Energy Sector Technology: Power Generation

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Arizona's Solar Market Analysis and Research Tool (Az SMART)

Arizona's Solar Market Analysis and Research Tool (Az SMART) is a breakthrough analysis environment that will enable stakeholders to examine the complex interaction of economic, security, environmental, and technological issues that impact Arizona's ability to become a global leader in solar power innovation, development and deployment. Multi-disciplinary research efforts and capabilities at Arizona State University and the University of Arizona are being utilized in close collaboration with partners from industry and government in the creation and use of Az SMART.

The goal of the three-year project is to develop a unique analysis tool, tailored to the examination of a successful rollout of large-scale solar energy infrastructure in Arizona, and the required electric grid technologies to enable that infrastructure.

The principal outputs of the project are Solar Feasibility research, a Solar Scorecard for Arizona, and ultimately, the analytical tool that integrates them into a decision support framework. The end product will be accessible by remote web access (www.azsmart.org), as well as at Decision Theater, a dynamic, immersive visualization environment facility at Arizona State University.

Arizona's Solar Scorecard

Researchers at the L. William Seidman Research Institute of the W. P. Carey School of Business at Arizona State University are developing Arizona's Solar Scorecard. The Solar Scorecard comprises metrics drawn from energy usage forecasts, environmental valuation analyses, economic development analyses, and energy security evaluations. It is assembled from a series of white papers that provide the research and analysis to translate commercial and public policy choices into measures of economic, environmental, social and energy security impact on Arizona. The thirteen white papers are as follows:

1. *Energy Sector Technology;*
2. *The Market-Determined Cost of Inputs to Utility-Scale Electricity Generation;*
3. *Incentives and Taxation;*
4. *Individual and Utility Decision Environment;*
5. *AZ Energy Demand Analysis;*
6. *Regulations and Standards;*
7. *Energy Usage/ Supply Forecasts;*
8. *Emissions/Pollution Analysis;*
9. *Solar Export Potential;*
10. *Environmental Valuation Analysis;*
11. *Solar Inter-State Competition;*
12. *Economic Development Analysis;*
13. *Energy Security Issues.*

About This Paper

The Energy Sector Technology paper is the second out of the series of thirteen white papers that make up the Solar Scorecard. The goal of this paper is to provide a guide to feasible energy technologies for the state of Arizona. It surveys technology options in the areas of energy demand (transportation, residential, commercial and industrial) and supply (generation, distribution and transmission) and, using broad criteria as a guide, analyzes each technology to determine its feasibility.

This paper focuses on power (electricity) generation technology options for the state and will develop over time and contribute to future papers in the Az SMART project. In subsequent revisions, the focus of the paper will shift to future research in the energy field, including transportation and energy usage.

Executive Summary

What people use energy for, its impact on the world, and the benefits of consuming it at a low cost are crucial topics to consider when investigating energy technology. For the state of Arizona, the evolution of electricity generation in Arizona from hydropower to nuclear to solar has given the state the tools to support a population, which grew from 500,000 in 1940 to nearly 6.6 million in 2009.[1]

In the future, Arizona will require feasible electricity generation technologies, which means they must be commercially available and able to satisfy a significant proportion of the state's electricity demand. This paper assesses all current and potential energy technologies against these two criteria. We define commercial availability using a technology readiness scale,[2] which identifies a technology's maturity and proximity to the market. The technology's ability to satisfy a significant amount of the state's electricity demand draws from the in-state potential capacity for each technology. In addition, we highlight potential difficulties associated with each energy technology (including fuel, land and water availability, intermittency and plant scalability).

Guide to Electricity Generation Technologies

- In 2009, *coal* fired power plants accounted for 44.6 percent of net electricity generation in the United States and 35.5 percent of net generation in Arizona.[3] The future of coal as a fuel for power generation revolves around implementing carbon capture and storage (CCS) technology to reduce greenhouse gas emissions and increasing plant thermal efficiency. CCS will decrease the amount of carbon emitted by coal plants by between 80 and 90 percent, but increase the cost of electricity generated. In addition, new coal plant designs incorporate improvements in thermal efficiency and overnight capital costs

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1 U.S. Census Bureau, Table 12. Resident Population – States: 1960 to 2009, available at http://www.census.gov/compendia/statab/cats/population.html.

2 The technology readiness level was developed by the Department of Energy to judge technology maturity using a 1-9 scale, with 1 being immature and 9 being in commercial use.

3 All percent shares of generation by fuel type for the U.S. and Arizona have been calculated using data published by the U.S. Department of Energy, Energy Information Administration ("EIA" from hereon).

using oxy-fueled pulverized coal combustion or integrated gasification and combined cycle (IGCC).

- In 2009, *natural gas*-fired power plants generated 23.3 percent of electricity in the U.S. and 31 percent in Arizona. The future of natural gas as an electricity generation source will be impacted primarily by the price and supply of natural gas. The ability of renewable resources to become cost effective and satisfy peak energy demand will be another determinant. Technologies like CCS, which may improve the emissions profile of coal, will also play a role in determining the future of natural gas, since some of the incremental natural gas power generating capacity tends to displace coal.

- In 2009, *nuclear* power accounted for 20.2 percent of energy generation in the United States and 27.4 percent in Arizona. Today, there are five generations of nuclear designs (I, II, III, III+, and IV). First generation reactors have been retired. Most of the reactors currently operating around the world belong to second and third generations. Each generation has represented attempts to improve the efficiency, safety, and cost of nuclear power plants. The key attributes emphasized in future nuclear energy designs (generations III+ and IV) are cost, safety, and minimization of radioactive waste, which is a contentious topic. Continuing opposition to proposals for burying radioactive waste in secure storage caverns means that such waste is presently stored on site.

- In 2009, *petroleum*-fired power plants generated less than one percent of the electricity in the United States. The reason for the relatively low petroleum use for electricity generation is the similarity in energy content of petroleum and natural gas,[4] which has historically been cheaper per British thermal unit (Btu). In addition to having a higher price, petroleum emits more carbon dioxide (CO_2) than natural gas during combustion.

- In 2009, power plants using *solar energy* generated less than 0.1 percent of electricity in both the United States and Arizona. There are two main types of solar energy technologies that can be used in electricity generation: *solar thermal* power (or

[4] About 53 megajoules per kilogram for natural gas vs. 42 to 46 megajoules per kilogram for distillate fuel oil.

concentrating solar power), which utilizes the heat from the sun to generate electricity, and *solar photovoltaic* (PV) power, which converts the light from the sun into electricity.

  - Among the four principal solar *thermal* power technologies, parabolic trough technology has been commercially available the longest. All solar thermal power technologies depend on availability of heat storage in order to compete with baseload technologies such as coal and nuclear in the future. Today, storing heat in molten salts, which provides between six and eight hours of storage, appears to be the most feasible option. The additional challenge of solar thermal power is the high requirement of water for cooling.
  - The future of solar PV technologies lies in the development of high efficiency, low cost solar cells as well as increasing the amount of energy storage available during nighttime. Currently, batteries offer the most effective storage technique, but "compressed air" and "central grid" are two large-scale, inexpensive methods of energy storage being explored, in addition to several other non-battery storage technologies.

- In 2009, *wind* power represented 1.8% percent of total electricity generated in the United States, but only 0.03% of that in Arizona. Despite its small contribution to the country's electricity portfolio, wind power has grown at a rapid pace since 2002 due to cost improvement, the rising popularity of renewable energy and support from the federal government. The future of wind power will rely on improvements in low wind speed technology, capital cost reductions and the ability to manage the variable nature of wind as an energy source.

- *Fuel cells* have yet to be used for large-scale electricity generation due to immature technology and high costs. The future of fuel cell technology depends on further cost cutting and the development of alternatives for obtaining hydrogen (the main energy source for fuel cells) from renewable sources as opposed to fossil fuels. (Today, nearly all hydrogen produced in the United States is obtained from natural gas).

- In 2009, *geothermal*, *biomass*, and *biogas* resources generated nearly 1.8 percent of electricity in the United States. Biomass and biogas are on the rise due to their ability to re-use potentially harmful waste products to generate electricity (and are thereby considered "carbon neutral"). In Arizona, the share of these resources in electricity generation remained under 0.2% in 2009.

- In 2009, *hydropower* accounted for 6.8 percent of electricity generated in the United States, and 5.7 percent in Arizona. Since the majority of large-scale hydropower sites have already been developed across the country, the future of hydropower is in small-scale generation and advanced hydro technology.

- Each of the following power generation technologies, *tidal, wave, osmotic, and vortex*, is either commercially unavailable (in the case of vortex power) or is unsuited for large-scale electricity generation in Arizona because of the state's landlocked geography (in the case of tidal, wave, and osmotic power technologies).

The evaluation of technologies is summarized in the following table:

Technology	*Feasibility Criteria*	*Additional Feasibility Issues*	
Coal	Commercially available. Able to satisfy 100 percent of the state's energy demand.	There is coal supply in Arizona as well as the U.S., but requires railroad access.	Requires 510 gallons of water per MWh.
Natural Gas	Commercially available. Able to satisfy 100 percent of the state's energy demand.	Natural gas is available, but requires pipeline access.	Has the highest energy content and least CO_2 emissions per unit of electricity generated from fossil fuels.
Petroleum	Commercially available. Able to satisfy 100 percent of the state's energy demand.	Petroleum is available, but requires pipeline access.	Has worse CO_2 emissions compared to natural gas. Transport demand for petroleum products (with no good substitutes) means the price of oil will remain high and volatile.

Technology	*Feasibility Criteria*	*Additional Feasibility Issues*		
Nuclear	Commercially available. Able to satisfy 100 percent of the state's energy demand.	Uranium is available.	Requires 785 gallons of water per MWh.	Most efficient when built large-scale. Spent fuel storage remains problematic.
Hydropower	Commercially available, but incremental resources not able to satisfy >1 percent of the state's energy demand.	Arizona and the surrounding region's hydroelectric resources have largely been exploited, thus large-scale additions to existing capacity is not possible.		
Solar Thermal	Commercially available. Able to satisfy >5 percent of the state's energy demand.	Arizona has the highest solar insolation in the country.	Requires energy storage for periods when there is no sunlight.	Most commercial CSP technologies require 800 to 1,000 gallons of water per MWh.
Solar Photovoltaic (PV)	Commercially available. Able to satisfy >5 percent of the state's energy demand.	Arizona has the highest solar insolation in the country.	Requires energy storage for periods when there is no sunlight.	
Wind	Commercially available. Able to satisfy >4 percent of the state's energy demand.	Limited wind potential in Northern Arizona.	Seasonal wind patterns in the state do not coincide with high summer demand. High-wind areas are located away from the state's main load centers.	
Geothermal, Biomass, Biogas, Fuel Cells	Commercially available, but not able to satisfy >1 percent of the state's energy demand.	Geothermal, biomass, and biogas technologies face challenges concerning availability of their respective primary energy sources in Arizona, whereas fuel cells are primarily hindered by high capital costs. Also difficult for all these technologies to be incorporated into the state's power supply mix at utility-scale.		
Solar Updraft Tower	Limited commercial availability due to uncertain costs and performance.	Arizona has the highest solar insolation in the country.	Has some inherent energy storage and requires no water for operation. A proposed solar updraft tower project in Arizona will set an important precedent about the future economic feasibility.	
Tidal, Wave	Commercially available, but geographically not possible in Arizona.			
Osmotic	Not commercially available; in demonstration phase.			

The Future of Power Generation Technologies in Arizona

In the next 25 years, Arizona is expected to face a significant increase in residential energy demand driven by population growth and increasing per capita residential power use. As a result, the state's utilities will need to make choices about their electricity generation portfolio. This paper suggests that the following technologies will be feasible for significant segments of that portfolio: coal, natural gas, nuclear, petroleum, solar thermal, solar PV, and wind. However, financial, environmental, and regulatory factors not addressed in this paper will also determine the ultimate feasibility of each electricity generation technology for Arizona.

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List of Acronyms

Abbreviation	*Definition*
Entities	
ARPA-E	Advanced Research Projects Agency-Energy
ACC	Arizona Corporation Commission
APS	Arizona Public Service Company
BLM	Bureau of Land Management
DOE	Department of Energy (United States)
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
IBM	International Business Machines
IEA	International Energy Agency
NASA	National Aeronautics and Space Administration
NSRD	National Solar Radiation Database
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
SRP	Salt River Project
USGS	U.S. Geological Survey
Other Terms	
a-Si	Amorphous Silicon
ABWR	Advanced Boiler Water Reactor
AC	Alternate Current
APWR	Advanced Pressurized Water Reactor
Btu	British thermal unit
BWR	Boiling Water Reactor
c-Si	Mono-crystalline Silicon
CC	Combined Cycle
CCS	Carbon Capture and Storage
CdTe	Cadmium Telluride
CHP	Combined Heat and Power
CIGS	Copper Indium Gallium Selenide
CO_2	Carbon Dioxide
CT	Combustion Turbine
DC	Direct Current
EPRI	Electric Power Research Institute
ERS	Electricity Retail Sales
GW	Gigawatt
GWh	Gigawatthour
IGCC	Integrated Gasification and Combined Cycle
Ksf	Thousand Square Feet

Abbreviation	*Definition*
kW	Kilowatt
kWh	Kilowatthour
Mcf	Thousand Cubic Feet
MW	Megawatt
MWh	Megawatthour
Nc-Si	Nano-crystalline Silicon
NO_x	Nitrogen Oxide
PC	Pulverized Coal
PV	Photovoltaic
PWR	Pressurized Water Reactor
RES	Renewable Energy Standard
RPS	Renewable Portfolio Standard
SO_2	Sulfur Dioxide
TRL	Technology Readiness Level
VIVACE	Vibration Aquatic Clean Energy Converter

1 Introduction

Advancement of technology in the energy field has become important due to the movement towards clean, renewable sources of power generation. This movement has spurred countries around the world to spend the equivalent of billions of dollars each year on new ways to generate electricity (National Renewable Energy Laboratory (NREL), 2009). One method that is gaining popularity is using the sun, whether through photovoltaic cells or solar thermal heat collectors, to generate electricity. However, solar is not the only promising energy technology available to generate electricity.

Solar is in competition with several different types of technologies, ranging from the established to the not yet commercialized. Wind and hydro have been used as power sources for centuries. Coal, natural gas, and petroleum have been in use for over a century. Nuclear has been in use for over half a century, while biomass, geothermal, and biogas have been used for electricity generation for several decades. Fuel cells have recently become commercialized for small-scale applications. Osmotic, tidal, wave, vortex and solar updraft tower are all technologies that have either been recently commercialized, or have not yet achieved that status.

The purpose of this paper is to survey established and emerging electricity generation technologies. With Arizona in mind, this paper seeks to identify those technologies that will be feasible for the state in the future. In addition to explaining how each technology generates electricity, the paper focuses on the current contribution of the technology to the state and country, as well as the direction of each technology in the near future.

Section 2 of this paper is an overview of the evolution of energy use throughout history. It provides the reader with an understanding of the importance of energy and the significance of the upsurge in renewable energy production. Section 3 presents the criteria that determine whether an energy technology is suitable for Arizona. Section 4 surveys the current and potential energy technologies in each energy area. The criteria from Section 3 are applied to determine which technologies satisfy the criteria. Section 5 is a summary of the future of each of the feasible technology areas and its potential for Arizona.

2 History of Energy and Power Technologies

What people use energy for, its impact on the world, and the benefits of consuming it at a low cost are crucial topics to consider when investigating energy technology. With that in mind, this section seeks to inform in four areas:

- The evolution of energy use through time;
- The rising importance of renewable energy sources;
- The evolution of electricity generation in Arizona;
- The important discoveries and milestones in the use of solar power.

2.1 Energy and Power in History

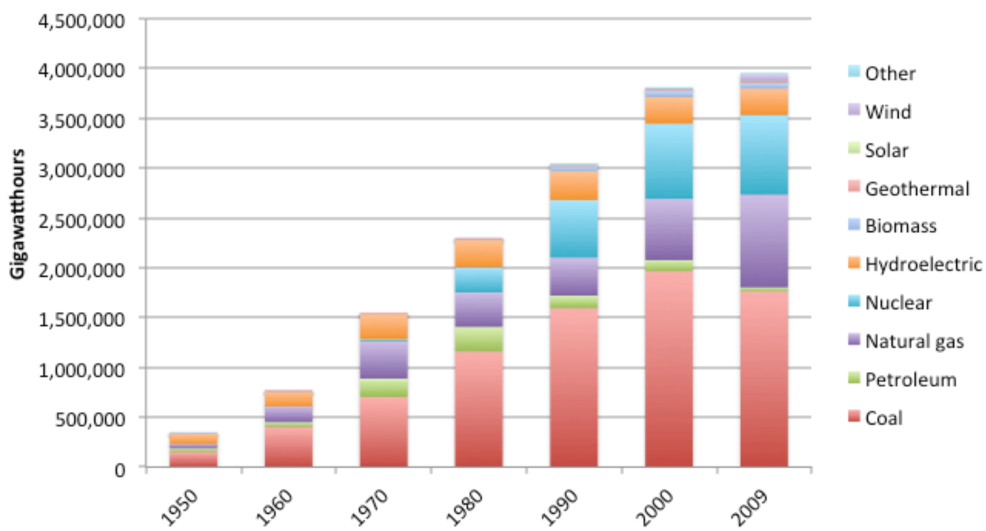
Early man's reliance on the sun for energy and warmth was a factor that limited the expansion of the species. The necessity of its warmth to humanity was evident in the concentration of early man in the warmest regions of the planet (Zhu, 2004). As man became increasingly sophisticated, tribes of Homo erectus, an early human species, were able to control fire for warming and cooking purposes. Occurring as far back as 1.5 million years ago or as recently as 230,000 years ago (James, 1989), early humans were able to compensate for a lack of sunlight by building fires from wood and other flammables. The ability to replace the sun as a source of energy allowed Homo erectus and later, more advanced human species, to spread into colder climates such as northern Europe, Asia, and North America. Over the next several hundred thousand years, man would use fire to treat stone for tools, make charcoal, wood working, light, heat, and many other essential operations (Brown, 2009). Biomass (wood and flammable waste products) remained the only significant source of energy for humanity until the domestication and use of animals for work around 5,000 to 6,000 B.C. (Conroy, 1986). Oxen were the first animals to be used to pull sleds and ploughs, but later horses, donkeys, and other animals were used, which increased the productivity of humanity.

Biomass remained the only fuel for industry until the invention of the water wheel. First mentioned by the Greek poet Antipater in the 5^{th} century BC, it was widely used in Europe, China and Persia over the following centuries (Vowles, 1932, Pacey, 1991, Munro, 2002). The water wheel was a useful energy generating tool but only available in areas with bodies of water. The first attempts by humanity to capture the power of the wind using windmills occurred much later. Windmills began to be used on a widespread scale between 500 and 900 A.D. in Persia and were primarily used to grind grain and pump water (Pacey, 1991).

Each of the innovations made in the field of energy allowed for less dependence on the sun. It was the use of coal, however, that would revolutionize the world. Though coal was used on a limited basis as early as 1000 BC, it would become essential from the early 18th century onward, when coke made from coal in blast furnaces began to be used (World Coal Institute, 2005). The invention of the steam engine and the availability of large amounts of coal spawned two centuries of coal-fired railroads, steamships, and machinery that connected the world and greatly expanded international trade (World Coal Institute, 2005).

Though oil was widely used in the middle of the 19th century as kerosene for heating, it was the invention of the automobile and its demand for gasoline that spurred oil to become the most used energy source in the United States by the 1950s (EIA, 2009). Natural gas also began to be used prominently as an energy source in the 19th century, as streetlights were fueled by gas (NaturalGas.Org, 2009). However, the discovery of electricity, which was safer than natural gas, caused most areas to switch to lights run on electricity (Museum of Electricity, 2009). Searching for other uses for natural gas, Robert Bunsen invented the Bunsen burner in 1885. The Bunsen burner mixes air with natural gas to provide heat for cooking and warmth (Jensen, 2005). Combined with its ability to be used in base load power plants, today, natural gas is widely used all over the world as fuel for power generation.

Figure 1. U.S. Electricity Generation by Primary Energy Source, GWh, 1950 Through 2009



Source: EIA, 2010.

As Figure 1 shows, until the 1970s, electricity in the United States was generated principally from power plants that used fossil fuels (coal, petroleum, natural gas) and from hydropower sources. Using technology developed as a result of the initial sustained nuclear reaction in 1942, engineers quickly discovered the potential for power production. The first commercial nuclear power plant in the United States began production in 1958. The development of coal, natural gas, and nuclear increased through the 20th century while share of hydropower declined,[5] such that, by the year 2010, the power generation mix of the United States was vastly different from 1950. As Table 1 shows, coal has maintained its share of the electricity generation market, while natural gas and nuclear have increased their share.

[5] This decline was due to a scarcity in preferred hydropower sites (EIA, 2009).

Table 1: Share of U.S. Electricity Generation by Primary Energy Source

Primary Energy Source	*1950*	*2009*
Coal	46.3%	44.6%
Natural Gas	13.3%	23.6%
Petroleum	10.1%	1.0%
Nuclear	--	20.2%
Hydroelectricity	30.2%	6.8%
Non-Hydro Renewables & Other	0.1%	3.8%

Source: EIA, 2010.

2.2 The Renewable Power Surge

Beginning in the late 1980s, there has been a significant global rise in the production of electricity from non-hydro renewable resources.[6] Human reliance on fossil fuels (coal, natural gas, oil) has brought many benefits and the world economy is dependent on them to function. However, these sources of energy are not infinite and release carbon dioxide into the atmosphere as a result of combustion. This has led the vast majority of scientists to conclude that the planet is experiencing an increase in average temperatures due to the greenhouse effect generated by higher concentrations of carbon dioxide in the atmosphere (NREL, 2009 and UNFCC, 2009). Partly in response to the growing evidence supporting global warming, as of June 2011, twenty-nine states and the District of Columbia have adopted renewable portfolio standards (RPS) (Database for State Incentives for Renewable Energy and Efficiency, 2011).[7]

As Table 2 illustrates, the growth in renewable energy use in power generation between 1980 and 1990 can be attributed to mainly biomass and geothermal energy sources. Since then, the expansion of the renewable electric generation sector has been dominated by investments in wind power facilities. The installed capacity of wind-powered generating plants in the United

6 The share of non-hydro renewables, including biomass, in total electricity generation worldwide was 0.6% in 1973, which rose to 2.8% in 2008, nearly a five-fold increase (International Energy Agency, 2010 Key World Energy Statistics).

7 Another eight states have renewable portfolio goals, but unlike RPS, these are not mandatory (DSIRE, 2011).

States, which was virtually non-existent until the 1980s, increased by nearly twenty times from 1990 to 2009.

Table 2: U.S. Net Summer Renewable Electric Generating Capacity by Energy Source (MW)

Year	*Biomass**	*Geothermal*	*Solar*	*Wind*
1950	13	-	-	-
1960	64	11	-	-
1970	71.5	78	-	-
1980	77.5	909	-	-
1990	8,061	2,666	314	1,799
2000	10,016	2,793	386	2,377
2009	11,353	2,351	603	33,542

(*) Biomass includes wood and waste. Of note, there was no generation capacity using waste biomass until 1985.
Source: EIA Annual EnergyReview (AER) 2009 Edition (issued August 2010). Table 8.11a, Electric Net Summer Capacity: Total (All Sectors), 1949-2000.

The EIA's definition of a renewable energy resource is an energy source that is naturally replenishing but flow-limited. It is virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Many pieces of legislature[8] go further in explaining in detail what constitutes a renewable energy resource, but there is no mention of a renewable resource having to be clean burning. This highlights a clear distinction between nuclear, which is clean but not renewable, and biomass, which is renewable but not clean. Biomass qualifies as a renewable resource while nuclear does not.[9] Other renewable energy resources include wind, solar, landfill gas, tidal and hydro.[10] Each of these resources may play a large role in states, such as Arizona, where renewable portfolio standards (RPS) have been adopted or are under consideration.

8 Texas (Fraser, 2009) and California (California Solar Center, 2009) are examples of states that have their own definitions of renewable resources.

9 U.S. Department of Energy (DOE) classification.

10 This is the EIA's official list of renewable energy resources. Municipal solid waste (MSW) is not included.

2.3 Electricity in Arizona

Throughout the state's history, the electricity generation needs of Arizona have been closely tied to its growing population. Prior to World War II, the state population was approximately 500,000 (Arizona Department of Commerce, 2009),[11] and its power generation needs were largely met by electricity from several large hydropower stations at Theodore Roosevelt Lake (38.9 MW) in 1927 and the Hoover Dam (2,080 MW) in 1937 (US Bureau of Reclamation, 2009). By 1960, the population had more than doubled to 1.3 million, due in large part to the development of air conditioning that made the hotter parts of the state much more comfortable. In addition to the growing population and its increasing power generation requirements, the movement of businesses to Arizona also increased the energy needs of the state. Between the years 1948 to 1960, the Phoenix area attracted more than 300 new manufacturing companies (Pollock, 2005). Several natural gas plants[12] were added to the Arizona energy infrastructure and, in 1964, the first hydropower unit at Glen Canyon Dam (1,312 MW) was constructed. The plant at Glen Canyon was the last significant hydro power addition in the state of Arizona, which began investing heavily in other forms of power generation in the 1970s and 80s due to a lack of sufficient hydro power resources.

With the continued boom in Arizona's population, which rose from 1.8 million in 1970 to 3.7 million in 1990, state utilities and independent power producers invested in a series of coal and natural gas power plants in the 1970s and 80s. As Figure 2 shows, over 4.5 GW of summer capacity[13] were added in coal plants in addition to approximately 1.86 GW of summer capacity in natural gas plants (Holmes, 2002). In addition, APS, the largest utility in the state of Arizona (EIA, 2009), began planning and construction of the largest nuclear power plant in the country. By the time the nuclear plant at Palo Verde was fully operational, the state had added 3.75 GW of nuclear power to its energy portfolio (whose capacity has since increased slightly due to a recent capacity uprate at the facility). The energy investment of the 1970s and 80s left the state with a large surplus of power generation, partly built to accommodate the power generation

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[11] 1940 was used as a base year.

[12] History of power generation infrastructure in Arizona gathered from several sources (Seidman, 2008, Holmes, 2002, Funding Universe, 2009).

[13] Summer capacity is the amount of power available for production in the summer months. This is important for Arizona, which experiences peak demand in the summer. Nameplate capacity is the highest possible power generation from the plant.

needs of California (Holmes, 2002). Table 3 lists Arizona's largest generation plants by installed capacity and their share in the state's total electricity supply capacity.

Table 3: Ten Largest Power Plants in Arizona by Generation Capacity, 2009

Plant	*Primary Energy Source*	*Net Summer Capacity (MW)*
1. Palo Verde	Nuclear	3,942
2. Navajo	Coal	2,250
3. Gila River Power Station	Gas	2,060
4. Springerville	Coal	1,614
5. Glen Canyon Dam	Hydroelectric	1,312
6. Santan	Gas	1,227
7. Mesquite Generating Station	Gas	1,073
8. Harquahala Generating Project	Gas	1,054
9. Hoover Dam	Hydroelectric	1,040
10. Cholla	Coal	1,021
Sub-total (MW)		**16,593**
Percent of total generating capacity in Arizona		**63%**

Source: EIA, 2010.

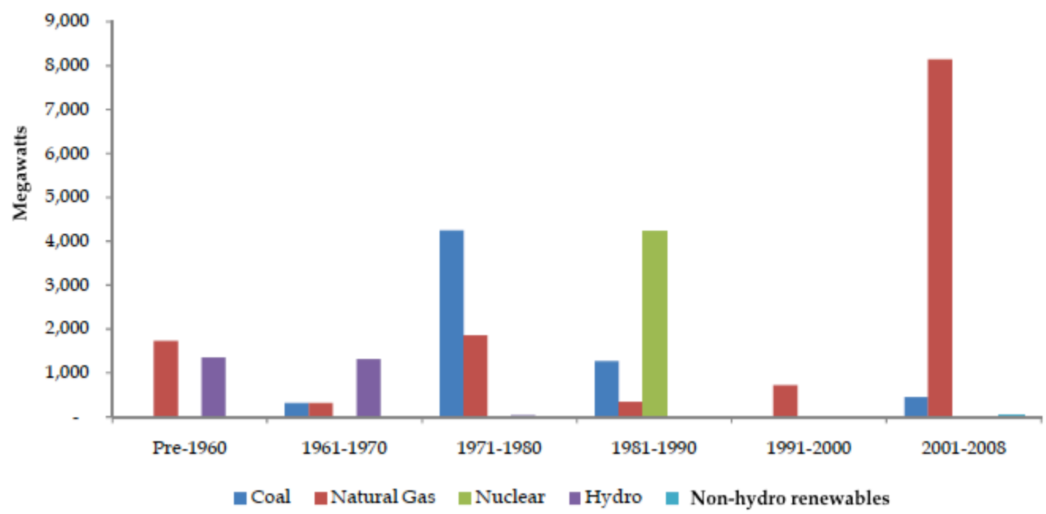
Due to the excess capacity built in the 1970s and 80s, the state added very little generating capacity in the 1990s. However, a growing population (estimated at 6.6 million in 2009), combined with an increase in individual energy consumption, necessitated a new investment in generation capacity. At the turn of the century, the low price of natural gas[14] encouraged state utilities to construct almost 10,000 MW of gas-fired power plants between 2000 and 2008. The construction of natural gas plants is critical for a state, which requires a significantly larger amount of its energy during peak hours.[15] The ability of natural gas combustion turbine plants to be turned on and off to meet demand will be important as the state plans its future generation mix. Figure 2 illustrates the clear distinction in electricity eras in the state. The hydro and natural gas era of the pre 1960s is noticeable, as is the expansion in coal-fired power plants in the 1970s and the construction of the Palo Verde Nuclear Plant in the 1980s. However,

14 The natural gas wellhead price was $2.60 per thousand cubic feet in 2000 (EIA, 2009).

15 Peak hours of energy demand in Arizona occur between 12-8 PM (SRP, 2009).

it is important for the reader to notice how the investment in natural gas stands out in the graph. It is a clear demonstration of the recognition by state utilities of the benefits of natural gas power generation for the state.

Figure 2. Electricity Eras in Arizona – Incremental Capacity Installed by Fuel Type (MW)



Source: EIA (2009) and Arizona Commerce Commission (2002).

In 2006, the Arizona Corporation Commission (ACC) passed the Renewable Energy Standard (RES), which mandates that by 2025, 15 percent of the state's electricity retail sales[16] must come from renewable energy sources (ACC, 2006). This is a drastic change for Arizona, which currently relies on coal (35.5 percent) and natural gas (31 percent) for two-thirds of the state's generated electricity, and the share of renewable energy sources in electric generation remains less than 1 percent. Assuming that by 2025 Arizona's internal electricity consumption reaches about 90,000 GWh (up from 73,433 GWh in 2009),[17] the RES means utilities will need to supply

[16] Supplies to the end-use sectors in Arizona. Either through self-generation, purchases from independent renewable electricity producers, or by acquiring renewable energy credits, RECs. These RECs could be acquired from renewable electricity producers located in our out of Arizona, but cannot be "paper" RECs – in other words, utilities must arrange for actual delivery of electricity underlying the REC. In essence, the rule treats RECs the same as physical purchases by the utilities.

[17] Arizona consumption estimate for 2025 is based on growth rates projected by the EIA for the Annual Energy Outlook (2011 edition) and the North American Electric Reliability Corporation (NERC)'s regional member Western Electric Coordinating Council (WECC) for the Arizona-New Mexico sub-region.

about 22,500 GWh of electricity from renewable sources.[18] State utility planners must account for this in their plans for the future, making solar power a central topic for Arizona.

2.4 A History of Solar Power: Arizona's Unique Advantage

It is only recently that human beings have been able to capture and use the sun's energy for a purpose other than warmth. The list of attempts and successes in utilizing the sun's energy is long and distinguished, but the greatest contributions to solar power research have been in the fields of solar photovoltaics and solar thermal research. Horace de Saussure's trapping of heat to cook food utilizing glass mirrors in 1767 encouraged innovation in new ways to utilize the sun's heat, while it was Edmond Becquerel's experiments that led to the uncovering of the photovoltaic effect (EERE, 2009). This discovery started a long process to capture and use the energy from the sun's rays. The timeline in Table 4 (on the following page) highlights the milestones in the development of solar power.

[18] Assuming renewable electricity generation technologies reach a 40 percent capacity factor by 2025 (today, installed facilities all types –solar, wind, biomass- of renewable electricity generation in the U.S. average about 30 percent capacity factor), this corresponds to a new build of 6,400 to 8,500 megawatts of renewable capacity in or around Arizona to meet the RES requirements.

Table 4: The Solar Energy Discovery Timeline

Year	*Solar Photovoltaic*	*Year*	*Solar Thermal*
1873	The photoconductivity of selenium is discovered	1860s	The first solar powered engines, predecessors of modern parabolic dish collectors, are built
1876	It is discovered that selenium, when exposed to light, produces electricity	1878	A reflector of flat silvered mirrors arranged in a semicircle is used to project radiation onto a stationary boiler
1883	The first solar cells made from selenium wafers are described	1883-1884	First solar engine using parabolic trough construction is invented
1918	Single-crystal silicon is first grown	1891	The first commercial water heater is patented
1932	The photoelectric effect in cadmium sulfide (CdS) is discovered	1909	Water heating system developed that separated the storage tank from the heating device
1954	The first silicon PV cell is made with 4 percent efficiency	1969	A solar furnace is built in France featuring an eight-story parabolic mirror
1955	The first commercial licenses for silicon PV technologies is sold	1973-1974	Oil embargo spurs investment in solar thermal devices
1960	14 percent PV cell efficiency	1981	California enacts 25 percent tax credit for renewable energy systems
1963	First solar PV module developed	1982	Solar One (10 MW) demonstrates the feasibility of power tower systems
1970s	Solar cell cost falls: $100/w to $20/w	1983-1989	Nine solar thermal facilities using parabolic trough technology are built in the California desert
1976	First amorphous silicon PV cells fabricated	1984	Solar dish system was first demonstrated to be commercially feasible
1977	PV production exceeds 500 kilowatts	1989	Federal regulations on solar power plant size are increased from 30 to 80 MW
1980	Thin film PV cell exceeds 10 percent efficiency	1990s	1.5 million buildings in Tokyo with solar water heaters
1982	PV production exceeds 9.3 megawatts	1990s	New homes in Israel require solar water heaters
1985	20 percent PV cell efficiency	1994	Stirling solar dish device tied to a utility grid
1994	30 percent PV cell efficiency	2007	First solar power tower built in Spain
1999	World installed PV capacity >1 GW	2007	64 MW parabolic trough facility built in Nevada
2007	42.8 percent PV cell efficiency	2008	First linear Fresnel plant built
2008	PV production exceeds 12.5 GW	2009	Over 10 million Japanese homes use solar water heaters PV solar cell efficiencies exceed 40% in research tests

Source: NREL, EERE, EIA, and Yole Developpement.

3 Power Generation Technology Criteria

The purpose of this section is to explain our selection of the criteria that an energy technology must satisfy in order to be considered technologically feasible for the state of Arizona. The goal is not to ascertain cost competitiveness, carbon content, or job creation, as these topics will be addressed in other Az SMART research streams. The only energy technologies that pass our criteria are those that are commercially available and can satisfy a significant amount of the state's electricity requirements. If an energy technology fails our criteria, the analysis for that source will cease, since it is not technologically feasible in the state. It is important to note that when we say a technology is not feasible for the state, we are not implying that it will not be built. Rather, the technology will not be able to significantly contribute to the electricity portfolio of the state's utilities.

In order to pass our criteria, a technology must be ready for commercial use and be able to satisfy a significant percentage of the state's electricity demand. Commercial use is determined using the Department of Energy's technology readiness scale, which assigns a number (1-9) to an energy technology based on its maturity and proximity to the market.[19] The ability of the technology to satisfy a significant amount of the state's electricity demand draws from reports that estimate the in-state potential capacity for each technology. In addition to our criteria section, there is a technology issues section, which highlights potential pitfalls for each energy technology that may prevent it from being feasible for the state.

Table 5: Energy Technology Feasibility Measures

Evaluation Criteria
Is the energy technology commercially ready for electricity generation?
Does the energy technology satisfy a significant amount of the state's electricity demand?
Additional Feasibility Measures
What are the potential concerns for the adoption of the technology to satisfy the state's electricity demand?

[19] A description of each TRL is available in Appendix 1.

3.1 Criteria

When the Department of Energy (DOE) began the Advanced Research Projects Agency-Energy (ARPA-E), it adopted the concept of technology readiness levels (TRL) that had been previously used by the Department of Defense and the National Aeronautics and Space Administration (NASA). These levels are used to distinguish immature technologies from those that are ready for use according to a 1-9 scale. When determining which electricity generation technologies would be feasible for Arizona, this criterion eliminates the technologies that are not commercially ready for use. In this paper, we consider levels eight and nine to be commercially ready for use. Technology readiness levels are described in Appendix 1.

Due to its growing electricity generation needs,[20] the state requires energy sources that can be adopted on a large scale. Determining what is meant by "large-scale" is important because it establishes a standard that energy technologies either pass or fail. Those that have insufficient in-state potential must be considered technologically infeasible. Measuring the electricity generation potential for each technology is done by calculating the amount of GWh the state is capable of producing. For example, any technology that requires an ocean has a potential of zero GWh due to Arizona's lack of a coastline.[21]

Once the amount of GWh the energy technology can produce in the state is calculated, it is expressed in two ways: number of homes powered and the percentage of the state's electricity demand met. Determining the number of homes powered by the technology requires the average electricity consumption of a U.S. household.[22] The percentage of the state's electricity demand met is calculated using the electricity retail sales (ERS) of Arizona in 2009.[23] Only energy technologies that are able to supply more than 1 percent of the state's electricity retail sales in 2009 are considered to meet the criteria.

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20 Electricity retail sales (ERS) In Arizona have grown by an average of 4 percent from 1980 to 2006. Data provided by APS, SRP and TEP.

21 It is important to note that energy source technology potential in the state only refers to energy that can be produced in the state and not imported from other states.

22 The average household in the United States used 10,896 kWh of electricity in 2009 (EIA, 2010).

23 Reported to be 73,433 GWh in 2009 (EIA, 2010).

3.2 Additional Feasibility Measures

The state of Arizona has unique traits that allow some technologies to thrive while others wither. For example, land requirements are important for some technologies and not for others. Concentrated solar thermal parabolic trough plants require large amounts of flat land while others, such as wind farms, can be built on hills (California Energy Commission, 2009). As a result, we identify the potential issues for each technology that could limit its adoption. This analysis is performed only for technologies that meet our criteria.

Fuel is the energy source for power plants. For coal-fired power plants, coal is used to run a combustion turbine and generate electricity. For wind turbines, wind is the energy source that spins the turbine and generates electricity. Additional infrastructure[24] can be required for certain technologies to receive a constant supply of fuel. For example, coal plants are unable to operate without a steady supply of coal, which is typically delivered via railway to minimize cost and often located near the mine.[25] If a new coal plant is built in an area where there is no rail access, this will entail an additional investment in rail infrastructure. Solar thermal power plants, on the other hand, require no outside fuel sources, which makes an investment in additional infrastructure unnecessary.

Water is a significant factor for a technology such as nuclear, which uses large amounts of water to run its steam turbines. However, it is not a factor for solar PV panels, which use no water in their electricity generation process. Water use for by a particular electricity generation technology is assessed by calculating the amount of water (in gallons) required to generate one megawatthour (MWh) of electricity. In addition, state counties are assessed for compatibility by determining their water surplus. Table 6 shows the water supply for the nine Arizona counties in which water is a critical issue.[26] While many of these counties do not expect water supplies to decrease drastically, it is important to note the substantial decrease projected in the three

24 Note that additional infrastructure, in this paper, does not refer to transmission lines.

25 Four of the six largest power plants in Arizona are located in the north and east parts of the state. This is close to the northeastern Arizona coal supply, as well as Colorado and New Mexico, which have large coal mining operations (EIA, 2009).

26 In Apache, Graham, Greenlee, La Paz, Navajo, and Yuma counties, the water surplus (deficit) was not calculated in the 2008 Seidman report due to no water problems being foreseen in these counties from 2008-2032.

county area[27] water supply, primarily since the majority of the state's population growth is expected to concentrate there (Seidman, 2008). Therefore, the availability and competing uses of water is a critical consideration for the future development of power plants in this area.

Table 6: Current and Projected Water Surplus (Deficit) for Selected Arizona Counties

County	*2010*	*2030*
Cochise	(12,344)	(15,246)
Coconino	(16,035)	(20,848)
Gila	(4,590)	(6,391)
Mohave	15,174	5,039
Santa Cruz	4,280	4,998
Yavapai	(935)	(16,345)
Three County Area	423,489	65,691

Source: Seidman, 2008.

Intermittency is a critical technology measure because technologies that depend on intermittent, or variable rate, energy resources cannot generate electricity consistently. While technologies such as coal-fired power plants, are able to generate electricity any time of the day, wind turbines can only generate electricity when the wind is blowing. This creates substantial planning issues for utilities. In addition to determining intermittency through the use of capacity factors, energy technologies are identified as peaking or non-peaking. Peaking technologies have an advantage over non-peaking technologies because they can be used when energy demand is highest, giving utilities flexibility in their electricity generation portfolio. It is important to note that the availability of large scale, inexpensive storage makes intermittency less of a concern.

The final energy technology measure is plant scalability and location. The ability to construct power plants that fit energy demand needs prevents over-investment and gives utilities greater planning flexibility. In addition to the cheap price of natural gas, the scalability of gas-fired power plants was a significant reason in their large-scale expansion over the past decade. Plant

[27] Maricopa, Pima and Pinal counties.

location is as important as plant scalability because it decreases the strain on utility transmission resources. Technologies that require new transmission resources incur an additional transmission expense, while technologies that can be located close to existing lines or load centers do not.

4 Guide to Power Generation Technologies

In the following sections, we analyze the power generation technologies that are available around the world and their feasibility for the state of Arizona. This analysis gives the reader an understanding of how the technology generates electricity, its importance in the United States (particularly Arizona), the future of the technology, and whether it passes our feasibility criteria.

4.1 Coal

In 2009, coal fired power plants accounted for 44.6 percent of net electricity generation[28] in the United States and 35.5 percent of net generation in Arizona (EIA, 2010).[29] Coal is used on such a large-scale due to a simple burning process and an inexpensive, domestic fuel source. As the lowest-cost fossil fuel source for baseload electricity generation,[30] coal is an important resource for Arizona due to its growing electricity requirements.[31] The United States possesses, by a significant margin, the largest coal reserves in the world (see Figure 3).

After coal is delivered to a power plant, it is crushed, processed, and pulverized to a fine powder. Once the substance is mixed with air, it is blown into the boiler for combustion. At this point, water is pumped through tubes and turned into steam by the intense heat generated by the coal combustion. This steam causes the turbine inside the power plant to spin rapidly, turning a shaft and creating an electric current.[32]

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28 Net electricity generation is equal to gross electricity generation minus the self-consumption of power plants.

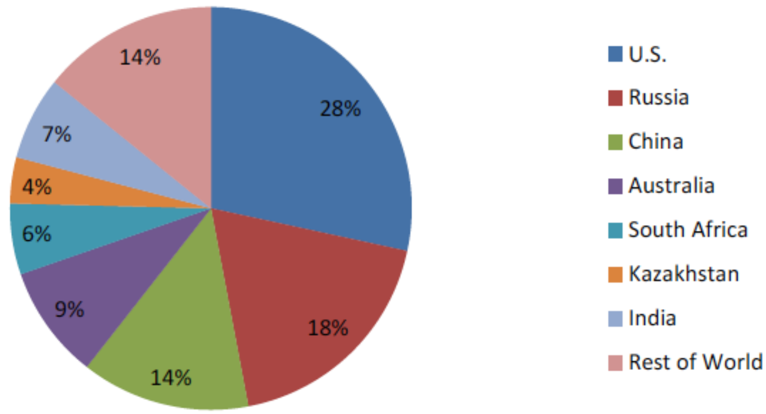
29 Note that there is a difference between actual electricity generation (given in watt-hours) and electricity generation capacity (given in watts, kilowatts (one thousand watts) and megawatts (one million watts)). A technology with a high utilization rate (called "capacity factor"), such as nuclear, would generate more energy per watt of capacity, or more watt-hours. Therefore, such plants contribute a larger share of total electricity generation compared with solar or wind, which have lower capacity factors.

30 A coal price of $2 per MMBtu compares favorably with $4-12 per MMBtu for natural gas and oil (MIT 2007 and EIA).

31 From 1980-2006, electricity consumption in Arizona has grown by an average of 4% annually (EIA, 2010). The average rate of growth has been slowing down: from 1980 to 1990, the annual average rate of growth was 4.4%; from 1991 to 2000, it was 3.8% and from 2001 to 2007, it averaged 3.6%. (The economic recession has caused energy consumption to contract as well, so the growth rates for 2008-2009 have been excluded).

32 Information on the operation of a coal plant taken from the Canadian Clean Power Coalition and the NETL.

Figure 3. Recoverable Coal Reserves of the World, 2008



Source: EIA, 2009.

Despite the abundant supply and favorable price of coal, the use of this fuel for power generation also means higher greenhouse gas emissions (which include sulfur dioxide, SO_2, and nitrous oxides, NO_x, as well as carbon dioxide). In fact, since coal is the most carbon-dense of fossil fuels, it is the worst emitter of carbon dioxide post combustion. A 500 MW coal-fired power plant produces approximately 3 million tons of CO_2 each year (MIT, 2007). In 2009, the United States as a whole produced over 1.7 billion tons per year of CO_2 from coal-fired power plants (EIA, 2010).

Table 7: U.S. CO_2 emissions from Fossil Fuels Used in Electric Power Sector (Metric Tons/MWh)

Fuel	*1990*	*2000*	*2009*
Petroleum	0.86	0.87	0.88
Coal	0.98	0.99	0.98
Natural Gas	0.57	0.55	0.41

Source: EIA, 2010, and Authors' Calculations.

As Table 7 shows, coal emissions per MWh of electricity generated exceeds all other fossil fuels used in electricity generation.[33] Not only coal emits more CO_2 than natural gas, but also supercritical pulverized coal combustion plants[34] are less efficient than natural gas combined cycle plants (MIT, 2007), which adds to emissions per megawatthour of electricity produced.[35]

Throughout the last 40 years, there have been several successful technological innovations to limit the emission of these gases. The first major change was the adoption of flue gas desulfurization units, or scrubbers, to reduce sulfur dioxide emissions, which, in addition to nitrous oxides, combines with water vapor to form acid rain (NETL, 2009). More advanced scrubbers have managed to decrease other pollutants, including particulates, acid gases, mercury, and other heavy metals. Nitrous oxides are an even greater threat, as they form harmful levels of ozone, in addition to being responsible for acid rain. Low NO_x burners have been responsible for reducing nitrogen oxide emissions by up to 60 percent (NETL, 2009).

Following these accomplishments to control SO_2 and NO_x emissions, the management of carbon dioxide emissions is through carbon capture and storage (CCS) technologies and increasing the thermal efficiency of coal-fired power plants (so that less fuel is necessary to generate each megwatthour of electricity) are crucial for the future of coal technology. There exists an overlap in these two efforts, as increased plant efficiency reduces emissions. As a result, new coal power plant technologies are designed for increased efficiency and CCS.

The 2007 Coal study by the Massachusetts Institute of Technology (MIT, 2007) identified carbon capture and storage technology as one of the five options for reducing greenhouse gas emissions from fossil fuels, and the only option that allowed for continued use of coal as a power generating resource.[36]

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33 Natural gas has a higher (about 4-to-1) hydrogen to carbon ratio than petroleum (about 2-to-1) or coal (1-to-1). The lower this ratio, the higher is the carbon content of a fuel, which results in higher carbon dioxide emissions after combustion. Since coal has the lowest hydrogen to carbon ratio, it has the highest unit carbon dioxide emissions of the three main fossil fuels.

34 This is the standard coal plant that would be built in the United States (MIT, 2007).

35 Higher heat rates require more fuel to generate electricity.

36 The other four are: improvement in the efficiency of energy use; increased use of renewable energy sources; expanding electricity production from nuclear energy; and switching to less carbon-intensive fuels.

4.1.1 Carbon Capture and Storage

Capturing CO_2 is a process that uses chemical absorption with amines to separate the CO_2 from the flue gas emitted during combustion. This process requires additional energy in the form of steam, which lowers the generation output of the plant. Therefore, a CCS plant that generates the same amount of electricity as a plant without CCS not only burns at a lower efficiency, but also requires more capacity, which increases the cost of the plant. A subcritical PC plant with CCS would require a 37 percent increase in generation capacity and experience a decline in efficiency from 34.3 to 25.1 percent. However, the CO_2 emitted will decrease from 466,000 kg/h to 63,600 kg/h, which represents an 86 percent decline in CO_2 emissions from the plant.

Once the carbon has been captured, it must be stored. Of the many attempts at carbon sequestration,[37] geological sequestration has the most promise in the near future.[38] There are many different geological sites for carbon sequestration, including saline formations, depleted oil and gas fields, deep coal seems, oil shades and flood basalts. These sites create physical barriers that prevent CO_2 from reaching the surface. Once the CO_2 is injected into these sites, it is expected to dissolve into other pore fluids, such as oil and gas, or brines where it would be fixed indefinitely.

4.1.2 Coal Power Plant Generation Efficiency

Power plant generation efficiency is the fraction of thermal energy in the fuel that is used in the net electricity that is generated.[39] There are many factors that affect generating efficiency, including coal type, steam temperature and pressure, and condenser cooling water temperature. The generating efficiency for typical modern coal plants range between 33 to 43 percent.

There are four air-blown coal generation technologies that are in use in the United States. These are subcritical pulverized coal (PC) that represents majority of existing coal-fired power plant

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[37] Sequestration is the long-term isolation of CO_2 from the atmosphere through physical, chemical, biological, or engineered process (MIT 2007).

[38] In this case, near future means until 2050 (MIT 2007).

[39] This practice uses the higher heating value of the fuel when calculating generation efficiency.

stock (34.3 percent efficiency), supercritical PC (38.5 percent), and ultra-supercritical PC (43.3 percent) and subcritical circulating fluid-bed (CFB) combustion designed for lignite coal (34.8 percent). Each of these plants can be equipped with carbon dioxide (CO_2) capture and storage (CCS) equipment. However, addition of a carbon capture process reduces the generating efficiencies across the board for these technologies: to 25.10 percent for subcritical PC; 29.30 percent of supercritical PC; 34.1 percent for ultra-supercritical PC and 25.5 percent for subcritical CFB. There are certain challenges associated with capturing carbon dioxide emissions from PC plants (for instance high amount of nitrogen in the flue gas due to combustion with air). One solution to this problem is to substitute oxygen for air, which eliminates the nitrogen, called the *Oxy-Fueled Pulverized Coal Combustion* technology. The second is to gasify the coal and capture the CO_2 prior to combustion, called the *Integrated Gasification and Combined Cycle (IGCC)* technology. These have been identified as the next generation of coal plants (MIT, 2007).

Plants equipped with Oxy-Fueled Pulverized Coal Combustion technology would burn coal with 95 percent oxygen (rather than air). The use of highly oxygen saturated air mix not only reduces greenhouse gas emissions from combustion but also allows for easier capture of CO_2 emissions during the process (by direct compression of the flue gas). Compared to the baseline technology of subcritical PC with carbon capture, it brings about an improvement in efficiency,[40] while decreasing the amount of carbon dioxide emitted[41]

In contrast, IGCC technologies work by gasifying the coal into a mixture of hydrogen and carbon monoxide called *syngas*. Syngas is then used as the primary fuel for a combined-cycle gas turbine to generate electricity.[42] In other words, IGCC uses a two-stage combustion process; the first, involves the partial combustion of coal with oxygen, and the second involves generation of (heat and) electricity in the gas turbine. If the plant is equipped with CCS

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40 Generating efficiency estimated at 30.6 percent, compared to the efficiency of 25.1 percent of subcritical PC plant and 29.3 percent for a supercritical PC plant, both with carbon capture. (MIT, 2007).

41 Net CO_2 emitted (total CO_2 emitted minus amount of CO_2 captured) 52,202 kg/h (kilograms per hour) for oxy-fueled PC versus 63,600 kg/h subcritical PC and 54,500kg/h for supercritical PC, both with carbon capture (MIT, 2007).

42 Note that syngas is not the same as natural gas: it has a heating that is three to eight times lower than natural gas.

technology, CO_2 would be removed from the syngas prior to combustion. The result of this process is increased efficiency,[43] less carbon dioxide emitted.[44]

In addition to the promise of lower carbon dioxide emissions, these two technologies also seemed to offer some capital cost savings with respect to supercritical PC plants (deemed the step-up from the current fleet of subcritical PC plants). However, today's estimates indicate that capital costs of advanced coal plants, whether a supercritical PC plant, an IGCC plant or an oxy-fueled combustion coal plant have been converging.[45]

4.1.3 Coal Feasibility Assessment

In the following section, we evaluate the feasibility of coal-fired power generation for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of coal, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

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43 Thermal efficiency estimated at 31.2 percent, compared to the efficiency of 25.1 percent of subcritical PC plant and 29.3 percent for a supercritical PC plant, both with carbon capture. (MIT, 2007).

44 Net CO_2 emitted 51,198 kg/h for IGCC with carbon capture versus 63,600 kg/h subcritical PC and 54,500kg/h for supercritical PC, both with carbon capture (MIT, 2007).

45 Overnight capital costs consist of the construction capital costs of a power plant without considering financing. At the time of the MIT report, capital costs for an oxy-fuel PC was estimated at $1,900 per kilowatt (kW, 1/1000th of a megawatt), compared with $2,230 per kW for a subcritical PC plant with carbon capture and $2,140 per kW for a supercritical PC plant, also with carbon capture (2007 dollars) (MIT, 2007). These estimates by MIT were consistent with the EIA's outlook at the time.

Since then, the EIA has revised some of these capital costs significantly upward --by as much as 40%-- due to a number of factors such as higher global commodity prices and the increased engineering complexity of constructing advanced coal plants. For instance, the most recent estimates by the EIA indicate that capital costs for a supercritical PC plant range from $2,844 to $3,167 per kW without carbon capture, and for IGCC, the comparable figure exceeds $3,200 per kW (2010 dollars). The EIA adds about $2,000 per kW for the inclusion of CCS in the plant design. For instance, according to the EIA, a supercritical PC plant with CCS would cost $4,579 to $5,099 per kW, whereas an IGCC plant with CCS would cost about $5,348 per kW (2010 dollars). While updated figures are not available for oxy-fueled combustion plants, we know from the 2007 MIT study that their capital costs were estimated to be approximately on par with that of IGCC plants with CCS, which means the current overnight capital cost for such plants is also above $5,000 per kW (2010 dollars). (EIA, Updated Capital Cost Estimates for Electricity Generation Plants, November 2010). (*All subsequent capital cost estimates in this document have been obtained from the same source, unless otherwise noted.*)

On the other hand, similarly recent estimates of capital costs by another division of the Department of Energy, the National Energy Technologies Laboratory (NETL) are lower (notwithstanding the fact that NETL estimates are in 2007 dollar terms). For instance, the NETL estimates capital costs with CCS to be $3,568 per kW for IGCC, and $3,570 per kW for PC technologies (2007 dollars). Capital costs without any CCS are estimated to be $2,505 per kW for IGCC and $2,010 per kW for PC technologies (2007 dollars) (NETL, November 2010).

Coal Criteria

Coal-fired plants have been in operation for more than 100 years in the United States, and more than 40 years in Arizona. Pulverized coal-fired power plants with scrubbers and low NO_x burners, as well as supercritical power plants, are currently in operation (TRL-9) (Susta, 2004), but there are other coal experiments that have not reached this level. Integrated Gasification and Combined Cycle (IGCC) coal-fired power plants have yet to be commercialized in the United States (TRL-7) (NETL, 2009). The FutureGen 2.0 is a commercial-scale demonstration project that combines the oxy-fuel combustion technology coal plant with carbon capture and storage (CCS). FutureGen 2.0 is being developed by an industry alliance, with the cooperation of the Department of Energy. The project is expected to become operational by 2016 (2018 latest).[46] (TRL-7) (DOE, FutureGen Alliance, and National Energy Technology Laboratory, 2011). Direct carbon fuel cells are another potential technology, but that has yet to move past the developing stage (TRL-5) (Georgi, 2009).

In addition to being a mature and commercially reliable technology, coal-fired power plants can satisfy 100 percent of the state's demand for electricity.[47] The reason for this is that the plant is dependent on coal for fuel, which is available in large amounts both in Arizona and its surrounding states (EIA, 2009).

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46 Originally, the FutureGen project was aimed at demonstrating the IGCC technology with CCS. In 2010, the configuration (for the power plant) was switched to an oxy-fuel combustion technology primarily due to the possibility of retrofitting an existing PC power plant (Unit 4 of Ameren's Meredosia plant, 202 MW, in Illinois) at a lower total cost than constructing an IGCC plant from scratch. The DOE was also more interested in studying the feasibility of oxy-fuel combustion technology rather than IGCC, and allocated $1 billion in funding in 2010 for this revised configuration, dubbed FutureGen 2.0. Currently, three Illinois sites are being reviewed for geologic storage of carbon dioxide. (DOE, http://www.fossil.energy.gov/news/techlines/2010/10033-Secretary_Chu_Announces_FutureGen_.html, National Energy Technology Laboratory, http://www.netl.doe.gov/publications/factsheets/project/FE0001882-FE0005054.pdf, and FutureGen Alliance, http://www.futuregenalliance.org/).

47 In 2009, electricity retail sales (ERS) in Arizona were 73,433 GWh (which has slightly declined since 2007 due to the economic recession). Prior to the recession, Arizona utilities had forecasted electricity demand (electricity retail sales, or ERS) to exceed 142,000 GWh by 2032 (according to data provided by APS, SRP and TEP). Under current market conditions, this forecast seems overly optimistic. The EIA's latest (2010) projections imply an annual average growth rate of demand for the Arizona-New Mexico sub-region of about 1.3%, which translates into an ERS under 100,000 GWh by 2032 (See Section 5).

Additional Coal Feasibility Issues

Coal-fired power plants rely on a regular provision of coal in order to keep generating electricity and, unlike oil and natural gas; the United States has plenty of coal.[48] Arizona contains fairly large coal reserves in the Black Mesa Basin, and can rely on the significant surrounding reserves in New Mexico (EIA, 2009). Since 2000, the state has consumed an average of about 21,145 thousand short tons of coal every year,[49] which, when compared to the estimated reserves of Arizona and New Mexico,[50] demonstrates that there is a sufficient amount of coal available to meet the state's demand. The location of these coal deposits would suggest that a coal-fired power plant be built in the northeastern portion of the state. It is no surprise, therefore, that four of the six coal plants in the state are located there.[51]

The infrastructure required to provision coal-fired power plants with coal is also an important consideration. Figure 4 is a map of the Arizona railroads, and each coal-fired power plant is situated near one of the railroads on the map. The reason for this is that the preferred method of coal transportation is by rail (Seidman, 2008). Any additional coal plants require building the power plant near one of the existing railroad lines or constructing new rail lines.

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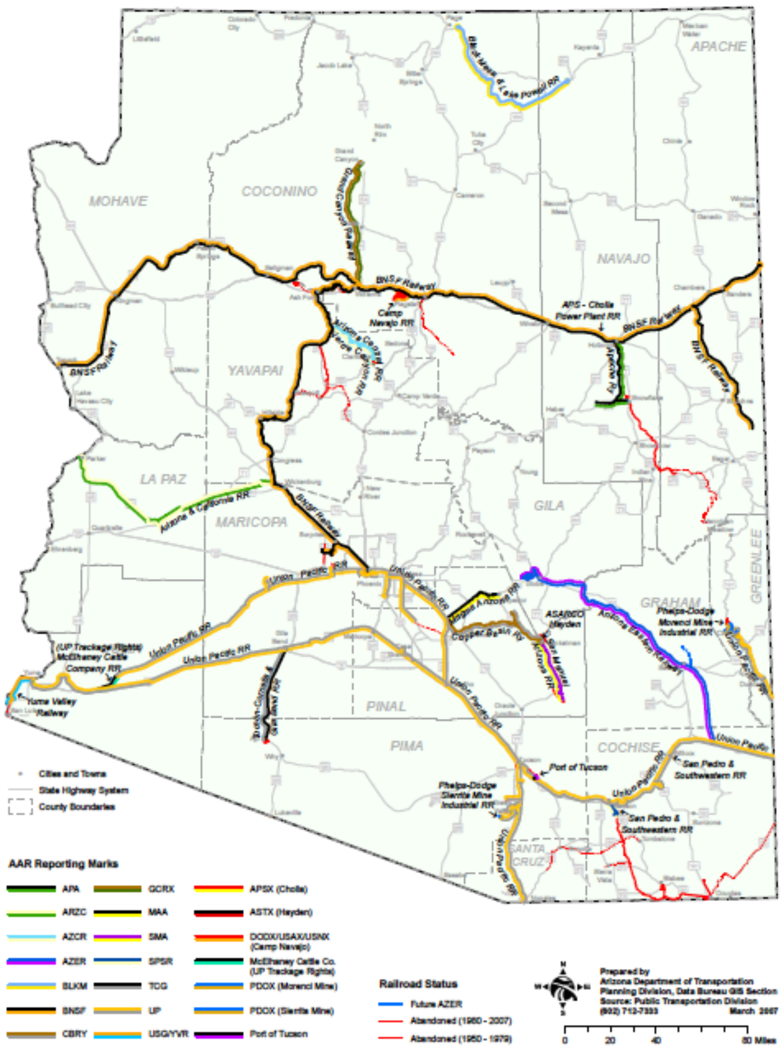
48 The United States has over 275 billion tons of recoverable coal, which is approximately 28 percent of the world total (MIT, 2007). The United States consumed 1.13 billion tons of coal in 2007 (EIA, 2009).

49 Nearly all coal consumption in Arizona is used for electricity generation.

50 Information on Arizona coal reserves is withheld by the EIA but the reserves are described as large. New Mexico has a demonstrated reserve base of 12,020 million shorts tons of coal (EIA, 2009).

51 Navajo, Cholla, Coronado, and Springerville coal-fired power plants are all located in Apache, Coconino, and Navajo counties. These are also the four largest coal plants in the state (EIA, 2009).

Figure 4. Map of Arizona Railroads



Source: Arizona Department of Transportation, 2007.

Water use is not as important an issue for coal as it is for nuclear. However, coal plants do use, on average, 510 gallons/MWh (Pasqualetti, 2008), which is the third highest of all the generating technologies considered in this paper.[52] The amount of acre-feet required for an average Arizona coal plant[53] is 10,968.[54] Unless there is an improvement in the availability of

52 Solar thermal (800 to 1,000 gallons per MWh) and nuclear (780 gallons per MWh) power technologies have the highest water use requirements for generation (Pasqualetti, 2009).

53 Assumed 1,000 MW capacity produces 7,008,000 MWh/year (capacity factor of 80 percent).

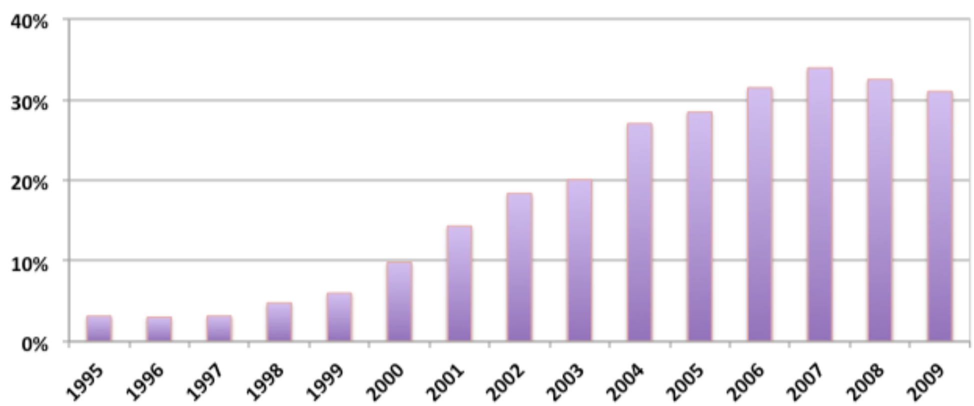
54 325,851 gallons = 1 acre foot (Western-Water, 2009).

Arizona's water resources,[55] coal-fired power plants are only feasible in Arizona counties that have a surplus water supply greater than 10,968 acre-feet.

4.2 Natural Gas

In 2009, natural gas-fired power plants generated 23.3 percent of electricity in the U.S. and 31 percent in Arizona (EIA, 2011). Relatively low natural gas prices (compared to oil), favorable greenhouse gas emissions of natural gas as fuel (compared to coal), combined with the low capital costs[56] and the flexible nature of gas-fired power plants,[57] and the ability to locate these plants near load centers have spurred investment in natural gas-fired power plants both in Arizona and across the United States. Figure 5 shows the substantial increase in the share of electricity generation in Arizona from natural gas beginning in 2000.

Figure 5. Share of Natural Gas Fueled Power Plants in Total Electricity Generation in Arizona (%), 1995-2009



Source: EIA (2010).

55 Currently, agriculture uses the most water in the state (>75 percent). If plants were built on current agricultural lands or there was a decline in agricultural water use, coal plants would become feasible in more locations (Pasqualetti, 2009).

56 The overnight capital cost for an advanced combined cycle gas plant is estimated at about $1,000 per kW compared to an advanced (supercritical) pulverized coal plant ranging from $2,844 to $3,167 per kW (2010 dollars) (EIA, 2010).

57 Depending on the turbine technology, natural gas-fired power plants can operate as baseload, mid-merit, or peaking facilities according to short-run demand conditions.

Natural gas is used to generate electricity in two types of power plants. The combustion turbine (CT) power plant heats the gas to run a combustion turbine and generate electricity (Tennessee Valley Authority, 2009). The capital costs of this type of plant are low,[58] so the CT technology is ideal for flexible operation (i.e., turning on and off) to satisfy peak demand. The second type of power plant is the combined cycle (CC) plant. Advanced CC plants also heat natural gas to run a combustion turbine and generate electricity. Unlike a CT plant, a CC plant utilizes the steam waste of combustion as by-product, which is captured to run a steam turbine and generate more electricity (Northwest Power Planning Council, 2002). In this fashion, the efficiency of a CC power plant is greater than a CT plant, but so is the capital cost.[59]

4.2.1 The Future of Natural Gas

The future of natural gas as an energy generation source will be impacted by CCS technologies, the price of natural gas, and the ability of renewable resources to become cost effective and satisfy peak energy demand. Similar to coal, natural gas emits carbon dioxide into the air (NREL, 2009) and, therefore, benefits from any attempts at CCS.[60] The technology is applicable for natural gas and, given the expected impact on coal, CCS will have a similar effect on cost,[61] efficiency,[62] and generation (output).[63]

Table 8: U.S. Natural Gas Supply (million cubic feet), 2001-2009

Year	*Domestic Production**	*Net Imports ***
2001	19,616,311	3,603,661
2002	18,927,788	3,499,230
2003	19,098,544	3,263,827

58 $665 per kW of overnight capital cost (EIA, 2010).

59 A new record efficiency for a combined cycle power plant was reached at Ambarli, Turkey of 52.5 percent. A combustion turbine power plant has yet to break 40 percent efficiency (Mechanical Engineering, 2004). The overnight capital costs for a natural gas CC plant is close to $1,000 per kW; nearly 50 percent higher than that of a natural gas CT power plant (EIA, 2010).

60 Natural gas-fired power plants in the United States emit nearly 50 percent less carbon dioxide than coal-fired power plants (see Table 7).

61 CCS increases the cost of a power plant because of the additional equipment required for the capture of CO_2 on site, the transport of captured CO_2 to storage, and for the long-term maintenance of the storage facility.

62 The carbon capture process requires steam energy to operate, reducing the efficiency of the plant.

63 Due to the energy requirements of the carbon capture process, the plant loses some generation output.

Year	*Domestic Production**	*Net Imports ***
2004	18,590,891	3,404,420
2005	18,050,598	3,612,433
2006	18,503,605	3,462,323
2007	19,266,026	3,785,128
2008	20,158,602	3,020,838
2009	20,580,076	2,679,003

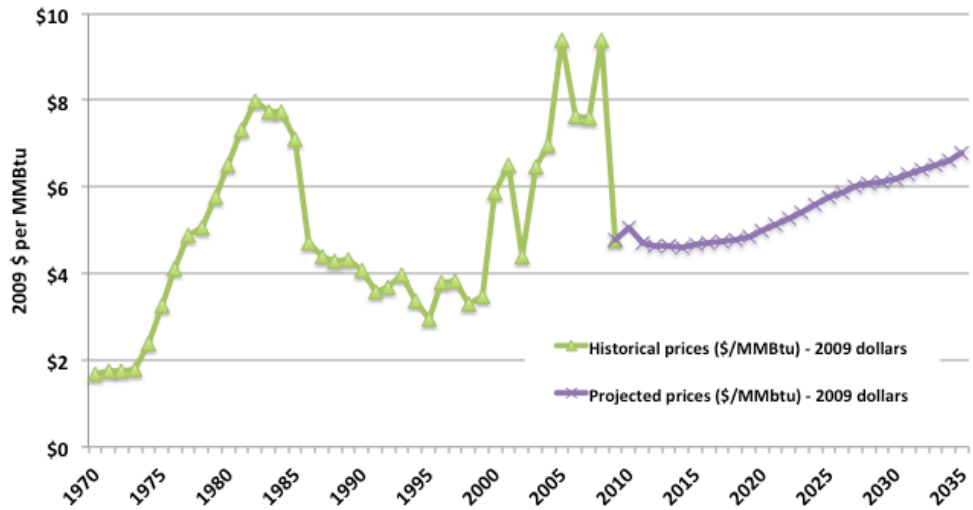
(*) Total dry natural gas production.
(**) Net imports = Total imports, including pipeline and liquefied natural gas imports, minus total exports.
Source: EIA, 2011.

As Table 8 demonstrates, nearly 90 percent of total natural gas supply in the United States is supplied by domestic production, and the balance comes from net imports into the country. Total natural gas imports peaked at 16 percent of total consumption in 2007, and have declined since then to about 12 percent in 2009. Almost all (99 percent) of natural gas imports to the United States come from Canada (EIA, 2010).[64]

Figure 6 illustrates the EIA's projections for delivered natural gas prices to the electric power sector through 2035, which indicates a growth rate of about 1.2% in annual average levels. There is some concern regarding short-term price fluctuations in spot natural gas prices: for instance, the spot price of natural gas skyrocketed from $2.60 per thousand cubic feet in 2000 to a high of $12.50 in June of 2008 and back down to $4.61 in June of 2009 (EIA, 2009). However, this will affect the electric power sector only to the extent they are exposed to short-term prices. Many electric utilities and independent power producers enter into long-term fuel supply agreements that tend to smooth out short-run price fluctuations. Nevertheless, it is expected that natural gas prices will rise in the future as it continues to be the fuel of choice for conventional power generation as well as the fuel source for emerging technologies like fuel cells, for distributed or back-up power sources, and for transport, among the many competing uses for natural gas.

64 Note that total consumption of natural gas does not always exactly equal total supply (production plus net imports) due injections into and removals from natural gas storage facilities.

Figure 6. Annual Average Delivered Natural Gas Prices to the U.S. Electric Power Sector, Historical 1970-2010 and Forecast through 2035, $/MMBtu, 2009 dollars



Source: EIA. Historical prices from the agency's State Energy Data System (SEDS), and projections from the Annual Energy Outlook 2011.

The expansion of renewable electricity generation will impact the growth in natural gas as an energy source for power generation in the United States. For baseload use, natural gas will compete with sources such as geothermal and biomass, which have minimal environmental impacts[65] and are relatively more cost competitive with natural gas (compared with other renewable energy resources).[66] For peaking use, natural gas will compete with concentrated solar thermal, which can provide electricity during the hours of peak demand using storage[67] and is becoming increasingly cost competitive as natural gas prices rise, and given low capacity factors for combustion turbine natural gas plants. In addition, the implementation of the Arizona RES, which requires state utilities to increase their supplies to end-users in the state from renewable energy sources, means there will be some level of substitution away from natural gas power plants as the dominant electric generation technology for new build in favor of electricity from renewable energy sources.

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65 EIA environmental forecast expects minimal environmental impact from development of biomass and geothermal energy sources.

66 The estimated levelized cost of new biomass and geothermal projects in Arizona to be similar to natural gas costs when the cost of natural gas exceeded $7 per thousand cubic feet (Black and Veatch, 2007).

67 Molten salt storage increases plant output availability by 6-8 hours, allowing the plant to continue producing electricity through midnight.

4.2.2 Natural Gas Feasibility Assessment

In the following section, we evaluate the feasibility of natural gas for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of natural gas, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Natural Gas Criteria

Similar to other energy sources, there are multiple technologies to consider for natural gas-fueled power generation. CT and CC power plants are currently in operation and are considered mature technologies (TRL-9) (Northwest Power Planning Council, 2002). Fuel cells are currently in use in small applications such as cell phone towers and landfills, but have yet to be adopted on a large scale (TRL-8) (Fuel Cells 2000, 2009). CCS technology is still in development, but a breakthrough in this technology will be applicable to natural gas plants as well as coal (TRL-7) (NETL, 2004). Micro-turbines, gas-fired reciprocating engines and industrial gas turbines are all in testing phases but have yet to be used in commercial situations (TRL-6) (U.S. DOE, Electricity Delivery & Energy Reliability, 2009).

Natural gas CT and CC plants are mature and commercially ready technologies, which can satisfy 100 percent of the state's energy demand. Gas-fired power plants require a steady stream of natural gas to operate, which is currently available to the state.

Additional Natural Gas Feasibility Issues

In a similar fashion to coal-fired power plants, gas plants require additional infrastructure, specifically gas pipelines, in order to operate (Northwest Power Planning Council, 2002). Arizona imports all of its natural gas from other states, particularly Texas (Seidman, 2008, EIA, 2009). Figure 7 shows the pipelines that facilitate the flow of natural gas through the state. It is important to note the flow from California and Texas. As natural gas demand increases, energy planners will need to consider other alternatives to secure the supply of gas for Arizona in the future. There is a critical need for natural gas storage facilities[68] to improve management of demand spikes and protect against pipeline breakdowns (EIA, 2009). There is also an opportunity to expand access to the Permian Basin in Texas and establish linkages to ports in Mexico to tap into worldwide natural gas supplies (Seidman, 2008). For a state that depends heavily on imported natural gas to provide energy, a disruption in flow would be extremely detrimental (Madigan, 2003). The construction of natural gas plants in and around the Phoenix area is partly due to the requirement to be near natural gas pipelines.

Figure 7. Natural Gas Pipelines Serving Arizona

Source: U.S. Department of Transportation, 2009.

Water is a non-issue for combined cycle gas-fired power plants, which require only 195 gallons per MWh of output (Pasqualetti, 2008). This amount is less than 40 percent of the water requirements of coal plants and less than 25 percent of the water requirements of nuclear plants.

[68] The state currently has no natural gas storage (Seidman, 2008). However, Multifuels LP, of Texas is proposing to build a natural gas storage facility that will utilize underground salt caverns north of Eloy, Arizona. The proposed facility, called Picacho Peak Gas Storage, will have up to 8 Bcf of total capacity and will be connected to nearby interstate pipelines. Multifuels LP plans to file with the Federal Energy Regulatory Commission to charge market-based rates and start construction during 2011. The facility is expected to be operational between 2013-2015. (Picacho Peak Gas Storage, LLC, 2011, http://www.picachopeakgs.com/default.htm).

Combustion turbine natural gas plants require 415 gallons/MWh (Pasqualetti, 2008), but they are mainly used as peaking plants and, therefore, do not operate and consume water for much of the year. A 500 MW natural gas plant requires 5,484.23 acre-feet of water, which makes it feasible for the three-county area and the other counties that do not face a water shortage.

4.3 Nuclear

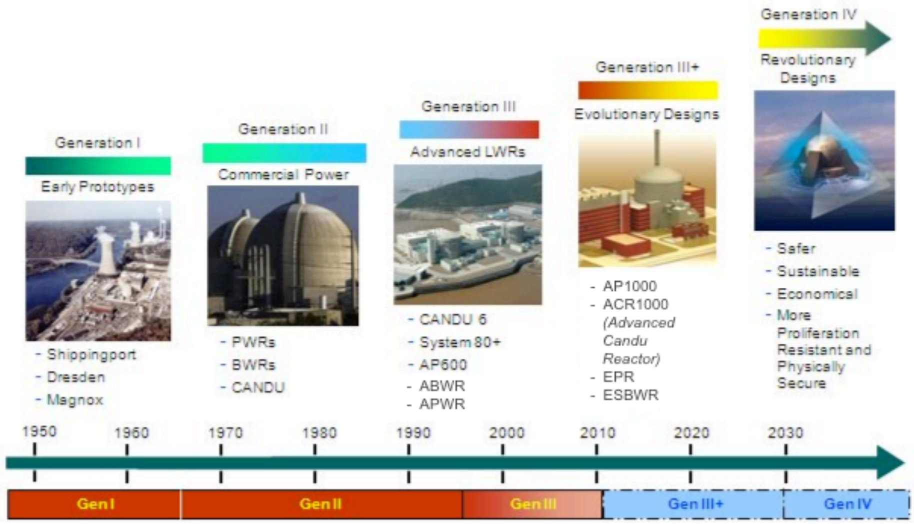
In 2009, nuclear power accounted for 20.2 percent of electricity generated in the United States and 27.4 percent in Arizona (EIA, 2011). All of the nuclear electricity generated in Arizona occurs at the Palo Verde nuclear power plant. The first unit of Palo Verde commenced operations in 1986, followed by unit two later in the year, and unit three in 1988 (EIA, 2009).

Nuclear power plants are attractive due to their high utilization rates (capacity factors), long continuous run times between refueling and maintenance outages, relatively low fuel costs and they have no greenhouse gas emissions. Nuclear power plants use uranium dioxide as fuel, which has historically had a stable supply at a much lower price than natural gas or coal.[69] On the other hand, nuclear power plants have high capital and fixed operating and maintenance (O&M) costs. They also have relatively little operating flexibility (i.e., turning them off and on is expensive). Nuclear power plants to thus well suited to provide baseload supplies of electricity.

Nuclear power technology can be split into five generations (I, II, III, III+, IV) based on advancements in reactor technology over time, as illustrated in Figure 8 below.

[69] The most recent figures indicate the dollar per MMBtu fuel cost for nuclear power plants is less than 50 cents, compared to about $2 for coal and about $4 to $5 for natural gas. Spot uranium prices have increased substantially since 2008 (from about $10 per pound of uranium dioxide in 2003 to as much as $46 per pound in 2009) (EIA, 2010). Utilities generally buy uranium through long-term contracts, so the average prices to the power sector would start to reflect the rising spot prices as these contracts are renegotiated. Nevertheless, this recent trend of rising market prices for uranium dioxide is not likely to jeopardize nuclear power's operating cost advantage, since fuel costs would still constitute a small portion of such operating costs.

Figure 8. Evolution of Nuclear Power Technology



Source: Adapted from Euratom.

Generation I nuclear plants followed the design of the first domestic commercial nuclear plant in 1957 in Shippingport, Pennsylvania. Today, there are no generation I plants in operation in the U.S. Improvements in nuclear plant design launched a series of generation II power plants. There are two different technologies employed in generation II plants. Pressurized water reactors (PWR) create heat from the nuclear core, which generates pressurized steam that turns the turbine and creates electricity (U.S. Nuclear Regulatory Commission). Boiling Water Reactors (BWR) use the heat to boil the water into steam that turns the turbine and creates electricity (U.S. Nuclear Regulatory Commission). Several generation II plants were built in the United States until the 1990s. Palo Verde is an example of a PWR plant.

The designs for generation III plants were approved in the 1990s. Since then, several nuclear power plants were built using these designs, mainly in Japan. Plants under construction in China today (more than two dozen projects) also rely on generation III designs. They present significant progress in fuel technology, thermal efficiency,[70] passive safety systems, and a standardized design to streamline licensing, reduce construction lead times and cut capital costs. Known as Advanced Pressurized Water Reactors (APWR) and Advanced Boiler Water

[70] Higher temperature burn-up of nuclear fuel will reduce fuel use and waste.

Reactors (ABWR), examples include the Mitsubishi APWR plant and the proposed expansion of the Comanche Peak nuclear power plant in Texas (Nuclear Regulatory Commission (NRC), 2011).[71]

Generation III+ plants are an extension of the design improvements in the generation III plants. The goal is to maintain the improvements in fuel technology and thermal efficiency while continuing to improve safety and cut costs. Designs include the Advanced CANDU reactor, the AP1000, the European Pressurized Reactor, the Economic Simplified Boiling Water Reactor, the APR 1400, and mPower (Nuclear Energy Institute, 2009).

Generation IV nuclear power plants, which are developed through a global research effort, will not be available for commercial operation in the next 15 to 20 years, as they are still in the research and development phase. The goal of research into these reactors is to improve safety and proliferation resistance, minimize waste and natural resource utilization, and decrease the cost to build and run such plants (EIA, 2009). Currently, there are six specifications considered generation IV nuclear plant designs, which are broken down into two categories. Thermal reactors use *slow neutrons* to sustain a nuclear chain reaction and include Very-High-Temperature Reactors, Supercritical-Water-Cooled Reactors, and Molten Salt Reactors (Idaho National Laboratory Nuclear Research, 2009). Fast Reactors sustain a nuclear chain reaction using *fast neutrons* and include Gas-Cooled Fast Reactors, Sodium-Cooled Fast Reactors, and Lead-Cooled Fast Reactors (Idaho National Laboratory Nuclear Research, 2009). The difference in using fast versus slow neutrons is that slow neutrons require a neutron moderator but do not require a fuel which is rich in fissile material to sustain a nuclear chain reaction (Idaho National Laboratory Nuclear Research, 2009).

In order to be permitted for construction in the United States, new nuclear power plant technologies need to undergo a design certification process and be approved by the NRC. As of July 2011, the Westinghouse AP1000 is the only Generation III+ plant that has completed the design certification. French company Areva's EPR technology and GE-Hitachi's ESBWR technology are still under review. In the United States, proposals to construct dozens of new

71 Final approval of the environmental impact statement for the Comanche Peak Units 3 & 4 has been issued in May 2011 by the NRC. The operating license for the plant is expected to be issued sometime in 2013 (NRC, 2011).

nuclear reactors using these three Generation III+ technologies have been filed with the NRC, however, currently none of them are beyond the planning stage.[72]

4.3.1 The Future of Nuclear Power

The nuclear energy design corrections stressed in generation III+ models are cost and safety. Safety is improved by adding extra checks and safeguards against a possible nuclear meltdown or radiation leak, while it is hoped that simpler, standardized designs and material substitutions will cut costs while maintaining safety (Nuclear Energy Institute, 2009). The March 2011 accident at Japan's Fukushima nuclear generating facility not only added to the existing worldwide public trepidation concerning nuclear power, but also solidified plans by several European countries to either phase out nuclear power (Germany, Switzerland, the Netherlands) or maintain moratoriums or bans on any future nuclear power development (Spain, Sweden, Austria, New Zealand, among others). France and Japan, where nuclear power supplies a large portion of electricity needs, and China and India remain resolutely pro-nuclear. In the United States, there are no such plans for a nuclear power phase-out, and recent surveys show public support for nuclear power has varied at about 30% to 50% of population (Pew Research Center, 2011).

Nuclear power plants have one of the highest capital costs and longest lead times of any electric generating technology,[73] which makes financing such projects a challenge. It is anticipated that any new nuclear facilities developed in the United States would be expansions or redevelopments at existing nuclear power plant sites to make permitting easier and moderate potential public opposition (as opposed to a greenfield development).

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[72] A map and updates on proposed new reactors in the United States can be found at NRC's website. See http://www.nrc.gov/reactors/new-reactors/col/new-reactor-map.html (at the time this document was prepared, the map was dated March 24, 2011). Some of these proposals use Generation III designs, like the previously mentioned Comanche Peak Units 3 & 4.

[73] The EIA's most recent (2010) estimates indicate nuclear power plant overnight capital costs to be in excess of $5,000 per kW (2010 dollars). The estimated capital cost for an advanced natural gas-fired combined cycle plant would be around $1,000 per kW, and for an advanced (supercritical) PC plant turbine, it would be about $3,000 per kW. With the inclusion of CCS technology for coal (at roughly an additional $2,000 per kW), nuclear becomes more competitive. Even then, lead times are expected to be significantly longer for the construction of a new nuclear reactor than they are for coal and natural gas-fired power plants. The 2005 Energy Policy Act (EPACT) has several provisions to mitigate this and financially support new nuclear developments in the United States.

Moreover, there is currently no long-term solution for storage or elimination of nuclear waste. This radioactive waste is split into high and low-level waste,[74] with different disposal requirements. Nuclear plants that are currently in operation store waste on-site. While nuclear planners have sought secure, underground caverns to store waste, there is no firm plan that has been approved (U.S. Nuclear Regulatory Commission, 2009).[75] The federal government also plans to develop a recycling technology for high-level waste to reuse parts of the fuel and reduce its toxicity (EPRI, 2008). Arizona must resolve each of these issues for a additional nuclear power to be developed in the state.

4.3.2 Nuclear Power Feasibility Assessment

In the following section, we evaluate the feasibility of nuclear for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of nuclear, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Nuclear Criteria

Determining the technology readiness level of nuclear requires looking at generation III, III+, and IV power plants, since these are the plants that will be built in the future. Generation III power plants are already in use around the world (TRL-9) (World Nuclear Association, 2009). . As of July 2011, there are several Generation III+ power plants under development around the

[74] High-level waste consists of spent reactor fuel and waste material remaining after spent fuel is reprocessed. It is considered highly radioactive and must be handled and stored with care. Low-level waste consists of items that have become contaminated due to exposure to neutron radiation. This includes shoes, clothing, mops, filters, and other items that could come into contact with contaminants.

[75] In 1982, the U.S. federal government passed the Nuclear Waste Policy Act, committing the government to remove used nuclear fuel from nuclear plant sites and to develop geologic (underground storage) to store the waste. Since then, nuclear power consumers have been contributing into the "Nuclear Waste Fund" to pay for federal management of used nuclear fuel from commercial reactors and to ensure that consumers of nuclear power would pay for the used nuclear fuel disposal program. Annual contributions to this fund have been around $750 million, and with earned interest, more than $30 billion has been collected to date. (Currently, the balance is about $24 billion after expenditures to study various storage options). In 2010, President Obama abandoned the most recent storage proposal at the Yucca Mountain site (Nevada), and ordered a two-year review of nuclear waste management options. Meanwhile, several lawsuits by the industry have been brought against the Department of Energy, demanding the mandatory contributions to the Nuclear Waste Fund be stopped if no repository is to be built. Industry insiders have also proposed a federal corporation to be setup for the management of spent fuel. (Nuclear Energy Institute, 2010).

world, which are estimated to become operational sometime between 2016-2020 (TRL-6).[76] Generation IV power plants are still in a developmental phase. The basic concepts of the plant technology are understood but there has yet to be an attempt to model the power plant (TRL-3) (World Nuclear Association, 2009).

Assuming that state utilities will build generation III or III+ plants,[77] it is possible for nuclear energy to meet 100 percent of the state's energy demand. This is because the underlying technology is commercially available and there are no foreseeable fuel supply constraints (uranium ore is available in large quantities in Arizona and the surrounding states). However, when taking into account high capital costs and the unresolved long-term uncertainty concerning spent fuel, it is unlikely that 100% of future new build in the state would be nuclear. Under today's circumstances, a revival or derivative of the original construction plans (that envisioned two additional reactors at the existing Palo Verde site) would be the most likely nuclear expansion scenario for Arizona.

Additional Nuclear Feasibility Issues

One of the important determinants in development of nuclear power generating capacity is the availability of fuel. The EIA estimates that Arizona, Colorado, and Utah have reserves of 53 million tons of uranium ore. Considering that annual uranium consumption by nuclear power plants in the United States has been about 24,500 tons, there are sufficient domestic resources for further nuclear development. Arizona's deposits are mainly concentrated in the northern part of the state near the Grand Canyon (Wenrich, 2006).

It is possible, however, that some of Arizona's uranium deposits might not be available for further mining. Though there is no mining currently going on in Arizona, though the trend of rising uranium prices over the last several years (EIA, 2010) has triggered a large number of new mining claims. There have been protests by Northern Arizona tribes to stop new mining

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76 There are four plants under development using Areva's Generation III+ EPR technology; one in Finland, one in France, and two in China. In addition, four nuclear power plants in China are being developed using Westinghouse's AP1000 Generation III+ technology. (Areva and Westinghouse Electric Co., 2011). Several U.S. utilities have expressed interest in using the AP1000 technology for potential future nuclear power development.

77 This assumption is based on the timeline of nuclear generation development provided by the Nuclear Regulatory Commission (NRC), which does not foresee generation IV plants being available in the near future.

activity (Fonseca, 2009). The current Secretary of the Interior has extended a 2009 moratorium to mine for uranium around the Grand Canyon for another six months in June 2011, and the federal government is considering a 20-year ban on new claims (U.S. Department of the Interior, 2009, 2011). Moreover, it is important to note that currently, more than 85% of total uranium purchased by nuclear power plants in the country is of foreign origin (mined outside the United States) (EIA, 2009).

While the availability of land is not a significant issue for nuclear, there are requirements for nuclear power plants that do not apply to other technologies. Nuclear plants require a plot of relatively flat land for the facility but, due to their hazardous nature, are not built close to load centers. They cannot be built near fault lines or in areas of any seismic activity. In addition, nuclear power plants present security risks, which needs to be considered during site selection.

Water is a significant resource issue for nuclear, which requires 785 gallons per MWh. This is the second highest amount of water required to generate electricity.[78] A plant the size of Palo Verde uses 22.94 billion gallons of water each year.[79] This is equivalent to 70,273 acre-feet,[80] making the addition of a nuclear facility of that size impossible in the six counties with water deficits and a strain on the three county area. The most likely addition to nuclear capacity in Arizona would be to add another unit to Palo Verde. The original plan for Palo Verde called for five units and there had been discussion of increasing capacity by a further 700 MW,[81] but this was cut short due to the large capital costs involved.

Nuclear power is a baseload technology because fuel supply is not intermittent (unlike wind, for instance) and the underlying power generation technology (fission) allows the plants to run continuously for long periods. However, given the long start-up times at a nuclear power plant and the relative difficulty of stopping generation (removing fuel rods and cooling them), nuclear power plants cannot be started up to solely meet peak electricity needs. Therefore, utilities build nuclear power plants to supply baseload power needs.

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78 Solar thermal parabolic trough power plants in the California desert use an average of 900 gallons/MWh (Pasqualetti, 2009).

79 Palo Verde's annual generation output is approximately 29,250 GWh (2008).

80 Using the conversion of 1 acre-foot = 325,851 gallons.

81 EIA Palo Verde Nuclear Plant Summary.

Unlike coal and natural gas plants, nuclear plants benefit from economies of scale in electricity generation. As a result, scalability is an issue, and any additional unit added to Palo Verde would likely exceed 700 MW (EIA, 2009), which does not give utility planners flexibility. Palo Verde ran into a similar problem during its initial development, but solved it by reaching an agreement with out-of-state utilities[82] to share the costs and own part of the plant's generation capacity.

Table 9: Ownership of Palo Verde Nuclear Plant

Owner	*Percentage*
APS	29.10%
Salt River Project (SRP)	17.50%
El Paso Electric Co.	15.80%
Southern California Edison Co.	15.80%
Public Service Co. of New Mexico	10.20%
Southern California PPA	5.90%

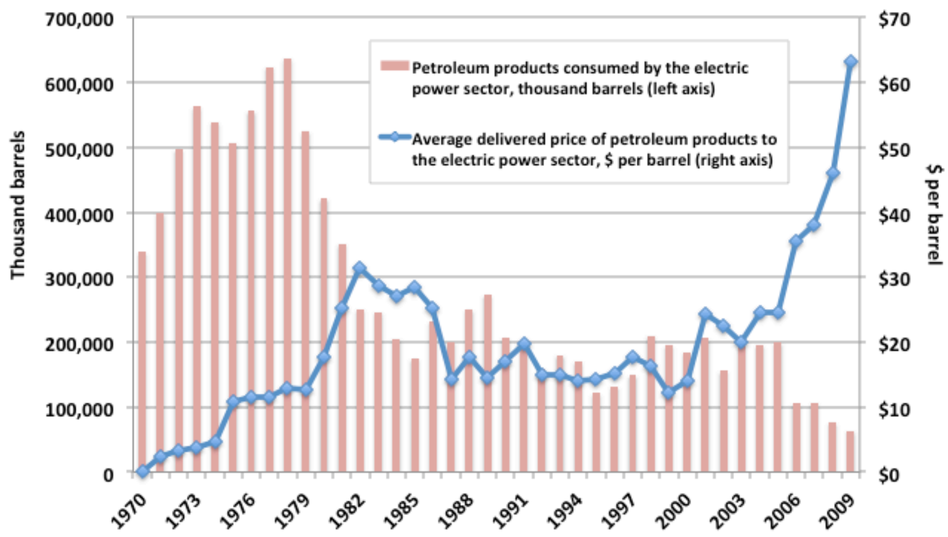
Source: EIA, 2009.

4.4 Petroleum

In 2009, the United States generated less than one percent of its electricity from petroleum-fired power plants (EIA, 2011). Compared with 1970 (12 percent) (EIA, 2009), this is a significant decline and due, largely to increasing oil prices (EIA, 2009). Figure 9 below illustrates the relationship between rising prices for petroleum products and falling consumption of petroleum products by the electric power sector in the United States.

82 For instance, see Table 9 for the breakdown in ownership for the Palo Verde Nuclear Plant.

Figure 9. Consumption of Petroleum Products by and Delivered Petroleum Product Prices to the Electric Power Sector, 1970-2009, $ per barrel and thousand barrels



Source: EIA, 2009. State Energy Data System: Petroleum and Fuel Ethanol through 2009.

In addition, petroleum-fired power plants in the United States have a nameplate capacity of 63,254 MW (2009), yet only produced about 38.8 million megawatt-hours of electricity that same year, meaning they are only operating at about 7 percent of full capacity.[83] Petroleum-fired power plants are used in a similar fashion to peaking gas plants, generating electricity during the peak hours of demand and then shut down for the remainder of the time. Petroleum-fired power plants are used mostly in the Eastern United States (EIA, 2009), but Arizona does operate several facilities for periods of peak power demand. The APS plant at Douglas is an example of a petroleum-fueled peaking plant (APS, 2009).

4.4.1 The Future of Petroleum-fired Power Plants

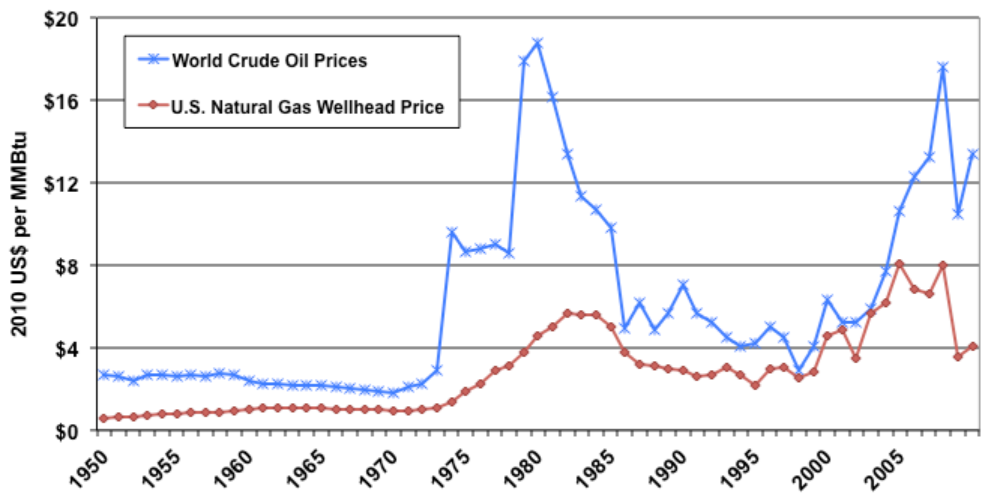
The future of petroleum-fired power plants is dim for several reasons. The first is carbon dioxide emissions. Petroleum liquids provide about three-fourths of the petroleum used in

83 Petroleum plants run at 80 to 90 percent capacity when fully operational. This figure, called the capacity factor, is found by dividing the total megawatt hours generated in a year by the total megawatt hours of possible output (=MW capacity * number of hours in a year (8760)) (EIA, 2009).

petroleum-fired power plants while petroleum coke provided the remainder. Both petroleum products have significantly higher CO_2 emissions than natural gas.[84]

The second reason is the increasing price and price volatility of oil. Crude oil prices have been steadily increasing and becoming more volatile, which is concerning for an industry which makes price forecasting a priority for long-term planning purposes (APS, 2009). Whereas the emissions of coal might be worse, on average, than petroleum, coal is more abundant domestically and its price much more competitive compared to petroleum.

Figure 10. Petroleum and Natural Gas Price Comparison (2010 $/MMBtu)



Note: 1 cubic foot of natural gas = 1,028 Btu, 1 barrel of crude oil = 5,800,000 Btu.

Sources: World crude oil prices: 1950-2006 from the BP Statistical Review of World Energy; 2007-2010 are Brent spot crude prices (FOB, dollars per barrel) from the EIA, 2010, World Crude Oil Prices. U.S. Natural Gas Wellhead Prices (dollars per thousand cubic feet), 1950-2010, also from the EIA, 2010. Nominal prices converted into real dollar terms using the U.S. consumer price index (CPI) from the U.S. Bureau of Labor Statistics (BLS), (Series ID CUUR0000SA0: 12-month percent change, all items, U.S. city average, not seasonally adjusted, base period 1982-84=100).

The third reason petroleum-fired power plants have an uncertain future is because the nature of their use puts them in competition with natural gas as a fuel source. Not only does natural gas

84 Emissions of carbon dioxide (pounds of CO_2 per million Btu) are as follows: Petroleum coke (225.1), petroleum liquids (161), coal (205.3-227.4) and natural gas (117.1) (EIA, Voluntary Reporting of Greenhouse Gases Program, Fuel Emission Coefficients, http://www.eia.gov/oiaf/1605/coefficients.html).

emit less carbon dioxide, but it has also been the relatively cheaper fuel on a dollar per Btu basis (see Figure 10).[85] While some industry analysts point to increasing evidence of price "coupling" between oil and natural gas, so far, the periods of price convergence have not persisted.

4.4.2 Petroleum Feasibility Assessment

In the following section, we evaluate the feasibility of petroleum-fired power generation for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of petroleum, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Petroleum Criteria

Petroleum-fired power plants use combustion turbines to generate power. This technology has been used for decades in the United States (TRL-9) (EIA, 2009). Due to the nature of the fuel, it can't be used in combined cycle plants like natural gas.

Similar to gas-fired power plants, petroleum plant capacity is dependent on the availability of fuel. Arizona receives a regular supply of petroleum products via pipelines. Therefore, state utilities could theoretically use petroleum to fuel power plants to meet 100 percent of the state's energy demand. This, however, would mean not only constructing new power plants but also potentially expanding pipeline capacity into the state.

Additional Petroleum Feasibility Issues

With little in-state production of crude oil, Arizona depends heavily on shipment of petroleum products into the state. Two pipelines, both owned and operated by Kinder Morgan Energy Partners, serve this need: the West Line transports petroleum products into the state from

[85] EIA's 2009 operating cost figures for U.S. electric power producers indicate fuel cost (in cents per kilowatt-hour) for coal-fired plants to be about ¢2.3; for natural gas-fired power plants about ¢3.9, compared with approximately ¢7.7 for petroleum-fired power plants. In other words, the fuel cost for petroleum fired power plants is nearly twice as high as natural gas-fired plants and three times that of coal-fired plants.

southern California, and the East Line from El Paso, Texas (California Energy Commission, 2009c). A small portion of gasoline is also trucked in from neighboring states. Past experience[86] showed the vulnerability of the state's transportation sector, the largest energy-consuming sector in Arizona, to supply disruptions. This precarious supply situation could potentially be resolved by the announced construction of the Pacific Texas Pipeline from El Paso to Phoenix.

In addition, the state's first ever refinery, projected to come into service in 2012, may also help diversify the supply of petroleum products. If and when operational, the *Arizona Clean Fuels Yuma* refinery will have the capability to process 163,000 barrels per day of crude oil from Alberta's oil sands into petroleum products that meet the fuel standards of California and Arizona.[87] The estimated output of the refinery, at about 6.3 million gallons per day of refined petroleum products, corresponds to roughly half of Arizona's daily demand.[88]

The state of Arizona will continue to import large amounts of petroleum products,[89] which can theoretically be used for power generation. However, the competing use for these fuels for vehicle transport, with no good substitute, has higher priority. This means only excess pipeline capacity would be available for supplying fuel to petroleum-fired power plants. Therefore, a proposal to add petroleum-fired electric generating capacity --sufficiently large to meet a significant portion of future demand-- would mean constructing new pipelines into Arizona, which would increase the cost.

86 A rupture in the pipeline from El Paso in the summer of 2003 not only caused a spill, but also resulted in the shut down of the pipeline section between Tucson and Phoenix. Even though the supply interruption involved only one of the pipelines serving the state and lasted about a month, it was sufficient to cause shortages at Phoenix gas stations. Kinder Morgan, the operator of the pipeline, had to pay $6 million in damages to Arizona. (Phoenix Business Journal, "Kinder Morgan to pay $6M for 2003 gas pipeline break," January 19, 2005, at http://www.bizjournals.com/phoenix/stories/2005/01/17/daily33.html, and Bruno, T.V., "Examination of Kinder Morgan's Tucson to Phoenix 8-Inch Pipeline," March 16, 2004 Report to the Office of Pipeline Safety, at http://www.azgovernor.gov/estf/opskm.pdf).

87 Such as CARB3 (California Air Resources Board specification), Arizona Clean Burning Gasoline, and ultra-low sulfur gasoline.

88 Arizona Department of Environmental Quality (ADEQ), Air Quality Division, Permits: Arizona Clean Fuels Yuma, http://www.azdeq.gov/environ/air/permits/acf.html.

89 In Arizona, the electric power sector represents less than 1% of total petroleum products consumption; the transport sector use is by far the largest component of total demand (90%), followed by the industrial sector (9%). (EIA, 2010).

4.5 Solar Power Generating Technologies: Solar Thermal

In 2009, less than 0.1 percent of electricity generated in the United States and Arizona was by plants that utilize solar energy technologies, which include solar thermal power plants, solar photovoltaics and other emerging technologies (EIA, 2011).

Solar thermal (or, concentrating solar power, CSP) technologies capture thermal energy from the sun and use it to generate heat. There are three principal collectors for this heat. Low temperature collectors are used to heat swimming pools. Medium temperature collectors are used for creating hot water. High temperature collectors are generally used for electric power production (EIA, 2007). As Table 10 shows, there has been more market activity in low and medium temperature collectors, mainly due to low costs per amount of heat energy created.

Table 10: U.S. Annual Shipments of Solar Thermal Collectors by Temperature (Ksf[90])

Year	*Low Temp.*	*Medium Temp.*	*High Temp.*
1998	7,292	443	21
1999	8,152	427	4
2000	7,948	400	5
2001	10,919	268	2
2002	11,126	535	2
2003	10,877	560	7
2004	13,608	506	0
2005	15,224	702	115
2006	15,546	1,346	3,852*
2007	13,323	1,797	33
2008	14,015	2,560	388
2009	10,511	2,307	980

(*) The spike in high temperature panels shipped in 2006 was due to the 64 MW Nevada Solar One power plant in construction at that time.

Source: *EIA, 2011.*

90 Thousand square feet.

Only the high temperature collectors are able to be used for electric power production. Using a series of lenses and mirrors, solar thermal panels capture thermal energy from the sun and use it to heat a substance. The steam produced from that process runs a steam turbine that produces energy (NREL, 2009). The problem is that this process can only heat the current substances used to roughly 550 degrees Celsius. There have been experimental efforts to use a different material, which is capable of being heated up to 800 degrees Celsius.[91] Higher temperatures also permit plants to use dry heat exchangers for thermal exhaust, reducing plant water use. There are four principal technology families that are either in use or in development for solar thermal power generation (IEA, 2010). They are grouped according to the technology used to receive (absorb) the sun's rays (fixed *vs.* mobile), and the way they then re-focus the sun's rays (line *vs.* point), as shown in Figure 11.

Figure 11. Types of Solar Thermal Power (or CSP) Technologies

Focus type / *Receiver type*	***Line focus*** Collectors track the sun along a single axis and focus irradiance on a linear receiver. This makes tracking the sun simpler.	***Point focus*** Collectors track the sun along two axes and focus irradiance at a single point receiver. This allows for higher temperatures.
Fixed Fixed receivers are stationary devices that remain independent of the plant's focusing device. This eases the transport of collected heat to the power block.	**Linear Fresnel Reflectors**	**Towers (CRS)**
Mobile Mobile receivers move together with the focusing device. In both line focus and point focus designs, mobile receivers collect more energy.	**Parabolic Troughs**	**Parabolic Dishes**

Source: IEA. Technology Roadmap: Concentrating Solar Power (2010).

Parabolic trough is the dominant solar thermal technology in use today. A long trough is constructed using mirrors to reflect thermal energy from the sun and heat a central tube, which is filled with a heat transfer fluid such as oil. Using the heat from the central tube and water, steam is created to run a turbine that generates electricity (Greenpeace, 2003). The adoption of this technology in the 1980s by the state of California led to the construction of nine parabolic trough solar thermal power plants with a total capacity of 354 MW (California Energy

91 Forsberg, 2007.

Commission, 2009).[92] The technology has been resurrected within the last few years with the construction of such plants as Nevada Solar One in 2007 (64 MW) and the Andasol solar power station in Spain in 2008. APS has operated the 1 MW Saguaro Solar Power Station since 2006 (APS, 2006). During 2010, Spain completed construction of nearly 700 MW of parabolic through solar thermal facilities, which are now operational. As of February 2011, another 850 MW was reported to be under construction.[93] Meanwhile, the world's largest parabolic through plant (about 968 MW) is currently under construction in Blythe, California.[94] Another large-scale plant using parabolic trough technology, Solana (280 MW), is being developed in Gila Bend, Arizona.[95]

Micro CSP is a smaller version of parabolic trough plants. It utilizes the same technology to provide relatively low cost renewable energy in areas that cannot finance large-scale power facilities (NREL, 2009). System size typically ranges from 500 kW (0.5 MW) to 20 MW. While several applications of the micro CSP technology exist around the world, these were mostly for generating heat and not electricity. The first micro CSP project to generate electricity has been the 2 MW Kona Desert demonstration project in Hawaii that uses 1,000 micro CSP panels. This project has been in operation since 2009, and based on its success a larger (5 MW) commercial facility using the same technology is underway.[96]

92 There were three more planned, but the projects were suspended in 1992 due to company bankruptcy.

93 The 700 MW of parabolic through capacity currently in operation in Spain includes 14 individual plants of 50 MW each. The 850 MW that was reported to be under construction consists of 17 plants of 50 MW each. (Asociación Española de la Industria Solar Termoeléctrica, February 2011, http://www.protermosolar.com/boletines/32/mapa.html.)

94 Developed by Solar Trust of America (a joint venture of two German companies, the solar thermal developer Solar Millennium and construction company Ferrostaal), the Blythe Solar Power Project will have four 242 MW plant when complete and is expected to cost $6 billion. The site is on federal lands that are managed by Bureau of Land Management. The project was approved in 2010, and backed by (conditional) federal loan guarantees of up to $2.1 billion in April 2011, and broke ground in June 2011. (DOE, June 2011, http://energy.gov/articles/ground-breaking-blythe-solar-power-project).

95 Arizona's largest utility APS has contracted with the developer and operator of plant (Abengoa Power of Spain) to purchase 100% of the output from the Solana plant. The federal government awarded $1.45 billion in loan guarantees to Solana in December 2010. The project is expected to be operational sometime in 2013. (APS and DOE, 2010, http://energy.gov/articles/doe-finalizes-145-billion-loan-guarantee-one-worlds-largest-solar-generation-plants).

96 The micro CSP panels in both projects are supplied by the Hawaiian firm Sopogy. The first demonstration project was developed by the Natural Energy Laboratory of Hawaii Authority, and the second commercial project is developed through a partnership between the State of Hawaii, Department of Hawaiian Home Lands (DHHL) and Keahole Solar Power (KSP). (Global Solar Thermal Energy Council, 2010, http://www.solarthermalworld.org/node/1043, and Sopogy, October 27, 2010 press release, http://sopogy.com/blog/2010/10/).

Solar power tower technology is the second most used solar thermal technology. A large number of mirrors are erected in a circle to direct heat from the sun to a central tower, which transfers the heat to a substance such as oil. This substance heats water into steam and runs a turbine to generate electricity (Greenpeace, 2003). Power tower technology has two advantages over parabolic trough. It is able to achieve higher temperatures, which allows for less water use and increased efficiency. Power tower plants can also be sited on land that is not flat. A drawback of this technology is that it requires a dual axis system to track the sun and transmit the heat to the central tower (NREL, 2009). Power towers are currently in commercial use in Spain[97] and the United States.[98] Several new commercial projects are under development around the world, including the world's largest solar power tower plant that is currently under construction in California's Mojave Desert.[99]

Parabolic dish technologies use a large, reflective dish to focus sunlight onto a single point, which captures the heat and then uses a Stirling[100] or steam engine to generate electricity. The dishes, which are small (1 to 25 kW in size), built to track the sun and maximize solar exposure. Most dishes have a stand-along engine/generator placed at the focal point. Dishes can achieve extremely high temperatures (over 1400°F) and as a result offer one of the highest solar-to-electric conversion rates of any solar thermal technology (upwards of 30%). In addition, the Stirling engine design is air-cooled and thus eliminates the need for cooling water. (A small amount of water is needed solely for cleaning the mirrors inside the dishes.) The dishes can also be installed on uneven land. On the other hand, these systems are not as compatible with thermal storage as other solar thermal power technologies. Moreover, the compact size of individual units requires installation of hundreds to thousands of dishes for constructing even the smallest utility-scale plant. These characteristics (small unit size, negligible water use, and poor thermal storage compatibility) place parabolic dishes in competition with solar

97 The PS10 (2007) and PS20 (2009) towers in Seville (by Abengoa Power of Spain), totaling 31 MW.

98 The 5 MW Sierra Sun Tower in Lancaster, California (by e-Solar), which started operations in 2009.

99 The Ivanpah project, developed by BrightSource Energy, will have a capacity of 392 MW, consisting of three separate plants. The site for the project is near California-Nevada border, also on federal lands like the Blythe project. BrightSource has secured $1.6 billion in loans guaranteed by the U.S. Department of Energy in late 2010, and the project broke ground soon after. Equity investors in the project include Google ($168 million) and NRG Solar ($300 million). The developer has also signed a long-term power sales agreement with two California utilities for the output of the plant. (BrightSource Energy, April 2011).

100 A Stirling engine uses the Stirling thermodynamic cycle to directly generate electricity without the need for producing steam first.

photovolatic technologies, as well as with other solar thermal power technologies (Department of Energy, 2010).

Commercial applications of parabolic dish technology are still in their infancy. The first U.S. plant of its kind, the 1.5 MW Maricopa Solar, has begun operations in January 2010.[101] Two large-scale projects using parabolic dish technology, Calico Solar and Imperial Valley Solar, were both approved in 2010, but financing and operational challenges have since forced the developer to sell these projects, also resulting in the design configurations either reducing the use of or removing parabolic dish technology entirely.[102]

Linear Fresnel Reflector (LFR) technology combines design elements of parabolic trough (tracking) and dish (focusing) systems. It uses long rows of flat or slightly bent mirrors to focus sunlight onto fixed linear receivers positioned above the mirrors (NREL, 2009). A more recent design, known as compact LFR uses two parallel receivers and therefore requires less land than parabolic troughs to produce a given level of output. The main advantage of LFR systems is that their simple design and fixed receivers, which results in lower investment costs. On the other hand, they have lower conversion efficiencies than parabolic troughs and incorporating storage into LFR systems is more difficult (International Energy Agency, 2010). Linear Fresnel technology is in limited commercial usage in the United States and Spain.[103]

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[101] Located in Peoria, Arizona, the plant is owned and operated by Tessera Solar and was constructed using the Stirling Energy Systems proprietary "SunCatcher" dishes.

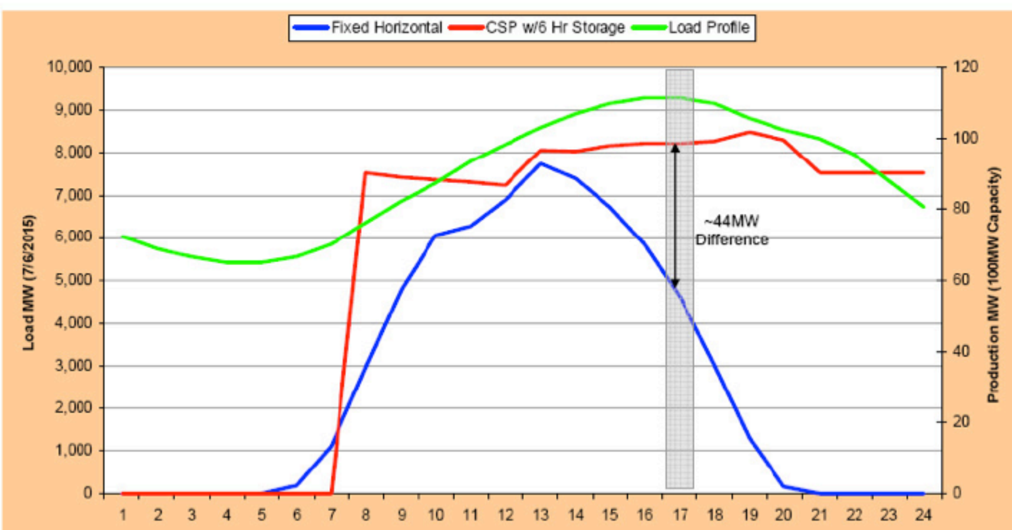
[102] Formerly called SES Solar One, the Calico Solar project was also going to be developed by Tessera Solar and involved the installation of 30,000 individual SunCatcher dishes. Even though the California Energy Commission approved of the plans in January 2010, after a potential power sales agreement between California utility Southern California Edison and Tessera fell through, Tessera sold the project to another developer (K Road Power), which has altered the configuration to use fewer parabolic dishes (up to 20% of total capacity) and rely on solar photovoltaics (PV) for the remainder. The final design configuration is not yet public. (California Energy Commission (CEC) (2010), http://www.energy.ca.gov/sitingcases/calicosolar/index.html, and Bureau of Land Management (2010), http://www.blm.gov/ca/st/en/prog/energy/fasttrack/calico.html). Tessera's second similar large-scale parabolic dish project, originally called SES Solar Two, then renamed Imperial Valley Solar, has also changed hands (acquired by AES Solar) in February 2011. A recent filing to the CEC indicates that the project will be PV-only. (CEC, http://www.energy.ca.gov/sitingcases/solartwo/compliance/documents/2011-06-30_Letter_to_Terminate_the_Energy_Commission_License_TN-61242.pdf).

[103] Kimberlina Solar Thermal Energy Plant in Bakersfield, CA (5 MW), and Puerto Errado 1 in Murcia, Spain (1.4 MW). The second phase of the Spanish Puerto Errado project, which, at 30 MW, will be much larger than the first phase, is reportedly under construction. (NREL, March 17, 2011, http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=159).

4.5.1 The Future of Solar Thermal Power Plants

The future of solar thermal technology will largely depend on thermal energy storage (NREL, 2009). If solar thermal plants only generate electricity only during daylight hours and have no thermal energy storage, the levelized cost of power produced increases. Lack of storage also makes these technologies less attractive to utilities because they cannot be counted on to supply electricity as needed. While storage increases upfront investment costs, it offers a solution to both of these problems by essentially extending the amount of time a solar thermal power plant can run, and thus reducing levelized cost of electricity. Figure 12 demonstrated how storage improves a solar thermal power plant's ability in satisfying the load requirements: Storage evens out the electrical output from a typical CSP plant ("CSP w/6hr Storage" line in red) and allows for this output to be available during the peak hours of electricity demand. The "fixed horizontal" line in blue illustrates how the CSP's output would rise and fall during daylight hours without any storage.

Figure 12. Impact of Storage on a 100 MW Concentrated Solar Thermal Power Plant



Source: APS, 2009.

The first solar thermal power plant in the world with storage was the SEGS I plant in California. Between 1985 and 1999, it used a mineral oil heat transfer fluid to generate three hours of full-load storage capacity (NREL, 2009). Within the last five years, molten salt has become very popular as a storage substance due to its high melting temperature. Various mixtures of molten salt are being studied for optimal thermal energy storage. For instance, the mixture[104] used at the Andasol I plant in Spain (50 MW) as storage medium allows the plant to generate an additional seven hours of electricity after direct sunlight is not available to the plant. The Solana solar thermal power plant (280 MW) currently under construction in Arizona will also utilize some type of molten salt storage, and is expected to get between six and eight hours of storage (APS, 2011).

The next step in solar storage is eliminating the heat transfer from a heat transfer fluid to a holding substance such as molten salt. The obstacle is in finding a mixture that does not require high temperatures (>120-220 Fahrenheit) to avoid freezing. A recently approved California solar thermal power project, Rice Solar Energy (150 MW), proposes to utilize molten salt for both heat transfer and as storage. If successful, it will provide greater plant efficiency, which reduces the levelized cost of the plant.[105]

Use of alternative storage mediums such as "phase-change materials" (such as synthetic mineral oil) and solids (such as concrete and ceramics) are also being studied, primarily due to the low cost of these storage mediums. However, advancing molten salt storage methods currently appear to be the primary focus of research into thermal storage (Department of Energy, Office of Energy Efficiency and Renewable Energy and NREL, 2010).

4.5.2 Solar Thermal Feasibility Assessment

In the following section, we evaluate the feasibility of solar thermal for the state of Arizona using the criteria established in section three. In addition to determining whether the state has

[104] Consisting of 60% sodium nitrate and 40% potassium nitrate. (Department of Energy, Office of Energy Efficiency and Renewable Energy, 2010).

[105] Developed by Solar Reserve. (CEC, 2010, http://www.energy.ca.gov/sitingcases/ricesolar/index.html.)

sufficient capacity and the technology readiness level of solar thermal, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Solar Thermal Criteria

There are four large-scale solar thermal power plant designs that are currently being considered by utilities for commercial use. Parabolic trough technology has been successfully operated in California since the 1980s (TRL-9). The solar power tower and linear Fresnel technologies have been implemented on a commercial scale in the last several years (TRL-9). The parabolic dish and micro CSP have limited commercial application (TRL-8). .

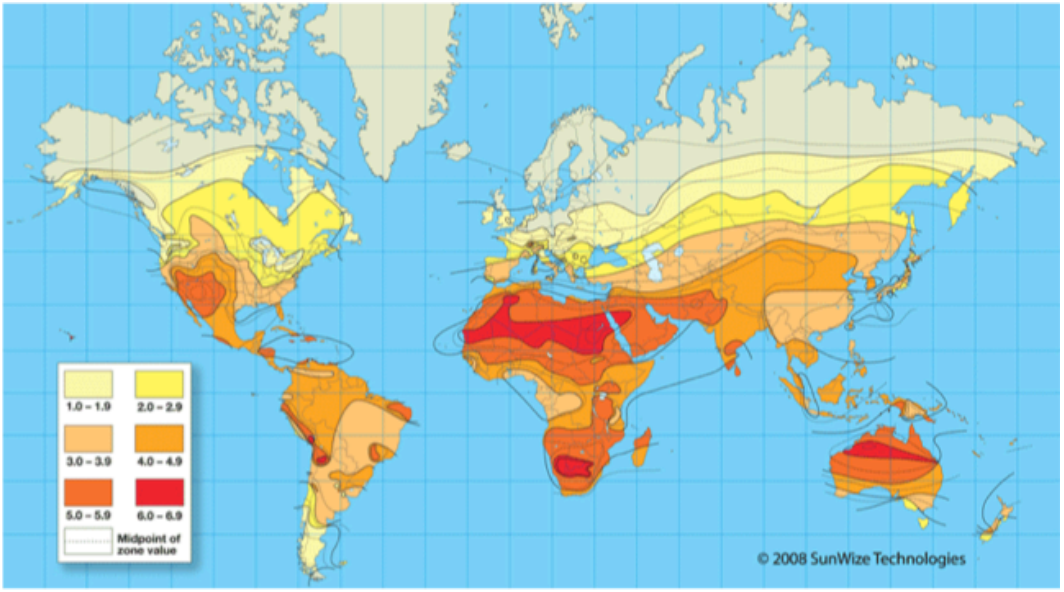
While current storage methods are not sufficient to qualify CSP technologies for baseload use, proposed facilities with 6 to 8 hours of storage would mean solar thermal can satisfy the state's energy demand during the operating hours of these plants plus any additional use-time made available by storage, as demonstrated earlier in Figure 12

Additional Solar Thermal Feasibility Issues

The state of Arizona is located in one of the highest areas of solar insolation in the world (Figure 13). Note that the most favorable areas exist in the Western United States, North and South Africa, the Middle East, and Northern Australia. The average number of days of sunshine in Phoenix is 334 (City of Phoenix, 2009). By comparison, Germany has an average of 73 days of sunshine, yet has a larger solar power presence.[106] With this level of solar insolation, the state of Arizona has great potential to develop solar thermal generation capacity.

106 At the end of 2009, Germany is had nearly 5.3 GW of cumulative installed solar capacity (mostly in the form of photovoltaic solar power), making it the worldwide leader (IEA, 2009). Note that the estimated annual solar insolation in Arizona is much greater than Germany, at 2,200 kWh/m^2 versus 1,250 kWh/m^2 (National Solar Radiation Database (NSRD), 2009).

Figure 13. World Solar Insolation Levels



Note: This map shows the amount of solar energy in hours, received each day on an optimally tilted surface during the worst month of the year. (Based on accumulated worldwide solar insolation data.)

Source: SunWize, 2008, http://www.sunwize.com/info_center/solar-insolation-map.php.

Available land is a critical issue for solar thermal power generation. For instance, the 280 MW Solana solar thermal power plant being built in Arizona requires 1,900 acres of land (Clean Edge News, 2008), which is approximately 3 square miles.[107] In addition to the size of the land, the area must be relatively flat for these plants, with the exception of parabolic dishes, which can be mounted on uneven terrain (NREL, 2009). In Arizona, there are many competing land uses (i.e., large portions of the state devoted to national parks, agriculture, and urban development and existence of tribal lands).[108] A solution is to utilize Bureau of Land Management (BLM) lands, particularly in the southwest portion of the state, which is an area of high solar insolation. Figure 14 shows a map of the BLM lands in Arizona as well as potential sites proposed (or made available) by the BLM for solar power development.

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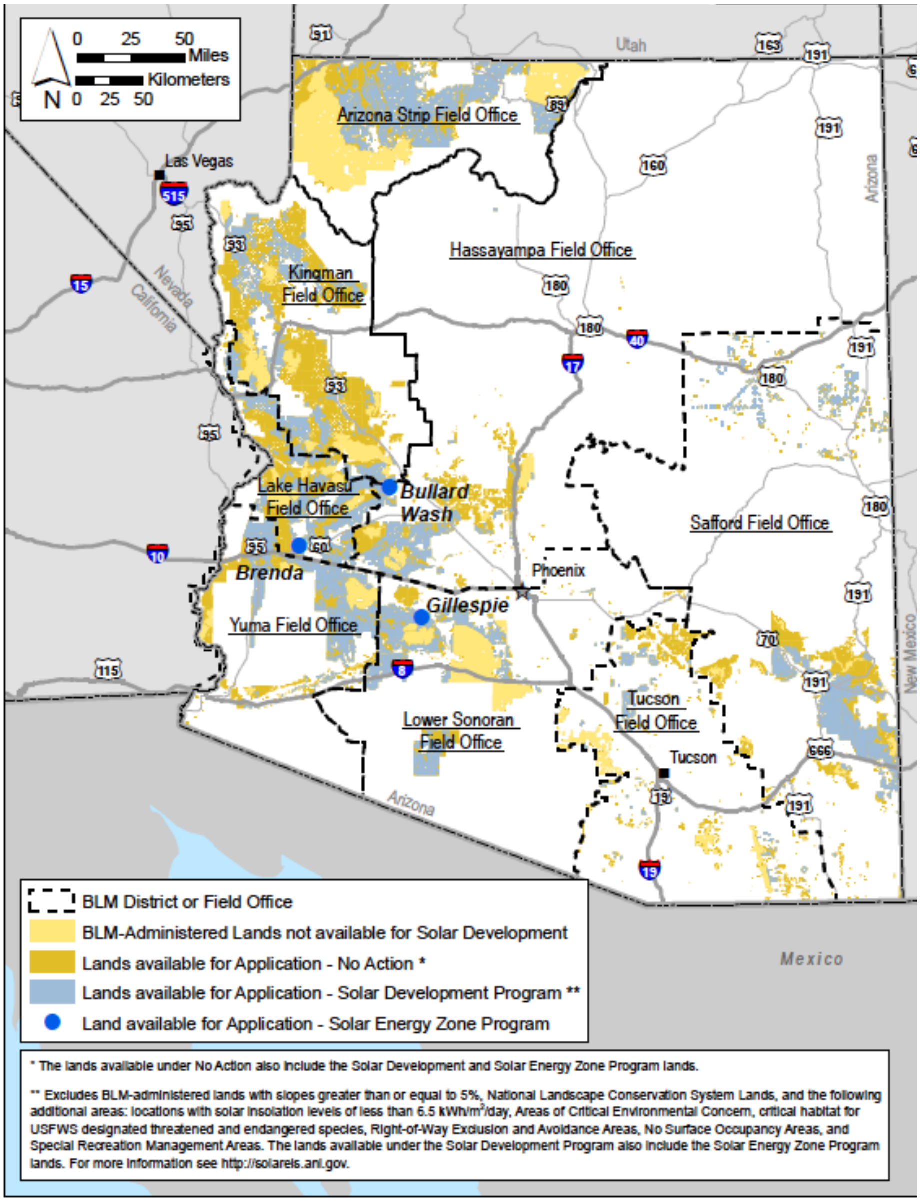
107 1 acre = .0015625 square miles.

108 Official breakdown of land ownership in the state is 42.1 percent federal 27.6 percent Indian trust, 17.6 percent private, and 12.7 percent state trust. Of the state trust land, over 92 percent is used for grazing (Arizona State Land Department, 2009).

Figure 14. Available BLM Lands in Arizona for Solar Power Development



Source: Bureau of Land Management, Department of Energy Office Energy Efficiency and Renewable Energy and the Department of Interior. Solar Energy Development Programmatic EIS, http://solareis.anl.gov/eis/index.cfm.

Water use is another consideration for solar thermal. For instance, the SEGS solar plants in California have reportedly required between 800-1,000 gallons of water per MWh of electricity generated, making their water use even higher than nuclear plants.[109] Water use at the new Solana plant is expected to be approximately 928 gallons per MWh (Pasqualetti, 2008). As stated in the nuclear power section, in Arizona, sufficient water resources to supply a power plant with those kinds of water requirements exist only in the three-county area.[110]

A recent study by the Department of Energy confirms these water requirement estimates for recirculating cooling (and finds that they are the highest for LFR, at about 1,000 gallons per MWh, followed by parabolic trough and power tower designs, which require up to 800 gallons per MWh, and lowest for parabolic dishes, at 20 gallons per MWh). However, the study also indicates that options exist for hybrid and dry (air) cooling that might significantly reduce these water requirements. The downside of these less water-intensive cooling methods is lost output (1 to 5 percent compared to recirculating cooling) and higher cost (2 to 9 percent, again, compared to recirculating methods) (DOE, 2010).

4.6 Solar Power Generating Technologies: Solar Photovoltaic

A solar photovoltaic (PV) cell is the basic building block of a solar PV power system.[111] The solar cell absorbs light and processes it into energy using the photovoltaic effect. In the photovoltaic effect, absorbed light is transferred to electrons in the atoms of the semiconductor material in a PV cell. The interaction of the absorbed energy with these electrons causes them to escape from their normal positions in the atom and creates an electrical flow.

The efficiency of a cell is a measurement of the response of the solar cell to the different wavelengths in the spectrum of light shining on the PV cell. There are two limits to efficiency which PV cells face. The first is called the Shockley-Queisser limit, which applies only to single-junction solar cells. Given the amount of sunlight lost in this process, the theoretical efficiency is 41 percent. If solar cells are constructed beyond the single-junction design, they run into the thermodynamic efficiency limit of 87 percent (EPRI, 2008). Particular designs and materials

[109] Nuclear plants use approximately 785 gallons of water per MWh (Pasqualetti, 2009).

[110] Maricopa, Pima, and Pinal counties.

[111] The description of solar photovoltaic cells was taken from the US DOE Energy Efficiency & Renewable Energy (EERE) website.

used have their own limitations based on the different spectrums of light that they are able to utilize, recombination,[112] natural resistance,[113] temperature,[114] reflection,[115] and electrical resistance.[116]

PV cells are small, usually producing one or two watts of power on average. In order to increase the power output of PV cells, they are connected into larger units called modules. Modules can be connected together to form larger structures called arrays. The rest of the PV system consists of tracking devices that point these arrays toward the sun, components that convert direct-current (DC) electricity to alternate-current (AC) electricity,[117] and a storage device, such as a battery. The various pieces of equipment that support the PV array are known as the balance-of-system components.[118] Solar PV can be used in distributed or concentrated form, but this paper largely covers the distributed form, as it is currently in use in Arizona.[119]

Since the first commercial license for solar PV was sold in 1955,[120] crystalline silicon has been the dominant photovoltaic technology (EPRI, 2007). Combining high efficiency cells with standardized methods of production, crystalline silicon is representative of what is known as the first generation of solar cells. First-generation solar cells are high-cost, high efficiency cells that use three principal materials to capture the solar spectrum and convert it to electricity (EERE, 2009). The earliest solar cells to be commercialized on the market were mono-crystalline silicon (c-Si) (NREL, 2009). However, they waste a large amount of refined silicon and are gradually being replaced by poly-crystalline silicon cells (EERE, 2009),[121] which are cut from square ingots instead of cylindrical ingots. Poly-crystalline silicon cells represent an attempt to lower the cost of silicon cells while maintaining high efficiency. This explains the move to

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112 Charge carriers in a solar cell may recombine before making it into the electrical circuit (EERE, 2009).

113 Resistance to electron flow is typically caused by the choice of cell material (EERE, 2009).

114 Solar cells lose efficiency as the temperature increases (EERE, 2009).

115 Solar cell materials can reflect as much as 30 percent of the sun's light (EERE, 2009).

116 The choice of darker colored contacts to limit electrical resistance causes a dilemma because the substance also blocks incident light (EERE, 2009).

117 AC electricity is preferred over DC electricity because it loses less electricity in transmission and the voltage is able to be changed (Different Sources of Electricity, 2009).

118 Description of the PV system was taken from the EERE website.

119 The only solar PV installations currently in Arizona are distributed (APS, 2009).

120 Western Electric licenses commercial solar cell technologies in 1955 (EIA, 2009).

121 Despite the movement towards poly-crystalline silicon cells, mono-crystalline solar panels are still being produced and sold in large quantities by leading firms such as Sharp and BP Solar (NREL, 2009).

ribbon silicon, which is a particular form of multi-crystalline silicon that cuts cost due to reduced silicon waste. The third type of first-generation cells is made from gallium arsenide (EERE, 2009). Gallium arsenide cells have achieved greater levels of efficiency than crystalline silicon cells, but have exorbitant costs due a lack of producers of single crystal gallium arsenide (Sandia National Laboratories, 2009). Their greater efficiency and ability to withstand higher levels of heat make gallium arsenide solar cells ideal for concentrated PV use.

Second-generation solar cells are the result of the experimentation in thin film cell technology. Thin film cells have been in commercial use since the 1970s, but have been overshadowed by silicon based solar cells due to low efficiency (Sandia National Laboratories, 2009). The goal of thin film solar cells is to use low cost photovoltaic materials that can substitute for or reduce the use of more expensive silicon. Thin film manufacturers believe that the lower costs compensate for the lower generating efficiency.

There are four materials that are most effective in thin film solar cells. Copper indium gallium selenide (CIGS) is used to form polycrystalline thin film photovoltaic solar cells (EERE, 2009). They are cheap to manufacture because the CIGS can be deposited directly onto glass sheets in a polycrystalline form instead of growing large crystals. Cadmium telluride (CdTe) replaces silicon due to the significant reduction in cost but has not achieved the efficiency rates of silicon (EERE, 2009). Amorphous silicon (a-Si) requires only 1 percent of the silicon needed for c-Si cells, which decreases efficiency but cuts cost (EERE, 2009). Micromorphous silicon is not found in nature, but is a combination of micro-crystalline and amorphous silicon. It maintains the low cost of thin film cells, while providing increased efficiency compared to other thin-film materials (Unine, 2009).

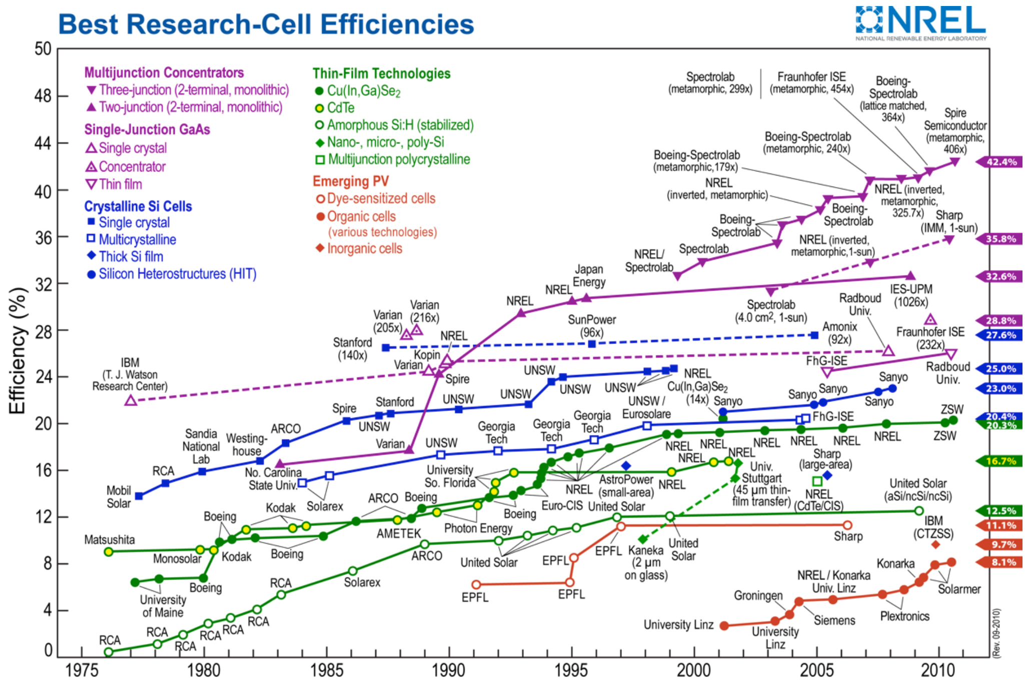
Third-generation solar cells attempt to combine the high-efficiency of silicon-based cells with the low cost of thin film designs. There are many different types of cells being experimented with, but the most successful are dye-sensitized, polymer, thermophotonics, nano-crystalline silicon, quantum dot, and multi-junction. Dye-sensitized solar cells attempt to combine the low cost of thin film solar cells with a higher efficiency (Swiss Federal Institute of Technology, 2009). However, they have yet to demonstrate efficiency for large-scale electric power generation. They are currently commercially available and are extremely flexible in application. Dye-sensitized cells can be used in any small-scale capacity, whether it is powering a drill or generating power as part of a tent or handbag (Heimbuch, 2009). Polymer solar cells are organic and designed to be low cost and high efficiency (Eindhoven University of Technology, 2009). They are similar to dye-sensitized cells in that, while they have not yet achieved high efficiency, they can be used in numerous applications. Examples include use in briefcases that can recharge laptops (Bullis, 2008).

Thermophotonics uses the excess heat caused by the photovoltaic process to create energy (Ioffe Physico-technical Institute, 2004). Nano-crystalline silicon (nc-Si) is combined with a-Si to increase efficiency in solar cells. The technology is still evolving but there are also several efforts underway to commercialize solar cells based solely on nc-Si (EERE, 2009). Quantum dot solar cells improve cell efficiency by extending the band gap of solar cells for harvesting more light in the solar spectrum and also generate more charge from a single photon. Quantum dot cells are further away from commercialization than any of the other third generation technologies listed (NREL, 2009). Multi-junction solar cells use multiple layers of thin film cells that capture more of the solar spectrum to convert to electricity. These cells have recorded the highest efficiency yet recorded[122] for a solar cell and utilize several different materials, including: gallium arsenide, germanium, and indium phosphide (EERE, 2009).

Below, Figure 15 illustrates the improvement in solar cell efficiency over time. The generations of solar cells are color coded, with blue representing first generation, green representing second generation, and purple and orange representing third generation. Latest estimates show that some of today's solar cells can achieve conversion efficiencies exceeding 40 percent.

[122] Exceeding 40 percent (NREL, 2009).

Figure 15. Solar PV Cell Efficiency Milestones



Source: Based on data compiled by Lawrence Kazmerski, National Renewable Energy Laboratory (NREL) as of September 2010.

The fundamental advancements in solar PV technology have been in cell generation technology, from first to second and third generation of PV solar cells. However, there have been several attempts to improve the systems without changing the cell composition. Solar concentrator technology concentrates solar light passing through a window, increasing efficiency (McGee, 2008). Concentrator PV uses a large lens to magnify the power of the sun, increasing it by a factor of ten. In order to prevent the solar structure from melting, researchers at International Business Machines (IBM) used computer-cooling devices to maintain temperature balance (IBM, 2008). In addition to changes in solar concentration, the movement in cell modification contains a lot of promise for the future of solar cells. Experimentation in up/down converters to utilize the area above and below the band gap to absorb extra photons will increase the efficiency of all photovoltaic cells (Pennicott, 2002). Likewise, the research into hot carrier cells, which will slow down the rate of photo-excited carrier cooling, will increase the voltage of the cell (Stanford University, 2008). It is clear that research into effective solar methods is not lacking, but it remains to be seen whether it will translate to greater market adoption.

4.6.1 The Future of Solar PV

Even though the output from photovoltaic installations in United States remains negligible (less than 0.1%), the installed capacity of PV systems has been growing steadily since 2001. Investment in grid-connected PV systems reached 890 MW in 2010, nearly double the amount recorded in the previous year. Of this 890 MW, approximately 40 percent was at industrial and commercial sites, 30% at residential locations, and the remaining 30% was utility-level installations. At the end of 2010, total grid connected PV capacity in the United States reached 2.15 GW. Electricity generation from solar PV continues to be hampered by high costs, however a number factors (improved access to capital, state and federal support mechanisms and the impact of RPS programs adopted by many states) have contributed to sustained interest in this technology (Interstate Renewable Energy Council, 2010).

These high costs a combination of high capital costs[123] and low capacity factors.[124] It is because of this combination that there has been a movement in solar PV cell research towards third generation technologies that will improve cell conversion efficiency (which will lead to higher capacity factors) while decreasing cost. However, the principal technologies in large-scale commercial operation are first-generation, silicon based (mono or poly-crystalline) or second-generation, thin film (CdTe or CIGS) cells. Any change in the market will begin with these four technologies (EPRI, 2007).

Storage is an essential ingredient in solar PV becoming more cost competitive. The ability to store the energy produced by a solar PV system during the day to feed the system in off hours is another opportunity to increase the capacity factor of solar PV. Currently, this storage is done principally through lead acid batteries (EERE, 2009). An effective battery for solar PV storage will be able to transfer energy at a highly efficient rate, offering high power, low cost, and a

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[123] The EIA's most recent estimates for overnight capital costs of a solar PV system range from $4,755 per kW for large scale installations (around 150 MW) to $6,050 per kW for smaller systems (under 10 MW), and $4,692 per kW for solar thermal power plants (2010 dollars) (EIA, 2010). A large portion of capital costs for PV units are driven by the cost of PV cells. In turn, the costs of PV cells are sensitive to the cost of silicon-based feedstock. A majority of PV panels in use today use *polysilicon* as a photovoltaic material, which is a grade of highly refined silicon. There is a supply and demand imbalance of polysilicon, which has resulted in rising feedstock prices to PV cell manufacturers. This imbalance is not caused by a lack of silicon (an abundant mineral in Earth's crust), but by a lack of capacity for purifying silicon to the level suitable for PV cell manufacturing (IREC, 2010).

[124] Compared to capacity factors for solar thermal with storage (estimated to 40+ percent), the average capacity factor for a residential solar PV system is under 20 percent (Black and Veatch, 2007).

large capacity. However, the batteries that currently offer such combination of efficiency, power, and cost effectiveness are only able to function in small systems.[125] Research into increasing battery storage and grid energy storage has been developing in the expectation that it will increase the capacity factor of solar PV[126] (EERE, 2009).

Compressed air energy storage (CAES) is another method of storing energy that could provide a solution to the intermittency concerns of energy sources such as solar PV and wind. Using electricity created by power generation systems, air is compressed into large underground storage facilities, such as salt caverns. The compressed air can be used to run a generator during periods of peak electricity demand. The biggest concern with compressed air storage is in finding suitable locations.

The CAES concept has been around for a few decades, though its application to renewable energy technologies is more recent.[127] A few CAES demonstration projects have recently received or are slated for government funding, such as New York State Electric and Gas (NYSEG)'s proposal to create a 150 MW CAES storage in a salt cavern in upstate New York. In California, Pacific Gas and Electric (PG&E) is analyzing the a 300 MW CAES project in partnership with the Department of Energy. CAES storage has lower efficiencies than battery technologies, but is estimated to be cheaper than batteries (by about a factor of three) (Greentech Media, 2010).

Until the CAER technology can become available in many parts of the country, battery technology will remain the primary medium for solar PV electricity storage.

The significant driver of PV growth in Arizona is the RES which requires utilities to supply not only 15 percent of their retail power sales from renewables, which include solar, but also asks that 4.5 percent come from distributed sources by 2025.[128] The RES has also recommended

[125] Such as the A123 and AltairNano products.

[126] Federal stimulus money has been poured into battery storage research (Riddell, 2009).

[127] Today, there are only two CAES plants in operation around the world: the 290 MW Huntorf plant in Germany, built in 1978, and the 110 MW McIntosh plant of SouthPower Electric Cooperative in Alabama, operating since 1991.

[128] Specifically, the RES indicates that electricity from distributed generation sources should make up 30% of the utilities' annual requirement starting in 2012 (reaching 4.5% of sales in 2025). Moreover, 50 percent of this

levels of solar PV that utilities should reach each year. For example, the 2009 distributed generation target for APS is estimated to be 88,000 MWh, which will increase to approximately 400,000 MWh in 2013.[129]

4.6.2 Solar PV Feasibility Assessment

In the following section, we evaluate the feasibility of solar photovoltaic for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of solar photovoltaic, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Solar PV Criteria

Due to the large investment in future solar technology development, there is a wide range of readiness levels for solar PV technologies. First generation cells dependent on silicon and gallium arsenide are mature, commercialized solar cells (TRL-9) (EERE, 2009). Second generation cells based on thin film designs are also at a mature, commercialized stage (TRL-9) (EERE, 2009). The third generation is complicated because of the breadth of technologies available. Dye-sensitized cells have already been approved for commercial use but have not been adopted on a significant scale by the market (TRL-8) (NREL, 2009). Thermophotonics, quantum dot, nano-crystalline, and multi-junction cells have all made significant strides in technical and cost feasibility in the laboratory, yet have not reached the commercialization stage (TRL-6) (NREL, 2009). Polymer cells are still in a developmental stage and, while they have undergone laboratory testing, are still waiting significant technical improvements before the commercialization process is considered (TRL-5) (NREL, 2009).

The state of Arizona is located in one of the highest areas of solar insolation in the world. However, due to the lack of sufficient storage for baseload use, solar photovoltaic will only be

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distributed generation requirement must be met by purchases from residential installations and the other half from non-residential (also non-utility) installations (Database of State Incentives for Renewable Energy, 2011).

129 Assuming a 20 percent capacity factor for solar PV, the implied capacity requirement for 2009 is approximately 50 MW. For 2013, it will be approximately 228 MW.

able to satisfy the state's energy demand during the operating hours of the technology plus the additional storage time gained from either batteries or central electricity storage.

Additional Solar PV Feasibility Issues

Similar to solar thermal, solar PV capability is determined by the amount of sunshine. The annual solar insolation in Arizona is greater than 2,200 kWh per square meter, compared to 1,250 kWh per square meter in Germany (NSRD, 2009). Uninterrupted sunshine is particularly critical for solar PV, since it relies on light rays from the sun versus solar thermal, which relies on the heat from the sun (EERE, 2009). With solar PV's ability to operate in a distributed manner, placement of solar panels is not a problem. In a recent study (Black and Veatch, 2007), it was estimated that Arizona has the capacity to supply the entire electricity needs of the state, provided that storage is available.

Solar PV does require a relatively flat surface in order to mount and operate a solar panel, but distributed solar PV has a significant advantage in being able to be mounted on roofs. Given a recent study's (Black and Veatch, 2007) assessment that there is enough available space and solar insolation to power the state, land is not an issue for solar PV.

Unlike solar thermal, less than a gallon of water is required to produce 1 MWh of electricity from solar PV.[130] In a state with six counties facing a future water deficit, the water conservation of solar PV is a major advantage.

The intermittent nature of solar PV is a problem not only because utility planners cannot depend on it as a baseload generation source, but also electricity output from solar panels declines in the early evening as electricity demand reaches its peak (APS, 2008). Unlike solar thermal power technologies, which can store potential energy in the form of heat (molten salt storage), solar PV currently relies mainly on battery storage (NREL, 2009).

[130] This is compared with the 800-1,000 gallons per MWh of water required by solar thermal (Pasqualetti, 2008).

4.7 Solar Power Generating Technologies: Solar Updraft Tower

The solar updraft tower is a unique solar thermal power technology that utilizes the greenhouse effect, chimney effect and wind turbine to create electricity, with no emissions. The design of a solar updraft tower consists of a large area of solar thermal collectors that trap heated air underneath the collectors. The concentration of hot air results in natural convection (due to temperature differences at the base and top of the solar chimney), which pushes the air through the turbines up the chimney. A solar updraft tower can be considered a type of solar thermal power technology, since it uses the heat energy of the sun. On the other hand, the turbine operation relies on air flow, which resembles a wind turbine. Due to these unique features, solar updraft tower technology is discussed separately from other solar thermal technologies in this document.

In solar updraft tower design, the size of the collector area, the height of the chimney, and the availability of storage determine the plant's power generation capability and usefulness in a utility setting. Adding more collectors and increasing the chimney height yield more output. The technology also has an inherent storage capability, even though in a limited amount, due to the greenhouse effect occurring underneath the collectors[131] (Schlaich, 2005). In addition, the solar tower technology does not require any water for cooling which is an attractive feature (EnviroMission, 2009). On the other hand, the need for a large land area and construction of very tall towers (several thousand feet) for utility-scale development result in high investment cost.

The first demonstration project using solar updraft tower technology was built in Spain in 1982 with a maximum power output of 50 kW (Schlaich, 2005). Since that time, there have been several plans to build a large-scale, cost effective plant, but many have yet to be realized.

In December 2010, the government of China announced the world's first commercial solar updraft tower with a capacity of 200 kW, located in Inner Mongolia.[132] Australian developer

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[131] To increase storage further, tubes filled with water can be installed underneath the greenhouse area to take advantage of water's relatively high heat capacity.

[132] Government of China official web portal (Gov.cn), "China's first solar chimney plant starts operating in desert," December 28, 2010.

EnviroMission has the most concrete plans towards building large-scale solar updraft towers in the United States. The company is planning to build two solar updraft towers in Arizona (200 MW each), which were originally intended to be constructed in Australia. The company hopes to start construction of the first of these towers, named the La Paz Solar Tower, in 2012, and power delivery from the project is planned for sometime 2015. The chimney structure of the facility will be 2,500 feet (800 meters) tall. The total cost of the project is estimated at $750 million. EnviroMission has signed a long-term power sales agreement with Southern California Public Power Authority for the output (EnviroMission, 2009 and Southern California Public Power Authority, 2010). Another large-scale solar tower (40 MW) is in early planning stages in Spain.

4.7.1 Solar Updraft Tower Feasibility Assessment

In the following section, we evaluate the feasibility of solar updraft tower technology for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of solar updraft towers, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Solar Updraft Tower Criteria

Solar updraft tower technology is still in an experimental phase, with several towers planned but only one small-scale project (under 1 MW) in commercial operation (TRL-8). There is still some uncertainty surrounding actual levelized costs of generation for solar updraft towers (Zaslavsky, 2009) and the capacity factors achievable by the plants. We conclude that solar updraft tower is has limited technological feasibility for Arizona at this time. On the other hand, the technology only requires sunlight as an energy source. Given Arizona's solar advantage[133] and the assessment of solar resources (Black and Veatch, 2007), there are sufficient in-state resources for the development of solar updraft towers. The experience during construction and operation of the La Paz Solar Tower project, which is currently in an advanced

[133] See feasibility criteria for solar thermal and solar PV.

planning stage, will set an important precedent for future large-scale solar updraft tower projects in Arizona.

4.8 Wind Power

In 2009, wind power represented 1.8 percent of total electricity generated in the United States, but less than 0.1 percent of that in Arizona (EIA, 2010). Even though relative contribution of wind power to total power generation is still low, this nevertheless represents significant growth, as wind power was almost non-existent in the country 25 years ago.

Although windmills have been used for thousands of years, the first used to generate electricity was in 1888 in Cleveland, Ohio. It was 12 kW, which pales in comparison to the 1.7 MW (or 1,700 kW) capacity of latest wind turbines.[134] The growth of large-scale fossil-fueled power plants and the extension of the electrical grid to rural areas limited wind power to minor experimentations.[135] The wind industry in the United States began to experience serious growth following the OPEC energy crisis of 1973. In response to the crisis, the federal government led a nationwide effort to reduce dependence on oil through the use of alternative methods, including wind. However, the wind movement did not reach a significant commercial stage until 1989, when California began operating what was, at the time, the largest concentration of wind power in the world. Up to the turn of the century, California continued to provide the majority of wind generation in the United States (California Energy Commission).

Beginning in 2002,[136] wind began to take off with the extension of the federal production tax credit for wind and other renewable energy sources in the United States. California accounted for the significant increase in wind power from 1985 to 1990, while Texas has been the leading wind installer since then (EIA, 2009). In 2006, Texas passed California as the state with the most wind power capacity in the United States. For the breakdown in wind generation in the United States over the last 25 years, see Table 11. Arizona has recently started to invest in its

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[134] The average turbine capacity for installed wind power turbines in the United States in 2009 was 1.74 MW (Department of Energy, Office of Energy Efficiency and Renewable Energy, 2011).

[135] For example, the 1.25 MW Smith-Putnam Machine was installed in Vermont in 1941.

[136] Table 12 does not show the difference between wind generation in the United States in 2001 (6,737,322 MWh) and 2002 (10,354,279 MWh).

wind resources. As of 2008, no state utility was receiving energy from in-state wind sources,[137] but in 2009, Arizona completed its first utility-scale wind power plant (the 63 MW Dry Lake Wind Power Project), which generated nearly 30,000 MWh of electricity in 2009 (EIA, 2010 and American Wind Energy Association, AWEA, 2010).

Table 11: Wind Power Generation in the United States (MWh)

Year	*Generation (MWh)*
1985	5,762
1990	2,788,600
1995	3,164,253
2000	5,593,261
2005	17,810,549
2009	73,886,132

Source: EIA, 2010.

The design of devices to generate energy from wind has changed very little over the last 70 years. The turbines built in the 1940s look very similar to those being constructed in large numbers in Texas today (Dodge, 2006). Despite the look, the details of the plants have changed dramatically. Standardizing height, changing blades, modernizing the turbine engine, and solidifying the structure have all been major improvements that have spurred tremendous growth in wind power (NREL, 2009). The goal of research today is to investigate methods to decrease the cost per unit of power generated by low wind speed areas. Low wind speed technology is important because high-speed sites (greater than 15 mph) are becoming scarce (NREL, 2009), leaving the next class of sites (13 to 15 mph) to be developed. The DOE has funded efforts to re-think the concepts, component technology, and application of advanced low speed wind turbines. For example, there are experiments in decreasing drivetrain weight to make taller towers more cost effective. Improved rotor designs are in place to allow for greater rotor diameter, which will increase the amount of energy captured by wind turbines (NREL, 2009). The newly designed Clipper wind turbine showcases many of the improvements in turbine blades, rotor, and drivetrain (NREL, 2009).

[137] Though APS and SRP had contracts to purchase wind power from outside the state (APS, 2009 and SRP, 2009).

In addition to standard wind turbines, there has also been development over the last decade in offshore and distributed wind turbines. Offshore water turbines have been very successful in northern Europe. At the end of 2010, it was estimated that the United Kingdom had nearly 1.3 GW of installed offshore wind power capacity (which represents more than half of total offshore capacity worldwide), followed by Denmark (854 MW), the Netherlands (249 MW), Belgium (195 MW), Sweden (164 MW), and Germany, Finland and Germany (each with 100 MW or less). Germany and the UK plan to develop an additional 16 GW of offshore wind power capacity over the next five years (Renewable Energy World, 2011). In the United States has several projects that are being planned, but none are in operation.[138] In early 2011, the U.S. Department of Energy unveiled a national offshore wind power strategy with the aim of spurring investment in the industry (Department of Energy, 2011).

Currently, shallow water wind turbines are feasible for offshore development. Deeper water facilities need further technological development. The advantage of offshore wind turbines is that they do not require land and take advantage of higher wind concentrations. However, turbines placed in the ocean require a different technology than those on land. They require piles to be driven into the seabed, a stronger structure to cope with wind-wave interaction, and protective coating to combat erosion.[139] These structures are bigger and equipped with a variety of systems to reduce maintenance, prevent lightning damage, and have attached navigation lights to prevent collisions. Building wind turbines in the outer continental shelf, which is deeper and potentially more hazardous, require even more maintenance and safety protection, as well as a completely new stability design (NREL, 2009).

Distributed wind turbines share many of the advantages of distributed solar PV in that they can be built in many different locations, are close to the load center, and do not require

[138] The outlook of the beleaguered Cape Wind offshore wind project (consisting of nearly 130 individual turbines of 3.6 MW each, adding up to 468 MW of total capacity) in the Nantucket Sound (off the southern shore of Massachusetts) is still uncertain despite completing all federal and state permitting processes and gaining approval from the local regulator (Cape Wind, 2010). This project has the potential to set an important precedent for any future offshore wind power development in the United States. Two other offshore developments, in Maine and New York, have also been announced.

[139] Alternative designs for deep-water floating turbines are also being considered. A demonstration installation of first such a deep-water floating turbine was completed in Norway in 2009 (Renewable Energy World, "Hywind Floating Turbine Installed," June 9, 2009). A U.S.-based firm, Principle Power, is using research grants from the Department of Energy to develop a similar floating offshore wind turbine technology (Department of Energy, 2011).

transmission. However, wind turbines can only be constructed in areas with significant wind and do not blend into their surroundings. In addition, they are an intermittent source of energy, which requires users to be tied into the grid. The growth of the industry has been limited by these factors, but the significant cost reductions and ongoing research have given this industry significant potential (EERE, 2009).

4.8.1 The Future of Wind Power

The future of wind power technology in Arizona will depend on further reductions in capital costs, the ability to manage wind intermittency (energy storage), and improvements in low wind speed technology.

As with other emerging renewable energy technologies, continued reduction in capital costs will greatly influence the adoption of wind power technology across the country.[140] However, the intermittency (or, the variable rate nature) of wind power is an issue that needs to be addressed regardless of reductions in capital costs. As with solar energy, the solution to the intermittency is large scale and economical energy storage, either in a central location (grid storage) or at the individual wind sites, using battery technologies or compressed air energy storage. Neither of these technologies is currently able to provide sufficiently large capacity storage at a low cost (NREL, 2009).

Low wind speed technology has the capability to enhance the existing wind power potential in Arizona. The majority of wind power sites in Arizona are class three, which have lower speed, and therefore, operate at a lower capacity factor. The ability to increase the efficiency of wind turbines to make class three sites economical will have a significant impact on wind power in Arizona. Table 12 shows the classification of wind sites in Arizona according to the Department of Energy's wind power class-scale (from 1 to 7, one being weakest, and 7 being strongest) and the estimated power generating potential in megawatt terms.

140 According to the IEA's most recent estimates, overnight capital costs for on-shore wind power plants are around $2,438 per kW, whereas capital costs for offshore installations are more than twice that amount, at $5,975 per kW (2010 dollars). These costs are 21 percent and 50 percent higher than previous year's estimates, for on-shore and offshore wind power, respectively (EIA, 2010).

Table 12: U.S. DOE Classes of Wind Power and Corresponding Wind Power Potential in Arizona (MW)

Class	*Density (W/m²) at 50 meters*	*Speed at 50 meters*		*MW Potential in Arizona**
		meters/second	miles/hour	
1	0 to 200	0 to 5.6	0 to 12.3	-
2	200 to 300	5.6 to 6.4	12.3 to 14.1	-
3	300 to 400	6.4 to 7.0	14.1 to 15.7	20,538
4	400 to 500	7.0 to 7.5	15.7 to 16.8	1,814
5	500 to 600	7.5 to 8.0	16.8 to 17.9	519
6	600 to 800	8.0 to 8.8	17.9 to 19.7	202
7	>800	≥ 8.8	≥ 19.7	20
			Total	**23,093**

Source: Department of Energy, National Renewable Energy Laboratory (2009). Wind Power Potential (MW) obtained from Black and Veatch (2007). The total wind power potential for Arizona (23,093 MW) identified in this table is notional and does not take into account any practical constraints to development due to land-use restrictions, transmission access and unsuitable terrain. These factors are discussed in the text.

4.8.2 Wind Feasibility Assessment

In the following section, we evaluate the feasibility of wind power for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of wind, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Wind Criteria

On-shore, offshore and distributed applications of wind turbine technology are in commercial use worldwide (TRL-9). Unlike energy areas like solar PV or nuclear, the technology for wind is mature and the future will consist of adaptations of the existing concept rather than an entirely new design (NREL, 2009).

Although Arizona is better known for its solar energy sources, the state also has some wind sites suitable for utility-scale wind power development. Accounting for terrain, transmission, land ownership and other factors, 1,490 MW of potential wind generation projects were identified for the state of Arizona in 2007.[141] A more recent estimate developed by the National Renewable Energy Laboratory (NREL) measures the wind power potential at 80 meters height above ground,[142] where the wind speeds are higher (while Table 12 measures it at 50 meters). Accounting for similar land-use, terrain and transmission-related constraints, this estimate puts Arizona's total ultimate wind power capability at 10,900 MW (NREL, 2010).

To put this in perspective, the state of Arizona consumed 73,433 GWh of electricity in 2009 (EIA, 2010). If all of these projects were developed, their combined output could meet anywhere from 5 to over 30 percent of Arizona's current electricity consumption and 4 to 29 percent of its forecasted demand in 2032.[143] Therefore, wind power technology is feasible and there is significant wind power potential in Arizona (especially for taller turbines). Wind power has the potential to become a major power generating source for the state over the next two decades and it would further contribute to the diversity of power generating sources in the state and help meet the state's RES requirements over time.

Additional Wind Feasibility Issues

Typical wind analysis focuses on sites that are class 3 and above due to the competitive cost of energy generation at that speed. Wind sites in Arizona demonstrate a potential for development of significant power generating capacity. A great portion of this capacity, however, would be at class 3 sites (refer to Table 12). In order to increase the amount of generation possible from Arizona's wind resources and make these class 3 wind sites more cost effective, improvements in low wind speed technology are necessary.

141 Since then, about 168 MW of total wind power capacity was constructed in Arizona (AWEA, 2010).

142 The measurement of wind power potential at 80 meters height above ground is not arbitrary. The average hub heights and rotor diameters for wind turbines have grown substantially over the past decade. The average hub height of wind turbines installed in the United States in 2010 was 79.8 meters. Since 1999, the average turbine hub height has increased by 43% (or 24.1 meters) (Department of Energy, Office of Energy Efficiency and Renewable Energy, 2011).

143 At 30 percent capacity factor, the lower estimate of 1,490 MW total capability would translate into total wind generation of nearly 4,000 GWh, whereas the higher NREL estimate (10,900 MW of potential) would translate into nearly 28,600 GWh of electricity supplied from wind power in Arizona. Based on 2009 total electricity consumption figures from the EIA for Arizona, wind power might meet 5 to over 39 percent of the state's electricity needs. Using a conservative estimate of demand growth (1.3 percent annually), these output levels correspond to 4 percent to 29 percent of total demand by 2030.

Land use is a significant factor for wind power due to the specific wind requirements for generation power and visual pollution created by large wind farms. Wind farms are typically constructed in areas where wind power is at least class three, which limits the amount of land available for wind turbine construction. Wind turbines are able to be constructed on hills as well as flat terrain (California Energy Commission, 2009), but the area must be free of trees or other obstacles to the operation of the wind turbine (Denholm, 2009).

Similar to solar PV, wind power does not have significant water requirements.[144] This is especially important in Arizona, since Coconino County contains many of the high-wind areas in the state and is projecting a water deficit (Seidman, 2008).

The intermittent (variable rate) nature of wind power is a significant challenge for utility load planners. While wind patterns are fairly regular looking at annual data, they are very hard to predict on a day-to-day basis. In fact, wind energy only becomes predictable in the hour-ahead time frame (Acker, 2007). As a result, utilities must be able to have sufficient generation to satisfy load requirements in case wind patterns change. These integration costs are estimated to range from $1 to as high as $9 per MWh (Department of Energy, Office of Energy Efficiency and Renewable Energy, 2011). In addition to its variable nature, wind reaches its peak generation potential in the spring, while the peak energy demand in Arizona occurs in the summer.

4.9 Fuel Cells

Fuel cell technology is rapidly growing in popularity and usage (NREL, 2009). Unlike fossil fuel power generation, which uses combustion to generate electricity, fuel cells reverse the process of electrolysis,[145] combining hydrogen and oxygen to generate electricity. Specific fuel cell models are differentiated based on the electrolyte[146] and structure used in the cell. Experiments with different materials have been attempted to improve cell flexibility, efficiency and lower

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[144] According to the California Energy Commission, wind turbines use less than a gallon of water to generate a MWh of electricity.

[145] Electrolysis is a chemical process in which an electric current is applied to water and creates hydrogen and oxygen.

[146] The electrolyte separates the oxygen and hydrogen in the fuel cell and facilitates the production of electricity. After the catalytic process that separates protons and electrons, the electrically insulating electrolyte forces the electrons to travel in an external circuit, which generates electricity.

cost. The flexibility of fuel cell application is due to the structure of a fuel cell, which can be stacked to provide power anywhere from 10 watts (W) to 100 MW (though typical applications in power generation have not yet exceeded a total of 2 MW in size). This is ideal for small applications, such as cell phones and laptops, as well as larger applications, such as industrial power supply or baseload utility power generation (U.S. Fuel Cell Council, 2009).

Fuel cell technology has principally been designed to operate with hydrogen as a fuel source.[147] However, fuel sources such as natural gas and biogas have proved to be applicable for use in fuel cells (NREL, 2009). This section specifically focuses on applications of fuel cells in power generation, whether they are fueled directly by hydrogen or by other gases (which are reformed into hydrogen within the fuel cell unit). Table 13 summarizes current fuel cell technologies. As the table indicates, the ability of a fuel cell technology to use multiple fuels, rather than just hydrogen, is considered an advantage in today's marketplace. This is primarily due to the high cost of hydrogen production and storage (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), 2011). Provided that there is a steady supply of fuel (hydrogen or other suitable gases), fuel cells can operate either as a baseload or peaking source due to quick start up and shut down capability (U.S. Fuel Cell Council, 2009).

147 It is important to note that hydrogen is technically not a fuel source, though is referred to as such for convenience. A primary fuel source is a substance that yields more energy than it takes to create it. Hydrogen is produced from other energy sources, and, therefore, is not a primary energy source (like coal). Rather, it is an energy carrier (like electricity).

Table 13. Types of Fuel Cell Technologies

Fuel cell type	*Typical stack size*	*Power generation application*	*Advantages*	*Disadvantages*
PEM (polymer electrolyte membrane fuel cell)	< 1 kW to 100 kW	Backup and portable power Stationary power Distributed generation	Solid electrolyte reduces corrosion Operates at relatively low temperatures Quick start-up	Sensitive to fuel impurities Uses precious metal catalysts that are expensive Uses only hydrogen as fuel Lower efficiency (35%)
SOFC (solid oxide fuel cell)	1 kW to 2 MW	Utility scale power Stationary power Distributed generation	Solid electrolyte Fuel flexibility High efficiency (60%) Can use a variety of catalysts	Operates at very high temperatures (1800ºF), which causes corrosion Long start-up time
MCFC (molten carbonate fuel cell)	300 kW to 3 MW (300 kW modules)	Utility scale power Distributed generation	Fuel flexibility High efficiency (45-50%) Can use a variety of catalysts	Very corrosive electrolyte Operates at high temperatures (about 1200ºF) Long start-up time
AFC (alkaline fuel cell)	10 kW to 100 kW	Auxiliary power (military and spacecraft)	High efficiency (60%) Low cost components	Process sensitive to carbon dioxide in fuel and air Very caustic medium Uses only hydrogen as fuel
PAFC (phosphoric acid fuel cell)	400 kW (100 kW modules)	Distributed generation	Most commercially developed fuel cell Operating temperature range is about 400ºF	Long start-up time Low current and power Uses only hydrogen as fuel

Source: Adapted from the following two tables: U.S. Department of Energy's Hydrogen Analysis Resource Center, Types of Fuel Cells table (not dated) at http://hydrogen.pnl.gov/filedownloads/hydrogen/datasheets/types_of_fuel_cells.xls and EERE's Fuel Cell Technologies Program, Comparison of Fuel Cell Technologies (February 2011) available at http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf.

Fuel cells using hydrogen can be considered renewable depending on how the hydrogen was produced. Currently, much of the world's hydrogen supply is produced from oil, coal or gas[148] and, as a result, is not renewable. However, hydrogen produced by renewable resources, such as wind, water, or solar, would be considered renewable. One of the challenges facing the fuel cells industry is therefore improving low-carbon hydrogen production (EERE, 2011). Table 14 shows the potential hydrogen available from renewable resources in Arizona.

148 National Hydrogen Association, 2009.

Table 14: Arizona Total Hydrogen Production Potential from Renewable Resources

Resource	*Production Potential (million kilograms)*
Biomass	142
Solar	27,433
Wind	727
Total	28,302

Source: Milbrandt (2007).

4.9.1 The Future of Fuel Cells

The future success of fuel cell technology depends on the ability to reduce costs, expand existing hydrogen production capabilities, and to utilize of renewable energy sources for obtaining hydrogen. Though overnight capital costs[149] have fallen significantly since early 2000s, they remain high relative to existing technologies, which prevent fuel cells from being adopted on a mass commercial scale (EERE, 2011). The high cost is typical[150] of many technologies that are still in a largely research and demonstration phase.[151] Therefore, the use of more cost effective materials, standardization of manufacturing, and variation in use will all lead to a reduction in cost and increased adoption of the technology. Hydrogen production is also a factor in the adoption of fuel cell technology. Currently, the United States produces more than nine million tons of hydrogen each year. The majority of this hydrogen is consumed at the place of manufacture or used in chemical processes, rather than used as a fuel (NHA, 2009). The production of large amounts of hydrogen for use in fuel cells, at low cost, is crucial for the development of fuel cell technology (U.S. Fuel Cell Council, 2009).

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149 $6,835 per kW for a 10 MW (= 25 x 400 kW) phosphoric acid fuel cell (PAFC) stationary power unit (2010 dollars) (EIA, 2010).

150 Solar PV, solar thermal, and wind technologies all suffered from high initial investment costs prior to their large-scale commercial adoption (EIA, 2009).

151 Most fuel cell technologies are still being tested and have limited commercial exposure (NREL, 2009). It is, however, worth noting that a diverse group of commercial and industrial end-users, universities, and military bases have embraced stationary power applications of fuel cells (such as Whole Foods, Albertsons, Coca-Cola, FedEx, UPS, Adobe, Walmart, Cox Enterprises, Bank of America, Safeway, Cypress Semiconductor, eBay and Google, California State University, World Trade Center site in New York City). In 2010, more than 25 MW of stationary fuel cell power generators were installed, many of which deploy fuel cells for combined heat and power (CHP) purposes, as well as for back-up power. Many of these systems can also utilize waste gas (biogas, or landfill gas) as fuel (EERE, 2011).

4.9.2 Fuel Cell Feasibility Assessment

In the following section, we evaluate the feasibility of hydrogen-based fuel cells for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of fuel cells, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Fuel Cell Criteria

The feasibility of fuel cells in Arizona for power generation is not restricted by the availability of either hydrogen[152] or natural gas, which can be reformed into hydrogen for use in certain types of fuel cells. However, the relative technological immaturity[153] and significant gap in cost competitiveness[154] between fuel cells and existing technologies means fuel cells are not feasible for power generation in Arizona in the near future (TRL-8).

4.10 Geothermal

In 2009, the United States obtained 0.4 percent of its electricity needs from geothermal energy (about 15,210 GWh). Currently, Arizona has no electricity generation from geothermal-energy resources (EIA, 2010). Geothermal energy is obtained from heat stored in the Earth. Similar to solar thermal, there are three types of geothermal energy. High temperature geothermal energy is used in power generation. Moderate-to-low temperature geothermal energy is utilized in direct applications such as district and space heating. Lower temperature geothermal energy is used to heat and cool buildings through the use of geothermal heat pumps (EIA, 2009). The use of geothermal energy goes back to Roman times, where hot springs provided heat for homes as well as the source for Roman baths (EIA, 2009).

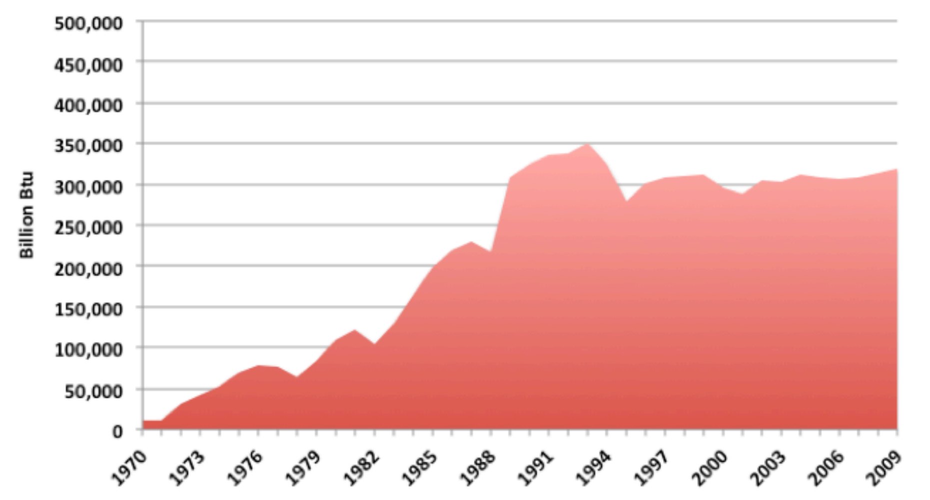
152 Recent estimates indicate that current hydrogen production in the United States can be significantly expanded (NHA, 2009).

153 The NREL notes that the technology is still in a developmental stage. In July, the DOE cut research spending on hydrogen fuel cell cars due to their lack of commercial readiness in the foreseeable future (U.S. Fuel Cell Council, 2009).

154 EIA's most recent estimates of overnight capital costs for fuel cells for power generation ($6,835 per kW) are much higher than capital costs for advanced pulverize coal or natural gas-fired combined cycle technologies, at $2,844 and $1,003 per kW, respectively (without any carbon capture and storage) (2010 dollars) (EIA 2010).

Between 2005-2010, worldwide direct use of geothermal energy (i.e., as heat energy) nearly doubled.[155] Worldwide installed geothermal power generation capacity in 2010 reached 10,717 MW. About 29 percent of this total capacity is located in the United States.[156] Figure 15 illustrates the increase in primary geothermal energy use for electric power between 1970 and 2009 in the United States. As the figure indicates, since the early 1990s, the growth in electricity output from geothermal plants has stagnated.

Figure 16. U.S. Primary Geothermal Energy Use for Electric Power, Billion Btu, 1970-2009



Source: EIA, 2010.

Geothermal power plants require a significant up-front investment and factors that determine investment feasibility are highly site-specific.[157] Before any actual power generation takes place, a potential investor must finance exploration, resource verification, and site preparation and construction. Once the site has gone through these steps, a production well is drilled to access the geothermal heat, which is pressurized, and provides sufficient energy to turn the turbine

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155 About 261,418 terajoules in 2005 compared to 438,071 terajoules in 2010 (International Geothermal Association, 2011, see http://www.geothermal-energy.org/246,direct_uses.html).

156 International Geothermal Association (2011). See http://www.geothermal-energy.org/226,installed_generating_capacity.html.

157 Depending on the type of technology, the EIA estimates overnight capital costs for geothermal power generation to range from $4,141 to $5,578 per kW (2010 dollars). This represents a 132% increase over previous year's estimate by the EIA due to site-specific factors that drive actual costs higher (EIA, 2010).

blades to generate electricity.[158] In most cases, used geothermal fluids are returned to the geothermal reservoir using an injection well (EERE, 2009). Once built, geothermal power generation is attractive due to high average capacity factors,[159] and low operating costs. In addition, the United States possesses large amounts of geothermal energy potential.[160]

4.10.1 Geothermal Feasibility Assessment

In the following section, we evaluate the feasibility of geothermal power generation for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of geothermal, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Geothermal Criteria

Arizona's geothermal power generation potential in the near to medium-term has been estimated to be 35 MW, which would produce approximately 215 GWh per year (Black and Veatch, 2007). This corresponds to less than 1% Arizona's electricity demand in 2009.[161] Therefore, the existing geothermal potential in the state is not sufficient to make geothermal a feasible contributor to the state's electricity resource mix.

4.11 Biomass

In 2009, the United States generated 1.8 percent, whereas Arizona generated less than 0.2% of their required electricity from biomass energy sources (EIA, 2010). Biomass consists of biological material such as forest residue, plant matter, and biodegradable wastes, but does not include fossil fuels (EERE, 2009). It is considered a renewable resource despite its carbon

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[158] The cost of this process varies from one site to another. Geothermal sites that are close to the surface require minimal exploration and drilling. However, these are have largely been utilized and many future projects will face increasing costs (MIT, 2006).

[159] Geothermal power plants have recorded capacity factors of up to 90 percent. The average is 73 percent (Fridleifsson, 2008).

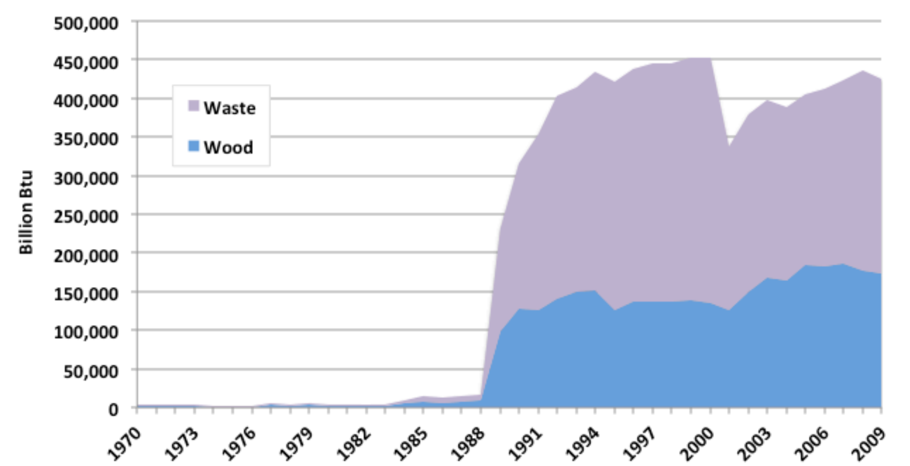
[160] Much of this potential is in the Western United States (EIA, 2009).

[161] Arizona's total electricity consumption in 2009 was 73,433 GWh.

content, because, unlike fossil fuels, biomass is a part of the recent carbon cycle and, as a result, does not disturb the carbon dioxide content in the atmosphere. In other words, biomass is considered a *carbon-neutral* energy source. (EIA, 2009). Humans have always burned biomass energy sources for heat and still continue to do so. However, efforts to use biomass to generate electricity have become important as the world searches for inexpensive and reliable renewable energy resources. Biomass is able to satisfy both of these criteria, as it is relatively inexpensive[162] and can be counted on as a baseload generation source.[163] Biomass is also well suited to industrial applications of combined heat and power (CHP), which is widely utilized.

In the United States, biomass resources were used in very small quantities for electricity generation until 1988. As Figure 17 shows, biomass consumption for electricity generation has remained relatively steady since then. In 2009, the U.S. generated a total of 54,337 GWh of electricity from biomass sources, which is enough to power nearly 5 million U.S. households.[164]

Figure 17. U.S. Primary Biomass Energy Use for Electricity Generation, Billion Btu, 1970-2009



Source: EIA, 2010.

162 Unlike coal or natural gas, there are no exploration or production costs for biomass as a fuel, since biomass either naturally occurs or is generated as waste by consumption or other processes. Much of the fuel costs for biomass-fueled power plants, therefore, are transport-related. Most recent estimate for overnight capital costs for a direct combustion biomass plant is $3,860 per kW, which compares favorably with the cost of solar thermal (ranging from $4,141 to $5,578 per kW) and solar PV (ranging from $4,692 to $6,050 per kW) (2010 dollars) (EIA, 2010).

163 This is especially important given the intermittency of wind and solar resources. Biomass plants can achieve capacity factors as high as 80 to 90 percent (EIA, 2009).

164 Based on the average U.S. household consumption of 10,896 kWh of electricity during 2009 (EIA, 2010).

The majority of biomass plants use direct-fired (or direct combustion) systems that heat biomass fuel to generate steam and run a steam turbine (NREL, 2009). Given the potential of biomass as a renewable energy resource, research efforts to improve the efficiency and reduce the cost of biomass fueled power generation technologies have increased.

4.11.1 The Future of Biomass

Experimentation has taken place with the turbine used to generate electricity (NREL, 2009). Screw type engines are compact, have low maintenance costs, and a long life, which makes them a proven and economical way of converting biomass to electricity (BIOS, 2009). Stirling engines are also in the commercial process as a method to generate power economically from energy generators of less than 100 kW size (BIOS, 2009). Vegetable oil engines are also being experimented with as a way to increase efficiency and cut costs. Using a basic combustion engine and melting down biomass into liquid form, this type of energy production must be pre-cleaned and heated before the operation begins. Filters remove impurities and the fuel is then used to run a combustion turbine. Emissions are a concern, so different technologies, including catalytic systems and particle filters, will be put in place to decrease emissions to the regulated level (BIOS, 2009).

In addition to turbine changes, it is hoped that two other technology shifts will bring greater efficiency and lower costs to biomass-fueled power plants. Organic Rankine Cycle technology is an attempt to replace water with an organic medium, which provides improved efficiency and allow for combined heating and power (CHP) applications (BIOS, 2009). Combined heating and power is the future for many biomass systems (similar to geothermal and other technologies that generate excess heat from electricity generation). Biomass CHP systems have been successfully implemented in Scandinavia and Eastern Europe (Cogen Europe, 2009).

Similarly, co-firing is a technique that involves mixing biomass with fossil fuels (mainly coal) to lower the net emissions of existing coal-fired power plants with little or no loss in generating efficiencies (Mann and Splath, 2001). An additional benefit is the avoided cost of building new infrastructure (i.e., like solar and wind) to displace such coal-fired capacity in order to reduce emissions. At the end of 2008, the United States had about 3,772 MW of biomass co-fired coal capacity (EIA, 2010).[165]

Another emerging biomass technology is the integrated biomass gasification combined cycle (or simply biomass combined cycle), which is currently in demonstration phase. Similar to IGCC (coal), biomass is first converted into syngas, and then syngas is used for power generation. The advantages of this technology over direct combustion include the ability to achieve higher generating efficiencies, and its lower water requirement and lower greenhouse gas emissions. On the other hand, the gasification process raises the total capital costs significantly (by a factor of two) compared to the traditional direct combustion biomass plant (NREL, 2009).

As with other renewable resources, increasing the attractiveness of biomass as an electricity generation source involves cutting costs. Each innovation listed above is aimed at improving system efficiency, increasing usage, or simplifying the process to make biomass more competitive with fossil fuels. However, given its designation as a renewable resource, biomass can be a part of the future of electricity generation even without significant cost reductions. Whether it is feasible for Arizona or not is dependent on how it responds to our three criteria.

4.11.2 Biomass Feasibility Assessment

In the following section, we evaluate the feasibility of power generation from biomass for the state of Arizona using the criteria established in section three. In addition to determining whether the state has sufficient capacity and the technology readiness level of biomass, we highlight potential roadblocks for the technology's large-scale adoption by the state in the near future.

Biomass Criteria

In 2007, three potential biomass sites were identified in Arizona (Black and Veatch, 2007). Two of these sites were suitable for biomass cofiring facilities with a capacity of 20 MW, while the

165 See http://www.eia.gov/cneaf/solar.renewables/page/trends/table9.html. This represents a large amount with respect to total biomass-fueled power generation capacity in the United States (over 11,000 MW in 2009), though very small compared to total coal-fired generation capacity (which is more than 314,000 MW in 2009) (EIA 2010).

other was suitable for the development of a biomass direct firing plant with a capacity of 20 MW (representing a total potential of 60 MW).[166] Combined, these plants would have the capability to produce up to 420 GWh of electricity annually, enough to power nearly 38,500 homes.[167] This total biomass potential represents less than 1 percent of Arizona's total electricity consumption in 2009. Moreover, the relative contribution of biomass would decline to even lower levels as demand grows over time (assuming the biomass resource potential of the state is fixed),[168] Therefore, biomass is not a feasible energy source for meeting Arizona's electricity needs in the near future.

4.12 Biogas

Biogas is a broad term that encompasses gases produced by the biological breakdown of organic matter. Landfill gas is a type of biogas, which consists of approximately 60 percent methane and 40 percent carbon dioxide, and is created by decomposition of food wastes, paper, and other forms of waste. Anaerobic digestion of biodegradable materials such as manure or energy crops can yield a mixture of gases that include nitrogen, hydrogen, methane, and carbon monoxide. Methane gas traps heat at 20 times the rate of carbon dioxide (Environmental Protection Agency, 2009). Therefore, utilizing the methane-dense biogas as an energy source is better for the environment (since it results in carbon dioxide emissions, rather than a direct release of methane into the atmosphere). In addition to reducing emissions through the use of biogas as an energy source, landfill gas, manure, energy crops, and other types of biodegradable materials are readily available, making them a cheap fuel source.

Operation of biogas power plants varies slightly depending on the location, but the basic principles are very similar. The gas is collected and, after undergoing water treatment, is used to run reciprocating engines or processed into a higher energy content gas, which can then be used to run gas turbines. During this process, sulfur and carbon dioxide are removed from the

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166 At the time, there was no operating biomass power plant in the state. Since then, one 24 MW facility, Snowflake Mountain Power, has commenced operations in Snowflake, Arizona in June 2008. SRP and APS have each signed power purchase agreements with the facility to purchase the power output (50 percent each, for a term of 15 years). (Biomass Power Association, 2010 and Renegy Power, 2010).

167 Based on the annual electricity consumption of the average U.S. household at 10,896 kWh in 2009 (EIA, 2010).

168 Arizona's total electricity consumption in 2009 was 73,433 GWh.

gas to prevent corrosion in the combustion equipment and prepare the gas for use in gas turbines (California Energy Commission, 2009).

4.12.1 The Future of Biogas

Landfill gas is ideal for use in Stirling and ORC engines, each of which have lower emissions and provide greater efficiency in comparison to reciprocating engines. In addition, future landfill gas electricity generation technologies are expected to be of smaller-scale, such as microturbines and fuel cells. These technologies bring greater flexibility, as they can be deployed in smaller landfills as needed. Their small size also allows for shorter lead times for making incremental capacity additions. Lastly, they have lower emissions in contrast to larger-scale generation technologies (U.S. Climate Change Technology Program, 2003). Fuel cells that can use landfill gas as fuel, are still in demonstration or early application stages.[169,170] The use of microturbine technology at landfills has been demonstrated since 2001 (in the United States mainly in California), but the experience from these applications point to high capital costs and low generating efficiencies (U.S. Environmental Protection Agency, 2002).

In 2008, the United States generated approximately 7,100 GWh from power plants fueled by biogas (EIA, 2010), providing enough electricity to power more than 650,000 American homes.[171] Currently, there is only one landfill gas plant in Arizona; it produces enough power for 2,000 homes.[172]

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169 For instance, a Finnish electrical engine developer, Wärtsilä, has announced it successfully tested a solid oxide fuel cell running on landfill gas in 2010. ("Wartsila tests landfill gas fuel cell unit," February 22, 2010 in Electric Light and Power, retrieved from http://www.elp.com/index/display/article-display/4386705060/articles/electric-light-power/renewable-energy/2010/02/Wartsila_tests_landfill_gas_fuel_cell_unit.html).

170 The automaker BMW has recently launched a pilot program at its South Carolina manufacturing facility to convert landfill gas into hydrogen, which will then be used to fuel the company's specialized fleet of fuel-cell powered materials handling vehicles (such as forklifts). ("Landfill Gas for Hydrogen Fuel Cell Pilot Project in U.S.," July 27, 2011 in Waste Management World, retrieved from http://renewable-energydatabase.com/index/display/article-display/6256952565/articles/waste-management-world/waste-to-energy/2011/07/Landfill_Gas _for_Hydrogen _Fuel_Cell_Pilot_Project_in_U_S_.html).

171 Based on the annual electricity consumption of the average U.S. household at 10,896 kWh in 2009 (EIA, 2010). Note that most statistics of renewable energy compiled by the EIA include biogas (or landfill gas) as a sub-category of biomass.

172 SRP landfill gas power plant at the Tri Cities Landfill with 4 MW capacity (SRP, 2009).

4.12.2 Biogas Feasibility Assessment

In the following section, we evaluate the feasibility of power generation from biogas for the state of Arizona using the criteria established in section three.

Biogas Criteria

There are several landfill gas and anaerobic digestion sites that have been identified in Arizona as suitable for developing a biogas fueled power plant (Black and Veatch, 2007). However, even if all of these sites were developed, they would represent a total capacity of 20 MW and generate approximately 137 GWh of electricity every year. This potential represents less than 0.2 percent of Arizona's 2009 electricity consumption[173] and is enough to power roughly 12,500 homes.[174] Even if we were to simply (and optimistically) assume the initial landfill gas-fueled power generation potential identified in the Black and Veatch study grows linearly with Arizona's population (i.e., higher population, more landfill waste), the relative contribution of biogas to the state's growing electricity demand would remain fixed. We therefore conclude that biogas is not a feasible energy resource for power generation for the state.

4.13 Hydroelectricity

Arizona is home to two of the largest dams in the United States.[175] However, the contribution of hydroelectricity (or hydropower) to the U.S. and Arizona energy portfolio, relative to coal and natural gas, has declined significantly in the last 60 years. In 1950, hydropower accounted for 29.1 percent of total electricity generation in the United States. In 2009, this share of hydropower was down to 6.8 percent in the United States, and 5.7 percent in Arizona. This is due to the natural limit on exploitable hydroelectric potential, while power demand continues to grow.

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173 Arizona's total electricity consumption in 2009 was 73,433 GWh.

174 Based on the annual electricity consumption of the average U.S. household at 10,896 kWh in 2009 (EIA, 2010).

175 Hoover Dam and Glen Canyon Dam (EIA, 2009).

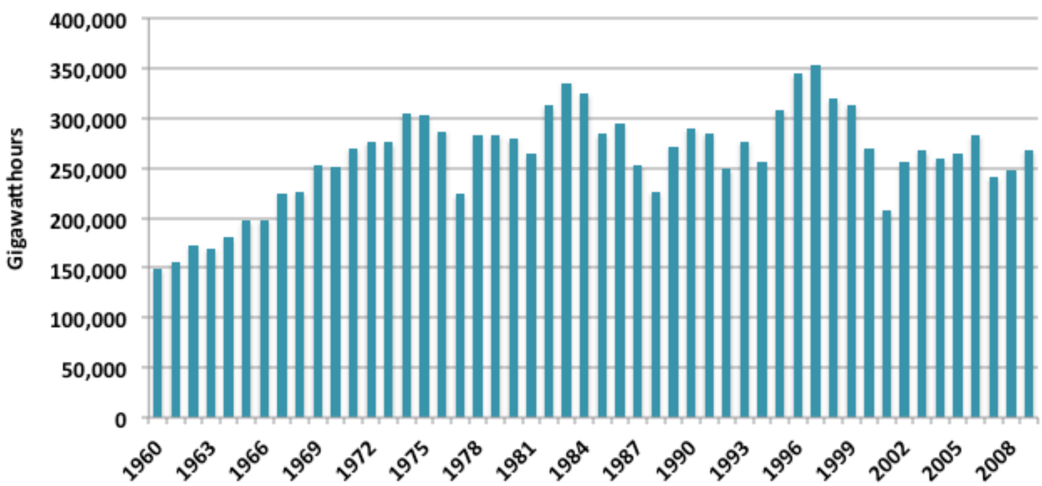
There are three main types of hydroelectric facilities built on rivers: conventional, pumped storage, and run-of-river. In conventional hydroelectric facilities, power is generated from dams that release a stream of flowing water from a higher towards a lower elevation. As the water streams down the dam, it operates turbines, which generate electricity (U.S. Geological Survey (USGS), 2009). In order to generate power on a significant scale, the body of water and surrounding area must be conducive to building a dam and reservoir. The majority of conventional hydroelectric facilities in the United States are located in the West. Generally, the main rationale for their construction was irrigation rather than power generation (EIA, 2010).

Hydropower sites have also proven extremely useful in the United States for pumped energy storage, which is now considered a primary form of grid energy storage. Pumped storage facilities use electrical pumps to transport water from a lower elevation to a reservoir at a higher elevation. The pumping process uses electricity, but takes advantage of low electricity demand (and lower wholesale electricity prices) during off-peak periods (mostly nighttime hours). The stored water at the higher elevation reservoir is then released to generate power during daytime hours, or peak periods of power demand, when wholesale electricity prices are also higher. The process is not technically efficient as pumped storage facilities usually use more power to pump than the power generated, making net electricity generation negative. However, these facilities allow utilities to better match their resources to demand across time (called load balancing), and may allow them to do so profitably at the wholesale level, where hourly power prices fluctuate. At the end of 2009, pumped storage facilities (21,858 MW) represented nearly 20 percent of total hydroelectric capacity in the United States (99,808 MW) (EIA, 2010).

Run-of-river hydroelectric plants are generally smaller in size compared to conventional dams. They either have small upstream reservoir, or no reservoir at all. Power output from plants with no reservoirs are highly seasonal (based on river flows) and these plants would be operated similar to peaking plants during these high water flow periods, while those even with limited reservoirs provide utilities the capability to better manage the timing of the power output and can be operated as peaking or to support baseload plants. The largest run-of-river facilities in the United States are in Washington and Oregon (EIA, 2010).

Today, almost all of the hydroelectric potential in the United States has already been developed (USGS, 2009), and since the 1970s, there have been no significant new additions to hydroelectric capacity in the country (EIA, 2010). The lack of significant capacity additions in hydroelectricity therefore reflects a scarcity of suitable locations rather than a decision to abandon hydropower due to cost, technology, public opinion, or other reasons. Figure 18 shows that since the 1970s, hydroelectric generation in the United States has fluctuated between 200,000 to 300,000 GWh (mostly as a result of climatic variation from year to year), averaging about 250,000 GWh of output annually.

Figure 18. U.S. Hydroelectric Generation, GWh, 1960-2009



Source: EIA, 2010.

4.13.1 The Future of Hydroelectricity

The future of hydropower lies in in small-scale generation and advanced hydro technology. The shortage of large-scale hydropower areas has accelerated a trend in hydropower to a smaller scale. Micro hydro systems are less than 100 kW and are designed to be used as a remote area power supply. Providing power for small communities that are either not tied into the grid or that receive electricity at a high cost will cause significant competition between micro hydro systems and other forms of distributed generation, such as solar PV panels and distributed wind turbines. Advances in hydroelectric technology have been centered on turbines that are more efficient and low impact. Ecological issues have dominated research into hydropower recently as the impact on species of fish and the surrounding estuaries of dams and hydropower generation have concerned ecologists globally (Idaho National Laboratory, 2005). Therefore, the potential damage of hydroelectric development along rivers to wildlife habitats needs to be balanced with its benefits as a low-emissions energy source.[176]

In addition to providing baseload electricity to the grid, some hydropower systems can also be used as peaking resources due to their ability to quickly start and stop operations (USGS, 2009). This is particularly important for a state such as Arizona, which experiences a spike in power use during summer afternoons. Arizona has historically relied on hydroelectricity to meet its power needs. Whether hydroelectricity can continue to play a role in Arizona's power supply depends on the suitable hydroelectric sites left in the state and the feasibility of hydroelectric technology.

4.13.2 Hydroelectricity Feasibility Assessment

In the following section, we evaluate the feasibility of hydropower for the state of Arizona using the criteria established in section three.

Hydroelectric criteria

Arizona has significant hydroelectric resources, but most of them have already been developed. Several remaining potential sites have been identified, representing a total capacity of 82 MW (Black and Veatch, 2007).[177] If all of this potential capacity was developed, it would contribute up to 320 GWh to the state's electricity supply every year. This amount is enough to meet

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[176] Most hydroelectric plants produce no greenhouse gas emissions during their operations, however, very large dams that flood areas that contained a large amount of organic matter prior to the creation of a reservoir cause methane emissions due to the gradual decay of this organic matter submerged under water. This is an important consideration especially in warmer climates and tropical regions where the organic material decays, and thus emits methane, faster (Nature Geoscience, 2011). Similarly, pumped storage facilities that use grid power to pump water upstream might be utilizing power generated from fossil fuel sources and therefore indirectly create emissions.

[177] Glen Canyon area constitutes 90 percent of the total potential capacity additions (Black and Veatch, 2007).

power needs of nearly 30,000 homes.[178] However, this amount represents only 0.4 percent of the Arizona electricity demand in 2009.[179] Assuming the remaining hydroelectric potential identified in the Black and Veatch study represents the natural limit of all such development for the foreseeable future, the relative contribution of hydroelectricity to Arizona's power supply would continue to decline over time. Therefore, we conclude hydroelectricity is not feasible for Arizona in the near future.

4.14 Ocean-based power generating technologies: Tidal, wave, and osmotic power

Because Arizona is landlocked, these ocean-based electricity generation technologies are not feasible in the state. We provide brief discussions of each for the reader's information.

4.14.1 Tidal power

Utilizing tides to generate electricity is a relatively new technology that has yet to be adopted on a large scale. There are three ways to generate electricity using tidal power (Tidal Energy, 2009). Tidal stream systems use the kinetic energy of moving water to spin turbines and generate electricity. It has the advantage of generating electricity at low costs while minimizing ecological impact. Barrages are dams across bodies of water that generate electricity in a similar method to hydropower. Water flowing in and out of the barrage spins turbines, which generate electricity. However, the ecological impact of barrages, combined with large capital costs, has slowed investment in this technology. The third tidal energy generation technology is the tidal lagoon, which is similar to the barrage technique but is a self-contained structure that reduces cost and ecological impact. Only barrages are currently in a testing phase in the United States.[180] Tidal power has been experimented with in large estuaries and bays.

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178 Based on the annual electricity consumption of the average U.S. household at 10,896 kWh in 2009 (EIA, 2010).

179 Arizona's total electricity consumption in 2009 was 73,433 GWh.

180 East River Tidal Project in New York City.

4.14.2 Wave Power

Waves are generated by wind passing over the surface of a relatively large body of water, which causes an energy transfer. There are many different methods used to capture energy from this transfer. The most successful to date has been the Pelamis Wave Energy Converter in Portugal, which utilizes three 750 KW devices (Pelamis Wave Power Company, 2009). The technology is still in a development phase, with commercial adoption in a limited number of areas (U.S. Department of the Interior, 2006).

4.14.3 Osmotic Power

Applications of osmotic power technology require locations where saltwater and freshwater meet. When freshwater meets saltwater, the resulting difference in osmotic pressure can be used to generate electricity. Reverse electrodialysis and pressure-retarded osmosis are two methods to retrieve the energy created. In reverse electrodialysis, saltwater and freshwater are brought together through a series of chemical reactions, and the chemical difference between the two solutions generates a voltage (Membrane Technology Group, 2009). Pressure retarded osmosis requires a semi-permeable membrane which separates the two solutions in the osmotic flow and forces a turbine to rotate (Harrysson et al, 1995). The first osmotic power plant began operations in Norway in 2009. This project, with a capacity of 2 to 4 kW, is a prototype intended to assess ways to reduce costs (mainly by improving membrane efficiency) and develop to technology for larger-scale commercial application (Statkraft, 2009).

Table 15: Summary of Technology Feasibility Criteria and Additional Feasibility Issues

Technology	*Feasibility Criteria*	*Additional Feasibility Issues*		
Coal	Commercially available. Able to satisfy 100 percent of the state's energy demand.	There is coal supply in Arizona as well as the U.S., but requires railroad access.	Requires 510 gallons of water per MWh.	
Natural Gas	Commercially available. Able to satisfy 100 percent of the state's energy demand.	Natural gas is available, but requires pipeline access.	Has the highest energy content and least CO_2 emissions per unit of electricity generated from fossil fuels.	
Petroleum	Commercially available. Able to satisfy 100 percent of the state's energy demand.	Petroleum is available, but requires pipeline access.	Has worse CO_2 emissions compared to natural gas. Transport demand for petroleum products (with no good substitutes) means the price of oil will remain high and volatile.	
Nuclear	Commercially available. Able to satisfy 100 percent of the state's energy demand.	Uranium is available.	Requires 785 gallons of water per MWh.	Most efficient when built large-scale. Spent fuel storage remains problematic.
Hydropower	Commercially available, but incremental resources not able to satisfy >1 percent of the state's energy demand.	Arizona and the surrounding region's hydroelectric resources have largely been exploited, thus large-scale additions to existing capacity is not possible.		
Solar Thermal	Commercially available. Able to satisfy >5 percent of the state's energy demand.	Arizona has the highest solar insolation in the country.	Requires energy storage for periods when there is no sunlight.	Most commercial CSP technologies require 800 to 1,000 gallons of water per MWh.
Solar Photovoltaic (PV)	Commercially available. Able to satisfy >5 percent of the state's energy demand.	Arizona has the highest solar insolation in the country.	Requires energy storage for periods when there is no sunlight.	
Wind	Commercially available. Able to satisfy >4 percent of the state's energy demand.	Limited wind potential in Northern Arizona.	Seasonal wind patterns in the state do not coincide with high summer demand. High-wind areas are located away from the state's main load centers.	

Technology	*Feasibility Criteria*	*Additional Feasibility Issues*	
Geothermal, Biomass, Biogas, Fuel Cells	Commercially available, but not able to satisfy >1 percent of the state's energy demand.	Geothermal, biomass, and biogas technologies face challenges concerning availability of their respective primary energy sources in Arizona, whereas fuel cells are primarily hindered by high capital costs. Also difficult for all these technologies to be incorporated into the state's power supply mix at utility-scale.	
Solar Updraft Tower	Limited commercial availability due to uncertain costs and performance.	Arizona has the highest solar insolation in the country.	Has some inherent energy storage and requires no water for operation. A proposed solar updraft tower project in Arizona will set an important precedent about the future economic feasibility.
Tidal, Wave	Commercially available, but geographically not possible in Arizona.		
Osmotic	Not commercially available; in demonstration phase.		

5 The Future of Power Generation Technologies in Arizona

In the next 25 years, we expect the fundamental relationships that have determined the historical patterns in Arizona's electricity and energy use to remain materially unchanged. For example, we expect the trend of growing residential energy demand (driven by population growth) and increasing per capita residential power use[181] to continue. In Arizona, population growth has also been the main driver of growth in commercial and industrial energy demand. We expect this relationship to hold as well.

From 1980 to 2007, Arizona's population grew at an annual average rate of 3 percent. Over the same period, total electricity consumption in the state grew by an average of 4 percent, and energy used by all sectors of the Arizona economy grew by an average of 3 percent annually. Per capita electricity consumption by Arizona residents increased at an annual average rate of nearly 1 percent, indicating electricity demand outpaced population growth. During this time, efficiency gains in air conditioners, refrigerators, and other household appliances have been more than offset by larger home sizes and the expansion in electronics and information technology applications. Prior to the recession, this trend (of rising per capita electricity use) was expected to continue, albeit at a decreased rate.

However, the future rates of growth in population and in electricity and energy consumption in Arizona are expected to be lower due to the ongoing economic recession that started in 2008. Projections done by Arizona Department of Economic Security prior to the recession indicated population in the state to exceed 10 million people by 2028. This was consistent with U.S. Census Bureau's 2005 estimates, which indicated the state's population would reach 10.7 million by 2030.[182] Annual population growth in Arizona, driven substantially by migration from other states, has also slowed down to about 1.5 percent since the recession.

During the two-year period (2008-2009), per capita electricity consumption in Arizona has contracted by more than 8 percent. Total electricity consumption declined by nearly 5 percent,

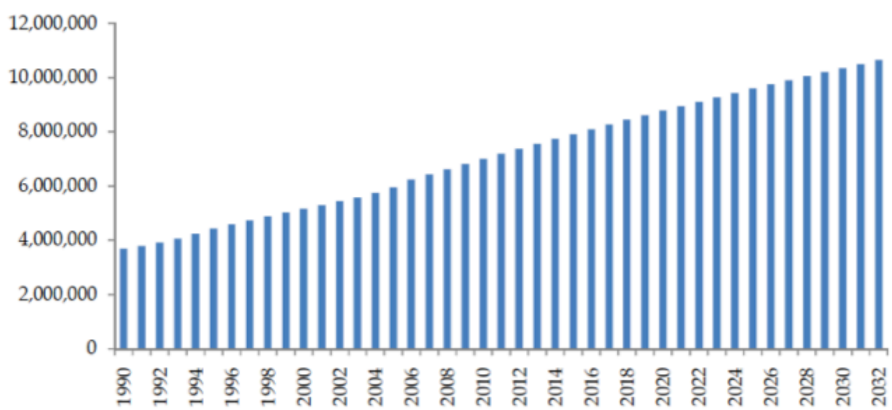
181 Calculated using data from EIA and U.S. Census Bureau, 2010.

182 U.S. Census Bureau, Interim State Population Projections (2005), http://www.census.gov/population/www/projections/projectionsagesex.html.

and total energy consumption (which includes, for instance gasoline demand for transport and natural gas use, in addition to electricity) declined by 7.5 percent. Currently, it is not clear how long it will take the state to recover to the pre-recession energy consumption levels before energy use starts to grow again. Therefore, we believe these population projections and any energy demand forecasts based on them need to be reconsidered and updated in light of current market conditions.

For illustrative purposes, Figure 19 below shows the population growth in Arizona from 1990 through 2007, and forecast population from 2008 through 2032, according to the 2008 calculations of Arizona's Department of Economic Security (thus, prior to the recession).

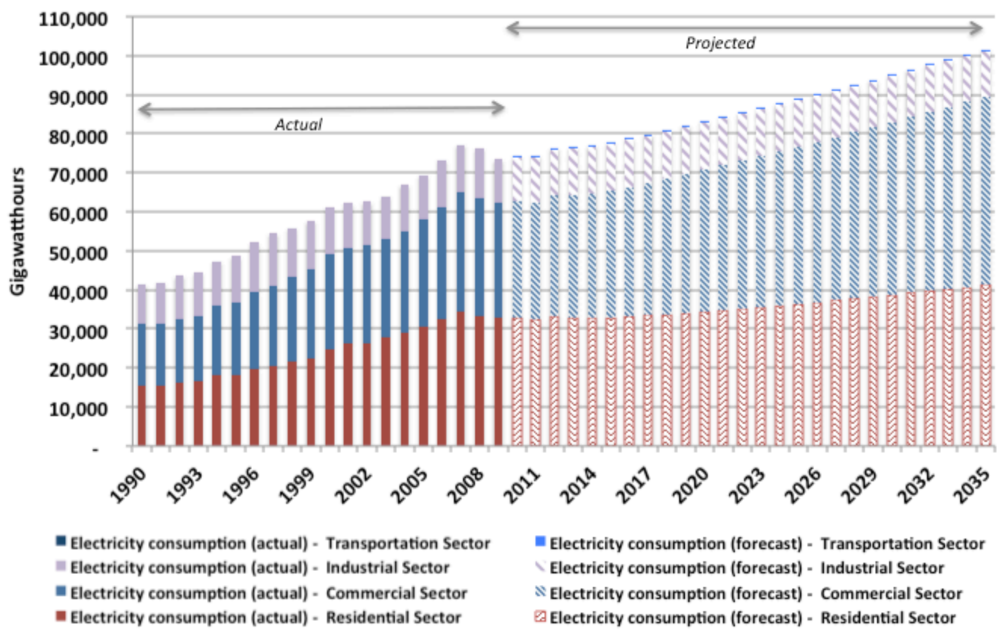
Figure 19. Arizona Population Growth, 1990-2007, and Forecast Population, 2008-2032 (2008)



Source: Arizona Department of Economic Security (DES), 2008 (http://www.workforce.az.gov/population-projections.aspx).

Similarly, prior to the recession, Arizona's utilities projected total electricity demand in the state would nearly double from 2006 through 2032, reaching 142,000 GWh by 2032. Under current market conditions, this projection might be overly optimistic. A more conservative outlook, which takes into account the recent declines in electricity use in the state and employs a lower annual average forecast rate of growth, is provided in Figure 20 (from 2010 through 2035).

Figure 20. Historical and Projected Electricity Consumption in Arizona by End Use Sector, GWh, 1990-2035



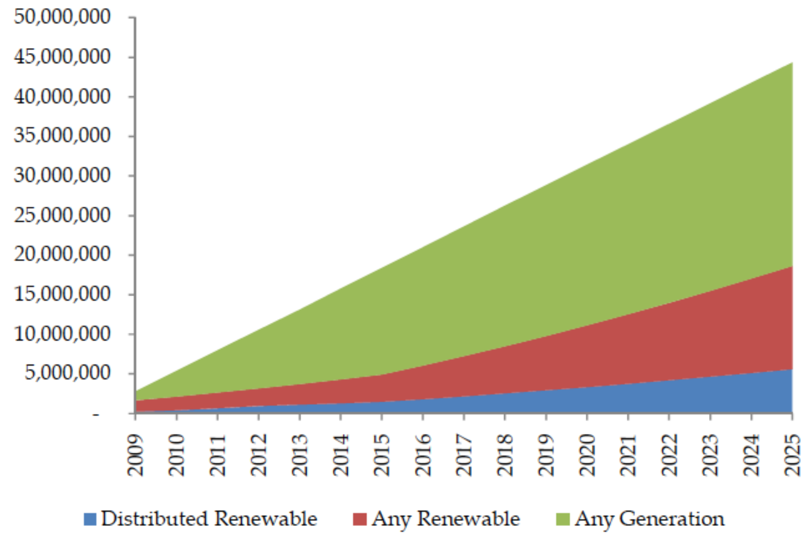
Note: Projections in this figure relies on the EIA's base case electricity consumption forecast by end-use sector in the latest Annual Energy Outlook (2011) edition, which is essentially the North American Electric Reliability Corporation (NERC)'s forecast for the Southwest sub-region (this sub-region covers Arizona and New Mexico). Our projection uses the yearly growth rates implied by this base case scenario for the two-state region and then applies these growth rates to 2009 electricity consumption levels (by end-use sector) in Arizona. This figure is provided for illustrative purposes only and estimates have not been confirmed by independent modeling of future supply and demand.

Source: EIA, 2010 and the author's calculations.

Regardless of the impact of the economic recession, electricity demand in Arizona will continue to grow. This, combined with the advancing age of several of the state's coal-fired power plants (EIA, 2009), requires that the state utilities still have to plan for capacity additions over the next 20 to 25 years. Some of these additions need to be from renewable energy resources in order to meet the state RES.[183] Figure 21 illustrates the additional generation that will be required, based on pre-recession electricity demand projections.

183 Arizona's Renewable Energy Standard (RES) calls for a rising proportion of the state's total electricity sales to end-users come from renewable energy sources, reaching 15 percent by 2025. There have been several proposals since 2006 for a federal renewable energy portfolio standard, but none of these have gained enough legislative traction.

Figure 21. Incremental Generation Needed to Meet Arizona Retail Electricity Supply Requirements (MWh)



Source: APS, 2008, SRP, 2008, TEP, 2008, EIA, 2008 and Author's Calculations.

It is important to note that, even though Arizona utilities might have to invest in a large amount of renewable energy generating capacity by 2025 in order to comply with the state RES, they will retain the flexibility to choose from a range of renewable and more traditional energy technologies (fossil fuel and nuclear) to meet the remaining (and the larger) portion of projected growth in demand.

The dilemma, therefore, for Arizona utility planners is: which generation technology, or what combination of technologies, is the right one for the state? In the following subsections, we summarize the ability of those technologies that have passed our feasibility criteria to meet the state's electricity requirements.

5.1 Coal Summary

In 2009, coal-fired power plants generated 35.5 percent of Arizona's net power generation. Coal is relied upon as fuel for baseload power and can be scaled to meet both small and large-scale electricity requirements. The plants must be located near railroads (in Arizona) to receive the required stock of coal. In addition, their substantial water requirements compel utility planners to choose sites with adequate water resources. However, the overriding issue with coal is carbon dioxide emissions. As a result, future coal plants strive for improved combustion efficiency and use of carbon capture and storage technology. These technologies are not yet in operation, but may be a reality for coal in the next 10 years (MIT, 2007). Given its low cost and stable generation output, coal-fired power generation will be a strong contender for Arizona over the next 25 years.

5.2 Natural Gas Summary

Gas-fired power plants generated 31 percent of Arizona's power in 2009. Natural gas is a flexible fuel technology that can be used in combined cycle plants for efficient base load generation or in combustion turbine plants for peaking generation. Due to its higher efficiency, compared to coal, natural gas requires less water for generation and can be scaled to meet both small- and large-scale electricity requirements. Gas-fired power plants in Arizona depend on pipelines from out of state for fuel (natural gas) supply. These pipelines also transport natural gas into the state for consumers in other sectors (residential, commercial, etc.) as well. Therefore, spare pipeline capacity is a consideration for future gas-fired power plants. Also, natural gas, like coal, is a fossil fuel and therefore emits carbon dioxide during combustion. However, natural gas emits much less carbon dioxide per MWh than coal, which makes the technology less vulnerable to potential future limits on such emissions. The future feasibility of natural gas-fired power plants do not only depends on carbon dioxide emissions, but also on the fluctuating average prices of natural gas. Despite these concerns, the flexibility of the technology, its lower capital costs compared to solar power technologies as well as coal-fired power plants (even without any carbon capture and storage), and the favorable carbon dioxide emissions properties of natural gas as a fuel vis-à-vis coal suggests that natural gas-fired power plants will remain in the future power supply mix in Arizona.

5.3 Nuclear Summary

In 2009, Arizona's sole nuclear power plant, Palo Verde, supplied 27.4 percent of total power generation in the state. Nuclear power is a baseload technology with a cheap, reliable, and stable fuel source. On the other hand, it has significant water requirements for cooling. In addition, the technology operates most efficiently on a large scale, which requires a very high initial investment, even though operating costs thereafter are very low compared to many other power generation technologies. Nuclear power plants also have very long project lead times. For example, the initial investment required at the Palo Verde nuclear plant required numerous investors from both inside and outside the state to pool their resources, and it took twelve years from the start of construction for the three reactor plant to become fully operational.[184]

Notwithstanding the high capital costs and long project lead times, today the biggest concerns facing new developments in nuclear power generation are operating safety and waste disposal. In the reactor designs under development,[185] engineers are striving for increased standardization (to cut costs) and improved safety features. Disposal of radioactive waste (spent fuel) from nuclear power plants is a critical issue that is yet to be resolved in the United States, though the federal government has been working to develop an alternative to the contentious Yucca Mountain storage plan that had to be abandoned. If the waste disposal issue is resolved, and the new generation of reactors are successfully brought into commercial operation in other parts of the world and the United States, the low cost and stable power generation from nuclear power plants makes building a new reactor in Arizona over the next 25 years feasible.

5.4 Petroleum Summary

In 2009, Arizona generated a minimal amount of power from petroleum-fired power plants (0.1 percent of total electricity generated). Such power plants are used as peaking resources in Arizona. However, petroleum is more expensive than both natural gas and coal, emits more carbon dioxide, and, as a result, is the least preferred fossil fuel for power generation. Although Arizona utilities currently operate two petroleum-fired plants, it is unlikely that any further investment will be made unless the price of petroleum falls significantly.

184 Construction began in 1976 and the third and final reactor was placed in service in 1988.

185 Generation III+ and IV.

5.5 Solar Thermal Summary

In 2009, Arizona generated less than 0.1 percent of its power from solar thermal power plants, but Arizona's unique geography and climate makes it well suited for future solar power development. There are several different solar thermal power plant technologies. These technologies all rely on sunlight, which is an intermittent energy source. Some form of energy storage, such as batteries, thermal storage, or grid storage, is necessary for these plants to provide electricity into evening peak hours of energy demand.[186] Also, today, the most widespread solar thermal power plant technology[187] has water requirements similar to nuclear reactors and coal-fired power plants. Notwithstanding the water needs, the primary concerns for solar thermal power technologies are high capital costs and the intermittent nature of sunlight as an energy source. As storage capability increases and these technologies mature, costs are expected to fall. In all, we expect solar thermal to be a part of the Arizona's future power generation portfolio.

5.6 Solar Photovoltaic Summary

In 2009, Arizona generated less than 0.1 percent of its power from solar PV. Solar PV can be used in either distributed or concentrated utility scale generation. Distributed PV panels have the advantage of providing power in areas that are not connected to the power grid. In addition, solar PV can be placed on rooftops, cars, airplanes, and even smaller applications such as tents, handbags, and power tools. In addition, the technology requires no additional infrastructure and very little water. Conversely, solar PV panels are intermittent and have very little potential for storage on a large scale. Combined with the significant cost of PV panels, growth in solar PV panel use has been limited. Given the tremendous investment in solar PV development around the world, and the inclusion of a distributed generation requirement in the Arizona RES, solar PV will have a future in Arizona.

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[186] In Arizona, peak demand during summer days occurs from 12 to 8 PM (SRP, 2009).

[187] Referring to the parabolic trough technology.

5.7 Wind Summary

The year 2009 marked the debut of wind power in Arizona, contributing less than 0.1 percent of the state's electricity supply. Wind is a renewable energy resource and wind turbines have low operating costs (mainly because there are no fuel costs). They also use less than a gallon of water to produce one MWh of electricity. On the other hand, wind is an intermittent (or variable rate) energy resource, and though largely predictable, wind speeds vary daily and seasonally. In particular, in Arizona, regional wind patterns indicate that the majority of wind power would be generated in the winter and spring. This seasonally variable nature of wind power generation is a potential obstacle in a state where utilities focus on meeting high summer demand for electricity. In addition, majority of the potential wind sites are located in northern Arizona, whereas much of the demand is concentrated in the urban centers of the south, and the need for transmitting power over long distances might be a costly obstacle. Despite its status as a renewable resource and low operating costs, wind might not be a utility-scale power generation alternative in Arizona due to its inability to provide energy in either a baseload or peaking capacity. Nevertheless, recent estimates indicate Arizona's wind power potential might be larger than originally thought. Utilities might consider wind power as an option for distributed generation and to meet the needs of smaller Arizona communities located closer to wind resources.

Glossary

Acre-foot: The volume of water that will cover an area of 1 acre to a depth of 1 foot.

Base load: The minimum amount of electric power delivered or required over a given period of time at a steady rate.

British thermal unit (Btu): The quantity of heat required to raise the temperature of 1 pound of liquid water by 1 degree Fahrenheit at the temperature at which water has its greatest density (approximately 39 degrees Fahrenheit).

Capacity factor: The ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period.

Cofiring: The process of burning natural gas in conjunction with another fuel to reduce air pollutants.

Combined cycle: An electric generating technology in which electricity is produced from otherwise lost waste heat exiting from one or more gas (combustion) turbines. The exiting heat is routed to a conventional boiler or to a heat recovery steam generator for utilization by a steam turbine in the production of electricity. This process increases the efficiency of the electric generating unit.

Combined heat and power (CHP) plant: A plant designed to produce both heat and electricity from a single heat source.

Gasification: A method for converting coal, petroleum, biomass, wastes, or other carbon-containing materials into a gas that can be burned to generate power or processed into chemicals and fuels.

Generator nameplate capacity: The maximum rated output of a generator under specific conditions designated by the manufacturer. Generator nameplate capacity is usually indicated in units of kilovolt-amperes and in kilowatts (kW) on a nameplate physically attached to the generator.

Greenhouse effect: The result of water vapor, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Gross generation: The total amount of electric energy produced by generating units and measured at the generating terminal in kilowatt hours (kWh) or megawatt hours (MWh).

Heat rate: A measure of generating station thermal efficiency commonly stated as Btu per kilowatthour.

Kilowatthour (kWh): A measure of electricity defined as a unit of work or energy, measured as 1 KW (1,000 watts) of power expended for 1 hour. One kWh is equivalent to 3,412 Btu. A megawatt (MW) is equal to 1,000 KW and a gigawatt is equal to 1,000 MW.

Levelized cost: The present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments. Costs are levelized in real dollars (i.e., adjusted to remove the impact of inflation).

Net generation: The amount of gross generation less the electrical energy consumed at the generating station(s) for station service or auxiliaries.

Net summer capacity: The maximum output, commonly expressed in MW, that generating equipment can supply to a system load, as demonstrated by a multi-hour test, adjusted to ambient weather conditions for summer peak demand (from June 1 through September 30).

Overnight capital cost: The capital cost of a project that does not include the interest cost of funds used during construction.

Peak demand: The maximum load during a specified period of time.

Peak load plant: A plant usually housing old, low-efficiency steam units, gas turbines, diesels, or pumped-storage hydroelectric equipment normally used during the peak-load periods.

Renewable energy resources: Energy resources that naturally replenish but are flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

Thermal efficiency: A measure of the efficiency of converting a fuel to energy and useful work; useful work and energy output divided by higher heating value of input fuel times 100 (for percent).

Turbine: A machine for generating rotary mechanical power from the energy of a stream of fluid (such as water, steam, or hot gas). Turbines convert the kinetic energy of fluids to mechanical energy through the principles of impulse and reaction, or a mixture of the two.

Appendix 1

Technology Readiness Level (TRL)

TRL-1. *Basic principles observed and reported*

This is the lowest level of technology readiness. Scientific research begins with a systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications or products in mind. The knowledge or understanding will later be translated into applied research and development. Example might include studies of a technology's basic properties.

TRL-2. *Technology concept and/or application formulated*

Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.

TRL-3. *Analytical and experimental critical function and/or characteristic proof of concept*

Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

TRL-4. *Component and/or breadboard[188] validation in laboratory environment*

Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity"[189] compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.

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[188] Breadboard: Integrated components that provide a representation of a system/subsystem and that can be used to determine concept feasibility and to develop technical data. These tools are typically configured for laboratory use to demonstrate technical principles of immediate interest. These may resemble final system/subsystem in function only.

[189] Low Fidelity: A representative of the component or system that has limited ability to provide anything but first order information about the end product. Low fidelity assessments are used to provide trend analysis.

TRL-5. *Component and/or breadboard validation in relevant environment*

Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity"[190] laboratory integration of components.

TRL-6. *System/subsystem model or prototype demonstration in a relevant environment*

Representative model or prototype system, which is well beyond that of RL-5, is tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.

TRL-7. *System prototype demonstration in an operational environment*

This represents a major step up from TRL-6. It requires the demonstration of an actual system prototype in an operational environment, such as in a light duty vehicle on the road. Examples include testing a prototype battery in an operational hybrid gas-electric vehicle.

TRL-8. *Actual system completed and qualified through test and demonstration*

Technology has been proven to work in its final form and under expected conditions. In almost all cases, this level represents the end of true system development. Examples include developmental test and evaluation of the system in its intended parent system to determine if it meets design specifications.

TRL-9. *Actual system proven through successful mission operations*

The technology is applied and operated in its final form and under real life conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development.

[190] High Fidelity: Addresses form, fit and function. High-fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.

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