).

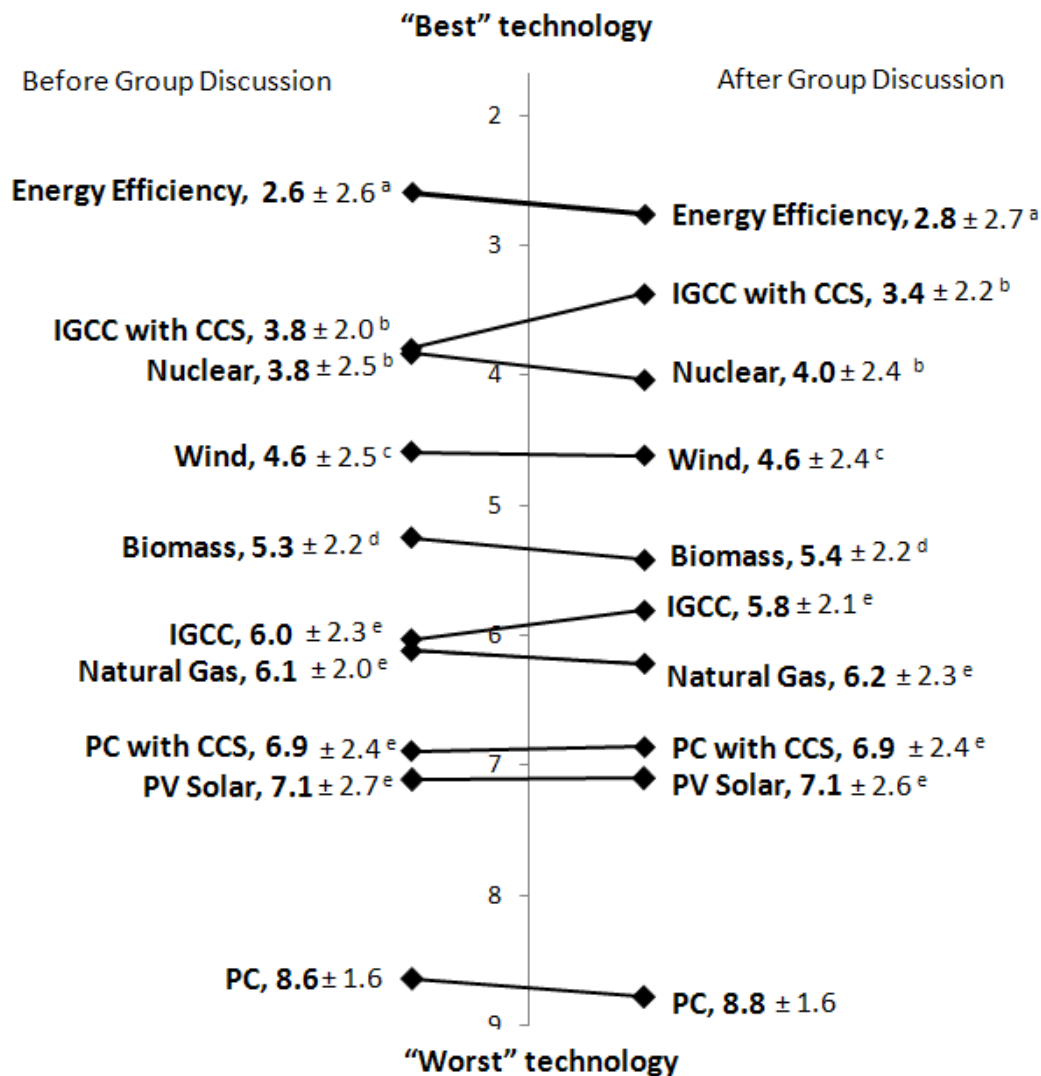
Figure 4.2 reports the mean *pre-discussion* (left) and *post-discussion* (right) *technology rankings*, where 1 is the “best” and 10 is the “worst”. Wilcoxon paired-rank tests indicated that, participants’ *pre-discussion rankings* were not significantly different from *post-discussion rankings* ( $p>0.05$ ) except for portfolio A, which was ranked significantly worse *post-discussion* ( $Z=-2.71$ ,  $p<0.01$ ) and portfolios E and F, which were ranked significantly better *post-discussion* ( $Z=-2.59$ ,  $p=0.01$  for E and  $Z=-3.78$ ,  $p<0.001$  for F).

We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants’ rankings for each possible pair of portfolios, as provided *pre-* and *post-discussion*. The superscripted letters in Figure 4.2 indicate, for each portfolio, the other technologies that were ranked as significantly “worse”. Due to the large number of these comparisons, we only report those that are significant at  $\alpha=0.01$ . Overall, portfolio F, which included a diverse portfolio with both IGCC with CCS and nuclear, received the best mean ranking. Portfolio B, which included the less diverse mix of IGCC with CCS and IGCC received the second best mean ranking *pre-discussion* and the third best mean ranking *post-discussion*. Portfolio E, which was similarly diverse to F but included only IGCC with CCS and no nuclear, had the third best mean ranking *pre-discussion* and the second best mean ranking *post-discussion*. The rankings of these three portfolios were not significantly different from one another *pre-discussion*. However, portfolio F was ranked better than E and B (as well as all the other portfolios) *post-discussion*. The other mean rankings in order were (4) the diverse portfolio D, with no CCS or nuclear, (5) portfolio G, with the natural gas and wind mix, (6) portfolio C, with the nuclear and PC mix, and (7) portfolio A with the simple mix of PC with CCS and PC. Thus, the pattern of results was similar to that observed with the technologies,



with rankings of the three portfolios including IGCC with CCS (B, E, and F) being preferred to all portfolios not including IGCC with CCS, including Portfolio A, the only mix including PC with CCS. In fact, all portfolios were ranked significantly better than Portfolio A.

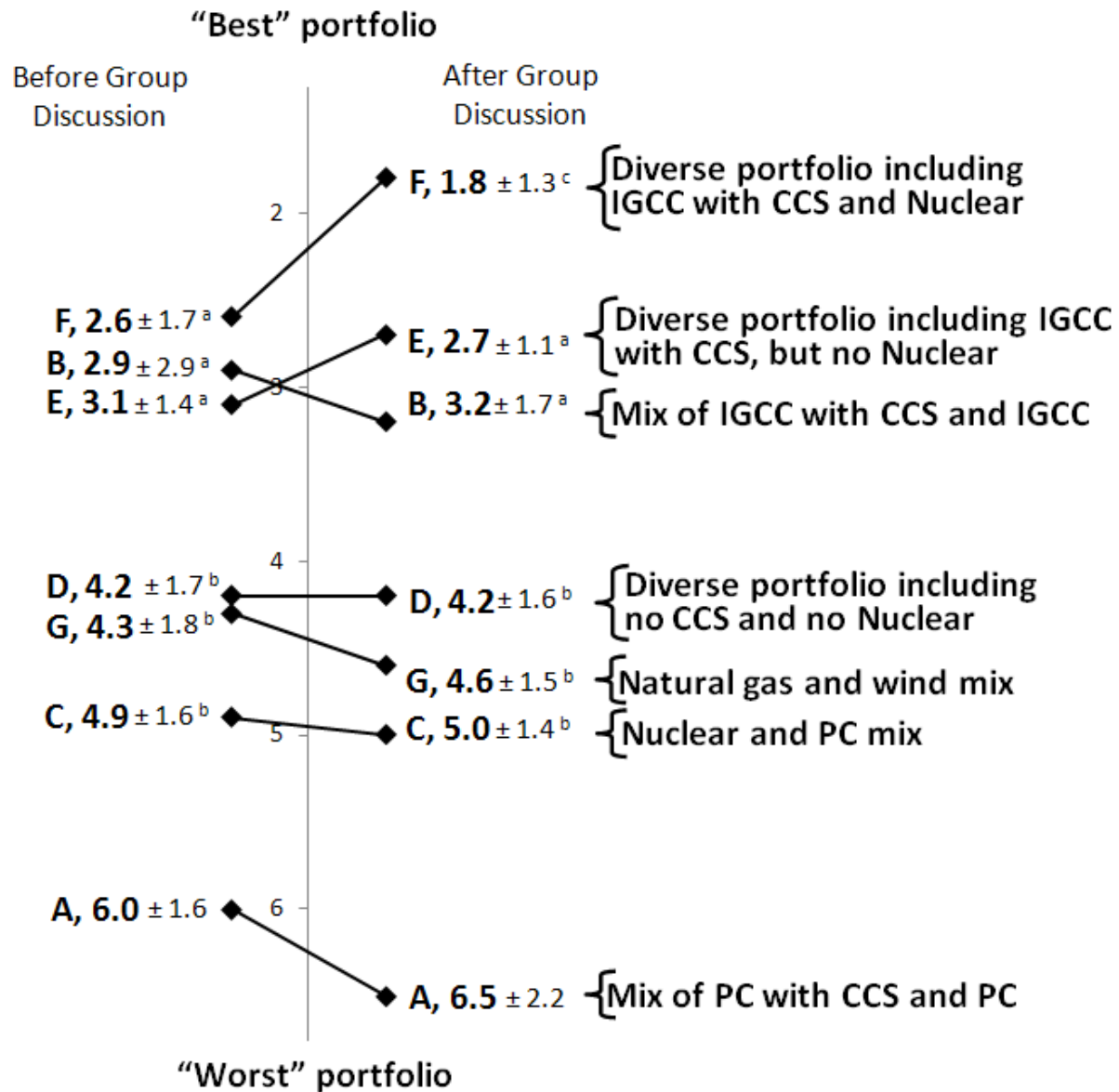
**Figure 4.1. Teachers' mean technology rankings  $\pm$  standard deviation, *pre-* (left) and *post-discussion* (right).**



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: Nuclear, Wind, Biomass, IGCC, NGCC, PC with CCS, PV Solar, PC were ranked significantly worse
- b: Biomass, IGCC, NGCC, PC with CCS, PV Solar, PC were ranked significantly worse
- c: IGCC, NGCC, PC with CCS, PV Solar, PC were ranked significantly worse
- d: PC with CCS, PV Solar, PC were ranked significantly worse
- e: PC was ranked significantly worse

**Figure 4.2. Teacher' mean portfolio rankings  $\pm$  standard deviation, *pre-* (left) and *post-* discussion (right)**



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: D, G, C, and A were ranked significantly worse
- b: A was ranked significantly worse
- c: E, B, D, G, C and A were ranked significantly worse

### 4.3.3 Viewpoints on Environmental Issues

Participants' responses to the 15 *NEP scale ratings* were scored such that higher ratings reflected stronger pro-environmental attitudes, and had good internal consistency (Cronbach's  $\alpha=0.74$ ). Participants' mean *NEP scale ratings* ( $M=4.92$ ,  $SD=0.90$ ) were significantly above the scale midpoint of 4 ( $t=8.43$ ,  $p<0.001$ ), suggesting pro-environmental attitudes. Spearman correlations between the mean *NEP scale ratings* and teachers' rankings (reverse-coded for these analyses, such that higher numbers reflect a higher preference) suggest that participants who were more pro-environmental preferred energy efficiency ( $r_s=0.37$ ,  $p<0.01$  for *pre-discussion* and  $r_s=0.22$ ,  $p=0.09$  for *post-discussion*), PV solar ( $r_s=0.37$ ,  $p<0.01$  for *pre-discussion* and  $r_s=0.34$ ,  $p<0.01$  for *post-discussion*) and wind ( $r_s=0.33$ ,  $p<0.01$  for *post-discussion*), as well as the portfolio including all three of these technologies (D) ( $r_s=0.31$ ,  $p=0.01$  for *post-discussion*). Pro-environmental teachers also tended to dislike coal technologies that did not include CCS (IGCC ( $r_s=-0.41$ ,  $p=0.001$  for *pre-discussion* and  $r_s=0.30$ ,  $p=0.02$  for *post-discussion*), PC ( $r_s=-0.45$ ,  $p<0.001$  for *pre-discussion* and  $r_s=-0.48$ ,  $p<0.001$  for *post-discussion*)).

### 4.3.4. Teacher Evaluation of Materials and Procedure

On a scale from “very hard to adapt” (=1) to “very easy to adapt” (=7), teachers' rated the overall procedure ( $M=5.27$ ,  $SD=1.65$ ), homework materials ( $M=5.62$ ,  $SD=1.54$ ), workshop materials ( $M=5.10$ ,  $SD=1.76$ ) and workshop ranking exercise ( $M=5.20$ ,  $SD=1.68$ ) relatively easy to adapt for their classroom, with all ratings being significantly above the scale midpoint ( $p<0.001$  for all). Teachers also agreed that the homework and workshop materials would help students to master the content that is required by the PA Science and Technology ( $M=5.56$ ,  $SD=1.23$  for homework, and  $M=5.74$ ,  $SD=1.23$  for workshop, both above the scale midpoint  $p < 0.001$ ) and Environment and Ecology Standards ( $M=5.87$ ,  $SD=1.10$  for homework and  $M=6.05$ ,

$SD=0.93$  for workshop, both above the scale midpoint  $p < 0.001$ ). While teachers did not think the homework materials would help students master the Mathematics Standards ( $M=4.11$ ,  $SD=1.55$ , not above the scale midpoint  $t=0.56$ ,  $p=0.58$ ), they thought the workshop materials could do so ( $M=4.67$ ,  $SD=1.57$ , above the scale midpoint  $t=3.45$ ,  $p=0.001$ ). A majority ( $>50\%$ ) of teachers indicated that the most appropriate grade level(s) for the *Problem Question* and *Technology Sheets* were 9<sup>th</sup>-12<sup>th</sup>, while the *Cost Comparison*, *Cost Comparison for Combinations*, *Pollution Comparison*, *Pollution Comparison for Combinations*, the *New Problem Question*, and *Power Plant Combinations* were most appropriate for the 10<sup>th</sup>-12<sup>th</sup> grades.

#### **4.3.5 Participant Evaluation**

Teachers found the group discussion ( $M=5.82$ ,  $SD=1.32$ ) and overall study ( $M=6.15$ ,  $SD=1.12$ ) “to be an enjoyable experience” (both above the scale midpoint,  $p<0.001$ ) that slightly “improved [their] knowledge of the electricity options” ( $M=4.94$ ,  $SD=1.65$ ,  $t=4.66$ ,  $p<0.001$ ). Indeed, they thought it allowed for them “to provide [their] own [opinion]” ( $M=6.37$ ,  $SD=0.83$ ,  $t=23.35$ ,  $p<0.001$ ) and “to consider other people’s views and perspectives” ( $M=6.30$ ,  $SD=0.89$ ,  $t=21.19$ ,  $p<0.001$ ). Despite having no facilitator for their subgroup discussions, teachers felt they were “able to come to an agreement in an orderly and systematic way” ( $M=5.78$ ,  $SD=1.29$ ,  $t=11.28$ ,  $p<0.001$ ) and that the discussion would *not* “have been better...[with] an independent third-party to facilitate it” ( $M=2.73$ ,  $SD=1.54$ ,  $t=-6.73$ ,  $p<0.001$ ).

Teachers further agreed that they “learned a great deal about the different electricity options from the study” ( $M=5.51$ ,  $SD=1.64$ ,  $t=7.60$ ,  $p<0.001$ ) and that the information provided to them was “applicable to my life outside of the classroom” ( $M=5.57$ ,  $SD=1.36$ ,  $t=9.51$ ,

$p<0.001$ ), as well as “applicable to my classroom lessons” ( $M=5.01$ ,  $SD=1.80$ ,  $t=4.65$ ,  $p<0.001$ ), and covered the topics that they felt were “important about the electricity options,” ( $M=5.68$ ,  $SD=1.26$ ,  $t=10.95$ ,  $p<0.001$ ). Teachers somewhat agreed that the information provided in the study “corrected some of [their] misconceptions about the electricity options” ( $M=4.63$ ,  $SD=1.88$ ,  $t=2.78$ ,  $p<0.01$ ) and “filled in many of the gaps in [their] knowledge about the electricity options” ( $M=4.76$ ,  $SD=1.85$ ,  $t=3.42$ ,  $p=0.001$ ).

#### **4.4. Discussion**

Our informed science and math teachers favored energy efficiency over the other low-carbon alternatives. Next, teachers favored IGCC with CCS, nuclear and wind, which were ranked, on average, second through fourth, respectively. These four technologies were also included in teachers’ most preferred portfolio, F, the diverse portfolio with nuclear and IGCC with CCS. This portfolio, as well as the other two portfolios including IGCC with CCS (B, the simple IGCC with CCS and IGCC mix, and E, the diverse mix with IGCC with CCS, but no nuclear), were significantly preferred to all other portfolios. However, the one other portfolio that included CCS, but with PC instead of IGCC, was ranked significantly worse than all other portfolios. A similar contrast in coal technology preference is also found with the technology rankings such that IGCC was preferred over PC, with or without CCS.

The technology and portfolio ranking results are strikingly similar to those elicited in our previous study with members of the general public (13). However, the order of the technology rankings in this study suggest that teachers preferred PV solar less than our lay public sample (ranked 9<sup>th</sup> for teachers vs. 7<sup>th</sup> for lay public) and preferred IGCC more than our lay public sample (ranked 6<sup>th</sup> for teachers vs. 9<sup>th</sup> for lay public). Possibly, our teachers were able to better

recognize the feasibility of these technologies in the state of Pennsylvania, where cloudy days are common and the sun is not very intense, while coal resources are readily available. Yet, those teachers with more pro-environmental attitudes still ranked PV solar (as well as wind and energy efficiency) better, and all four coal technologies worse.

Unlike our sample with the general public (13), group discussion did seem to influence teachers' rankings of some technologies and portfolios. Indeed, their rankings of IGCC with CCS, and the two diverse portfolios with IGCC with CCS (E and F), were better *post-discussion*, while the portfolio with PC with CCS was ranked worse after the discussion. Possibly, those teachers with strong feelings were able to present very compelling arguments (that could sway others) during the group discussion because of their teaching experience.

Overall, our teachers enjoyed the study experience and group discussion. The sub-group discussion structure actually seemed to be preferred by teachers who thought a facilitator would not have helped their small group discussions. Our teachers thought they learned new information about the low-carbon technologies that was applicable to their life inside and outside of the classroom. The information provided to teachers corrected their misconceptions and knowledge gaps and was thought to be easy to adapt for a high school classroom. In their classrooms, teachers felt it would help students master the content that is required by the PA education standards for Science and Technology, and Environment and Ecology.

We conclude that the technology and portfolio information we developed for a previous study (13) could also benefit science teachers. Not only could it help them learn important concepts related to low-carbon technologies, but they could then effortlessly use the same materials as a curriculum module with their students. As a result of the lack of specificity and importance currently placed on climate change in PA state standards, curriculum about low-

carbon technologies may not be readily available for teachers. Many times, a teacher's knowledge about environmental issues is only as thorough as the lessons they teach their students (6). Since the PA Board of Education does not explicitly require teachers to know, for instance, the tradeoffs between different low-carbon technologies, they may be less likely to correct common public misconceptions among their students (11).

The current generation of adolescents will likely be our policy- and decision-makers when the dire consequences of climate change become a reality. Thus, we must create an awareness of the challenges with low-carbon electricity generation, equipping students with the information to make informed decisions about climate change mitigation. We must find ways to facilitate their education now through their teachers. By offering teachers course curricula that compile information in a technically accurate, yet understandable way, we believe the teachers will be more willing and able to teach the topic, providing balanced opinions to their students that are informed based on fact and providing our next generation with the tools they need to help the U.S achieve a low-carbon energy future.

## References

1. Pennsylvania State Board of Education (2002) State Academic Standards.
2. National Science Foundation (2010) Program Solicitation, NSF 10-542: Climate Change Education (CCE): Climate Change Education Partnership Program (CCEP).
3. Kalipci E, Yener Y, & Ozkadif S (2009) The opinions of teacher candidates about global warming, greenhouse effect and ozone layer. *World Applied Science Journal* 7(1):67-75.
4. Michail S, Stamou AG, & Stamou GP (2007) Greek primary school teachers' understanding of current environmental issues: An exploration of their environmental knowledge and images of nature. *Science Education* 91(2):244-259.

5. Summers M, Kruger C, Childs A, & Mant J (2000) Primary School Teachers' Understanding of Environmental Issues: an interview study. *Environmental Education Research* 6:293-312.
6. Yilmaz-Tuzun O, Teksoz-Tuncer G, & Aydemir M (2008) An investigation of the elementary teachers' knowledge about air pollution issues. *Hacettepe Universitesi Journal of Education* 35:374-385.
7. Groves FH & Pugh AF (1999) Elementary Pre-Service Teacher Perceptions of the Greenhouse Effect. *Journal of Science Education and Technology* 8(1):75-81.
8. Groves F & Pugh A (2002) Cognitive Illusions as Hindrances to Learning Complex Environmental Issues. *Journal of Science Education and Technology* 11(4):381-390.
9. Liarakou G, Gavrilakis C, & Flouri E (2009) Secondary School Teachers' Knowledge and Attitudes Towards Renewable Energy Sources. *Journal of Science Education and Technology* 18(2):120-129.
10. Spiropoulou D, Antonakaki T, Kontaxaki S, & Bouras S (2007) Primary Teachers' Literacy and Attitudes on Education for Sustainable Development. *Journal of Science Education and Technology* 16(5):443-450.
11. Fleishman L, Bruine de Bruin W, & Morgan MG (2011) How much do science teachers know about low-carbon electricity technologies? *Working Paper*.
12. Feinstein N (2009) Education for Sustainable Development in the United States of America. (Department of Curriculum and Instruction, University of Wisconsin-Madison School of Education, Madison, WI), p 51.
13. Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.
14. Flesch R (1948) A new readability yardstick. *Journal of Applied Psychology* 32(2):221-233.
15. Kincaid JP, Fishburne RP, Rogers RL, & Chissom BS (1975) Derivation of new readability formulas (Automated Readability Index, Fog Count and Flesch Reading Ease Formula) for Navy enlisted personnel. (Naval Technical Training, U.S. Naval Air Station Memphis, TN).
16. Dunlap RE, Van Liere KD, Mertig AG, & Jones RE (2000) New Trends in Measuring Environmental Attitudes: Measuring Endorsement of the New Ecological Paradigm: A Revised NEP Scale. *Journal of Social Issues* 56(3):425-442.



## **Chapter 5. Informed Public Choices for Low-Carbon Electricity Portfolios Using a Portfolio-Building Computer Decision Tool**

### **Abstract**

In the study described in Chapters 3 and 4, we asked members of the general public to rank a set of electricity technologies and low-carbon portfolios composed of the technologies after providing them with multi-attribute information about the costs, risks, benefits and limitations of each. However, the results of our previous studies were limited because we only provided participants with a choice of seven pre-defined low-carbon portfolios. Thus, in the study presented here, we allowed participants to design their own portfolio, using a computer tool that constrains the portfolio designs to be realistic, reliable, and to meet a specific CO<sub>2</sub> emissions limit. As participants increased or decreased the technology percentages in their portfolio, the interactive tool provided immediate output on the quantitative attributes for increased electricity cost, CO<sub>2</sub> emissions, and health, land and water impacts. The results of our study suggest that our participants could use the computer tool to consistently show which technologies they would support for inclusion in a low-carbon electricity generation portfolio to be constructed in PA in the next 25 years. Our informed participants preferred energy efficiency, nuclear, IGCC with CCS, natural gas and wind, and designed diverse portfolios including these technologies. Participants' portfolio designs converged after group discussion and became slightly more consistent with their preferences for the quantitative attributes. We conclude that the computer tool, supplemental materials and procedure may have value to educate the general public about low-carbon electricity generation.

## **5.1. Introduction**

In the study described in Chapters 3 and 4 (1), we presented members of the general public with multi-attribute information, including the costs, risks, benefits and limitations, about ten technologies (e.g., coal with CCS, natural gas, nuclear, various renewables, and energy efficiency), and seven realistic low-carbon portfolios composed of these technologies. By presenting our participants with multi-attribute information, they could systematically compare the technologies and portfolios, informing their decision to support a specific alternative by focusing on the attributes they most valued. We asked participants to provide their opinion as a ranking of the technologies and portfolios, individually and as part of a discussion in small group settings. By providing a ranking of realistic low-carbon generation portfolios, participants' opinions were reported in a decision-relevant and realistic context that could be used to inform climate energy policy. Our results showed that our informed members of the general public preferred diverse portfolios that contained CCS and nuclear over alternatives once they fully understood the benefits, cost and limitations of each. This is in stark contrast to other studies (e.g., (2, 3) (with less informed participants and less realistic decision contexts), which showed much less favorable opinions for these two technologies.

However, the results of our previous studies were limited because we only provided participants with a choice of seven pre-defined low-carbon portfolios. And while we attempted to design these portfolios to comprise a range of plausible low-carbon electricity future portfolios, they were certainly not the only possible combinations. Furthermore, while our seven portfolios were designed to comply with many of the limitations presented by the different technologies (e.g., natural gas technologies were included in portfolios with intermittent technologies to fill in electricity for times when it would not be windy or sunny; technologies with greater CO<sub>2</sub>

emissions were also limited to achieve the CO<sub>2</sub> emissions limit; etc.), these may not have been explicitly evident to study participants. Thus, in the study presented here, we allowed participants to design their own portfolios, using a computer tool that constrains the portfolio designs to be realistic, reliable, and to meet a specific CO<sub>2</sub> emissions limit. As participants increased or decreased the technology percentages in their portfolio, the interactive tool provided immediate feedback about the quantitative attributes for increased electricity cost, CO<sub>2</sub> emissions, and health, land and water impacts. Thus, participants could “learn by doing” through their own trial-and-error process.

In this study, we allowed participants to create their own portfolios. Our objective was to examine participants’ (1) technology preferences and portfolio designs, (2) comprehension of, and satisfaction with, the computer tool, and (3) ability to use the computer tool to construct portfolios that are consistent with their technology and attribute preferences and consistent over time, as well as increased participant agreement after group discussion.

## **5.2. Methods**

### **5.2.1. Materials**

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

- (1) 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 photovoltaic (PV) solar; and
- (5) reducing electricity consumption through energy efficiency.

Each technology was described on a separate *Technology Sheet* (see Figure 5.1 for an example). To facilitate comparisons, each sheet systematically described the same attributes: *How it works, Availability, Reliability, Limits of use, Current Use, Safety and Environmental Impacts*. Technologies were systematically compared on additional comparison sheets (See Chapter 2 for more detail), including:

- 1) *Reach the Goals*, with graphs for *CO<sub>2</sub> Released* (presenting direct CO<sub>2</sub> emissions (in kg/MWh) by each technology as a percent of the emissions from a PC plant without CCS) and *Electricity Produced by the Average Plant* (presenting annual electricity generation in TWh);
- 2) *Health, Water and Land Impacts*, with graphs for *Annual Health Costs* (presenting the externality health costs per TWh by each technology as a result of mortality and morbidity from Nitrogen Oxides (NO<sub>x</sub>), Sulfur Dioxide (SO<sub>x</sub>) and particulate matter emissions), *Annual Water Use* (presenting life-cycle water consumption (in gallons/TWh) by each technology as Olympic-size swimming pools per TWh) and *Land Use* (presenting life-cycle land use (in m<sup>2</sup>/TWh) by each technology as football fields per TWh)
- 3) *Cost Comparison* (presenting best estimates with uncertainty bars for the *increase* in electricity cost per kilowatt-hour (over the current PA average of \$0.11/kWh(4)) and estimated monthly electricity bill increases for the median Pennsylvania household).

# Wind

**How it Works:** Modern wind machines are much larger than the old windmills in Holland, or the metal windmills that pumped water for cattle in the American West. They are often between 100 and 300 feet high. That is about as tall as a 10 to 30 story building. The machines have blades that look like an airplane propeller. The wind turns the blades, and this runs a generator to make electricity.



Modern wind turbines in Somerset, PA  
Source: [www.solutions-site.org/](http://www.solutions-site.org/)

<b>Availability</b>	Wind farms work well when built in windy areas. PA has lots of wind on hilltops in the center of the state. However, even the best wind farms in PA only make 28% of the power that would be possible if the wind was always blowing. They cannot make 100% because sometimes the wind is not blowing. Wind farms are often located far away from where people live, since this is where it is the windiest. It is expensive to transmit the wind electricity across long distances.
<b>Reliability</b>	<ul style="list-style-type: none"> <li>• Wind varies in strength, which can make it less dependable for making electricity. Because of this, wind farms cannot consistently make electricity. Natural gas plants must be built to "back up" or fill in electricity during times when it is not windy. In the future, we might use very large batteries to store electricity from wind, but that is very costly to do today.</li> <li>• On average, a newly built wind farm in PA can make about 0.5 TWh of electricity over the course of the year. The natural gas plant built to fill in electricity when it is not windy will have to make about 1.2 TWh over the course of the year.</li> </ul>
<b>Limits to Use</b>	If many wind farms are built, there will be a lot of CO <sub>2</sub> released by the "back-up" natural gas plants. The more wind farms you build, the more indirect CO <sub>2</sub> that is released to the air. So wind farms can only be used to make up 28% of the additional electricity needed for PA if we want to reduce the CO <sub>2</sub> released from all new plants by 50%. This would be about 16.5 TWh of the 60 TWh.
<b>Current Use</b>	There are more than 100 wind farms working in the U.S. today.
<b>Environmental Impacts</b> (*Read Note Below)	<ul style="list-style-type: none"> <li>• There is almost no solid waste from wind farms.</li> <li>• Wind farms with many machines require hundreds of acres. If the machines are built on farm land, most of it can still be used for farming. In forests, trees must be cleared to build the machines. This can disturb the plants and animals. On mountain ridges, wind farms can be very visible.</li> <li>• Wind farms make some low noise. It is less than the noise from most other power plants. But, since wind farms are in the country, the noise is often more noticeable.</li> <li>• The blades of wind machines sometimes strike and kill birds and bats. New wind machines are being located away from bird (migration) flight paths. Less is known about how to prevent bat deaths.</li> </ul>
<b>Safety</b>	Wind farms present very few risks to people.

\* Note: Health, Water and Land Impacts are shown on a Separate Sheet

Figure 5.1 Example *Technology Sheet*

Participants were also presented with an MS Excel-based portfolio-building computer decision tool (Figure 5.2) to facilitate the design of low-carbon portfolios that could reliably supply a 25% increase in electricity demand in Pennsylvania in the next 25 years (See Chapter 2 and Appendix A for more details). Portfolio designs were limited in the computer tool by a specific carbon constraint requiring direct CO<sub>2</sub> emissions to be at least 50% less than emissions from a status quo scenario in which Pennsylvania increases 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). Portfolio reliability was achieved by the automatic addition of 1 W of natural gas plant capacity for every 1 W of intermittent renewable technology (i.e., wind and PV solar) capacity added by the computer tool user (5). Energy efficiency was also constrained in the computer tool to 20% of a participants' portfolio (6, 7), while PC plants co-fired with biomass were limited to 18% of the portfolio due to constraints on growing switch-grass in PA (8). Each of these constraints is explained further in Appendix A. The capacity of all other technologies in the computer tool was only limited by the CO<sub>2</sub> emissions constraint.

As participants changed the percent of technologies in their portfolio (using the *Build Center* in Figure 5.2), they could observe the change in (1) CO<sub>2</sub> emissions (relative to the status quo) and electricity generated (both in the *Goal Center* in Figure 5.2), (2) Annual Health Costs, Land Use and Annual Water Use (in the *Impacts* area in Figure 5.2) and (3) the increased cost in monthly electric bill and energy-driven increased cost-of-living (in the *Cost* area in Figure 5.2). Participants could then compare up to three proposed portfolios on a separate *Compare* screen (Figure 5.3), which presented a summary view of the three portfolios across the quantitative

attributes of CO<sub>2</sub> emissions, increased cost in monthly electric bill, annual health costs, land use and annual water use.

The design and development of materials and the computer tool were informed by materials and results of a previous study (1), as well as by additional input from subject-matter experts with knowledge in the relevant areas to ensure balance and technical accuracy. Content and computer tool design functionality were iteratively pilot-tested with members of the general public (9-11). Subsequently, the materials and computer tool were revised to improve identified concerns and misunderstandings, and double-checked by subject matter experts. Despite the complexity of the information materials, all were written at a 6<sup>th</sup> to 8<sup>th</sup> grade reading level, as reflected in the Flesch-Kincaid Grade Level readability statistic (12, 13). The complete set of the materials, including those described above, are available in Appendix B.

### ***5.2.2. Participants***

A sample of 69 participants was recruited through community organizations in the Greater Pittsburgh Metropolitan Area. Participants were 22 to 85 years old ( $M = 53.9$ ). 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.

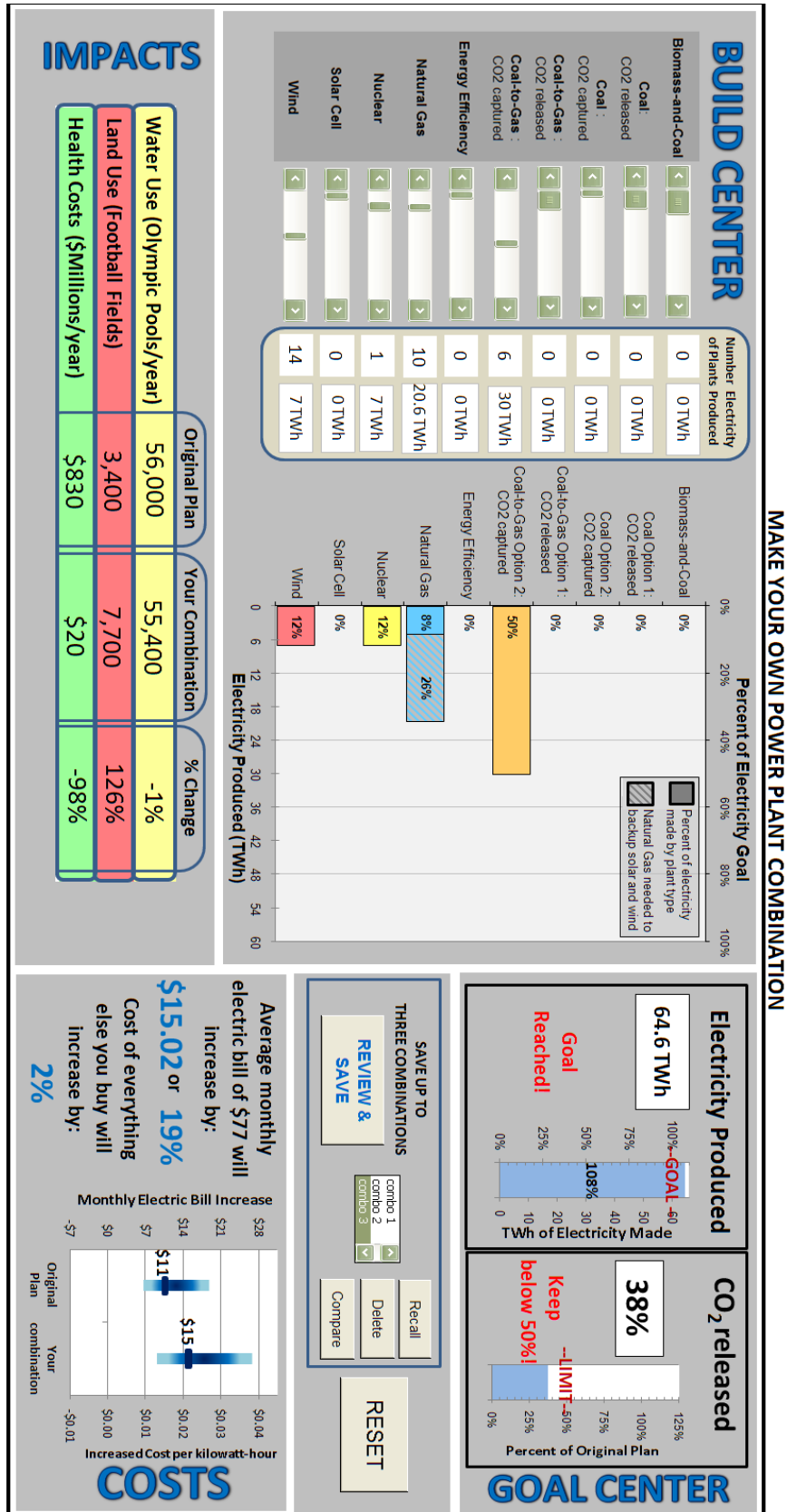


Figure 5.2. Screen shot of the Portfolio-Building Computer Decision Tool





Figure 5.3. Screen shot of the *Compare* Screen of the Portfolio-Building Computer Decision Tool

### 5.2.3. Procedure

After signing up for the study, participants received “homework” materials by mail, including the *Technology Sheets*, the *Reach the Goals* sheet, *Health, Water and Land Impacts* and the *Cost Comparison*. They were presented with an introduction about climate change, and the following problem question:

“Today, the power plants in 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<sub>2</sub> 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<sub>2</sub> [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 reading the homework materials, but prior to attending the group meeting, participants provided *technology rankings* ranging from best (=1) to worst (=10). They also provided *homework comprehension ratings* of the seven information sheets, on a scale anchored at very hard (=1) and very easy (=7). Participants then answered 24 *true-or-false knowledge questions* about their homework materials, focusing on those issues that had been most commonly misunderstood in the pilot tests described above.

We conducted ten workshops, each involving four to nine participants, held in local communities, lasting 2.5 to 3.5 hours, and following a careful script adapted from previous

studies with a similar methodology (1, 14, 15). 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 through an initial presentation and a subsequent step-by-step exercise. Prior to using the computer tool to create a portfolio on their own, participants answered questions on a *computer knowledge test* in which participants were directed to use the computer tool and answer questions about values shown on the computer screen. They also provided *attribute ranks* for the ranges of the five quantitative attributes (16) (i.e., CO<sub>2</sub> emissions, increased electric bill cost, annual health costs, land use and annual water use) to indicate which attribute they thought would be the “most important to change” from its maximum to minimum outcome in the computer tool (e.g., from 50% to 0% for CO<sub>2</sub> emissions, from \$18/month to \$7/month for increased electric bill cost, etc.) where 1 was “the characteristic that you would want to change first” and 5 was “the characteristic that you would want to change last.”

Finally, participants were provided with a *New Problem Question*, 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<sub>2</sub> that would have been released [under a status quo scenario].*” As previously stated, the status quo entailed a scenario in which the additional capacity needed in PA would be achieved by building plants in a similar ratio to those that exist in PA 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). Subsequently, participants used the computer tool to build three proposed portfolios and after comparing these on the *Compare screen*, provided the composition (i.e. technology percentages)

of one portfolio as their *pre-discussion technology percentages* such that those percentages summed to 100%.

Next, participants engaged in a group discussion where they volunteered to share their chosen portfolio, including their perceptions and opinions about the technologies, with the group. The experimenter would “build” each participant’s portfolio on a computer tool that was projected onto a screen and provide a comparison of the participants’ portfolios in the group using a *Compare* screen that could compare up to 10 portfolios.

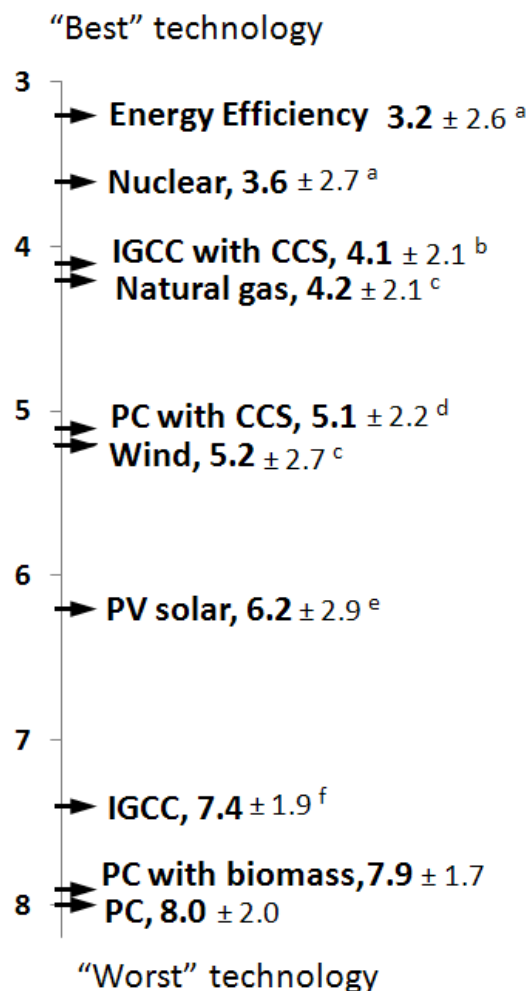
Participants then individually reviewed their personal portfolio choice and were given the chance to revise this choice as *post-discussion technology percentages*. Finally, they also answered individual *computer comprehension ratings* about the six computer tool areas and the computer tool as a whole, anchored on a scale from very hard (=1) and very easy (=7), as well as *self-evaluation ratings* about their satisfaction with the study and how much they learned, anchored on a scale from completely disagree (=1) and 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.

### **5.3. Participants’ Technology Preferences and Portfolio Designs**

#### **5.3.1 Technology Rankings**

Figure 5.4 reports the mean *technology rankings*, where 1 is the “best” and 10 is the “worst.” We used Wilcoxon paired-rank tests to examine whether there was a significant difference in participants’ rankings for each possible pair of technologies. The superscripted letters in Figure 5.4 indicate, for each technology, the other technologies that were ranked as significantly “worse.” Due to the large number of these comparisons, we only report those that

are significant at  $\alpha = 0.01$ . Overall, energy efficiency, nuclear, IGCC with CCS and natural gas, ranked on average first through fourth respectively, were not ranked significantly different from one another. The other mean rankings were, in order, (5) PC with CCS, (6) wind, (7) solar PV, (8) IGCC without CCS, (9) PC co-fired with biomass, and (10) PC without CCS. Each coal technology (IGCC, PC) with CCS was significantly preferred to that without CCS. Furthermore, the gasified coal technology (IGCC) was significantly preferred over the more conventional coal technology (PC)—whether with or without CCS.



**Figure 5.4 Participants' mean *technology ranking* ± standard deviation**

Note: Superscripted letters next to mean technology rankings refer to Wilcoxon paired-rank tests results ( $p < 0.01$ ), suggesting that:

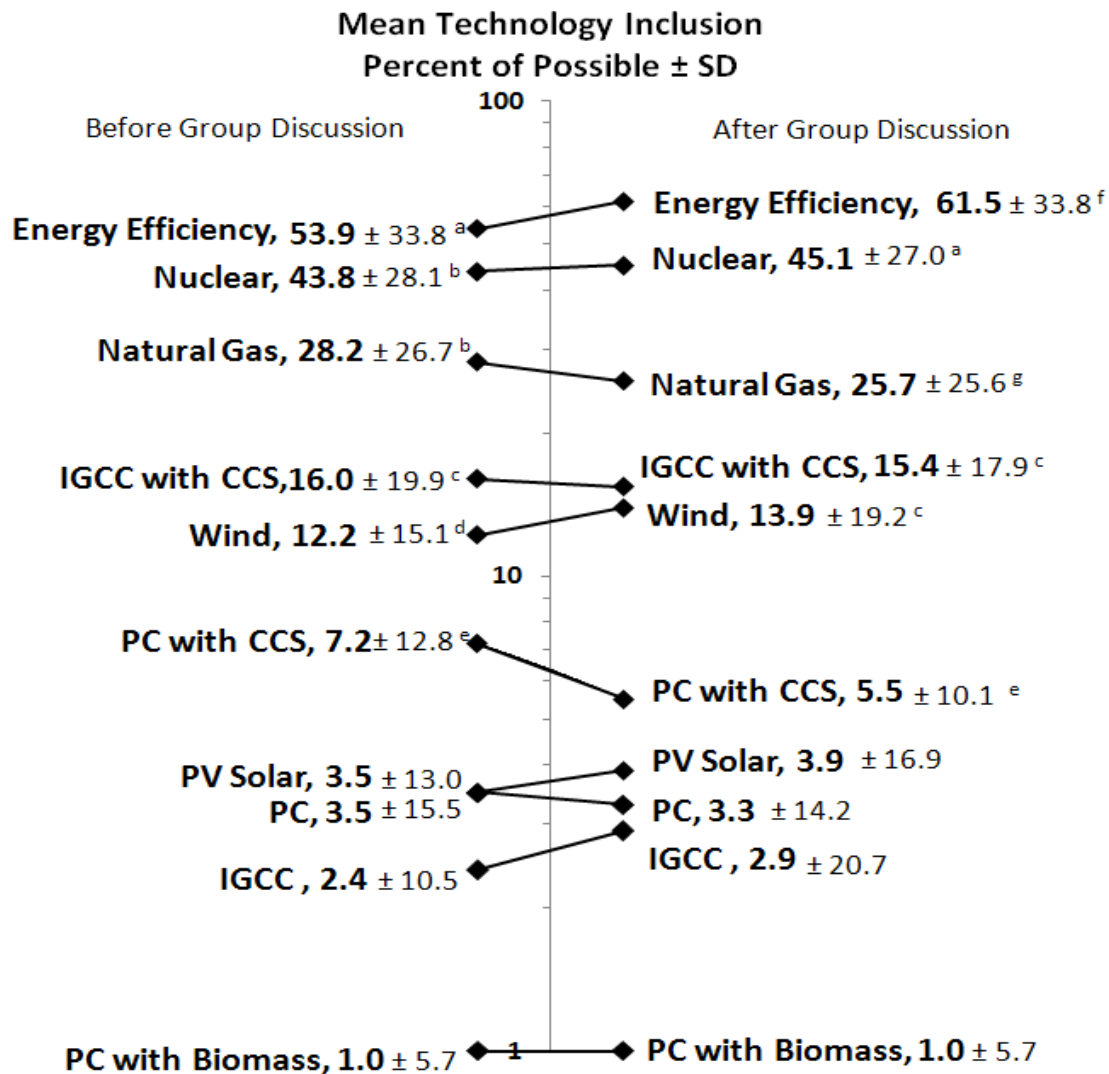
- a: PC with CCS, Wind, PV Solar, IGCC, PC with biomass and PC were ranked significantly worse
- b: PC with CCS, PV Solar, IGCC, PC with biomass and PC were ranked significantly worse
- c: PV Solar, IGCC, PC with biomass and PC were ranked significantly worse
- d: IGCC, PC with biomass and PC were ranked significantly worse
- e: PC with biomass and PC were ranked significantly worse
- f: PC was ranked significantly worse

### 5.3.2 Portfolio Designs

The composition of participants' portfolio designs were examined by focusing on the percentage of each technology included in that portfolio. We evaluated participants' portfolio designs by dividing each of the *technology percentages* by the maximum percentage for that technology permitted by the computer tool. Thus, each of these *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 inclusion of that technology in the portfolio. Figure 5.5 reports the mean *pre-discussion* (left) and *post-discussion* (right) *standardized technology percentages*. The overall pattern of revealed preferences for technologies with participants' portfolio designs (Figure 5.5) is similar to the technology rankings show in Figure 5.4.

The superscripted letters in Figure 5.5 indicate, for each technology, the other technologies whose *standardized technology percentages* were significantly less. Due to the large number of these comparisons, we only report those that are significant at  $\alpha = 0.01$ . Overall, energy efficiency had the largest *standardized technology percentage*, both *pre-* and *post-discussion*. This percentage 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 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.

Figure 5.6 displays the distribution of the *standardized technology percentages* for each technology *pre-* and *post-discussion*. The distributions for PC with biomass, PC, PC with CCS, and IGCC are uni-modal, with 90% of participants excluding these technologies from their portfolios *pre-* and *post-discussion*. PV solar is similarly distributed, with 80% of participants excluding it *pre-* and *post-discussion*. The distributions of IGCC with CCS (median of 8.0% *pre-* and *post-discussion*), natural gas (median of 20.6% *pre-discussion* and 19.0% *post-discussion*) and wind (median of 7.1% *pre-discussion* and 10.7% *post-discussion*) also appear uni-modal, but with a more positive skew. On the other hand, the distribution for the inclusion of energy efficiency (median of 65.0% *pre-discussion* and 70.0% *post-discussion*) and nuclear (median of 44.8% *pre-* and *post-discussion*) are more evenly distributed. While the mode for the inclusion of energy efficiency remains at a high level from *pre-* to *post-discussion*, the mode for the inclusion of nuclear changes from a lower percentage *pre-discussion* to a higher percentage *post-discussion*.

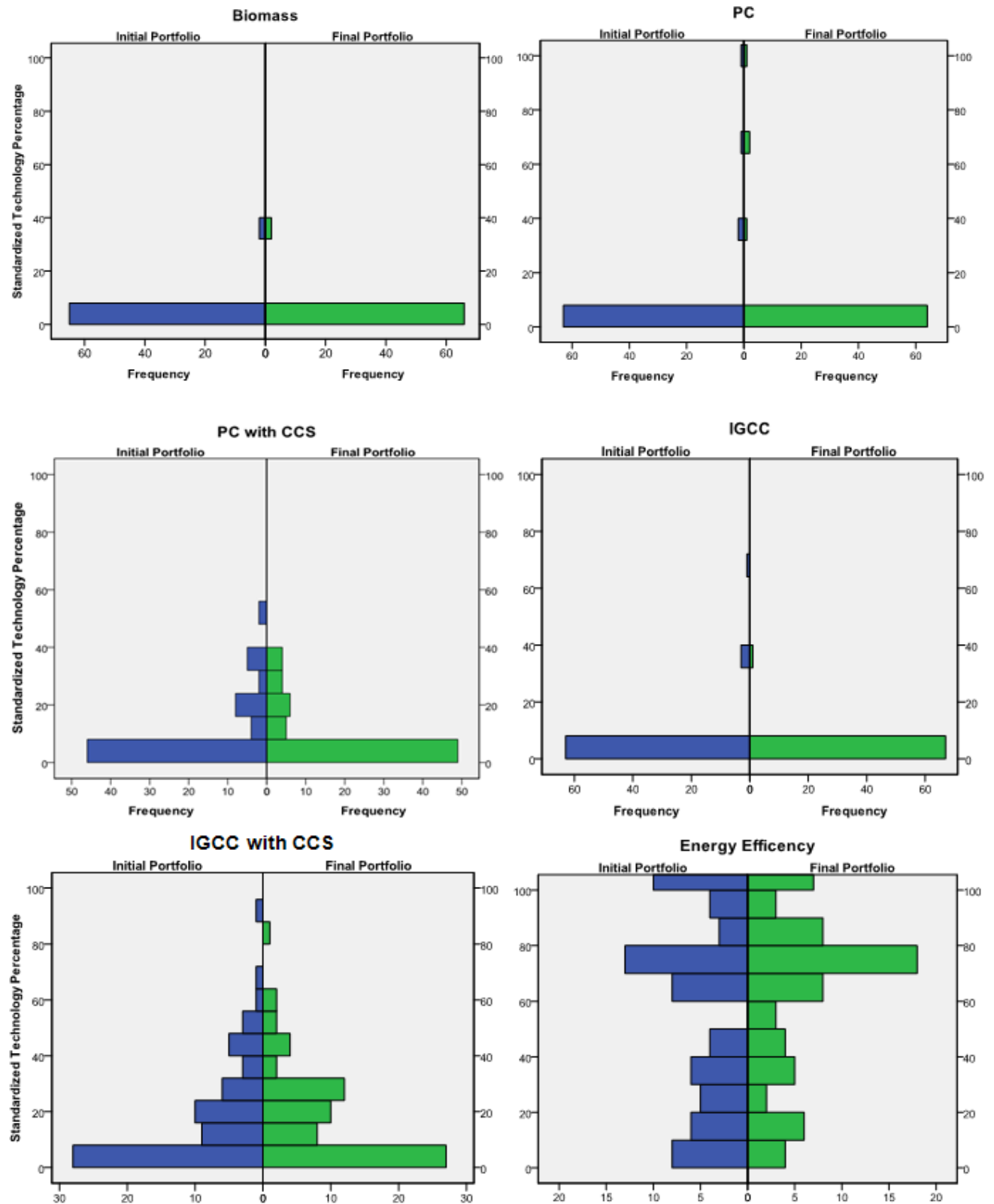


**Figure 5.5. Participants' mean standardized technology percentages  $\pm$  standard deviation, where 0 is no inclusion in portfolio and 100 is full inclusion in portfolio**

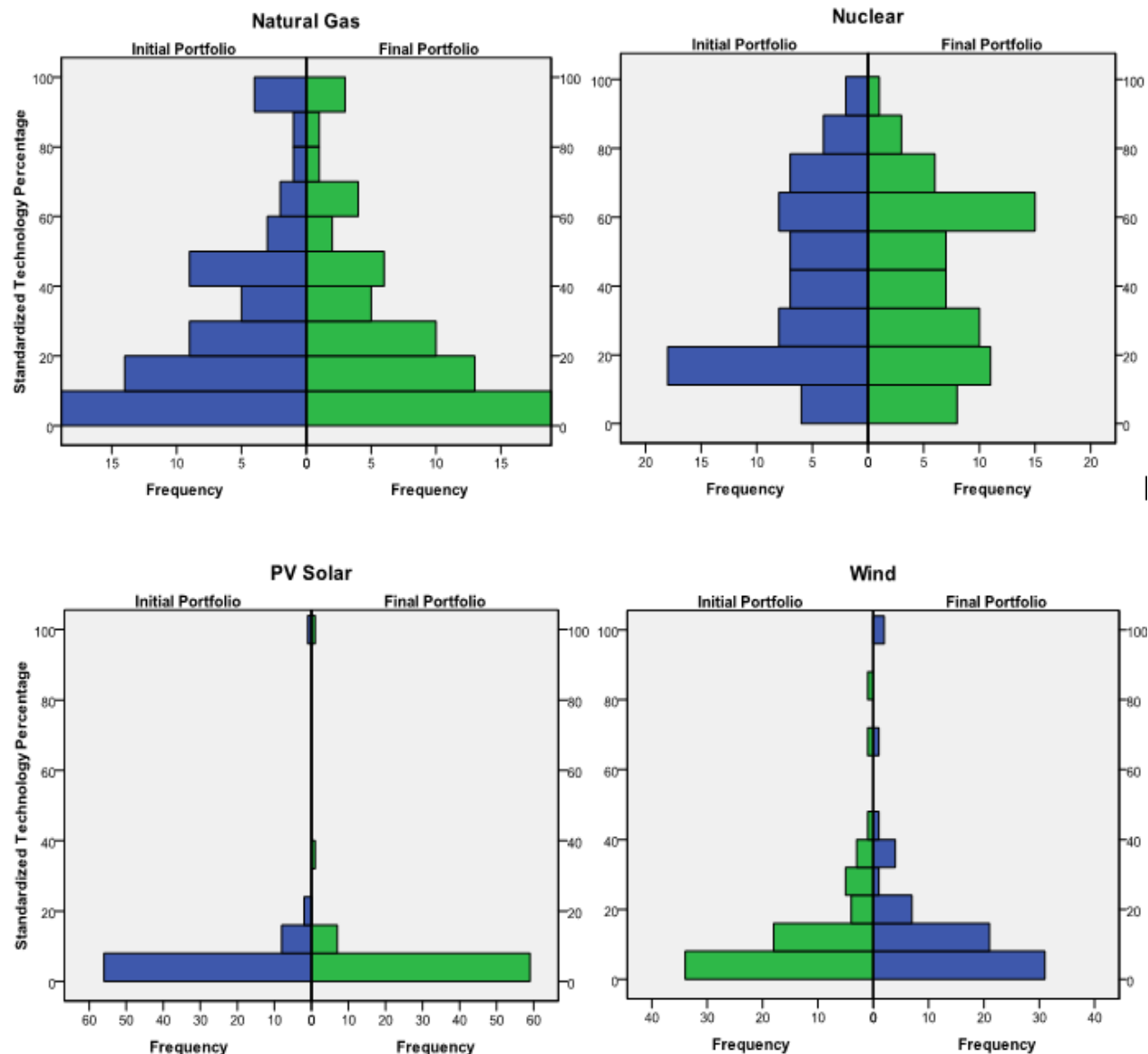
Note: Superscripted letters next to mean *standardized technology percentages* refer to *t*-test results ( $p < 0.01$ ) suggesting that *standardized technology percentages* of:

- 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
- f: all other technologies were significantly less
- g: wind, PC with CCS, PV Solar, PC, IGCC, and PC with biomass were significantly less





**Figure 5.6** Distribution of Participants' *Standardized Technology Percentages*, *pre-* (left) and *post-discussion* (right)



**Figure 5.6 (continued) Distribution of Participants' *Standardized Technology Percentages*, *pre-* (left) and *post-discussion* (right)**

To design a portfolio that could generate 60 TWh of electricity per year under the carbon constraint provided, participants had to include at least one of the following low-carbon baseload technologies: coal (IGCC or PC) with CCS, nuclear or natural gas. In fact, 58.2% of participants *pre-discussion* and 60.3% of participants *post-discussion* chose a portfolio that included all three technologies. Portfolios including nuclear and natural gas as the only two low-carbon baseload

technologies were the second most frequent design both *pre-* (19.4% of participant designs) and *post-discussion* (17.6% of participant designs). Portfolios in which nuclear was the sole low-carbon baseload technology made up 11.6% of the chosen portfolios *pre-discussion* and 7.4% *post-discussion*, and was the third most frequently chosen portfolio. The most frequent portfolio (31% of portfolio designs *pre-discussion*, 38% *post-discussion*) included energy efficiency, nuclear, natural gas, coal with CCS and wind.

## **5.4. Participants' Comprehension and Satisfaction**

### ***5.4.1 Participant Comprehension***

Across the 24 *true-or-false knowledge questions* answered after the homework but before the group meetings, participants obtained an average score of 90% correct ( $SD = 11\%$ ; range 46–100%). Using a one-sample *t*-test, we found these scores to be significantly better ( $t = 28.2$ ,  $p < 0.001$ ) than chance performance due to pure guessing (i.e., 50% correct, with true/false statements), suggesting a basic understanding of the materials. The most difficult question, which was only answered correctly by 21% of participants, concerned a statement explicitly addressed in the technology sheets, “If you turn off lights when you don’t need them, this is considered energy efficiency.” The second most difficult question was answered correctly by 80% of participants.

Across the 13 *computer knowledge test* questions answered after the experimenter’s explanation of the computer tool, participants obtained an average score of 93% correct ( $SD = 10\%$ ; range 62–100%). The most difficult question, which was answered correctly by 87% of participants, asked participants to ‘build’ 6 wind farms with the computer tool and to provide the amount of electricity generated by these wind farms. It is unclear whether the participants who

provided incorrect answers for this question added an incorrect number of wind farms, or did not know where to look on the computer screen to retrieve this answer, or both.

Participants' *homework comprehension ratings* also suggest a basic understanding of the materials prior to receiving the experimenter's verbal explanation or group discussion. The *Cost Comparison* received the lowest mean *comprehension rating* ( $M = 5.42$ ,  $SD = 1.54$ ), which was still significantly above the midpoint of 4 ( $t = 7.51$ ,  $p < 0.001$ ). Similarly, the *computer comprehension ratings* suggest an understanding of the computer tool by the end of the group meeting. Again, the *Cost Center* of the computer tool received the lowest mean *comprehension rating* ( $M = 6.36$ ,  $SD = 1.12$ ), which was still significantly above the midpoint of 4 ( $t = 17.17$ ,  $p < 0.001$ ). All other *comprehension ratings* for the computer tool areas and information materials were also found to be significantly above the scale midpoint ( $p < 0.001$  for each).

#### **5.4.2. Participant satisfaction**

Participants thought that using the computer tool was “an enjoyable experience” ( $M=6.5$ ,  $SD=1.0$ ) and “a valuable use of [their] time” ( $M=6.3$ ,  $SD=1.1$ ) (both above the scale midpoint of 4,  $p<0.001$ ). They further agreed 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” ( $M=5.7$ ,  $SD=1.7$ ,  $t=8.3$ ,  $p<0.001$ ).

## 5.5. Consistency of Participants' Portfolios

In this section, we assess participants' ability to use the computer tool, in terms of constructing portfolio designs showing (1) consistency with technology preferences and over time, (2) consistency with preferences for the five ranked attributes, and (3) increased agreement after group discussion.

**Table 5.1. Consistency Measures for Participants' Portfolio Designs**

<b>Technology</b>	<b>Spearman correlation between technology rankings and pre-discussion technology percentages</b>	<b>Paired <i>t</i>-test between pre- and post-discussion technology percentage</b>	<b>Pearson correlation between pre- and post-discussion technology percentage</b>
PC with biomass	$r_s = 0.09, p = 0.46$	$t = 1.00, p = 0.32$	$r = 0.70, p < 0.001^{***}$
PC	$r_s = 0.26, p = 0.04^*$	$t = -0.48, p = 0.64$	$r = 0.84, p < 0.001^{***}$
PC with CCS	$r_s = 0.22, p = 0.08^+$	$t = 1.49, p = 0.14$	$r = 0.56, p < 0.001^{***}$
IGCC	$r_s = 0.09, p = 0.46$	$t = -0.19, p = 0.85$	$r = -0.03, p = 0.78$
IGCC with CCS	$r_s = 0.50, p < 0.001^{***}$	$t = 0.76, p = 0.45$	$r = 0.69, p < 0.001^{***}$
Energy efficiency	$r_s = 0.34, p < 0.01^{**}$	$t = -3.10, p < 0.01^{**}$	$r = 0.62, p < 0.001^{***}$
Natural gas	$r_s = 0.29, p = 0.02^*$	$t = 0.70, p = 0.48$	$r = 0.80, p < 0.001^{***}$
Nuclear	$r_s = 0.40, p < 0.001$	$t = -0.52, p = 0.61$	$r = 0.83, p < 0.001^{***}$
PV solar	$r_s = 0.31, p = 0.01^*$	$t = 0.30, p = 0.77$	$r = 0.60, p < 0.001^{***}$
Wind	$r_s = 0.27, p = 0.03^*$	$t = -1.40, p = 0.17$	$r = 0.68, p < 0.001^{***}$

Notes: Technology rankings reverse-coded for these analyses, such that higher numbers reflect a higher preference; Spearman correlations for natural gas technology percentages are controlled for wind and solar technology percentages. Significance levels noted as such: + for  $p < 0.10$ , \* for  $p < 0.05$ , \*\* for  $p < 0.01$  and \*\*\* for  $p < 0.001$ .

### 5.5.1. Consistency of Portfolio Designs with Technology Preferences and Over Time

Table 5.1 displays three measures that examine whether participants were able to consistently use the computer tool over the course of the study to design portfolios that are

aligned with their technology preferences. Technology preference consistency across measures (i.e., between technology rankings and portfolio designs) and over time (i.e., between *pre-* and *post-discussion* portfolio designs) would suggest that participants were able to use the computer tool as intended. First, we calculated 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. Participants' *technology rankings* were significantly positively correlated ( $p < 0.05$ ) to their *technology percentages* for all technologies<sup>3</sup> except for PC co-fired with biomass, IGCC and PC with CCS, which also had correlations in the same direction. This result suggests that participants were able to design portfolios that were consistent with their technology preferences. Next, we calculated (1) *t*-tests and (2) Pearson correlations between participants' *pre-* and *post-discussion technology percentages* for each technology. Between *pre-* and *post-discussion*, participants' *technologies percentages* were (1) not significantly different for all technologies ( $p > 0.10$ ), except energy efficiency ( $p < 0.01$ ), and (2) significantly positively correlated for all technologies ( $p < 0.001$ ), except IGCC ( $p > 0.10$ ). These both suggest that participants had enough time and knowledge before the group discussion to design their desired portfolio (i.e., they did not change their portfolio designs much after group discussion).

### **5.5.2. Consistency of Portfolio Designs with Attribute Preferences**

Table 5.2 reports participants' mean *attribute importance ranks*. Overall, participants found the CO<sub>2</sub> emissions attribute the most important, valuing health costs second and increased

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<sup>3</sup> This correlation controls for the technology percentage of natural gas included in a portfolio as back-up for wind and solar.

monthly electric bill costs third. Water use and land use were the two least valued attributes of the five, ranking, on average fourth and fifth, respectively.

**Table 5.2. Participants' Mean Attribute Importance Ranks, where 1 is the most important and 5 is the least important**

Attribute	Mean importance rank
CO <sub>2</sub> emissions <sup>4</sup>	1.9 ± 1.3
Health costs	2.0 ± 0.8
Increased monthly electric bill	3.3 ± 1.2
Water use	3.4 ± 1.0
Land use	4.4 ± 0.8

To examine whether participants designed portfolios that were consistent with their attribute preferences, we assessed the desirability of different portfolio designs based on participants' preferences (i.e., ranks) for these five attributes. That is, we calculated the *expected utility* (17) of each portfolio design, where an *expected utility* closer to 1 represents what should be a more desirable portfolio, while an *expected utility* closer to 0 represents an undesirable portfolio. Calculating *expected utility* first required us to calculate *attribute weights* for the five quantitative attributes of CO<sub>2</sub> emissions, increased monthly bill cost, health costs, land use and water use. We used the reciprocal of rank method<sup>5</sup> with participants' *attribute importance ranks* to obtain *attribute weights* that summed to 1. These *attribute weights*, then, represented the importance participants placed on each attribute relative to the others. We then computed

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<sup>4</sup> While CO<sub>2</sub> emissions were constrained by the computer tool, users could design portfolios with a range of CO<sub>2</sub> emissions, with a maximum of 50% of the status quo scenario. For this ranking, CO<sub>2</sub> emissions could range between 0% and 50%.

<sup>5</sup> The reciprocal of rank method calculates the weight of the *i*th attribute,  $w_i$ , using the equation:

———— such that R is the rank for attribute *i*, where  $i=1, 2, \dots, 5$ .

*attribute values* for each of participant's portfolios design by standardizing the range of each attribute from 0 to 1 using a linear scale (such that higher attribute values are computed for more desirable outcomes). For instance, since the range of possible health costs using the computer tool is \$0 to \$460 million, a portfolio with a health cost of \$230 million would receive an *attribute value* of 0.5, while one with health costs of \$460 would be standardized to 0. The summed product of *attribute weights* and *attribute values* for portfolios provided a *pre-* and *post-discussion portfolio expected utility* for each participant. The *expected utility* of participants' portfolios ranged from 0.41 to 0.91, where an *expected utility* of 0 would be the least desirable and an *expected utility* of 1 would be the most. A Wilcoxon paired-ranked test shows that the *expected utility* of participants' portfolios *post-discussion* ( $M = 0.72$ ,  $SD = 0.13$ ) were greater than that for *pre-discussion portfolios* ( $M = 0.70$ ,  $SD = 0.13$ ), (Wilcoxon  $z = -3.07$ ,  $p = 0.002$ ), suggesting that the group discussion may have helped participants to design portfolios that were more consistent with their attribute preferences.

### **5.5.3. Participant Agreement**

Agreement among participants' rankings and portfolio designs would suggest that our participants were applying the same set of objectives during the study (i.e., providing advice to the PA Governor of which power plants to build in the future under a carbon constraint). We computed Kendall's coefficient of concordance ( $W$ ) to examine the agreement of participants' personal rankings of the 10 technologies. It showed significant agreement between participants' *technology rankings* ( $W = 0.35$ ,  $p < 0.001$ ). The composition of participants' portfolio designs were examined by focusing on the percentage of each technology included in that portfolio. Kendall's coefficient of concordance showed significant agreement among participants'



portfolios, as shown between participants' *pre-discussion technology percentages* ( $W = 0.53$ ,  $p < 0.001$ ). Kendall's coefficient further increased between their *post-discussion technology percentages* ( $W = 0.61$ ,  $p < 0.001$ ), suggesting that the group discussion increased participant agreement of their portfolio designs.

## **5.6. Discussion**

Our informed participants preferred energy efficiency, nuclear, IGCC with CCS, natural gas and wind, and designed diverse portfolios including these technologies. Their preference for coal technologies (IGCC and PC) with CCS over coal without CCS was evident in their rankings and portfolio designs. A majority of our participants included a combination of at least one of the coal with CCS technologies, with both natural gas and nuclear. Most participants included only a relatively small amount of IGCC with CCS, natural gas and wind in their portfolio designs, while excluding PC with biomass, PC, PC with CCS, IGCC and PV completely. In contrast, very few participants excluded energy efficiency and nuclear from their portfolio designs, for which rankings suggest as the two most preferred technologies. Indeed, participants included the largest percentage of these technologies compared to the total possible.

Our participants were able to use the computer tool to select portfolio designs that were consistent with their technology preferences and over time, and consistent with their attribute rankings. Moreover, they tended to be in agreement with each other about their technology rankings and portfolio designs. These results suggest that they reliably used the computer tool as intended by the study. While their designs (as measured by the technologies included) did not significantly change after the group discussion, they did tend to converge, as seen by the increase in portfolio design agreement across technologies. Possibly, the group discussion caused

participants to slightly change their portfolio design to be closer to those of their peers. These slight changes in technology percentages could have improved their portfolio when evaluated by the importance they placed on the five quantitative attribute. Indeed, the expected utility of participants' portfolio designs did slightly, but significantly, increase from *pre-* to *post-discussion*.

However, caution should be used when interpreting the expected utility results of this study. First, we only measured the importance of five attributes in this utility function, while our homework materials included many more attributes that participants likely considered when designing their own portfolios. For instance, anecdotal evidence from the group discussions suggest that participants likely also considered the diversity of the portfolio, the regional economic outcomes (e.g., in a state with a large resource of coal), and the importance of including renewables in the portfolio. These attributes all suggest that our participants may have based their portfolio designs on a combination of attribute and technology preferences. Furthermore, the additive utility function, used in this study may not be the most appropriate. However, linear utility functions, even when randomly selecting weights, tend to outperform those based on other functions or decision-maker judgment (18)

The results of our study suggest that our participants could use the computer tool to consistently show which technologies they would support for inclusion in a low-carbon electricity generation portfolio to be constructed in PA in the next 25 years. Indeed, participants believed that they learned a great deal from the study, which is likely because they found the homework materials and computer tool easy to understand. Their high knowledge test scores for the materials and computer tool confirm this result. Furthermore, participants enjoyed using the computer tool and agreed that they found it a valuable use of their time.

While the feasibility of people effectively using the computer tool without payment is uncertain, the computer tool could easily be adapted for other educational settings such as a science classroom or museum. Indeed, our participants found the computer tool relatively easy to use. They were able to build portfolios and observe how the costs and environmental indicators changed as they changed the percentages of technologies. Their ability to systematically compare the technologies and portfolios across their costs, risks, benefits and limitations likely allowed them to make informed, deliberate decisions about their portfolio designs. This suggests that the computer tool and supplemental materials may have value to educate the general public about low-carbon electricity generation.

While the computer tool may be useful to inform members of the general population about general public choices for low-carbon technologies, people living near specific energy infrastructure sites may have different informational needs. 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” (19-21). However, it 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 (e.g., 1, 22, 23).

One limitation of our study is the use of a local convenience sample from the Pittsburgh Metropolitan area, with an older mean age and a larger percentage of females than that of the general U.S. population (24). Thus, firm conclusions cannot be drawn about the portfolio designs or technology and attribute preferences of an informed public in other locations or with

different demographic characteristics. However, our results do suggest that our computer tool and materials gave participants a stable basic understanding, and may be useful for helping members of the general public to make more informed decisions about which low-carbon technologies to support. Furthermore, our participants' technology preferences were fairly similar to those found in our paper-based studies (Chapters 4 and 5), one of which included a demographic sample more similar to the general U.S. population. In all three studies, energy efficiency, nuclear and IGCC with CCS were the three most preferred technologies, while PC was consistently the least preferred. Notably, while the technology rankings for wind were significantly better than natural gas in both the paper studies, they were not significantly different from each other in this study. This could be a result of the revisions we made to the “homework” materials for this study, which provide a more detailed explanation of the need for natural gas technologies to back-up for intermittent renewables. Furthermore, 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 the paper-based studies (i.e., a diverse portfolio with energy efficiency, nuclear, IGCC with CCS, natural gas, wind and PC). Thus, while these studies were conducted with considerable time in between each (over the course of 3 years), our informed participants have consistently preferred energy efficiency, nuclear, IGCC with CCS, natural gas and wind, and diverse portfolios including these technologies. This portfolio is very similar to those recommended by electricity and energy policy experts who attest that there is no one silver bullet technology (e.g., 25). Instead, achieving a 50 - 80% reduction in CO<sub>2</sub> emissions over the next few decades is going to take every low-carbon technology that is available to us. Our participants were able to come to similar conclusions once they were given adequate time and the proper tools to inform their low-

carbon energy policy decision. We can only hope that policy-makers learn a thing or two from our informed participants.

## References

1. Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.
2. Palmgren CR, Morgan MG, Bruine de Bruin W, & Keith DW (2004) Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. *Environ Sci Technol* 38(24):6441-6450.
3. Reiner D, *et al.* (2006) American Exceptionalism? Similarities and Differences in National Attitudes Toward Energy Policy and Global Warming. *Environ Sci Technol* 40:2093-2098.
4. Energy Information Administration (2010) State Electricity Profiles, Pennsylvania, 2008.
5. Katzenstein W & Apt J (2009) Response to Comment on “Air Emissions Due to Wind and Solar Power”. *Environmental Science & Technology* 43(15):6108-6109.
6. Azevedo I, Palmer K, Morgan M, & Lave LB (under review) Energy Efficiency in the U.S. Residential Sector. *PNAS*.
7. Azevedo I (2009) Energy Efficiency in the U.S. Residential Sector: An Engineering and Economic Assessment of Opportunities for Large Energy Savings and Greenhouse Gas Emissions Reductions. (Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA).
8. Morrow WR, Griffin WM, & Matthews HS (2007) State-Level Infrastructure and Economic Effects of Switchgrass Cofiring with Coal in Existing Power Plants for Carbon Mitigation. *Environmental Science & Technology* 41(19):6657-6662.
9. Converse J & Presser S (1986) *Survey Questions: Handcrafting the standardized questionnaire* (Sage, Thousand Oaks, CA).
10. Presser S & Blair J (1994) Survey Pretesting: Do Different Methods Produce Different Results? *Sociological Methodology*, ed Marsden P (Jossey-Bass, San Francisco, CA), pp 73-104.

11. Morgan MG, Fischhoff B, Bostrom A, & Atman CJ (2002) *Risk Communication: A Mental Models Approach* (Cambridge University Press, New York).
12. Flesch R (1948) A new readability yardstick. *Journal of Applied Psychology* 32(2):221-233.
13. Kincaid JP, Fishburne RP, Rogers RL, & Chissom BS (1975) Derivation of new readability formulas (Automated Readability Index, Fog Count and Flesch Reading Ease Formula) for Navy enlisted personnel. (Naval Technical Training, U.S. Naval Air Station Memphis, TN).
14. Florig KH, *et al.* (2001) A deliberative method for ranking risks (I): Overview and test bed development. *Risk Analysis* 21(5):913-921.
15. Morgan KM, *et al.* (2001) A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers. *Risk Analysis* 21(5):923-937.
16. Barron FH & Barrett BE (1996) Decision Quality Using Ranked Attribute Weights. *Management Science* 42(11):1515-1523.
17. Hastie R & Dawes RM (2000) *Rational Choice in an Uncertain World* (Sage, Thousand Oaks, Ca.).
18. Dawes RM & Corrigan B (1974) Linear models in decision making. *Psychological Bulletin* 81(2):95-106.
19. Wong-Parodi G & Ray I (2009) Community perceptions of carbon sequestration: insights from California. *Environmental Research Letters* 4(3):1-8.
20. Wallquist L, Visschers VHM, & Siegrist M (2009) Lay concepts on CCS deployment in Switzerland based on qualitative interviews. *International Journal of Greenhouse Gas Control* 3(5):652-657.
21. Schaffer MB (2011) Toward a viable nuclear waste disposal program. *Energy Policy* 39(3):1382-1388.
22. Pidgeon NF, Lorenzoni I, & Poortinga W (2008) Climate change or nuclear power—No thanks! A quantitative study of public perceptions and risk framing in Britain. *Global Environmental Change* 18(1):69-85.
23. de Best-Walldorfer M, Daamen D, & Faaij A (2009) Informed and uninformed public opinions of CO<sub>2</sub> capture and storage technologies in the Netherlands. *International Journal of Greenhouse Gas Control* 3(3):322-332.
24. U.S. Census Bureau (2010) American Factfinder: S0101. Age and Sex: Data Set: 2005-2009 American Community Survey 5-Year Estimates.

25. James R, Richels R, Blanford G, & Gehl S (2007) The Power to Reduce CO2 Emissions: The Full Portfolio. (The EPRI Technology Assessment Center, Electric Power Research Institute, Palo Alto, CA.).

## Chapter 6. What do science teachers know about low-carbon electricity technologies?<sup>6</sup>

### Abstract

The widespread deployment of low-carbon electricity generating technologies to mitigate climate change will partially depend on public acceptance. However, public misconceptions about these technologies are pervasive and may increase or decrease support for the wrong reasons. Education is needed to correct common public misconceptions, which may develop as early as adolescence. Science teachers are in an excellent position to minimize and correct misconceptions. However, very little is known about the climate-change related knowledge of science teachers in the U.S. To examine whether teachers have sufficient knowledge to correct misconceptions among their students, we presented 58 6<sup>th</sup>-12<sup>th</sup> grade science teachers from Pennsylvania with seven knowledge questions about low-carbon technologies, targeting misconceptions that have been identified as common among the general public. On average, teachers correctly answered 70% of these misconception questions. However, many teachers shared public misconceptions about the possibility of meeting all of Pennsylvania's electricity needs with wind and solar power, the cost of solar power, whether nuclear plants emit CO<sub>2</sub>, and the existence of carbon capture and sequestration. Misconceptions were more pronounced among teachers who displayed more pro-environmental attitudes and more support for climate change policies. Hence, teachers who may be most motivated to include climate-related topics in their curriculum may not be able to correct common misconceptions among their students. Science teachers and their students would greatly benefit from unbiased, technically accurate and understandable information explaining the costs, benefits and limitations of climate change

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<sup>6</sup> This chapter is based on a paper prepared for possible publication in the *Proceedings of the National Academy of Sciences*.



mitigation strategies. We conclude that education about low-carbon technologies should better target science educators.

## **6.1. Introduction**

To escape the worst climate change scenarios, current U.S. CO<sub>2</sub> emissions from electricity generation must be reduced by 80% by 2050 (1). That goal can only be achieved through an aggressive deployment of a diverse energy portfolio including improved end-use efficiency and low-carbon electricity generating technologies such as natural gas, wind, nuclear, and coal with carbon capture and sequestration (CCS), a technology that separates CO<sub>2</sub> from the flue gas of electricity-generating plants and sequesters it in deep geological formations (2, 3). The successful widespread deployment of any of these individual low-carbon electricity generating technologies will be at least partially contingent on their public acceptance. In the past, public resistance has arisen against oil refineries (4), nuclear power plants (5), and even wind farms (6), creating a major obstacle to the cost-effective development of new energy infrastructure. More recently, a lack of local support for the Barendrecht CCS project in the Netherlands caused major delays, and eventually, the cancellation of the national government project (7). In contrast, the rallying of public support for CCS technologies in Mattoon, Illinois likely contributed to that town being selected for the FutureGen CCS site (7, 8).

To make informed decisions about low-carbon electricity generating technologies, people need to understand the risks, costs, benefits and limitations of the available alternatives. However, misconceptions about low-carbon electricity generating technologies are pervasive (9). Many people: are unaware of CCS (10-12) or biomass technologies (13-15); mistakenly believe that nuclear power emits greenhouse gases that contribute to climate change (9, 16, 17); lack

awareness about the intermittency of wind and solar power and their resulting limited ability to meet electricity demands (14, 18); and dramatically underestimate the cost-effectiveness of solar power (19). For example, in a qualitative interview conducted for a previous study (20), a 46-year-old female Pittsburgh resident exclaimed that “[power from] the sun is free!”

In adolescence, many individuals first begin to shape their political and moral identity, including environmental views and behaviors (21-24). Moreover, cognitive development tends to be completed by adolescence, providing teenagers with the ability to make informed decisions about complex topics such as climate change mitigation and low-carbon electricity generating portfolios (25-27). Hence, science teachers in middle school and high school have the opportunity to provide adolescents with the detailed information they need to make such informed decisions (28). If that opportunity is missed, adolescents may form misconceptions (29), which can be hard to change once they have been formed (30, 31).

To date, almost no research has examined whether middle-school and high-school science teachers have the knowledge to correct common public misconceptions about different climate change mitigation options. However, it has been shown that pre-service and elementary-school teachers in various countries may not have sufficient understanding of climate change and low-carbon electricity generating technologies to teach these topics (15, 16, 32-36).

Here, we exclusively focus on whether middle-school and high-school science teachers in the U.S. have the knowledge to correct common public misconceptions about low-carbon electricity technologies (e.g., 9, 11, 19) that hamper informed public debate. Specifically, we asked 58 6<sup>th</sup>-12<sup>th</sup> grade science teachers from Pennsylvania to answer the following seven true/false/don’t know statements: (1) Pennsylvania could make all of its electricity from wind power and solar power if we built enough wind and solar farms in the state, (2) Solar power costs

less to make than coal power, (3) Nuclear power plants release no carbon dioxide (CO<sub>2</sub>) into the air, (4) Engineers have developed equipment that can capture the carbon dioxide released by power plants, putting it underground instead of releasing it into the atmosphere, (5) The carbon dioxide released by electric power plants is not flammable, (6) Electricity can be made by burning woody products such as farm crops, wood chips and paper mill products, and (7) The natural gas used in power plants to make electricity is not flammable.

**Table 6.1: Knowledge Statement Responses: True-False-Don't Know**

	Statement (Correct Answer: T or F)	Participant Response Percent		
		Correct	Incorrect	Don't Know
1	Pennsylvania could make <u>all</u> of its electricity from wind power and solar power if we built enough wind and solar farms in the state. (F)	52.6%	21.1%	26.3%
2	Solar power costs <u>less</u> to make than coal power. (F)	56.9%	20.7%	22.4%
3	Nuclear power plants release <u>no</u> carbon dioxide (CO <sub>2</sub> ) into the air. (T)	62.1%	24.1%	13.8%
4	Engineers have developed equipment that can capture the carbon dioxide released by power plants, putting it underground instead of releasing it into the atmosphere. (T)	65.5%	6.9%	27.6%
5	The carbon dioxide released by electric power plants is <u>not</u> flammable. (T)	81.0%	3.4%	15.5%
6	Electricity can be made by burning woody products such as farm crops, wood chips and paper mill products. (T)	86.2%	3.4%	10.3%
7	The natural gas used in power plants to make electricity is <u>not</u> flammable. (F)	87.9%	0%	12.1%

*Note: Responses showed high internal consistency (Cronbach's alpha = 0.60), which could not be improved by deletion of any items – suggesting that all items measured the same underlying construct (e.g., knowledge about low-carbon technologies) and included no trick questions.*

## 6.2. Results

Overall, science teachers answered on average 70%  $\pm$  24% of the seven true/false statements correctly, performing significantly above the (50% chance) performance that would have been expected if they had been purely guessing ( $t(57) = 6.55, p < 0.001$ ) However, many

had insufficient knowledge to correct three of seven common public misconceptions about low-carbon technologies (Table 6.1): (1) 21% incorrectly believed that wind and solar could meet all of Pennsylvania's electricity needs (which of course they cannot given their intermittent nature), with an additional 26% being unsure; (2) 21% incorrectly believed that solar power costs less than coal power (which experts estimate it will not for the foreseeable future (37)), with an additional 22% being unsure; (3) 24% incorrectly believed that nuclear plants release CO<sub>2</sub>, with an additional 14% being unsure. Additionally, 28% were unsure of the existence of CCS, with an additional 3% answering incorrectly. Responses showed high internal consistency (Cronbach's  $\alpha = 0.60$ ), which could not be improved by deletion of any individual items. This finding suggests that items measured the same underlying construct (e.g., knowledge about low-carbon electricity generating technologies) and included no trick questions -- that could have been misinterpreted by otherwise well-informed teachers.

Teachers' responses to the 15 environmental statements appearing on the Dunlap et al. (38) new ecological paradigm (NEP) scale, were scored such that higher ratings (on a 1-7 Likert scale) reflected stronger pro-environmental attitudes, and had good internal consistency (Cronbach's  $\alpha=0.82$ ). Teachers' mean NEP scale ratings ( $M=5.00$ ,  $SD=0.92$ ) were significantly above the scale midpoint of 4 ( $t=8.26$ ,  $p<0.001$ ), suggesting pro-environmental attitudes. Furthermore, science teachers' agreement with the statements that, "the continuing release of CO<sub>2</sub> into the earth's atmosphere during this century may result in serious climate change" ( $M=5.57$ ,  $SD=1.69$ ) and "government regulation should begin to significantly limit the amount of CO<sub>2</sub> that is released into the earth's atmosphere" ( $M=5.50$ ,  $SD=1.84$ ), were both significantly above the scale midpoint of 4 ( $p<0.001$  for both). This suggests that these teachers also believed in climate change and showed support for a national climate change policy.

Misconceptions were more pronounced among teachers reporting stronger pro-environmental attitudes ( $r=0.39, p=0.003$ ), and stronger support for a national climate change policy ( $r=0.31, p=0.02$ ). Both correlations held after controlling for age, gender and completion of graduate degree(s) ( $r=0.35, p=0.01$  for pro-environmental attitudes;  $r=0.25, p=0.07$  for climate change policy).

### **6.3. Discussion**

To make informed decisions about low-carbon electricity generating technologies, people need accurate information about the costs, risks and benefits of the available options. Middle-school and high-school science teachers have the opportunity to address common public misconceptions about low-carbon electricity generating technologies in their curriculum. Overall, the middle-school and high-school science teachers in our sample seem to have sufficient knowledge to correct most of these common misconceptions. On average, they answered 70% of our true-false items correctly, performing significantly better than they would have if they had been purely guessing. These true/false items were selected to reflect misconceptions about low-carbon electricity generating technologies that are common among members of the general public (e.g., 9, 11, 19) and pre-service and elementary-school teachers (15, 16).

Our sample of science teachers held fairly strong pro-environmental attitudes, concerns about climate change and support for climate mitigation policies. However, those science teachers who were most pro-environmental and most in support of a national climate change policy also had more misconceptions about the electricity technologies that could mitigate climate change. Hence, science teachers who may be most motivated to include climate- and

environmental-related topics in their curriculum may not be able to correct, or may inadvertently reinforce (e.g., 39, 40), common misconceptions among their students.

Arguably, the level of electricity technology deployment in a carbon-constrained world will be contingent upon technology costs, CO<sub>2</sub> emissions and reliability. However, these were the topics addressed in the four questions that were least likely to be answered correctly by our middle-school and high-school science teachers. The ability of renewables to meet electricity needs reliably and cost-effectively in the near-term were overestimated by teachers, while the carbon-reducing ability of coal with CCS or nuclear was underestimated or unknown. These misconceptions were stronger among teachers with stronger concerns about the environment and climate change. While this could be explained by the more pro-environmental teachers misconstruing some statements as “trick” questions (e.g., while nuclear power plants do not directly emit CO<sub>2</sub>, building the plant and transporting the fuel do produce emissions), this is unlikely since the reliability of responses (i.e., Cronbach’s alpha) could not be improved by deletion of any items. More likely, that belief pattern may reflect a confirmation bias, with individuals being more likely to seek information that confirms their beliefs (41). Hence, more pro-environmental individuals may be more willing to believe more favorable information about “green” technologies including renewables, and less favorable information about coal and nuclear power (42) – even if that information is incorrect. Of course, the confirmation bias may also play a role in shaping the beliefs of less pro-environmental individuals who may favor other technologies.

To avoid the worst climate change scenarios, we will likely need to use a diverse portfolio including all low-carbon alternatives, including nuclear, natural gas, wind and coal with CCS. Science teachers and their students would greatly benefit from unbiased, technically

accurate and understandable information that stress the costs and benefits, and tradeoffs between different climate change mitigation strategies. Thus, there is a great need for educational efforts about all low-carbon technologies – especially targeting science teachers in charge of educating our future policy-makers.

## **6.4. Methods**

### **6.4.1. Participants**

Twenty-eight math and science teachers participated in the present study as part of a three-day continuing education workshop entitled “What is Research?” coordinated by the Carnegie Mellon University’s Leonard Gelfand Center for Service Learning and Outreach. An additional 40 math and science teachers responded to an email sent out by the Gelfand Center. Our analyses exclude the 10 teachers who exclusively taught math. Teachers participating in this study as part of the “What is Research?” workshop received \$25/hour from the Gelfand Center and Act 48 continuing education hours from the Pennsylvania Department of Education. Remaining teachers received \$95 and three continuing education hours for participating in our workshops. The research was approved by the Carnegie Mellon University Institutional Review Board and informed consent was obtained from all participants.

Teachers were 23 to 64 years old ( $M=42.0$ ), 59% female, and 93% white. All had Bachelor’s degrees, and 76% had a Master’s or Ph.D. Nearly 80% were high school (9<sup>th</sup>-12<sup>th</sup> grade) teachers.

### **6.4.2. Procedure**

Science teachers’ responses to the knowledge statements were elicited as a part of a larger study on perceptions of low-carbon electricity generation technologies, following the

workshop procedure outlined by Fleishman et al. (20). Teachers received the measures analyzed here by mail, and completed them at home before participating in the workshops. These homework materials included seven true/false/don't know statements referring to common public misconceptions about low-carbon electricity generation technologies: (1) Pennsylvania could make all of its electricity from wind power and solar power if we built enough wind and solar farms in the state, (2) Solar power costs less to make than coal power, (3) Nuclear power plants release no carbon dioxide (CO<sub>2</sub>) into the air, (4) Engineers have developed equipment that can capture the carbon dioxide released by power plants, putting it underground instead of releasing it into the atmosphere, (5) The carbon dioxide released by electric power plants is not flammable, (6) Electricity can be made by burning woody products such as farm crops, wood chips and paper mill products, and (7) The natural gas used in power plants to make electricity is not flammable. To ensure their accuracy, statements were reviewed by a survey design expert, a subject-matter expert, and a continuing-education trainer working with science teachers.

Homework materials also included the Dunlap et al. (38) 15-item new ecological paradigm (NEP) scale measuring pro-environmental attitudes, and the climate change statements “The continuing release of CO<sub>2</sub> into the earth's atmosphere during this century may result in serious climate change” and “Government regulation should begin to significantly limit the amount of CO<sub>2</sub> that is released into the earth's atmosphere”, all with responses anchored at completely disagree (=1) and completely agree (=7). Participants' responses to the NEP scale were scored such that higher ratings reflected stronger pro-environmental attitudes.



## References

1. IPCC (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. ed B. Metz ORD, P.R. Bosch, R. Dave, L.A. Meyer (Cambridge, United Kingdom and New York, NY).
2. James R, Richels R, Blanford G, & Gehl S (2007) The Power to Reduce CO<sub>2</sub> Emissions: The Full Portfolio. (The EPRI Technology Assessment Center, Electric Power Research Institute, Palo Alto, CA.).
3. Pacala S & Socolow R (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science* 305(5686):968-972.
4. Mouward J (May 9, 2005) No New Refineries in 29 Years? There Might Well Be a Reason. New York Times.
5. Guigni M (2004) *Social protest and policy change: ecology, antinuclear, and peace movements in comparative perspective* (Rowman and Littlefield, Lanham, MD).
6. Firestone J & Kempton W (2007) Public opinion about large offshore wind power: Underlying factors. *Energy Policy* 35(3):1584-1598.
7. WRI (2010) CCS and Community Engagement: Guidelines for Community Engagement in Carbon Dioxide Capture, Transport, and Storage Projects. (World Resources Institute, Washington, DC).
8. Lair B (July 13, 2007) Mattoon area best site for FutureGen. Journal Gazette Times Courier.
9. Reynolds TW, Bostrom A, Read D, & Morgan MG (2010) Now What Do People Know About Global Climate Change? Survey Studies of Educated Laypeople. *Risk Analysis* 30(10):1520-1538.
10. Huijts NMA, Midden CJH, & Meijnders AL (2007) Social acceptance of carbon dioxide storage. *Energy Policy* 35(5):2780-2789.
11. Reiner D, *et al.* (2006) American Exceptionalism? Similarities and Differences in National Attitudes Toward Energy Policy and Global Warming. *Environ Sci Technol* 40:2093-2098.
12. Palmgren CR, Morgan MG, Bruine de Bruin W, & Keith DW (2004) Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. *Environ Sci Technol* 38(24):6441-6450.

13. Liarakou G, Gavrilakis C, & Flouri E (2009) Secondary School Teachers' Knowledge and Attitudes Towards Renewable Energy Sources. *Journal of Science Education and Technology* 18(2):120-129.
14. Plate R, Monroe M, & Oxarart A (2010) Public Perceptions of Using Woody Biomass as a Renewable Energy Source. *Journal of Extension* 48(3):1-15.
15. Yilmaz-Tuzun O, Teksoz-Tuncer G, & Aydemir M (2008) An investigation of the elementary teachers' knowledge about air pollution issues. *Hacettepe Universitesi Journal of Education* 35:374-385.
16. Groves FH & Pugh AF (1999) Elementary Pre-Service Teacher Perceptions of the Greenhouse Effect. *Journal of Science Education and Technology* 8(1):75-81.
17. Read D, Bostrom A, Morgan MG, Fischhoff B, & Smuts T (1994) What Do People Know About Global Climate Change? 2. Survey Studies of Educated Laypeople. *Risk Analysis* 14(6):971-982.
18. Farhar B & Buhrmann J (1998) Public Response to Residential Grid-Tied PV Systems in Colorado: A Qualitative Market Assessment A Qualitative Market Assessment. (National Renewable Energy Laboratory, Golden, CO).
19. Ansolabehere S (2007) Public attitudes toward American's energy options : report of the 2007 MIT Energy Survey. (Massachusetts Institute of Technology. Center for Energy and Environmental Policy Research., Cambridge, MA).
20. Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.
21. Marcia JE (1980) Identity in adolescence. *Handbook of Adolescent Psychology*, ed Adelson J (Wiley, New York).
22. Erikson EH (1968) *Identity: Youth and Crisis* (W. W. Norton, New York).
23. Erikson EH (1980) *Identity and the Life Cycle* (W. W. Norton, New York).
24. Kals E & Ittner H (2003) Children's environmental identity: Indicators and behavioral impacts. *Identity and the natural environment*, eds Clayton S & Opatow S (MIT Press, Cambridge, MA), pp 135-157.
25. Quadrel MJ, Fischhoff B, & Davis W (1993) Adolescent (In)vulnerability. *American Psychologist* 48(2):102-116.
26. Fischhoff B, *et al.* (2000) Teen Expectations for Significant Life Events. *The Public Opinion Quarterly* 64(2):189-205.

27. Fischhoff B (2008) Assessing adolescent decision-making competence. *Developmental Review* 28(1):12-28.
28. Anonymous (1996) National science education standards. (National Research Council, Washington, DC).
29. Black PJ & Lucas AM (1993) *Children's Informal Ideas in Science* (Routledge, London).
30. Slovic P (1987) Perception of Risk. *Science* 236:280-285.
31. Anonymous (2005) How students learn: Science in the classroom. (National Research Council, Washington, DC).
32. Kalipci E, Yener Y, & Ozkadif S (2009) The opinions of teacher candidates about global warming, greenhouse effect and ozone layer. *World Applied Science Journal* 7(1):67-75.
33. Spiropoulou D, Antonakaki T, Kontaxaki S, & Bouras S (2007) Primary Teachers' Literacy and Attitudes on Education for Sustainable Development. *Journal of Science Education and Technology* 16(5):443-450.
34. Papadimitriou V (2004) Prospective Primary Teachers' Understanding of Climate Change, Greenhouse Effect, and Ozone Layer Depletion. *Journal of Science Education and Technology* 13(2):299-307.
35. Summers M, Kruger C, Childs A, & Mant J (2000) Primary School Teachers' Understanding of Environmental Issues: an interview study. *Environmental Education Research* 6:293-312.
36. Groves F & Pugh A (2002) Cognitive Illusions as Hindrances to Learning Complex Environmental Issues. *Journal of Science Education and Technology* 11(4):381-390.
37. Curtright AE, Morgan MG, & Keith DW (2008) Expert Assessments of Future Photovoltaic Technologies. *Environmental Science & Technology* 42(24):9031-9038.
38. Dunlap RE, Van Liere KD, Mertig AG, & Jones RE (2000) New Trends in Measuring Environmental Attitudes: Measuring Endorsement of the New Ecological Paradigm: A Revised NEP Scale. *Journal of Social Issues* 56(3):425-442.
39. Sanders M (1993) Erroneous ideas about respiration: The teacher factor. *Journal of Research in Science Teaching* 30(8):919-934.
40. Yip DY (1998) Identification of Misconceptions in Novice Biology Teachers and Remedial Strategies for Improving Biology Learning. *International Journal of Science Education* 20(4):461-477.
41. Nickerson RS (1998) Confirmation Bias: A Ubiquitous Phenomenon in Many Guises. *Review of General Psychology* 2(2):175-220.

42. Spence A, Poortinga W, Pidgeon NF, & Lorenzoni I (2010) Public Perceptions of Energy Choices: The Influence of Beliefs About Climate Change and the Environment *Energy and Environment* 21(5):385-407.

**Chapter 7. The value of CCS public opinion research: *A letter in response to Malone, Dooley and Bradbury (2010) “Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement”***<sup>7</sup>

In their article entitled “Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement,” Malone, Dooley and Bradbury (1) argue that previous research on public perceptions of carbon capture and sequestration (CCS) has been relatively uninformative, because it has (1) focused on the perceptions of the general public rather than communities living near potential CCS sites, (2) used structured surveys to examine perceptions of CCS rather than qualitative methods that allow for discourse, and (3) examined participants’ preferences for CCS and other low-carbon technologies without first providing them with the information needed to make informed decisions. Here, we argue that there is merit to conducting research with both members of the general public and with populations living near proposed sites, using a combination of qualitative and survey methodologies, both before and after providing detailed information about CCS and other low-carbon electricity generation technologies.

First, there are differential benefits to examining the perceptions of members of the general public and of individuals living near potential CCS sites. To examine whether there is public support for national policies including CCS, research should be conducted with members of the general population. To examine whether there is public support for a specific CCS site, research should be conducted in the nearby community. Although we agree with Malone et al. that opinions expressed in a research setting may not translate into action (e.g., organizing rallies

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<sup>7</sup> This chapter reproduces a letter sent to the editor of the *International Journal of Greenhouse Gas Control*

for or against CCS), such concerns apply to both the research conducted with members of the general public and with individuals living near potential CCS sites. Even if most people do not act on their beliefs, democratic governments should consider public opinion when making decisions about whether or not to include CCS in a national energy portfolio, and where to locate CCS sites. Indeed, many existing public policies are informed by public opinion (2-5).

Second, there are strengths and weaknesses in the qualitative research methods that Malone and colleagues recommend, as well as to the structured survey methods they criticize. Qualitative research methods allow researchers to characterize individuals' full set of beliefs regarding the topic of interest, but because administering them is very labor-intensive, they impose constraints on the size and the generalizability of the sample (e.g., 6, 7, 8). Structured surveys allow researchers to understand the prevalence of beliefs and their correlation with preferences, but results can only reveal beliefs that are covered by the questions (e.g., 9, 10). Hence, survey methodologists commonly advise to use a mixed-method approach to learn about an audience's beliefs, with survey questions being designed to ask about the beliefs that have been expressed in qualitative research (7, 11, 12).

Third, there are differential benefits to examining an audience's current (potentially un- or under-informed) beliefs and preferences, and to examining how beliefs and preferences change after an audience has been informed with communication materials. When examining current beliefs, qualitative research can identify gaps and misconceptions in people's knowledge that need to be addressed by subsequent communications (e.g., 12). Subsequent surveys can reveal the prevalence of these gaps and misconceptions, as well as their relationships to preferences, thus suggesting which information needs to be highlighted in the communications (9, 12). When examining responses to communications (i.e., after the provision of information),

qualitative research can help to identify which sections are in need of improvement, and structured surveys can help to systematically examine how specific beliefs and preferences change after the communications are disseminated to a larger sample. Furthermore, unlike the approach suggested by Malone and colleagues, this mixed-method procedure is commonly recommended for evaluating the effectiveness of communications (12-14). Indeed, any communication efforts, including the interactive town hall meetings that Malone and colleagues recommend, will benefit from the formative research they criticize. Otherwise, these communications may fail to understandably address the gaps and misconceptions that are necessary to facilitate informed decision-making.

In a recent study (15), we provided participants with comprehensive and balanced information about the costs, benefits, risks and limitations of a set of electricity technologies (i.e., coal with CCS, coal without CCS, renewables, nuclear and natural gas), and low-carbon portfolios composed of those technologies. The materials were specifically designed to address gaps and misconceptions in participants' knowledge, as well as issues about which they wanted more information, as identified in previous qualitative and survey research. The content of the communications was then adapted on the basis of qualitative interviews with subject-matter experts to ensure balance and accuracy, and with members of the general public, to ensure their understanding (15). As recommended by Malone and colleagues, our participants spent the better part of a day engaging in group discussions to weigh the pros and cons of different electricity technologies and low-carbon portfolios. Additionally, as Malone et al. recommend, we framed our questions in a decision- and policy-relevant context, asking participants to provide advice to the Pennsylvania Governor on which low-carbon portfolio they think should be built in the next 25 years. Finally, our informed participants reported their beliefs and

preferences on a survey that covered topics that had been identified as relevant in qualitative research. We found that our materials improved recipients' understanding and led to preferences that were relatively in favor of CCS if linked to integrated gasification combined-cycle coal power plants.

Hence, it is *not*, as Malone and colleagues claim “impossible to design a survey instrument that communicates all possible pros and cons for all potential energy sources” or “impossible for a respondent to weigh all the pros and cons together to answer survey questions,” as stated in the Malone et al. (1) article. Moreover, our efforts to develop and evaluate these comprehensive written communications would not have been possible without the groundwork laid by the previous CCS public perception studies that Malone et al. so vehemently – and we believe unfairly -- criticize. While we agree with the authors that interactive town hall meetings may help to inform residents near potential CCS sites, we also see benefit to making effective written communications available to all members of the general public. After all, everyone's opinions deserve to be considered as part of the discussion about CCS infrastructure development feasibility.

## References

1. Malone EL, Dooley JJ, & Bradbury JA (2010) Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement. *International Journal of Greenhouse Gas Control* 4(2):419-425.
2. Brace P & Boyea BD (2008) State Public Opinion, the Death Penalty, and the Practice of Electing Judges. *American Journal of Political Science* 52(2):360-372.
3. Burstein P (2003) The Impact of Public Opinion on Public Policy: A Review and an Agenda. *Political Research Quarterly* 56(1):29-40.



4. Lax JR & Phillips JH (2009) Gay Rights in the States: Public Opinion and Policy Responsiveness. *American Political Science Review* 103(03):367-386.
5. Wald M (March 18, 2009) Once a defender of Indian Point Plant, the State pushes to close it. *The New York Times*.
6. Fishkin J (2006) Strategies of Public Consultation. *Integrated Assessment* 6(2):57-72.
7. Fowler F (1995) *Improving Survey Questions: Design and Evaluation* (Sage, Thousand Oaks, CA).
8. Presser S & Blair J (1994) Survey Pretesting: Do Different Methods Produce Different Results? *Sociological Methodology*, ed Marsden P (Jossey-Bass, San Francisco, CA), pp 73-104.
9. Converse J & Presser S (1986) *Survey Questions: Handcrafting the standardized questionnaire* (Sage, Thousand Oaks, CA).
10. Tourangeau R, Rips L, & Rasinksi K (2000) *The psychology of survey response*. (Cambridge University Press, Cambridge, UK).
11. Jobe J & Mingay D (1989) Cognitive research improves questionnaires. *American Journal of Public Health* 79:1053-1055.
12. Morgan MG, Fischhoff B, Bostrom A, & Atman CJ (2002) *Risk Communication: A Mental Models Approach* (Cambridge University Press, New York).
13. Bruin de Bruine W, Fischhoff B, Güvenç U, Caruso D, & Armstrong CM (2009) A model-based scenario approach to communicating the risks of xenotransplantation. *Risk Analysis* 29:1105-1115.
14. Fischhoff B, Bruine de Bruin W, Güvenç U, Brilliant L, & Caruso D (2006) Analyzing disaster risks and plans: An Avian Flu Example. *Journal of Risk and Uncertainty* 33:131-149.
15. Fleishman L, Bruine de Bruin W, & Morgan M (2010) Informed Public Preferences for Electricity Portfolios with CCS and Other Low-Carbon Technologies. *Risk Analysis* 30(9):1399-1410.

## **Chapter 8. Future Work**

The computer tool developed as a part of this thesis may be further enhanced by addressing some of its limitations described in Chapter 5. In this chapter, we propose future work that could validate the feasibility of the computer tool. First, in Section 8.1, we propose that the computer tool be adapted for use on the internet, which would make it available to the wider public. In Section 8.2, we propose for the computer tool to be equipped with the capability to track users' key strokes, which would allow for a quantitative assessment of how people use the tool. In Section 8.3., we propose a study that could test the consistency of participants' portfolio designs between an attribute- and a technology-focused approach. Finally, Section 8.4 proposes a study to test and increase computer tool user understanding of the uncertainty surrounding some of the quantitative impacts (e.g., costs) presented in the tool. Each of these proposals would provide insight into the general public's ability to consistently and correctly use the tool to design portfolios that reflect their technology and attribute preferences.

### **8.1. Adapting the Computer Tool for the Web**

The rather simple design of the computer tool would allow for easy adaptation to the internet. The motivation for designing and implementing the web-based tool could either be purely for educational outreach purposes or to collect data without the time-consuming process involving an experimenter and group workshop. In the previous case, the computer tool could be placed on the internet with a set of instructions and links to supplemental "homework" materials could be offered for interested users.

If the objective is to elicit portfolios from well-informed users, the paper materials that are usually sent as "homework" could be offered through a web-based procedure that could help to verify that users had read the information. Users could follow a procedure with the computer

tool similar to the one currently used in the small group meeting. A tutorial or manual would need to be developed as a learning aid for new users. If data collection was the primary purpose for internet adaptation, a web-based survey or an internet form for user feedback could be designed. The internet tool could reach many more (computer and internet literate) people than a tool used as a part of a group-based exercise. The development process would entail a number of pilot tests to ensure that participants could use the tool and properly follow the instructions without the aid of an experimenter. Given that we were able to devise instructions for participants in the completed study to follow the ‘homework’ materials, a similar set of systematic instructions could likely be developed to lead participants through the individual use of the computer tool.

## **8.2. Tracking Users’ Choices**

Additional functionality that could be established in the tool is the ability to track the decisions of participants who use the tool. This tracking functionality would require the tool to be connected with a simple database environment to record the users’ actions. One linked table will be necessary to include this functionality. The table will track users by accepting a ‘dump’ of information from the computer tool each time the user changes the portfolio design. Each column of the table could represent a different technology. Each row, then, could track one point in time. The first row recorded for each user in the table would show the percentages of each technology in their initial portfolio and each following row would track every change in these percentages chosen by the user. An extra column inserted in the table could indicate whether a user submits the portfolio as their final (or favorite) portfolio. An example table with this database design is shown in Table 8.1 below.

Furthermore, this database functionality will allow for the collection of data that itemizes each incremental decision made by the user to reach their optimal portfolio. This data could be quantitatively or qualitatively analyzed using a number of approaches. At a minimum, the ability to graphically observe the pattern of people's decisions would be qualitatively interesting. As a quantitative assessment, the data could be analyzed to observe whether users display any cost or emission threshold preferences or if any correlation exists between users' decisions and the level of environmental externality indicators.

While the tool tracks user choices, it could also record the length of time taken to build a portfolio. It would be interesting to compute whether some participants finished their design quickly (with relatively little iteration or experimentation), while others used a more systematic or lengthy decision process. This could be correlated to users' satisfaction with their designed portfolio, which could help to correct this limitation in Chapter 5. We could explore whether users' actually like their portfolios, spend lots of time trying to optimize their design or satisfice based on one of more preferences.

**Table 8.1. Example Table to Track User Choices**

User	Biomass	IGCC	IGCC CCS	Nuclear	NGCC	EE	PC	PC CCS	PV	Wind	Final Choice
1	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	
1	10%	10%	11%	10%	10%	10%	10%	10%	9%	10%	Yes

### **8.3. Attribute-Focused Study with Computer Tool**

As opposed to simply focusing on a study to elicit technology preferences, another interesting follow-up study to chapter 6 would involve a focus on the technology attributes. Similar to the risk ranking studies (1, 2), where participants are shown how their holistic evaluation of a risk and the evaluation of the attributes that characterize that risk differ, we could provide participants with a portfolio that optimized their attribute preferences. For instance, the

homework materials could focus on the attributes before characterizing them for any technology. At each step, participants could rank the attributes in order of importance and then be presented with a technology or portfolio that best optimized their preferences. Thus, they could compare a “holistic” portfolio that they design based on the technologies with a portfolio that had been optimized based on their attribute preferences. This would hopefully improve the consistency between participants’ technology preferences and values (i.e., attribute preferences). Based on the findings of the computer tool study (Chapter 5), the quantitative attributes included to describe the technologies would likely need to be expanded and revised. Qualitative interviews with members of the general public could support the choice of an updated set of attributes.

#### **8.4. Comparison of Graphical Displays of Uncertainty**

As a supplemental study, which could help to inform the displays of uncertain values (e.g., *Cost Comparison*) in the computer tool, a systematic comparison of these displays could be prepared using psychometric studies with non-technical members of the general public. In the completed study we displayed cost uncertainty using a shaded bar with a darker center to represent the mean. While participants seemed to understand this display, it only communicated information about the mean and the range of the future cost distribution for different technologies. In the proposed study, we plan to explore whether there are better ways to display this information, as well as to explore ways to display medians and the probability of costs being greater than or between two values (i.e.,  $p(x > a)$  or  $p(b > x > a)$ ). Comparisons between displays will be made following a similar methodology to that implemented in Ibrenk and Morgan (3).

This proposed extension could begin by first generating a number of graphical displays that each communicate uncertain technology cost information. After some initial pilot testing of

these displays, we will survey a number respondents to discern whether the quantities of mean, median,  $p(x>a)$  and  $p(b>x>a)$  are easily communicated in those displays. The study may also compare if other factors, such as a text explanation or a legend, aide respondents in their understanding of the uncertainties. Survey questions may also include respondent self-ratings of how much they like each display, how confident they were in their answers to questions about each display and how long it took them to understand and obtain information from the display. The results will be used to inform the design of the computer decision tool. Additionally, the study will fill a gap in the risk communication literature on the systematic testing of best pictorial methods for communicating uncertain quantities to the general non-technical public.

#### References

1. Florig KH, *et al.* (2001) A deliberative method for ranking risks (I): Overview and test bed development. *Risk Analysis* 21(5):913-821.
2. Morgan KM, *et al.* (2001) A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers. *Risk Analysis* 21(5):923-937.
3. Ibrenk H & Morgan MG (1987) Graphical Communication of Uncertain Quantities to Nontechnical People. *Risk Analysis* 7(4):519-529.

## **Appendix A. Assumptions and Calculations for the Portfolio-Building Computer Tool and Supplemental Materials**

This appendix provides references, assumptions and explanations for the calculations to estimate the quantitative input and output values used in the computer decision tool and the supplemental paper materials. First-order (or, in some cases, zero-order) estimate values were calculated to obtain additional annual electricity generation demand for Pennsylvania (PA) in 25 years, and for each electricity technology: (1) average electricity generated each year (in TWh/year), (2) direct carbon dioxide and other air pollutant emissions (in kg/MWh), (3) annual cost of health damages from air emissions (in \$/TWh) (3) a range of values for the levelized cost of electricity (LCOE) (in \$/kWh), (3) annual water consumption (in L/TWh and Olympic size swimming pools/TWh), and (5) land transformed (in m<sup>2</sup>/TWh and football fields/TWh). The references, calculations and assumptions used are reviewed in the following sections. One final section explains the decision to present facts about solid waste from these technologies in qualitative form only.

### **A.1. Average Electricity Generated Per Year**

The computer tool presents an electricity generation goal of 60 TWh/year. This value was chosen to represent the expected additional electricity generation needed to keep pace with electricity demand in Pennsylvania for the next 25 years. The model assumes that 2% of plants retire over the next 25 years. In 2008, PA generated 222 TWh of electricity (1). It is assumed that electricity demand increases at a rate of 1% per year (2) and that an increase in electricity demand is equal to the increase in electricity generation. Thus, in 25 years, PA will need to make

$222 \times (1.01)^{25} - (222 \times .98) = 30\%$  more electricity per year or about 66 TWh/year. The increased generation needed was rounded to 60 TWh to reduce the complexity of the task for lay users of the tool.

Since the user will be building technologies to generate 60 TWh/yr, the average annual electricity generated by each technology must be chosen (Table A.1). These were chosen by identifying the expected nameplate capacity for each technology in new construction projects. Capacity factors were chosen based on those developed as part of the cost estimates (see section below). Finally, TWh/year were rounded to obtain simpler values for users of the computer decision tool. The following table provides these calculations, where annual electricity generated is calculated by  $\text{MW} \times \text{CF}\% \times 8760 \times 10^{-6} = \text{TWh}$

**Table A.1. Electricity Generation Assumptions**

	Nameplate capacity (MW)	Average Capacity Factor	Electricity Generated (TWh )
PC co-fired with 10% biomass	533	75%	3.5
PC	761	75%	3.5
PC with CCS	761	75%	3.5
IGCC	761	75%	3.5
IGCC with CCS	761	75%	3.5
Energy Efficiency	Negawatt unit equal to 0.83% of electricity generation needed/yr		0.5
Natural gas	381	75%	2.5
Nuclear	888	90%	7
PV solar	105	11%	0.1
Wind	205	28%	0.5

## **A.2. Technology Constraints Modeled in the Computer Tool**

Technology capacity was constrained for three of the technologies included in the tool. Assuming an energy density of switchgrass of 8000 btu/lb (3) and a 10 year regrowth period, two



PC co-firing with 10% biomass would need to harvest 4.8 million tons of switchgrass every ten years. Using biomass supply curves for PA (4, 5), 3 co-firing plants places the cost at the top of the supply curves. Energy efficiency was constrained to 20% of the portfolio, based on residential demand-response ability (6). Finally, natural gas was automatically added to back up wind and solar capacity additions. This was added at a 1 Watt to 1 Watt ratio. This ratio is based on the assumption that utilities will need to use the full availability of installed wind and PV solar capacity to meet a renewable energy portfolio standard or future capacity carbon constraint, such as the one hypothetically proposed in our *Problem Question*. In this situation, we assume that utilities will need to have spinning natural gas reserves to fill in for large fluctuations in electricity generated by wind or PV solar (7). This is consistent with the results from the distributed generation model created by Katzenstein and Apt (7), in which they find that attempting to balance the variability in wind/solar with a ratio less than this “does not smooth output enough to cover deep and fast power drops.” The capacity factor for natural gas back up was calculated as 90% - capacity factor of wind/solar (i.e., 62% for backup of wind and 79% for backup of solar). We assumed that the availability of wind or solar over the next 25 years was 90%, and thus, the planned natural gas under a renewable energy standard would only back up to this amount.

### **A.3. Emission Values**

Emission values for fossil fuel plants were obtained using the new version of the IECM accessed on May 27, 2010 (8). The plants in the model were configured using the default setting with only these changes (9):

- PC Plant: Using supercritical setting, post-combustion emissions controls of a Hot-side SCR for NO<sub>x</sub>, a wet FGD for SO<sub>2</sub> and a fabric filter for particulates. Two different SO<sub>2</sub> scrubbers were available in the IECM. The reverse gas fabric filter was chosen because over 90% of baghouses in U. S. utilities use reverse-gas cleaning. This is an off-line bag cleaning technique in which an auxiliary fan forces a relatively gentle flow of filtered flue gas backwards through the bags causing them to partially collapse and dislodge the rust cake (8). No mercury controls were chosen because the health impact calculations (see section below) are independent of mercury concentrations. A wet cooling tower was chosen.
- The PC with CCS plant used all the same settings as the PC, except CCS technologies were added.
- The IGCC plant used a GE gasifier and wet cooling tower with all other default settings. The IGCC with CCS only added CCS technologies.
- The NGCC used a wet cooling tower.

To obtain emissions for a PC plant co-fired with 10% biomass, data from Mann and Spath (10) was used. Table 3 of Mann and Spath (10) calculates the percent change in emission rates from co-firing for a 15% and 5% PC/Biomass blend. Percentages were averaged between the 15% and 5% blend cases to obtain a 10% blend estimate for input into the computer tool. This estimates that SCPC emissions would be reduced for NO<sub>x</sub>, SO<sub>2</sub>, PM and CO<sub>2</sub> by 5, 7.5, 7.5 and 4% respectively when it is co-fired with 10% biomass. The SCPC emissions values from the IECM were decreased accordingly. Table A.2 shows the emissions used in the computer tool

**Table A.2 Emissions from fossil fuels technologies**

	PC	PC with CCS	IGCC	IGCC with CCS	Natural gas	PC with 10% biomass
lb/kWh						
NO <sub>x</sub>	8.84E-04	1.44E-03	1.83E-04	2.04E-04	1.88E-04	8.39E-04
SO <sub>2</sub>	5.27E-03	1.84E-06	6.40E-04	8.41E-05	0	4.88E-03
PM	1.31E-04	1.09E-04	9.47E-06	1.10E-05	0	1.21E-04
CO <sub>2</sub>	1.81E+00	3.00E-01	1.87E+00	2.04E-01	0.8258	1.74E+00
kg/MWh						
NO <sub>x</sub>	0.40	0.65	0.08	0.09	0.09	0.38
SO <sub>2</sub>	2.39	0.00	0.29	0.04	0.00	2.21
PM	0.059	0.049	0.004	0.005	0.000	0.05
CO <sub>2</sub>	821	136	850	92	375	787.8

**A.4. Residential Levelized Cost of Electricity**

LCOE of the ten electricity technologies were obtained from an in-depth cost analysis completed by Samaras (11), using values from Lazard Ltd. (12) and NEMS (13). Samaras' assumptions were modified at times to account for PA-specific capacity factors. All estimates are in 2008 \$USD, use a 20 year annualized payment and a 9% capital charge rate. All capital cost and non-fuel fixed O&M costs are provided from the Lazard report. Coal and gas fuel cost ranges of \$1.5-\$5 and \$3-\$13/MMBTU, respectively, are assumed using the base case fossil prices from the EIA (14). The assumed nuclear fuel cost is from Lazard with a range of \$0.40-0.60/MMBTU. PC plants co-fired with biomass assume a switchgrass cost of \$3.45/MMBtu to \$9.03/MMBtu, for an overall fuel cost of \$1.69 - \$5.40/MMBtu. All heat rates are from NEMS (13) except for the co-fired plant, with heat rates from Qin et al. (15). Intermittency charges are included for wind and solar in the range of \$0.005-0.03/kWh. Capacity factors were chosen based on Rubin et al. (16) for fossil fuels. Renewable capacity factors were chosen to be PA-specific (8-14% for Solar PV and 23-33% for onshore wind). Demand reduction costs of

electricity were adapted from megawatt ranges calculated for a 20 year period with a 9% discount rate using a model from Azevedo(6). Finally, transmission and distribution charges of \$0.071 were added (17) to all types of electricity except demand reduction. The values (not including transmission, distribution or residential fees) are represented in the Table A.3, where the darker portion of the bar graph shows the best estimate.

**Table A.3 Levelized cost of electricity for the technologies in the computer tool (not including transmission and distribution)**

	PC co-fired with biomass	PC	PC with CCS	IGCC	IGCC with CCS	Energy Efficiency	Natural Gas	Nuclear	Solar PV	Wind
High Cost (\$/kWh)	0.125	0.107	0.172	0.133	0.157	0.025	0.153	0.134	0.691	0.191
Low Cost (\$/kWh)	0.060	0.054	0.082	0.072	0.085	0.015	0.040	0.088	0.338	0.091
Base Cost (\$/kWh)	0.079	0.069	0.110	0.091	0.107	0.020	0.076	0.107	0.462	0.127

The average PA residential price of electricity was \$0.11/kWh in 2008 (1). Thus, we presented electricity costs in the model as an incremental (increased) cost from 2008 rates. Assuming electricity capacity increases and retirements above, 30% of electricity would be generated from these new plants. Thus, if a portfolio was built as 100% nuclear (\$0.18/kWh with transmission and distribution), the cost would be  $\$0.11 * 0.7 + \$0.18 * 0.3 = \$0.13/\text{kWh}$ , and the increased cost would be \$0.11/kWh.

#### **A.5. Technology Cost Curves**

The costs associated with electricity from biomass and energy efficiency were input in the model as a function of the amount of electricity generated (or saved in the case of energy

efficiency). Based on an efficiency (demand-response) curve from models designed by Azevedo (refs), a linear cost curve was constructed such that up to an electricity savings of 15% (9 TWh), each percentage point saved (each 0.6 TWh) cost \$0.013/kWh. Between 15% and 20% savings, the cost increased from \$0.04/kWh - \$0.19/kWh. This cost assumed \$0.02/kWh for program implementation and that consumers waited until less efficient products were broken to replace them.

The cost associated with electricity from biomass used supply curves for PA from (4, 5) ranging from \$30/dry ton of switchgrass with a supply of 0 tons and \$100/dry ton with a supply of 4.9 million tons. Cost curves assumed that switchgrass would have to be continuously grown to supply the electricity for 10% of that generated by a PC plant.

#### **A.6. Health Damages**

Health damages were calculated using data from NAS (18). Spreadsheets were obtained from the NAS study that provided health-related damages associated with emissions from coal- and gas-fired power plants in the U.S. These spreadsheets provided a monetary value of damage per kg of PM, SO<sub>2</sub> and NO<sub>x</sub> for each of the coal and natural gas plants in the PA based on mortality and morbidity rates associated with emissions from nearby plants using \$6 million per statistical life. After adjusting damages for the population in each county, a weighted average was calculated for damages (health cost) per kg for each pollutant. Table A.4 presents the \$/ton for each pollutant.

**Table A.4 Health Damages per ton of pollutant for PA**

\$/ton	SO <sub>2</sub>	NO <sub>x</sub>	PM <sub>2.5</sub>	PM <sub>10</sub>
Coal	\$9,900	\$1,600	\$21,600	\$970
Natural Gas	\$10,800	N/A	N/A	N/A

Multiplying \$/ton of damage for each emission type by ton/GWh for each technology (from IECM calculations) provides the \$Damage/GWh values in Table A.5.

**Table A.5 Health Damages per GWh for each technology**

<b>\$/GWh</b>	<b>Total Cost</b>	<b>SO<sub>2</sub></b>	<b>NO<sub>x</sub></b>	<b>PM<sub>2.5</sub></b>	<b>PM<sub>10</sub></b>
<b>PC</b>	\$27,600	\$26,000	\$690	\$900	\$20
<b>PC w/ CCS</b>	\$1,900	\$9	\$1,100	\$740	\$20
<b>PC &amp; Biomass</b>	\$25,600	\$24,100	\$650	\$820	\$20
<b>IGCC</b>	\$3,400	\$3,200	\$140	\$60	\$2
<b>IGCC w/ CCS</b>	\$700	\$400	\$160	\$80	\$2
<b>Natural Gas</b>	\$140	\$0	\$140	\$0	\$0

#### **A.7. Water Use**

Water use values were obtained from Fthenakis and Kim (19). The paper reviews previous studies to present life-cycle analyses for water withdrawal and consumption. Consumption numbers were chosen as the measure to present in the computer tool, such that it equals the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment. Impacts of withdrawal (effluent and heated water) are discussed qualitatively in the materials

Fuel acquisition, preparation and transport for all fossil fuel and nuclear systems were derived from Table 2 of the paper. Since 80% of the coal production occurs underground in PA, water use values were weighted as such (20). The paper assumes that surface and underground mining of uranium are evenly distributed. Additionally, the paper states that 50% of uranium enrichment is completed by diffusion and 50% by centrifuge. For the CCS-inclusive coal technologies, a 30% energy penalty was applied to the total water consumption from fuel

acquisition and transport. This assumes that 30% more coal must be mined and transported to make the same amount of electricity. Biomass was assumed to be rain-fed in PA. Thus, a zero figure for water associated with biomass was multiplied by 10% because the pc/biomass co-fire plant presented in the computer tool is assumed to use a 10% biomass blend configuration. Ninety percent of water use from fuel acquisition is obtained from the coal number.

Water consumption at the plant for fossil fuel (without CCS) and nuclear plants are derived from tables 6 and 7. The low and high values are chosen for each type of cooling tower. These are weighted by the percentage of each cooling tower type used in US fossil fuel plants today (presented in table A.9). PV and Wind plant water consumption estimates are obtained from table 8. PC with CCS and IGCC with CCS plant water consumption are calculated by using a percentage increase above their respective coal without CCS technology. The percentage increase is calculated from values in table 7. These factors are multiplied by the low and high values for their respective coal plant water consumption. The increase in water used for shale gas was included in the natural gas numbers. A water use figure of 1.3 gallons per MMBtu of gas extracted was assumed (21), which is about 44 L/MWh of electricity generated from natural gas. It was assumed that one-third of the natural gas used for electricity in PA would come from shale.

Water consumption values from the plant and fuel acquisition were summed. The averages of the low and high values were obtained. Table A.6 presents these values. We presented values to participants in Olympic size swimming pools assuming that its volume was 2.5 million liters.

**Table A.6. Water Consumption for Life-cycle of Electricity Technology in L/MWh**

L/MWh	High	Low	Average
PC	4,100	1,500	2,800
IGCC	4,300	1,200	2,700
PC co-fire biomass	4,100	1,500	2,800
IGCC with CCS	5,900	1,500	3,700
PC with CCS	7,400	2,700	5,000
Nuclear	3,000	1,800	2,400
Natural Gas	750	300	500
PV solar	20	20	20
Wind	10	10	10
EE	0	0	0

**A.8. Land Use**

Life-cycle data on land transformation by different electricity technologies is scarce. While many data sources are available for wind and solar land transformation, much less is available for non-renewable power plants beyond the footprint of the plant itself. One paper that presents a comparison of many technologies is Fthenakis and Kim (22). The paper presents life cycle (including mining, transport, plant, waste disposal) land use figures. The coal values used as input for the computer tool are from Tables 1 and 2. It is assumed that 80% of coal produced from mines in PA comes from underground mining and that 32% of the land used for railroads in the Eastern U.S is for coal. Nuclear and natural gas land use values are provided in Figures 1 and 2, respectively (only direct land transformation is used for our comparison). PV land use values that use the average solar insolation of the US are provided in Table 5. The two US cases that are outlined in the paper and shown in Table 6 are used as the wind power land use range. Similar to water use, values provided for biomass in Table 8 and Figure 3 were multiplied by 10% because the pc/biomass co-fire plant is assumed to use a 10% biomass blend configuration. Ninety percent of land use from coal power is obtained from the coal number. Finally, since the paper



does not provide values for CCS (and in an effort to only use one source for a data comparison), it was assumed that land used per GWh for the transport and sequestration of CO<sub>2</sub> was approximately equivalent to that of natural gas pipeline transport and storage. These values were included in addition to the coal land use to obtain the land used by coal with CCS. Table A.7 presents these values. We presented values to participants in terms of football fields assuming that its area was 5,351 square meters.

**Table A.7. Life-cycle land transformation for electricity technologies (in m<sup>2</sup>/GWh)**

m <sup>2</sup> /GWh	Low	High	Base
Nuclear			120
Natural gas			260
PV solar	400	450	430
PC/IGCC	100	700	400
PC/IGCC with CCS	300	900	600
PC co-fired with biomass	5,900	6,500	6,200
Wind	2,000	2,800	2,400

#### References

1. Energy Information Administration (2010) State Electricity Profiles, Pennsylvania, 2008.
2. Energy Information Administration (2010) Annual Energy Outlook, 2010.
3. Aden A, *et al.* (2002) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stove. (National Renewable Energy Laboratory).
4. Morrow WR, Griffin WM, & Matthews HS (2007) State-Level Infrastructure and Economic Effects of Switchgrass Cofiring with Coal in Existing Power Plants for Carbon Mitigation. *Environmental Science & Technology* 41(19):6657-6662.
5. De La Torre Ugarte DG & Ray DE (2000) Biomass and bioenergy applications of the POLYSYS modeling framework. *Biomass and Bioenergy* 18(4):291-308.

6. Azevedo I (2009) Energy Efficiency in the U.S. Residential Sector: An Engineering and Economic Assessment of Opportunities for Large Energy Savings and Greenhouse Gas Emissions Reductions. (Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA).
7. Katzenstein W & Apt J (2009) Response to Comment on “Air Emissions Due to Wind and Solar Power”. *Environmental Science & Technology* 43(15):6108-6109.
8. Berkenpas MB, Rubin ES, & Zaremsky CJ (2010) Integrated Environmental Control Model User Manual: Integrated Environmental Control Model.
9. Mantripragada H (2010) Personal Communication.
10. Mann MK & Spath PL (1997) Life cycle assessment of a biomass gasification combined-cycle power system. (U.S. DOE NREL).
11. Samaras C (2010) Personal Communication.
12. Lazard Ltd. (2008) Levelized Cost of Energy Analysis. in *NARUC*.
13. National Energy Modeling System (2010) Assumptions for the Annual Energy Outlook 2010.
14. Energy Information Administration (2008) Base case fossil prices from November 2008, from Electric Power Monthly, Feb 2009.
15. Qin X, Mohan T, El-Halwagi M, Cornforth G, & McCarl B (2006) Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment. *Clean Technologies and Environmental Policy* 8(4):233-249.
16. Rubin ES, Chen C, & Rao AB (2007) Cost and Performance of fossil fuel power plants with CO<sub>2</sub> capture and storage. *Energy Policy* 35:4444-4454.
17. Newcomer A, Blumsack SA, Apt J, Lave LB, & Morgan MG (2008) Short Run Effects of a Price on Carbon Dioxide Emissions from U.S. Electric Generators. *Environmental Science and Technology* 42(9):3139-3144.
18. National Research Council of the National Academy of Sciences (2010) Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. (The National Academies Press, Washington, DC).
19. Fthenakis V & Kim HC (2010) Life-cycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews* 14(7):2039-2048.
20. Energy Information Administration (2010) Coal Production and Number of Mines by State and Mine Type.

21. Mielke E, Anadon LD, & Venkatesh Narayanamurti (2010) Water Consumption of Energy Resource Extraction, Processing, and Conversion. (Energy Technology Innovation Policy research group, Belfer Center for Science and International Affairs, Harvard Kennedy School).
22. Fthenakis V & Kim HC (2010) Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews* 13(6-7):1465-1474.

## **Appendix B: Information Materials Used in the Paper-based Studies (Chapters 3 and 4) and the Computer Tool Study (Chapter 5)**

This appendix displays each information sheet from the paper- and computer-based studies. They are displayed in the order received by the participants. Materials received as “homework” are displayed first, with the group meeting materials displayed subsequently.

### **B.1. Materials from Chapters 3 and 4**

#### ***B.1.1. Homework Materials***

##### **Introduction**

Coal, oil and natural gas are called fossil fuels. Fossil fuels are burned to make energy. Burning fossil fuels also releases CO<sub>2</sub> (carbon dioxide) gas into the atmosphere. Most air pollutants (such as sulfur dioxide) don't stay in the atmosphere very long. CO<sub>2</sub> is different. Much of it stays in the atmosphere for over 100 years, until it is finally absorbed by the ocean.

CO<sub>2</sub> is found naturally in the earth's atmosphere. When we breathe in oxygen, we breathe out CO<sub>2</sub>. Plants use CO<sub>2</sub> to grow.

CO<sub>2</sub> is a "greenhouse gas." It traps heat from the sun and helps make the earth a pleasant place to live. If too much CO<sub>2</sub> is in the air, it will trap too much heat. The temperature of the earth will increase. This is called “global warming” or “climate change.” This may lead to a hotter, dryer climate, more intense storms, more floods and droughts, and rising sea levels. The change in climate can have an effect on crops, plants and animals.

Humans have burned ever growing amounts of coal, oil and natural gas (fossil fuels) over the past few hundred years. This has caused the amount of CO<sub>2</sub> in the earth's atmosphere to increase. There is about 30% more CO<sub>2</sub> in the atmosphere today than there was a few hundred years ago. The amount continues to grow ever more rapidly

Power plants that use fossil fuels to make electricity release the most CO<sub>2</sub> of all man-made sources.

In Pennsylvania (PA), we get most of our electricity from burning fossil fuels (coal, oil and natural gas). 56% comes from coal power plants and 6% from natural gas plants. The other large source of our electricity is nuclear plants, at 35%.

## **Problem Question**

### **The Current Situation**

Today, much of the electricity in Pennsylvania (PA) comes from traditional coal plants and nuclear plants. Traditional coal plants release CO<sub>2</sub> (carbon dioxide) into the air. CO<sub>2</sub> is a gas that contributes to climate change.

### **The Future Situation**

PA will need more electricity in 25 years than the power plants it has now can make. So, new plants will need to be built. The original plan was to build all traditional coal plants. But, suppose that the U.S. Congress has just passed a law to reduce the CO<sub>2</sub> 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<sub>2</sub>. 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 Task**

Your job is to rank the different power plant types from best to worst.

### **Power Plant Types**

The attached envelopes have information about these power plant types:

- Advanced biomass power (which is made from wood chips and farm crops).
- Advanced coal plants with CO<sub>2</sub> capture equipment (which cuts the CO<sub>2</sub> released by the plant).
- Advanced coal plants (without CO<sub>2</sub> capture equipment).
- Advanced nuclear plants.
- Natural gas plants.
- Solar cell power.
- Traditional coal plants with CO<sub>2</sub> capture equipment (which cuts the CO<sub>2</sub> released by the plant).
- Traditional coal plants (without CO<sub>2</sub> capture equipment).
- Wind power.

An additional option that could reduce the number of new plants that have to be built is:

- Energy efficiency or using less electricity (such as using more efficient appliances or insulating buildings). If we use less electricity, fewer plants need to be built.

### **What's in the other Envelopes**

- The sheets in Envelope #2 will give you general information about each power plant type.
- The sheets in Envelope #3 will give more detail about (a) how much each power plant type pollutes and (b) the cost of electricity made by each power plant type.

### **Your Instructions (Please read through all of the instructions before beginning).**

1. Look at the next page. Use this "Power Plant Ranking" sheet to take any notes you want about the power plant types. Think about what you like and dislike about each one as you read through the information.
2. Open Envelope #2. Read the sheets in the order they are provided.
3. Open Envelope #3. Before looking at the graphs on each sheet, read all of the text at the top of the page. Note that each power plant type has been assigned a color. This color is the same for both graphs in Envelope #3. It also matches the color border to the corresponding power plant sheet in Envelope #2.
4. Rank the power plant types from best to worst. To do this, we suggest that you look at your "Power Plant Ranking" notes. You may also want to take the power plant sheets from Envelope #2 and sort the sheets in order from best to worst. When you have made a decision, write the numbers 1 to 10 on the "Power Plant Ranking" sheet. 1 will be the best, 2 will be the second best and so on. 10 will be the worst.
5. Finally, open up Envelope #4 to learn about the next steps.
6. Now, go back to Step 1 of these instructions and begin. Make sure to refer back to these instructions between every step in the process.

# Advanced Biomass Power

**How it Works:** Biomass comes from farm crops, paper mills, and wood chips. It is heated to make a gas. This gas is burned. Its heat is used as fuel in a type of engine, called a "turbine". This turbine then runs a generator to make electricity. The left-over hot gas is used to make steam. The steam also fuels a turbine, which runs a second generator to make more electricity. Because it uses two turbines, the plant is more efficient.



Biomass power plant in Burlington, VT.  
Source: [www.nrel.gov/biomass/photos.html](http://www.nrel.gov/biomass/photos.html)

## MORE INFORMATION (ABOUT ADVANCED BIOMASS POWER)

<b>Cost *</b>	The cost of biomass power can vary. It depends on whether the biomass "fuel" is also needed for other reasons, such as for food (from farm crops). The first few power plants built in PA would likely be able to use leftover biomass from farms and forestry businesses. As more plants are built, new plants and trees would be grown to make biomass power. Growing biomass can be expensive. So, the cost of biomass power would go up.*
<b>CO<sub>2</sub> released *</b>	Biomass adds no new CO <sub>2</sub> to the air. Biomass fuel is made from trees and plants. Plants and trees take in CO <sub>2</sub> from the air when they are alive. So, most of the CO <sub>2</sub> released into the air when biomass is burned is not "new". It was in the air recently. This is different than the "new" CO <sub>2</sub> from coal and gas plants, which has not been in the air for millions of years. *
<b>Other Pollution/ Waste *</b>	<ul style="list-style-type: none"> <li>• The air pollution released is like that of a natural gas plant. These plants put nitrogen oxides and sulfur dioxide into the air. These pollutants can cause people to have some health problems. *</li> <li>• Biomass is sometimes grown especially to make fuel. The chemicals used to grow biomass pollute the soil and water.</li> <li>• Turning biomass into a gas makes ash, which may in some cases contain hazardous chemicals. It is disposed of in landfills.</li> <li>• Advanced biomass plants use a lot of water to cool the plant's equipment. The amount is less than traditional coal plants. 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.</li> </ul>
<b>Availability</b>	Biomass can be found everywhere in the U.S. But, many types of biomass are traditionally used for other things. This means that electricity companies will have to compete with other buyers of the biomass "fuel".
<b>Reliability</b>	Biomass power can provide steady and dependable electricity.
<b>Limits of use</b>	If biomass plants made all (or most) of our electricity, we would need to begin to grow biomass. Growing biomass is expensive. Electricity would cost a lot. Lots of land would be used up. So, biomass plants cannot make all of the electricity that is needed for PA. Other types of plants must also be built.
<b>Noise</b>	These plants are about as loud as average street traffic.
<b>Land use and ecology</b>	Some of the biomass comes from waste products. But, at a larger scale, new trees or plants will need to be grown for biomass. This could mean that farms will grow less food, driving food prices up. Land may need to be cleared to grow biomass, causing soil erosion and disturbing the animals and plants.
<b>Safety</b>	These plants are quite safe for operators.
<b>Lifespan</b>	The lifetime of any plant is uncertain. But, a new advanced biomass plant built today would likely make electricity for at least 30 years.
<b>Current Use</b>	There are dozens of these plants working in the U.S. today. Most are small. Larger biomass plants do exist in the U.S. But, they work differently than the ones described here (more like traditional coal plants).

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



# Advanced Coal Plants

## Option 1: CO<sub>2</sub> is released into air

**How it Works:** Traditional coal plants burn coal to make electricity. *Advanced coal plants* turn coal into gas. This gas is burned. Its heat is used as fuel in a type of engine, called a “turbine”. This turbine then runs a generator to make electricity. The left-over hot gas is used to make steam. The steam also fuels a turbine, which runs a second generator to make more electricity. Because *advanced coal plants* use two turbines, they are more efficient than traditional coal plants.



An Advanced Coal Plant in Indiana  
Source: [www.clean-energy.us](http://www.clean-energy.us)

When coal is burned, CO<sub>2</sub> is released by the plant. In **Option 1**, this CO<sub>2</sub> escapes into the air because no equipment is added to capture the CO<sub>2</sub>.

MORE INFORMATION (ABOUT ADVANCED COAL PLANTS)	
Cost *	Because these plants use new equipment, costs are somewhat uncertain.
CO <sub>2</sub> released *	Advanced coal plants release slightly less CO <sub>2</sub> to the air than traditional coal plants. *
Other Pollution/ Waste *	<ul style="list-style-type: none"> <li>• <i>Advanced coal plants</i> release nitrogen oxides and sulfur dioxide to the air. The amount is much less than traditional coal plants. These pollutants can cause people to have many different health problems. These plants release almost no mercury or particulates. *</li> <li>• These plants produce about half as much solid waste as traditional coal plants. The waste may contain a small amount of hazardous chemicals. Some of it can be recycled, such as to make concrete. The leftover waste is usually put in a landfill near the plant.</li> <li>• <i>Advanced coal plants</i> use a lot of water to cool the plant's equipment. The amount is less than traditional coal plants. 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.</li> </ul>
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	Advanced coal plant release a lot of CO <sub>2</sub> . They cannot make all of the electricity that is needed in PA if we want to reduce CO <sub>2</sub> . 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 advance coal plant built today would likely make electricity for at least 50 years.
Current Use	There are two advanced coal plants working in the U.S. today. Electric utility companies have plans to build more advanced coal plants in the near future.

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

# Advanced Coal Plants

## Option 2: CO<sub>2</sub> is captured

**How it Works:** This is the same plant as that described in "Advanced Coal Plants, Option 1". But in Option 2, additional equipment is added to capture the CO<sub>2</sub> before it escapes to the air. This CO<sub>2</sub> is turned into a liquid. A pipeline takes it from the plant and puts it permanently in rock formations more than half a mile (about 2,500 feet) underground. This is shown in the diagram to the right. The rock formations will be tested ahead of time to make sure the CO<sub>2</sub> will stay trapped in there. The CO<sub>2</sub> will also be monitored to make sure that it stays in place. After a few decades, the CO<sub>2</sub> will dissolve (and become trapped) in the water in the rocks. Over thousands of years, it will likely change into solid minerals.

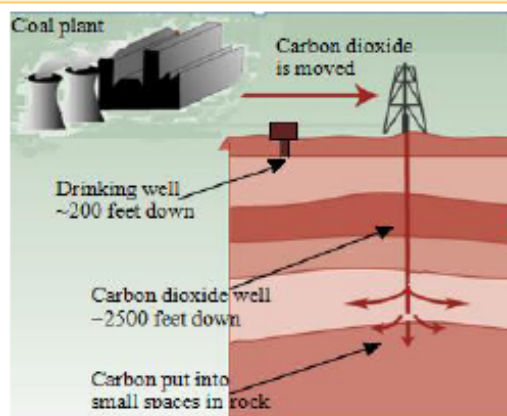


Diagram of a coal plant with carbon capture and disposal. Modified from [www.co2crc.com.au](http://www.co2crc.com.au)

### MORE INFORMATION (ABOUT CO<sub>2</sub> CAPTURE EQUIPMENT)

Cost *	It is cheaper to add CO <sub>2</sub> capture equipment to <i>advanced coal plants</i> than to traditional coal plants.*
CO <sub>2</sub> released *	Advanced coal plants with CO <sub>2</sub> capture equipment release very little CO <sub>2</sub> into the air. *
Other Pollution/Waste *	<ul style="list-style-type: none"> <li>The equipment alone makes very little air or water pollution.*</li> <li>If CO<sub>2</sub> gets in underground drinking water, the water can become contaminated. That risk is small because CO<sub>2</sub> wells will be built more than 10 times deeper than most wells for drinking water.</li> <li>Adding CO<sub>2</sub> capture equipment increases the water used by advanced coal plants by a small amount.</li> </ul>
Availability	<ul style="list-style-type: none"> <li>There are suitable rock formations in much of PA and the rest of the U.S. Before use, they will be tested to make sure that they can safely hold the CO<sub>2</sub>.</li> <li>There are thousands of miles of gas pipelines in the U.S. today. CO<sub>2</sub> is moved through similar pipelines. CO<sub>2</sub> pipelines are already used in the U.S., but more need to be built.</li> </ul>
Reliability	Capturing CO <sub>2</sub> does not make advanced coal plants less dependable.
Limits of use	Advanced coal plants with CO <sub>2</sub> capture equipment could make all the electricity needed for PA.
Noise	There would be little change in the noise from the advanced coal plant if CO <sub>2</sub> capture equipment is added.
Land use and ecology	The CO <sub>2</sub> will cause very little harm to living plants or animals once it is in the deep underground rock formations. Some CO <sub>2</sub> is also naturally found in the ground.
Safety	<ul style="list-style-type: none"> <li>Unlike oil or gas, CO<sub>2</sub> cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of CO<sub>2</sub> did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the CO<sub>2</sub> could build up for a while. In this case, people and animals could suffocate if the leak was large enough.</li> <li>There is a small chance that CO<sub>2</sub> could leak out of an underground space. These leaks would be very slow. In almost all cases, the CO<sub>2</sub> would mix into the air before harming anyone.</li> <li>The CO<sub>2</sub> in the ground can be monitored with underground equipment. If the CO<sub>2</sub> starts to move to places where it should not be, there are ways that this could be fixed. For example, the leak could be plugged up or the CO<sub>2</sub> could be moved to some other location.</li> <li>Pumping CO<sub>2</sub> into the ground builds up underground pressure. This could increase the risk of small earthquakes in some areas. However, PA is not prone to earthquakes.</li> <li>After a few decades, the CO<sub>2</sub> dissolves in the deep underground water. This reduces many of the risks. Leaks become very unlikely. The CO<sub>2</sub> can no longer move to contaminate drinking water. It cannot move to places it should not be. It cannot cause earthquakes.</li> <li>Once an underground space is full and closed, and shown to be secure, the government will take control and continue to monitor it for safety. Experts disagree on how long government should continue to monitor it.</li> </ul>
Lifespan	There is enough underground space to capture CO <sub>2</sub> for the entire life of any coal plant built.
Current Use	The U.S. Government is capturing CO <sub>2</sub> underground in 25 test sites across the U.S. today.

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



# Advanced Nuclear Plants

**How it Works:** Nuclear plants use uranium that has been slightly processed, or “enriched”. In a nuclear plant, the uranium releases heat that is used 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. Advanced nuclear plants have a different design than existing ones. While existing plants are very safe, the new design makes a nuclear accident virtually impossible.



Nuclear plant in McCandless, PA.  
Source: [www.nrc.gov](http://www.nrc.gov)

## MORE INFORMATION (ABOUT ADVANCED NUCLEAR PLANTS)

Cost *	Because advanced nuclear plants are new, costs are somewhat uncertain. *
CO <sub>2</sub> released *	Advanced nuclear plants release no CO <sub>2</sub> to the air. *
Other Pollution/ Waste *	<ul style="list-style-type: none"> <li>• Normally operating nuclear plants cause almost no air or water pollution. *</li> <li>• Nuclear plants release almost no radiation into the air, ground or water. So, a person who lives near a plant gets almost no radiation.</li> <li>• The leftover fuel from a nuclear plant will produce radiation for many years. Radiation can cause cancer in people. Today, this waste is being stored in facilities next to the nuclear plants. The government has plans to permanently store the nuclear waste in a central location either under or above ground. How soon that will happen is not clear.</li> <li>• Advanced nuclear plants use a lot of water to cool the plant's equipment. Existing nuclear plants use about the same amount as traditional coal plants. But, advanced nuclear plants will likely use much less. 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.</li> </ul>
Availability	There is enough uranium available to power any new nuclear plants built in PA for the life of the plants.
Reliability	Nuclear power can provide steady and dependable electricity.
Limits of use	Nuclear plants could make all the electricity that is needed for PA.
Noise	These plants are about as loud as average street traffic.
Land use and ecology	Uranium fuel must be mined. This can disturb land, plants and animals. The amount of uranium that is mined is much less than that of coal.
Safety	<ul style="list-style-type: none"> <li>• There is a very small chance of nuclear accidents. Nuclear material might leak into the air and water if there is an accident. But, nuclear plants cannot explode like an atomic bomb.</li> <li>• Unlike plants in some parts of the world (Russia), U.S. plants are built inside strong concrete buildings. These prevent leaks if there is an accident.</li> <li>• There has been one accident at a U.S. nuclear plant. It was in 1979 at the Three Mile Island plant in Central PA. The plant's concrete building kept the radiation from leaking. No plant workers were hurt and no one died. Plants have been fixed to be much safer since the accident.</li> <li>• Some people worry about terrorism involving a nuclear plant. The government, electric utility companies and other industries are working to make all industrial plants safer against terrorism.</li> <li>• These plants are quite safe for operators. All mining is dangerous for the miners. But mining uranium is generally much safer than mining coal.</li> </ul>
Lifespan	The lifetime of any plant is uncertain. But, a new advanced nuclear plant built today would likely make electricity for at least 60 years.
Current Use	There are a few advanced nuclear plants in the world, but none in the U.S. The U.S. does have 103 older nuclear plants in operation.

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

# Energy Efficiency

**How it Works:** Energy efficiency cuts the amount of electricity we use. Fewer power plants will be built if we use less electricity. Less CO<sub>2</sub> will then be released into the air. There are many ways to cut electricity use. For example, people can use more efficient light bulbs. They can buy more efficient refrigerators, air conditioners and other appliances. Buildings can also be better insulated.



Energy efficient house in North Carolina (renovated rather than newly constructed).  
Source: [www.newsweek.com](http://www.newsweek.com)

Energy efficiency can help a lot. Vermont and California have programs to promote it. As a result, people in VT use about 20% less electricity than people in PA. Californians use about 40% less.

## MORE INFORMATION (ABOUT ENERGY EFFICIENCY)

<b>Cost *</b>	<ul style="list-style-type: none"> <li>If your house uses less electricity, your bills will go down. Yet, there may be a large initial cost to buy a new efficient appliance or insulation. Over time, you would recoup this cost from the money you save each month on your electric bill. So, you may save more money in the end than you initially spent. Some states like Vermont help you with the initial cost.*</li> <li>There is a point when you may no longer recoup the costs from buying efficient things. This happens when you try to cut your electricity use by about 13% or more. *</li> <li>Energy efficiency means that you spend money now and get the savings later. A \$10 energy efficient light bulb costs more than a regular light bulb. But, it lasts 10 times longer and saves 50 to 80% more electricity.</li> </ul>
<b>CO<sub>2</sub> released *</b>	Energy efficiency appliances release no CO <sub>2</sub> to the air. *
<b>Other Pollution/ Waste *</b>	<ul style="list-style-type: none"> <li>There is no direct air or water pollution from energy efficiency. Because energy efficiency cuts the amount of electricity we use, it can help to reduce the pollution in the air and water because fewer power plants will need to be built.*</li> <li>There is no direct solid waste made from energy efficient products.</li> <li>Energy efficient products, in many cases, use less water than those they replace.</li> </ul>
<b>Availability</b>	You may be able to cut your electricity use by up to 18% at little extra cost in PA. The government may give incentives for buying efficient products. This helps to get larger savings.
<b>Reliability</b>	Most energy efficient products are as dependable as those they replace.
<b>Limits of use</b>	We can buy all efficient products. We can insulate all of our buildings. But, we will always need some electricity to live comfortably. Also, there is a point at which cutting our electricity use by any more becomes very costly. Some power plants will need to be built even if we do our best to cut electricity use.
<b>Noise</b>	Energy efficient products are no louder than those they replace.
<b>Land use and ecology</b>	Fewer power plants will be built if we use less electricity. Building power plants can disturb the surrounding land, plants and animals. Energy efficiency would stop some of this from occurring.
<b>Safety</b>	Energy efficient appliances and buildings are as safe as those they replace.
<b>Lifespan</b>	The lifetime of efficient appliances vary. Efficient light bulbs last much longer than traditional bulbs. Insulation in a building can last for as long as the building stands.
<b>Current Use</b>	Energy efficient appliances are in stores now. Most have an "energy efficiency" rating. Much more can also be done to better insulate and cool buildings. But, people must learn about these options and take action on them.

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



# Natural Gas

**How it works:** Most of the natural gas in western PA is used to heat homes. But, it can also be used in power plants to make electricity. In the plant, natural gas is burned. Its heat is used as fuel in a type of engine, called a "turbine". This turbine then runs a generator to make electricity. The left-over hot gas is used to make steam. The steam also fuels a turbine, which runs a second generator to make more electricity. Because it uses two turbines, the plant is more efficient.



Natural gas plant near Albany, New York.  
Source: www.pseg.com

## MORE INFORMATION (ABOUT NATURAL GAS PLANTS)

<b>Cost *</b>	The cost of electricity from natural gas plants is very dependent on the price of natural gas. The price varies with demand and supply. Demand for natural gas is expected to increase in the future. This will likely cause the price of natural gas to rise. *
<b>CO<sub>2</sub> released *</b>	Natural gas plants release about half as much CO <sub>2</sub> to the air as traditional coal plants. *
<b>Other Pollution/Waste *</b>	<ul style="list-style-type: none"> <li>Natural gas plants release nitrogen oxides into the air. These plants are often used along with solar plants or wind power. Natural gas plants fill in power when it is not sunny or windy. In this case, the natural gas plant must be turned on quickly. This can increase the nitrogen oxides released into the air. This pollutant can cause people to have some health problems. *</li> <li>There is almost no solid waste from gas plants.</li> <li>Natural gas plants use a lot of water to cool the plant's equipment. The amount is less than traditional coal plants. 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.</li> </ul>
<b>Availability</b>	<ul style="list-style-type: none"> <li>U.S. supplies of natural gas are running low, even though new sources are still being found. There is lots of gas in other parts of the world. New plants built in PA could run for their entire lifespan on this world supply. It would be transported to the U.S. in large tanker ships.</li> <li>Gas prices have gone up and down a lot in the past 10 years. Since the U.S. has limited supplies, some of our future gas will come from places like the Middle East. A portion of U.S. government funds is used to make sure we can get gas and oil from the Middle East.</li> </ul>
<b>Reliability</b>	Natural gas, when available, can provide steady and dependable electricity.
<b>Noise</b>	These plants are about as loud as average street traffic.
<b>Limits of use</b>	The cost of natural gas may increase in the future. Since U.S. supplies are running low, we may also become more dependent on foreign (Middle East) natural gas. For these reasons, it is risky to make all the electricity needed for PA with natural gas.
<b>Land use and ecology</b>	These plants do not use much land. But, pipelines sometimes must be built under private land. The landowner and pipeline company will have to agree about how to maintain the land around the pipeline. Drilling for natural gas can disturb local land, plants and animals. This is especially true in unpopulated areas, like Alaska.
<b>Safety</b>	These plants are quite safe for operators. It is rare for natural gas to leak from a pipeline. If it does occur, unlike CO <sub>2</sub> , the gas can burn or explode. Like CO <sub>2</sub> , people can suffocate from the gas.
<b>Lifespan</b>	The lifetime of any plant is uncertain. But, a new natural gas plant built today would likely make electricity for at least 30 years.
<b>Current Use</b>	There are more than 350 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.

# Solar Cell Power



A solar plant in Fresno, CA.  
Source: www.nrel.gov

**How it works:** There are two ways to make electricity from sunlight. In the first, sunlight is absorbed into solar cells. The energy from sunlight is then turned directly into electricity. In deserts, a second way is used. The heat from the sun is used 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. While the second way is cheaper, it cannot be used in PA because here the sun is not hot enough.

Solar cells can be put on your home’s roof. The initial cost would be very large. So, this is not discussed further here. Instead, many solar cells can be joined together on open land. This makes a solar power plant.

## MORE INFORMATION (ABOUT SOLAR CELL POWER)

<b>Cost *</b>	Solar cell power costs more in PA than in sunnier states like Arizona and California. *
<b>CO<sub>2</sub> released*</b>	Solar plants release no CO <sub>2</sub> to the air. *
<b>Other Pollution/Waste *</b>	<ul style="list-style-type: none"> <li>Solar plants, by themselves, release no air or water pollution. However, solar plants alone cannot make a steady amount of electricity. When it is not sunny, the solar plants need natural gas plants to fill in these gaps in electricity. These natural gas plants do release nitrogen oxides into the air. *</li> <li>Solar cells are made of some toxic materials. There may be some pollution if they are not properly disposed of at the end of their lifetime.</li> <li>Solar plants use a very small amount of water to clean the solar cells.</li> </ul>
<b>Availability</b>	There is no sunlight at night. There is less sunlight on cloudy days. In PA, the solar plants only make about 10% of their possible power. They cannot make 100% because the sun does not shine at maximum strength or for 24 hours per day.
<b>Reliability</b>	The dependability of solar cell power varies with the amount of sunlight. If more than about 5% of the electricity made in PA comes from solar cells, then other kinds of plants will have to be built to make up for nighttime and cloudy days. In the future, we might use very large batteries to store electricity from the sun, but that is very costly to do in PA today.
<b>Limits to use</b>	Solar power is intermittent because it is not sunny all the time. So, solar plants cannot make all of the electricity that is needed for PA. Other types of plants (usually natural gas) must also be built.
<b>Noise</b>	Solar plants are silent.
<b>Land use and ecology</b>	Many solar cells must be put together to make a solar plant. Therefore, they use a lot of land. Unlike wind, this land cannot be used for other purposes.
<b>Safety</b>	These plants are quite safe for operators.
<b>Lifespan</b>	The lifetime of any plant is uncertain. But, a new solar plant built today would likely make electricity for at least 20 years.
<b>Current Use</b>	There are five solar cell plants working in the U.S. today (in Arizona and California).

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



# Traditional Coal Plants

## Option 1: CO<sub>2</sub> 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](http://www.industcards.com/st-coal-usa-pa.htm)

When coal is burned, CO<sub>2</sub> is released by the plant. In **Option 1**, this CO<sub>2</sub> escapes into the air because no equipment is added to capture the CO<sub>2</sub>.

### 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 <sub>2</sub> capture equipment to traditional coal plants. *
CO <sub>2</sub> released *	Traditional coal plants release CO <sub>2</sub> to the air. *
Other Pollution/ Waste *	<ul style="list-style-type: none"> <li>While these plants are much cleaner than in the past, they still release CO<sub>2</sub>, nitrogen oxides, sulfur dioxide, mercury and particulates to the air. These pollutants can cause people to have many different health problems. *</li> <li>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.</li> <li>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.</li> </ul>
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 <sub>2</sub> . They cannot make all of the electricity that is needed in PA if we want to reduce CO <sub>2</sub> . 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.

# Traditional Coal Plants

## Option 2: CO<sub>2</sub> is captured

**How it Works:** This is the same plant as the one described in "Traditional Coal Plants, Option 1". But in Option 2, additional equipment is added to capture the CO<sub>2</sub> before it escapes to the air. This CO<sub>2</sub> is turned into a liquid. A pipeline takes it from the plant and puts it permanently in rock formations more than half a

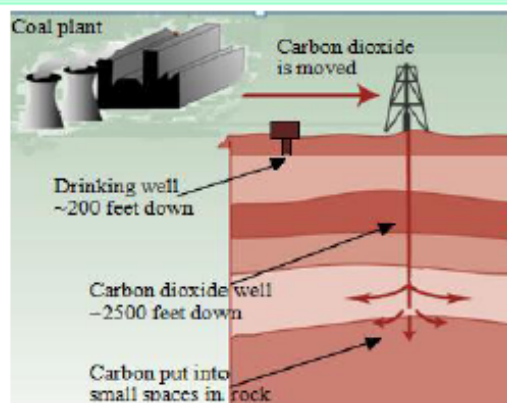


Diagram of a coal plant with carbon capture and disposal.  
Modified from [www.co2crrc.com.au](http://www.co2crrc.com.au)

mile (about 2,500 feet) underground. This is shown in the diagram to the right. The rock formations will be tested ahead of time to make sure the CO<sub>2</sub> will stay trapped in there. The CO<sub>2</sub> will also be monitored to make sure that it does stay in place. After a few decades, the CO<sub>2</sub> will dissolve (and become trapped) in the water in the rocks. Over thousands of years, it will likely change into solid minerals.

### MORE INFORMATION (ABOUT CO<sub>2</sub> CAPTURE EQUIPMENT)

Cost *	It costs more to add CO <sub>2</sub> capture equipment to <i>traditional coal plants</i> than to advanced coal plants.*
CO <sub>2</sub> released *	Traditional coal plants with CO <sub>2</sub> capture equipment release very little CO <sub>2</sub> into the air. *
Other Pollution/Waste *	<ul style="list-style-type: none"> <li>• The equipment alone makes very little air or water pollution. *</li> <li>• If CO<sub>2</sub> gets in underground drinking water, the water can become contaminated. That risk is small because CO<sub>2</sub> wells will be built more than 10 times deeper than most wells for drinking water.</li> <li>• Adding CO<sub>2</sub> capture equipment will make traditional coal plants use about twice as much water.</li> </ul>
Availability	<ul style="list-style-type: none"> <li>• There are suitable rock formations in much of PA and the rest of the U.S. Before use, they will be tested to make sure that they can safely hold the CO<sub>2</sub>.</li> <li>• There are thousands of miles of gas pipelines in the U.S. today. CO<sub>2</sub> is moved through similar pipelines. CO<sub>2</sub> pipelines are already used in the U.S., but more need to be built.</li> </ul>
Reliability	Capturing CO <sub>2</sub> does not make advanced coal plants less dependable.
Limits of Use	Traditional coal plants with CO <sub>2</sub> capture equipment could make all the electricity needed for PA.
Noise	There would be little change in the noise from the traditional coal plant if CO <sub>2</sub> capture equipment is added.
Land use and ecology	The CO <sub>2</sub> will cause very little harm to living plants or animals once it is in the deep underground rock formations. Some CO <sub>2</sub> is also naturally found in the ground.
Safety	<ul style="list-style-type: none"> <li>• Unlike oil or gas, CO<sub>2</sub> cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of CO<sub>2</sub> did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the CO<sub>2</sub> could build up for a while. In this case, people and animals could suffocate if the leak was large enough.</li> <li>• There is a small chance that CO<sub>2</sub> could leak out of an underground space. These leaks would be very slow. In almost all cases, the CO<sub>2</sub> would mix into the air before harming anyone.</li> <li>• The CO<sub>2</sub> in the ground can be monitored with underground equipment. If the CO<sub>2</sub> starts to move to places where it should not be, there are ways that this could be fixed. For example, the leak could be plugged up or the CO<sub>2</sub> could be moved to some other location.</li> <li>• Pumping CO<sub>2</sub> into the ground builds up underground pressure. This could increase the risk of small earthquakes in the some areas. However, PA is not prone to earthquakes.</li> <li>• After a few decades, the CO<sub>2</sub> dissolves in the deep underground water. This reduces many of the risks. Leaks become very unlikely. The CO<sub>2</sub> cannot get in drinking water. It cannot move to places it should not be. It cannot cause earthquakes.</li> <li>• Once an underground space is full and closed, and shown to be secure, the government will take control and continue to monitor it for safety. Experts disagree on how long government should continue to monitor it.</li> </ul>
Lifespan	There is enough underground space to capture CO <sub>2</sub> for the entire life of any coal plant built.
Current Use	The U.S. Government is capturing CO <sub>2</sub> underground in 25 test sites across the U.S. today.

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



# Wind Power

**How it Works:** Modern wind machines are much larger than the old windmills in Holland, or the metal wind mills that pumped water for cattle in the American West. They are often between 100 and 300 feet high. That is about as tall as a 10 to 30 story building. The machines have blades that look like an airplane propeller. The wind turns the blades, which runs a generator to make electricity.



Modern wind turbines in Somerset, PA  
Source: [www.solutions-site.org/](http://www.solutions-site.org/)

## MORE INFORMATION (ABOUT WIND POWER)

<b>Cost *</b>	<ul style="list-style-type: none"> <li>The cost of wind power has been decreasing as larger and better machines are made. *</li> <li>The large wind machines used today make cheaper wind power than the smaller ones used in the past.</li> </ul>
<b>CO<sub>2</sub> released *</b>	Wind machines release no CO <sub>2</sub> to the air. *
<b>Other Pollution/Waste *</b>	<ul style="list-style-type: none"> <li>Wind farms, by themselves, release no air or water pollution. However, wind farms alone cannot make a steady amount of electricity. When it is not windy, the wind farms need natural gas plants to fill in these gaps in electricity. These natural gas plants do release nitrogen oxides into the air. *</li> <li>There is almost no solid waste from wind farms.</li> <li>Wind farms use a very small amount of water to clean the wind machines.</li> </ul>
<b>Availability</b>	Wind farms work well when built in windy areas. PA has lots of wind on hilltops in the center of the state. However, even the best wind farms in PA only make 30% of the power that would be possible if the wind was always blowing. They cannot make 100% because sometimes the wind is not blowing. To get the best results from a wind farm, the wind needs to blow fast, but not too fast.
<b>Reliability</b>	Wind varies in strength, which can make it less dependable for making electricity. If more than 10% of the electricity made in PA comes from wind, then gas plants will have to be built to make up for times when it is not windy. In the future, we might use very large batteries to store electricity from wind, but that is very costly to do in PA today.
<b>Limits of use</b>	Wind power is intermittent because it is not windy all the time. So, wind farms cannot make all of the electricity that is needed for PA. Other types of plants (usually natural gas) must also be built.
<b>Noise</b>	Wind farms make some low noise. It is less than the noise from most other power plants. But, since wind farms are in the country, the noise is often more noticeable.
<b>Land use and ecology</b>	Each wind machine needs between 45 and 75 acres. That is about the size of 35 to 55 football fields. Wind farms with many machines require hundreds of acres. If the machines are built on farm land, most of it can still be used for farming. In forests, trees must be cleared to build the machines. This can disturb the plants and animals. On mountain ridges, wind farms can be very visible.
<b>Safety</b>	Wind farms do not harm people. The blades of wind machines do sometimes strike and kill birds and bats.
<b>Lifespan</b>	The lifetime of any plant is uncertain. But, a new wind farm built today would likely make electricity for at least 25 years.
<b>Current Use</b>	There are more than 100 wind farms working in the U.S. today.

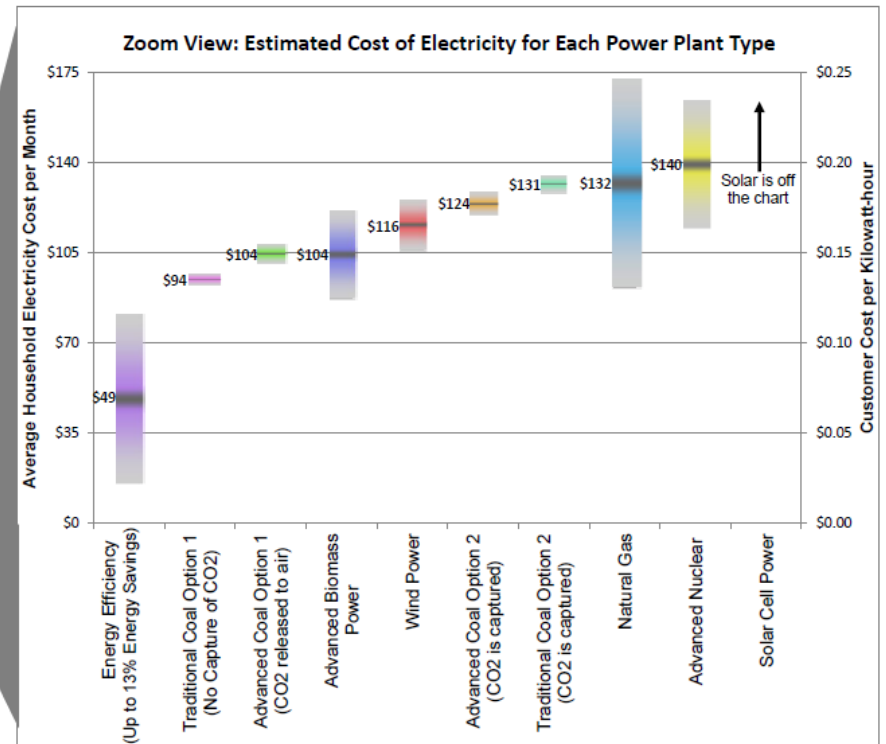
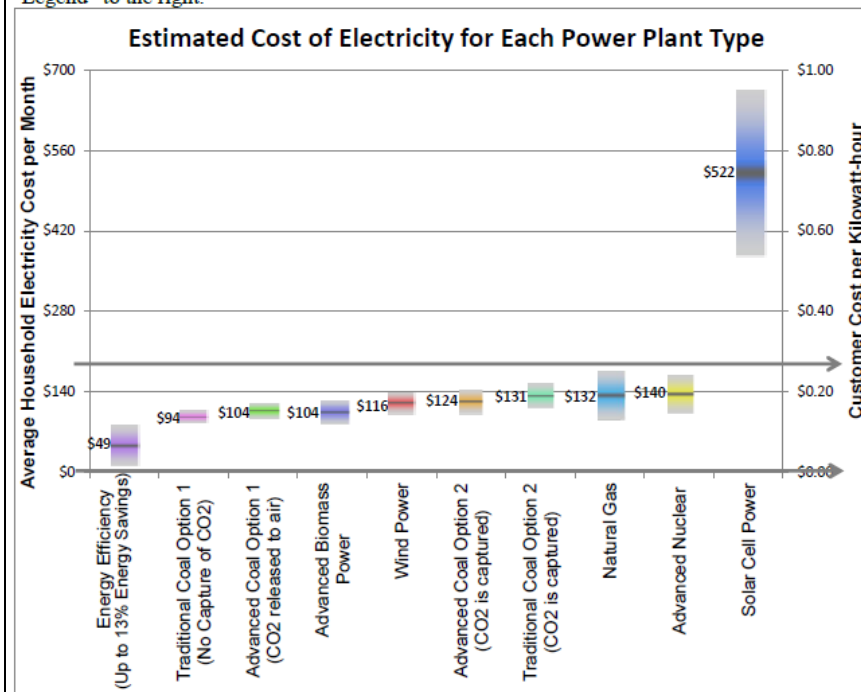
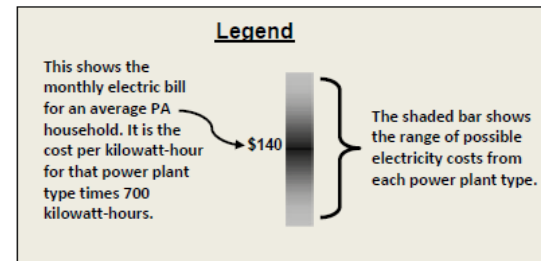
\* More cost and pollution information is available in "Cost Comparison" and "Pollution Comparison" sheets in Envelope #3

# Cost Comparison

The graph below on the left shows the estimated cost of electricity from each power plant type. The graph below on the right zooms in on types that cost less than \$0.25 per kilowatt-hour. A kilowatt-hour is a measure of electricity use. One kilowatt-hour can power a 100-watt light bulb for 10 hours. The average PA household uses about 700 kilowatt-hours each month. Your house may use more if it has electric heating or electric water heating, if it is very large or if it uses lots of air conditioning.

The numbers on the right side of each graph are the cost of electricity in dollars per kilowatt-hour. The numbers on the left side are the monthly bill for an average PA household if their electricity had the cost shown on the right. The numbers on the right are multiplied by 700 kilowatt-hours to get the monthly bill numbers on the left. Let's say that electricity costs \$0.20 per kilowatt-hour. Then, the monthly bill would then be \$140.

Since experts are not certain about future electricity costs, each bar shows a range. The gray center of the bar (and the dollar value just to its left) show the most likely monthly electric bill. The longer the shaded bar, the more uncertain experts are about the costs. This is also explained in the box titled "Legend" to the right.





### Types of Pollution

**CO<sub>2</sub> (Carbon Dioxide)** – Coal and natural gas plants release CO<sub>2</sub> into the air. The CO<sub>2</sub> can contribute to climate change. This may lead to a hotter, dryer climate, more intense storms, more floods and droughts, and rising sea levels. The change in climate can have an effect on crops, plants and animals.

**Nitrogen Oxides** – Coal, natural gas and biomass plants release nitrogen oxides into the air. The nitrogen oxides can cause smog and acid rain. It can also contribute to the creation of particulates (see the 'Particulates' box below). The smog can make your eyes, nose, and throat hurt. It can also cause lung problems, especially in young children. The acid rain can turn lakes and rivers acidic. It can also damage trees, and wear down statues and paint on buildings.

**Sulfur Dioxide** – Coal and biomass plants release sulfur dioxide into the air. The sulfur dioxide can contribute to the creation of particulates (see the 'Particulates' box below). It also can cause breathing problems, especially in people with asthma. Breathing it for long periods of time can lead to lung problems and worsen heart disease. It also causes acid rain. This can turn lakes and rivers acidic. It can also wear out trees, statues and paint on buildings.

**Particulates** – Traditional coal plants release particulates into the air. Nitrogen oxides and sulfur dioxide also make particulates. They are very small particles. When they get in the air, it looks hazy. The smaller ones can pass through your nose and throat. They get deep into your lungs. That can lead to breathing problems and worsen heart or lung disease.

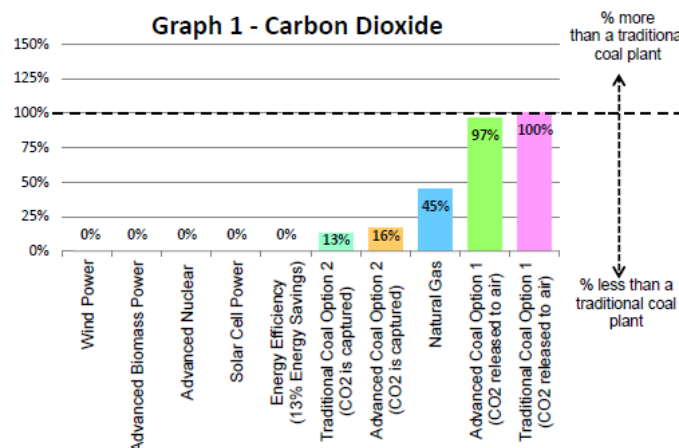
**Mercury** – Traditional coal plants release mercury into the air. Some of the mercury ends up in water, where it can get inside fish. If people eat too much fish with mercury, that can harm their brain, heart, kidneys, lungs, and immune system. This is especially true for children.

## Pollution Comparison

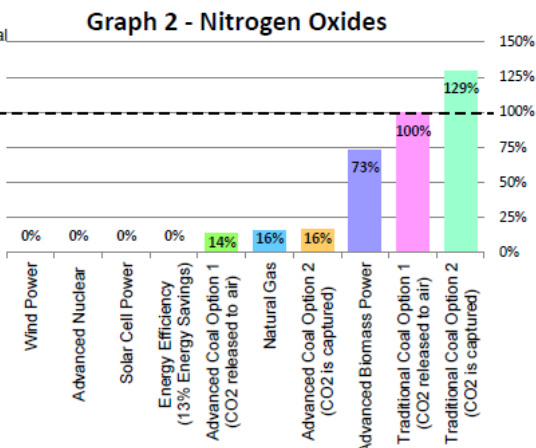
Five types of pollution are shown on this sheet. Each is described in the table to the left. Read the table, "Types of Pollution" to learn more.

The graphs below compare traditional coal plants with other power plant types. The graphs show these 5 types of pollution: (1) CO<sub>2</sub> (carbon dioxide), (2) nitrogen oxides, (3) sulfur dioxide, (4) particulates and (5) mercury. The size of each bar shows the percent of pollution put out by that plant compared to that from traditional coal plants. The pollution from traditional coal plants is always shown as 100%. If a power plant type pollutes less than traditional coal plants, the graph will show a percentage that is less than 100%. If it pollutes more, a percentage greater than 100% is shown. So, the smaller the percentage, the less pollution put out by that plant. A graph shows 0% if a power plant type puts out (almost) no pollution. Overall, shorter bars on the graph are better than longer ones.

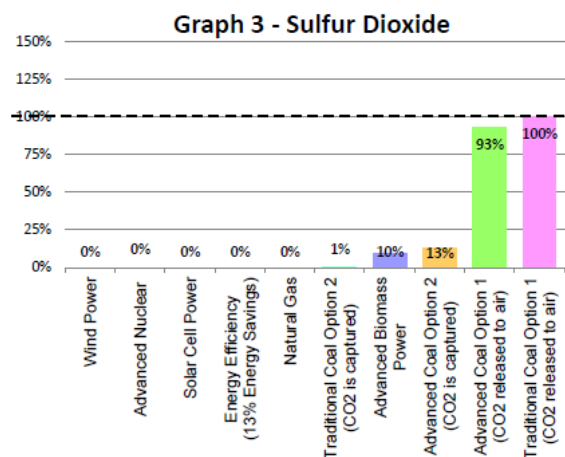
Graph 1 - Carbon Dioxide



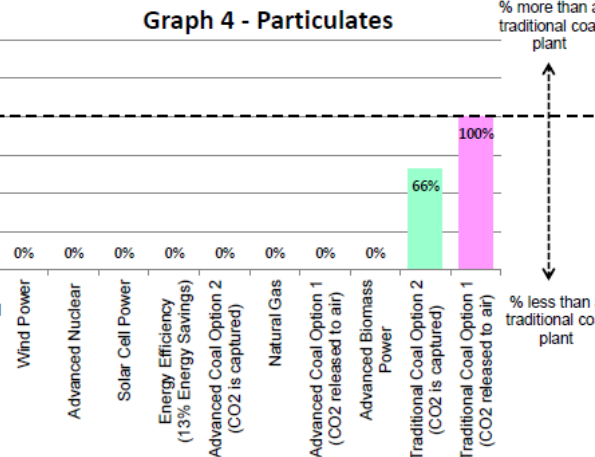
Graph 2 - Nitrogen Oxides



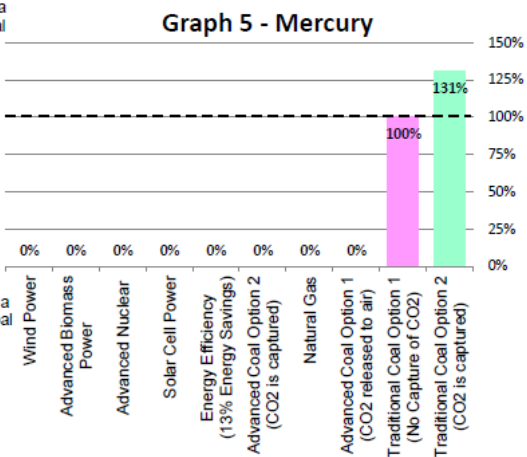
Graph 3 - Sulfur Dioxide



Graph 4 - Particulates



Graph 5 - Mercury



### B.1.2. Group Meeting Materials

#### **NEW PROBLEM QUESTION**

##### **The Current Situation**

Today, much of the electricity in Pennsylvania (PA) comes from traditional coal plants and nuclear plants. Traditional coal plants release CO<sub>2</sub> (carbon dioxide) into the air. CO<sub>2</sub> is a gas that contributes to climate change.

##### **The Future Situation**

PA will need more electricity in 25 years than the power plants it has now can make. So, new plants will need to be built. The original plan was to build all traditional coal plants. But, suppose that the U.S. Congress has just passed a law to reduce the CO<sub>2</sub> 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. 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<sub>2</sub>. 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 Task**

Your job is to rank the seven power plant combinations from best to worst.

##### **Power Plant Information**

The attached folder has information about seven power plant combinations. They are each made up of the following types of power plants:

- Advanced biomass power (which is made from wood chips and farm crops).
- Advanced coal plants with CO<sub>2</sub> capture equipment (which cuts the CO<sub>2</sub> released by the plant).
- Advanced coal plants (without CO<sub>2</sub> capture equipment).
- Advanced nuclear plants.
- Natural gas plants.
- Solar cell power.
- Traditional coal plants with CO<sub>2</sub> capture equipment (which cuts the CO<sub>2</sub> released by the plant).
- Traditional coal plants (without CO<sub>2</sub> capture equipment).
- Wind power.



An additional option that could reduce the number of new plants that have to be built is:

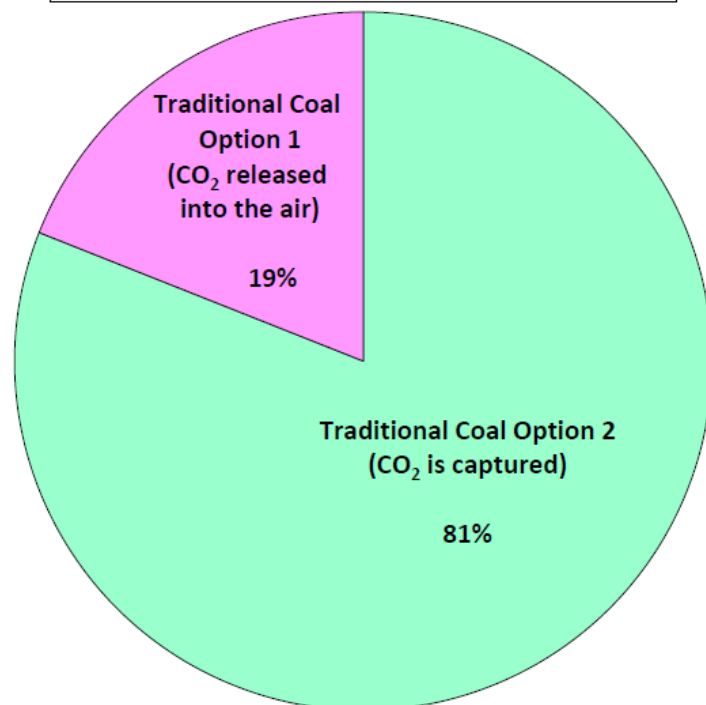
- Energy efficiency or using less electricity (such as using more efficient appliances or insulating buildings). If we use less electricity, fewer plants need to be built.

##### **Power Plant Combinations**

Some power plant types can only make a small amount of the total electricity needed for PA. These plants types include wind power, solar cell power, advanced biomass power and energy efficiency. You have read about these "limits of use" in the power plant information sheets. The PA Governor considered this when choosing the power plant combinations. Therefore, the seven combinations are realistic.



### Power Plant Combination A

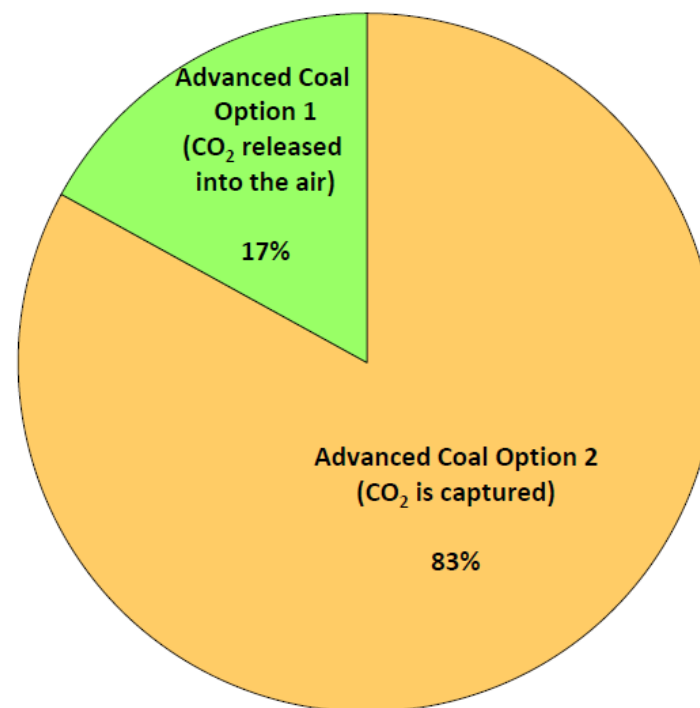
	Traditional Coal Option 2 (CO <sub>2</sub> is captured)	81%
	Traditional Coal Option 1 (CO <sub>2</sub> released into the air)	19%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.



### Power Plant Combination B

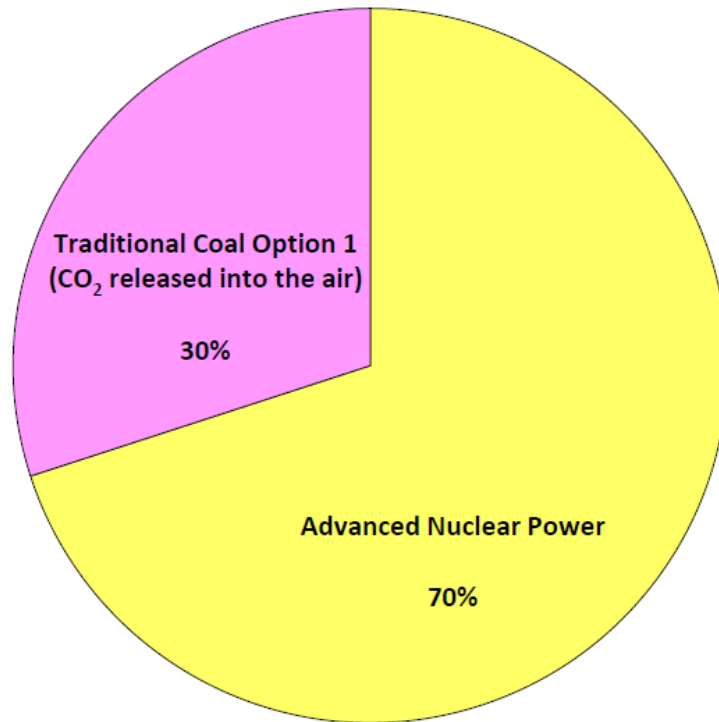
	Advanced Coal Option 2 (CO <sub>2</sub> is captured)	83%
	Advanced Coal Option 1 (CO <sub>2</sub> released into the air)	17%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.







### Power Plant Combination C

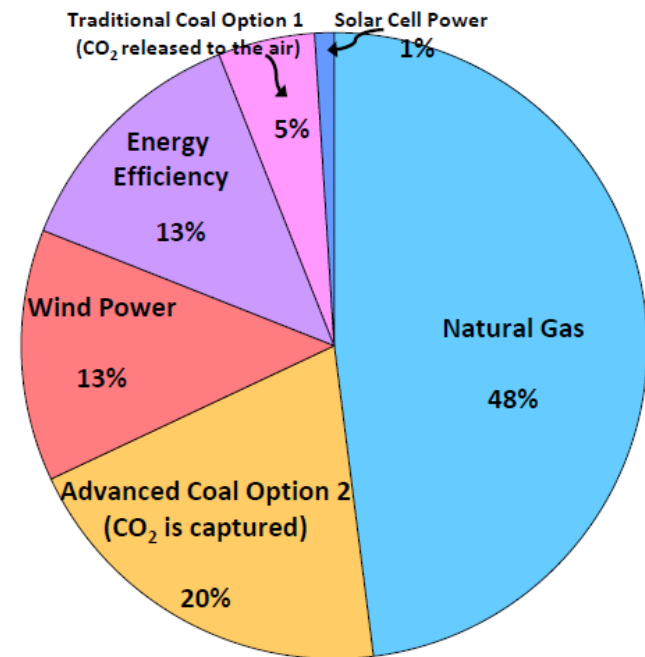
	Advanced Nuclear Power	70%
	Traditional Coal Option 1 (CO <sub>2</sub> released into the air)	30%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.






### Power Plant Combination E

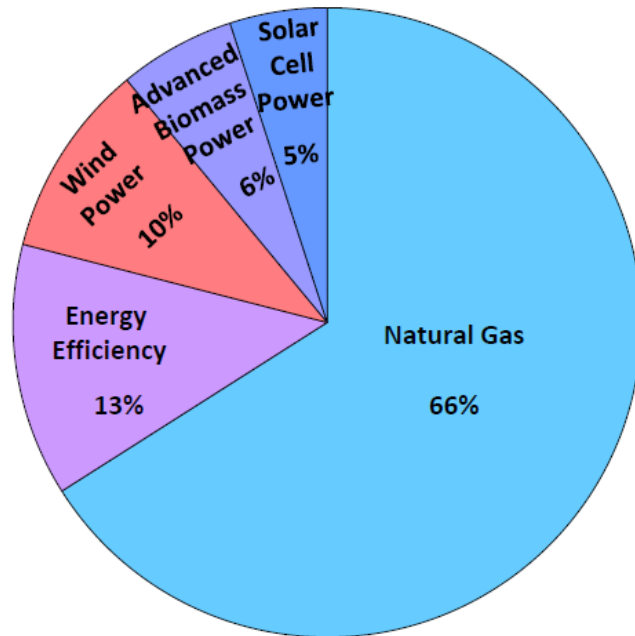
	Natural Gas	48%
	Advanced Coal Option 2 (CO <sub>2</sub> is captured)	20%
	Wind Power	13%
	Energy Efficiency	13%
	Traditional Coal Option 1 (CO <sub>2</sub> released to air)	5%
	Solar Cell Power	1%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.







### Power Plant Combination D

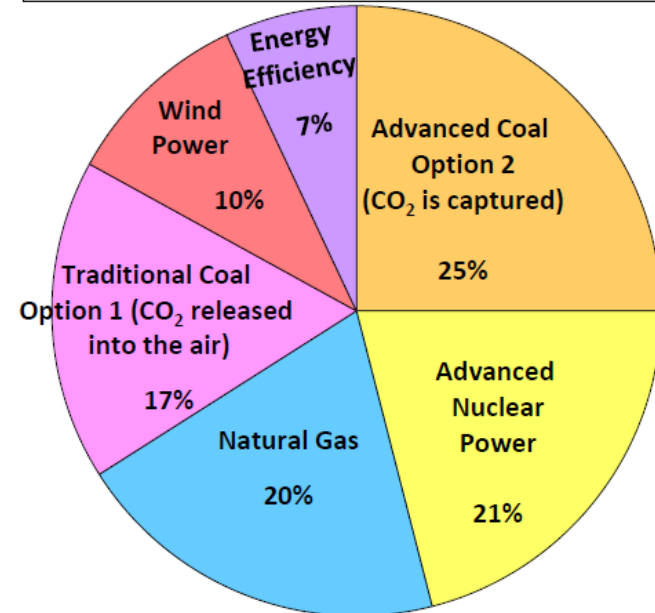
	Natural Gas	66%
	Energy Efficiency	13%
	Wind Power	10%
	Advanced Biomass Power	6%
	Solar Cell Power	5%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.



### Power Plant Combination F

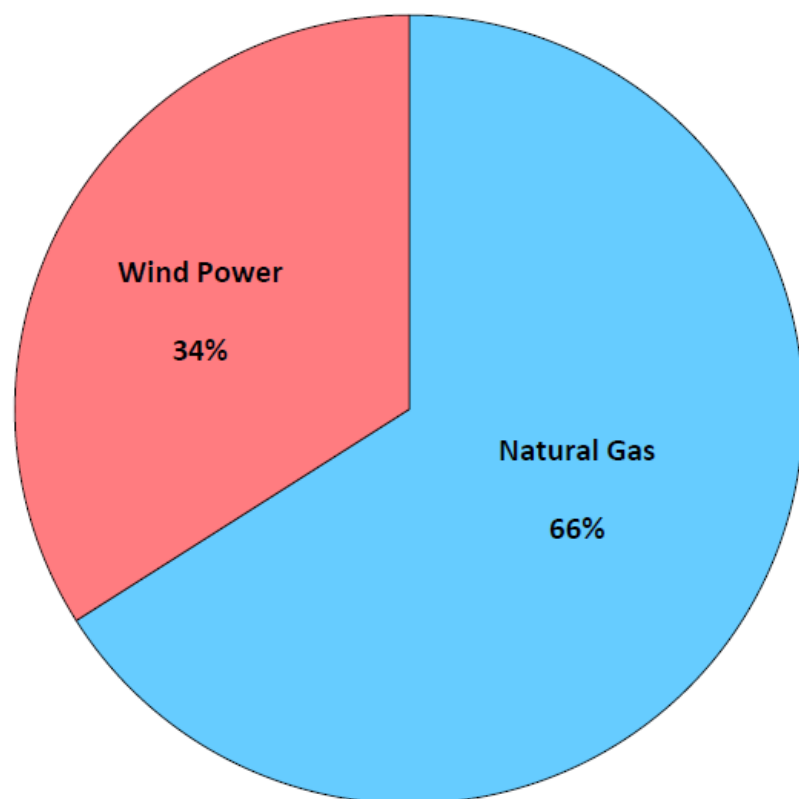
	Advanced Coal Option 2 (CO <sub>2</sub> is captured)	25%
	Advanced Nuclear Power	21%
	Natural Gas	20%
	Traditional Coal Option 1 (CO <sub>2</sub> released into the air)	17%
	Wind Power	10%
	Energy Efficiency	7%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.

### Power Plant Combination G

	Natural Gas	66%
	Wind Power	34%



The pie chart above shows the percentage of each power plant type in this combination. General information about these power plant types is provided behind this page. Each power plant type has an assigned color in the pie chart. It matches the border of the power plant information sheet behind this page.

### Types of Pollution

**CO<sub>2</sub> (Carbon Dioxide)** – Coal and natural gas plants release CO<sub>2</sub> into the air. The CO<sub>2</sub> can contribute to climate change. This may lead to more hurricanes, tornadoes, floods and droughts, and rising sea levels. The change in weather can harm crops, plants and animals.

**Nitrogen Oxides** – Coal, natural gas and biomass plants release nitrogen oxides into the air. The nitrogen oxides can cause smog and acid rain. The smog can make your eyes, nose, and throat hurt. It can also cause lung problems, especially in young children. The acid rain can turn lakes and rivers acidic. It can also wear out trees, statues and paint on buildings.

**Sulfur Dioxide** – Coal and biomass plants release sulfur dioxide into the air. The sulfur dioxide can cause breathing problems, especially in people with asthma. Breathing it for long periods of time can lead to lung problems and worsen heart disease. It also causes acid rain. This can turn lakes and rivers acidic. It can also wear out trees, statues and paint on buildings.

**Particulates** – Traditional coal plants release particulates into the air. Particulates are a mix of very small dust and droplets. They can make the air look hazy. They can pass through your nose and throat. They get deep into your lungs and heart. That can lead to breathing problems and worsen heart or lung disease.

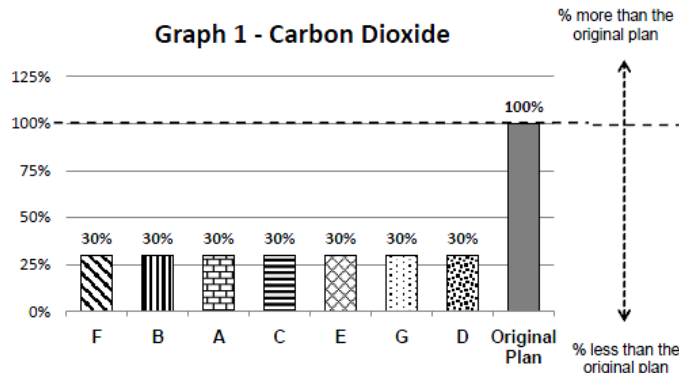
**Mercury** – Traditional coal plants release mercury into the air. The mercury will settle in water and get inside fish. If people eat too much fish with mercury, it can harm their brain, heart, kidneys, lungs, and immune system. If birds or animals eat fish with mercury, they can die or have reproduction and growth problems.

## Pollution Comparison for Combinations

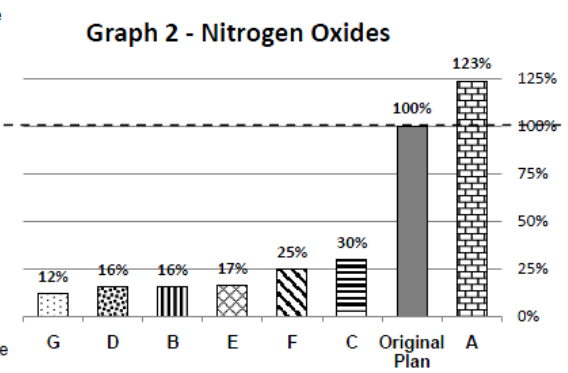
Five types of pollution are shown on this sheet. Each is described in the table to the left. Read the table, “Types of Pollution” to learn more.

The graphs below compare the seven power plant combinations to the “original plan” of building all traditional coal plants. The graphs look at these types of pollution: (1) CO<sub>2</sub> (carbon dioxide), (2) nitrogen oxides, (3) sulfur dioxide, (4) particulates and (5) mercury. The size of each bar shows the percent of pollution put out by that combination relative to the “original plan”. The pollution from the “original plan” is always shown as 100%. If a power plant combination pollutes less the “original plan”, the graph will show a percentage that is less than 100%. If it pollutes more, a percentage greater than 100% is shown. So, the smaller the percentage, the less pollution put out by that combination. A graph shows 0% if a power plant combination puts out (almost) no pollution. Overall, shorter bars on the graph are better than longer ones.

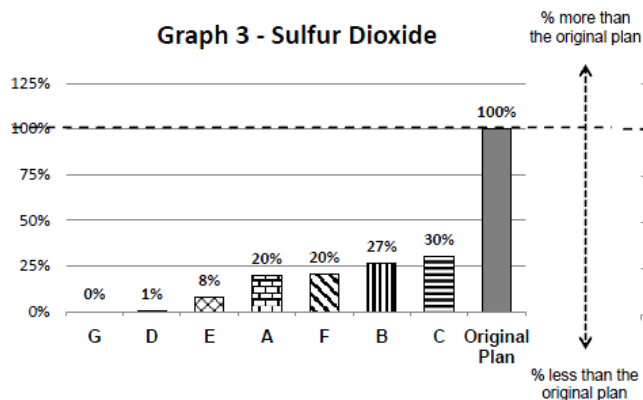
Graph 1 - Carbon Dioxide



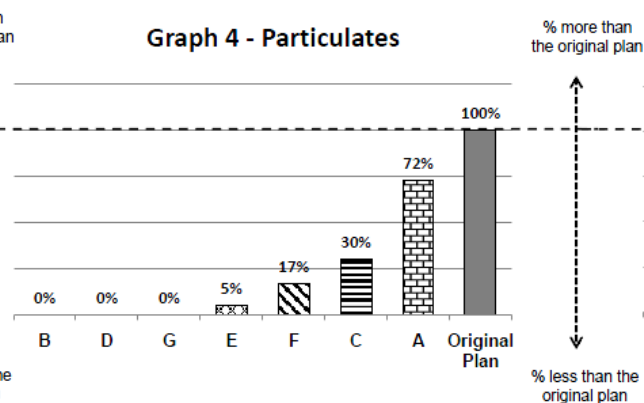
Graph 2 - Nitrogen Oxides



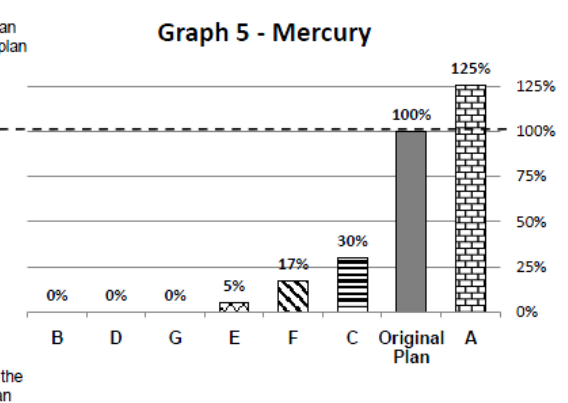
Graph 3 - Sulfur Dioxide



Graph 4 - Particulates



Graph 5 - Mercury





# Cost Comparison for Combinations

The graph below shows the estimated cost of electricity from each power plant combination.

The numbers on the right side of the graph are the cost of electricity in dollars per kilowatt-hour. A kilowatt-hour is a measure of electricity use. One kilowatt-hour can power a 100-watt light bulb for 10 hours. The average PA household uses about 700 kilowatt-hours each month. Your house may use more if it has electric heating, is very large or uses lots of air conditioning.

The numbers on the left side of the graph are the monthly bill for an average PA household if their electricity had the cost shown on the right of the graph. The numbers on the right are multiplied by 700 kilowatt-hours to get the monthly bill numbers on the left. Let's say that electricity costs \$0.20 per kilowatt-hour. The monthly bill would then be \$140.

Since experts are not certain about future electricity costs, each bar shows a range. The darker center of the bar (and the dollar value to its left) show the most likely monthly electric bill for that power plant combination. The longer the shaded bar, the more uncertain experts are about the costs. This is also explained in the legend below.

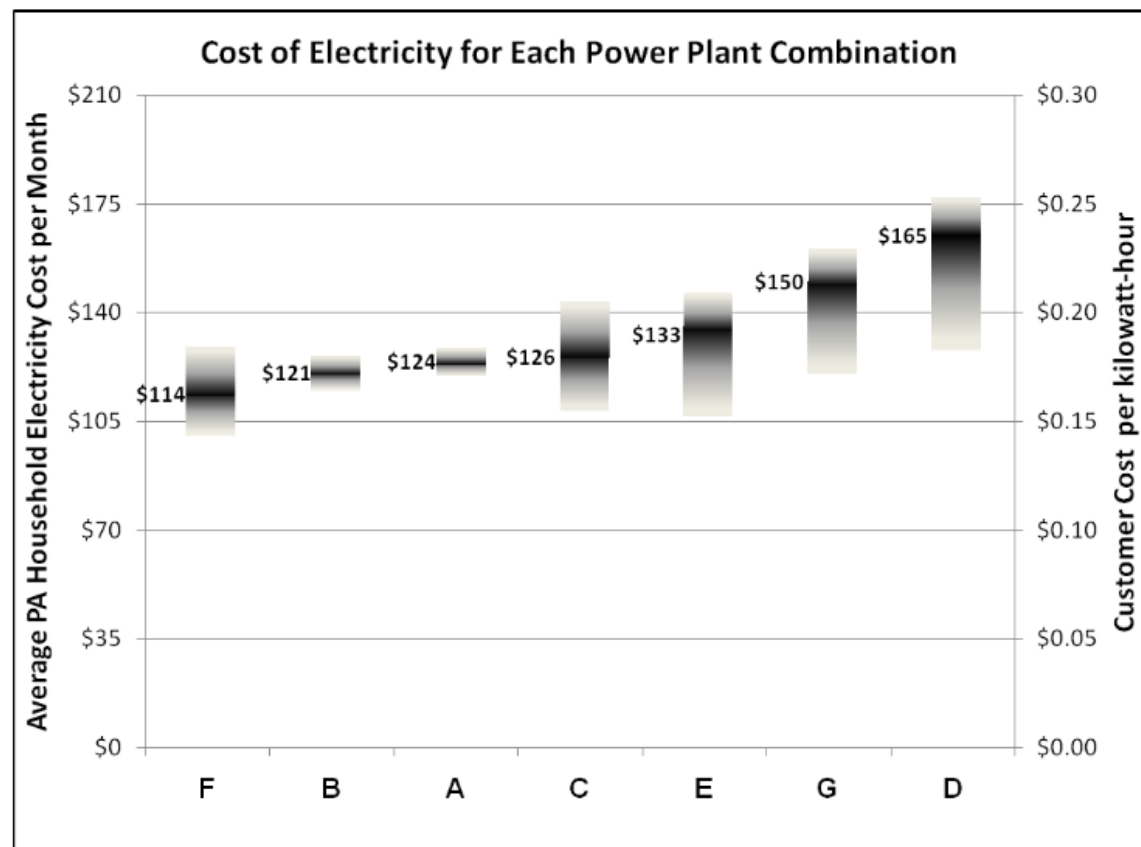
## Legend

This shows the monthly electric bill for an average PA household for each power plant combination.

\$140

It is the cost per kilowatt-hour for that power plant combination times 700 kilowatt-hours.

The shaded bar shows the range of possible electricity costs for each power plant combination.





## B.2. Materials from Chapter 5

### B.2.1. Homework Materials

#### Introduction

Coal, oil and natural gas are called fossil fuels. Fossil fuels are burned to make energy. Burning fossil fuels also releases  $\text{CO}_2$  (carbon dioxide) gas into the atmosphere. Most air pollutants (such as sulfur dioxide) don't stay in the atmosphere very long.  $\text{CO}_2$  is different. Much of it stays in the atmosphere for over 100 years, until it is finally absorbed by the ocean.

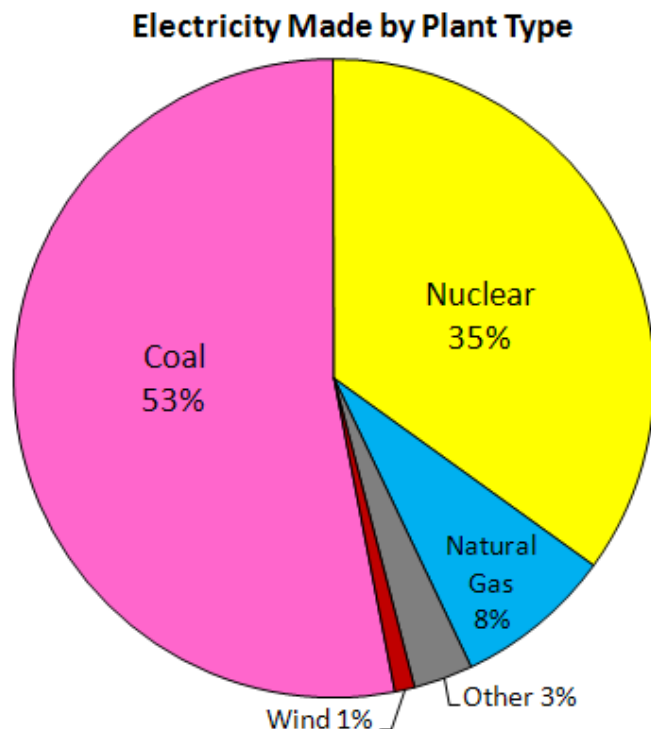
$\text{CO}_2$  is found naturally in the earth's atmosphere. When we breathe in oxygen, we breathe out  $\text{CO}_2$ . Plants use  $\text{CO}_2$  to grow.

$\text{CO}_2$  is a "greenhouse gas." It traps heat from the sun and helps make the earth a pleasant place to live. If too much  $\text{CO}_2$  is in the air, it will trap too much heat. The temperature of the earth will increase. This is called "global warming" or "climate change." This may lead to a hotter, dryer climate, more intense storms, more floods and droughts, and rising sea levels. The change in climate can have an effect on crops, plants and animals.

Humans have burned ever-growing amounts of coal, oil and natural gas (fossil fuels) over the past few hundred years. This has caused the amount of  $\text{CO}_2$  in the earth's atmosphere to increase. There is about 30% more  $\text{CO}_2$  in the atmosphere today than there was a few hundred years ago. The amount continues to grow ever more rapidly.

Power plants that use fossil fuels to make electricity release the most  $\text{CO}_2$  of all man-made sources.

In Pennsylvania (PA), we get most of our electricity from burning fossil fuels (coal and natural gas). Coal plants in PA make 53% of PA's electricity and natural gas plants make about 8%. Nuclear plants make 35% of our electricity. The pie chart shows this break down.



### **Problem Question**

#### The Current Situation

Today, the power plants in PA make about 225 terawatt-hours (TWh) of electricity each year. A TWh is a measure of electricity use. One TWh is a lot of electricity. In comparison, an average household in PA uses less than 0.001% of one TWh of electricity per year. Much of PA's 225 TWh of electricity comes from coal plants. Coal plants release CO<sub>2</sub> (carbon dioxide) into the air.

#### The Future Situation

The demand for electricity in PA increases every year. In 25 years, the power plants in PA will need to make about 285 TWh of electricity each year to keep up with demand. 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. The original plan was to build all coal plants. But, suppose that the U.S. Congress has just passed a law to reduce the CO<sub>2</sub> released by power plants built in the future. As a result of this law, the State of PA must rethink what power plant types will be built here over the next 25 years. These power plants will collectively need to release 50% less CO<sub>2</sub>. 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 Task

Your job is to rank the power plant types from best to worst. This will help to inform the Governor about which plants should be built in PA to make the additional 60 TWh of electricity needed each year.

#### Power Plant Types

You will be given information about nine power plant types:

- 5 types of coal plants: (a) Coal Plants, (b) Coal plants with equipment that captures the CO<sub>2</sub> (so it won't be released to the air), (c) Coal-and-Biomass plant (uses coal that is mixed with materials made from wood chips and farm crops), (d) Coal-to-Gas plants (plants that turn coal into gas before making electricity), and (e) Coal-to-Gas plants with equipment that captures the CO<sub>2</sub> (so it won't be released to the air).
- 4 other plant types: (a) Natural gas plants, (b) Nuclear plants, (c) Solar cell power, and (d) Wind power

An additional option that could reduce the number of new plants that have to be built is:

- Energy efficiency or using less electricity (such as using more efficient appliances or insulating buildings). If we use less electricity, fewer plants need to be built.

# Coal

*(CO<sub>2</sub> released into the air)*

**How it Works:** Coal plants burn coal to make steam. The steam is used to power a type of engine, called a “turbine”. This turbine runs a generator to make electricity.



The Armstrong coal plant in Pennsylvania.  
Source: [www.industcards.com/st-coal-usa-pa.htm](http://www.industcards.com/st-coal-usa-pa.htm)

When coal is burned, CO<sub>2</sub> is released by the plant. In this plant, the CO<sub>2</sub> escapes into the air because no equipment is added to capture the CO<sub>2</sub>.

Availability	Experts say that the U.S. has enough coal to meet its needs for at least 50 to 100 years. PA is the 4 <sup>th</sup> largest coal producing state in the U.S.
Reliability	Coal can provide steady and dependable electricity.
Limits to Use	Coal plants release a lot of CO <sub>2</sub> . They can only be used to make 25% of the additional electricity needed for PA if we want to reduce the CO <sub>2</sub> released from all new plants by 50%. This would be about 15 TWh of the 60 TWh. Other types of plants must also be built.
Current Use	There are more than 1,000 of these plants working in the U.S. today.
Environmental Impacts (*Read Note Below)	<ul style="list-style-type: none"> <li>• These plants produce a lot of solid waste (ash). Coal mining also produces waste products. The waste may contain a small amount of hazardous chemicals and radioactive materials.</li> <li>• Some solid waste produced by these plants can be recycled, such as to make concrete. The leftover waste is usually put in a landfill near the plant. Unlike disposal of household waste, the disposal of coal waste in landfills is not regulated by the federal government.</li> <li>• 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.</li> </ul>
Safety	These plants are quite safe for operators. Coal mining is dangerous for the miners. However, coal-mining related deaths have gone down over time. Mining now has stricter regulations and safer mining equipment.

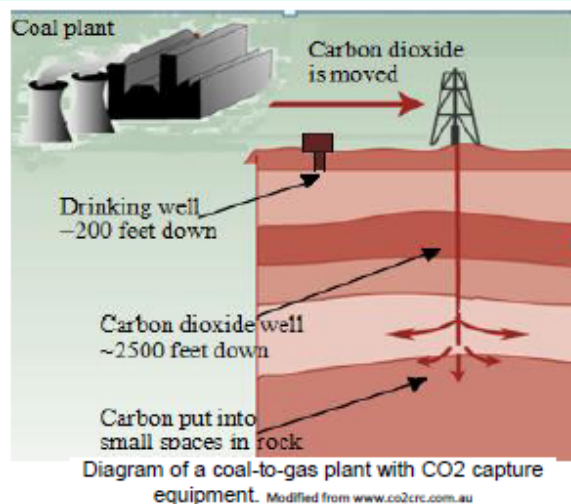
\* Note: Health, Water and Land Impacts are shown on a separate sheet



# Coal (*CO<sub>2</sub> is captured*)

**How it Works:** This is the same plant described in “Coal, CO<sub>2</sub> released”. But in this plant, additional equipment is added to capture the CO<sub>2</sub> before it escapes to the air. This CO<sub>2</sub> is turned into a liquid. A pipeline takes it from the plant and puts it permanently in rock formations more than half a mile (more than 2,500 feet) underground. This is shown in the diagram to the right. The rock formations will be tested ahead of time to make sure the CO<sub>2</sub> will stay trapped there.

The CO<sub>2</sub> will also be monitored to make sure that it does stay in place. After a few decades, the CO<sub>2</sub> will dissolve (and become trapped) in the water in the rocks. Over thousands of years, it will likely change into solid minerals.



Availability	<ul style="list-style-type: none"> <li>There are suitable rock formations in much of PA and the rest of the U.S. Before use, they will be tested to make sure that they can safely hold the CO<sub>2</sub>.</li> <li>There are thousands of miles of gas pipelines in the U.S. today. CO<sub>2</sub> is moved through similar pipelines. CO<sub>2</sub> pipelines are already used in the U.S., but more need to be built.</li> </ul>
Reliability	Capturing CO <sub>2</sub> does not make coal plants less dependable.
Limits to Use	Coal plants with CO <sub>2</sub> capture equipment could make all of the additional 60 TWh of electricity needed for PA.
Current Use	The U.S. Government is capturing CO <sub>2</sub> underground in 25 test sites across the U.S. today. A few large-scale CO <sub>2</sub> capture sites are currently being used in other countries.
Environmental Impacts (*Read Note Below)	<ul style="list-style-type: none"> <li>The waste made by these plants and the coal mining impacts are about the same as “Coal, CO<sub>2</sub> released” plants.</li> <li>The CO<sub>2</sub> will cause little or no harm to living plants or animals once it is in the deep underground rock formations. Some CO<sub>2</sub> is also naturally found in the ground.</li> </ul>
Safety	<ul style="list-style-type: none"> <li>If CO<sub>2</sub> gets in underground drinking water, the water can become contaminated. That risk is small because CO<sub>2</sub> wells will be built more than 10 times deeper than drinking water wells.</li> <li>Unlike oil or gas, CO<sub>2</sub> cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of CO<sub>2</sub> did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the CO<sub>2</sub> could build up for a while. In this case, people and animals could suffocate if the leak was large enough.</li> <li>There is a small chance that CO<sub>2</sub> could leak out of an underground space. These leaks would be very slow. In almost all cases, the CO<sub>2</sub> would mix into the air before harming anyone.</li> <li>The CO<sub>2</sub> in the ground can be monitored with equipment underground and on the surface. If the CO<sub>2</sub> starts to move to places where it should not be, there are ways that this could be fixed. For example, the leak could be plugged up or CO<sub>2</sub> could be moved to some other location.</li> <li>Pumping CO<sub>2</sub> into the ground builds up underground pressure. This could increase the risk of small earthquakes in some areas. However, PA is not prone to earthquakes.</li> <li>After a few decades, the CO<sub>2</sub> dissolves in the deep underground water. This reduces many of the risks. Leaks become very unlikely. CO<sub>2</sub> can no longer move to contaminate drinking water. It cannot move to places it should not be or cause earthquakes.</li> <li>Once an underground space is full and closed, and shown to be secure, the government will take control and continue to monitor it for safety. Experts disagree on how long the government should continue to monitor it.</li> </ul>

\* Note: Health, Water and Land Impacts are shown on a separate sheet

# Coal-to-Gas

*(CO<sub>2</sub> released into the air)*

**How it Works:** Regular coal plants burn coal to make electricity. *Coal-to-gas plants* turn coal into gas. This gas is burned. Its heat is used to power a type of engine, called a “turbine”. This turbine then runs a generator to make electricity.

The left-over hot gas is used to make steam. The steam also powers a turbine connected to a second generator to make more electricity. Because *coal-to-gas plants* use two turbines, they are more efficient than coal plants.

When the gas made from coal is burned, CO<sub>2</sub> is released by the plant. In these plants, this CO<sub>2</sub> escapes into the air because no equipment is added to capture the CO<sub>2</sub>.



An Coal-to-gas Plant in Indiana  
Source: coalgasificationnews.com

Availability	Experts say that the U.S. has enough coal to meet its needs for at least 50 to 100 years. PA is the 4 <sup>th</sup> largest coal producing state in the U.S.
Reliability	Coal can provide steady and dependable electricity.
Limits to Use	Coal-to-gas plants release a lot of CO <sub>2</sub> . They can only be used to make 25% of the additional electricity needed for PA if we want to reduce the CO <sub>2</sub> released from all new plants by 50%. This would be about 15 TWh of the 60 TWh. Other types of plants must also be built.
Current Use	There are two coal-to-gas plants working in the U.S. today. Electric utility companies have plans to build more coal-to-gas plants in the near future.
Environmental Impacts (*Read Note Below)	<ul style="list-style-type: none"> <li>• Coal-to-gas plants release less air pollution than regular coal plants.</li> <li>• These plants produce a lot of solid waste (ash). Coal mining also produces waste products. The waste may contain a small amount of hazardous chemicals and radioactive materials.</li> <li>• Some solid waste produced by these plants can be recycled, such as to make concrete. The leftover waste is usually put in a landfill near the plant. Unlike disposal of household waste, the disposal of coal waste in landfills is not regulated by the federal government.</li> <li>• Coal mining near the surface can disrupt and pollute 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.</li> </ul>
Safety	These plants are quite safe for operators. Coal mining is dangerous for the miners. However, coal-mining related deaths have gone down over time. Mining now has stricter regulations and safer mining equipment.

\* Note: Health, Water and Land Impacts are shown on a separate sheet



# Coal-to-Gas

(CO<sub>2</sub> is captured)

**How it Works:** This is the same plant described in “Coal-to-gas, CO<sub>2</sub> released”. But in this plant, additional equipment is added to capture the CO<sub>2</sub> before it escapes to the air. The capture equipment for a coal-to-gas plant can capture a little more CO<sub>2</sub> than the capture equipment of a coal plant. The CO<sub>2</sub> is turned into a liquid. A pipeline takes it from the plant and puts it permanently in rock formations more than half a mile (more than 2,500 feet) underground. This is shown in the diagram to the right. The rock formations will be tested ahead of time to make sure the CO<sub>2</sub> will stay trapped there. The CO<sub>2</sub> will also be monitored to make sure that it stays in place. After a few decades, the CO<sub>2</sub> will dissolve (and become trapped) in the water in the rocks. Over thousands of years, it will likely change into solid minerals.

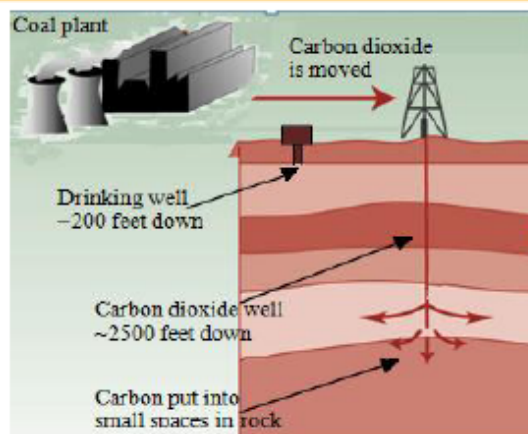


Diagram of a coal plant CO<sub>2</sub> capture equipment.  
Modified from [www.co2crr.com.au](http://www.co2crr.com.au)

<b>Availability</b>	<ul style="list-style-type: none"> <li>There are suitable rock formations in much of PA and the rest of the U.S. Before use, they will be tested to make sure that they can safely hold the CO<sub>2</sub>.</li> <li>There are thousands of miles of gas pipelines in the U.S. today. CO<sub>2</sub> is moved through similar pipelines. CO<sub>2</sub> pipelines are already used in the U.S., but more need to be built.</li> </ul>
<b>Reliability</b>	Capturing CO <sub>2</sub> does not make coal-to-gas plants less dependable.
<b>Limits to Use</b>	Coal-to-gas plants with CO <sub>2</sub> capture equipment could make all of the additional 60 TWh of electricity needed for PA.
<b>Current Use</b>	The U.S. Government is capturing CO <sub>2</sub> underground in 25 test sites across the U.S. today. A few large-scale CO <sub>2</sub> capture sites are currently being used in other countries.
<b>Environmental Impacts</b>	<ul style="list-style-type: none"> <li>The waste made by these plants and the coal mining impacts are about the same as “Coal-to-gas, CO<sub>2</sub> released” plants.</li> </ul>
<b>(*Read Note Below)</b>	<ul style="list-style-type: none"> <li>The CO<sub>2</sub> will cause little or no harm to living plants or animals once it is in the deep underground rock formations. Some CO<sub>2</sub> is also naturally found in the ground.</li> </ul>
<b>Safety</b>	<ul style="list-style-type: none"> <li>If CO<sub>2</sub> gets in underground drinking water, the water can become contaminated. That risk is small because CO<sub>2</sub> wells will be built more than 10 times deeper than drinking water wells.</li> <li>Unlike oil or gas, CO<sub>2</sub> cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of CO<sub>2</sub> did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the CO<sub>2</sub> could build up for a while. In this case, people and animals could suffocate if the leak was large enough.</li> <li>There is a small chance that CO<sub>2</sub> could leak out of an underground space. These leaks would be very slow. In almost all cases, the CO<sub>2</sub> would mix into the air before harming anyone.</li> <li>The CO<sub>2</sub> in the ground can be monitored with equipment underground and on the surface. If the CO<sub>2</sub> starts to move to places where it should not be, there are ways that this could be fixed. For example, the leak could be plugged up or CO<sub>2</sub> could be moved to some other location.</li> <li>Pumping CO<sub>2</sub> into the ground builds up underground pressure. This could increase the risk of small earthquakes in some areas. However, PA is not prone to earthquakes.</li> <li>After a few decades, the CO<sub>2</sub> dissolves in the deep underground water. This reduces many of the risks. Leaks become very unlikely. CO<sub>2</sub> can no longer move to contaminate drinking water. It cannot move to places it should not be or cause earthquakes.</li> <li>Once an underground space is full and closed, and shown to be secure, the government will take control and continue to monitor it for safety. Experts disagree on how long the government should continue to monitor it.</li> </ul>

\* Note: Health, Water and Land Impacts are shown on a separate sheet

# Wind

**How it Works:** Modern wind machines are much larger than the old windmills in Holland, or the metal windmills that pumped water for cattle in the American West. They are often between 100 and 300 feet high. That is about as tall as a 10 to 30 story building. The machines have blades that look like an airplane propeller. The wind turns the blades, and this runs a generator to make electricity.



Modern wind turbines in Somerset, PA  
Source: [www.solutions-site.org/](http://www.solutions-site.org/)

Availability	Wind farms work well when built in windy areas. PA has lots of wind on hilltops in the center of the state. However, even the best wind farms in PA only make 28% of the power that would be possible if the wind was always blowing. They cannot make 100% because sometimes the wind is not blowing. Wind farms are often located far away from where people live, since this is where it is the windiest. It is expensive to transmit the wind electricity across long distances.
Reliability	<ul style="list-style-type: none"> <li>Wind varies in strength, which can make it less dependable for making electricity. Because of this, wind farms cannot consistently make electricity. Natural gas plants must be built to "back up" or fill in electricity during times when it is not windy. In the future, we might use very large batteries to store electricity from wind, but that is very costly to do today.</li> <li>On average, a newly built wind farm in PA can make about 0.5 TWh of electricity over the course of the year. The natural gas plant built to fill in electricity when it is not windy will have to make about 1.2 TWh over the course of the year.</li> </ul>
Limits to Use	If many wind farms are built, there will be a lot of CO <sub>2</sub> released by the "back-up" natural gas plants. The more wind farms you build, the more indirect CO <sub>2</sub> that is released to the air. So wind farms can only be used to make up 28% of the additional electricity needed for PA if we want to reduce the CO <sub>2</sub> released from all new plants by 50%. This would be about 16.5 TWh of the 60 TWh.
Current Use	There are more than 100 wind farms working in the U.S. today.
Environmental Impacts (*Read Note Below)	<ul style="list-style-type: none"> <li>There is almost no solid waste from wind farms.</li> <li>Wind farms with many machines require hundreds of acres. If the machines are built on farm land, most of it can still be used for farming. In forests, trees must be cleared to build the machines. This can disturb the plants and animals. On mountain ridges, wind farms can be very visible.</li> <li>Wind farms make some low noise. It is less than the noise from most other power plants. But, since wind farms are in the country, the noise is often more noticeable.</li> <li>The blades of wind machines sometimes strike and kill birds and bats. New wind machines are being located away from bird (migration) flight paths. Less is known about how to prevent bat deaths.</li> </ul>
Safety	Wind farms present very few risks to people.

\* Note: Health, Water and Land Impacts are shown on a Separate Sheet



# Natural Gas

**How it works:** Most of the natural gas in western PA is used to heat homes. But, it can also be used in power plants to make electricity. In the plant, natural gas is burned in a type of engine, called a “turbine”. This turbine then runs a generator to make electricity. The left-over hot gas is used to make steam. The steam also powers a turbine connected to a second generator to make more electricity. Because it uses two turbines, the plant is more efficient.



Natural gas plant near Albany, New York.  
Source: www.pseg.com

Natural gas comes from several sources. *Conventional* natural gas is found deep underground in sandstone and other sponge-like layers of rock. Gas wells are created by drilling down into these rocks, which causes the gas to naturally rise to the surface because of changes in pressure underground. One type of *unconventional* natural gas is shale gas. This natural gas is also found deep underground, but it is trapped inside hard layers of rock called shale. To get to this gas requires first drilling down deep underground. Next a hole is drilled sideways through the shale. A salty water solution is pushed down through the well at high pressure to break up the rock. This releases the natural gas from the rock, and the gas can then rise to the surface.

<b>Availability</b>	<ul style="list-style-type: none"> <li>Today, most natural gas used in PA comes by pipeline from the Gulf Coast. This natural gas is produced from conventional gas wells or transported from foreign countries (such as the Middle East) in large tanker ships. In the future, more natural gas will come from unconventional sources.</li> <li>Experts say that the U.S. has enough natural gas to meet its needs for at least 100 years. Much of this is from unconventional sources, including gas shales.</li> </ul>
<b>Reliability</b>	Natural gas can provide steady and dependable electricity.
<b>Limits to Use</b>	<ul style="list-style-type: none"> <li>The cost of electricity from natural gas plants is very dependent on the price of natural gas. The price varies with demand and supply. Demand for natural gas is expected to increase in the future. This will likely cause the price of natural gas to rise.</li> <li>While gas plants release about half as much CO<sub>2</sub> as coal plants, it is still a lot. Therefore, they can only be used to make 63% of the additional electricity needed for PA if we want to reduce the CO<sub>2</sub> released from all new plants by 50%. This would be about 37.5 TWh of the 60 TWh.</li> </ul>
<b>Current Use</b>	There are more than 350 of these plants working in the U.S. today.
<b>Environmental Impacts</b> (*Read Note Below)	<ul style="list-style-type: none"> <li>There is almost no solid waste from gas plants.</li> <li>Natural gas pipelines sometimes must be built under private land. The landowner and pipeline company will have to agree about how to maintain the land around the pipeline. Drilling for natural gas can disturb local land, plants and animals. This is especially true in unpopulated areas, like parts of Alaska.</li> </ul>
<b>Safety</b>	<ul style="list-style-type: none"> <li>These plants are quite safe for operators. It is rare for natural gas to leak from a pipeline. If it does occur, unlike CO<sub>2</sub>, natural gas can burn or explode. Like CO<sub>2</sub>, people can suffocate from natural gas.</li> <li>All types of natural gas production must meet strict environmental and safety standards. Thus, drilling for gas shale should be just as safe as it is for other types of natural gas.</li> </ul>

\* Note: Health, Water and Land Impacts are shown on a separate sheet



# Nuclear

**How it Works:** Nuclear plants use uranium that has been slightly processed, or “enriched”. In a nuclear plant, the uranium atoms break apart and release heat that is used to make steam. The steam is used to power a type of engine, called a “turbine”. This turbine runs a generator to make electricity. Nuclear plants built in the future will have a more advanced design than existing ones. While existing plants are very safe, the new design is expected to make a nuclear accident virtually impossible.



Nuclear plant near Shippingport, PA  
Source: www.nrc.gov

<b>Availability</b>	There is enough uranium available to power any new nuclear plants built in PA for the life of the plants.
<b>Reliability</b>	Nuclear power can provide steady and dependable electricity.
<b>Limits to Use</b>	Nuclear plants could make all of the additional 60 TWh of electricity needed for PA.
<b>Current Use</b>	The U.S. has 103 existing nuclear plants in operation. There are a few advanced nuclear plants in the world, but none operating in the U.S.
<b>Safety</b>	<ul style="list-style-type: none"> <li>• Like coal plants, nuclear plants are safe for operators. All mining is dangerous for the miners. But mining uranium is generally much safer than mining coal.</li> <li>• Nuclear plants release almost no radiation into the air, ground or water. So, a person who lives near a plant gets almost no radiation.</li> <li>• The chance of a nuclear accident is very small. Nuclear material might leak into the air and water if there is an accident. But, nuclear plants cannot explode like an atomic bomb.</li> <li>• Unlike older plants in some parts of the world (Russia), all U.S. plants are built inside strong concrete buildings. These prevent leaks if there is an accident. There has been one accident at a U.S. commercial nuclear plant. It was in 1979 at the Three Mile Island plant in Central PA. The plant's concrete building kept the radiation from leaking. No plant workers or people living near the plant were harmed. Plants have been fixed to be much safer since the accident.</li> <li>• Some people worry about terrorism involving a nuclear plant. The government, electric utility companies and other industries are working to make all industrial plants safer against terrorism. In France, Japan and England, portions of the nuclear fuel are separated and reused. This process changes the fuel into a product that could be used in nuclear weapons. By not reusing the fuel, the U.S. is trying to make terrorist acts more unlikely. However, if the U.S. reused the fuel, there would be less hazardous nuclear waste produced by the plants.</li> </ul>
<b>Environmental Impacts</b> (*Read Note Below)	<ul style="list-style-type: none"> <li>• Uranium fuel must be mined, but the amount that is mined is much less than that of coal.</li> <li>• Nuclear plants do have a small amount of waste. It is much less than the waste from coal plants.</li> <li>• The leftover fuel (waste) from a nuclear plant will produce radiation for thousands of years. Radiation can cause cancer in people. Today, the leftover fuel is being stored in facilities next to the nuclear plants. The government has plans to permanently store the fuel in a central location either under or above ground. How soon that will happen is not clear. Engineers can design nuclear waste storage facilities that prevent radiation from getting out. It should be safe for hundreds to thousands of years. Of course, no one can be certain about the future thousands of years from now.</li> </ul>

\* Note: Health, Water and Land Impacts are shown on a separate sheet

# Solar Cell

**How it works:** There are two ways to make electricity from sunlight. In the first, sunlight is absorbed into solar cells. The energy from sunlight is then turned directly into electricity. In deserts, a second way is used. The heat from the sun is used to make steam. The steam is used to power a type of engine, called a "turbine". This turbine runs a generator to make electricity. While the second way is cheaper, it cannot be used in PA because here the sun is not intense enough.



A solar plant in Fresno, CA.  
Source: [www.nrel.gov](http://www.nrel.gov)

Many solar cells can be joined together on open land to make a large-scale solar power plant. On a smaller scale, solar cells can be put on the roofs of homes and businesses. Even though the State of PA may provide some rebates, the initial cost to the home- or business-owner would be very large.

<b>Availability</b>	There is no sunlight at night. There is less sunlight on cloudy days. In PA, the solar plants only make about 11% of their possible power. They cannot make 100% because the sun does not always shine at maximum strength or for 24 hours per day.
<b>Reliability</b>	<ul style="list-style-type: none"> <li>The dependability of solar cell power varies with the amount of sunlight. Because of this, solar plants cannot consistently make electricity. Natural gas plants must be built to "back up" or fill in electricity during times when it is not sunny. In the future, we might use very large batteries to store electricity from solar power, but that is very costly to do today.</li> <li>On average, a newly built large-scale solar farm in PA can make 0.1 TWh of electricity over the course of the year. The natural gas plant built to fill in electricity when it is not sunny will have to make about 0.8 TWh over the course of the year.</li> </ul>
<b>Limits to Use</b>	<ul style="list-style-type: none"> <li>If many solar plants are built, there will be a lot of CO<sub>2</sub> released by the "back-up" natural gas plants. The more solar plants you build, the more indirect CO<sub>2</sub> that is released to the air. So solar plants can only be used to make up 9% of the additional electricity needed for PA if we want to reduce the CO<sub>2</sub> released from all new plants by 50%. This would be about 5.1 TWh of the 60 TWh.</li> <li>Solar cell power costs much more in Pennsylvania than in sunnier states like Arizona and California</li> </ul>
<b>Current Use</b>	There are five large-scale solar cell plants working in the U.S. today (in Arizona and California).
<b>Safety</b>	These plants are quite safe for operators and for the people who live around them.
<b>Environmental Impacts</b> (*Read Note Below)	<ul style="list-style-type: none"> <li>While there is almost no solid waste from solar cell power, the cells are made of some toxic materials. There may be some pollution if they are not properly disposed of at the end of their lifetime.</li> <li>Many solar cells must be put together to make a solar plant. Therefore, they use a lot of land. Unlike wind, this land cannot be used for other purposes.</li> </ul>

\* Note: Health, Water and Land Impacts are shown on a separate sheet



# Energy Efficiency

**How it Works:** Energy efficiency cuts the amount of electricity we use. Fewer power plants will be built if we use less electricity. Less CO<sub>2</sub> will then be released into the air.



Energy efficient house in North Carolina  
(renovated rather than newly constructed).  
Source: www.newsweek.com

Energy efficiency refers to using more efficient things. For example, people can use more efficient light bulbs. They can also buy more efficient refrigerators, air conditioners and other appliances. Buildings can also be better insulated. You can also cut electricity use through conservation. For instance, turning off the lights or buying fewer new things (which take electricity to be produced) is called conservation. Conservation is important, but is *not* what “energy efficiency” means.

To get better energy efficiency, you often spend money now to get the savings later. A \$10 energy efficient light bulb costs more than a regular light bulb. But, it lasts 10 times longer and saves 50 to 80% of the electricity you would have used with regular light bulbs. If your house uses less electricity, your bills will go down. Yet, there may be a large initial cost to buy a new efficient appliance or insulation. Over time, you would recoup this cost from the money you save each month on your electric bill. So, you may save more money in the end than you initially spent.

Energy efficiency can help a lot. Vermont and California have programs to promote it. As a result, the average person in VT uses about 20% less electricity than the average person in PA. Californians use about 40% less.

<b>Availability</b>	Energy efficient appliances are in stores now.
<b>Reliability</b>	Most energy efficient products are as dependable as those they replace.
<b>Limits to Use</b>	<ul style="list-style-type: none"> <li>We could buy all efficient products. We could insulate all of our buildings. But, we will always need some electricity to live comfortably. Some power plants will need to be built even if we do our best to cut electricity use.</li> <li>You may be able to cut your household’s electricity use by up to 20% (by buying efficient things) at little extra cost in the long-run. The government may give incentives for buying efficient products. This helps to get larger savings.</li> </ul>
<b>Current Use</b>	Energy efficient appliances are in stores now. Most have an “energy efficiency” rating. Much more can also be done to better insulate and cool buildings. But, people must learn about these options and take action on them.
<b>Safety</b>	Energy efficient appliances and buildings are as safe as those they replace.
<b>Environmental Impacts</b> (*Read Note Below)	Because energy efficiency cuts the amount of electricity we use, fewer power plants will be built. Building power plants can make pollution and disturb the surrounding land, plants and animals. Energy efficiency would reduce these negative effects.

\* Note: Health, Water and Land Impacts are shown on a separate sheet

# Biomass-and-Coal

**How it Works:** This plant is very similar to the one described in "Coal, CO<sub>2</sub> released". But in this plant, some biomass is mixed in with the coal. Biomass comes from farm crops, paper mills, and wood chips. In these mixed plants, biomass is substituted for 10% of the coal. The coal-biomass mixture is burned to make steam. The steam is used to power a type of engine, called a "turbine". This turbine runs a generator to make electricity.



Biomass-coal power plant in Dunkirk, NY  
Source: [www.ens-newswire.com](http://www.ens-newswire.com)

Biomass fuel is made from trees and other plants. Plants and trees take in CO<sub>2</sub> from the air when they are alive. So, most of the CO<sub>2</sub> released into the air when biomass is burned is not a new addition. It was in the air recently and is just recycled back into the air. This is different than the "new" CO<sub>2</sub> released by power plants that burn coal and natural gas. The CO<sub>2</sub> trapped in these "fossil fuels" has not been in the air for millions of years. So, a biomass-coal plant releases less CO<sub>2</sub> than a coal plant (CO<sub>2</sub> released) because the biomass adds no "new" CO<sub>2</sub> to the air. The more biomass in the mixture, the less CO<sub>2</sub> released by the power plant.

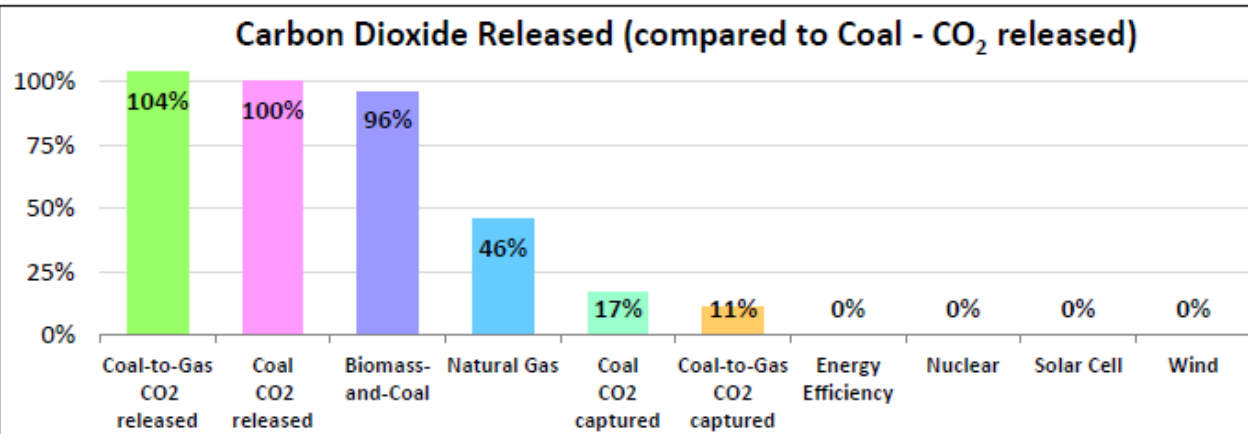
<b>Availability</b>	Experts say that the U.S. has enough coal to meet its needs for at least 50 to 100 years. Biomass can be found everywhere in the U.S. But, many types of biomass are traditionally used for other things, such as for food (from farm crops). This means that electricity companies will have to compete with other buyers of the biomass "fuel".
<b>Reliability</b>	Biomass- coal power can provide steady and dependable electricity.
<b>Limits to Use</b>	<ul style="list-style-type: none"> <li>If biomass-coal plants made up much of our electricity, we would need to begin to grow biomass. Growing biomass is expensive. So, the cost of electricity from biomass will go up with each biomass-coal plant built in PA. Lots of land would be used up.</li> <li>While these mixture plants release less CO<sub>2</sub> than Coal plant (CO<sub>2</sub> released), they still release a lot of CO<sub>2</sub>. So, biomass-and-coal plants can only be used to make about 18% of the additional electricity needed for PA if we want to reduce the CO<sub>2</sub> released from all new plants by 50%. This would be about 10.5 TWh of the 60 TWh. Other types of plants must also be built.</li> </ul>
<b>Current Use</b>	There are dozens of biomass-coal power plants working in the U.S. today. Many are small and make a small amount of electricity. But, larger biomass-coal plants do exist in the U.S.
<b>Environmental Impacts</b> (*Read Note Below)	<ul style="list-style-type: none"> <li>Biomass is sometimes grown especially to make fuel. Chemicals used to grow biomass can pollute the soil and water.</li> <li>Some biomass comes from woody waste products. But, on a larger scale, new trees or plants will need to be grown for biomass. This could mean that farms will grow less food, driving food prices up. Land may need to be cleared in the U.S. or abroad to grow more biomass or food. This could cause soil erosion and disturb the animals and plants.</li> <li>The coal mining impacts and the waste made by these plants are about the same as "Coal, CO<sub>2</sub> released" plants. But, they are slightly less because these plants use slightly less coal.</li> </ul>
<b>Safety</b>	<ul style="list-style-type: none"> <li>These plants are quite safe for operators. Coal mining is dangerous for the miners.</li> <li>The biomass will be transported by trucks to the power plant. This will greatly increase truck traffic, which can cause accidents.</li> </ul>

\* Note: Health, Water and Land Impacts are shown on a separate sheet

## Power Plant Comparison: Reach the Goals

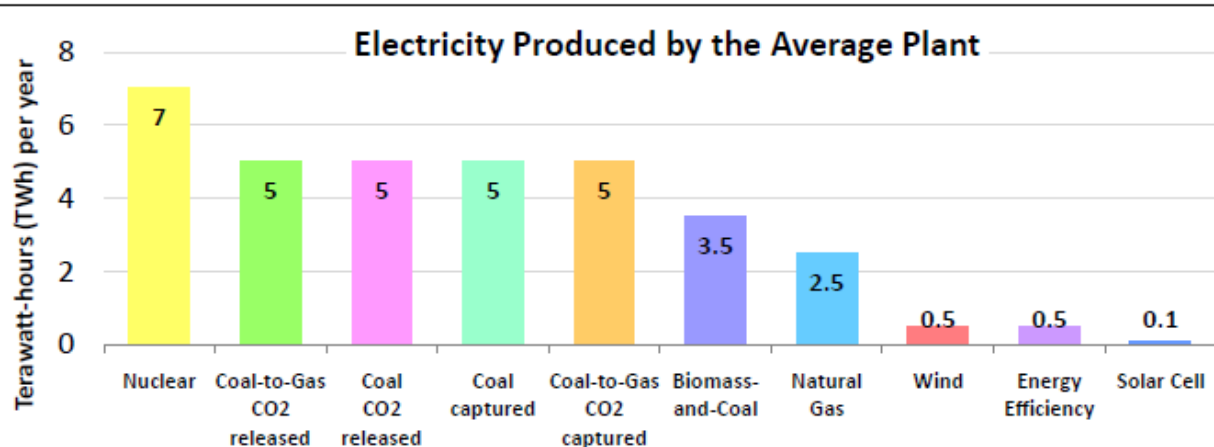
### Goal 1: PA must build plants that collectively release less CO<sub>2</sub>

Releasing CO<sub>2</sub> into the air contributes to climate change. The less CO<sub>2</sub> released by a power plant, the less it contributes to climate change. This graph compares the CO<sub>2</sub> released by each power plant type. The size of each bar shows the percent of CO<sub>2</sub> released by a power plant type compared with that from a coal plant (in which the CO<sub>2</sub> is released to the air). The CO<sub>2</sub> from the coal plant (CO<sub>2</sub> released) is always shown as 100%. If a power plant type pollutes less than this coal plant, the graph will show a percentage that is less than 100%. If it pollutes more, a percentage greater than 100% is shown. So, the smaller the percentage, the less CO<sub>2</sub> put out by that plant. A graph shows 0% if a power plant type puts out no CO<sub>2</sub>. Overall, shorter bars on the graph are better than longer ones.



### Goal 2: Build enough power plants to make 60 TWh of additional electricity each year

This graph compares the amount of electricity made by each power plant type in one year. No plant can run all the time – they need maintenance. Wind and solar plants can only run when it is windy or sunny. The graph below shows the average amount of electricity each type of power plant in PA makes in a year. For instance, an average natural gas plant makes 5 times as much electricity as an average wind farm. So, you would need to build 5 wind farms to make the same amount of electricity as 1 natural gas plant. Think about how many of each of these plants would need to be built to make 60 TWh of electricity.

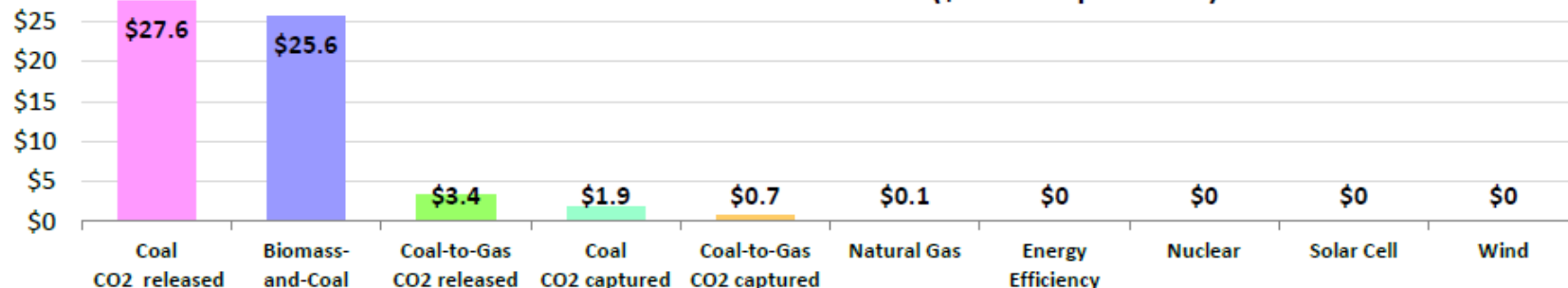




## Health Impacts

Some power plants release pollutants into the air called particulates, nitrogen oxides and sulfur dioxides. People who are exposed to this air pollution may have a higher risk of health problems and even dying. They also have more emergency room visits, hospitalizations and lost work days. You could build the power plants further away from where the people are living. But, then the electricity would cost more because it is expensive to transmit electricity over long distances. The health cost bar graph below shows the annual cost to PA (in millions of dollars) from these health effects (per TWh of electricity) from each type of power plant. These costs would likely increase the cost of health insurance and state taxes that are used for health programs.

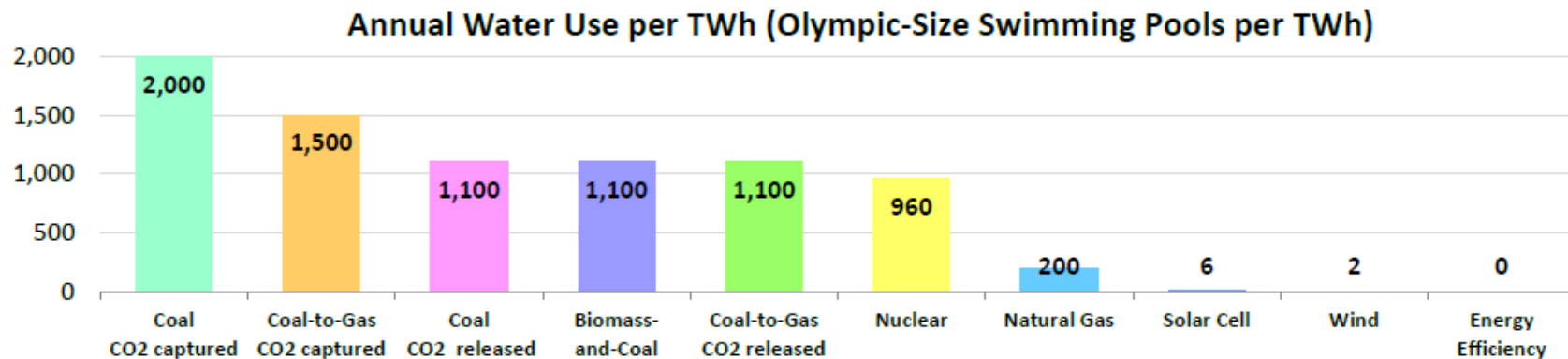
**Annual Health Costs from Air Pollution (\$Million per TWh)**



	Coal CO <sub>2</sub> released	Biomass- and-Coal	Coal-to-Gas CO <sub>2</sub> released	Coal CO <sub>2</sub> captured	Coal-to-Gas CO <sub>2</sub> captured	Natural Gas	Energy Efficiency	Nuclear	Solar Cell	Wind
<b>Particulates:</b> The power plants that are checked at right are a source of small particles that get into air called particulates. They make the air look hazy. The smaller ones can pass through your nose and throat. They get deep into your lungs. They can cause a variety of health problems such as asthma attacks, which may result in death.	✓	✓	✓	✓	✓					
<b>Nitrogen Oxides and/or Sulfur Dioxide:</b> The power plants that are checked at right release nitrogen oxides and/or sulfur dioxide into the air. These gases can be converted into small particles and cause smog and acid rain. The smog can make your eyes, nose, and throat hurt. Breathing it for long periods of time can lead to lung problems and worsen heart disease. The acid rain can turn lakes and rivers acidic and can damage trees.	✓	✓		✓		✓				
<b>Indirect Nitrogen Oxides:</b> Since the power plants checked at right cannot produce electricity when it is not windy or sunny, natural gas plants must be built back them up. The natural gas plants do release nitrogen oxides.									✓	✓
<b>No Direct Air or Water Pollution:</b> The power plants checked at right do not release any direct air or water pollution when operating normally.							✓	✓	✓	✓

## Water Impacts

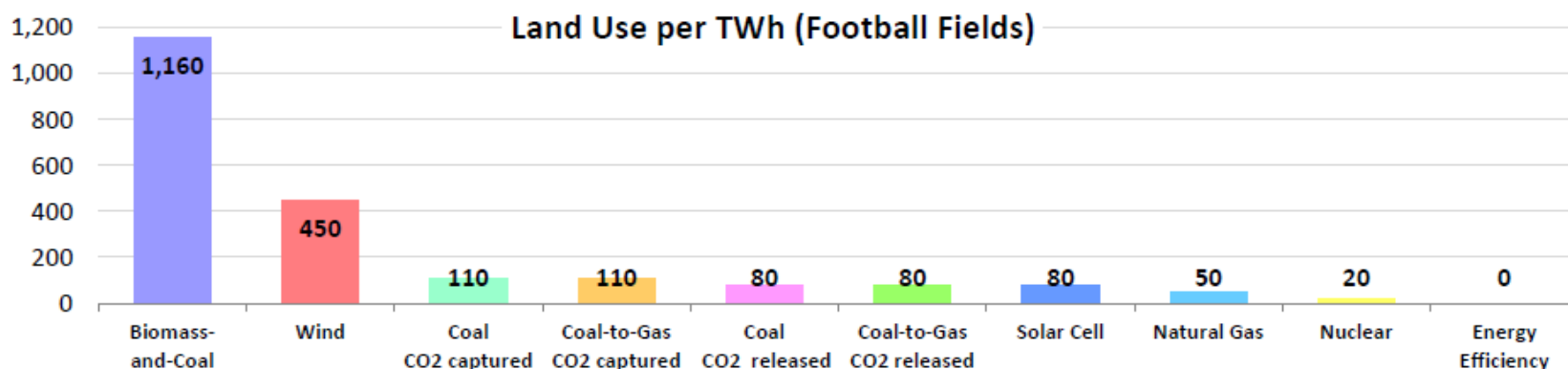
Many power plants use water – mostly for cooling purposes and small amounts to clean equipment. Sometimes the water can be recycled. Sometimes it evaporates or is “used up”. During summer droughts or in dryer climates, conservation of water is especially important. The water use graph shows how much water is consumed or “used up” by the power plant type at all points in the supply chain (for example, coal plants use water at the coal mine and at the plant). It does not include the water that can be recycled. The graph shows the annual amount of water used (per TWh of electricity) from each type of power plant. This water volume is shown in terms of Olympic size swimming pools. One Olympic size pool holds about 650,000 gallons of water



	Coal CO <sub>2</sub> captured	Coal-to- Gas CO <sub>2</sub> captured	Coal CO <sub>2</sub> released	Biomass- and-Coal	Coal-to-Gas CO <sub>2</sub> released	Nuclear	Natural Gas	Solar Cell	Wind	Energy Efficiency
<b>Hot Water Is Released:</b> The power plants checked at right use water to cool down the steam that has been used in the plant. The water comes from wells, lakes, rivers or oceans. When the water is returned to its source, it is hot. This may disturb plants and animals living in the water.	✓	✓	✓	✓	✓	✓	✓			
<b>Water for Cleaning Only:</b> Most of the water use by the power plants checked at right is for cleaning purposes.								✓	✓	

## Land Impacts

Some power plants use up a lot of land. This can be harmful to the environment if for example, forests and animal habitats are disturbed. The land use graph shows how much land is used by the power plant at all points in the supply chain (for example, coal plants use land at the coal mine and at the plant). The graph includes the land that can be used for other purposes (for instance, land around a wind machine is included, even though it can sometimes be used for farming). The graph shows the amount of land used (per TWh of electricity) by each type of power plant. The land area is shown in terms of football fields.



	Biomass-and-Coal	Wind	Coal CO <sub>2</sub> captured	Coal-to-Gas CO <sub>2</sub> captured	Coal CO <sub>2</sub> released	Coal-to-Gas CO <sub>2</sub> released	Solar Cell	Natural Gas	Nuclear	Energy Efficiency
<b>Drilling and Mining:</b> For the power plants checked at right, mining and/or drilling can disturb the local land, plants and animals.	✓		✓	✓	✓	✓		✓	✓	
<b>Land may also be Used for Other Purposes:</b> Some of the land use area included for the plants checked at right may also be used for other purposes (for example, the land above underground gas pipelines or the land between wind machines).		✓	✓	✓				✓		



# Cost Comparison

This graph shows the estimated *increase* in cost of electricity from building each power plant type. Electricity used in your home is measured in kilowatt-hours. One kilowatt-hour can power a 100-watt light bulb for 10 hours. The average household in PA pays about \$0.11 per kilowatt-hour of electricity used. It also uses about 700 kilowatt-hours each month. Since  $0.11 \times 700 = \$77$ , the average PA monthly bill is \$77. Your bill may be more if your house has electric heating or electric water heating, if it is very large, or if it uses lots of air conditioning.

Since we need to build more power plants in the next 25 years, the cost of electricity will go up. The numbers on the bottom side of the graph show how much the cost of electricity will go up in dollars per kilowatt-hour. The numbers on the top side show how much the monthly bill would go up for the average PA household. The numbers on the bottom are multiplied by 700 kilowatt-hours to get the monthly bill numbers on the top.

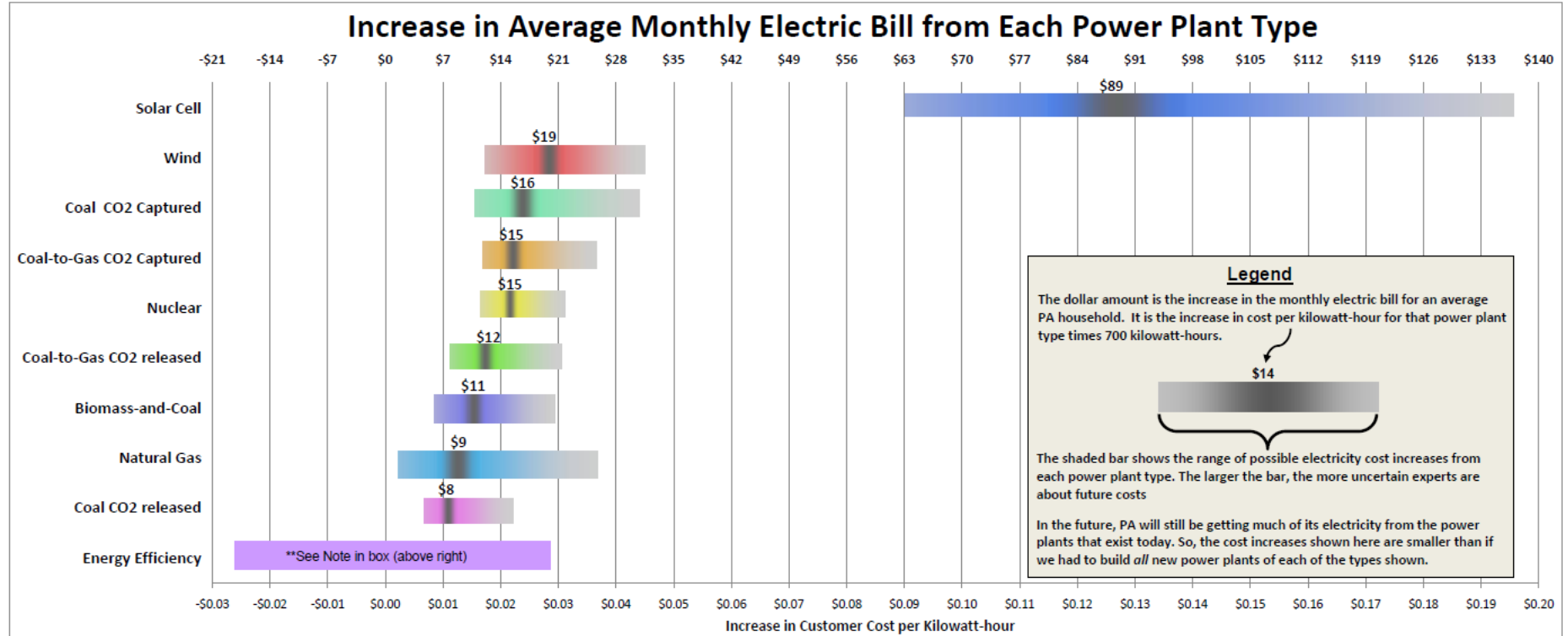
Let's say the cost increase would be \$0.02 per kilowatt-hour. Since  $0.02 \times 700 = 14$ , the monthly bill increase would then be \$14. This means that the average PA household would now be paying  $\$77 + \$14 = \$92$ .

Experts are not certain about future electricity costs. So, each bar shows a range. The gray center of the bar (and the dollar value just to its left) show the most likely increase in the monthly electric bill. The longer the shaded bar, the more uncertain experts are about the costs. This is also explained in the Legend. Before reading on, look at the Legend and try to decipher the graph.

We use electricity outside of our homes too. For instance, it is needed to make clothing or produce groceries. So, the cost of electricity will affect more than just your monthly electric bill. Think about how building certain power plants could also change the cost of everything else you buy.

**\*\*Note:** The cost estimate for energy efficiency is different from the others. It depends on how much electricity you want to save. Efficient things like light bulbs are cheap. Others things like insulating a building are more expensive. People tend to buy the cheaper things first and the more expensive things later. So the more electricity you want to save, the more expensive it gets. The cost of the efficient products will eventually begin to greatly outweigh the savings on your electricity bill. The low end of this bar shows the costs for a small amount of energy efficiency. The high end of the bar shows the cost for a large amount of energy efficiency.

The cost shown here assumes that you only buy efficient products as a replacement for broken or old things. For instance, you wait until your light bulbs burn out or your dishwasher is broken to shop for an efficient replacement. If you buy efficient things when you otherwise wouldn't have needed a replacement, the cost is much higher.



### *B.2.1. Group Meeting Materials*

#### **Problem Question**

##### The Current Situation

Right now, the power plants in PA make about 225 terawatt-hours (TWh) of electricity each year. A TWh is a measure of electricity use. One TWh is a lot of electricity. In comparison, an average household in PA uses less than 0.001% of one TWh of electricity per year.

##### The Future Situation

PA will need more electricity in 25 years than the power plants it has now can make. The power plants in PA will need to make about 285 TWh of electricity each year to keep up with demand. 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.

**The original plan was to build the following power plants in PA: 6 coal power plants (in which the CO<sub>2</sub> is released into the air), 4 natural gas power plants, 3 nuclear power plants and 1 wind farm.** But, suppose that the U.S. Congress has just passed a law to reduce the CO<sub>2</sub> 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 plants will collectively need to release 50% less CO<sub>2</sub> than the original plan. **A different combination of power plants will need to be built.** Imagine that the Governor of Pennsylvania has asked you to serve on a Citizen's Advisory Panel **to give advice on how many of each plant type should be built in PA.**

##### Your Task

Your job is to use the computer tool to provide this advice. You will **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<sub>2</sub> that would have been released using the original plan.**