Global Wind Energy Expansion: Gauging Vulnerabilities to Climate Change

Submitted by: Eric Joseph Teeters
Project Advisor: Rhey Solomon
The Johns Hopkins University
May 2013

Submitted in partial fulfillment of the requirements for the
Degree of Master of Science in Environmental Science and Policy
Concentration in Environmental Management

Abstract

Global demand for low emission renewable energy production continues to intensify. Wind turbine power plants, which harness the kinetic energy from wind to generate electricity, continue to proliferate due to the technology's high scalability, ease of deployment, capacity for reducing greenhouse gas emissions, ability to diversify energy portfolios, and for meeting world energy demands. Herein a review is conducted of the investments being made in wind energy technologies by the United States of America, the European Union, the People's Republic of China, and the Republic of India. As technology advances Geographic Information Systems are being utilized to quantify the wind resources in a given region and to locate the best possible sites for wind energy development. Many renewable energy technologies, including wind energy, are dependent on many factors of which climatic conditions are essential. As the climate changes, the wind resource is vulnerable to positively or negatively change on a regional basis and as such the total electricity output from wind turbines could be directly impacted. As the investment in renewable energies has become a determining factor in the adaptation and mitigation of climate change, in addition to addressing rising global energy demands, it is necessary for future wind siting assessments to consider how a changing climate may jeopardize the continued exploitation of wind energy and the security of investments.

Table of Contents

List of Figures

List of Tables

List of Global Climate Models

List of Equations

List of Abbreviations

Abbreviation	Definition
AOGCM	Atmospheric-Ocean General Circulation Models
ARA	American Recovery Act
ASEAN	Association of Southeast Asian Nations
AWEA	American Wind Energy Association
BC	Black Carbon
BLM	Bureau of Land Management
CAFÉ	Corporate Average Fuel Economy standards
CFCs	Chloroflurocarbons
CH_4	Methane
China	People's Republic of China
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO_2	Carbon Dioxide
DOE	Department of Energy
ENSO	El Niño Southern Oscillation
EPA	United States Environmental Protection Agency
ER	Electromagnetic Radiation
ETS	Emissions Trading Scheme
EU	European Union
EWEA	European Wind Energy Association
FWS	United States Fish and Wildlife Service
GCM	Global Climate Model
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GtC	Gigatons of Carbon
GW	Gigawatts
GWEC	Global Wind Energy Council
GWP	Global Warming Potential
h	hour
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IPCC-DDC	Intergovernmental Panel on Climate Change - Data Distribution Center
IPCC-FAR	Intergovernmental Panel on Climate Change Fourth Assessment Report
kW	kilowatts
m	meter
m/s	meter per second
MEPC	Marine Environment Protection Committee
Montreal Protocol	Montreal Protocol on Substances that Deplete the Ozone Layer

MW	Megawatts
N2O	Nitrous Oxide
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrous Oxides
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Center
OECD	Organization for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PM	Particulate matter
ppm	parts per million
RCM	Regional Climate Model
RE	Renewable Energy
RMB	Renminbi
SLCF	Short Lived Climate Forcer
SO2	Sulfur Dioxide
UNECE	United Nations Economic Commission for Europe
UNEP	United National Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
US	United States of America
WENDI	Wind Energy Data Information
WMO	World Meteorological Organization

Acknowledgments

This capstone would not have been possible without the help of many people. It is also the product of a large measure of serendipitous and fortuitous encounters with people who knowingly or not have changed the course of my academic career.

I am genuinely appreciative for the many professors at Johns Hopkins University, in particular my mentor Rhey Solomon, who gave me the freedom to explore on my own, and at the same time the guidance to recover when my steps faltered. I also offer my sincerest gratitude for Dr. Thomas Jenkin, whose excitement and knowledge of the energy technologies spurred my wonder about the topic of this capstone. I am indebted to his generous and practical advice, as well as for commenting on my views and helping me understand and enrich my ideas presented in this paper.

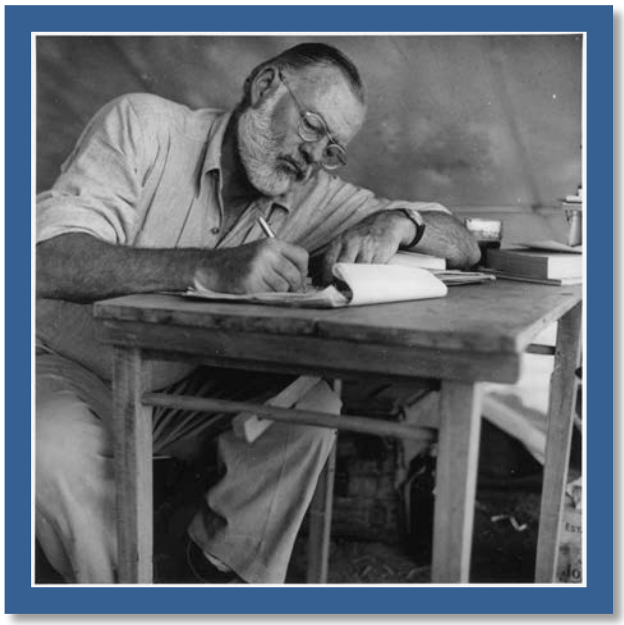
To my many coworkers, near and far, their brilliance compels me to rise to levels I did not know I could reach. Their help and ever-kind words of encouragement have touched me and will not be forgotten; nor will the offers to edit my many papers!

To the many friends who have helped me stay sane throughout these difficult years, their support and care helped me overcome setbacks and stay focused on my graduate studies. I greatly value their friendship and I deeply appreciate their belief in me.

I would like to thank my family, especially my mom, dad, sister, and grandmother. My parents have made numerous sacrifices throughout their lives for my sister and myself and have provided unconditional love and care. I love them very much, and I would not have made it this far without them. My twin sister has been my best friend all my life and I love her dearly and thank her for all her advice and support. My grandmother has been the epitome of strength, love, and kindness throughout my life and I am forever grateful for everything you taught me. This process has made me truly realize I always have my family to count on when times are rough.

I would also like to thank my dog, Watson. We have spent too many nights and beautiful weekends sitting on the couch, bed, or at the kitchen table studying and writing papers. Your companionship has earned you lots of exciting adventures in the future.

Lastly, and surely the most important of all, I would like to express my deepest gratitude to my partner Jason. There are no words to convey how much I love him. Jason has been a true and great supporter and has unconditionally loved me during my good and bad times. He has been non-judgmental of me and instrumental in instilling confidence. He has faith in my intellect and me even when I felt like digging hole and crawling into it because I did not have faith in myself. These last few years have not been an easy ride, both academically and personally. I truly thank Jason for sticking by my side, even when I was irritable. I feel that what we both learned a lot about life and strengthened our commitment and determination to each other and to live life to its fullest.



Look Magazine ca. 1953

"If the wind rises
it can push us against the flood
when it comes."

~ Ernest Hemingway, 1970

1.0 Introduction

The drive to integrate renewable energy (RE) sources into electric grids across the world, specifically wind energy, indicates a significant momentum for widespread development and proliferation of these RE technologies. Although the amount fluctuates, the potential for these technologies to harness the wind's kinetic energy to generate electricity exists universally across the Earth. As one of the most advanced and invested in RE technologies, wind power plants are now operating in a multitude of countries (Sahin 2004, GWEC 2012a, Sesto et al. 1998), which has permitted the diversification of domestic energy portfolios. Precise wind measurements are fundamental to the wind energy industry since no wind project can be started before the available wind resource has been documented and justifies the likelihood for a successful return on the investment.

Large rates of investment have led to the expansion of the wind energy industry in the United States of America (US), the European Union (EU), the People's Republic of China (China), and the Republic of India (India) (Blanco et al. 2008, Chiangliang et al. 2009, Cradden 2009, Elliott et al. 2002, IEA 2011, Lema et al. 2006, Mostafaeipour 2010, Pryor et al. 2010, DOE 2012, GWEC 2011, GWEC 2012a, GWEC 2012b). Technological advances and better access to reliable data for many of these regions has led to maximizing the strategic placement of wind power plants in the best areas to address growing energy demands. More specifically, wind farm site assessments are being developed using Geographic Information System (GIS) programs to quantify the current wind resources in specific regions (Rodman et al. 2005, Sliz-Szkliniarz et al. 2011, Hossain et al. 2011, Aydin et al. 2010, Zhou et al. 2011). GIS technologies have quickly become imperative to accurately analyze the many factors (i.e. ecologically important areas, slope of terrain, distance from airports and existing transmission lines linking into the electric grid) necessary for determining wind energy sites.

Despite the increasing role GIS has in wind energy, data on climate change is traditionally not included when planning wind energy sites even though global near-surface wind fields are projected to change as a result of climate change. Any changes in the wind resource, particularly average wind speeds, will have significant implications on the potential of harnessing wind as an energy resource (Pryor et al. 2005), and therefore should be included in long-term wind energy site selection.

Although the subject of climate change attracts enormous attention, there are a limited number of analyses dealing with climate change impacts on power system planning (Pašičko et al. 2012). Historically, the analyses considering both RE sources and climate change focus on how renewable energy might mitigate or aid in the adaptation to climate change through the reduction of emitting greenhouse gases (GHG) (Pašičko et al. 2012). To date very few studies consider the role future climate change will have on impacting the production of energy from these RE sources (Pašičko et al. 2012). This project expands upon available studies and seeks to: review where wind energy is expanding; examine how GIS technologies are used to quantify potential wind energy sites; and determine the long-term climate change-related risks the US and China will face through the year 2100.

It is the intent of this study to better understand wind energy vulnerability to a changing climate through the best available science. It is the hope in doing so will help ensure a country's preparedness to the threat of climate change and ultimately safeguard against harm to the economy, environment, and energy security.

2.0 Background

Modern standards of living demand a constant and reliable supply of energy. Currently, a majority of the world's energy supply comes from fossil fuels and nuclear sources (Sesto et al. 1998). Despite growing ever closer to running out of the finite fossil fuel resources and the lacking of permanent storage solutions for radioactive material, these sources of energy seem likely to continue to be an important link to providing energy worldwide for several generations.

Energy issues have routinely been subjected to intense debate, especially following the first oil supply shock in 1974 (Sesto et al. 1998, Cradden 2009). Questions regarding peak oil, energy security, energy independence, climate change, pipelines, and fracking have passed from technical discussion to political issues for the general public worldwide. The questions remain: will there be enough energy for a country or region's energy needs; will it be affordable; and will it be environmentally friendly enough to safely use? Answers to these questions are necessary as policy discussions continue.

It is common knowledge fossil fuel resources are limited. Regardless of the amount currently left within the Earth, this seemingly dependable energy supply should not be taken for granted as it will one day no longer exist. As the world's population continues to rise and as more countries become industrialized, global energy demands will swell, all the while fossil fuel resources will likely shrink (Sahin 2004), which may result in supply and demand issues leading to an escalation in energy prices. In order to ensure the supply of energy will be able to remain at the status quo and the costs for energy remain reasonable, alternative and "clean" energy sources must be further explored and expanded and need to be integrated into the electric grids at a large scale to meet such a demand.

With the threat of a changing climate having the potential to impact many or all living organisms on Earth, RE technologies will not only aid in ensuring a secure future for domestic energy production, but RE will play a significant role in reducing carbon dioxide (CO_2) emissions and will generate economic growth and technological advancement (Pašičko et al. 2012, Sahin 2004, Cradden 2009).

3.0 The Evolution of Harnessing Wind

3.1 History

Wind turbines have been used in some capacity for at least three millennia (Burton et al. 2001, Cradden 2009). Wind energy propelled boats along the Nile River as early as 5000 B.C. and by 200 B.C. windmills in China were pumping water, while vertical-axis windmills with woven reed sails were grinding grain in Persia and the Middle East (Sahin 2004, Hills 1991, Sen 2000, Sen 2001, DOE 2011).

New ways of using the energy of the wind eventually spread around the world. By the 11th century, people in the Middle East were using windmills extensively for food production;

returning merchants and crusaders carried this idea back to Europe, where the Dutch honed the windmill technology and adapted it for draining lakes and marshes in the Rhine River Delta (Sahin 2004, DOE 2011). When settlers took this technology to North America in the late 19th century, they began using windmills to pump water for farms and ranches, and later, to generate electricity for homes and industry (DOE 2011).

American colonists would grind wheat and corn, pump water, and cut wood at sawmills using windmills; however, with the arrival of the Industrial Revolution a gradual decline occurred in the use of windmills as the steam engine replaced these traditional methods (Sahin 2004, DOE 2011). Over time with the development of electric power, the windmill recovered by being integrated generating electricity. As early as 1890 in Denmark, electricity producing windmills began appearing and have grown in capacity to generate electricity and in size over time (Sahin 2004, DOE 2011).

The popularity of using the energy in the wind has always fluctuated with the price of fossil fuels. After World War II fuel prices fell, along with interest in wind turbines; but when the price of oil skyrocketed in the 1970s, so did the interest in wind power plants (Cradden 2009, DOE 2011). The research and development following the oil embargoes of the 1970s refined old ideas and introduced new ways of converting wind energy into useful power (DOE 2011). Many of these approaches have been demonstrated in wind power plants, which generate and feed electricity into the electric grid (DOE 2011).

Wind energy is the world's fastest-growing RE source (Cradden 2009) and its expansion will continue to power industry, businesses, and millions of homes with clean and renewable electricity for many years and generations to come; especially as wind-generated electricity is now very close in cost compared to the power from conventional (i.e. coal and natural gas) sources of power generation (DOE 2011).

3.2 Wind Energy Production

For any power plant to produce electricity it needs fuel, and for a wind power plant, the fuel is wind. It is reasonable to ask if the wind resource at a potential location is stable and if that stability will last through the course of a wind power plant’s lifetime. Without climate change the wind resource at a given site or region still has the potential to change over time due to changes in surface roughness (i.e urbanization and changing vegetation cover), as well as a result of changing weather patterns associated with the El Niño Southern Oscillation (ENSO) and La Niña cycles (Sahin 2004).

Wind resource site assessments are developed to estimate how much fuel will be available for a wind power plant over the course of its anticipated lifespan. Therefore, stability and eliminating both short and long-term uncertainties is an important part of the process of locating sites for new wind farms, as it will determine the amount of potential energy the plant will produce and in turn will approximate the hypothetical costs and revenues investors may expect.

Wind turbines convert the kinetic energy in the wind into mechanical power (Cradden 2009), which can be used for specific tasks, such as grinding grain or pumping water, or it may act as a generator and convert this mechanical power into electricity. Horizontal axis, or propeller-like wind turbines (Sesto et al. 1998), range in capacity from several kilowatts (kW) up to a few Megawatts (MW) and have increased in size over time (Sahin 2004, DOE 2012).

Modern wind turbines rely on the principles of aerodynamic lift. When wind comes into contact with the wind turbine, it causes the propeller-like blades to begin to rotate; the driving torque results from the lift force of the wind contacting the blades being perpendicular to a multiple of the drag force in the direction of the airflow (Sahin 2004, Gipe 1995, Gasch 1996, Gasch 1982, Snel 1998, Walker et al. 1997). The nacelle also contains the mechanisms to point the turbine in the direction of the wind to harness more energy or to turn the turbine away from the wind if wind speeds are over 26 meters per second (m/s), which could damage the turbine structure (Sahin 2004, Pašičko et al. 2012). As the turbine blades rotate, the gears within the nacelle begin moving and subsequently start generating electricity, which can be used for a variety of purposes, including, but not limited to, linking into the main electrical grid and therefore offsetting the amount of fossil fuels that would have been used to generate electricity.

4.0 Regional Wind Energy Expansion

4.1 Global Wind Energy

Since 1990, the annual growth rate for installed global wind energy capacity has increased by more than 26% each year through 2011, and it is estimated wind energy comprises 19% of Portugal and Spain's, 18% of Ireland's, 11% of Germany's, and 3.3% of the US's cumulative electricity generation (DOE 2012).

According to a joint report by the International Energy Agency (IEA) and the US Department of Energy (DOE), energy security refers to a country's uninterrupted access and supply of energy sources at affordable prices (Lantz et al. 2012). In order for a country to improve upon its energy security it must establish diversity, efficiency, and flexibility within the energy sector. Typically, on the near-term this means being responsive and prepared for energy emergencies; while on the long-term the focus is on economic development and the conservation and preservation of the environment, reducing one's reliance on limited foreign sources of energy, and reducing GHG emissions by adding low emission RE into the energy portfolio.

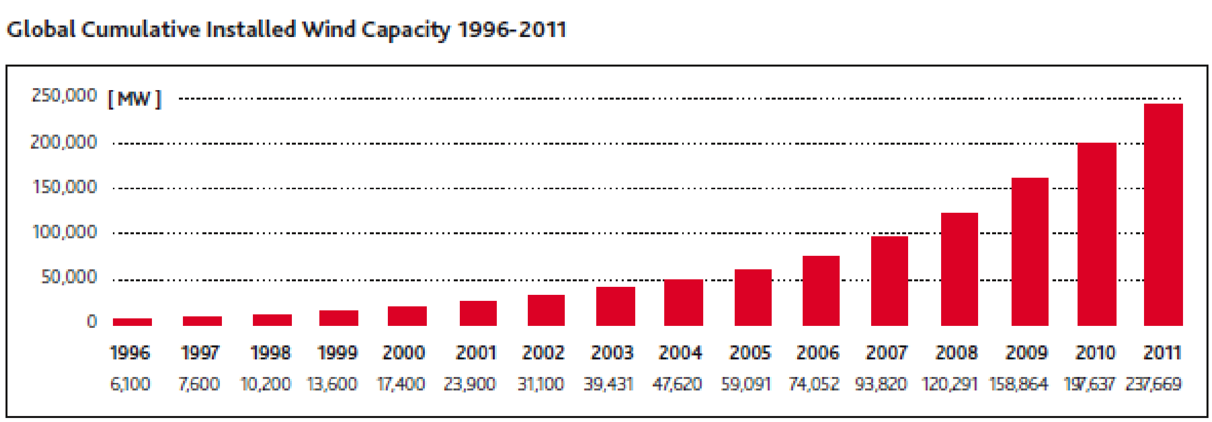
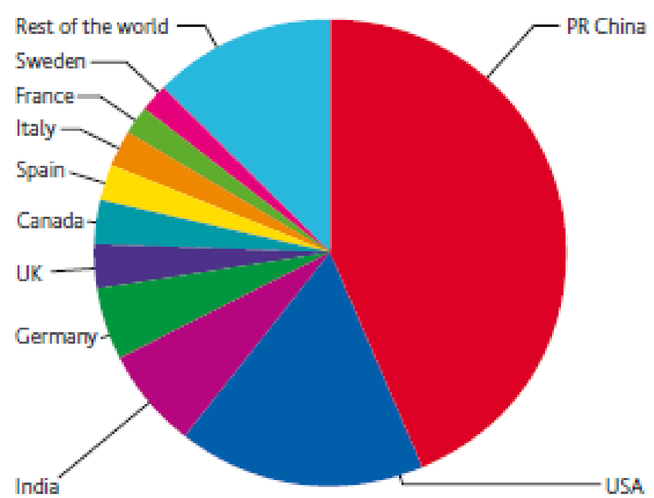


Figure 1: Global Cumulative Installed Wind Capacity 2006-2011 (GWEC 2012)

The Global Wind Energy Council (GWEC) affirms at the end of 2011 the wind energy sector was producing 238 gigawatts (GW) of electricity and was preventing millions of tons of CO_2 emissions each year from entering the atmosphere (GWEC 2012). Also in that year, globally 40.5 GW of wind power was added with €50 billion in investments, and non-Organization for Economic Co-operation and Development (OECD) countries exhibiting the largest amount of wind energy installations for the second year in a row (GWEC 2012). The top 5 countries in 2011 added a total of 30.839 MW of wind energy, which accounted for 75.2% of the total added capacity: China 17,631 MW (43%); US 6,810 MW (17%); India 3,019 MW (7.0%); Germany 2,086 MW (5%), and the United Kingdom 1,293MW (3.2%) (GWEC 2012). With both the public and private sectors in the US, the EU, China, and India making large investments in wind energy technologies it is pertinent to make sure science validates the short and long-term usage of this technology in each of these regions. Doing so will prevent having to invest again in other REs at a future date if the average wind resources were to change gradually or abruptly due to climate change.

Top 10 new installed capacity Jan-Dec 2011



Country	MW	% SHARE
PR China	17,631	43
USA	6,810	17
India	3,019	7
Germany	2,086	5
UK	1,293	3.2
Canada	1,267	3.1
Spain	1,050	2.6
Italy	950	2.3
France**	830	2.0
Sweden	763	1.9
Rest of the world	4,865	12.0
Total TOP 10	35,699	88
World Total	**40,564**	**100.0**

Figure 2: Top 10 New Installed Capacity Jan-Dec 2011 (GWEC 2012)

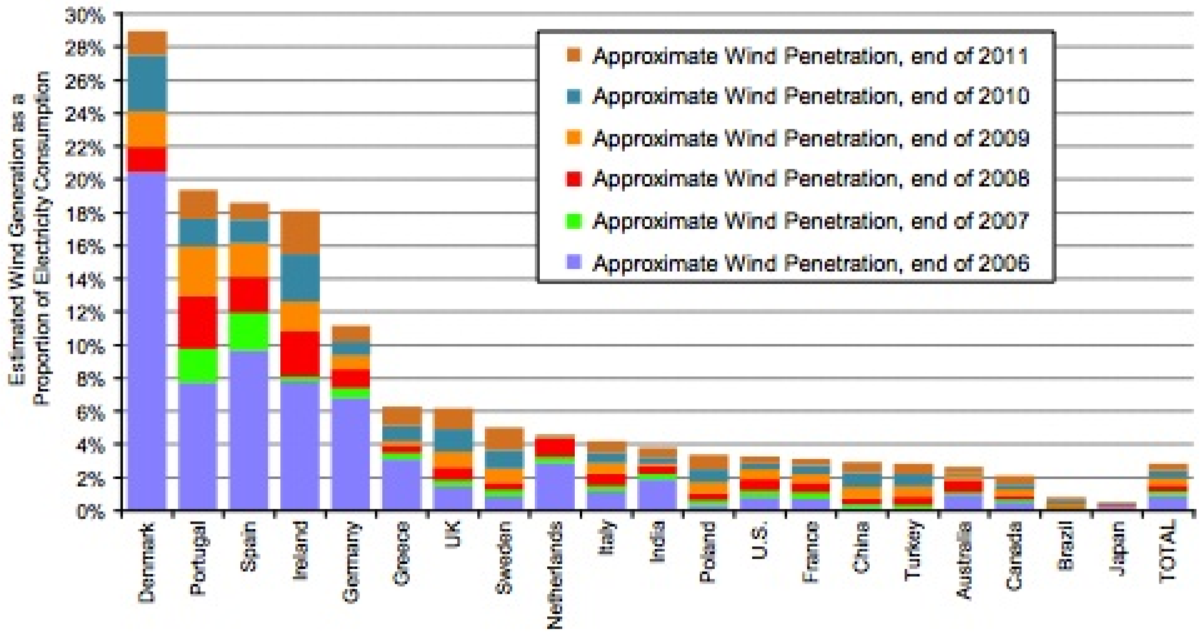


Figure 3 (above): Percent of Wind Generation from Total Electricity Generation (DOE 2012)

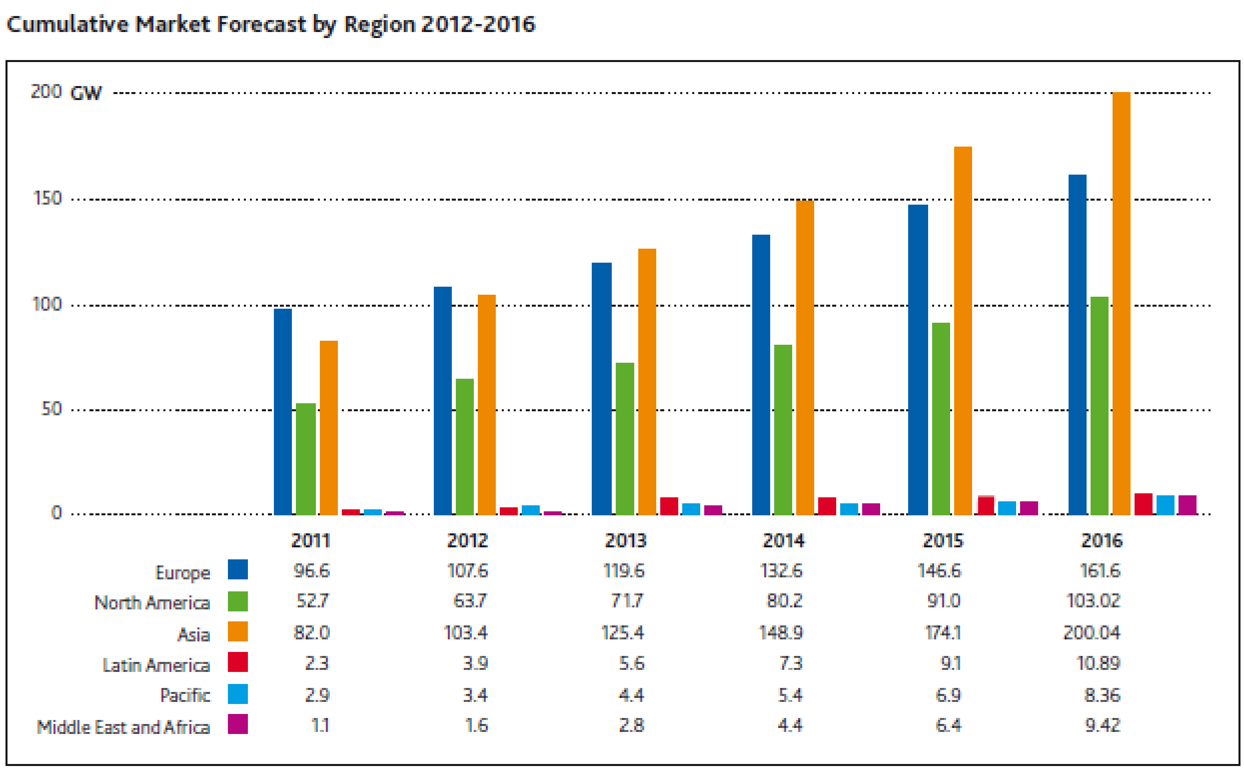


Figure 4 (above): Cumulative Market Forecast by Region 2012-2016 (GWEC 2012)

4.2 United States of America

In 2011, GWEC published a Global Wind Report articulating the US installed 6.8 GW of wind power (GWEC 2012), which is 1.7 GW more in installed capacity compared to installations in 2010 (GWEC 2011). As of 2011 the US had a total of 46.919 GW of wind power capacity spread throughout 38 states with wind turbine part manufacturing facilities covering 43 states (GWEC 2012). The American Wind Energy Association (AWEA) has determined approximately 400 manufacturing plants exist in the US (see Figure 9) with 60% of all wind energy industry products being produced within the U.S (AWEA 2011, GWEC 2012). AWEA has forecasted if current trends remain stable by 2020 the wind energy industry could be able to support roughly 500,000 jobs, increase leasing payments to rural landowners and farmers to $600 million, and save 20 billion gallons of water that conventional fossil fuel-based power plants would have used (AWEA 2011). A GWEC 2010 report notes the recent slowdown in US market growth, compared to growth in years passed, to be a result of the 2008 economic downturn and legislative uncertainty, but it is believed to only be a short-term and temporary setback (GWEC 2011).

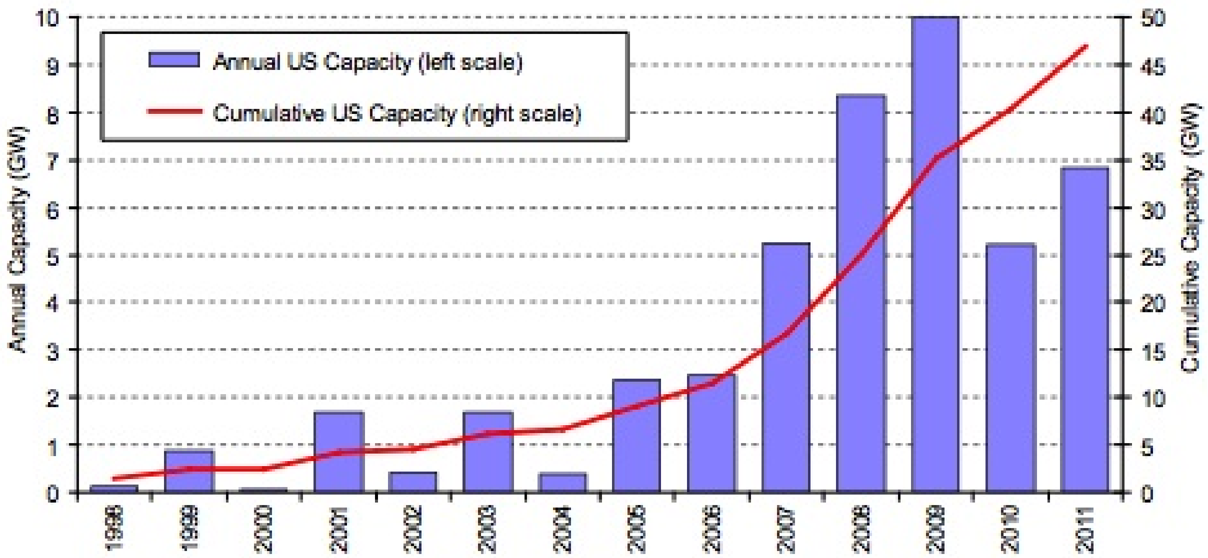


Figure 5: Annual and Cumulative Wind Energy Growth in the US (DOE 2012)

AWEA asserts 89% of US citizens, across all political party affiliations, support the utilization of wind energy (AWEA 2011). In 2008, the DOE published a report concluding the US possesses a sufficient amount of wind resources to produce 20% of its cumulative electricity from wind energy by 2030 (Saidur et al. 2010). Despite the support of DOE and the American people, GWEC's 2010 Global Wind Report postulates if political stalemate continues it will result in declines the amount of wind energy being installed annually within the US (GWEC 2011). The gridlock in the US Congress and budget constraints led to the DOE wind program's budget being cut from $63 million to $50 million in 2009 (Saidur et al. 2010). As of 2013, the effects of the federal government-wide budget cuts, commonly referred to as sequestration, are relatively new and the long-term effects are still largely unknown; however, the sequestration is largely known to have Federal agencies cut their spending, with some programs being hit harder than others, such as a $400 million (~8%) reduction in DOE's Office of Science (Malakoff 2012).

These budget cuts are disheartening as most energy policy in the US is determined by temporary federal tax credits or incentives as no long-term policy has been enacted within the US to date. Although temporary, these federal incentives play an integral role in the expansion of RE, and wind energy in particular. In March 2009, as a part of the American Recovery Act (ARA): the US invested $3.2 billion in energy efficiency and energy conservation programs; extended the production tax credit through December 31, 2012; and allowed wind energy investors and taxpayers to receive an equivalent financial grant if they wished to forego claiming the tax credit (Saidur et al. 2010). While much of the US was facing economic hardship and scaling back, these incentives helped create manufacturing and construction jobs, prevented a complete halt in wind energy installation, and led to the integration of more wind energy into the total energy generation capacity of the US. Delays in the US Congress for enacting legislative action could make the 20% by 2030 goal unattainable in the US, but as most US citizens support the utilization of wind energy, hope remains toward establishing a long-term policy, which ensures incentives for RE investments and further expansion of the wind energy industry.

4.3 European Union

Wind energy generation capacity in some countries within the EU has already developed into being a significant portion of the total electricity generation capacity (Barthelmie et al. 2008, GWEC 2012). According to the European Wind Energy Association (EWEA) in 2009 the EU produced 4.8% of total electricity from wind energy (EWEA 2010). In fact, as of 2006 Denmark generated 16.8% of its total electricity from wind energy (IEA 2006, Barthelmie et al. 2008), and has since been the first country to surpass producing 30% of its total electricity generation from wind energy and is well on its way to meeting its goal of 50% by 2030 (Danish Wind Industry Association 2013). This feat is remarkable in comparison to many of the other countries within the EU, which are hoping to reach 20% installed wind energy capacity by 2020.

As the electricity supply system has evolved to integrate RE sources a number of different strategies have been developed, and in 2007, the EU committed itself to a goal of 20% of the energy consumed within the EU being produced by REs by 2020 (Blanco et al. 2008). In doing so the EU would be able to cut CO_2 emissions by 20% of 1990 levels during the third phase of their Emissions Trading Scheme (ETS), which runs from 2013 through 2020 (Blanco et al. 2008). This phase of the ETS also discusses a directive of how to split the 20% by country and by industry (Blanco et al. 2008). As a part of this 2007 agreement, by 2020 the EU also seeks to reach an installed wind energy capacity of 190 GW onshore and 40 GW offshore (EWEA 2010). This would be equivalent to about 14-17% of the EU's total electricity being created by wind energy alone while averting 333 million tons of CO_2 emissions from entering the atmosphere each year, in addition to saving €28 billion in fuel costs and €8.3 billion in CO_2 related costs (EWEA 2010).

By producing 4.8% of their total energy from wind energy in 2009 the EU countries were able to reduce their total CO_2 emissions by 106 million tons, which is equivalent to taking 25% of EU cars off the road (EWEA 2010). It is also said to have saved €6 billion in fuel costs, and additionally has employed 192,000 people (EWEA 2010).

By 2030, the EU has set targets to produce 250 GW of onshore and 150 GW of offshore energy from wind turbines, which translates to about 26-35% of the EU's total electricity, avoiding 600 million tons of CO_2 being injected into the atmosphere per year, and saving €56 billion in fuel costs and €15 billion in CO_2 related costs (EWEA 2010). To date the EU is still on track of meeting their 20% by 2020 goals.

EWEA's 2011 annual market report states EU countries installed 9,616 MW of wind energy in 2011 (EWEA 2012). The report goes on to list six of the top ten countries in the world with the highest cumulative installed wind energy capacity as being located in the EU: Germany (29,060 MW); Spain (21,674 MW); Italy (6,747 MW); France (6,800 MW); United Kingdom (6,540 MW); and Denmark (3,871 MW) (EWEA 2012).

Although the EU has fallen behind in total cumulative installed wind energy capacity in recent years to the US and China, the European Commission formed the European Wind Initiative: to maintain Europe's technology leadership in onshore and offshore wind power; to make onshore wind the most competitive energy source in the EU by 2020, with offshore following by 2030; to achieve a 20% share of wind energy in EU total electricity consumption by 2020; and to create 250,000 new skilled jobs in the EU by 2020 (EWEA 2013). This initiative illustrates the EU's continued leadership in the wind energy industry while also improving its energy security.

Figure 6: 2011 Wind Energy Installed Capacity by European Country (EWEA 2012)

4.4 People's Republic of China

China's economy is currently booming with double-digit rates of economic growth for most of the past two decades and this has ultimately led to the country having large increases in the demand and use of fossil fuel energy (Saidur et al. 2010). Coal accounts for 74% of China's energy (Lema et al. 2006), and because of its growing population and economy this has resulted in China becoming the largest producer of CO_2 emissions in the world.

Despite the ongoing financial crisis in the US and EU, China's government has recognized an opportunity for economic development, both domestically and internationally, by investing in RE technologies, specifically in wind energy. China is a large country composed of an expansive coastline and landmass, which currently possesses a considerable amount of exploitable areas for utilizing wind energy, and therefore has led to considerable growth in the manufacturing and installation of wind power products in recent years (Jungfeng et al. 2010). In 2011 alone, China added 17.63 GW of wind energy to its energy market, which spreads throughout 30 Chinese provinces, cities, and autonomous regions (Junfeng et al. 2012). This impressive amount of newly installed wind energy is a 6.9% decrease from China's 18.64 GW installed in 2010; however, it was still more than double the 6.8 GW the US added over the same amount time (GWEC 2012).

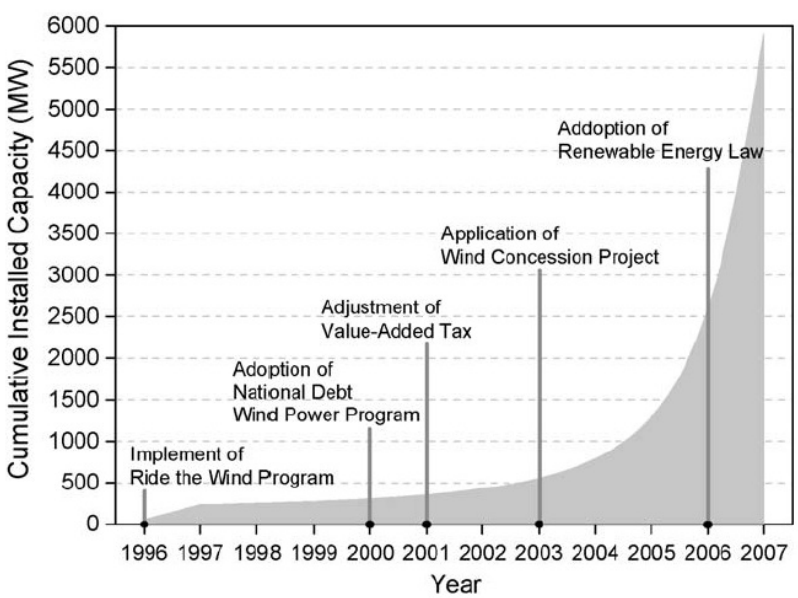


Figure 7: Political Milestones for wind power development in China (Changliang et al. 2009)

According to the 2010 China Wind Power Outlook report produced by the Chinese Renewable Energy Industries Association, GWEC, and Greenpeace, China installed 13.8 GW of energy in 2009 with a value of 150 billion renminbi (RMB) and created 150,000 jobs (Junfeng et al. 2010). On January 1, 2006 China implemented a policy on RE development and the Chinese National Energy Administration began selecting areas with the best wind resources to set targets to be reached by 2020 and offered economic incentives to developers (GWEC 2011). Lema et al. state China's RE policy has led to a strengthening of the RE industry and its ability to provide stable output levels of wind energy, as well as prove to investors its commitment to ensuring a long-term and stable market for wind turbines within China (Lema et al. 2007). China's ability to enact legislation and devote capital and resources to wind energy is showing the country's commitment to cutting emissions and to leading the world into an era of RE technology (Lema et al. 2007).

China's rate of installed capacity has increased dramatically since 2008, when it was producing just 12 GW of power from wind energy total. In 2009, China doubled their installed capacity to 25.8 GW, and then up to 42.2 GW in 2010 (GWEC 2011), and 62.4 GW at the end of 2011 (GWEC 2012). By 2015, China will reach 100 GW of installed wind energy capacity. According to its "Renewable Energy Twelfth Five-Year Plan" about 5 GW should come from offshore wind power in 2015 and 30 GW in 2020 (Junfeng et al. 2012). Although its land-based wind energy expansion has increased rapidly, the successful implementation of offshore wind energy projects has taken longer to establish a solid foundation. By the end of 2011, the completed installed capacity of offshore wind projects totaled 242.5 MW, with 2.3 GW in early development (Junfeng et al. 2012). Utilization of its offshore wind resources is a very important one for China for a variety of reasons, including; a majority of China's population lives in coastal regions; China possesses 18,000 km of coastline; and China has more than 6,000 islands. With these regions being highly populated, and as the economy with all likelihood will continue developing, investment in new infrastructure and cleaner energy sources will be vital for bringing positive returns and growth to the region.

China's strong focus on integrating wind energy into their energy portfolio has created significant challenges. Despite having been installed, many wind turbines remain idle because they were built in remote areas still in need of being connected to the electric grid or need transmission lines upgraded to carry the electricity to where it is needed (Roney 2012).

At the current rate, China's primary energy demand is projected to double by 2030, which would raise its emissions to 11.4 Gt (IEA 2007). Through this swift proliferation of installed wind energy, China is well on its way of achieving its 2020 goal of: producing 200 GW of energy from wind; cutting 440 million tons of CO_2 emissions; creating 500,000 jobs; and adding RMB 400 billion to the industry's value (Junfeng et al. 2010).

4.5 Republic of India

Currently, the economy of India is growing annually at more than 6% and may rise to 8%, and this growth is resulting in electricity shortages of 8% to 12%, with a 12% to 25% shortage during peak capacity times (Hossain et al. 2011). Due to energy generation having not expanded quick enough approximately 40% of India's population still does not have access to modern forms of electricity (GWEC 2012b).

India's Central Electricity Authority expects its energy demand to increase exponentially, with its National Electricity Plan stating India's total power capacity will need to be between 350-360 GW by 2022 (GWEC 2012b). Although the overall installed capacity has continually increased over recent years, India continues to struggle with meeting the demand and thus India is in a continual state of trying to catch up with its peoples' demand for access to modern forms of energy.

For India to satisfy its demand for energy it has been projected under the New Policies Scenario of the World Energy Outlook, the total power capacity in India must reach 779 GW in 2035 (IEA 2011). As of 2012, India had an installed capacity of 207.8 GW (GWEC 2012b). For it to be possible to reach 779 GW India would need its energy sector to grow by 20 GW per year from 2009 through 2035; however, to date India's largest amount of installed capacity is 18 GW per year (GWEC 2012b). This mix of consumer demand and weak infrastructure may lead to having a significant inhibiting effect on India's economic rate of growth in the coming years.

In order for India to reach the necessary levels of energy demand it is focusing its attention on expanding its RE industry and in particular promoting wind energy development. India has a coastline of over 7500 km, and like many other countries the government is seeking to expand the development and installation of wind energy projects along coastal states. In the southern state of Tamil Nadu, it has been projected at 80m there is 127 GW of energy, which may be produced from wind turbines (GWEC 2012b) and shows the development of offshore wind resources is promising in this region.

In comparison to recent years (See Figure 8), 2011 was a remarkable year for wind energy installation in India. For the first time India was able to add more than 3 GW of new wind energy capacity to total 17.9 GW throughout the country (GWEC 2012b). As of March 2012, RE accounted for 12.2 percent of all energy generated and 16.5 percent of newly installed capacity (GWEC 2012b). In comparison, this number is up from 1995 when RE accounted for 2 percent of installed capacity (GWEC 2012b). For India to reach the level of energy outputs that are needed, it is essential to invest in RE, as well as develop long-term policies and strategies so the market will remain effective and become more efficient.

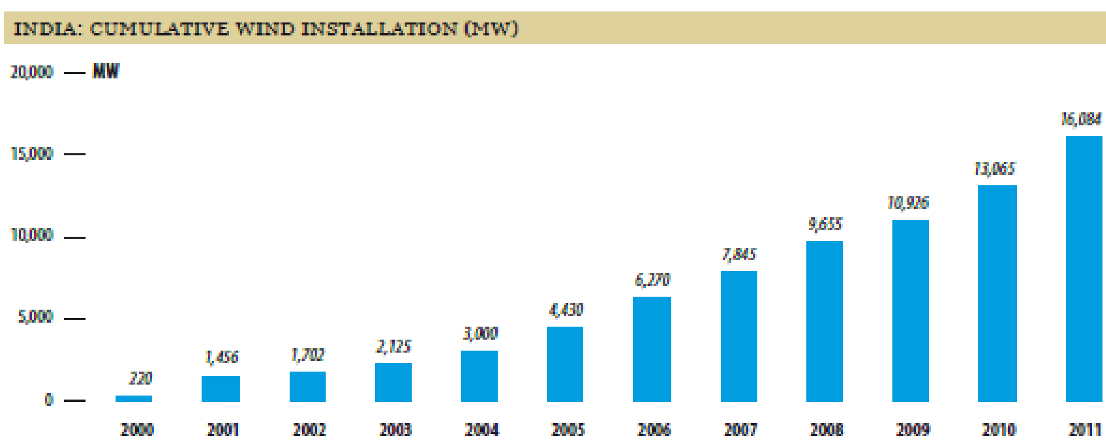


Figure 8: India: Cumulative Wind Installation (MW) (GWEC 2012b)

5.0 Utilizing Wind Energy Data Resources

Due to high upfront financial costs for the construction of wind power plants—relative to their operational and maintenance costs—both short and long-term analyses of wind speed variability play a central role in determining wind energy's economic feasibility. Large quantities of research are being conducted across the wind science fields, many of which are beginning to incorporate climate modeling and GIS technologies (See Section 6.0). The availability and accessibility of this data and this technology is pertinent for determining the best locations for wind turbine installation now and in the future. Because of this many governments have already recognized the importance of providing this data to the general public for free over the internet.

There are a multitude of variables directly affecting the wind industry, which include: access roads, transmission lines, urban and residential areas, airports, important habitat (ecological factors), slope of terrain, topography, state-owned and tribal lands, average wind speeds and direction, etcetera (Rodman et al. 2005, Sliz-Szkliniarz et al. 2011, Hossain et al. 2011, Aydin et al. 2010, Zhou et al. 2011). Many public and private organizations from around the world are working together: to provide better and quicker access to data; to improve upon data quality; to be able to convey the data to a non-scientific community effectively; and to implement strategic policies and incentive programs that allow wind energy expansion. Once the data has been provided to the public then industry, policymakers, researchers, and students are able to develop case studies, which will be discussed in a later section, to determine the best possible locations to utilize wind energy.

5.1 Oak Ridge National Laboratory (ORNL)

In March 2010, the DOE Wind and Water Power Program established the Wind Energy Data and Information (WENDI) Gateway within the Environmental Sciences Division of the ORNL located in Tennessee (ORNL 2012). The WENDI Gateway sought to satisfy a broad range of stakeholders from both the wind industry and the general public, and maintained an open resource system used for the archiving and delivering a host of wind energy data (ORNL 2012). The WENDI Gateway maintained the Wind Energy GIS tool, which allowed users to browse, query, and download US wind energy-related spatial data to compile many layers including average wind speeds, wind manufacturing facilities, electrical transmission lines, transportation infrastructure, topography, geopolitical layers, land cover types, ecosystem types, and many more (ORNL 2012). Having these datasets all in the WENDI Gateway was an extremely valuable and easily found tool for stakeholders to have access to as it cut down on the time it would take to gather all of this information from many independent sources. WENDI also provided the user the ability decide on what and how to analyze the data for wind energy assessments. Due to budget constraints, as of March 2013, this program no longer exists and much of the data once easily found through this program is difficult to find or is in the process of being transferred to a DOE open access database (ORNL 2012).

5.2 National Renewable Energy Laboratory (NREL)

Funded through DOE's Wind Program, NREL's National Wind Technology Center (NWTC) has been a premier partner in the deployment of wind power by continually seeking to: improve wind farm energy production, reduce wind turbine costs, improve reliability and reduce operational and maintenance costs, and eliminating the barriers to large-scale deployment (NREL 2012). NWTC provides technical assistance in wind resource management and assessment, as well as the development and validation of both high and low-resolution wind maps. NREL utilizes GIS mapping tools and an array of satellite, weather balloon, and meteorological tower data, and combine those with computer models to provide more accurate data, which allows for the identification of areas to construct wind farms that were once thought unsuitable (NREL 2012). The NREL GIS team also creates choropleth maps depicting the amount of installed wind energy capacity there is in each US state at the end of each year (See Appendix 2), as well as uses targeted analysis tools that can help determine availability of different RE resources across the US (NREL 2013b).

Although NREL has made available maps for mean annual wind speeds at 50m over the United States, the agency only provides datasets for 46 of those states and specifically does not include the states of Florida, Mississippi, Alabama, and Louisiana (NREL 2013a). When contacted, the company that provides NREL with these datasets wanted to charge a fee of $20,000 per state. This practice of only providing some and not all data imposes limits on students and researchers from being able to adequately conduct analyses, as they must seek other resources or find funding. Open and free access to data being used by the government is the norm and NREL should complete its access to wind speed data to include the southeastern US.

5.3 National Oceanic and Atmospheric Administration (NOAA)

NOAA's National Climatic Data Center (NCDC) uses GIS-based map interfaces to provide open-access to US and global climate/weather data. NCDC collects data which are received from a wide variety of sources, including satellites, radar, remote sensing systems, aircraft, ships, radiosonde, wind profilers, solar radiation networks, and NWS Forecast/Warnings/Analyses Products, all of which may be used to assess and monitor climate variation and change (NOAA 2012), and can be brought into GIS programs for analysis. For instance, NOAA maintains datasets and presents that data on GIS maps, which can depict daily, monthly, and annual average wind speeds, wind anomalies, tornadoes, hurricane tracks, temperature, precipitation, and etcetera (NOAA 2012).

5.4 American Wind Energy Association

AWEA is a lobbying association representing wind energy manufacturers, researchers, utility companies, and others involved in the wind industry within the US (AWEA 2012). Like many other lobbying groups, AWEA integrates much of their wind energy data into short factsheets and incorporates easy-to-read tables, as well as GIS maps to convey their campaign messages to busy policymakers. Figure 9 is an example of how AWEA is able to show the public how wind energy supports jobs and job creation across much of the US.

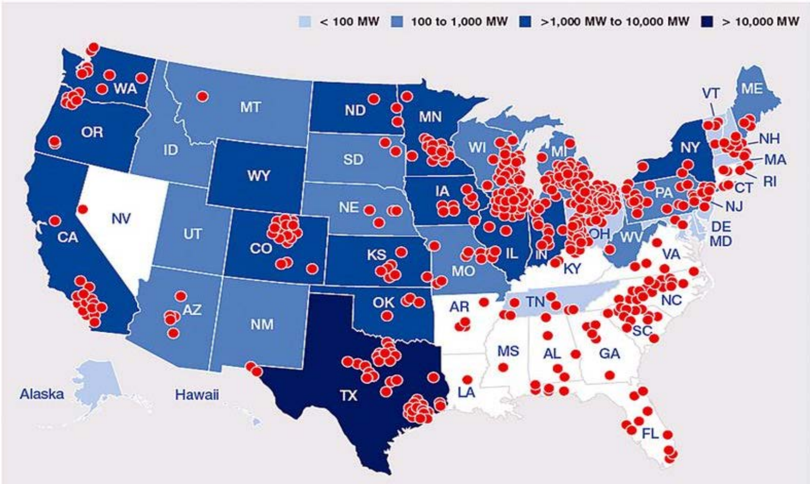


Figure 9: All Online Wind-Related Manufacturing Facilities (AWEA 2012)

5.5 Intergovernmental Panel on Climate Change (IPCC) Data Distribution Center

The IPCC Data Distribution Centre (IPCC-DDC) was established in 1998 to facilitate the timely distribution of consistent sets of observed climate data, global climate model data and scenarios, and related environmental and socio-economic factors, all of which may be of use in climate impact and adaptation assessments (IPCC-DDC 2012). Ultimately, the intention is to establish consistency in climate science and to feed into the review process of the IPCC.

6.0 Wind Energy and GIS-based Case Studies

As noted, the US, EU, India, and China are investing significant amounts of time, effort, and money constructing and integrating wind energy into electric grids, and GIS has a significant and a compelling role in the analysis of the many variables to be taken into account in order to determine suitable sites for installing wind turbines. As quality data becomes more readily accessible numerous studies have been conducted on many different regions around the world.

6.1 Northern California

6.1.1 Background

Rodman and Meentemeyer adopt a rule-based GIS model to analyze the suitability of wind energy facilities already developed or proposed in Northern California so that energy planners can use information to predict the extent to which wind energy can be further expanded based on land availability and public perception (Rodman et al. 2005).

6.1.2 Methodology

Three models were used: physical features, human impact, and environmental. Those three models were combined to create a fourth model. The three base models used variables including: physical features such as wind speed, obstacles, and terrain; impacts on humans like the proximity to populated or recreational areas; and an environmental model taking into account vegetation, land use, endangered species, and wetlands. The data was mapped in a GIS program, converted into a raster format, and formatted to a 30m x 30 m cell size, and converted to a 30m resolution for the overlay analysis (Rodman et al. 2005).

These models were chosen to allow weighted inputs of the different variables and developed a binning system to represent each variable's significance to the overall suitability measurement. For example, in the layer used to measure wind speeds, the minimum threshold speed adequate for wind energy is 7 m/s for large turbines. As such, areas sited with average wind speeds greater than 7m/s were given a score of 4, meaning they were excellent for site suitability, while areas sited for less than 7m/s were given a score of 0, meaning they were unsuitable for wind energy sites (Rodman et al. 2005).

6.1.3 Results

Using a rule-based spatial analysis, Rodman and Meentemeyer created a model for each feature with scores ranging from unsuitable (0), poor (1), fair (2), good (3), or excellent (4). If a location received a 0 from any individual model it was determined to be unsuitable for the combined model. The analysis results were verified as only three sites in the studied region were selected as suitable locations and they were within the vicinity of existing wind farm developments (Rodman et al. 2005).

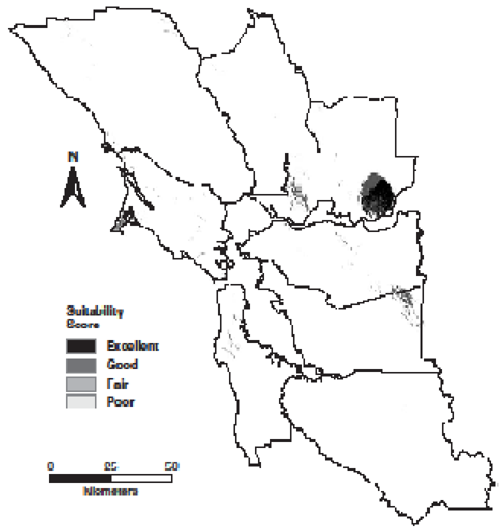


Figure 10: Potential Wind Energy in Northern California (Rodman and Meentemeyer 2005)

6.2 Poland - Kujawsko-Pomorshie Voivodeship

6.2.1 Background

In response to the European Commission approving a mandatory 20% target of renewable energy sources, and with Poland being expected to increase its renewable sources to 15% by the year 2020, Sliz-Szkliniarz and Vogt develop an approach to support the decision making process for wind energy site projects using a GIS (Sliz-Szkliniarz et al. 2011). Sliz-Szkliniarz and Vogt's goal of was to provide a regional planning instrument that would lead to a more sustainable energy policy and multiple benefits for government authorities and individual developers (Sliz-Szkliniarz et al. 2011).

The Kujawsko-Pomorshie Voivodeship is characterized as having suitable terrain conditions and both good and very good wind speed zones, with the region being determined to have the third most favorable wind conditions for wind energy utilization in the Poland (Sliz-Szkliniarz et al. 2011).

6.2.2 Methodology

Sequential steps incorporated characteristics and restrictions including ecological, infrastructural, technical, and economic criteria to provide a new framework for spatial planning and wind energy site selection (Sliz-Szkliniarz et al. 2011). The model incorporated a list of 42 criteria reflecting both ecological and spatial policies to create exclusion zones. Then wind speed data sets were added and the number of full load hours was estimated based on Raleigh probability distribution parameters and power curves, which were overlaid by available locations for wind farm construction in the region (Sliz-Szkliniarz et al. 2011). Finally, unit costs of wind energy were estimated for the grid cells to take into account economic viability (Sliz-Szkliniarz et al. 2011).

6.2.3 Results

Sliz-Szkliniarz and Vogt do not state the type of analysis this comprehensive model used other than "GIS-based;" however, the model analyzed the locations of suitable areas that did not have infrastructure or ecological restrictions (Sliz-Szkliniarz et al. 2011). Sliz-Szkliniarz and Vogt placed symbols on a map comparing the amount of available area usuable for future wind turbine placement and the sum of the area already covered by wind turbines (Sliz-Szkliniarz et al. 2011). Even with excluding areas with infrastructure and ecological restrictions there are almost 7,500 km^2 within the Kujawsko-Pomorshie Voivodeship suitable for wind energy sites (Sliz-Szkliniarz et al. 2011). These results show incredible potential for wind energy expansion in the region.

Ultimately, wind energy expansion will depend on whether the communities are willing and accepting to integrating these installations. Sliz-Szkliniarz and Vogt look to further expand on this approach in the future to provide policymakers and organizations with ample information to facilitate the transition of national targets (Sliz-Szkliniarz et al. 2011).

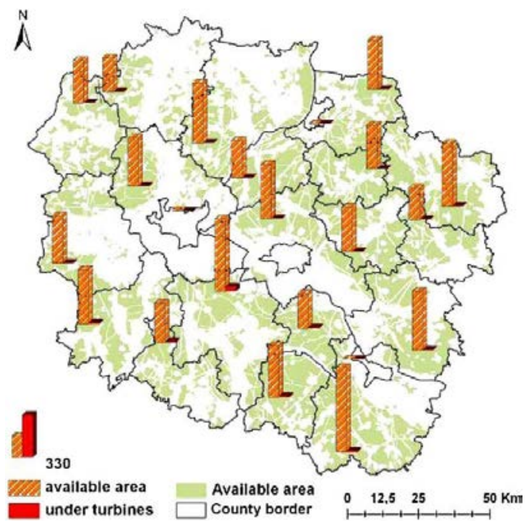


Figure 11: Wind energy Kujawsko-Pomorshie Voivodeship (Sliz-Szkliniarz et al. 2011)

6.3 India

6.3.1 Background

Hossain et al. assess the possibility of India using wind energy, along with GIS, to meet energy demands both now and in the future. With India's economy growing, an energy shortage may constrain further growth and as such, this study seeks to find whether wind energy is a suitable energy source for India from a national planning and policy perspective (Hossain et al. 2011).

6.3.2 Methodology

The methodology begins assuming all of India is covered by wind farms and it sets up a grid of $1km^2$ over regions of interest, which includes mostly the peninsular India as the terrain in Northern India becomes very complex when nearing the Himalayas (Hossain et al. 2011). Within each grid a single land use type is established and wind speed data from 20m is interpolated (Hossain et al. 2011). Urban areas, rural areas, environmentally sensitive, and water bodies are excluded, while the study assumes wind farms possess no environmental hazards or social issues (Hossain et al. 2011). The study then assumes the electricity grid and infrastructure would be developed to accommodate wind energy installation strategies, and finally, a Rayleigh distribution and the normalized power curve are used to compute the annual energy output and this potential is then assessed for each grid by its land-use category (Hossain et al. 2011).

6.3.3 Results

There is roughly 2075 GW of potential wind energy in India, which is significantly more than previously evaluated (Hossain et al. 2011). The researchers also note the potential wind energy could be higher if there were better measurements of wind speeds at higher altitudes where there is less surface friction and turbulence (Hossain et al. 2011). Hossain et al. do not state the type of GIS analysis this model used other than referring to using the GIS platform ArcEditor 9.3 (Hossain et al. 2011). Despite this, the model analyzed each grid that was created and then analyzed the data based on the land-use categories each grid cell fell under.

Hossain et al. notes this is the first time a GIS platform has been used to this extent to research India’s wind energy potential, and go on to determine wind energy potential in India is sufficient to move forward and wind energy could help India meet its energy needs; however, believe the challenge will lie in redesigning the existing electricity grid to make it compatible with this type of energy generation (Hossain et al. 2011).

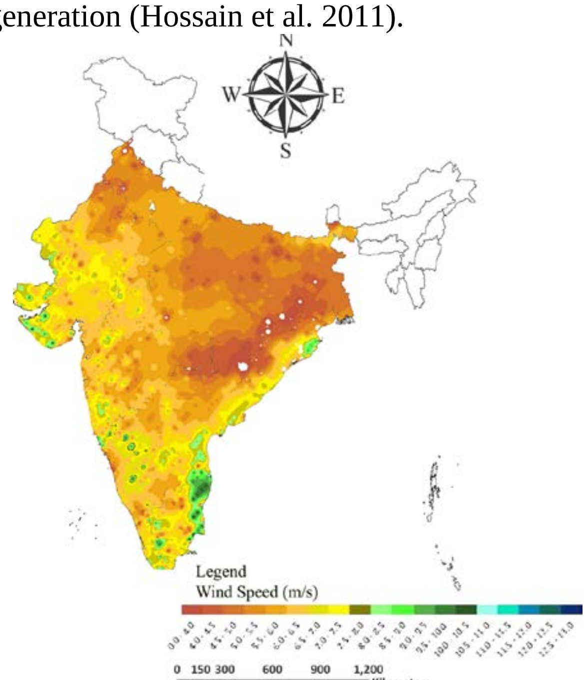


Figure 12: Wind power potential of India by plant load factor (Hossain et al. 2011)

6.4 Western Turkey

6.4.1 Background

Aydin, Kentel, and Duzgun aim to create a decision support system for site selection of wind turbines using GIS tools. The researchers decide, for this particular study, wind energy potential needs to be evaluated alongside environmental concerns. (Aydin et al. 2010). Potential environmental impacts on wind energy potential is identified by Turkish law and represented as "fuzzy objectives of the decision problem" (Aydin et al. 2010).

6.4.2 Methodology

The methodology of this assessment begins with identifying and quantifying the environmental objectives (Aydin et al. 2010). This information is then created into spatial data layers and run through a fuzzy membership process, which in turn assigns individual satisfaction degrees to each and calculates an overall environmental performance index (Aydin et al. 2010). Finally, a wind energy potential fuzzy overlay set is added to the overall environmental performance index and suitable sites for wind turbines are identified (Aydin et al. 2010).

6.4.3 Results

The study concludes investment in wind energy is economically sound, and since the investments in wind energy are on the rise in Turkey it is crucial to determine priority wind energy sites (Aydin et al. 2010).

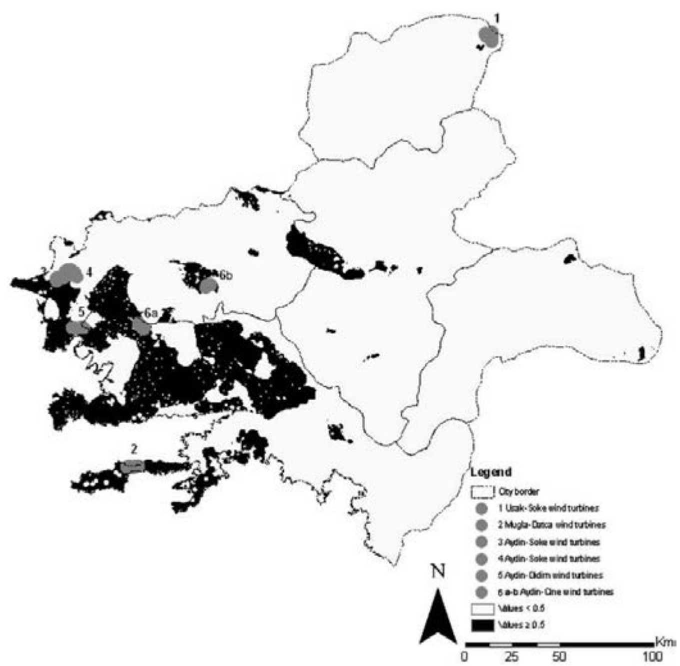


Figure 13: Priority Wind Energy Sites for Western Turkey (Aydin et al. 2010)

6.5 Jiangsu, China

6.5.1 Background

Zhou, Wu, and Liu state the Jiangsu province, which is an eastern coastal province in China, has to tackle increasingly serious power shortages due to the rapid economic expansion of the region (Zhou et al. 2011). Due to its geographic location, Jiangsu has abundant wind resources and the aforementioned researchers seek to further support the continued exploitation and utilization of this clean energy (Zhou et al. 2011). This study acknowledges the exploitation of this resource is determined by many factors, including topographical, political, economic factors, and as such seeks to estimate the technological available potential of wind energy in the Jiangsu province (Zhou et al. 2011).

6.5.2 Methodology

The methodology of this study begins with acquiring historical meteorological data from 1979 to 2008, which includes information including the daily average temperature, pressure, air density, and wind speeds, as well as land-use map data (Zhou et al. 2011). The researchers use an equation for wind power density, which is defined as the wind power available per unit area swept by the turbine blades (Zhou et al. 2011). The equation is defined as:

Equation 1:

$$D_{WP} = \frac{1}{2n}\sum_{j=1}^{n}(\rho)(vj^3)$$

Where the numbers of records being averaged defines *n*, ρ is the air density (kg/m^3), and *v* is the wind speed (m/s) (Zhou et al. 2011). Once calculated, this data is then uploaded into a GIS software program (ARCGIS 9.3) and a number of factors limiting site selection are then inserted as an overlay to mark unfavorable areas for wind farms (Zhou et al. 2011).. For this study an unfavorable condition includes high altitude, high slope, areas near airports, protected areas (forests and national parks), railways, residential areas, factories, rivers, and lakes (Zhou et al. 2011).

6.5.3 Results

This study concludes wind energy resources in the Jiangsu province are currently rich and the wind energy potential decreases as you move from the coast to the inland areas (Zhou et al. 2011). A total of 1,813 km^2 was found to be suitable for installing 2.0 MW turbines with the potential to generate 146,336 GWh annually (Zhou et al. 2011). The researchers do not go as far to explicitly state the Jiangsu province should invest heavily in offshore wind farms; however, they repeatedly state the best wind energy sources lie along the coasts (Zhou et al. 2011). This would imply offshore wind farms would likely be a logical step for expanding wind energy in the Jiangsu Province.

Station	Longitude (E)	Latitude (N)	WPD (W/m^2)	H (h)	Station	Longitude (E)	Latitude (N)	WPD (W/m^2)	H (h)
Dongshan	120.43	31.07	52	5125	Nanjing	118.78	32.04	40	4216
Shuyang	119.48	31.43	22	1824	Sheyang	120.25	33.76	224	6023
Changzhou	119.95	31.79	48	2200	Jiangying	120.26	32.98	41	2156
Lusi	121.6	32.07	156	6564	Huaian	119.15	33.28	25	3456
Nantong	120.88	31.98	51	4867	Xuyi	118.52	32.58	22	6428
Dongtai	120.28	32.85	52	5216	Ganyu	119.11	34.83	50	2400
Gaoyou	119.45	32.8	51	2300	Xuzhou	117.2	34.26	39	2226

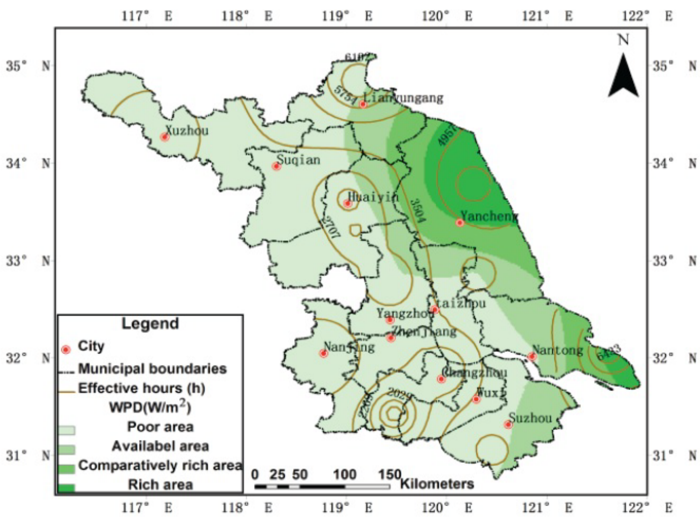


Figure 14: The distribution of wind energy across the Jiangsu Province (Zhou et al. 2011)

7.0 Wind Energy in a Changing Climate

Wind is simply air in motion, which is moving from a high-pressure region to low pressure region, which are due to the uneven heating of the Earth as a result of its diurnal rotation (Nix 1995). This uneven heating spawns air masses with potential energy and pressure forces that be transformed into kinetic energy (Sahin 2004). Average wind speeds vary and are dependent upon latitude, longitude, attitude, and time (Sahin 2004).

Climate is characterized in terms of long-term patterns of various aspects of the atmosphere-hydrosphere-land surface system over a period of months or more while additionally taking into account and comparing this data to historically-averaged variables (American Meteorological Society 2009). The climate is studied by taking averages of precipitation, temperature, humidity, sunshine, wind velocity, fog, frost, hail storms, and other measurements of the weather that occur over a long period (years to decades to centuries to millennia) in a particular place (American Meteorological Society 2009).

Climate change is a normal part of the Earth’s natural variability, which is related to interactions among the atmosphere, ocean, and land, as well as changes in the amount of solar radiation reaching the earth (Cradden 2009). The geologic record includes significant evidence for large-scale climate changes in Earth’s past (Cradden 2009). Climate change, however, represents one of the greatest scientific, socio-economic, and political challenges for the world over the rest of this century and for centuries to come. Studies of the planet show the climate has had natural variations over the course of its lifetime (Cradden 2009). Although the natural changes in the Earth's climate are still present, the climatic changes being observed and projected to occur in the coming decades are most likely due to anthropogenic forcing (Sahin 2004), through the release of billions of tons of CO_2 and other heat-trapping gases, referred to as GHG, into the atmosphere (National Research Council 2010). In fact, scientific experts believe anthropogenic emissions of CO_2 and other GHG is leading to climatic changes on a scale beyond which could be expected under natural variability (Sahin 2004). This anthropogenic-caused forcing has the potential to incite both predictable and unpredictable climatic changes globally and those changes may also have an impact on the wind.

Winds occurring frequently in a particular direction are typically referred to as prevailing winds and are arranged in a series of belts around the globe (Figure 15) (Ackerman 2013). These belts are influenced by the Three Cell Model and represent the ordinary circulation patterns of the atmosphere and are used to describe the atmospheric transport of energy.

The first cells are the Hadley Cells, which begin by relatively weak winds converging and moving in an easterly fashion along the equator, where the powerful incoming solar radiation in the equatorial region creates rising air that will cool, condense, and move northward toward lower pressure areas (Ackerman 2013). Large cumulous clouds and heavy precipitation characterize this region, which is called the Inter-Tropical Convergence Zone (Ackerman 2013). By the time the air moving northward reaches about 30°N it has become a westerly wind due to the Coriolis force and due to the conservation of angular momentum, the poleward moving air increases speed (Ackerman 2013). This poleward moving air piles up forming an area of high pressure at the surface, causing some of the upper air to sink toward the surface, and is typically very dry and this descending air hinders cloud formation, which is the reason many large deserts are found in the vicinity of 30°N and 30°S (Ackerman 2013). Once the sinking air reaches the ground, some flows toward the west in the northern hemisphere, due to the Coriolis force, which forms the trade winds that blow steadily from the northeast

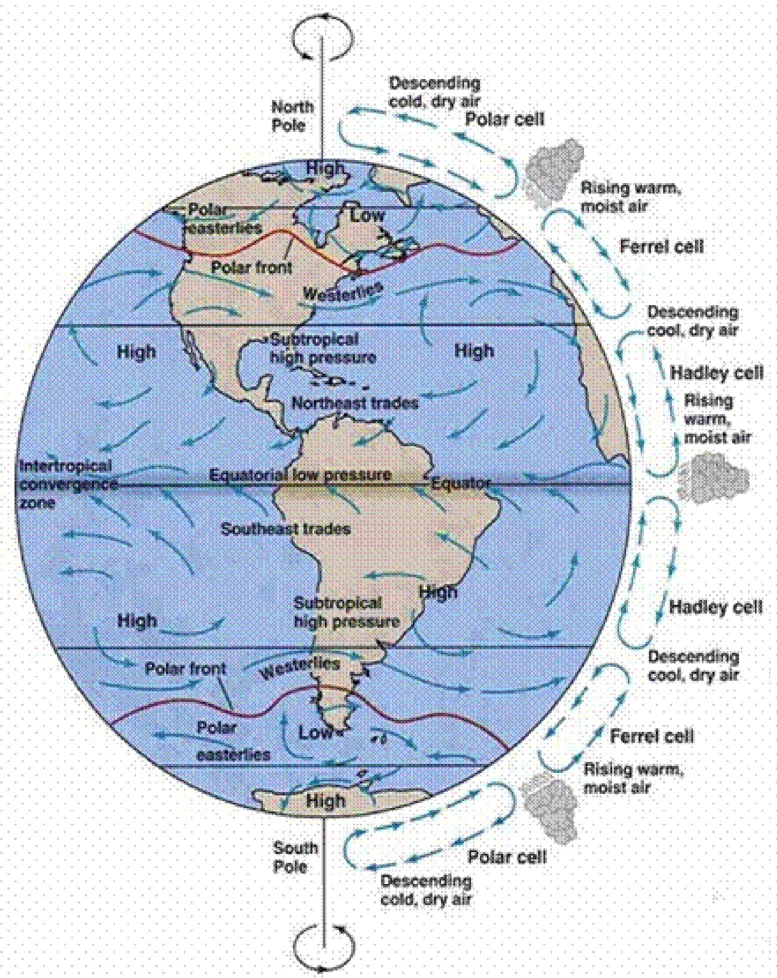


Figure 15: General Atmospheric Circulation (University of Texas 2013)

in the northern hemisphere and southeast in the southern hemisphere (Ackerman 2013).

The second cell, is the Ferrel Cell, and spans across the mid-latitude region. Some of the air at the surface near 30°N starts to move poleward and gets deflected to the east by the Coriolis force, resulting in the prevailing westerly winds at the surface (Ackerman 2013). At about 60°N the air will begin to rise, where it cools and then condenses to forms clouds and precipitation (Ackerman 2013). At this point, the air has reached the general region of the polar front.

The final cell, or the Polar Cell, fully encompasses the high latitudes. Here sinking air will warm and result in a near constant high pressure system over the poles (Ackerman 2013). At the surface, the poleward winds are pulled to the right by the Coriolis force (in the northern hemisphere) and will form the polar easterly winds (Ackerman 2013). The cold polar air meets with the warm subtropical air moving poleward and forms a boundary between these two air masses known as the polar front (Ackerman 2013). The warm air from the subtropics pushes up over the cold equatorward moving polar air, and is the source of much of the dynamic weather in the midlatitudes, particularly in fall, winter and spring (Ackerman 2013).

Although winds generally flow in this direction they are variable and not fixed to always flow in the same direction, at the same time, and with the same speed (Sahin 2004).

7.1 An Uncontrollable Resource

Researchers Paul Breslow and David Sailor discuss the variability of wind regimes and the output of wind energy as being sensitive to temperature, humidity, precipitation, and most importantly mean wind speeds (Breslow et al. 2002). Theoretically it is estimated, if dissipated uniformly over the entire surface area of the Earth, wind energy possesses the ability to harness 10,800 x 10^{18} J of power, which is more than 22 times the world's current energy needs (Lu et al. 2009). In practice though the exploitable potential is noticeably less (Sesto et al. 1998); however, the energy industry is now being supported as a clean way to manage energy needs, which can be seen through the continual rise of installed wind energy capacity around the world.

Despite the previously mentioned global expansion in installed wind energy capacity, researchers have observed an overall trend of declining mean wind speeds since the 1970s in many locations within the mid-latitudes (McVicar et al. 2010, Mears et al. 1999, Vautard et al 2010, Rasmussen et al. 2011, Pryor et al. 2009, Pryor et al. 2010), while notable increases in mean wind speeds may appear in higher latitudes (McVicar et al 2012). Many attributes may be the cause of these changes: land use changes, reforestation, urbanization (Vautard et al. 2010) or increased atmospheric aerosol levels (Jacobson 2006). In 2011, there were notable record lows in global mean surface wind speeds, with the frequency being 25% lower than frequencies measured in the 1980s (Vautard et al. 2012).

As many countries hope to become more energy secure and to diversify their energy portfolio, there is great interest in better understanding or developing comprehensive assessments on the vulnerability of regional wind energy resources to climate change (Pryor et al. 2006).

7.2 Reporting the Best Climate Science Available

The IPCC was formed in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) as an objective international body, which would disseminate the best scientific, technical, and socio-economic information available (IPCC 2013b). Although the IPCC does not make or enforce policy it seeks to get unbiased scientific theories and facts to policy-makers, who ultimately will make the policy decisions by semi-frequently publishing reports with the most relevant scientific opinions on nearly all facets of climate change, including but not limited to: the impacts of climate change; proposed mitigation measures; and adaptation strategies (IPCC 2013b). The most updated and accepted analysis was published in the 2007 IPCC *Fourth Assessment Report* (IPCC-FAR). In this document the IPCC states that temperature observations showed a warming trend over the 20th century, with a global average increase in surface temperature of about 0.7°C (Trenberth et al. 2007), with temperatures in the Arctic having increased by 1.9°C in the same time period (Rosenweig et al. 2007). Globally seas have risen at an average 1.8mm per year from 1961 to 2003 (Bindoff et al. 2007). According to the IPCC most of the observed increase in the globally averaged temperature is very likely due to an increase in anthropogenic GHG concentrations (Hegerl et al. 2007).

One of the most recognizable pieces of climate change science was discovered by Charles D. Keeling in 1958, when he noticed in remote areas CO_2 measurements consistently measures 310 parts per million (ppm) (NOAA 2013). A program was set up at Mauna Loa, Hawaii to record CO_2 concentrations in the atmosphere (NOAA 2013). What resulted was a jagged trend with a gradual upward slope showing seasonal fluctuations and rising CO_2 levels in Earth's atmosphere. This chart, now referred to as the Keeling Curve, is arguably the best-known icon illustrating the impact of humanity on the planet as a whole and reflects the importance of taking precautionary measures to prepare and adapt to climatic changes (NOAA 2013).

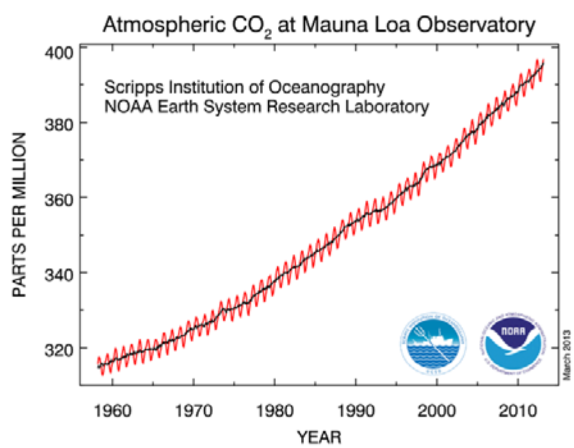


Figure 16: Monthly mean atmospheric CO_2 at Mauna Loa Observatory, Hawaii (NOAA 2013)

7.3 Site Availability Changes in High Latitudes

Not all regions will experience the same shifts in wind regimes and because of this the wind resource at a given location could be affected positively, negatively, or remain at status quo. Although not addressed specifically within the parameters of this study it is important to note many of the effects of climate change on wind energy production are specific to high latitude regions and is strongly affecting many aspects of systems related to snow, ice, and frozen ground (specifically permafrost) (Rosenweig et al. 2007). Icing on wind turbines currently presents a major challenge to the installation and operation of wind farms in high altitudes and latitudes because ice build-up on turbine blades can degrade the performance and durability of the turbine and can also lead to safety concerns associated with ice shedding (Pryor et al. 2010). A warming climate may mean sites previously deemed unsuitable for wind turbine deployment due to icing could become available for development (Pryor et al. 2010), further studies nevertheless should be conducted prior to using this justification to begin installing wind turbines in areas which experience large amounts of snow and ice.

The development of offshore wind farms has opened many opportunities for utilizing coastal regions for wind energy projects specifically in offshore areas which are generally considered public space, which makes the issue of offshore renewable energy development public in nature (Mostafaeipour 2010). Melting sea ice can cause greater rates of iceberg calving, which is a cause of concern for offshore wind energy developers since upon entering the open ocean an iceberg may drift and interfere or damage offshore wind turbine foundations and thus represents a critical issue in the deployment of offshore wind energy in higher latitudes (Pryor et al. 2010). Continual warming of the oceans and further melting of sea ice on the other hand would eventually reduce this interference, allowing more areas that can be targeted for use, but as with icing, further studies should be conducted to fully quantify the specific impact melting or calved sea ice could have on offshore wind turbines.

The effects of warming trends on the extent and depth of permafrost have made it increasingly challenging to design turbine foundations that will not be damaged and rendered useless in these regions (Pryor et al. 2010). Continual warming of the surface layer would result in melting permafrost, and may have a profound impact on road construction and repair, which may also influence access for wind farm installation and maintenance (Pryor et al. 2010). Another final challenge resulting from melting permafrost is being able to perform maintenance on damaged wind turbines resulting in less electricity being generated and lost revenues for the investor. These factors may play a role in public and private industry decisions on whether or not to move forward with investing in wind energy technology in cold regions until further analysis is conducted.

7.4 Atmospheric Change and the Effect on Wind

Atmospheric conditions play a significant role in the design and operation of wind power plants (Pašičko et al. 2012, Barthelmie et al. 2010, Pryor et al. 2010). As temperatures increase due to continued anthropogenic forcing, the atmosphere is being directly impacted (Pryor et al. 2010). A few factors which, may be impacted are the variability of wind speeds, rising air temperatures, and changes in wind direction (Pryor et al. 2010). These atmospheric changes will have a significant impact on the amount of energy generated from the wind at a given location (Pryor et al 2010).

Some researchers have found climate change may have an effect on altering the amount of wake and turbulence generated between turbines at a wind power plant, which would subsequently cause reductions in the amount of energy produced (Pašičko et al. 2012, Barthelmie et al. 2010, Pryor et al. 2010). Pašičko et al. however, state climate change would most affect wind energy generation due to changes to the average wind speed at a location (Pašičko et al. 2012, Pryor et al. 2010). Pašičko et al. suggest a decrease in average wind speeds, at a location, would influence the timing of operation and the amount of energy produced, while an increase in wind speeds would affect the reliability and the safety of the wind turbine equipment (Pašičko et al 2012). Variability of the wind can therefore have a significant impact on the amount of energy produced, as well as affect the necessary alternatives needed to generate energy when wind turbines are unable to produce adequate levels of energy.

Air density and wind speed changes can have a global impact across many regions and could therefore have an effect on already installed or proposed wind turbine sites and thus overall wind energy production at those sites (Pryor et al. 2010). A decline in air density is seen when there is an increase in temperature and humidity (Pryor et al. 2010) which results in a decline in the air's mass per unit volume in the atmosphere, which is derived from the Ideal Gas Law (Equation 2),

Equation 2: $$PV = NkT$$

where P is the pressure, V is the volume of the gas, N is the number of particles in the gas molecule, k is the Boltzmann Constant (1.38 x 10^{-23} JK^{-1}), and T is the temperature (Rebbi 2005). A change in air density affects the potential power that can be harnessed within a given region, which is referred to as the energy density (Pryor et al. 2010). Pryor and Barthelmie state air density is directly proportional to the energy density in the wind (See Equation 3) and hence the power output of wind turbine is inversely proportional to air temperature (Pryor et al. 2010). This means rising temperatures and atmospheric water vapor content have a direct impact on reducing the air density and therefore the potential power for a region:

Equation 3: $$E = \frac{1}{2}\rho U^3$$

where E is the energy density (Wm^{-2}); ρ is the air density (Kgm^{-3}); and U is the wind speed (ms^{-1}). Pryor et al.'s research shows only modest air density changes but these changes are notable as the amount of electricity produced from the wind is the cube of wind speed, a small change can have substantial consequences for the wind energy resource (Pryor et al. 2010).

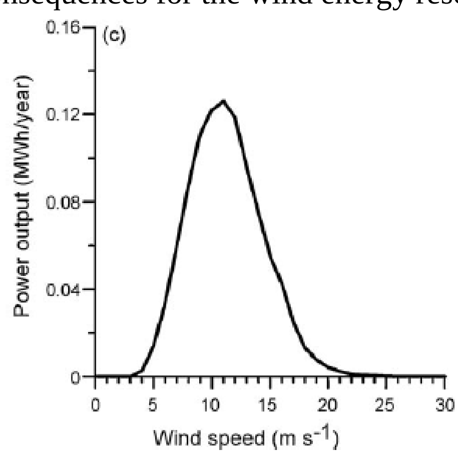


Figure 17: Power Output (MWh/year) vs. Wind Speed (m/s) (Pryor et al. 2010)

The impact of slight changes in the wind climate on wind energy production is concerning as Breslow and Sailor state analyses of past climates have identified natural variability cycles found in the climate record revealing climate anomalies associated with climate changes (Breslow et al. 2002). In a study conducted by Mahasenan et al. found that the planet is currently in a trough of a 160-year natural variability cycle (Mahasenan et al. 1997). If Breslow's and Sailor's analysis is accurate climate change may be exacerbated by an increased natural variability trend over the coming decades (Breslow et al. 2002). If the global climate is in a variable temperature trough, there could be unprecedented increases in temperatures that have not been adequately incorporated in adaptation and mitigation efforts. Ultimately this would further alter air density and wind speed, and thus wind energy output. Better understanding the potential climate change impacts on the wind may allow the wind energy industry to more effectively determine whether or not wind energy is the most cost effective strategy for short and long-term energy strategies and climate change mitigation efforts.

8.0 Wind Climate Change Predictions

When deciding upon locations for wind turbine installation many climatic factors may also be taken into account as slight changes could have a significant influence on the overall costs of the investment, the amount of energy output, and the amount of CO_2 offset. Winds are variable by nature (Cassola et al. 2008), and as such wind-siting assessments cannot solely measure the wind speed at a particular time and place. Instead they should characterize atmospheric conditions over a wide range of spatial and temporal scales. Researchers Pryor and Barthelmie are using Global Climate Models (GCMs) to extract higher resolution data projections so as to better understand the geographical distribution of the impacts climate change will have on the wind resource (Pryor et al. 2010). As the tipping points of climate change grow ever closer, the regional effects on wind climates must be considered so utility scale wind power plants will be just as economically advantageous towards the end of their lifespan as well as be beneficial to the consumer's energy needs.

8.1 United States

Given the importance of regional changes to wind regimes and the expansion of wind energy in the US, researchers have used climate models to simulate different scenarios in order to gain perspective of changing atmospheric circulation patterns over the contiguous US (Pryor et al. 2009). Pryor and Barthelmie postulate the determining of the magnitude of wind speed changes in a given location and time presents a difficult challenge to climate science (Pryor et al. 2010). The most direct manner climate change may impact the wind energy industry is by changing the distribution of, the average speed of, and/or the inter- and intra-annual variability of the wind resource (Pryor et al. 2010, Pašičko et al. 2012).

Pryor et al. conducted simulations over the US, using Regional Climate Models (RCM), which proved to have no clear consensus of regional regime changes across eight data sets (Pryor et al. 2009). In these simulations data sets that were exhibiting significant increases in mean wind speed trends were at the same time exhibiting significant negative trends in inter-annual variability, and vice versa (Pryor et al. 2009). Despite the lack of consensus across the eight RCM data sets Pryor et al. ran, two of their data sets exhibited consistent negative trends across the entire contiguous US with the trends being the largest over the Midwest and the eastern US (Pryor et al. 2009). In 2010, Pryor et al. went on to assess two Atmospheric-Ocean General Circulation Models (AOGCMs) which suggest slight declines in mean wind speeds (< 3%) by 2060 and less than 5% by 2110 (Pryor et al. 2010) with some areas of increases. In 2011, Pryor and Barthelmie determined over the next 50 years the US wind resource spatial patterns will not change much compared to the historical envelope and therefore the wind energy industry can and will continue to contribute to producing electricity for at least the next several decades (Pryor et al. 2011). As the wind resources over the continental US is vast, it is promising these studies establish a rather consistent opinion that the wind resource over the US will not change much for the time being.

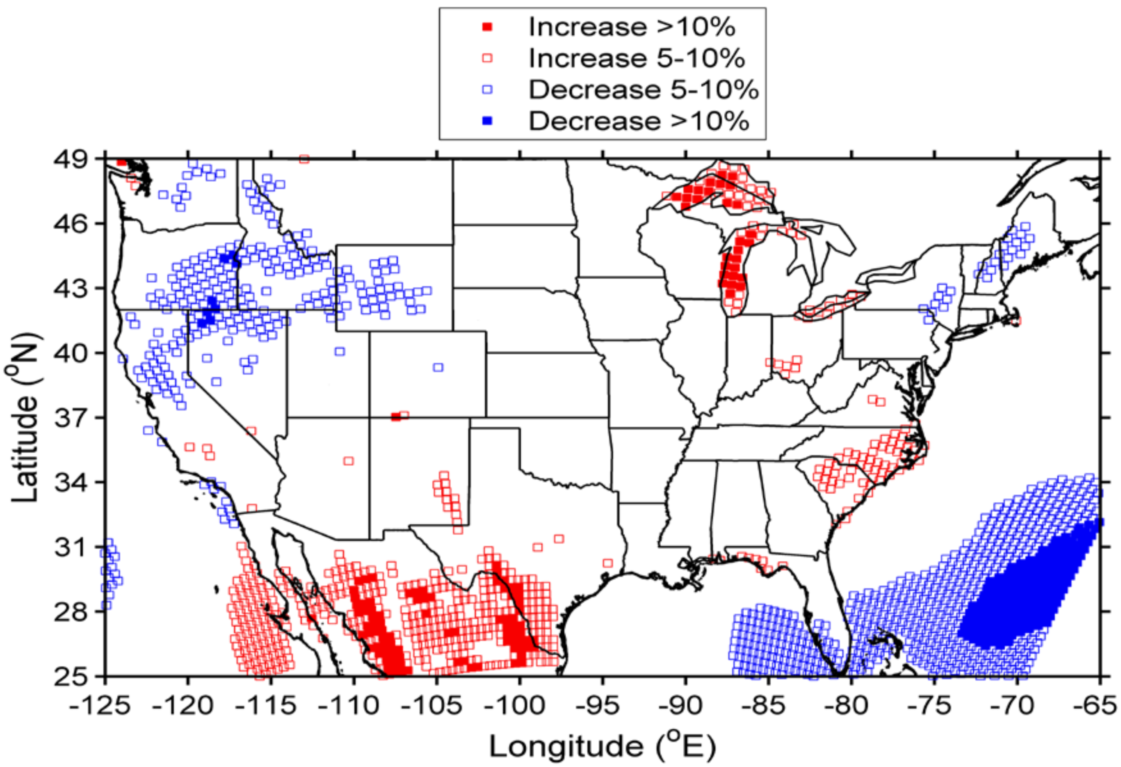


Figure 18: US Wind Speed Change for 2041-2062 (Pryor 2011)

8.2 European Union

Climate modeling results indicate a lack of change in wind energy density up until roughly 2050 for the EU countries. Pryor et al. report during 2071-2100 northern Europe is expected to experience a gradual increase of wind speeds (Pryor et al. 2005). The increases from the models seem to be plentiful (<±10%) and are comparable to the current variability manifested in downscaling from multiple AOGCMs and the natural variability within the climate system (Pryor et al. 2010). But since energy density is directly proportional to the cube of the wind speed seemingly small changes can have major impacts on power production and the economics of the investment (Pryor et al. 2009). Southern Europe, however, according to a 2008 article by North American Windpower, will experience declines in near-surface wind speeds (Eichelberger et al. 2008). Consequently, northern EU countries will likely experience benefits to their wind energy industry as a result of a changing climate while southern EU countries will likely experience a loss. The previously mentioned research suggests countries such as Germany, the United Kingdom, and Denmark would likely benefit from further wind energy investments as the research shows market stability (Pryor et al. 2006). Further research should be conducted though so countries such as Spain, Italy, and France might better determine whether or not other RE technologies would prove to be better in those countries for long-term investments.

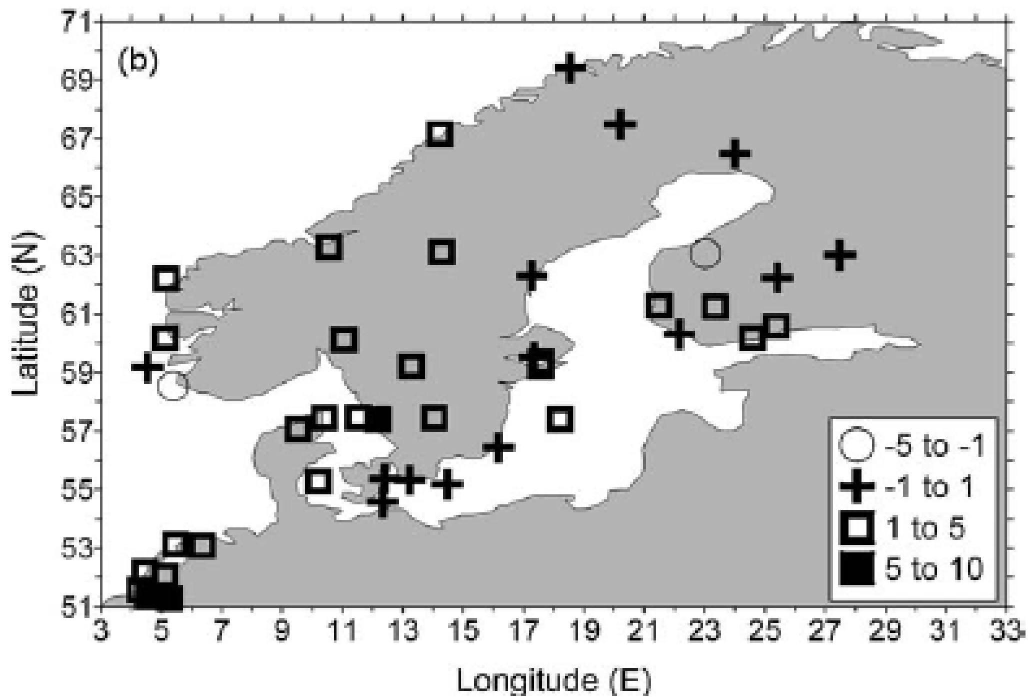


Figure 19: Wind speed change from 2081-2100 in Northern Europe (Pryor 2010)

8.3 China

Despite China's major investment in recent years in RE development, climate change could still severely impact the region. Saidur et al. predicts if climate change occurs as expected, China would be one of the worst impacted countries in terms of its wind resources (Saidur et al. 2010). Coupled GCMs back up this prediction suggesting all regions within China will experience a negative shift in average annual wind speed, with the most economically valuable land-based investment regions experiencing the most severe reductions in wind speed and will do so at quick rates (Ren 2010). Researchers have further conducted wind speed change models suggesting: 1) summer mean wind speeds for 2020 through 2029 will be lower compared to those in 1990 through 1999 in most areas of China; 2) annual and winter mean wind speeds for 2081 through 2100 will be lower than the historical reference period of 1971 through 1990 across all of China; and 3) the changes of summer mean wind speeds for 2081 through 2100 are uncertain (Jiang et al. 2010).

Moreover, China's reliance on foreign energy supplies has been increasing (Changliang 2009) and its primary energy demand is anticipated to more than double between 2005 and 2030 (International Energy Agency 2007, Changliang 2009). With both private investors and the centralized government of China investing a great deal of resources and capital to integrate wind energy into its electric grid, further research to eliminate uncertainties in the modeled predictions must occur to determine whether or not other RE technologies would prove to be a better investment.

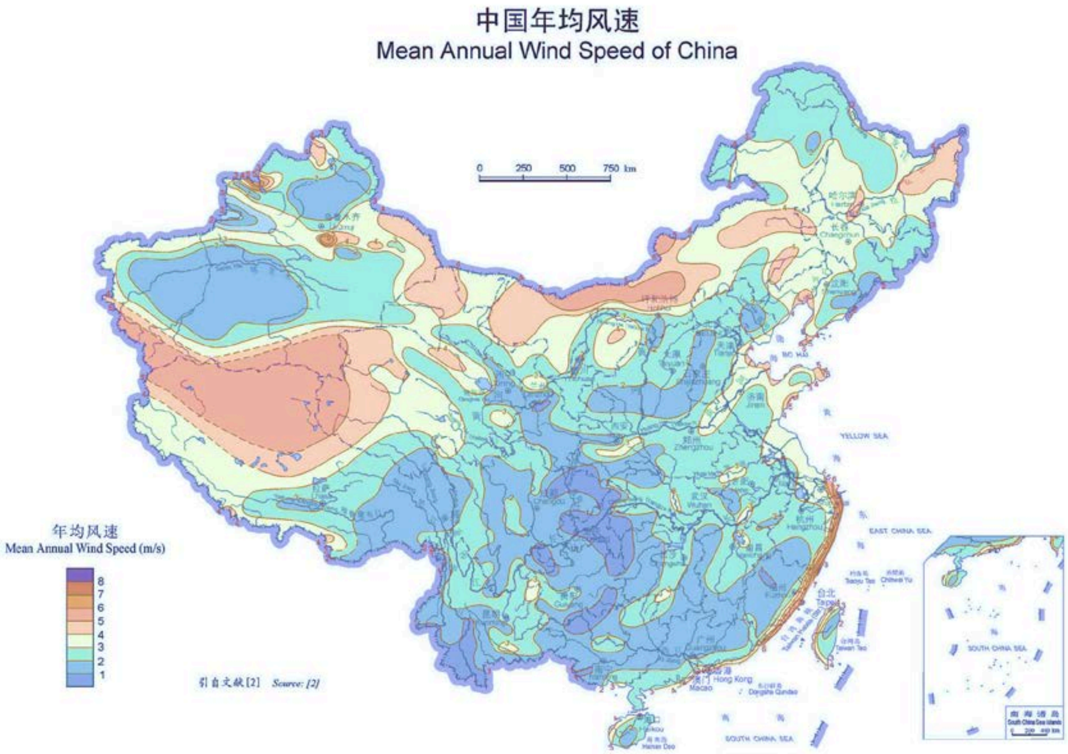


Figure 20: China Mean Annual Wind Speed (Bejing Normal University 2006)

9.0 Climate Change and Wind Energy in the US and China

9.1 Objective

This study seeks to further evaluate changes in inter-annual mean wind speeds across the US and China as these are currently the two largest wind energy markets with the most installed capacity. This study seeks to aid investors in the regional placement of wind power plants as climate change progresses by determining who will win or lose in the context of the wind energy industry in a given country facing climate change through 2100.

9.2 Background

Along with changing temperatures, precipitation patterns, rising sea levels, desertification, and reductions in biodiversity, global near-surface wind fields are projected to change as a result of climate change. The energy sector continues to expand to meet rising demand; despite the fact this industry is already responsible for about two-thirds of GHG emissions (Pryor et al. 2011) mostly from the burning of fossil fuels. With a majority of scientists and growing evidence of the potential effects of climate change, along with the inevitability of fossil fuel extinction, RE are being invested in to provide electricity generation.

Not only can these technologies reduce the reliance on fossil fuels, but wind, solar, and hydroelectric technologies are essentially free of GHG emissions. Therefore, the expansion of RE industries is and will continue to aid in human mitigation and adaptation to climate change. But as previously mentioned many RE including wind energy are dependent on climatic conditions to provide the fuel for generating energy.

Trying to determine how atmospheric composition may change over the next century is beset with uncertainties since it is necessary to make assumptions about how both natural forces and anthropogenic emissions of GHG will change which, in turn, is dependent on assumptions regarding population growth, economic activity, energy use, land use change, etcetera. As such, climate models are used as a tool for improving the understanding and predictability of climate behavior on numerous climate variables over time. Projected changes on the various climate variables take into account different scenarios to produce estimates of future climates. The results therefore produce essential information to improve the forecasting abilities of scientists and decision makers.

9.3 Classifying Wind Energy Winners and Losers

The idea of global climate change producing winners and losers is a common and widely accepted notion (O'Brien et al. 2003). The idea of winning and losing though is ill-defined and largely subjective and is dependent on the context of what is being discussed: ecology, sociology, economics, or political theory. Many involved with climate change policy negotiations consider discussions of winners and losers to be detrimental to the development of a global accord for climate change abatement (O'Brien et al. 2000). Still, scientists, policymakers, and the general public continually point out some countries, people, or species are more sensitive or vulnerable to a changing climate while others will be less vulnerable and able to adapt (O'Brien et al. 2003). For the context of wind energy and its relation to climate change, due to the substantial amount of capital being provided through not only private entities, but also public institutions, determinations of possible winners and losers is needed to ensure long-term investment in wind energy are to some extent protected and based on the best available information.

Studies generally consider a winner or loser based upon the ability for a species or economy to adapt to change. However, studies typically do not consider a country's energy resources in a similar fashion, and as such, it is important to determine what a winner and loser may be in the context of understanding the variability of the wind resource in a given region as a result of climate change. Therefore, there is no known definitive classification for a wind energy winner or loser as the models being used for determining climatic changes are not absolute nor are they meant to be perceived as entirely accurate, since they are predicting events decades to centuries into the future. But, for the context of this particular analysis, a winner and a loser may be defined as a country being independently judged based on whether its average annual wind speeds show a positive or negative trend existing, or if a stable (remains at status quo) or unstable (inconsistent fluctuation between models) trend is established through the year 2100, in comparison to the historical baseline of average annual wind speeds. More specifically a winner would be determined if positive or stable average wind speeds appear to be trending, while a loser would be defined as a nation with negative or unstable wind speed averages across climate models. To establish a fair distinction of winning and losing a comparison between nations will not be used to conclude who is deemed a winner or a loser.

Self-identification or admittance as a winner or loser would provide a country with several key advantages, which may include: developing and implementing energy diversification and preparedness strategies; increasing incomes and revenues; more allotted time for observing and bettering the environment; and the opportunity to change course and invest in a less risky RE.

The objective is to develop a system of as many winners as possible by ensuring investment in the best RE for a given region and not to dissuade investment in RE technologies based on the fact that they may be a loser in the context of wind energy alone. For instance, if the models predict two nations have relative increases in average wind speeds, and thus wind energy potential, with climate change occurring, than both countries would be judged independently and considered winners. As the wind resource is not constant across all countries and all terrains a conclusion of comparing the two hypothetical countries and making the distinction of one country being a winner and the other a loser, when there may be a hosts of factors differentiating them, would seem arbitrary. This is especially true, as major advancements have been made in the harnessing of wind energy at low levels of wind and previous low wind speed locations may now be able to invest in these technologies that previously had not existed and can bring some losers over into the winners category.

According to O'Brien, of the University of Oslo, and Leichenko, of Rutgers University, the disadvantage of self-identification as a winner or loser is that one may identify itself in a way to favor personal or political motives (O'Brien et al. 2003). It is their determination there are certain psychological factors of being able to identify as a winner and one is more likely to promote themselves as winners in order to avoid political ramifications of admitting a specific policy decision may not worked or had the desired effect; even when there is evidence to support the opposite is true (O'Brien et al. 2003); however, it can and is advantageous, especially in international climate change negotiations, to identify as a loser. The self-identification and evidence of being a loser in some aspect of climate change offers that nation the ability to have more influence to negotiate for policies that would benefit their country and people as a whole.

Wind energy winners and losers as a result of climate change are therefore difficult to identify in absolute terms. Inevitably if winners and losers can be identified with a great deal of certainty a more unified strategy can be developed either nationally or at an international level. As globalization spreads, being able to have tested and proven strategies will help enhance research, and it will reduce the notion of being a winner and loser is a permanent condition. As previously mentioned the goal of this study is to help create more wind energy winners so as to reduce fossil fuel reliance and to therefore improve the overall health of the climate system.

9.4 Methodology

According to the IPCC FAR, the A2 emissions scenario describes a very heterogeneous world: where there is an underlying theme of self-reliance and preservation of local identities; where renewable energy development is delayed; where fertility patterns across regions converge very slowly, which results in continuously increasing population; where economic development is primarily regionally oriented; and where per capita economic growth and technological change are more fragmented and slower than other emission scenarios (Rosenweig et al. 2007).

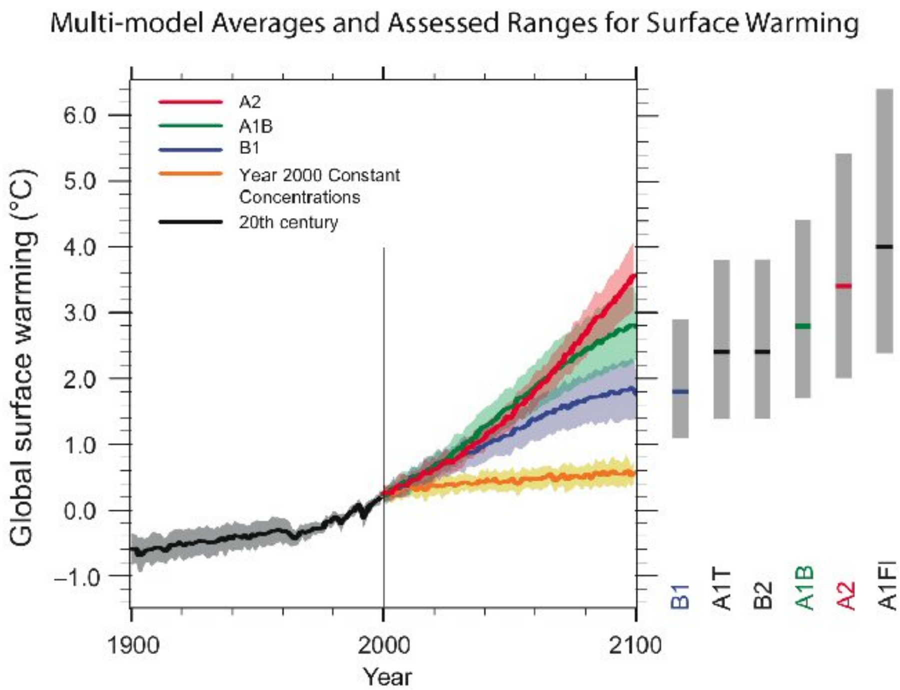
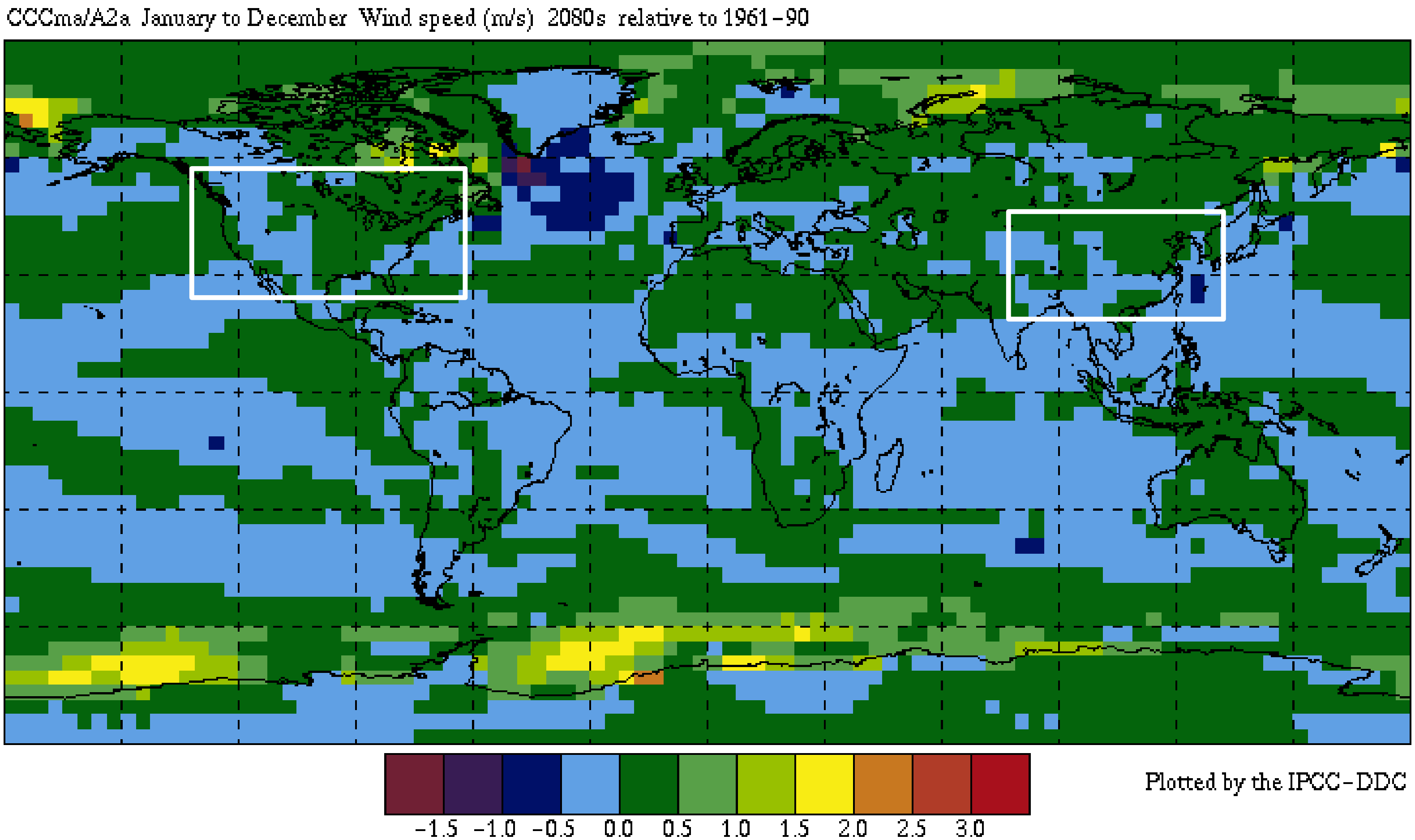


Figure 21: Multi-model means of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th-century simulation (Meehl et al. 2007)

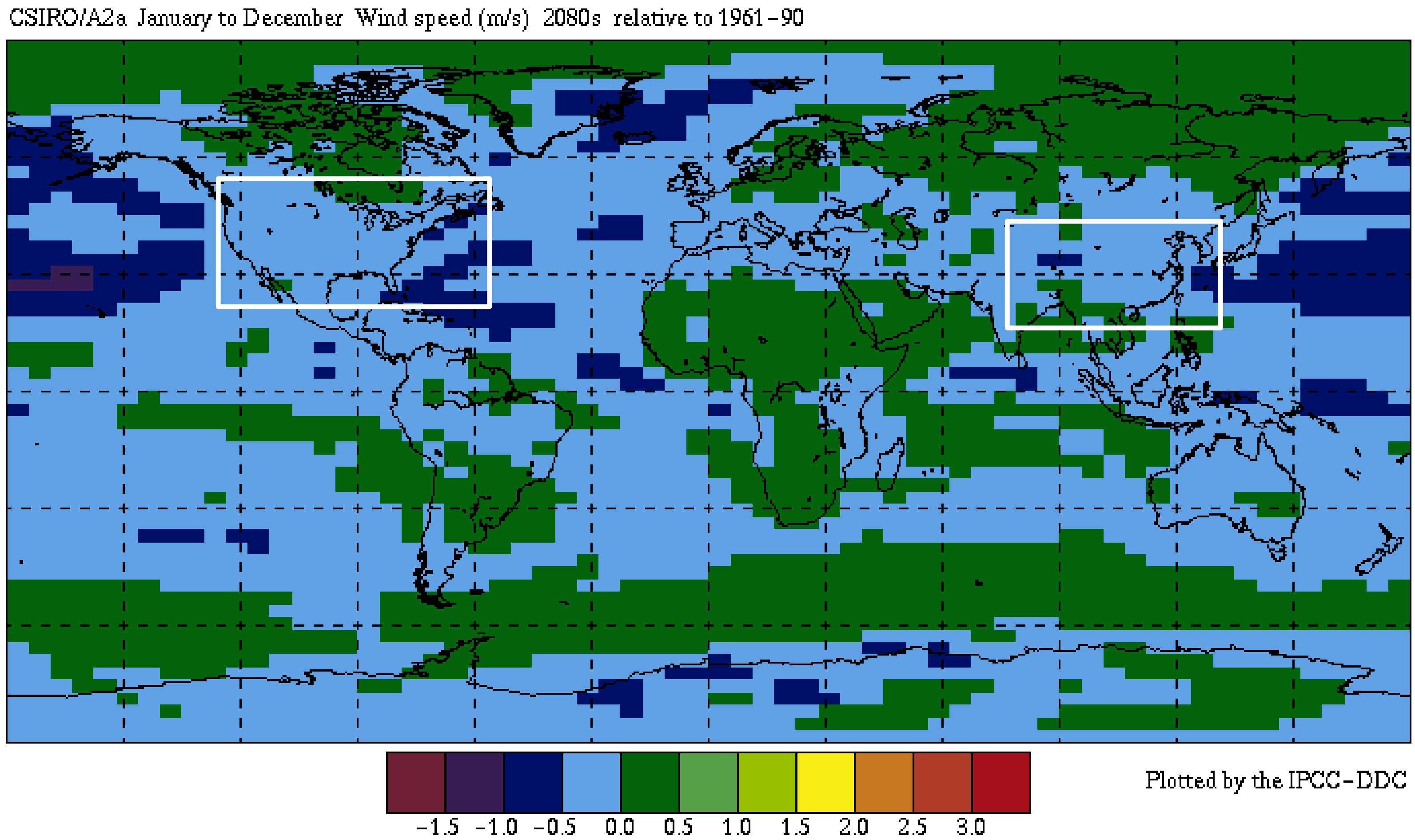
As such, the A2 scenario projects the largest anticipated increase in global surface warming. It is the intent of this study to suppose preparing and adapting to higher levels of climate change will put the US and China in a better position economically should the effects of climate change be less than anticipated. This is in comparison to making climate change preparations based upon following a lower anticipated rise in global emissions and therefore a lower average warming and rate of climate change. If preparations for a lower emissions scenario were made and a higher emissions rate actually ensued, then the US and China would be forced to play catch-up and would have to quickly expand their energy industry, which may lead rising energy prices and may have a severe impact on economic growth.

This study employs five global climate models (GCM) from the IPCC-DDC to conduct an analysis on annual wind speed changes in m/s for a period of 2070 to 2099 with a historical reference period of 1961 to 1990. Each model is also run for a period of 2010 to 2039, as well as 2040 to 2069, which are included in Appendix 1. The models compiled in Appendix 1 are not included here as this particular study strives to determine whether wind energy is a sound investment for public and private entities in the US and China through at least the end of the 21st century. All GCMs included in this study have been run through the IPCC-DDC with an A2 emissions scenario classification. The specific model rules are: CCCma/A2a, CSIRO/A2a, ECHAM4/A2a, HadCM3/A2a, and NIES99/A2a. Though each map shows average annual wind speed changes globally, only the areas within the white boxes over the US and China are examined for purposes of this study.

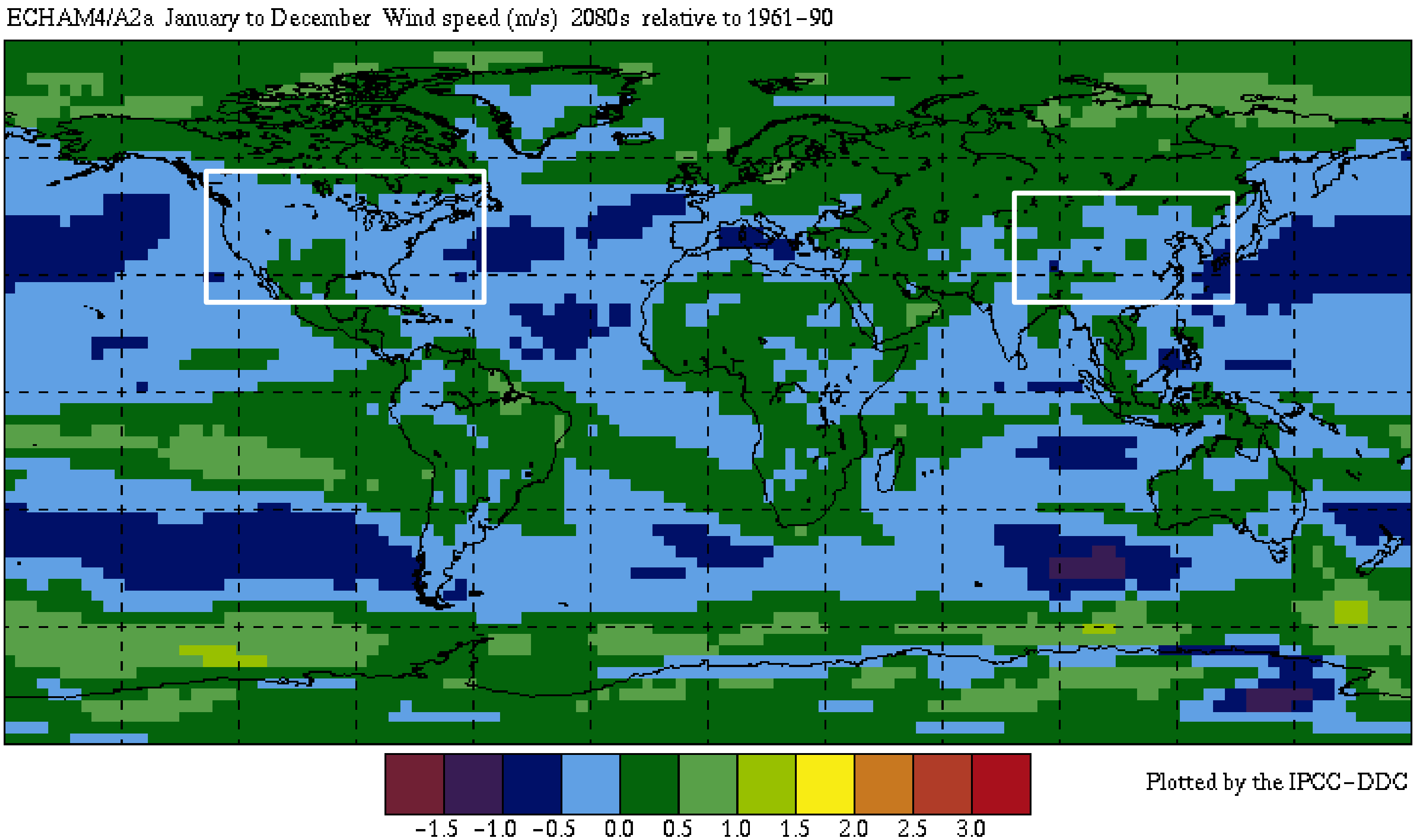
Model Run 1: Over the US, this CCCma/A2a model run indicates a slight decline (<0.5 m/s) in wind speed in the Pacific Northwest and Rocky Mountain state regions, as well as over Virginia, North Carolina, South Carolina, and Georgia. A slight increase (<0.5 m/s) in wind speed is noted over California, Florida, and most of the Mid-West, Great Lakes, and Northeastern states. Over China, this model assigns slight increases (<0.5 m/s) in wind speeds over most of China, with slight decreases over the Tibet, Xinjian, Yunnan, Guizhou, Guangxi, Hunan, Jiangxi, Shanghai, Guangdong, Zhejiang, and Fujian Provinces. Source: IPPC-DDC 2013



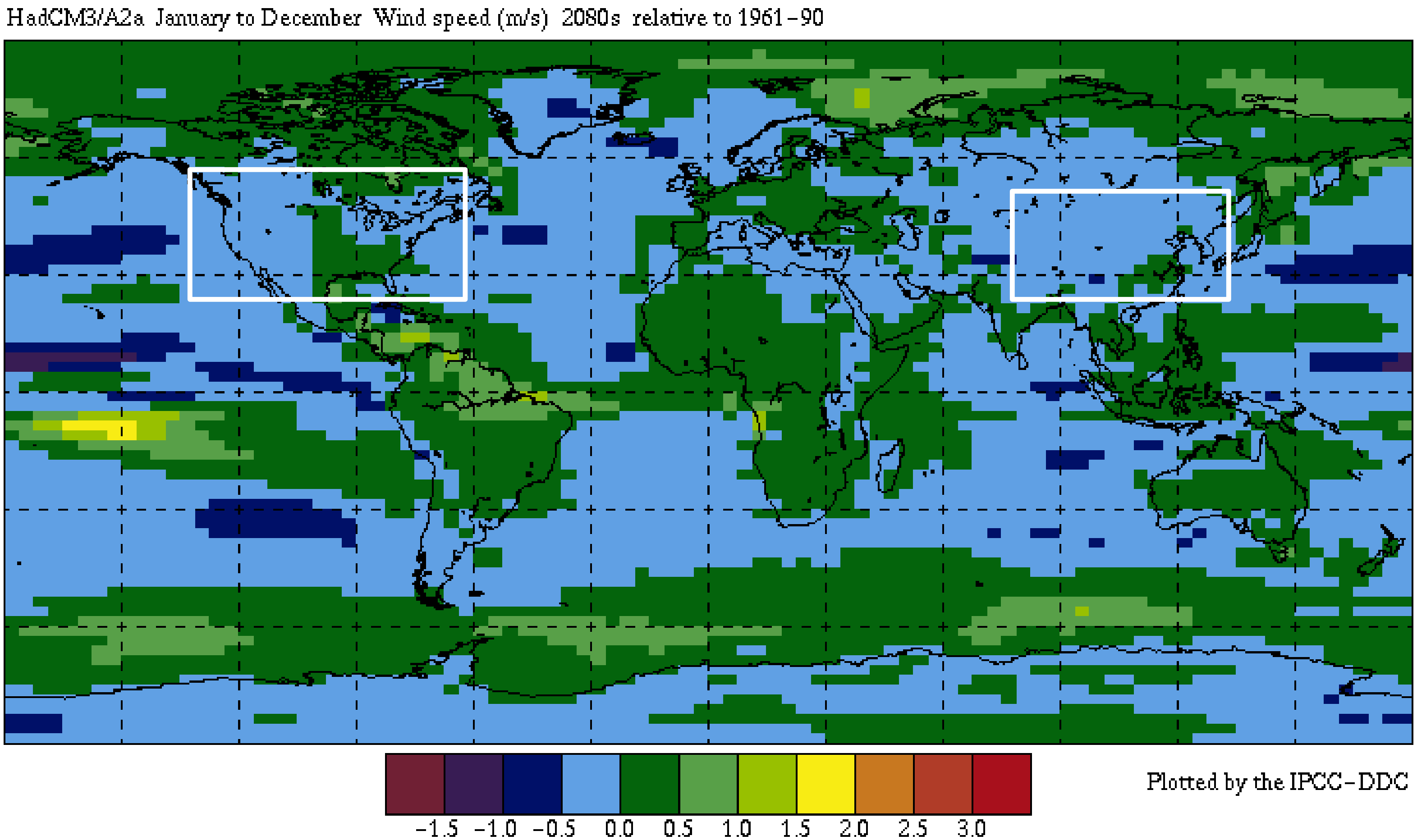
Model Run 2: This CSIRO/A2a model run demonstrates there will likely be slight declines (<0.5 m/s) in wind speeds over the entire lower-48 contiguous United States. Like this US, this model appears to show China will have slight declines (<0.5 m/s) over much of the country, as well as more notable decreases (≤1 m/s) along its eastern coasts and parts of the Tibet and Xinjiang Provinces. Source: IPPC-DDC 2013



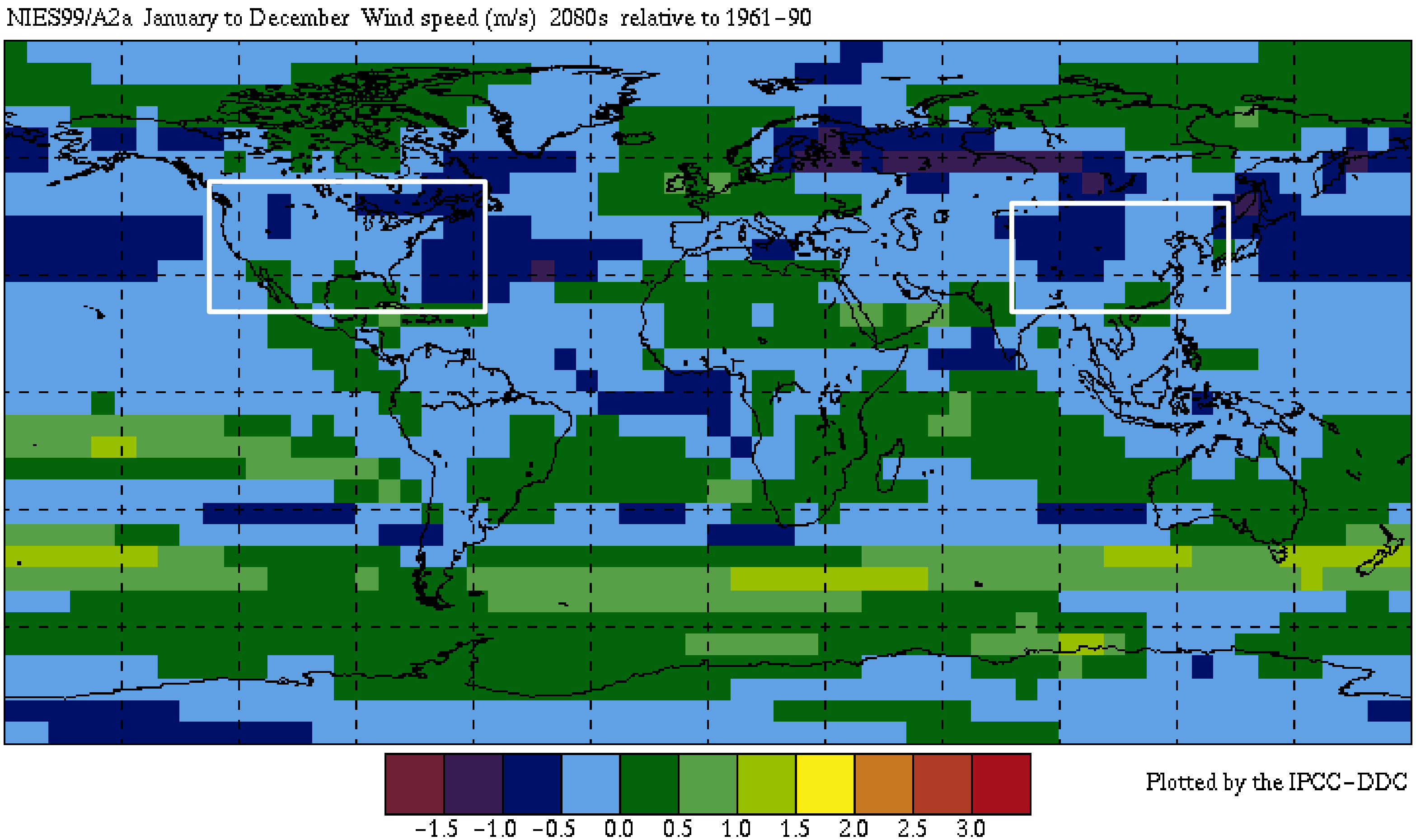
Model Run 3: This ECHAM4/A2a model run displays slight declines (<0.5 m/s) in wind speeds over most of the United States; however, it projects a slight increase (<0.5 m/s) in wind speeds over Arizona, New Mexico, Texas, Oklahoma, and Kansas. This model appears to show China will have slight declines (<0.5 m/s) over much of the southern regions of the country, as well as more notable decreases (≤1 m/s) along its eastern coasts and an area in southwestern China. Slight increases (<0.5 m/s) are noted in the northern Provinces of Xinjiang, Gansu, Inner Mongolia, Jilin, Heilongjiang. Source: IPPC-DDC 2013



Model Run 4: This HadCm3/A2a model run suggests there will be slight declines (<0.5 m/s) over Western, Northeastern, Mid-Atlantic, and Great Lake states, while a slight increase (<0.5 m/s) in wind speeds is possible over the Mid-West and Southeast states. . This model appears to show China will have slight declines (<0.5 m/s) over much of the country, with only slight increases (<0.5 m/s) over the Guizhou, Hunan, Jiangxi, Fujian, Shanghai, Zhejiang, Hubei, Anhui, and Jiangsu Provinces. Source: IPPC-DDC 2013



Model Run 5: This NIES99/A2a model run denotes slight declines (<0.5 m/s) over most of the United States, slight increases (<0.5 m/s) over Southern California and Florida, Arizona, and part of the Gulf of Mexico. Notable decreases (≤1 m/s) in wind speeds may occur over the Northern Mid-West and New England states. This model indicates notable decreases (≤1 m/s) in wind speeds across most of western and the northeastern regions of China, with slight declines (<0.5 m/s) in mean wind speeds over the rest of the country. Source: IPPC-DDC 2013



According to the five climate model runs, in addition to the aforementioned studies over the US, as well as the studies over China, total wind resources in each country will alter as the climate changes. As Pryor and Barthelmie previously concluded, and which is reaffirmed in this study, much of the US should expect a gradual decline of less than 5 m/s in average annual wind speeds (Pryor et al 2009) while some areas show an increase or maintain status quo. The GCMs clearly indicate a negative trend of less than 5 m/s through the year 2100 in average annual wind speeds across the eastern coastal regions of China, while there is some uncertainty on whether wind speeds will increase in the northern and western Provinces and by how much.

Several cities in the US and China were then selected based on the availability of reliable information for annual wind speeds. These numbers were then combined with a specified amount of change in average wind speeds (m/s) to project the average wind speed in the year 2100 based on the data from the IPCC-DDC GCMs in this study. This resulted in a projected percentage of change in annual wind speeds through 2100 for each city represented.

	Yr 2013 Wind Speed Average (m/s)	Change in Wind Speed in Yr 2100 (m/s)	Yr 2100 Projected Average Wind Speed (m/s)	Yr 2100 Projected Percent Change (%) Wind Speed
China				
Changjiangao, Fujian	8*	-0.5	7.5	-6
Laoyemiao, Jiangxi	6*	-0.5	5.5	-8
Dongwangsha, Shanghai	6.3*	-0.5	5.8	-8
United States				
Cape Hatteras, North Carolina	4.9**	0.5	5.4	10
Pendleton, Oregon	3.8**	-0.5	3.3	-13
Amarillo, Texas	6**	0	6	0

Table 1: Depicts Average Annual Wind Speeds for a total of six cities in China and the US. Taking into account the analysis of potential wind speed changes from the five GCMs run through the IPCC-DDC, wind speed averages were projected for 2100 and the percent change in wind speeds was calculated (*Elliott et al. 2002, **NOAA 2008)

As previously stated, the power output of a wind turbine corresponds to the cube of the wind speed. Therefore, an increase in wind speed of .5 m/s (meters per second), from 5.0 to 5.5 m/s, will increase the energy density (power output) by over 30% (Pryor et al. 2010), while a decrease in wind speed by the same amount would result in a 30% decline in energy density.

With the velocity of the wind having such a significant impact on the amount of power being generated it is important to look at current wind energy installation trends to determine whether or not the US and China are investing in wind energy technologies in the best locations over the long-term (See Table 2 and Table 3).

State Names	2009	2010	2011	2012	Percent Change 2011-2012
Alabama	0	0	0	0	0%
Alaska	9	9	11	59	436%
Arizona	63	128	139	238	71%
Arkansas	0	0	0	0	0%
California	2798	3253	3917	5549	42%
Colorado	1244	1299	1805	2301	27%
Connecticut	0	0	0	0	0%
Delaware	0	2	2	2	0%
Florida	0	0	0	0	0%
Georgia	0	0	0	0	0%
Hawaii	63	63	92	206	124%
Idaho	147	353	618	973	57%
Illinois	1547	2045	2742	3568	30%
Indiana	1036	1339	1340	1543	15%
Iowa	3604	3675	4322	5137	19%
Kansas	1021	1074	1274	2712	113%
Kentucky	0	0	0	0	0%
Louisiana	0	0	0	0	0%
Maine	175	266	397	431	9%
Maryland	0	70	120	120	0%
Massachusetts	15	18	47	100	113%
Michigan	138	164	377	988	162%
Minnesota	1810	2205	2718	2986	10%
Mississippi	0	0	0	0	0%
Missouri	309	457	459	459	0%
Montana	375	386	386	645	67%
Nebraska	153	213	337	459	36%
Nevada	0	0	0	152	15200%
New Hampshire	25	25	26	171	558%
New Jersey	8	8	8	9	13%
New Mexico	597	700	750	778	4%
New York	1274	1274	1403	1638	17%
North Carolina	0	0	0	0	0%
North Dakota	1203	1424	1445	1679	16%
Ohio	7	10	112	426	280%
Oklahoma	1031	1482	2007	3134	56%
Oregon	1758	2104	2513	3153	25%
Pennsylvania	748	748	789	1340	70%
Rhode Island	2	2	2	9	4%
South Carolina	0	0	0	0	0%
South Dakota	313	709	784	784	0%
Tennessee	29	29	29	29	0%
Texas	9403	10089	10394	12212	17%
Utah	223	223	325	325	0%
Vermont	6	6	46	119	159%
Virginia	0	0	0	0	0%
Washington	1849	2104	2573	2808	9%
West Virginia	330	431	564	583	3%
Wisconsin	449	469	631	649	3%
Wyoming	1099	1412	1412	1410	-0.10%
Total:	34863	40267	46916	59884	28%

Table 2: Total US Installed Capacity by State for 2009-2012 (NREL 2013b)

Provinces	2010 Capacity (MW)	2011 Capacity (MW)	Percent Change 2011-2012
Inner Mongolia	13,858.00	17,594.40	27
He Bei	4,794.00	6,969.50	45
Gansu	4,944.00	5,409.20	9
Liao Ning	4,066.90	5,249.30	29
Shan Dong	2,637.80	4,562.30	73
Ji Lin	2,940.90	3,563.40	21
Hei Longjiang	2,370.10	3,445.80	45
Ning Xia	1,182.70	2,886.20	144
Xin Jiang	1,363.60	2,316.10	70
Jiang Su	1,595.30	1,967.60	23

Table 3: Total Installed Capacity for 10 of China's Provinces for 2010-2011 (Qiao 2012)

9.4 Results

Global climate change may change the geographic distribution and/or the annual variability of wind speeds. From the above analysis, whilst it is clear many climate parameters such as changing temperatures and precipitation patterns are important and do contribute to the overall calculated energy output of a proposed wind energy site, mean wind speed is the most important factor to consider when considering wind energy siting in a changing climate. On the whole, the US and China should expect changes in the distribution and velocity of wind speeds over the course of this century, but the extent and locations may vary.

This study indicates the US may not expect to see many regions with increases or declines in mean annual wind speeds. Specifically, only subtle changes are expected to occur in the Midwest and Great Plains regions, where both wind speeds and wind energy installation are currently the highest in the country. This indicates investment in these regions is sound through the year 2100. Consequently, this signifies the US to be considered a 'winner' in the sense it currently has good wind resources in specific regions and climate change will not greatly impact those resources and as such investment in the US, and especially in the central US, should continue and further expand.

This analysis determines negative trends exist in much of the eastern coastal regions of China and uncertainties exist over the northern and western Chinese Provinces. The available information on installed capacity by Province only includes northern Provinces in China. Although the average annual wind speeds in those northern regions are currently acceptable for wind energy projects, and subsequently so are the high rates of wind energy expansion in these regions, the uncertainties in the GCM runs warrants further research being conducted on these regions and a more cautious approach at making investments in these Northern Provinces. It is the determination of this study China, or at least its northern provinces, may be over-investing in wind energy in regions where the resource may no longer be good over the long-term, and as such may be considered a 'loser' in the context of how climate change will affect China's wind energy production. China now has an opportunity, as well as the resources, to make sound decisions on where to place wind power plants, and therefore could move into the wind energy winner category if caution is heeded and adjustments are made to current wind turbine siting practices.

10.0 The Future of Wind Energy in the Face of a Changing Climate

The IPCC-FAR states adaptation is essential in the short and long-term to address potential impacts resulting from even the lowest projected emission scenarios (Rosenweig et al. 2007). Unmitigated climate change would, in the long-term, be likely to exceed the capacity of natural, managed, and human systems to adapt (Rosenweig et al. 2007). In order to properly manage the barriers, limits, and costs of utilizing wind energy, researchers should conduct further analyses incorporating climate model projection information into wind energy assessments. Based upon the aforementioned studies climate change impacts will likely continue to be imperative in the expansion of the wind energy industry and the wind energy industry will likely need to adapt to changing wind speeds and other climate related factors. This section will discuss recommendations on how the wind energy industry may evolve and adapt to a changing climate.

10.1 Utilization of Public Lands

The potential to harness the wind to generate energy exists across public and state-owned lands, but to date has been largely untapped. For instance, the US Department of Interior Bureau of Land Management owns 68 percent of the land in the state of Nevada, and research shows 46 percent of this land could be commercially developed for wind energy (The Need Project 2008). In fact, the public lands of Arizona, California, Colorado, Nevada, New Mexico, and Utah could realistically provide 34 GW of solar, wind, and geothermal energy over the next two decades, while stimulating $137 billion in investments, create more than 209,000 jobs, and power seven million homes (Goad et al. 2012). Interest in utility-scale wind energy development has increased substantially in recent decades and many of the consistently windy areas are found on publicly owned or controlled lands and as such, many state and local governments, as well as wind energy development companies, are interested in learning how much wind could be harnessed for energy production with specific details on the area’s mean wind speeds and the usable area for wind energy development (Vermont Environmental Research Associates 2003). Expansion of wind energy into public lands would allow governments the ability to strategically place wind energy farms in the best areas to address growing domestic energy demands and to increase its energy security, as well protect avifauna, create jobs, and spur further growth in the domestic manufacturing resources for wind turbine products.

10.2 Interconnecting Wind Farms

Being able to connect to the electric grid has been proven to be a difficult ordeal for the wind energy industry, as many remote or rural areas lack or have outdated transmission lines. The further away a wind farm is from a transmission line the more it will cost to install and connect the wind farm to the electric grid. GIS has proven imperative in locating transmission lines and predicting costs early in the wind assessment process to improve upon site selection.

Some researchers; however, are now suggesting connecting wind farms to the main electrical grid is unnecessary and an idea has been presented to interconnect wind farms into their own grid to produce power for a given region (Cassola et al. 2008). This idea is thought to improve the overall reliability of the wind power industry. Cassola et al. present this idea, which suggests if wind is calm in one location it will be higher at another (Cassola et al. 2008). This theory of addressing long-term variability advocates the interconnecting of wind farms into its own grid would improve the overall performance and generate more consistent energy output levels; this is compared to an individual wind farm which is subject to its own wind variability changes.

Cassola et al. tested this hypothesis in Corsica and found through interconnecting wind farms across ten defined regions on the island there was a significantly higher mean annual energy production per turbine: 2030MWh versus 1795MWh (Cassola et al. 2008). As such in this particular case this hypothesis is accurate and infers this methodology should be further tested in other locations to see if it can be upheld. If this hypothesis can be proven, it would assure public and private investors there are more options to adapting to changes in wind regime variability and it is possible for a RE, such as wind energy, to produce reliable and stable energy output levels and prosper at long-term time scales even if climate change occurs as predicted.

10.3 Diversifying Wind Turbine Sizes

Small wind turbines can provide power directly to homes, farms, schools, businesses, boats, and industrial facilities, which can offset the need to purchase some portion of the host's electricity from the grid; such wind turbines are also able to provide power to off-grid sites (DOE 2012). This technology allows individuals the ability to generate their own power and cut their energy bills while also helping to protect the environment. According to the DOE, these small wind turbines generally range in size from a few hundred watts to 100 kW, which is much smaller than the larger 1+ MW turbines used at wind power plants (DOE 2012). According to the AWEA, the U.S. leads the world in the production of small wind turbines, which are defined as having rated capacities of 100 kilowatts and less, and the market is expected to continue strong growth through the next decade (AWEA 2012). The utilization of smaller wind turbines will allow previously under-utilized urban and suburban areas. Due to the friction and turbulence created at the surface, the higher placement of small wind turbines on the top of large buildings could provide an opportunity to access stronger untapped winds. This is evident as wind speed averages at higher elevations are regularly faster than those at lower elevations. For detailed average wind speed maps at different heights see Appendix 3.

Not only could smaller turbines be beneficial, but bigger ones would be as well. Cohen et al. estimate in the absence of new design innovations, taller wind turbines could increase annual energy production by 11% (Cohen et al.). On the other hand, with some new innovation in reducing loads and blade weight it would increase efficiency and would allow moving to larger rotor diameters and as a result would increase annual energy production by as much as 10% to 30% (Cohen et al. 2008).

Wind turbine technology has become more standard and efficient, which is evident in the relatively similar production costs, in comparison to coal and natural gas-generated electricity. As such, the technology may now be further tested and exploited in areas previously thought of as bad sites for wind energy production. Further improvements in diversifying these technologies may reduce costs while increasing the ability of wind energy to continue expanding, which ultimately may help in reducing the reliance on fossil fuels as energy sources.

10.4 Near-term Climate Change Policy Solutions

Delays in establishing robust legislation addressing reductions to GHG, and particularly CO_2, have made it necessary to look toward the development of international policies to begin addressing emission limits and reductions to short-lived climate forcers (SLCF), and specifically black carbon (BC). Ultimately, the regulation of BC emissions would offer the international community a much-needed delay in the near-term effects of climate change and to establish the necessary reductions in CO_2 emissions in an attempt to mitigate the long-term effects of climate change.

BC is a byproduct of the incomplete combustion of biomass and fossil fuel sources and is a consequence of industrial pollution, transportation, forest fires, and residential energy use. BC is one of the many components of soot and has a graphite-like structure and dark color, which allows it to absorb light, to be resistant to oxidation, and to be reagent-insoluble (Andreae et al. 2006, Bond et al. 2006, Watson et al. 2005, Zhi et al. 2011). Research now shows BC is the second or third strongest contributor to global warming next to CO_2 and methane (CH_4) (Ramanthan et al. 2005). BC is made up of fine particulate matter (PM) usually measuring less than 2.5 microns ($PM_{2.5}$) in diameter. Particles over 1 micron tend to fall to the surface soon after emission, while any PM under 1 micron tends to have a greater impact on the climate as they stay aloft long enough to absorb solar and infrared radiation and have a significant impact on warming (Bond et al. 2004). Due to the mass of BC particles being greater than that of air they will eventually fall out of the atmosphere and be deposited on the earth's surface, where it may continue having a warming impact.

Unlike many other atmospheric warming agents, BC differs in that it is an aerosol made up of PM and is not gaseous like CO_2, CH_4, nitrous oxide (N_2O), and other GHG. During the combustion of biomass or fossil fuels, BC is emitted with other aerosols including sulfates, nitrates, and organic carbon. Typically, when a GHG is emitted into the atmosphere it will only absorb infrared radiation from the earth's surface and re-emit half of the radiation back towards the surface and the other towards space (Levitsky 2011). The trapping of infrared radiation from the surface causes warming to occur, and this natural process is commonly referred to as the greenhouse effect (Levitsky 2011). BC, however, has the ability to absorb both incoming solar radiation and infrared radiation coming from the earth's surface. When solar radiation is absorbed the BC particle converts these high frequency waves to infrared radiation, which is then emitted into the surrounding air molecules. Simultaneously, infrared radiation being emitted from the Earth's surface is absorbed by the BC particle, thus re-emitting half of the total radiation back towards the surface and half towards space (Baron et al. 2009). By absorbing both sources of radiation, the BC particle releases a significant amount of heat into the surrounding air molecules. This heat will remain and accumulate in the atmosphere overtime and travel long distances, while the BC particle will fall out of the atmosphere after a few days and land on the Earth's surface.

Jacobson estimates the global warming potential (GWP), or the estimated amount of heat trapped in the atmosphere by gases or aerosols, by establishing a baseline of the gas being measured equal to the same mass of CO_2. Jacobson estimates, without any other aerosols, over a twenty-year period BC could have a GWP of 4,470 (i.e. BC could trap 4,470 times more heat than CO_2) (Jacobson 2005). In comparison, over a 100-year period its GWP is estimated to be between 450 and 2,240 (Jacobson 2005, Kandlikar et al. 2009). The difference in GWP over a long period of time is due to BC only residing in the atmosphere for a few days to weeks, which means BC has a larger impact on forcing global warming over a short period of time.

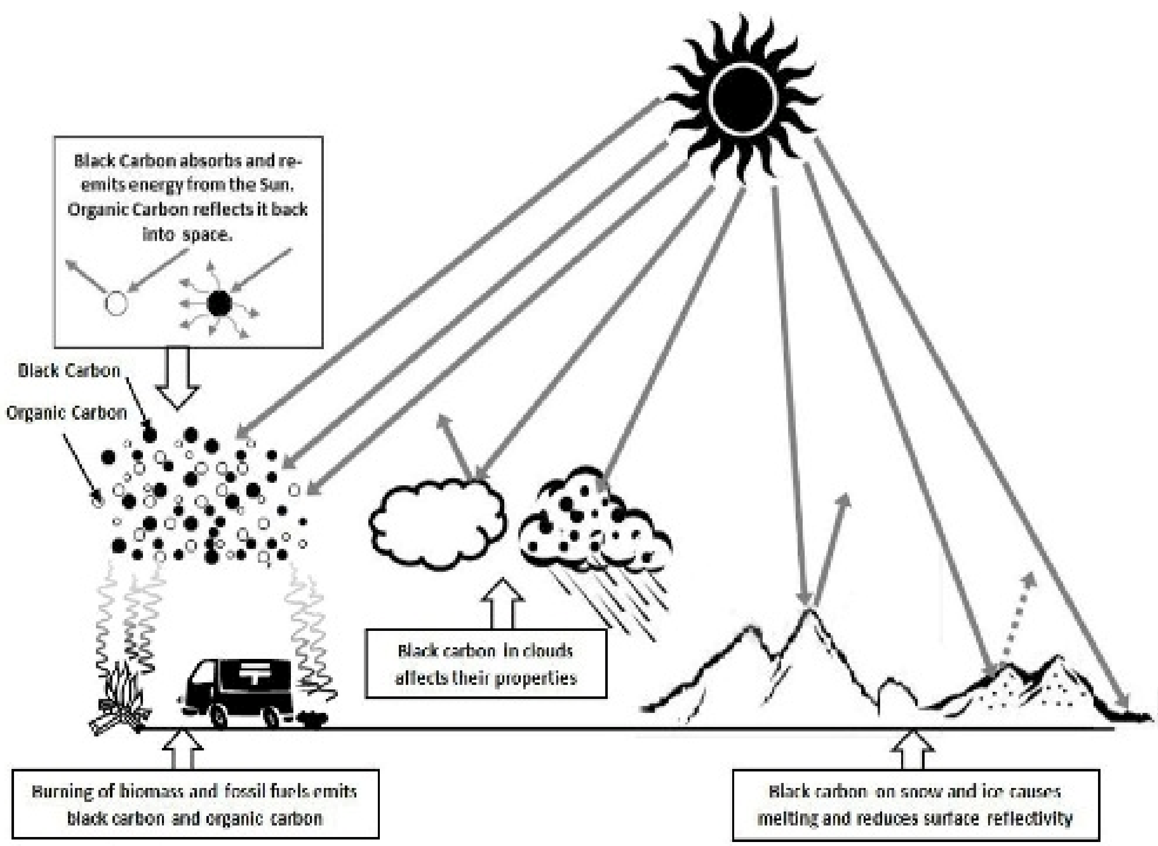


Figure 22: How Black Carbon Warms the Atmosphere (Levitsky 2012)

In recent years policymakers, both on a domestic and international level, have developed reports and established working groups to better understand and recommend policy options for regulating BC. Scientific evidence continues to grow and further supports the need for action to be taken by the international community. It has been estimated with existing technologies, BC emissions could be reduced by 50% (Wallack et al. 2009), which would offset the equivalent amount of warming that CO_2 would have over the course of one to two decades (Zhi et al. 2011). Many technologies and policies already in use, offer various BC mitigation responses from key sources, namely the burning of raw coal or biomass indoors, diesel transportation, and open biomass burning. Putting limitations on BC emissions in the near future will reduce the costs future generations would be subjected to as critical climate and ecological thresholds approach. Delaying climate change would also be beneficial to the wind energy industry as it would provide scientists and manufacturers more time to better understand the exact impacts climate change will have on wind resources and, if needed, the time to adopt new turbine designs which can replace old wind turbines at the end of their life cycles. Further information and specific policy recommendations on BC may be found in Appendix 4.

11.0 Conclusion

Throughout much of the world there is mutual consensus among scientists and a growing consensus among policymakers and the general public that GHG emissions must start to level off and decline, and replacing traditional fossil fuels with clean RE is the key to curbing the worst effects of climate change (Ramanthan et al. 2008). A region's overall wind climate is determined by the energy density (potential power) that can be harnessed (Pryor et al. 2010), and the amount of GHG emissions deterred should also play a role in expanding RE sources. Further research of the effects of climate change on the wind energy industry is needed, as many climate studies still only address storm climates or wind speed extremes and not the evolution or the distribution of wind regimes as a result of climate change (Pryor et al. 2005).

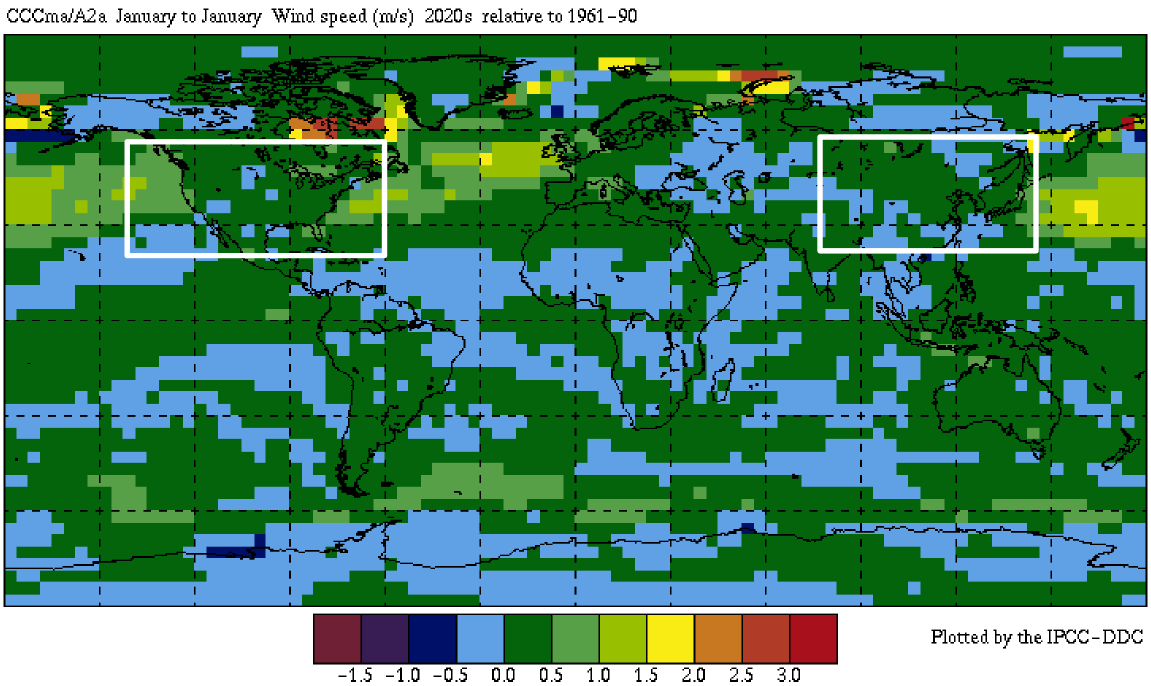
Many new technologies, such as GIS, are now offering a path for scientists, researchers, and engineers to identify suitable sites for wind energy projects by conducting complex analyses. The variability of wind speeds, wind indices, and energy densities are natural functions of regional climates and changes to climate regimes interferes with these natural fluctuations and will likely have either a positive or negative effect on wind energy production. In order to continue with its current momentum the wind energy industry must continue integrating GIS technologies in wind energy planning, as well as start taking into consideration the changing climate so as to better understand the potential risks inherent in investments.

Overall, wind energy proves to be a promising technology to address reducing the reliance on fossil fuels, to becoming more energy secure, and to cutting GHG emissions. Many of the countries who are leading the way in wind energy installation have offered incentives to wind energy investors in the form of tax credits or grants, which seems to be a vital aspect of a country showing its commitment and enticing investment and expansion in the wind energy sector.

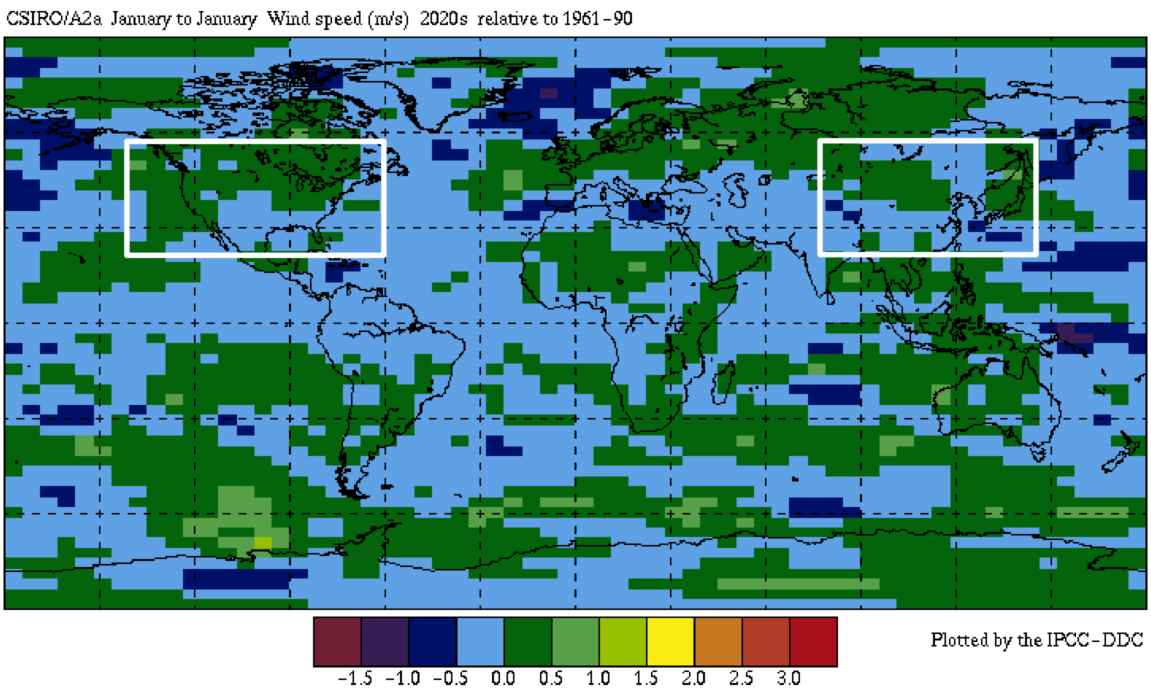
Looking at the rate of expansion in the US and China, investment in wind energy must also be met with comprehensive analyses conducted at the global and regional levels and incorporate climate projections. This will ensure the investments being made will be beneficial on a long-term scale so as to provide the greatest economic and environmental benefits to each region and country.

Appendix 1 –Projections of Wind Speed Changes for Periods of 2010-2040 and 2040-2069

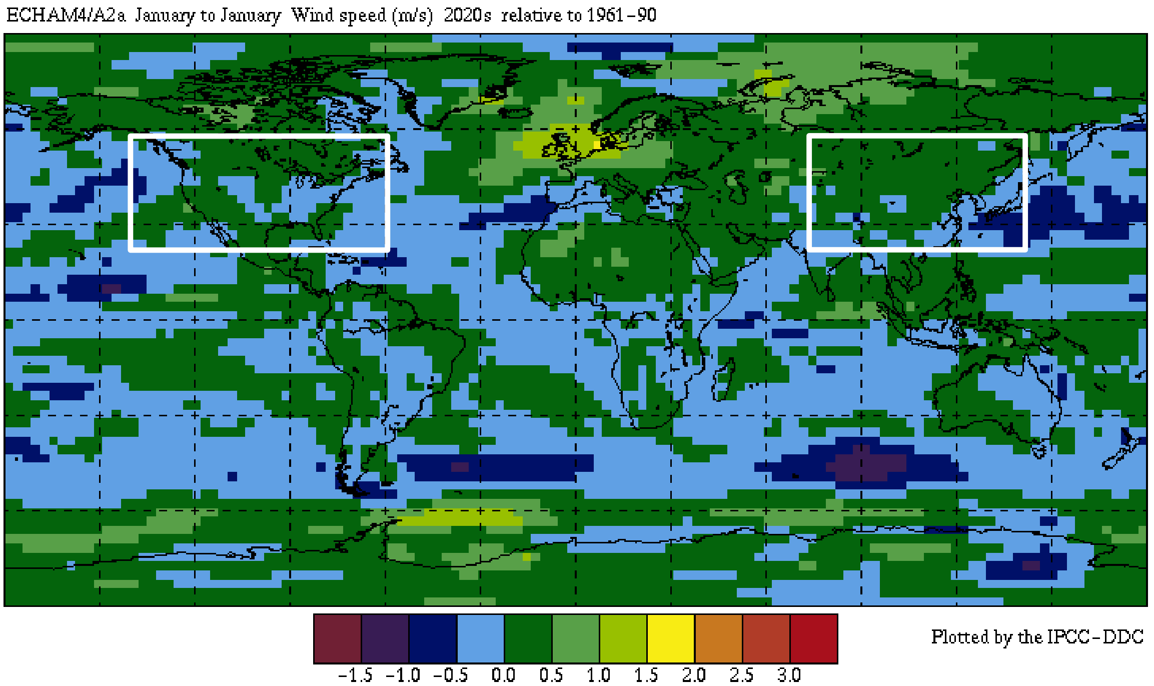
<u>Wind Speeds 2010 to 2049:</u> The five maps below have been run through the IPCC-DDC with an A2 emissions scenario classification. The specific model rules are: CCCma/A2a, CSIRO/A2a, ECHAM4/A2a, HadCM3/A2a, and NIES99/A2a. Each model presents the change in annual wind speed in meters per second (m/s) between the years 2010 to 2049.



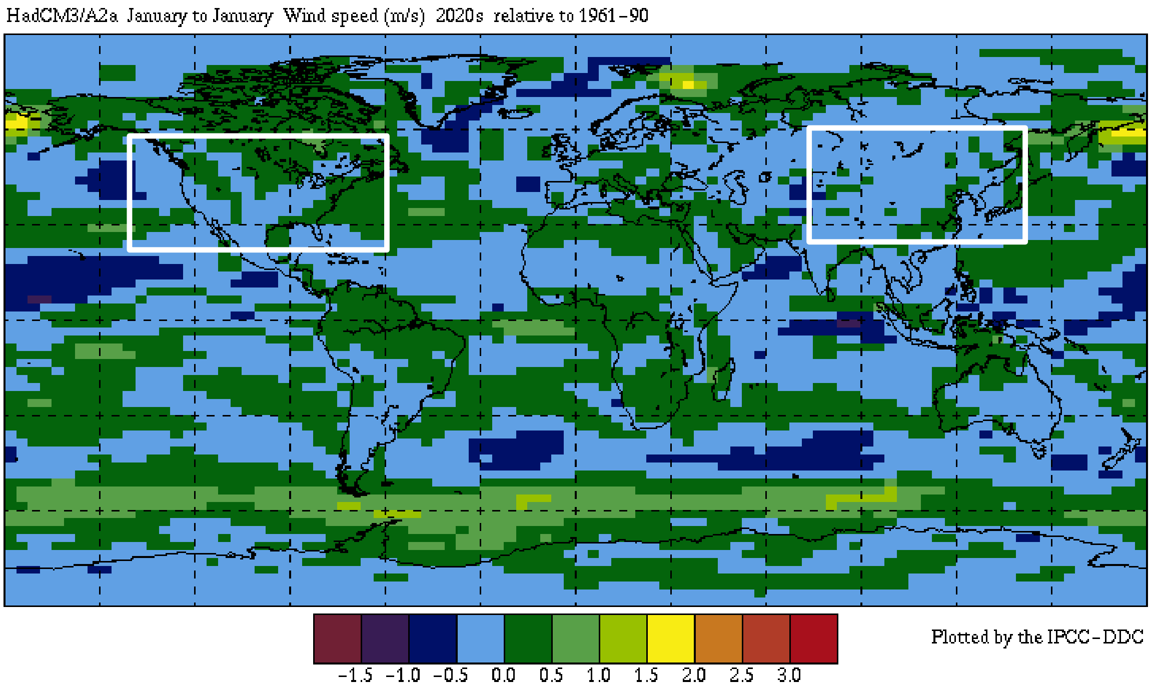
Source: IPPC-DDC 2013



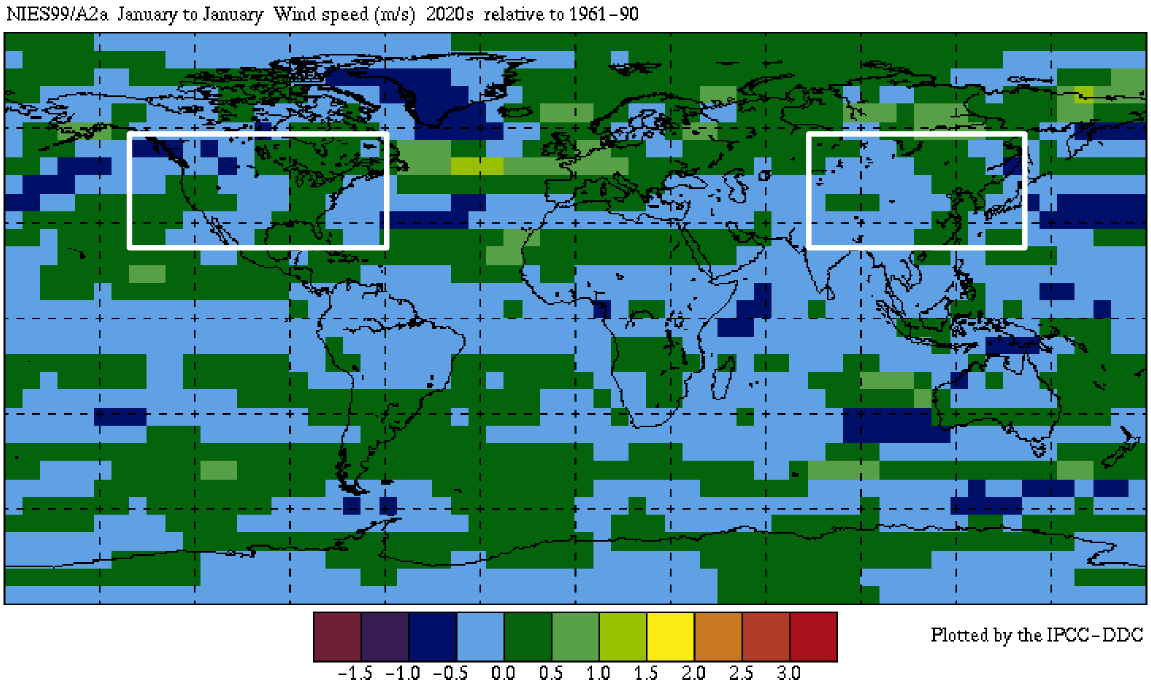
Source: IPCC-DDC 2013



Source: IPPC-DDC 2013

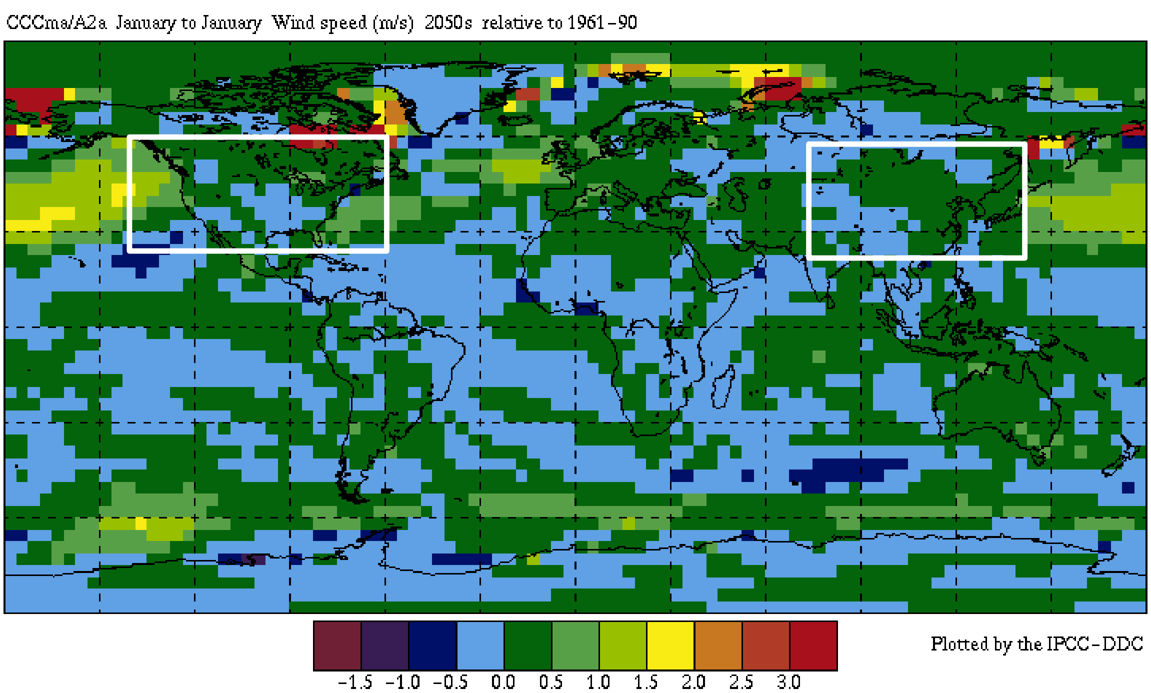


Source: IPPC-DDC 2013

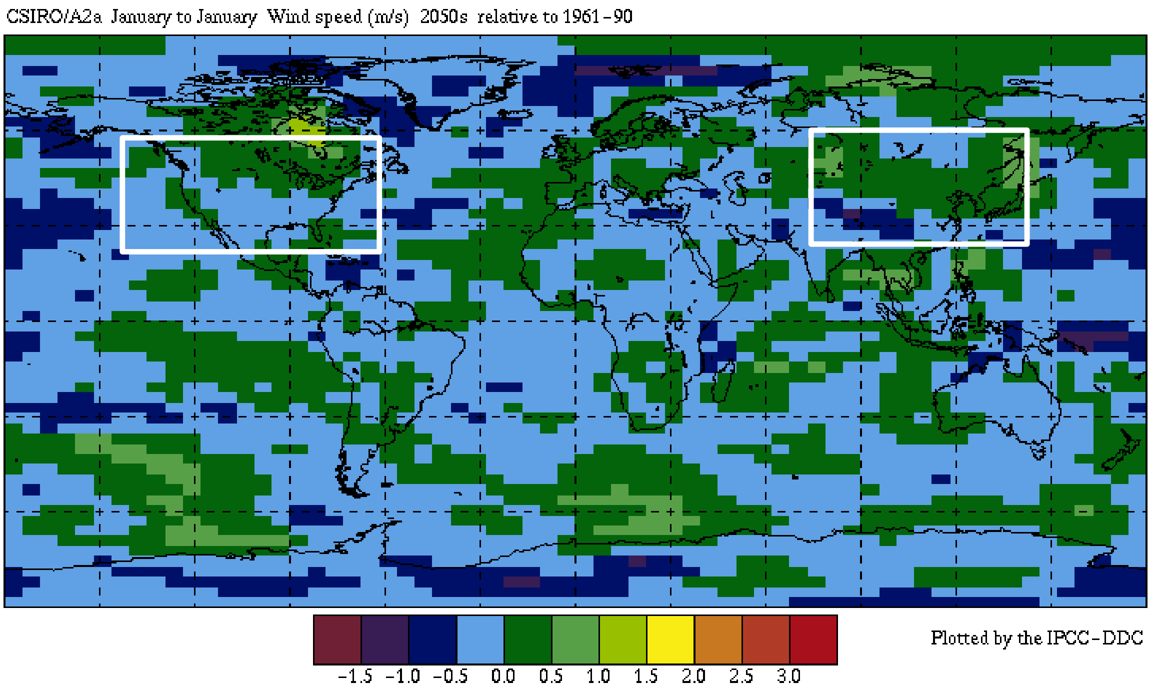


Source: IPPC-DDC 2013

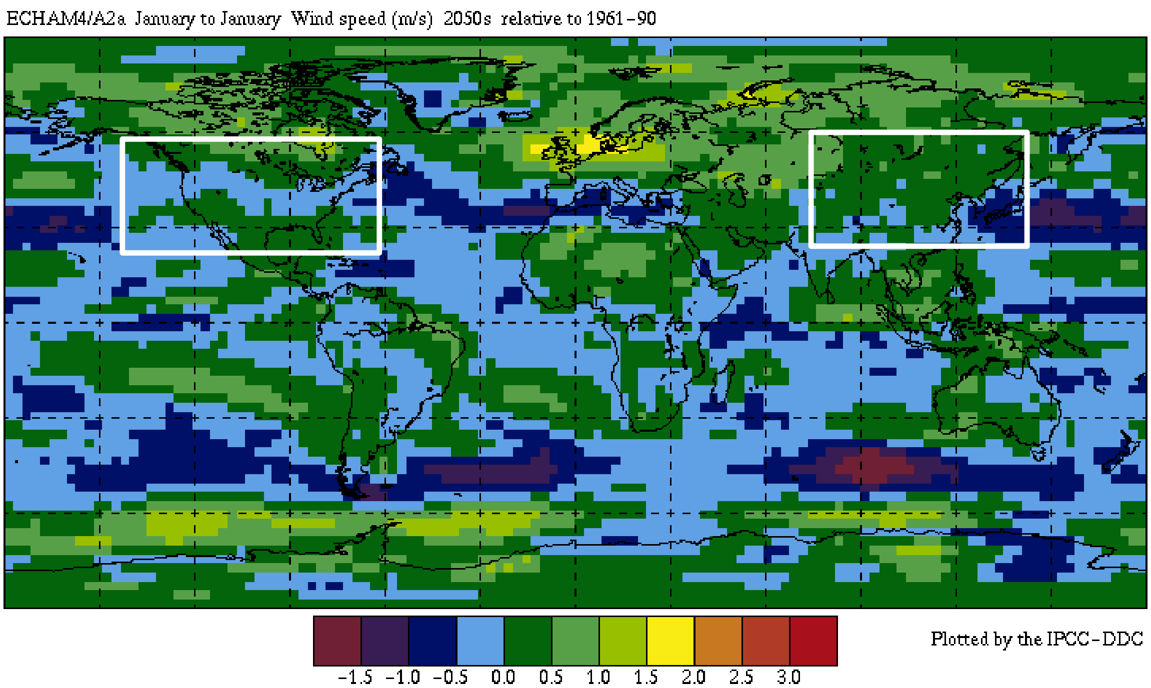
<u>Wind Speeds 2040 to 2069:</u> The five maps below have been run through the IPCC-DDC with an A2 emissions scenario classification. The specific model rules are: CCCma/A2a, CSIRO/A2a, ECHAM4/A2a, HadCM3/A2a, and NIES99/A2a. Each model presents the change in annual wind speed in meters per second (m/s) between the years 2040 to 2069.



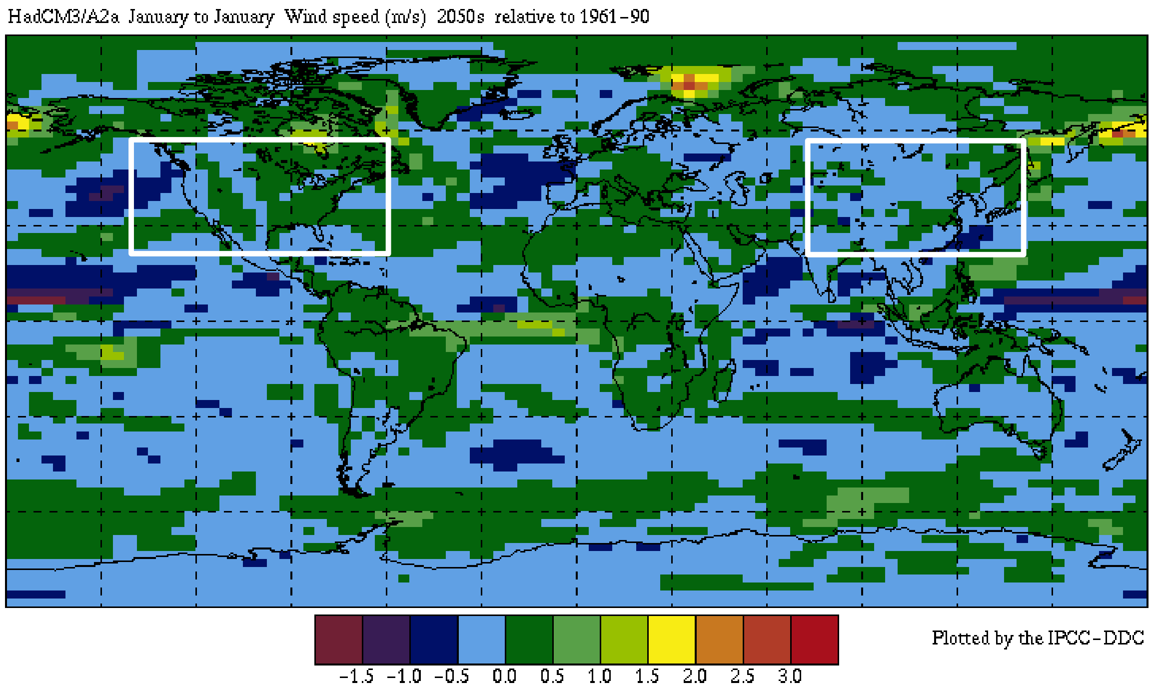
Source: IPPC-DDC 2013



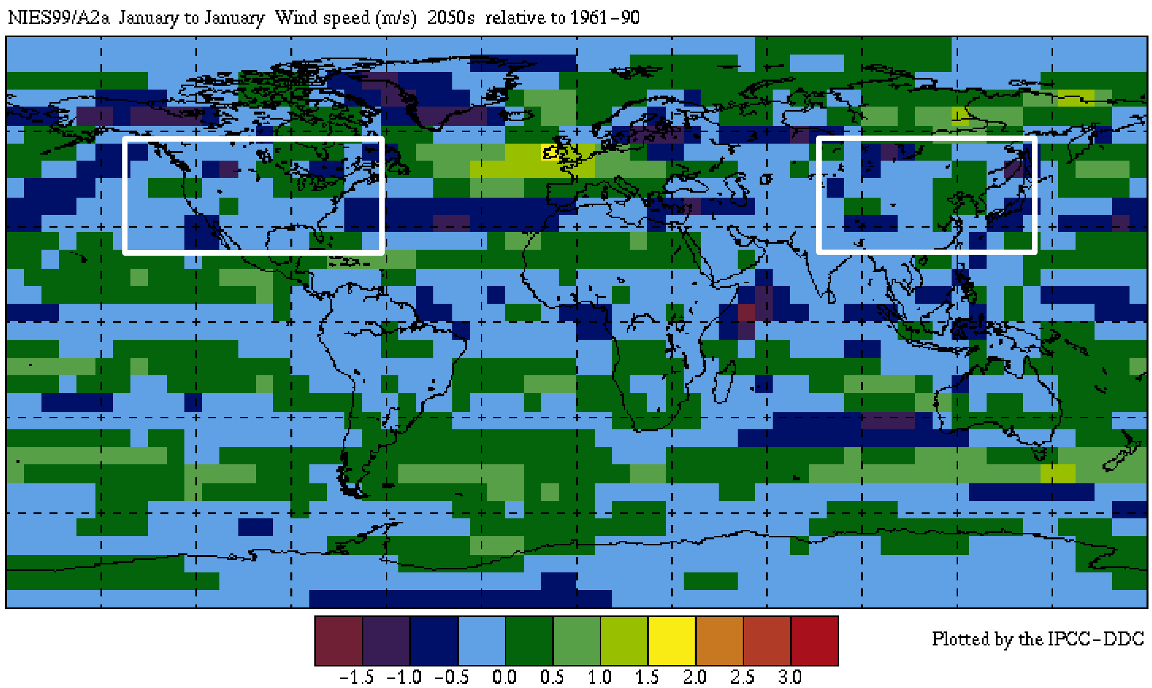
Source: IPPC-DDC 2013



Source: IPPC-DDC 2013

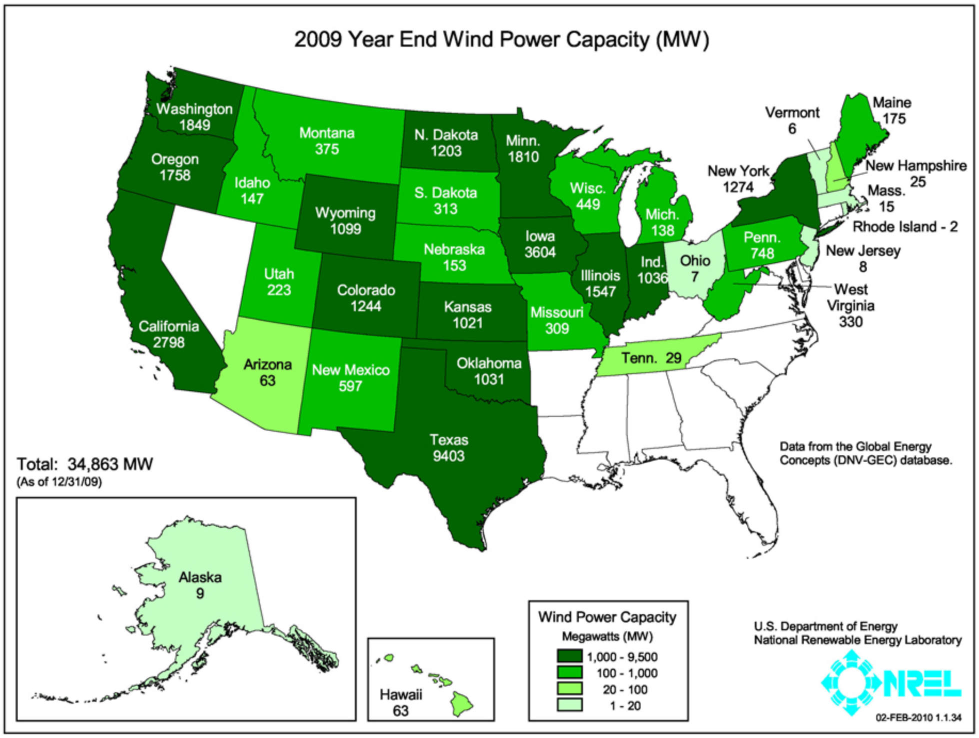


Source: IPPC-DDC 2013

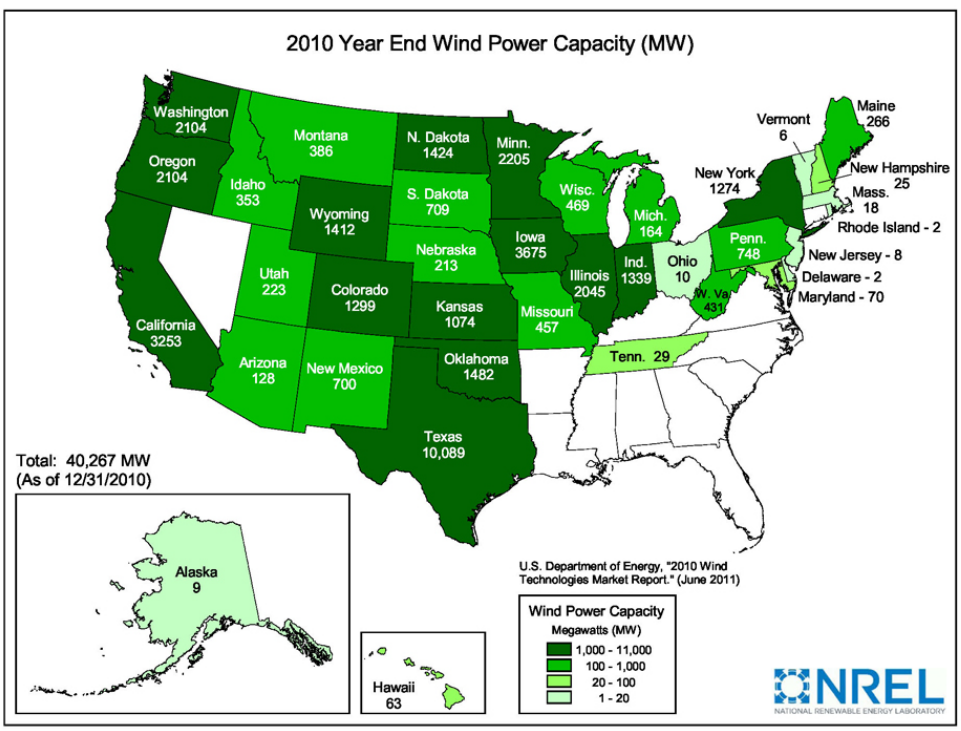


Source: IPPC-DDC 2013

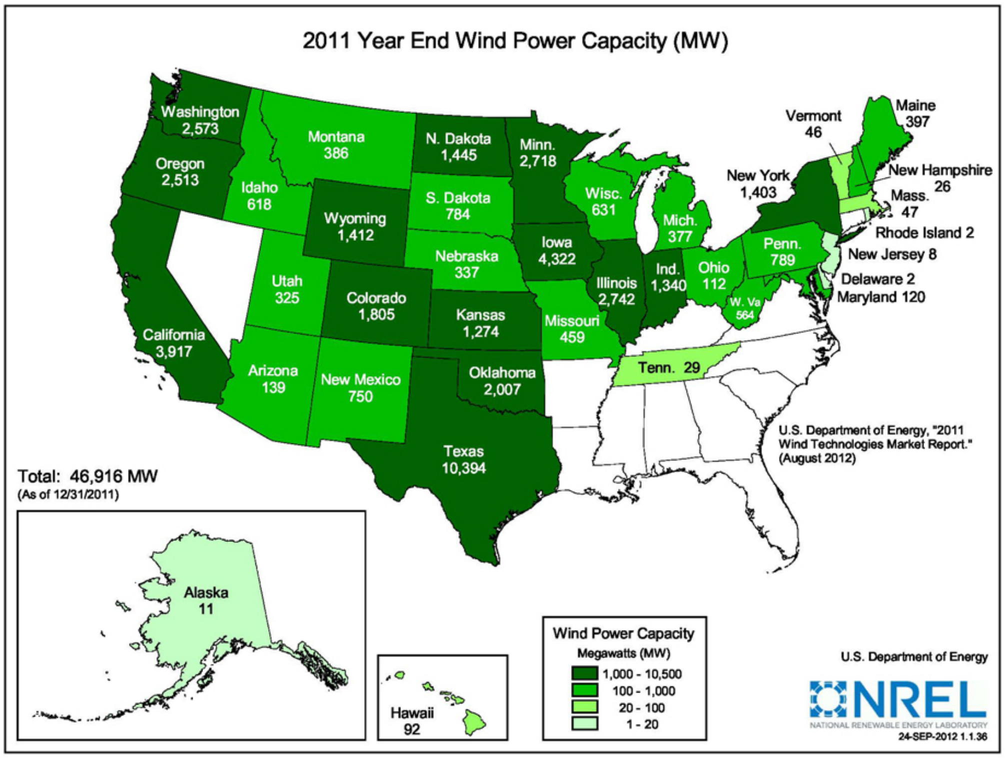
Appendix 2 – Year End Wind Power Capacity 2009 to 2012



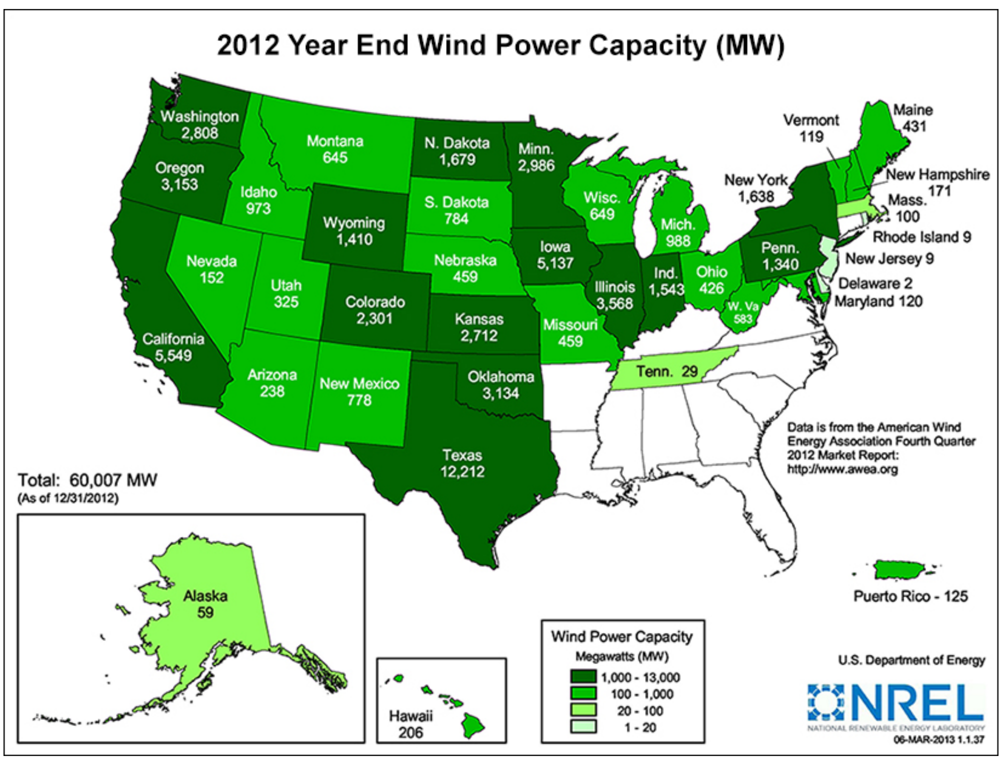
Source: NREL 2013b



Source: NREL 2013b

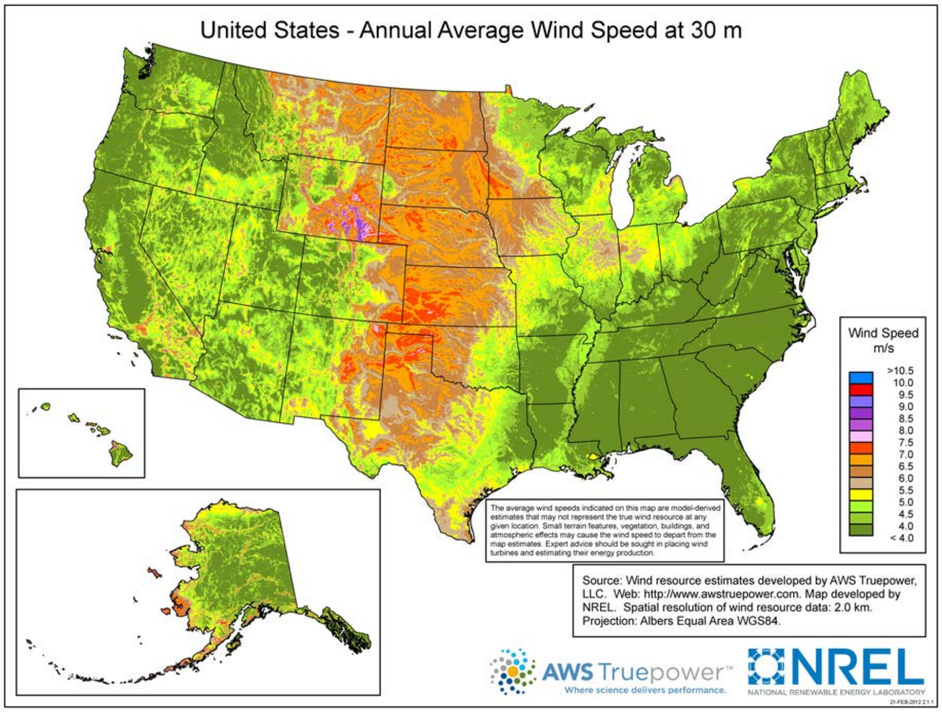


Source: NREL 2013b

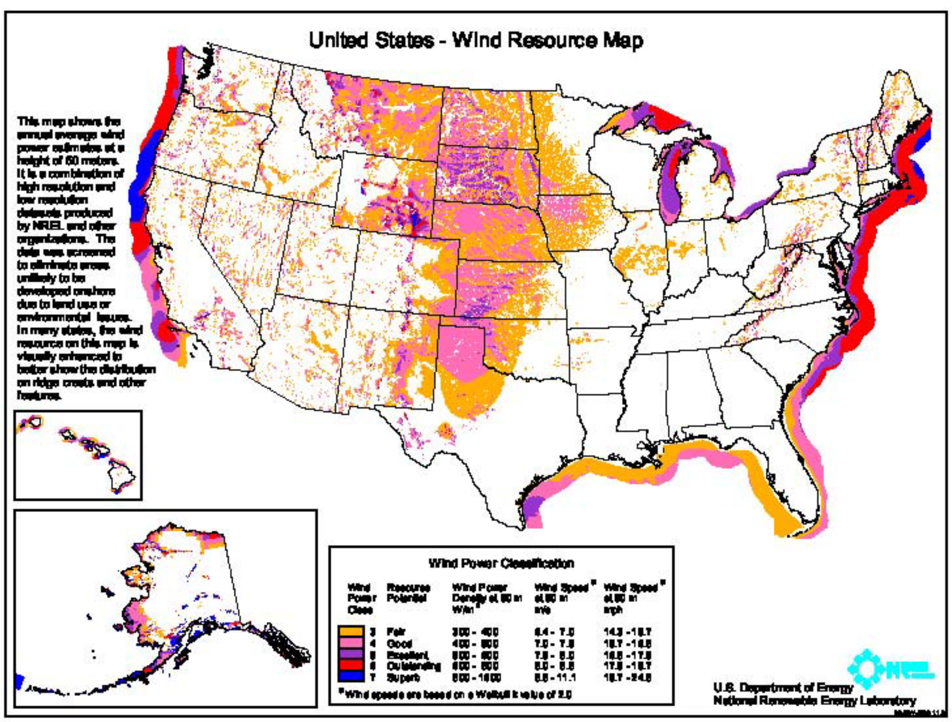


Source: NREL 2013b

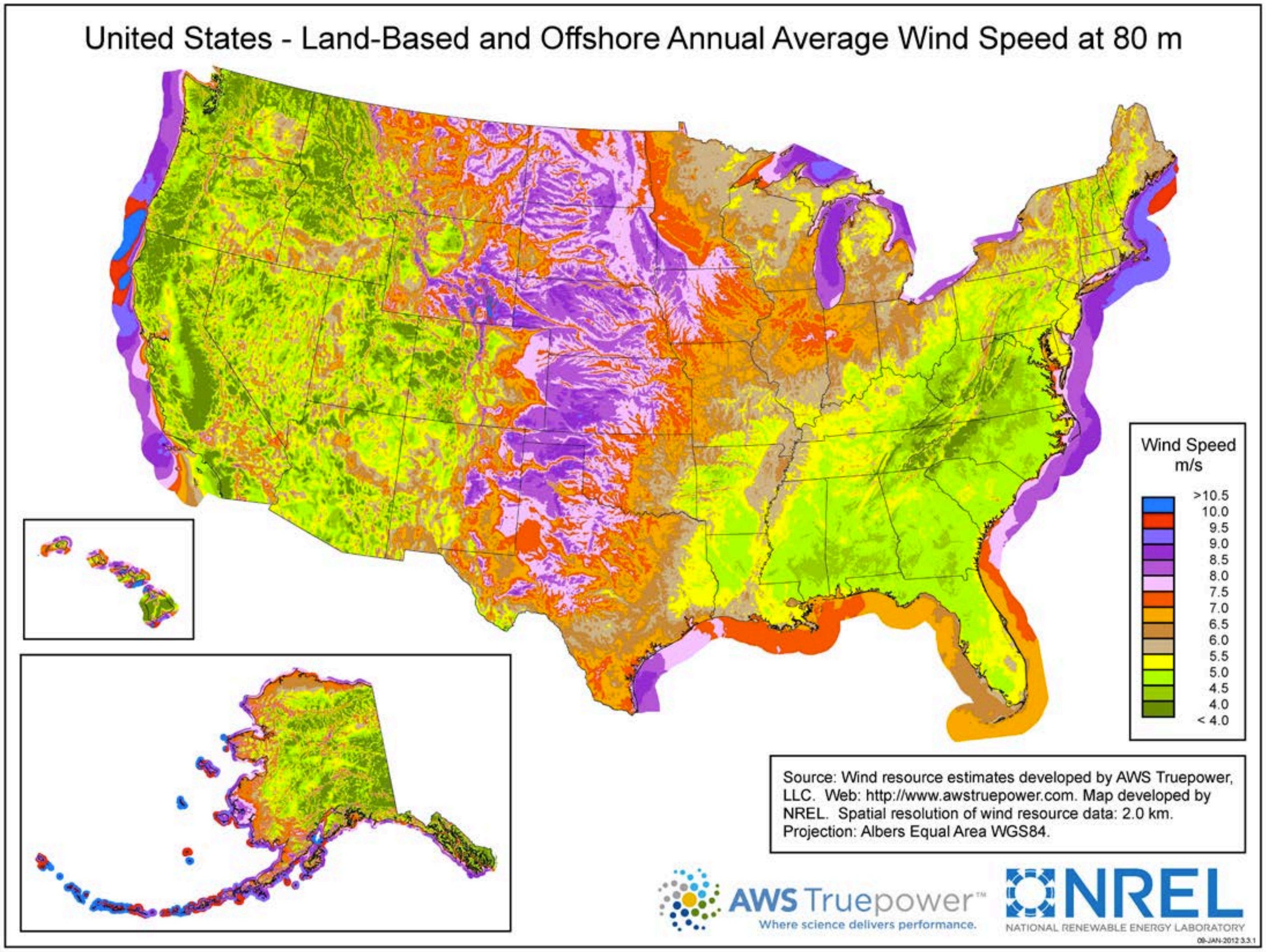
Appendix 3 – US Annual Wind Speed Averages at 30m, 50m, 80m



Source: NREL 2013a



Source: NREL 2013a



Source: NREL 2013a

Appendix 4: Black Carbon: An International Response To Addressing Near-term Climate Change

1.0 Introduction

Delays in establishing robust legislation addressing reductions to greenhouse gases (GHG), and particularly carbon dioxide (CO_2), have made it necessary to look toward the development of international policies that would begin addressing emission limits and reductions to short-lived climate forcers, such as black carbon (BC), as a source for slowing the near-term impacts of climate change. Regulation of BC has the unique capability of improving public health and slowing the effects of climate change. For the international community to begin addressing the need to limit emissions of BC first the science must be fully understood, as well as the possible technologies available to reduce BC emissions. As such this paper will discuss the basic science behind the significant effects BC has on climate change and public health, the current BC reducing technologies being used throughout the international community, and the suggested avenues within the international community to begin regulating BC emissions in relation to climate change. Ultimately, the regulation of BC emissions would offer the international community a much-needed delay in the near-term effects of climate change and to establish the necessary reductions in CO_2 emissions in an attempt to mitigate the long-term effects of climate change.

2.0 Background

For decades climate change mitigation efforts have focused on reducing carbon dioxide (CO_2) emissions (Molina et al 2009). During this time scientific advancements were made that reduced some of the uncertainties, while climate policies that would make the necessary CO_2 reductions to prevent climate change have met continual challenges. Scientists now suggest atmospheric warming agents, other than CO_2, must be targeted in order to maintain global temperatures below the 2°C of warming agreed upon under the United Nations Framework Convention on Climate Change (UNFCC) 2009 Copenhagen Accord. While CO_2 may reside in the atmosphere for more than 100 years, BC remains in the atmosphere for a few days or at most a couple of weeks (Ramanthan et al. 2008). Because CO_2 lingers in the atmosphere it is transported worldwide and becomes well-mixed in the atmosphere; conversely BC has a relatively short atmospheric lifespan and thus has proven difficult to quantify. As BC emissions do not travel far from their source, it creates the possibility for rapid results if emission reductions are implemented through available technology and cooperative legislation between countries (Zaelke et al. 2009, Baron et al. 2009).

Despite the possibility of near immediate results, reducing BC emissions has not been at the front of international climate change policy negotiations because the uncertainties of BC forcing vary by location. In 2011, the United Nations Environment Programme (UNEP) called attention to the fact that short-lived climate forcers (SLCF) have climate change impacts that are on par with CO_2 and thus the strong international need to reduce both emissions types in tandem (Schmidt, 2011). In recent years some policy makers have been developing reports and establishing working groups to better understand and recommend policy options for regulating BC. Scientific evidence continues to grow and further supports the need for action to be taken by the international community. Putting limitations on BC emissions in the near future will reduce the costs future generations would be subjected to as critical thresholds approach.

3.0 Black Carbon and Its Effect on Climate

3.1 Defining Black Carbon

As previously stated BC is defined as a byproduct of the incomplete combustion of biomass and fossil fuel sources and is a consequence of industrial pollution, transportation, forest fires, and residential energy use. BC, which is one of the many components of soot and has a graphite-like structure and dark color, which allows it to absorb light, to be resistant to oxidation, and to be reagent-insoluble (Andeae et al. 2006, Bond et al. 2006, Watson et al. 2005, Zhi et al. 2011). Due to its ability to absorb incoming solar radiation and outgoing infrared radiation, BC is now thought to be the second or third strongest contributor to global warming next to CO_2 and methane (CH_4) (Ramanthan et al. 2008, Bond et al. 2005, Hansen 2002). This heat will remain and accumulate in the atmosphere overtime and travel long distances, while the BC particle will fall out of the atmosphere after a few days and land on the earth's surface. As the mass of BC particles is greater than that of air these molecules will fall out of the atmosphere and be deposited on the earth's surface.

3.2 The Role of Co-Emitted Pollutants

The ratio of non-BC to BC aerosols is dependent on the combustion source type and is an important factor in determining the potential warming of BC emissions. This is due to the non-BC aerosol particles reflecting sunlight and thus has a cooling effect on the atmosphere, while BC aerosols absorb sunlight and as such exhibit a warming effect on the atmosphere. As these aerosols are co-emitted during combustion, making reductions in BC emissions would also reduce the amount of atmospheric cooling resulting from the non-BC aerosol emissions. Dr. Mark Jacobson, a Professor of Civil and Environmental Engineering at Stanford University, asserts about half to two-thirds of the actual global warming to date is being masked by the cooling properties of non-BC aerosols, and goes on to suggest as those cooling particles are removed by reducing air pollution levels a significant amount of warming could occur, which is why ensuring heat absorbing PM, like BC, simultaneously is important (Jacobson 2007). Jacobson also states BC may contribute about 16% of the total global warming seen to date, but through establishing controls on BC emissions there could be a 40% reduction of the net global warming (Jacobson 2007). Therefore, BC reductions are necessary for the international community to address in order to reduce the rate of atmospheric warming and to stay within critical temperature thresholds.

3.3 Global and Regional Climate Effects of Black Carbon

3.3.1 Impact of Radiative Forcing Effects on Snow and Ice

When BC particles are deposited on the earth's surface a positive feedback cycle will begin due to a reduction in the earth's albedo (reflectivity). This is especially true in regions covered in snow and ice, such as the Arctic and Himalaya Mountains. Deposition of BC on the snow or ice has a significant effect on melting, even with concentrations not noticeable to the naked eye (Levitsky 2011). Due to their high albedos, snow and ice typically reflect a majority of solar radiation back into space. As BC is deposited it darkens these surfaces and they begin to absorb solar radiation (Flanner et al. 2007) and subsequently begin emitting heat into the surrounding particles and the lower atmosphere, which promotes the melting of snow and ice (Abrahammson et al. 2011). This melting exposes the underlying surfaces, such as the ocean and tundra, which have much lower albedos compared to snow and ice and results in further absorption of solar radiation and an additional warming of the lower atmosphere, specifically in the Arctic and Himalaya regions.

3.3.2 Black Carbon Effects in the Arctic and Himalaya Regions

The Arctic climate is changing faster than some scientists expected. A continuing decline in summer sea ice, warmer temperatures, changes in vegetation, and other indicators signal polar changes that will affect the rest of the globe. Two separate studies of two locations both estimate that approximately half of the observed warming is due to BC. A 2009 study by Shindell and Faluvegi, notes BC may be responsible for up to half of the observed 1.9°C average temperature increase in the Arctic (Shindel et al. 2009). Comparably, in a 2008 study, Ramanthan and Carmichael claim since the 1950s, warming on the Tibetan side of the Himalaya mountains has increased by 1.0°C with BC expected to have caused about half of that warming (Ramanthan et al. 2008). These results are significant in that it shows a commonality of how BC emissions in snow and ice covered regions really is having a significant and similar impact in both areas. A joint report released by UNEP and the World Meterological Organization (WMO) discusses how in the high valleys of the Himalayas, BC levels can be as high as in a mid-size city (Steiner et al. 2011). With rising temperatures and melting occurring in these regions BC plays a significant role not only in warming temperatures, but also sea level rise, access to fresh drinking water, seasonal melt, phenological shifts, and weather patterns.

3.4 Other Black Carbon Effects

BC may also play a role in cloud formation and the cloud albedo effect, and is currently undergoing significant amounts of research. Dr. Veerabhadran Ramanthan, Professor of Atmospheric and Climate Sciences at the Scripps Institution of Oceanography, University of California, San Diego, suggests continued BC forcing leads to a surface dimming, meaning there would be a redistribution of direct solar radiation being absorbed between the surface and the atmosphere, and result in a weakening of convection and ultimately lead to a decline in evaporation and rainfall (Ramanthan 1981). Surface dimming therefore could make a significant contribution to changing weather patterns at both a regional and global level. Ramanthan and Carmichael suggest the effects of BC on surface dimming is already happening with a noticeable increase in drought and a substantial weakening of monsoonal circulation over South Asia (Ramanthan et al. 2008). Furthermore, Ramanthan and Carmichael suggest during cloud formation, non-BC aerosols promote cloud droplet formation, while BC does the opposite leading to a reduction in low clouds and their albedo, and can further promote the warming effects of BC (Ramanthan et al. 2008). More research needs to be conducted to develop accurate models to understand and predict variations in weather patterns as a result of continued BC forcing.

3.5 Black Carbon Sources

Due to its short atmospheric residency time and its ability to continue promoting warming after deposition on the Earth's surface the resulting effects of BC are for the most part regional. As previously noted, ratios of non-BC to BC aerosols emitted during combustion are dependent upon the source type, with biomass typically having higher ratios of non-BC aerosols and fossil fuels being higher in BC. BC emissions originate from a variety of sources including: 42% from open biomass burning (i.e. forest fires and land clearing), 24% from residential burning (i.e. domestic heating or cooking), 24% from transportation (i.e. diesel trucks and marine vessels), and 10% from industrial activities (i.e. power generation) (Bond 2007). BC emissions originate in both industrialized and developing countries, with the developing countries emitting as much as 80% of the total BC emissions, primarily from the residential heating and cooking sector (Bice et al. 2009). In the past, the now developed countries were the primary sources of BC emissions, but these countries have been able to make significant reductions in their BC emissions through standing air pollution legislation and through having access to more efficient technologies. Comparably, developing countries continue to lack access to BC reducing technologies and the funding to establish programs to reduce BC emissions. With populations rising in many developing countries, alongside the current reliance on biomass and coal for indoor heating and cooking, BC forcing may lead to further warming and the continued negative effects on the climate and public health.

4.0 Human Exposure and Health Effects of Black Carbon

In addition to BC's effect on the changing climate, it also leads to adverse health effects in humans and is one of the largest contributors to indoor air pollution and human exposure levels (Grieshop et al. 2009). The U.S. Environmental Protection Agency (EPA), notes that even low levels of exposure to $PM_{2.5}$ can lead to cardiovascular illness, respiratory illnesses, and mortality, and also suggests exposure to $PM_{2.5}$ may have an effect on reproductive capabilities and cancer rates (EPA 2009). This is likely due to the fine PM being able to enter the respiratory system and be deposited deep in the lining of the bronchial airways, which creates the potential for developing into serious health issues (Armstrong et al. 2004, Mumford et al. 1987, O'Neill et al. 2005, Zhi et al. 2011). The incident rate of illness and fatalities linked to BC and other PM exposure is significantly higher within developing countries due to the use of coal and biomass for indoor heating and cooking with poor ventilation conditions. Ezzati et al. estimate high indoor concentrations of PM, containing BC, is the world's fourth leading cause of disease next to malnutrition, unsafe sex, and poor sanitation (Ezzati et al. 2002). UNEP and WMO estimate reductions in BC emissions could prevent an average of 2.4 million (with a range of 0.7-4.6 million) premature deaths each year (Steiner et al. 2011)**.** Ratios are higher among women and children because they are exposed to the indoor air pollution more often and for longer periods of time compared to men (Ezzati et al. 2011). Wallack and Ramanathan articulate nearly 50 percent of world's population, and up to 95 percent in rural areas, rely on biomass and coal as fuel indoors, which are linked to one-third of the fatal acute respiratory infections in children under five years old, which equates to seven percent of all fatalities among children (Wallack et al. 2009). Technological advancements and air pollution regulations have allowed developed countries to shift away from traditional heating and cooking practices, and has led to the primary source of BC emissions affecting people's health in developed countries being emitted outdoors from diesel fuels, industrial activities, older automobiles, etcetera (Molina et al. 2004). With the proper technology and regulations BC emission reductions will reduce the effects of climate change and also prevent health issues and premature fatalities.

5.0 Technology Solutions

5.1 Black Carbon Mitigation Potential

The technology to make BC emission reductions already exists and can make a dramatic impact. Pacala and Socolow present an argument to stabilize CO_2 concentrations under 500ppm (parts per million) for the next fifty years, using seven wedges from a list of fifteen different strategies (see Appendix 5), each of which are able to reduce emissions by 25 gigatons of carbon (GtC) over fifty years (Pacala et al. 2004). Greishop et al. argue current BC reduction technologies have the ability to reduce 25 GtC from entering the atmosphere over the next 50 years (Grieshop et al. 2009). Therefore, this could be considered a sixteenth wedge to add to those listed by Pacala and Socolow and acts as an addition to the international community's range of options for preventing irreversible damage to the fragile climate system within the next fifty years.

5.2 Available Black Carbon Reducing Technology

For BC emissions to be reduced enough to provide one of the aforementioned mitigation wedges, regulation within the international community must take place. It has been estimated that with existing technologies, BC emissions could be reduced by 50% Wallack 2009), which would offset the equivalent amount of warming that CO_2 would have over the course of one to two decades (Zhi et al. 2011). Many technologies and policies already in use, offer various BC mitigation responses from key sources, namely the burning of raw coal or biomass indoors, diesel transportation, and open biomass burning. A UNEP and WMO assessment suggests options for decreasing BC emissions: diesel particle filters requirements; elimination of in- and off-road high-emitting vehicles; replacing raw coal for coal briquettes in stoves; replacing stoves in developed countries that burn biomass with stoves that use fuel made of recycled wood waste or sawdust; introduce clean-burning cooking stoves in developing countries; replacing traditional kilns with vertical shaft kilns; and banning open field burning of agricultural waste (Sterner et al. 2011). The Arctic Council also mentions all of these technologies in a 2011 assessment, but also includes the diesel particulate filter requirements for international shipping vessels entering into the Arctic region (Abrahammson et al. 2011). With regional BC emission trends varying between regions due to economic and technological development, a variety of measures targeting BC reductions could be combined in order to begin protecting the climate and public health.

6.0 Domestic Environmental Policy Solutions

At the national level there are many instances where governments implement legislation or nationwide programs designed to address air pollution and declining biomass issues (i.e. deforestion), and many of these initiatives have the possibility of simultaneously lowering BC emissions. For example, cook stove improvement programs have been attempted in the past to replace traditional cook stoves, which historically are open indoor fires with no flue and lack proper ventilation, which traps smoke within the household and is subsequently inhaled. These open fires are extremely inefficient and on average have a 10% efficiency transfer of heat from the fire to the cooking instrument, meaning a large amount of biomass or coal is unnecessarily used to cook or heat a residence (Kammen 1995, Wallenstein 2003). The Chinese cook stove replacement programs started in the 1980s and have been operating in some form ever since. These programs have focused on improving thermal efficiency to address the shortage of fuel for consumption, as well as the resulting environmental impacts (Grieshop et al. 2011). Grieshop, Marshall, and Kandlikar determined that these programs provided over 100 million improved stoves and reduced the burden on biomass sources, but these programs did not discourage against the introduction of stoves that did not reduce pollutant emissions and as such human exposure levels remain high (Grieshop et al. 2011). A similar program in India, the Indian National Programme on Improved Chulhas, ran through 2002, but it was much less successful due to a low level of improved stove uptake due to poor durability and performance of the stoves being distributed (Grieshop et al. 2011). Recently a new stove program, the National Biomass Cookstove Initiative, has been announced in India with the goal of widely disseminating highly efficient and low emission biomass stoves (Barnes et al. 1994, Venkataraman et al. 2010, Grieshop et al. 2011). A final example is UNEP's TUNZA youth network, which has been training and informing the world's poor on the importance of clean cooking techniques, primarily through the promotion of using the jiko kisasa, which is a 60% more efficient ceramic cook stove originally from Kenya (UNEP 2012). Not all programs can be developed using the same strategic design and implementation plan as there are many factors to consider, such as local cooking style, food sources, and fuel supplies. However, it may be that the phasing out of traditional stoves is possible by just presenting alternatives to local populations. Regardless, it will take time to implement BC reduction programs because there are millions of people using traditional cook stoves around the world that cannot afford a new stove. All cook stove replacement or upgrade programs should address project funding, increasing the thermal efficiency of stoves to promote more efficient combustion, reducing emissions, and improving ventilation. As various populations within developing countries still use traditional stoves for cooking and residential heating purposes, national programs like those in China and India are extremely important in initiating the lowering of BC emissions and reducing human exposure levels, while the international community continues to decide how to proceed with implementing BC reduction legislation.

Technologies in existence are able to make significant reductions in BC emissions from fossil fuel sources, without actually having to prohibit using the sources of those fossil fuels. This is evident in the fact that developed countries have reduced their BC emissions by a factor of five or more since 1950 through requiring devices that filter out PM (and thus BC) (Seddon et al. 2009). Many developed countries including the U.S. and the European Union have implemented PM emission standards on vehicles, which has caused the co-benefit of large reductions having been made in these countries' BC emission levels. In the U.S. the regulations enacted by the U.S. Environmental Protection Agency (EPA) are expected to reduce BC emissions from diesel vehicles by 70% (Hansen et al. 2008), which equates to an overall decrease in BC emissions from the U.S. of 42% by 2020 (Bahner et al. 2007). This is largely being done through requiring all new diesel vehicles to be fitted with diesel particulate filters (DPF), with an average cost of $5,000-$8,000 these filters can eliminate up to 90% of BC emissions when using ultra-low sulfur diesel fuel (Hill 2012, Bice et al. 2009). The DPF technologies could also be used for shipping vessels, especially ones that travel into the Arctic region where BC is more likely to be deposited on snow or sea ice and promote its melting (Abrahammson et al. 2011). Jacobson proposes a second strategy for reducing BC in the transport sector: replace diesel with gasoline (Jacobson 2002). Although diesel gets better gas mileage and emits less CO_2 compared to gasoline, Jacobson argues that due to the high GWP of BC, even if BC emissions are lowered to 0.02-0.04 grams/mile the warming effect on the climate system that diesel has over 100 years is still greater than the amount of additional CO_2 that would have been emitted if that vehicle had been using gasoline instead of diesel (Jacobson 2002). The phasing out of BC emissions through DPFs or shifts away from diesel fuels to gasoline offer options for how individual countries, regions, or even cities can regulate BC emissions.

Across the globe, many cities have not waited for their State governments or the international community to address rising public concerns on urban air pollution. For example in Santiago, Chile, authorities adopted emissions standards for urban buses with one-third of the fleet retrofitted with DPFs in 2010 and the entire fleet expected to be retrofitted by 2018 (Steiner et al. 2011). In 2000 and 2003, New York City adopted regulations to retrofit buses and off-road construction vehicles with DPFs, and London and other cities have adopted low emissions zones that create incentives for owners to retrofit their diesel vehicles before entering the city limits (Steiner et al. 2011), with many cities now following suit with clean bus fleets. In New Delhi, India a court ordered all public transport vehicles to shift away from diesel fuels and begin using compressed natural gas (Zaelke et al. 2009). Even though these areas are only focusing their attention on this subject due to its effect on public health (and not climate change) the success of these programs is noteworthy for future BC initiatives.

7.0 Mitigation Overview: Strategic Development for Near-term Climate Protection

Regardless of whether a city, country, region, or the whole international community decides to move forward with regulating BC emissions through modern technological advancements, scientific uncertainties must be resolved to build confidence within the international community. Some of the uncertainties that remain are: a rough estimate on the indirect effect of BC forcing on the properties and formation of clouds; an estimate of the role BC has played in warming since pre-industrial times; a more refined calculation for the GWP of BC; the role of brown carbon in the atmosphere, which has weak light-absorbing properties; and an estimate in the warming or cooling that would occur with the simultaneous removal of non-BC co-emitted aerosols when BC is removed (Zhi et al. 2011). Because there has been a great deal of criticism based on some of the uncertainties of climate change science, many experts believe the aforementioned BC uncertainties must be further researched and refined in order for the international community to actively start pushing for regulation of BC as a climate issue and not just a public health issue.

Bice et al. recognize that in order to have the international community unite for a global public good there must be a consensus on the problem and an effective solution to that problem Bice et al. 2009). The international community has the opportunity to establish policies that will slow down climate change on the near term and improve public health while utilizing the previously discussed technology options that can immediately begin reducing BC emissions. Significant near-term effects offered through the regulation of BC would contribute to the UNFCC Copenhagen Accord's goal of keeping global temperature increases below 2°C, and by providing the international community more time to establish long-term CO_2 reduction policies. In order to make this significant contribution the international community would need to establish unwavering mechanisms for regulating BC as well as strategic investment plans for countries that cannot afford to divert funding away from other projects.

7.1 Waiting for the Next Report

It is anticipated the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report will be released in 2013. This new report is expected to specifically take into account the effect BC and other aerosols have on climate change and resolve many of the uncertainties in the science (IPCC 2013a). Currently all BC reduction measures have been enacted on the basis of bettering public health, and not on mitigating or slowing the effects of climate change specifically. Until the new IPCC report is released, or until uncertainties are resolved, the international community will likely wait to establish any BC related policies until the IPCC renders a definitive stance one way or the other in this new report. If the IPCC report says BC is likely to have an impact on climate change, the first steps would be to form regional agreements or to regulate it within existing treaties that have the authority to do so. If the IPCC report says BC is not likely to affect climate change the international community should still regulate BC but as a public health issue. In the meantime some international organizations such as UNEP, WMO, the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Arctic Council, the International Maritime Organization, and the World Bank have taken it upon themselves to develop reports addressing possible BC regulations and strategies to reduce BC emissions based on its effect on climate change.

7.2 Potential International Policy Approaches

To date no international instrument regulates or monitors BC on the basis of its effect on climate, even though reducing emissions of BC is seen as potentially a positive political project, as benefits would result from slowing climate change and reducing BC related health issues (Wallack et al. 2009). However, because the effects of BC are largely felt at the regional level the climate benefits that would ensue would be most widely felt in the snow and ice-covered Arctic and the Himalayan regions. The BC sources that affect the Arctic region tend to be a result of fossil fuels, particularly from diesel emissions, while the BC sources that influence melting of the Himalayan and Tibetan glaciers are significantly affected by the burning of biomass in the residential sector. Also there are obvious differences between the cultures, accessibility to technologies, and economic resources between developed and developing countries. A single global framework would be one way to merge the different strategies for reducing BC emissions and establish an overarching funding mechanism. However, because of its strong regional influence a single global framework may not be the most suitable venue for BC mitigation efforts. Rather, existing or new bilateral and multilateral agreements in geographically similar regions would likely be a more useful venue to be able to work through the negotiation process, as there are shared and common responsibilities, which would allow governments to develop feasible implementation strategies for specific regions.

7.2.1 Convention on Long-Range Transboundary Air Pollution

In the coming years it seems as though the most likely place for BC regulations to develop is under the patronage of the United Nations Economic Commission for Europe (UNECE) secretariat's 1979 CLRTAP. This multilateral agreement now has 51 Parties, including countries in North America, Europe, and Russia, and has eight protocols addressing issues relating to different air pollutants that travel across State boundaries namely: sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds, ammonia, heavy metals, and persistent organic compounds. CLRTAP has also established the 1999 Gothenburg Protocol, which addresses setting emissions ceilings on multiple pollutants. In recent years the international community has become interested in using CLRTAP's Gothenburg Protocol as a forum for addressing the regulation of BC emissions and other SLCF. In September 2010, an Ad-Hoc Expert Group on Black Carbon, co-chaired by the United States of America and Norway, prepared a report assessing the available data on BC and articulated a rationale for addressing near-term climate change impacts on the region, particularly the Arctic, and the impact BC has on human health and ecosystems within the authority of its Gothenburg Protocol (Bodanksy 2011, CLRTAP 2010). The Expert Group's report recommends the Parties to gather and share data with parties outside CLRTAP, to improve inventories and identify BC sources, inform the International Maritime Organization (IMO) of its concern for BC emissions from shipping on the Arctic environment, and argues that there are advantages from combining strategies for addressing air quality and climate change as one will likely effect the other (CLRTAP 2010). The report continues on and suggests the Executive Body to consider: adequate funding resources; using non-binding emission reduction goals; and revising the Gothenburg Protocol to include PM (CLRTAP 2010). The report also discusses the first step towards establishing reduction policies will depend on how quickly and accurately an inventory of BC sources can be identified within each country (CLRTAP 2010). The fact that CLRTAP has gone so far as to establish an Ad Hoc Expert Group, and for that group to have provided its recommendations to the Executive Body, it seems promising some sort of action will follow.

7.2.2 The Arctic Council

In 1996, the Ottawa Declaration formerly established the Arctic Council, with eight member states: Canada, Russia, Norway, Denmark (including Greenland and Faroe Islands), Iceland, the United States of America, Sweden, and Finland. The Arctic Council was established as a "high level intergovernmental forum to provide a means for promoting cooperation, coordination and interaction within the Arctic States, with the involvement of the Arctic Indigenous communities and other Arctic inhabitants on common Arctic issues, in particular issues of sustainable development and environmental protection in the Arctic" (Arctic Council 2011). The April 2009 Arctic Council Ministerial Tromsø Declaration documented the role of SLCF, including BC, on the changing climate in the Arctic environment and how reducing these emissions could slow the rate of melting snow, sea ice, and ice sheets in the Arctic region (Abrahammson et al. 2011). This Declaration established the Arctic Council Task Force on Short-Lived Climate Forcers and commissioned a report to identify measures already in existence, as well as new mitigation measures, to reduce SLCF, and to recommend immediate actions that can be taken (Abrahammson et al. 2011).

Compared to the report produced by CLRTAP, the Arctic Council report goes further in depth by including current inventories by sector within each of the member countries, as well as discussing the trends through 2030 of each sector of each individual country, and the combined trends for all Arctic Council member States through 2030. This section of the report seems to be in response to CLRTAP's assessed need for more specific data; proving that the data does exist and is now accessible and available to be used. It appears that the Arctic Council is urging CLRTAP to move forward rapidly with making revisions to the Gothenburg Protocol to include BC reduction requirements. The policy measures suggested within the Arctic Council report offer specifics about potential areas for reductions in each the domestic heating, transportation, and international maritime shipping, and fishing vessel sectors. Like CLRTAP, the Arctic Council suggests engagement of the IMO in establishing BC reductions from marine shipping in and near the Arctic region, specifically under Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) (Abrahammson et al. 2011). If CLRTAP does not move forward with regulation of BC emissions it is likely the Arctic Council would form a multilateral agreement to address the rising concerns of BC deposition in the Arctic environment.

7.2.3 The Nordic Council

A move in the direction of a multilateral organization being formed in the Arctic region recently occurred among the members of the Nordic Council. The Nordic Council is an inter-parliamentary forum for establishing and maintaining cooperation between Nordic countries. In March 2012, the Nordic Council met to discuss reducing Nordic emissions of SLCF, such as BC, and this meeting led to the Svalbard Declaration on Shortlived Climate Forcers, which states that "Based on our close co-operation and shared values, we, the Nordic environment ministers, will intensify our efforts to reduce emissions of SLCFs at national, regional and global level. We will act as a driving force and work more closely together in international fora to advocate more ambitious international regulation of emissions of GHG and SLCFs" (Nordic Council 2012). This regional agreement commits its members to establish SLCF reduction plans, support the development of a mechanism to regulate SLCF under CLRTAP, and to promote a global climate agreement under UNFCC (Nordic Council 2012). This recent advancement is a significant step forward showing CLRTAP and other regional organizations there is significant support among various CLRATAP Parties for implementing BC reduction measures.

7.2.4 The International Maritime Organization

In response to the CLRTAP and Arctic Council concerns regarding BC emissions from shipping in or near the Arctic region, at its 62nd session in July 2011, the IMO Marine Environment Protection Committee (MEPC), instructed the Sub-Committee on Bulk Liquids and Gases to develop a report due in 2014, that will develop a definition for BC emissions from international shipping, develop methods for measuring BC emissions from international shipping, and investigate enforcement measures to reduce the impacts of BC emissions from international shipping (MEPC 2011). This is a significant step forward as maritime shipping in or near the Arctic region is expected to increase in the coming years as the summer sea ice cover continues to retreat and open new shipping lanes. Although many IMO Parties in the Arctic region are supportive of establishing measures to reduce BC emissions, there are many IMO Parties that are not currently addressing the rising concerns of the effect of BC on climate change.

7.3 Developing Countries

Even though many regional multilateral agreements similar to CLRTAP have emerged among developing countries, these multilateral agreements seem less motivated to discuss the regulation of BC emissions compared to those among developed nations. Examples include: the Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effects for South Asia, which includes India, Pakistan, and Bangladesh, was established in 1998 and focuses on air quality issues including tropospheric ozone (O_3) and PM; the Association of Southeast Asian Nations (ASEAN) is an agreement that in part manages particulate pollution from forest fires and land clearing activities; and the Air Pollution Network for Africa, which monitors air pollution from many African countries. This lack of interest in BC's effect on climate change could possibly be due to the fact that the effect of BC on many of these developing countries is more evident as a public health issue rather than a climate change issue. Also, it would be necessary to depend on national regulatory agencies of member nations to develop, implement, and enforce requirements. As many of the governments in these regions lack the regulatory infrastructure and the funding to address environmental challenges on top of the many developmental challenges they already face, it would be necessary for them to rely on funding and expertise from the international community to begin negotiations among their member States.

7.4 International Funding Options

As a majority of BC emissions are emitted by developing countries it is necessary to make sure that they are not left behind in establishing international mitigation responses, especially when the technologies already exist to make substantial and immediate reductions in BC emissions. A UNEP and WMO report suggests international financing and technology support would accelerate the adoption of BC reduction measures particularly in developing countries (Steiner et al. 2011). Zaelke and Clare suggest this funding could come from multiple sources including: establishing a new funding source that uses grants, loans, and matching funds incentives; using World Bank Climate Investment Funds; and emphasizing the health benefits and receiving support from the World Health Organization (Zaelke et al. 2009). The World Bank published a report in 2011, encouraging the formation of international agreements that would develop projects and policies reflecting the benefits BC reductions would have on both the environment and public health. The report also discusses improving costs and benefits evaluations for reducing BC, in addition to identifying and supporting project investment suggestions (Levitsky 2011). As such, the World Bank is interested in ensuring a fair and equitable system for funding BC reduction, but it seems as though the World Bank would like the international community to develop a funding mechanism unto its own that specifically takes into account BC reduction projects.

8.0 Policy Recommendations

Reducing emissions of BC will save lives and would slow the rate of climate change to limit global warming to 2°C during the twenty-first century. Control and mitigation approaches do in fact exist; however, the number of sources and the wide distribution of those sources present significant challenges to develop policies to control BC emissions.

8.1 Domestic Black Carbon Reduction Policies

As previously noted, developed countries are expected to continue to reduce their BC emissions (Wallack et al. 2009). Bond et al. estimate roughly 57% of diesel PM is composed of BC and this is a concern because that is a much higher level than gasoline vehicles (Bond et al. 2004). The US has a managed to curb many of environmental and health impacts of new diesel engines through regulations put in place by the EPA that requires the use of particular filters and ultra-low sulfur diesel fuels. However, older vehicles are still a concern, but domestic policies can be put in place providing incentives to retrofit those vehicles. In doing so the US will be able to continue using domestic policy avenues to maintain its downward trend in reducing BC emissions. Having access to cleaner and more efficient technologies, and having had strong air pollution policies in place for many years is providing the US an opportunity to demonstrate to the rest of the international community its renewed commitment to moving forward with acting on climate change and improving the world's public health.

As 90 percent of the US BC emissions come from the diesel transportation sector (Wallack et al. 2009) most domestic BC reduction policies should be focused on this sector, but BC can and should still be reduced in other sectors when possible. A few possible suggestions to further reduce the US BC emission levels are to:

- Improve vehicle fuel efficiency through more stringent Corporate Average Fuel Economy (CAFE) standards
- Expand funding for DPF retrofitting programs by providing tax incentives or loan guarantees for retrofitting older vehicles.

- Encourage the expansion, growth, and use of clean forms of transportation, such as electric vehicles.
- Establish a program to target getting high BC emitting vehicles off the roads or implement a dirty vehicle tax that would incentivize the worst BC emitters to retrofit their vehicles.
- Promote trains and ships to transport cargo to reduce the quantity of diesel trucks, as well as the number of their trips.
- Evaluate emission standards for residential wood heaters, provide incentives for retrofitting woodstoves and furnaces, or establish programs to promote the replacement of inefficient residential heaters.
- Broaden forest fire prevention efforts and reduce land-clearing activities in high latitudes near the Arctic region.

The US now only emits a fraction of the world's BC and though it is making great strides in reducing its BC emission levels through air pollution controls it cannot reduce BC emissions enough globally to warrant inaction from others within the international community (Wallack et al. 2009). Many of the policy options listed above for the US could be exported into the domestic BC policy solutions for countries throughout the world, particularly for other developed countries where diesel sources are the primary sources of BC.

8.2 Global Black Carbon Policy Solutions

Once released into the atmosphere GHG and PM emissions know no real boundaries. As BC emissions are transboundary the emissions of one foreign country can have a considerable effect on the public's health and the future climate of neighboring countries. Increased international cooperation between both developed and developing countries is necessary to bring awareness to the topic and establish a dialogue to achieve a consensus on the problem and to agree upon an effective solution. A few possible solutions could result from:

- Revise the CLRTAP's Gothenberg Protocol to include $PM_{2.5}$, including BC, in order to strengthen the efforts being made by developed countries to reduce BC emissions.
- Establish regional treaties in the areas most impacted by BC, such as the Arctic or Himalaya regions, as well as in BC sensitive areas, such as the countries that might be impacted by the weakening of the Asian Monsoon.
- Institute global standards from emissions from diesel engines and facilitate technology transfer to bring particulate filters and ultra-low sulfur diesel fuels to more countries.
- Found programs to donate energy efficient and culturally appropriate technologies to developing countries with an emphasis on reducing emissions from cook stoves and other sources of residential heating.
- Launch education initiatives to teach citizens of developing countries of the potential health impacts of poor indoor ventilation and the potential benefits for reducing the inhalation of $PM_{2.5}$.

- Develop a funding mechanism for developed countries to invest in BC reducing projects in developing countries.

Regional bilateral and multilateral agreements seem to be the most promising source of potential regulation of BC, but a single global framework could occur depending on the result of the IPCC's Fifth Assessment Report in 2013. The fact that many multilateral organizations are conducting reports is a step closer to the international community taking a step in the direction to acknowledging the threat of BC. If the IPCC Fifth Assessment report confirms BC as a significant contributor to climate change, the international community will be in the position to move forward with forming new legislation to regulate BC.

8.2.1 Developing a Transnational Black Carbon Framework and the Montreal Protocol

In establishing a framework to address BC the international community could consider referencing the successful provisions within the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol)—an agreement under the 1985 Vienna Convention on the Protection of the Ozone Layer. The Montreal Protocol established a mechanism to control ozone-depleting substances, as well as placed controls on how certain chlorofluorocarbons (CFCs) and halons were produced and used.

Since implementation the Montreal Protocol has had many notable successes by establishing programs that require inventories, labeling, permits, and self-reporting mechanisms. These programs have been funded by both private and public funds and have led to research being conducted on new technologies to find CFC substitutes. Despite its success, implementation of the the Montreal Protocol has not been without its difficulties, which include: low financial assistance to developing countries; restrictions on CFCs and other chemical imports have been undermined by incorrect labeling; and enforcement is difficult when it involves home appliances and refrigerants (Kesselaar et al. 2012).

Like CFCs, it is difficult to take an exact inventory of all CFC sources and many of the sources reside within households. Under the Montreal Protocol countries have been bound to phase out CFC products by specific dates; however, as a provision within the Montreal Protocol, developing countries have been given more time to phase out CFC use (Department of Sustainability, Environment, Water, Population, and Communities 2012). This delay mechanism could play an integral role in securing support among developing countries to commit to binding BC reductions. Therefore, the phase out of BC will be more easily implemented in developed countries, especially within the EU and US where there have already been significant strides in reducing BC due to air pollution regulations.

As such, a transnational BC framework would need to be cognizant of the inevitable delay that will occur for developing countries to implement new BC reduction policies due to: the lack of policy infrastructure and access to technology; the ability to afford and operate the more efficient technologies; the ability to enforce the new measures; and for the multitude of different cultures to adapt to new cooking techniques. Like in the US, many of these countries may best be able to start making BC reductions by requiring particulate filters on new stoves and vehicles, and slowly go on to developing policies and incentives to target older BC emission sources.

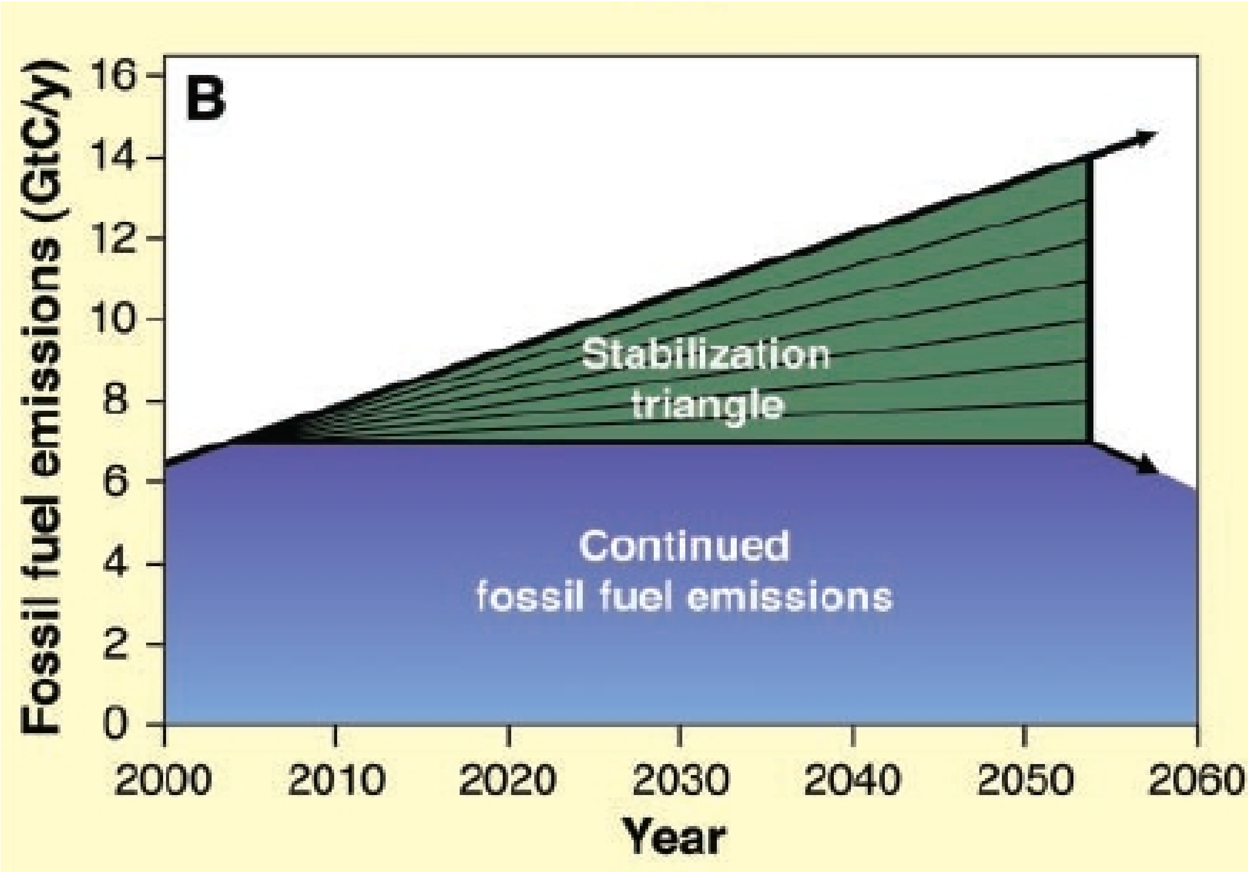
9.0 Conclusion

In order for a new global agreement between both developed countries and developing countries there must be a continued affirmation of the idea of Common but Differentiated Responsibilities, which states that “the developed country Parties should take the lead in combating climate change and the adverse effects thereof” (UNFCC 1992, Nanda 2011). Although BC does not remain in the atmosphere for more than a few weeks at any given time it is constantly being replenished. Despite the fact that the developed countries are no longer the primary producers of BC emissions, it is the responsibility of the developed countries to take the lead in making reductions to BC emissions because they are the ones who have exported old technologies to the markets in the developing countries and new lower BC emitting technologies may still be too expensive to incorporate into many of these peoples’ lifestyles. As many of the developed countries are already seeing significant trends of declining BC emissions due to regulations that have been enacted to reduce pollution and airborne particulate matter (PM), it is much more likely to see developed countries to sign and ratify an international agreement to reduce BC emissions than if these policies were not already in place. Despite any action taken by developed countries, developing countries particularly in Asia must also work towards making BC reductions that are binding and enforceable. Ultimately, all countries share the commonality of needing to reduce BC for both the benefits of slowing climate change in the near term and reducing public health issues, but developing countries are and will likely continue to be dependent on developed countries to provide the expertise and funding for projects to reduce BC emissions.

As BC has strong regional effects on climate change, comprehensive BC inventories must be conducted on all regions to gather information for the international community to make informed decisions. Upon receiving all necessary data, the international community should begin analyzing and developing climate change mitigation policies that address SLCF, and particularly BC due to its significant influence on warming the atmosphere, melting snow and ice, and altering the properties of cloud formation. As it is likely regulations will develop in some form among the countries in the Arctic region, those countries and the international community must understand that any action to reduce near-term climate change through BC reductions should in no way deter the international community from addressing the bigger issue of making substantial reductions in CO_2 emission levels. Although developing countries do not seem to be moving forward with BC regulations as a climate issue, regulating BC as a public health issue would prevent a multitude of preventable diseases and deaths especially within developing countries. There will likely be issues between the developed and developing countries on the premise of who has the primary responsibility for reducing BC emissions and who will pay for the reductions, but BC regulations seem to be an easy, relatively quick, and less expensive step, in comparison to CO_2 reductions, in the process to mitigate climate change. The regulation of BC will provide the international community with an opportunity to make the necessary reductions in CO_2 and delay, by a decade or more, the world from reaching the critical irreversible thresholds.

Appendix 5 – Pacala and Socolow Stabilization Wedges

In 2004, Stephen Pacala and Robert Socolow developed a flexible model for tackling climate change within the next 50 years using only currently existing technologies. Pacala and Socolow listed 15 measures, each of which could reduce carbon emissions by 1 billion tons per year by 2054, claiming climate change could be manageable, though still a serious problem, if seven of these measures were carried out by that time (Pacala 2004). Figure 1 depicts how seven equally divided wedges could be used to level off carbon emissions. Figure 2 lists the fifteen categories and what can be done to make the necessary carbon reductions.



Source: Stacey 2011

Energy Efficiency and Conservation	Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of reduction of 1.96% per year to 2.11% per year)	Can be tuned by carbon policy
	1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
	2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles per year	Urban design, mass transit, telecommuting
	3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054	Weak incentives
	4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
Fuel shift	5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (4 times the current production of gas-based power)	Competing demands for natural gas
CO_2 Capture and Storage (CCS)	6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production
	7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)	H_2 safety, infrastructure
	8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels per day from coal (200 times Sasol), if half of feedstock carbon is available for capture	Increased CO_2 emissions, if synfuels are produced *without* CCS
	Geological storage	Create 3500 Sleipners	Durable storage, successful permitting
Nuclear Fission	9. Nuclear power for coal power	Add 700 GW (twice the current capacity)	Nuclear proliferation, terrorism, waste
Renewable Electricity and Fuels	10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30×10^6 ha, on land or off shore	Multiple uses of land because windmills are widely spaced
	11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2×10^6 ha	PV production cost
	12. Wind H_2 in fuel-cell car for gasoline in hybrid	Add 4 million 1-MW-peak windmills (100 times the current capacity)	H_2 safety, infrastructure
	13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250×10^6 ha (1/6 of world cropland)	Biodiversity, competing land use
Forests and Agricultural Soils	14. Reduced deforestation, plus reforestation, afforestation and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)	Land demands of agriculture, benefits to biodiversity from reduced deforestation
	15. Conservation tillage	Apply to all cropland (10 times the current usage)	Reversibility, verification

Source: Stacey 2011

References

Abrahammson, R., et al. 2011. *An Assessment of Emissions and Mitigation Options for the Arctic Council*. Arctic Council. 1-R-9.

Ackerman, Steve. General Circulation of the Atmosphere. *University of Wisconsin-Madison, Cooperative Institute for Meteorological Satellite Studies*, Accessed 29 April 2013, from http://cimss.ssec.wisc.edu/wxwise/class/gencirc.html.

American Meteorological Society. 2009. Glossary of Meteorology. Accessed 22 February 2013, from http://glossary.ametsoc.org/wiki/Main_Page.

American Wind Energy Association (AWEA). 2011. U.S. Small Wind Turbine Market Report. Accessed 14 April 2013. http://www.awea.org/learnabout/smallwind/upload/AWEA_SmallWindReport-YE-2011.pdf.

American Wind Energy Association. 2013. American Wind Power. Accessed 14 April 2013. http://awea.org/learnabout/publications/upload/AmericanWindpowerBrochure.pdf.

Andreae, M.O., and A. Gelensér. 2006. Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols. *Atmospheric Chemistry and Physics* 6:3131–3148.

Arctic Council Chairmanship Secretariat. About the Arctic Council, Updated 7 April 2011, Accessed 13 April 2013: http://www.arctic-council.org/index.php/en/about-us.

Armstrong, B., et al. 2004. Lung cancer risk after exposure to polycyclic aromatic hydrocarbons: A review and meta-analysis. *Environmental Health Perspectives* 112:970–978.

Australian Government, Department of Sustainability, Environment, Water, Population, and Communities. 2012. Montreal Protocol on Substances that Deplete the Ozone Layer. Updated 9 July 2012, Accessed 13 April 2013. http://www.environment.gov.au/atmosphere/ozone/legislation/montp.html.

Aydin, N.Y., E. Kentel, and S. Duzgun. 2010. GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey. *Renewable and Sustainable Energy Reviews* 14:364–373. doi: 10.1016/j.rser.2009.07.023.

Bahner, M.A., K.A. Weitz, A. Zapata, and B. DeAngelo. 2007. Use of Black Carbon and Organic Carbon Inventories for Projections and Mitigation Analysis. *U.S. Environmental Protection Agency*. http://www.epa.gov/ttnchie1/conference/ei16/session3/k.weitz.pdf.

Barnes, D.F., K. Openshaw, K.R. Smith, and R. van der Plas. 1994. What makes people cook with improved biomass stoves? A comparative international review of stove programs. World Bank Technical Paper.

Baron, R.E., W.D. Montgomery, and S.D. Tuladhar. 2009. *An Analysis of Black Carbon Mitigation as a Response to Climate Change*. Copenhagen Consensus Center.

Barthelmie, R.J., and L.E. Jensen. 2010. Evaluation of wind farm efficiency and wind turbine wakes at the Nysted offshore wind farm. *Wind Energy* 13:573–586. doi: 10.1002/we.408

Barthelmie, R.J., F. Murray, and S.C. Pryor. 2008. The economic benefit of short-term forecasting for wind energy in the UK electricity market. *Energy Policy* 36:1687–1696. doi: 10.1016/j.enpol.2008.01.027.

Bejing Normal University, College of Geography and Remote Sensing, Key Laboratory of Regional Geography. 2006. China Mean Annual Wind Speed. Accessed 13 April 2013: http://course.bnu.edu.cn/course/cgeography/en/html/7ziyuan/2ditu/img/p5-1.jpg.

Bice, K., et al. 2009. *Black Carbon: A Review and Policy Recommendations*. Woodrow Wilson School of Public & International Affairs.

Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan. 2007. Observations: Oceanic Climate Change and Sea Level. In S. Solomon et al. (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 385–432. New York: Cambridge University Press.

Blanco, M.I., and G. Rodrigues. Can the Future EU ETS Support Wind Energy Investments? 2008. *Energy Policy* 36:1509–1520. doi: 101016/j.enpol.2007.12.025.

Bodansky, D. 2011. *Multilateral Climate Efforts Beyond the UNFCC*. Center for Climate and Energy Solutions.

Bond, T.C. 2007. Testimony for the Hearing on Black Carbon and Climate Change, House Committee on Oversight and Government Reform, 18 October 2007.

Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo, and Z. Klimont. 2004. A Technology-based Inventory of Black Carbon and Organic Carbon Emissions from Combustion. *Journal of Geophysical Research* 109:1–43. doi:10.1029/2003JD003697

Bond, T.C., and H. Sun. 2005. Can Reducing Black Carbon Emissions Counteract Global Warming? *Environmental Science & Technology* 39:5921-5926.

Bond, T.C., and R.W. Bergstrom. 2006. Light absorption by carbonaceous particles: An investigative review. *Aerosol Science and Technology* 40:27–67.

Breslow, P.B., and D.J. Sailor. 2002. Vulnerability of Wind Power Resources to Climate Change in the Continental United States. *Renewable Energy* 27:585–598. doi: 10.1016/S0960-1481(01)00110-0.

Burton, T., D. Sharpe, N. Jenkins, E. Bossanyi. 2001. Wind Energy Handbook. *J. Wiley and Sons*, Chichester.

Cassola, F., M. Burlando, M. Antonelli, and C.F. Ratto. 2008. Optimization of the Regional Spatial Distribution of Wind Power Plants to Minimize the Variability of Wind Energy Input into Power Supply Systems. *Journal of Applied Meteorology and Climatology* 47:3099–3116. doi: 10.1175/2008JAMC1886.1

Changliang, X., and S. Zhanfeng. 2009. Wind energy in China: Current scenario and future perspectives. *Renewable and Sustainable Energy Reviews* 13:1966–1974. doi: 10.1016/j.rser.2009.01.004.

Cohen, J., T. Schweizer, A. Laxson, S. Butterfield, S. Schreck, L. Fingersh, P. Veers, and T. Ashwill. 2008. *Technology Opportunities for Low Wind Speed Turbines and Implications for Cost of Energy Reduction*. NREL/TP-500-41036. Golden, CO: National Renewable Energy Laboratory.

Convention on Long-Range Transboundary Air Pollution. 2010. *Report of the Expert Group on Black Carbon*. United Nations Economic Commission for Europe.

Cradden, Lucy Catherine. 2009. The Impact of Climate Change on Wind Energy Generation in the UK. *University of Edinburgh*:1-388.

Danish Wind Industry Association. 2013. Wind Energy Surpasses 30%. Updated 31 January 2013, Accessed 12 April 2013, http://www.windpower.org/en/news/news.html#727.

Eichelberger, S., et al. 2008. Climate Change Effects on Wind Speed. *North American Windpower* July:1–4. http://www.3tier.com/static/ttcms/us/documents/NAWP-July08.pdf.

Elliott, D., M. Schwartz, G. Scott, S. Haynes, D. Heimiller, and R. George. 2002. Wind Energy Resource Atlas of Southeast Asia. National Renewable Energy Laboratory. Accessed 14 April 2013: NREL/TP-500-32781. http://library.uoregon.edu/ec/e-asia/read/32781.pdf.

European Wind Energy Association (EWEA). 2010. Wind Energy Fact Sheets. Accessed 9 April 2013, 1-30. http://www.ewea.org/fileadmin/ewea_documents/documents/publications/factsheets/Factsheets.pdf.

EWEA. 2012. *Annual Report 2011*. Accessed 9 April 2013, http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/EWEA_Annual_Report_2011.pdf.

EWEA. 2013. The Wind Energy Initiative: Wind power research and development to 2020. Accessed 9 April 2013: http://www.ewea.org/fileadmin/files/library/publications/reports/EWI_2013.pdf.

Ezzati, M., A. Lopez, A. Rodgers, S. Vander Hoorn, C.J.L. Murray, and the Comparative Risk Assessment Collaborating Group. 2002. Selected major risk factors and global and regional burden of disease. *The Lancet* 360:1347–1360.

Ezzati, M., et al. 2006. *Comparative Quantification of Mortality and Burden of Disease Attributable to Selected Risk Factors*. In A.D. Lopez et al. (eds.), *Global Burden of Disease and Risk Factors*, pp. 241–268. New York: Oxford University Press.

Flanner, M.G., C.S. Zender, J.T. Randerson, and P.J. Rasch. 2007. Present-day Climate Forcing and Response from BC in Snow. *Journal of Geophysical Research—Atmospheres* 112:D11.

Gasch, R. (ed.). 1996. *Windkraftanlagen*, 3rd ed. Stuttgart, Germany: B.G. Teubner.

Gasch, R. 1982. *Wind turbine generators*. MIT Press.

Gipe, P. 1995. *Wind energy comes of age*. Wiley.

Global Wind Energy Council. (GWEC). 2011. Global Wind Report: Annual market update 2010. Accessed 13 April 2013: 1-72. http://gwec.net/wp-content/uploads/2012/06/GWEC_annual_market_update_2010_-_2nd_edition_April_2011.pdf.

Goad, Jessica, Daniel J. Weiss, and Richard W. Caperton 2012. The Vast Potential of Renewable Energy in the American West—Developing Wind, Solar, and Geothermal Energy on Public Lands. *Center for American Progress*. Accessed 30 April 2012. http://www.americanprogress.org/issues/green/report/2012/08/06/12002/the-vast-potential-for-renewable-energy-in-the-american-west/.

GWEC. 2012a. Global Wind Report: Annual market update 2011. Accessed 13 April 2013: 1-68. http://gwec.net/wp-content/uploads/2012/06/Annual_report_2011_lowres.pdf.

GWEC. 2012b. India Wind Energy Outlook 2012. Accessed 13 April 2013: 1-40. http://www.gwec.net/wp-content/uploads/2012/11/India-Wind-Energy-Outlook-2012.pdf.

Grieshop, A.P., C.O.R. Conor, M. Kandlikar, and H. Dowlatabadi. 2009. A black-carbon mitigation wedge. *Nature Geoscience* 2:533–534.

Grieshop, A.P., J.D. Marshall, and M. Kandlikar. 2011. Health and Climate Benefits of Cookstove Replacement Options. *Energy Policy* 39:7350–7542.

Hansen, J. 2002. A Brighter Future. *Climate Change* 53:435.

Hansen, J., M. Sato, P. Kharecha, D. Beerling, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos. 2008. Target Atmospheric CO_2: Where Should Humanity Aim? *Open Atmospheric Science Journal* 2:217–231.

Hegerl, G.C., F.W. Zwiers, P. Branconnot, N.P. Gillet, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner, and P.A. Stott. 2007. Understanding and attributing climate change. In S. Solomon et al. (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 663–746. New York: Cambridge University Press.

Hemingway, Ernest. "Islands in the Stream: A Novel," Charles Scribner's Sons (1970): 1-448.

Hill, L.B. 2005. Diesel Engines: Emissions Controls and Retrofits. Clean Air Task Force. Accessed 13 April 2013, http://www.scribd.com/doc/40210013/Diesel-Engines-Emissions-Controls-and-Retrofits.

Hills, R. L. Mechanical engineering in the medieval near East. *Scientific American*, May 1991.
Hossain, J., V. Sinha, and V.V.N. Kishore. 2011. A GIS based assessment of potential for windfarms in India. *Renewable Energy* 36(12):3257-3267. doi: 10.1016/j.renene.2011.04.017.

Intergovernmental Panel on Climate Change Data Distribution Centre. 2012. About the IPCC Data Distribution Centre. Updated June 2012, Accessed 13 April 2013: http://www.ipcc-data.org/ddc_about.html.

Intergovernmental Panel on Climate Change Data Distribution Centre. 2013. SRES GCM change fields. Accessed 13 April 2013: http://www.ipcc-data.org/cgi-bin/ddcvis/gcmcf.

Intergovernmental Panel on Climate Change. 2013a. Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis. Accessed 13 April 2013. http://www.ipcc.ch/pdf/ar5/wg1-outline.pdf.

Intergovernmental Panel on Climate Change. 2013b . History. Accessed 13 April 2013. http://www.ipcc.ch/organization/organization_history.shtml#.UYAeSndWKF8.

International Energy Agency (IEA). 2006. IEA Wind Energy Annual Report 2006. Accessed 12 April 2013, http://www.ieawind.org/annual_reports_PDF/2006.html.

IEA. 2007. World Energy Outlook 2007: Fact sheet—China. Accessed 12 April 2013, http://www.worldenergyoutlook.org/media/weowebsite/factsheets/Factsheets_2007.pdf.

IEA. 2011. World Energy Outlook 2011. Accessed 13 April 2013, http://www.worldenergyoutlook.org/publications/weo-2011/ and http://www.scribd.com/doc/72512781/World-Energy-Outlook-2011.

Jacobson, M.Z. 2002. Control of fossil-fuel particulate black carbon and organic carbon, possibly the most effective method of slowing global warming. *Journal of Geophysical Research* 107:1–22.

Jacobson, M.Z. 2005. Correction to "Control of fossil-fuel particulate black carbon and organic carbon, possibly the most effective method of slowing global warming." *Journal of Geophysical Research* 110(D14104):1–5.

Jacobson, M.Z. 2007. Written Testimony for the Hearing on Black Carbon and Global Warming, House Committee on Oversight and Government Reform, United States House of Representatives. Stanford University Atmosphere/Energy Program.

Jiang, Y., Y. Luo, Z. Zhao, Y. Shi, Y. Xu, and J. Zhu. 2010. Projections of Wind Changes for 21st Century in China by Three Regional Climate Models. *Chinese Geographical Science* 20(3):226–235. doi: 10.1007/s11769-010-0226-6.

Junfeng, L., C. Fengbo, Q. Liming, X. Hongwen, G. Hu, Y. Xiaosheng, T. Wenqian, W. Weiquan, L. Xiuqin, L. Ang, T. Wenqian, and L. Shuo. (2012). *China Wind Energy Outlook*. Global Wind Energy Council. Accessed 13 April 2013: 1-75. http://www.gwec.net/wp-content/uploads/2012/11/China-Outlook-2012-EN.pdf.

Jungfeng, L., S. Pengfei, and G. Hu. 2010. *2010 China Wind Power Outlook*. Global Wind Energy Council. Accessed13 April 2013: 1-92. http://gwec.net/wp-content/uploads/2012/06/wind-report0919.pdf.

K. Chandrika. 2011. Associating Weather Conditions with Ramp Events in Wind Power Generation. Paper presented at the Institute of Electrical and Electronics Engineers Power Systems Conference and Exposition, Phoenix, Arizona, March 20–23, 2011). LLNL-CONF-457176.

Kammen, D. 1995. Cookstoves for the Developing World. *Scientific American* 273:72–75.

Kandlikar, M., C.C.O. Reynolds, and A.P. Greishop. 2009. *A Perspective Paper on Black Carbon Mitigation as a Response to Climate Change*. Copenhagen Consensus Center.

Kesselaar, H., and I. Moreno. 2013. Montreal Protocol: Enforcement of Chlorofluorocarbons (CFC) and Related Requirements. Fourth International Conference on Environmental Compliance and Enforcement, Accessed 13 April 2013: From http://www.inece.org/4thvol2/mpws.pdf.

Lantz, E., R. Wiser, M. Hand, A. Arapogianni, A. Ceña, E. Simonot, and E. James-Smith. 2012. *IEA Wind Task 26*. Golden, CO: National Renewable Energy Laboratory.

Lema, A., and K. Ruby. 2006. Towards a Policy Model for Climate Change Mitigation: China's Experience With Wind Power Development and Lessons For Developing Countries. *Energy for Sustainable Development* 10:5–13. doi: 10.1016/S0973-0826(08)60551-7.

Lema, A., and K. Ruby. 2007. Between Fragmented Authoritarianism and Policy Coordination: Creating a Chinese Market for Wind Energy. *Energy Policy* 35:3879–3890. doi: 10.1016/j.enpol.2007.01.025.

Levitsky, M. 2011. *Black Carbon and Climate Change*. The World Bank.

Look Magazine, Photographer, Ernest Hemingway Writing at Campsite in Kenya, John F. Kennedy Library, Columbia Point, Boston, MA, (ca. 1953): ARC Identifier 192655.

Lu, Xi, McElroy, Michael B., Kiviluoma, Juha. 2009. Global potential for wind-generated electricity. *Proceedings of the National Academy of Sciences* 106(27):10933-10938. doi: 10.1073/pnas.0904101106.

Mahasenan, N., R.G. Watts, and H. Dowlatabadi. 1997. Low-frequency Oscillations in Temperature Proxy Records and Implications for Recent Climate Change. *Geophysical Research Letters* 24:563–566. doi: 10.1029/97GL00319.

Malakoff, D. 2012. Sequestration Would Cut U.S. Science Budgets By 8.2%, White House Estimates. *Science*, September 14, 2012. Accessed: 13 April 2013, http://news.sciencemag.org/scienceinsider/2012/09/sequestration-would-cut-us-scien.html.

Marine Environment Protection Committee. 2011. IMO environment meeting completes packed agenda. International Maritime Organization, 62nd session. Updated 19 July 2011, Accessed 13 April 2013. http://www.imo.org/MediaCentre/PressBriefings/Pages/43%20MEPC62ENDS.aspx.

Marquis, M., et al. 2011. Forecasting the Wind to Reach Significant Penetration Levels of Wind Energy. *American Meteorological Society* 92:1159–1171. Accessed 13 April 2013. doi:10.1175/2011BAMS3033.1

McVicar, T.R., et al. 2008. Wind speed climatology and trends for Austrailia, 1975-2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters* 35:L20403. doi: 10.1029/2008GL035627.

McVicar, T.R., et al. 2012. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology* 416/417:182–205.

Mears, C.A., and F.J. Wentz. 2009. Construction of the RSS V3.2 lower tropospheric temperature records from the MSU and AMSU microwave sounders. *Journal of Atmospheric and Oceanic Technology* 26:1492–1509.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Molina, M. et al. Reducing Abrupt Climate Change Risk Using the Montreal Protocol and Other Regulatory Actions to Complement Cuts in CO_2 Emissions. 2009. *Proceedings of the National Academy of Sciences* 106:20616–20621.

Molina, M., and L. Molina. 2004. Megacities and atmospheric pollution. *Journal of the Air Waste Management Association* 54:644–680.

Mostafaeipour, A. 2010. Productivity and Development Issues of Global Wind Turbine Industry. *Renewable and Sustainable Energy Reviews* 14:1048–1058. doi: 10.1016/j.rser.200910.031.

Mumford, J.L., et al. 1987. Lung cancer and indoor air pollution in Xuan Wei, China. *Science* 235:217–220.

Nanda, A.D. 2011. India's Environmental Trump Card: How Reducing Black Carbon Through Common But Differentiated Responsibilities Can Curb Climate Change. *Denver Journal of International Law and Policy* 39(3):523–552.

National Oceanic and Atmospheric Administration (NOAA). 2012. About NCDC. National Climate Data Center. Accessed 13 January 2013: http://www.ncdc.noaa.gov/oa/about/whatisncdc.html.

NOAA. 2008. Wind Average – Wind Speed – (MPH). National Climate Data Center. Accessed 13 January 2013: http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgwind.html.

NOAA. 2013. Monthly mean atmospheric CO_2 at Mauna Loa Observatory, Hawaii. Earth System Research Laboratory. Accessed 12 April 2013: http://www.esrl.noaa.gov/gmd/ccgg/trends/.

National Renewable Energy Laboratory (NREL). 2012. National Wind Technology Center. Accessed 13 April 2013: http://www.nrel.gov/wind/.

Nix, Gerald R. 1995. Wind Energy as a Significant Source of Electricity. *National Renewable Energy Laboratory*. Prepared for: 18th World Energy Engineering Conference. Atlanta, Georgia. November 8-10, 1995.

NREL. 2013a. Wind Maps. Accessed 13 April 2013: http://www.nrel.gov/gis/wind.html

NREL. 2013b. Wind Powering America, Installed Wind Capacity. Accessed 13 April 2013: http://www.windpoweringamerica.gov/wind_installed_capacity.asp.

National Research Council. 2010. *Advancing the Science of Climate Change*. Washington, DC: The National Academies Press. Accessed 12 April 2013: http://dels.nas.edu/resources/static-assets/materials-based-on-reports/reports-in-brief/Science-Report-Brief-final.pdf.

Nordic Council of Ministers. 2012. Svalbard Declaration on Shortlived Climate Forcers. Accessed 13 April 2013, http://www.norden.org/en/nordic-council-of-ministers/councils-of-ministers/nordic-council-of-ministers-for-the-environment-mr-m/declarations-and-statements/svalbard-declaration-on-shortlived-climate-forcers.

O'Brien, K.L., and R.M. Leichenko. 2000. Double exposure: Assessing the impacts of climate change within the context of economic globalization. *Global Environmental Change* 10:221–232.

O'Brien, K.L., and R.M. Leichenko. 2003. Winners and Loser in the Context of Global Change. *Annals of the Association of American Geographers* 93(1):89–103.

O'Neill, M.S. et al. 2005. Diabetes enhances vulnerability to particulate air pollution-associated impairment in vascular reactivity and endothelial function. *Circulation* 111:2913–2920.

Oak Ridge National Laboratory. 2012. *Wind ENergy Data and Information (WENDI)*. Originally Accessed 12 August 2012, Accessed 20 March 2013. http://windenergy.ornl.gov/node/1.

Pacala, S., and R. Socolow. 2004. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years With Current Technologies. *Science* 305:968–972 and supporting online material 1-53.

Pašičko, R., Č. Branković, and Z. Šimić. 2012. Assessment of climate change impacts on energy generation from renewable sources in Croatia. *Renewable Energy* 46:224–231. doi: 10.1016/j.renene.2012.03.029.

Pryor, S.C., and R. J. Barthelmie. 2010. Climate Change Impacts on Wind Energy: A Review. *Renewable and Sustainable Energy Reviews* 14:430–437. doi: 10.1016/j.rser.2009.07.028.

Pryor, S.C., and R. J. Barthelmie. 2011. Assessing climate change impacts on the near-term stability of wind energy resource over the United States. *Proceedings of the National Academy of Sciences* 108:8167–8171. doi: 10.1073/pnas.1019388108/-/DCSupplemental.

Pryor, S.C., J.T. Schoof, and R. J. Barthelmie. 2006. Winds of Change? Projections of Near-Surface Winds Under Climate Change Scenarios. *Geophysical Research Letters* 33:1–5. doi: 10.1029/2006GL026000.

Pryor, S.C., J.T. Schoof, and R.J. Barthelmie. 2005. Climate Change Impacts on Wind Speeds and Wind Energy Density in Northern Europe: Empirical Downscaling of Multiple AOGCMs. *Climate Research* 29:183–198. doi: 10.3354/cr029183.

Pryor, S.C., R. J. Barthelmie, D. T. Young, E.S. Takle, R.W. Arritt, D. Flory, W.J. Gutowski Jr., A. Nunes, and J. Roads. 2009. Wind Speed Trends Over the Contiguous United States. *Journal of Geophysical Research* 114:1–18. doi: 10.1029/2008JD011416.

Qiao,L. 2012. *China Wind Energy Development Update 2012*. Global Wind Energy Council. Accessed 14 April 2013, http://www.gwec.net/china-wind-market-update/.

Ramanthan, V. 1981. The role of ocean-atmosphere interactions in the CO_2 climate problem. *Journal of Atmospheric Science* 38:918–930.

Ramanthan, V., and G. Carmichael. 2008. Global and regional climate changes due to black carbon. *Nature Geoscience* 1:221–227.

Rasmussen, C.J., T. Holloway, and G.F. Nemet. 2011. Opportunities and challenges in assessing climate change impacts on wind energy—a critical comparison of wind speed projections in California. *Environmental Research Letters* 6:1–9. doi: 10.1088/1748-9326/6/2/024008.

Rebbi, C. 2005. Principles of Physics: Lecture 11, Boston University. Accessed 13 April 2013. http://physics.bu.edu/~rebbi/py251_lect11.pdf.

Ren, D. 2010. Effects of Global Warming on Wind Energy Availability. *Journal of Renewable Sustainable Energy* 2:052301-052301-5. doi: 10.1063/1.3486072.

Rodman, L.C., and R.K. Meentemeyer. 2006. A geographic analysis of wind turbine placement in Northern California. *Energy Policy* 34:2137–2149.

Roney, J. Matthew. 2012. World Wind Power Climbs to New Record in 2011. *Earth Policy Institute*, March 14, 2012. Accessed 13 April 2013. http://www.earth-policy.org/indicators/C49/wind_power_2012.

Rosenweig, C., et al. 2007. Assessment of Observed Changes and Responses in Natural and Managed Systems. In M.L. Parry et al. (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 79–131. United Kingdom: Cambridge University Press. Accessed 13 April 2013. http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter1.pdf.

Sahin, A.D. 2004. Progress and recent trends in wind energy. *Progress in Energy and Combustion Science* 30:501–543. doi: 10.1016/j.pecs.2004.04.001.

Saidur R., et al. 2010. A Review on Global Wind Energy Policy. *Renewable and Sustainable Energy Reviews* 14:1744–1762. doi: 10.1016/j.rser.2010.03.007.

Schmidt, C.W. The Dark Horse of Climate Change Drivers. *Environmental Health Perspectives* 119:172–175.

Seddon, J., and V. Ramanathan. 2009. The Other Climate Changers. *Foreign Affairs* 88(5):105–113.

Sen, Z. 2000. Rüzgar turbine tarihi gelişme süreci. UTES, Istanbul, Turkey, III:375-384.

Sen, Z. 2001. Water robotics during the twelth century and Abou-l-iz-al-Jazari case. *International Water History Association Conference*, Bergen, Norway.

Sesto, E., and C. Casale. 1998. *Exploitation of wind as an energy source to meet the world's electricity demand. Journal of Wind Engineering.* 74-76:375–387.

Shindell, D., and G. Faluvegi. 2009. Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience* 2:294–300.

Snel, H. 1998. Review of the present status of rotor aerodynamics. *Wind Energy* 1:46–69.

Stacey, A. 2011. Stabilization wedges. The Azimuth Project. Updated 7 November 2011, Accessed 13 April 2013: http://www.azimuthproject.org/azimuth/show/Stabilization+wedges.

Steiner, A., and M. Jarruaud. 2011. *Integrated Assessment of Black Carbon and Troposhperic Ozone*. World Meterological Organization and the United Nations Environment Programme.

The National Energy Education Development (NEED) Project. 2008. Energy on Public Lands. *funding and technical assistance from the Bureau of Labor Management and the U.S. Department of the Interior*: 1-27.

Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tan, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden, and P. Zhai. 2007. Observations: surface and atmospheric climate change. In S. Solomon et al. (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 235–336. New York: Cambridge University Press.

U.S. Department of Energy (DOE). 2012. *2011 Wind Technologies Market Report*.

U.S. DOE. 2011. *2011 History of Wind Energy.* Accessed 13 April 2013, http://www1.eere.energy.gov/wind/wind_history.html.

U.S. Environmental Protection Agency. 2009. *Integrated Science Assessment for Particulate Matter (Final Report).* Washington, DC. EPA/600/R-08/139F.

United Nations Environment Programme. 2013. *Cookstove in Kenya, A local solution to a global problem*. Accessed: 12 April 2013, http://www.unep.org/tunza/youth/Actions/CookStoveinKenyaalocalsolutiontoaglobal/tabid/6289/Default.aspx.

United Nations Framework Convention on Climate Change, art. 3(1), 9 May 1992, 31 I.L.M. 849.

University of Texas. 2013. *General Atmospheric Circulation*. Accessed 12 April 2013: http://research.utep.edu/Default.aspx?tabid=36037.

Vautard, R., M. D. Moran, E. Solazzo, R. C. Gilliam, V. Matthias, R. Bianconi, C. Chemel, J. Ferreira, B. Geyer, A. B. Hansen, A. Jericevic, M. Prank, A. Segers, J. D. Silver, J. Werhahn, R. Wolke, S. T. Rao, and S. Galmarini. 2012. Evaluation of the meteorological forcing used for the Air Quality Model Evaluation InternationaI Initiative (AQMEII) air quality simulations. *Atmospheric Environment* 53:15-37. doi:10.1016/j.atmosenv.2011.10.065.

Vautard, R., T.R. McVicar, J.-N. Thépaut, and M.L. Roderick. 2012. Surface Winds: Land surface winds and atmospheric evaporative [in State of the Climate 2012]. *Bulletin of the American Metrological Society* 93(7):S36–S38.

Venkataraman, C., G. Habib, N. Lam, and K. Smith. 2010. The Indian national initiative for advanced biomass cookstoves: the benefits of clean combustion. *Energy for Sustainable Development* 14(2):63–72.

Vermont Environmental Research Associates, Inc. 2003. *Estimating the Hypothetical Wind Power Potential on Public Lands in Vermont*. Vermont Department of Public Service.

Walker, J.F., and N. Jenkins. 1997. *Wind Energy Technology*. Chichester, UK: Wiley.

Wallenstein, T. 2003. *From Climate to Cookstoves: An Analysis of Black Carbon Reduction Policies*. New York: Columbia University.

Watson, J.G., J.C. Chow, and L. Chen. 2005. Summary of organic and elemental carbon/black carbon analysis methods and intercomparisons. *Aerosol and Air Quality Research* 5(1):65–102.

Zaelke, D., and D. Clare. 2009. *Reducing Black Carbon May Be the Fastest Strategy for Slowing Climate Change*. Institute for Governance & Sustainable Development.

Zhi, G., Z. Guorui, X. Zhang, H. Cheng, J. Jin, F. Zhang, T. Wang, and X. Zhang. 2011. Practical Paths Towards Lowering Black Carbon Emissions. *Advances in Climate Change Research* 2:12–22.