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

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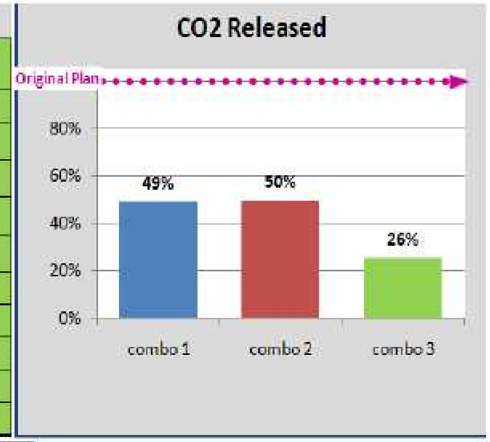
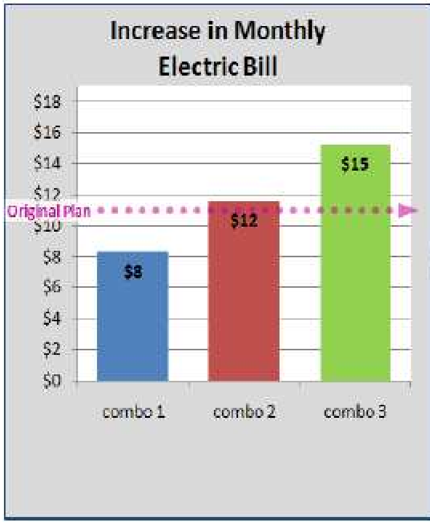
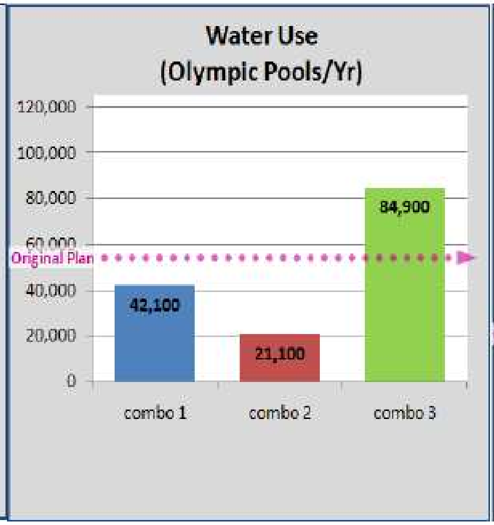
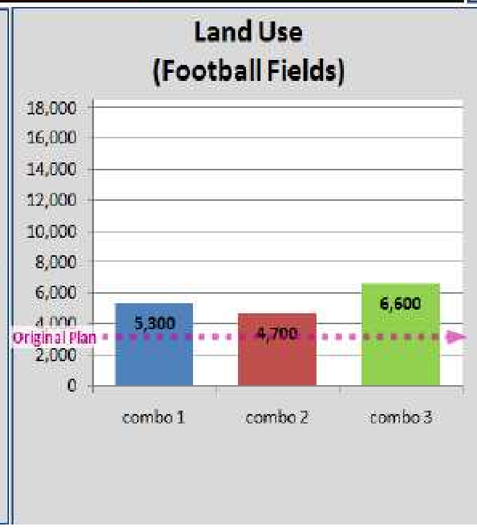
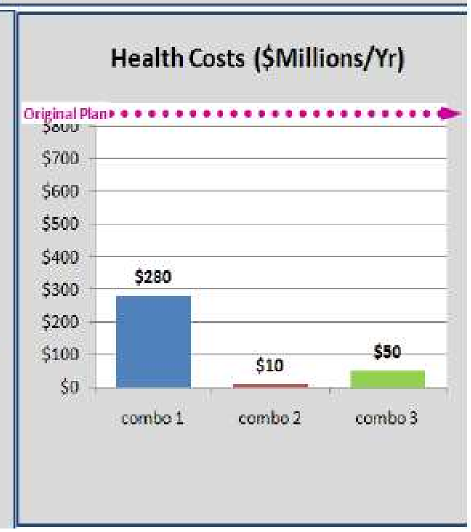
	Your Combinations (Percent of Each Power Plant Type)		
	combo 1	combo 2	combo 3
Biomass-and-Coal	0%	0%	0%
Coal: CO_2 released to air	17%	0%	0%
Coal: CO_2 captured	0%	0%	33%
Coal-to-Gas: CO_2 released to air	0%	0%	0%
Coal-to-Gas: CO_2 captured	17%	0%	42%
Energy Efficiency	15%	4%	0%
Natural Gas	21%	62%	9%
Nuclear	23%	23%	12%
Solar Cell	0%	2%	0%
Wind	9%	9%	4%











Coal

(CO_2 released into the air)

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

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.

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

Availability	Experts say that the U.S. has enough coal to meet its needs for at least 50 to 100 years. PA is the 4th 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_2. They can only be used to make 25% of the additional electricity needed for PA if we want to reduce the CO_2 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)	• 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. • 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. • 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. 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_2 is captured)*

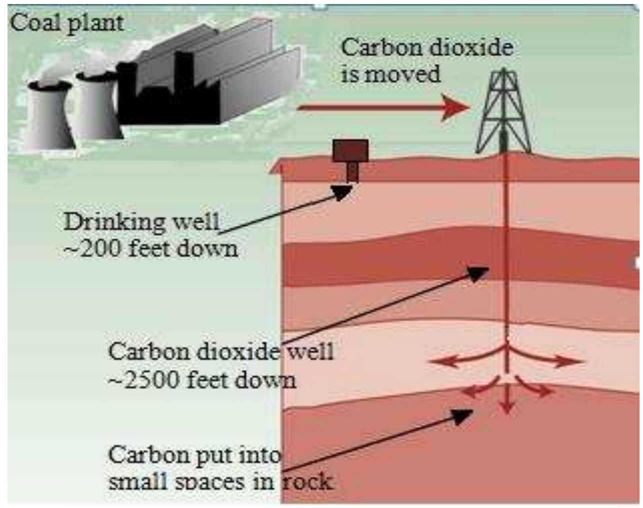


Diagram of a coal-to-gas plant with CO2 capture equipment. Modified from www.co2crc.com.au

How it Works: This is the same plant described in *"Coal, CO_2 released"*. But in this plant, additional equipment is added to capture the CO_2 before it escapes to the air. This CO_2 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_2 will stay trapped there. The CO_2 will also be monitored to make sure that it does stay in place. After a few decades, the CO_2 will dissolve (and become trapped) in the water in the rocks. Over thousands of years, it will likely change into solid minerals.

Availability	• 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_2. • There are thousands of miles of gas pipelines in the U.S. today. CO_2 is moved through similar pipelines. CO_2 pipelines are already used in the U.S., but more need to be built.
Reliability	Capturing CO_2 does not make coal plants less dependable.
Limits to Use	Coal plants with CO_2 capture equipment could make all of the additional 60 TWh of electricity needed for PA.
Current Use	The U.S. Government is capturing CO_2 underground in 25 test sites across the U.S. today. A few large-scale CO_2 capture sites are currently being used in other countries.
Environmental Impacts (*Read Note Below)	• The waste made by these plants and the coal mining impacts are about the same as "Coal, CO_2 released" plants. • The CO_2 will cause little or no harm to living plants or animals once it is in the deep underground rock formations. Some CO_2 is also naturally found in the ground.
Safety	• If CO_2 gets in underground drinking water, the water can become contaminated. That risk is small because CO_2 wells will be built more than 10 times deeper than drinking water wells. • Unlike oil or gas, CO_2 cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of CO_2 did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the CO_2 could build up for a while. In this case, people and animals could suffocate if the leak was large enough. • There is a small chance that CO_2 could leak out of an underground space. These leaks would be very slow. In almost all cases, the CO_2 would mix into the air before harming anyone. • The CO_2 in the ground can be monitored with equipment underground and on the surface. If the CO_2 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_2 could be moved to some other location. • Pumping CO_2 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. • After a few decades, the CO_2 dissolves in the deep underground water. This reduces many of the risks. Leaks become very unlikely. CO_2 can no longer move to contaminate drinking water. It cannot move to places it should not be or cause earthquakes. • 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.

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

Coal-to-Gas

(CO_2 released into the air)

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

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_2 is released by the plant. In these plants, this CO_2 escapes into the air because no equipment is added to capture the CO_2.

Availability	Experts say that the U.S. has enough coal to meet its needs for at least 50 to 100 years. PA is the 4th 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_2. They can only be used to make 25% of the additional electricity needed for PA if we want to reduce the CO_2 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)	• Coal-to-gas plants release less air pollution than regular coal plants. • 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. • 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. • 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.
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_2 is captured)

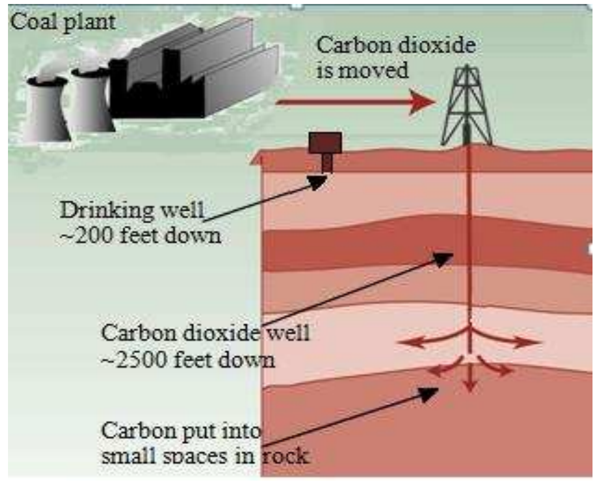


Diagram of a coal plant CO2 capture equipment.
Modified from www.co2crc.com.au

How it Works: This is the same plant described in *"Coal-to-gas, CO_2 released"*. But in this plant, additional equipment is added to capture the CO_2 before it escapes to the air. The capture equipment for a coal-to-gas plant can capture a little more CO_2 than the capture equipment of a coal plant. The CO_2 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_2 will stay trapped there. The CO_2 will also be monitored to make sure that it stays in place. After a few decades, the CO_2 will dissolve (and become trapped) in the water in the rocks. Over thousands of years, it will likely change into solid minerals.

Availability	• 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_2. • There are thousands of miles of gas pipelines in the U.S. today. CO_2 is moved through similar pipelines. CO_2 pipelines are already used in the U.S., but more need to be built.
Reliability	Capturing CO_2 does not make coal-to-gas plants less dependable.
Limits to Use	Coal-to-gas plants with CO_2 capture equipment could make all of the additional 60 TWh of electricity needed for PA.
Current Use	The U.S. Government is capturing CO_2 underground in 25 test sites across the U.S. today. A few large-scale CO_2 capture sites are currently being used in other countries.
Environmental Impacts (*Read Note Below)	• The waste made by these plants and the coal mining impacts are about the same as "Coal-to-gas, CO_2 released" plants. • The CO_2 will cause little or no harm to living plants or animals once it is in the deep underground rock formations. Some CO_2 is also naturally found in the ground.
Safety	• If CO_2 gets in underground drinking water, the water can become contaminated. That risk is small because CO_2 wells will be built more than 10 times deeper than drinking water wells. • Unlike oil or gas, C_{O2} cannot burn or explode. As with oil and gas pipelines, the chance of pipeline leaks is low. If lots of C_{O2} did leak from a pipeline, it would usually mix into the air. But if the leak happened in a valley or tunnel, the C_{O2} could build up for a while. In this case, people and animals could suffocate if the leak was large enough. • There is a small chance that CO_2 could leak out of an underground space. These leaks would be very slow. In almost all cases, the CO_2 would mix into the air before harming anyone. • The CO_2 in the ground can be monitored with equipment underground and on the surface. If the CO_2 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_2 could be moved to some other location. • Pumping CO_2 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. • After a few decades, the CO_2 dissolves in the deep underground water. This reduces many of the risks. Leaks become very unlikely. CO_2 can no longer move to contaminate drinking water. It cannot move to places it should not be or cause earthquakes. • 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.

** 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/

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	• 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. • 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.
Limits to Use	If many wind farms are built, there will be a lot of CO_2 released by the "back-up" natural gas plants. The more wind farms you build, the more indirect CO_2 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_2 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)	• There is almost no solid waste from wind farms. • 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. • 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. • 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.
Safety	Wind farms present very few risks to people.

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

Natural Gas

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

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 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.

Availability	• 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. • 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.
Reliability	Natural gas can provide steady and dependable electricity.
Limits to Use	• 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. • While gas plants release about half as much CO_2 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_2 released from all new plants by 50%. This would be about 37.5 TWh of the 60 TWh.
Current Use	There are more than 350 of these plants working in the U.S. today.
Environmental Impacts (*Read Note Below)	• There is almost no solid waste from gas plants. • 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.
Safety	• These plants are quite safe for operators. It is rare for natural gas to leak from a pipeline. If it does occur, unlike CO_2, natural gas can burn or explode. Like CO_2, people can suffocate from natural gas. • 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.

** 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

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 to Use	Nuclear plants could make all of the additional 60 TWh of electricity needed for PA.
Current Use	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.
Safety	• 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. • 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. • 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.
Environmental Impacts (*Read Note Below)	• Uranium fuel must be mined, but the amount that is mined is much less than that of coal. • Nuclear plants do have a small amount of waste. It is much less than the waste from coal plants. • 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.

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

Solar Cell

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 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.

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.

Availability	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.
Reliability	• 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. • 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.
Limits to Use	• If many solar plants are built, there will be a lot of CO_2 released by the “back-up” natural gas plants. The more solar plants you build, the more indirect CO_2 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_2 released from all new plants by 50%. This would be about 5.1 TWh of the 60 TWh. • Solar cell power costs much more in Pennsylvania than in sunnier states like Arizona and California
Current Use	There are five large-scale solar cell plants working in the U.S. today (in Arizona and California).
Safety	These plants are quite safe for operators and for the people who live around them.
Environmental Impacts (*Read Note Below)	• 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. • 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.

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

Energy Efficiency

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

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_2 will then be released into the air.

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.

Availability	Energy efficient appliances are in stores now.
Reliability	Most energy efficient products are as dependable as those they replace.
Limits to Use	• 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. • 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.
Current Use	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.
Safety	Energy efficient appliances and buildings are as safe as those they replace.
Environmental Impacts (*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

Biomass-coal power plant in Dunkirk, NY
Source: www.ens-newswire.com

How it Works: This plant is very similar to the one described in *"Coal, CO_2 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.

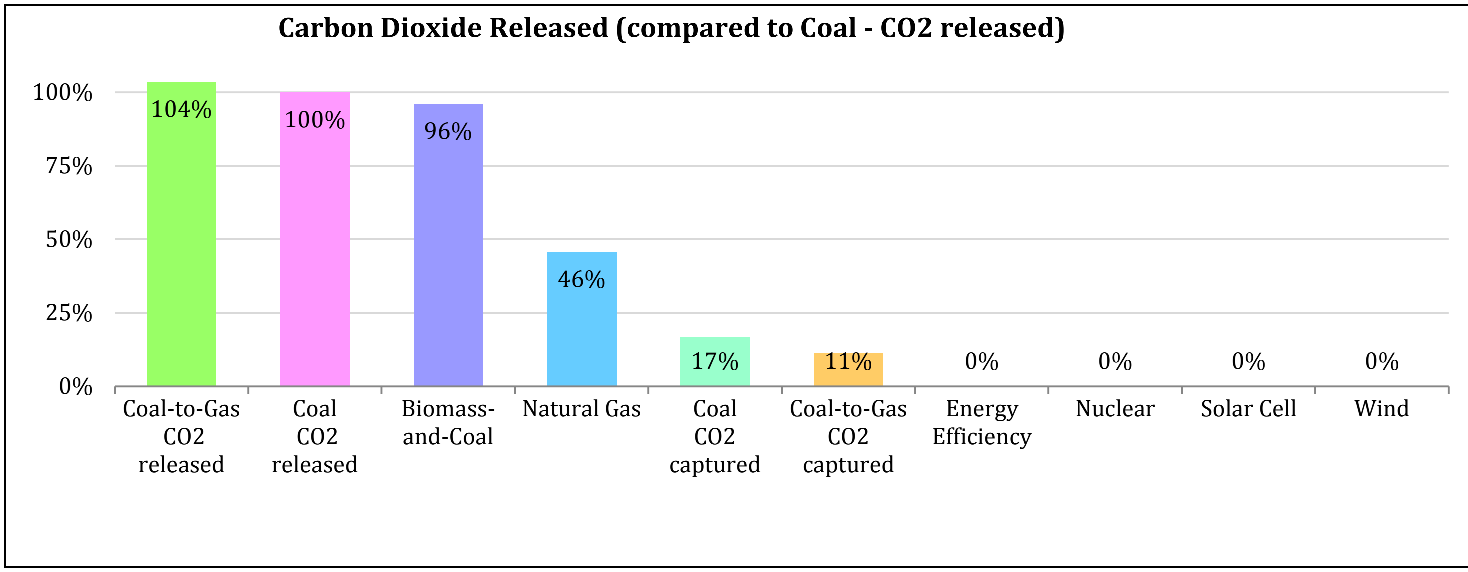
Biomass fuel is made from trees and other plants. Plants and trees take in CO_2 from the air when they are alive. So, most of the CO_2 released into the air when biomass is burned is not a new addition. It was in the air recently and is just recycled back into the air. This is different than the "new" CO_2 released by power plants that burn coal and natural gas. The CO_2 trapped in these "fossil fuels" has not been in the air for millions of years. So, a biomass-coal plant releases less CO_2 than a coal plant (CO_2 released) because the biomass adds no "new" CO_2 to the air. The more biomass in the mixture, the less CO_2 released by the power plant.

Availability	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".
Reliability	Biomass- coal power can provide steady and dependable electricity.
Limits to Use	• 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. • While these mixture plants release less CO_2 than Coal plant (CO_2 released), they still release a lot of CO_2. 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_2 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.
Current Use	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.
Environmental Impacts (*Read Note Below)	• Biomass is sometimes grown especially to make fuel. Chemicals used to grow biomass can pollute the soil and water. • 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. • The coal mining impacts and the waste made by these plants are about the same as "Coal, CO_2 released" plants. But, they are slightly less because these plants use slightly less coal.
Safety	• These plants are quite safe for operators. Coal mining is dangerous for the miners. • The biomass will be transported by trucks to the power plant. This will greatly increase truck traffic, which can cause accidents.

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

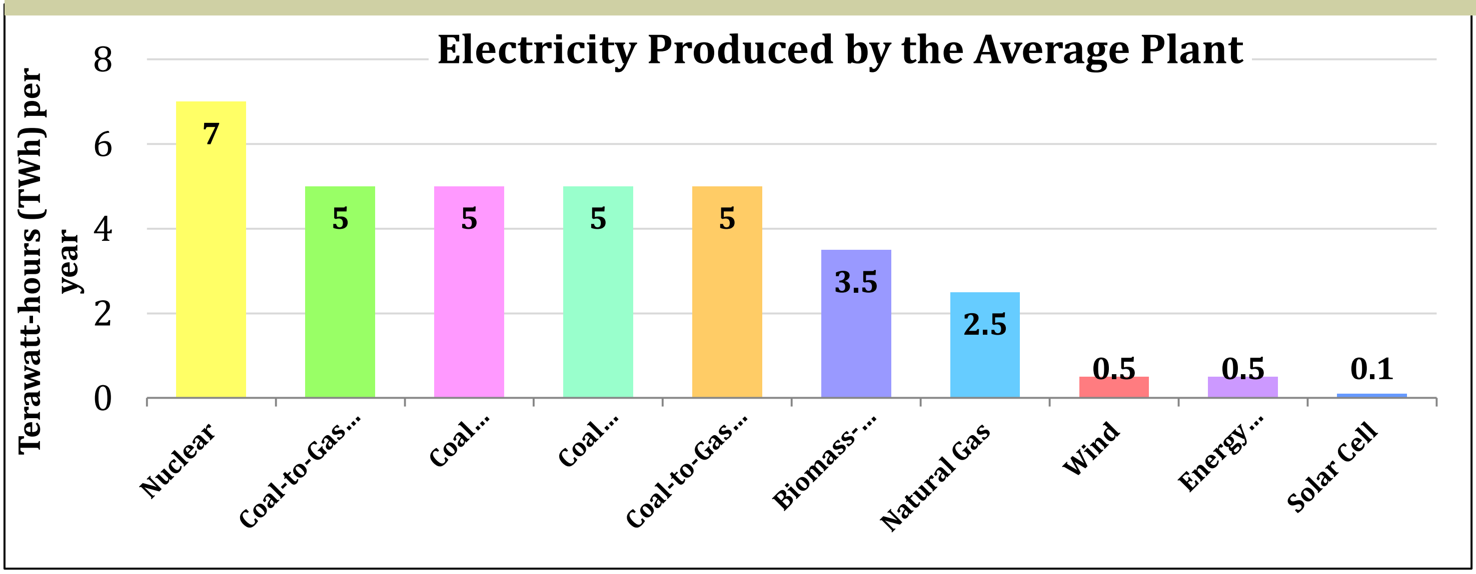
Goal 1: PA must build plants that collectively release less CO_2

Releasing CO_2 into the air contributes to climate change. The less CO_2 released by a power plant, the less it contributes to climate change. This graph compares the CO_2 released by each power plant type. The size of each bar shows the percent of CO_2 released by a power plant type compared with that from a coal plant (in which the CO_2 is released to the air). The CO_2 from the coal plant (CO_2 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_2 put out by that plant. A graph shows 0% if a power plant type puts out no CO_2. 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.



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 × 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.

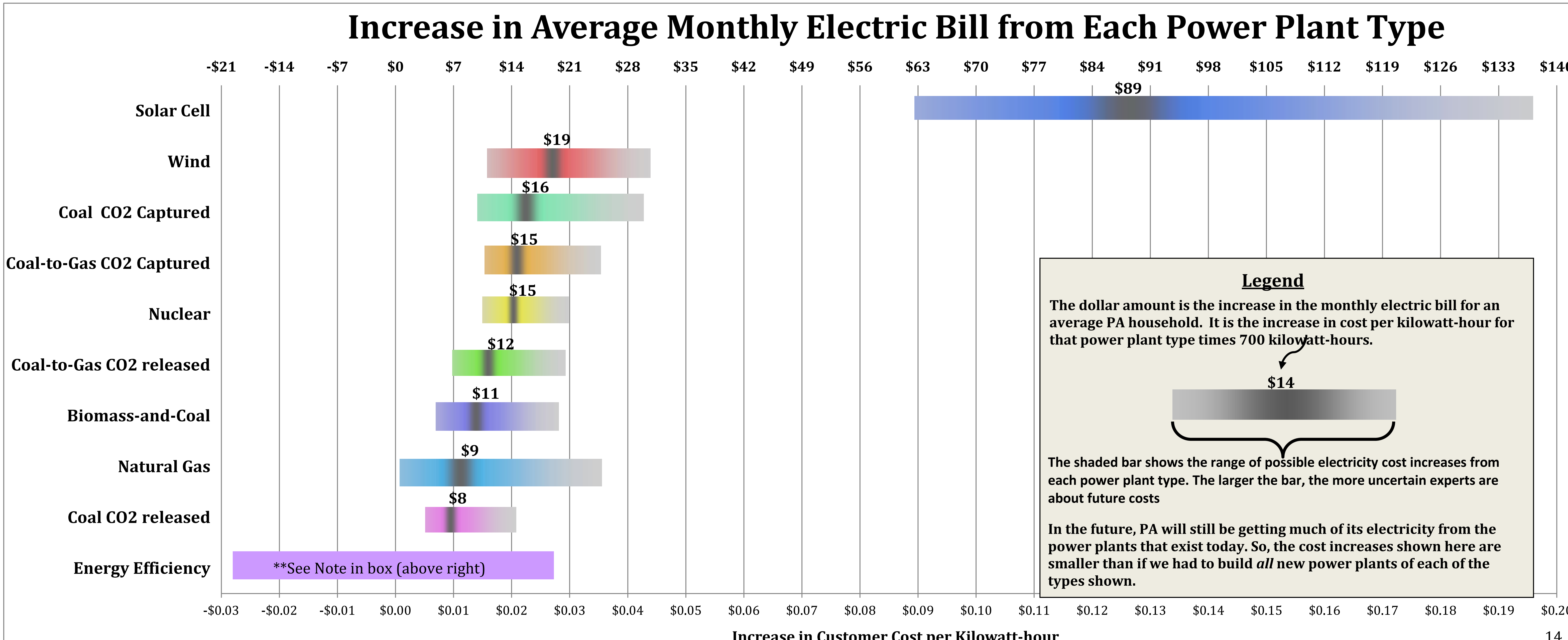
Let’s say the cost increase would be $0.02 per kilowatt-hour. Since 0.02 × 700 = 14, the monthly bill increase would then be $14. This means that the average PA household would now be paying $77 + $14 = $92.

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.

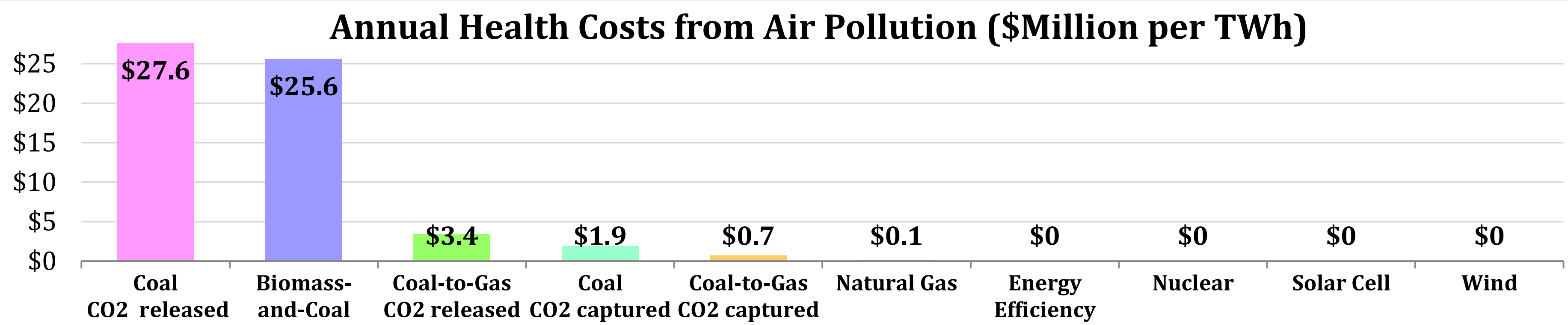
**Note: The cost estimate for energy efficiency is different from the others. It depends on how much electricity you want to save. Efficient things like light bulbs are cheap. Others things like insulating a building are more expensive. People tend to buy the cheaper things first and the more expensive 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.



Health Impacts

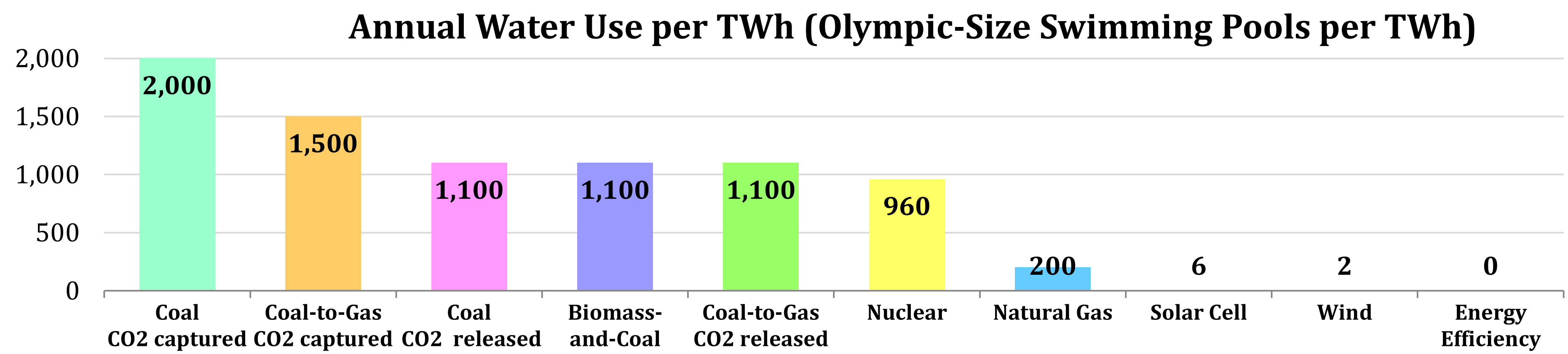
Some power plants release chemicals into the air called particulates, nitrogen oxides and sulfur dioxides. People who are exposed to this air pollution may have a higher risk of health problems and even dying. They also have more emergency room visits, hospitalizations and lost work days. You could build 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.



	Coal CO_2 released	Biomass-and-Coal	Coal-to-Gas CO_2 released	Coal CO_2 captured	Coal-to-Gas CO_2 captured	Natural Gas	Energy Efficiency	Nuclear	Solar Cell	Wind
Particulates: The power plants that are checked at right release very small particles into the 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.	✓	✓	✓	✓	✓					
Nitrogen Oxides and/or Sulfur Dioxide: The power plants that are checked at right release nitrogen oxides and/or sulfur dioxide into the air. These pollutants can 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. These pollutants can also make more particulates.	✓	✓		✓		✓				
Indirect Nitrogen Oxides: Since the power plants checked at right are not always dependable, natural gas plants must be built to make up for times when it is not windy or sunny. The natural gas plants do release nitrogen oxides.									✓	✓
No Direct Air or Water Pollution: The power plants checked at right do not release any direct air or water pollution when operating normally.							✓	✓	✓	✓

Water Impacts

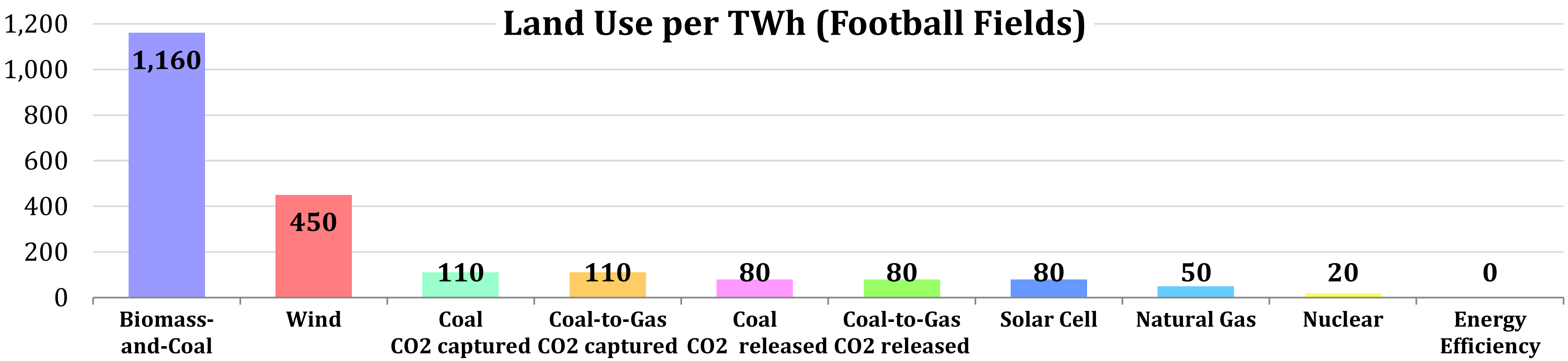
Many power plants use water – most times to cool off and clean equipment. Sometimes the water can be recycled. Sometimes it evaporates or is "used up". During summer droughts or in dryer climates, conservation of water is especially important. The water use graph shows how much water is consumed or "used 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_2 captured	**Coal-to-Gas** CO_2 captured	**Coal** CO_2 released	**Biomass-and-Coal**	**Coal-to-Gas** CO_2 released	**Nuclear**	**Natural Gas**	**Solar Cell**	**Wind**	**Energy Efficiency**
Hot Water Is Released: The power plants checked at right use water to cool off their equipment. 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.	✓	✓	✓	✓	✓	✓	✓			
Water for Cleaning Only: 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 cleared away. 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_2 captured	Coal-to-Gas CO_2 captured	Coal CO_2 released	Coal-to-Gas CO_2 released	Solar Cell	Natural Gas	Nuclear	Energy Efficiency
Drilling and Mining: For the power plants checked at right, mining and/or drilling can disturb the local land, plants and animals.	✓		✓	✓	✓	✓		✓	✓	
Land also Used for Other Purposes: Some of the land use area included for the plants checked at right can also be used for other purposes (for example, the land above CO_2 and natural gas pipelines or the land between wind machines).		✓	✓	✓				✓		

Assumptions and Calculations for the Portfolio-Building Computer Tool

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^2/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 $222*(1.01)^{25} – (222*.98)$ = 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 MW x CF% x 8760 x 10^{-6} = 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 NOx, a wet FGD for SO_2 and a fabric filter for particulates. Two different SO_2 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_x, SO_2, PM and CO_2 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_x	8.84E-04	1.44E-03	1.83E-04	2.04E-04	1.88E-04	8.39E-04
SO_2	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_2	1.81E+00	3.00E-01	1.87E+00	2.04E-01	0.8258	1.74E+00
kg/MWh						
NO_x	0.40	0.65	0.08	0.09	0.09	0.38
SO_2	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_2	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 negawatt 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/ 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 [6], 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_2 and NO_x 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_2	NO_x	$PM_{2.5}$	PM_{10}
Coal	$9,900	$1,600	$21,600	$970
Natural Gas	$10,800	$1,500	$34,800	$1,600

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

$/GWh	Total Cost	SO_2	NOx	$PM_{2.5}$	PM_{10}
PC	$27.600	$26,000	$690	$900	$20
PC w/ CCS	$1,900	$9	$1,100	$740	$20
PC & Biomass	$25,600	$24,100	$650	$820	$20
IGCC	$3,400	$3,200	$140	$60	$2
IGCC w/ CCS	$700	$400	$160	$80	$2
Natural Gas	$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 CO2 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^2/GWh)

m^2/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

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