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A Systems Approach To Sustainable Energy Portfolio Development

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A SYSTEMS APPROACH TO SUSTAINABLE ENERGY PORTFOLIO DEVELOPMENT

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ABSTRACT

Adequate energy supply has become one of the vital components of human development and economic growth of nations. In fact, major components of the global economy such as transportation services, communications, industrial processes, and construction activities are dependent on adequate energy resources. Even mining and extraction of energy resources, including harnessing the forces of nature to produce energy, are dependent on accessibility of sufficient energy in the appropriate form at the desired location. Therefore, energy resource planning and management to provide appropriate energy in terms of both quantity and quality has become a priority at the global level. The increasing demand for energy due to growing population, higher living standards, and economic development magnifies the importance of reliable energy plans. In addition, the uneven distribution of traditional fossil fuel energy sources on the Earth and the resulting political and economic interactions are other sources of complexity within energy planning. The competition over fossil fuels that exists due to gradual depletion of such sources and the tremendous thirst of current global economic operations for these sources, as well as the sensitivity of fossil fuel supplies and prices to global conditions, all add to the complexity of effective energy planning.

In addition to diversification of fossil fuel supply sources as a means of increasing national energy security, many governments are investing in non-fossil fuels, especially renewable energy sources, to combat the risks associated with adequate energy supply. Moreover, increasing the number of energy sources also adds further complication to energy planning. Global warming, resulting from concentration of greenhouse gas emissions in the atmosphere, influences energy infrastructure investments and operations management as a result of international treaty

obligations and other regulations requiring that emissions be cut to sustainable levels. Burning fossil fuel, as one of the substantial driving factors of global warming and energy insecurity, is mostly impacted by such policies, pushing forward the implementation of renewable energy polices. Thus, modern energy portfolios comprise a mix of renewable energy sources and fossil fuels, with an increasing share of renewables over time. Many governments have been setting renewable energy targets that mandate increasing energy production from such sources over time. Reliance on renewable energy sources certainly helps with reduction of greenhouse gas emissions while improving national energy security. However, the growing implementation of renewable energy has some limitations. Such energy technologies are not always as cheap as fossil fuel sources, mostly due to immaturity of these energy sources in most locations as well as high prices of the materials and equipment to harness the forces of nature and transform them to usable energy. In addition, despite the fact that renewable energy sources are traditionally considered to be environmentally friendly, compared to fossil fuels, they sometimes require more natural resources such as water and land to operate and produce energy. Hence, the massive production of energy from these sources may lead to water shortage, land use change, increasing food prices, and insecurity of water supplies. In other words, the energy production from renewables might be a solution to reduce greenhouse gas emissions, but it might become a source of other problems such as scarcity of natural resources.

The fact that future energy mix will rely more on renewable sources is undeniable, mostly due to depletion of fossil fuel sources over time. However, the aforementioned limitations pose a challenge to general policies that encourage immediate substitution of fossil fuels with renewables to battle climate change. In fact, such limitations should be taken into account in

developing reliable energy policies that seek adequate energy supply with minimal secondary effects.

Traditional energy policies have been suggesting the expansion of least cost energy options, which were mostly fossil fuels. Such sources used to be considered riskless energy options with low volatility in the absence of competitive energy markets in which various energy technologies are competing over larger market shares. Evolution of renewable energy technologies, however, complicated energy planning due to emerging risks that emanated mostly from high price volatility. Hence, energy planning began to be seen as investment problems in which the costs of energy portfolio were minimized while attempting to manage associated price risks. So, energy policies continued to rely on risky fossil fuel options and small shares of renewables with the primary goal to reduce generation costs. With emerging symptoms of climate change and the resulting consequences, the new policies accounted for the costs of carbon emissions control in addition to other costs. Such policies also encouraged the increased use of renewable energy sources. Emissions control cost is not an appropriate measure of damages because these costs are substantially less than the economic damages resulting from emissions. In addition, the effects of such policies on natural resources such as water and land is not directly taken into account. However, sustainable energy policies should be able to capture such complexities, risks, and tradeoffs within energy planning. Therefore, there is a need for adequate supply of energy while addressing issues such as global warming, energy security, economy, and environmental impacts of energy production processes. The effort in this study is to develop an energy portfolio assessment model to address the aforementioned concerns.

This research utilized energy performance data, gathered from extensive review of articles and governmental institution reports. The energy performance values, namely carbon footprint, water footprint, land footprint, and cost of energy production were carefully selected in order to have the same basis for comparison purposes. If needed, adjustment factors were applied. In addition, the Energy Information Administration (EIA) energy projection scenarios were selected as the basis for estimating the share of the energy sources over the years until 2035. Furthermore, the resource availability in different states within the U.S. was obtained from publicly available governmental institutions that provide such statistics. Specifically, the carbon emissions magnitudes (metric tons per capita) for different states were extracted from EIA databases, states' freshwater withdrawals (cubic meters per capita) were found from USGS databases, states' land availability values (square kilometers) were obtained from the U.S. Census Bureau, and economic resource availability (GDP per capita) for different states were acquired from the Bureau of Economic Analysis.

In this study, first, the impacts of energy production processes on global freshwater resources are investigated based on different energy projection scenarios. Considering the need for investing on energy sources with minimum environmental impacts while securing maximum efficiency, a systems approach is adopted to quantify the resource use efficiency of energy sources under sustainability indicators. The sensitivity and robustness of the resource use efficiency scores are then investigated versus existing energy performance uncertainties and varying resource availability conditions. The resource use efficiency of the energy sources is then regionalized for different resource limitation conditions in states within the U.S. Finally, a sustainable energy planning framework is developed based on Modern Portfolio Theory (MPT)

and Post-Modern Portfolio Theory (PMPT) with consideration of the resource use efficiency measures and associated efficiency risks.

In the energy-water nexus investigation, the energy sources are categorized into 10 major groups with distinct water footprint magnitudes and associated uncertainties. The global water footprint of energy production processes are then estimated for different EIA energy mix scenarios over the 2012-2035 period. The outcomes indicate that the water footprint of energy production increases by almost 50% depending on the scenario. In fact, growing energy production is not the only reason for increasing the energy related water footprint. Increasing the share of water intensive energy sources in the future energy mix is another driver of increasing global water footprint of energy in the future. The results of the energies' water footprint analysis demonstrate the need for a policy to reduce the water use of energy generation. Furthermore, the outcomes highlight the importance of considering the secondary impacts of energy production processes besides their carbon footprint and costs. The results also have policy implications for future energy investments in order to increase the water use efficiency of energy sources per unit of energy production, especially those with significant water footprint such as hydropower and biofuels.

In the next step, substantial efforts have been dedicated to evaluating the efficiency of different energy sources from resource use perspective. For this purpose, a system of systems approach is adopted to measure the resource use efficiency of energy sources in the presence of trade-offs between independent yet interacting systems (climate, water, land, economy). Hence, a stochastic multi-criteria decision making (MCDM) framework is developed to compute the resource use efficiency scores for four sustainability assessment criteria, namely carbon

footprint, water footprint, land footprint, and cost of energy production considering existing performance uncertainties. The energy sources' performances under aforementioned sustainability criteria are represented in ranges due to uncertainties that exist because of technological and regional variations. Such uncertainties are captured by the model based on Monte-Carlo selection of random values and are translated into stochastic resource use efficiency scores. As the notion of optimality is not unique, five MCDM methods are exploited in the model to counterbalance the bias toward definition of optimality. This analysis is performed under "no resource limitation" conditions to highlight the quality of different energy sources from a resource use perspective. The resource use efficiency is defined as a dimensionless number in scale of 0-100, with greater numbers representing a higher efficiency. The outcomes of this analysis indicate that despite increasing popularity, not all renewable energy sources are more resource use efficient than non-renewable sources. This is especially true for biofuels and different types of ethanol that demonstrate lower resource use efficiency scores compared to natural gas and nuclear energy. It is found that geothermal energy and biomass energy from miscanthus are the most and least resource use efficient energy alternatives based on the performance data available in the literature. The analysis also shows that none of the energy sources are strictly dominant or strictly dominated by other energy sources.

Following the resource use efficiency analysis, sensitivity and robustness analyses are performed to determine the impacts of resource limitations and existing performance uncertainties on resource use efficiency, respectively. Sensitivity analysis indicates that geothermal energy and ethanol from sugarcane have the lowest and highest resource use efficiency sensitivity, respectively. Also, it is found that from a resource use perspective,

concentrated solar power (CSP) and hydropower are respectively the most and least robust energy options with respect to the existing performance uncertainties in the literature.

In addition to resource use efficiency analysis, sensitivity analysis and robustness analysis, of energy sources, this study also investigates the scheme of the energy production mix within a specific region with certain characteristics, resource limitations, and availabilities. In fact, different energy sources, especially renewables, vary in demand for natural resources (such as water and land), environmental impacts, geographic requirements, and type of infrastructure required for energy production. In fact, the efficiency of energy sources from a resource use perspective is dependent upon regional specifications, so the energy portfolio varies for different regions due to varying resource availability conditions. Hence, the resource use efficiency scores of different energy technologies are calculated based on the aforementioned sustainability criteria and regional resource availability and limitation conditions (emissions, water resources, land, and GDP) within different U.S. states, regardless of the feasibility of energy alternatives in each state. Sustainability measures are given varying weights based on the emissions cap, available economic resources, land, and water resources in each state, upon which the resource use efficiency of energy sources is calculated by utilizing the system of systems framework developed in the previous step. Efficiency scores are graphically illustrated on GIS-based maps for different states and different energy sources. The results indicate that for some states, fossil fuels such as coal and natural gas are as efficient as renewables like wind and solar energy technologies from resource use perspective. In other words, energy sources' resource use efficiency is significantly sensitive to available resources and limitations in a certain location.

Moreover, energy portfolio development models have been created in order to determine the share of different energy sources of total energy production, in order to meet energy demand, maintain energy security, and address climate change with the least possible adverse impacts on the environment. In fact, the traditional "least cost" energy portfolios are outdated and should be replaced with "most efficient" ones that are not only cost-effective, but also environmentally friendly. Hence, the calculated resource use efficiency scores and associated statistical analysis outcomes for a range of renewable and nonrenewable energy sources are fed into a portfolio selection framework to choose the appropriate energy mixes associated with the risk attitudes of decision makers. For this purpose, Modern Portfolio Theory (MPT) and Post-Modern Portfolio Theory (PMPT) are both employed to illustrate how different interpretations of "risk of return" yield different energy portfolios. The results indicate that 2012 energy mix and projected world's 2035 energy portfolio are not sustainable in terms of resource use efficiency and could be substituted with more reliable, more effective portfolios that address energy security and global warming with minimal environmental and economic impacts.

To my family. Without their support this work was not possible

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CHAPTER 1: INTRODUCTION

1.1   Overview

With the world population increasing by more than 1.2 percent per year and the failure of the traditional economic systems to respond to growing global demands, the increasing scarcity of natural resources, global climate change, hunger, and other social and environmental issues, many governments are striving to substitute the inefficient conventional and long-established development and production policies with more effective ones to address the aforementioned concerns in a sustainable manner. The existing situation has emerged as the consequence of economic activities designed to maximize economic prosperity based on the fast paced consumption of natural resources, regardless of the secondary effects imposed by such practices on the environment. Continuance of this trend is found to be unsustainable as the associated natural resources consumption rate is much faster than the regeneration rate, which will ultimately result in an economic downturn. As a result, moving toward sustainability to address the needs of the current generation while minimizing effects on the environment to preserve it for future generations has become a global concern in recent years.

To have sustainable development, energy is of a particular importance as all the mechanisms and infrastructures within a society need some sort of energy to operate. In fact, energy as the essential part of the whole system provides the basis for other system components to supply goods and services to society. As a result, moving toward sustainability requires sustainable energy development plans as well, in order to produce and supply the demanded energy levels with acceptable environmental, economic, and social effects.

Traditionally, conventional fossil fuels including oil, coal, and natural gas, have been the major source of energy production for industrial, residential, commercial, transportation, and electric power sectors worldwide. Oil has been mostly used in the transportation and industrial sectors; coal has been the primary fuel option to produce electricity; and natural gas has been providing energy to the industrial, residential, commercial, and electric power sectors. These fossil fuels, however, are becoming less accessible for extraction and new reserves are becoming harder to find. As a result, the dependency of the current energy systems on limited fossil fuel resources endangers the national energy security of many countries (UNEP, 2011). In addition, fossil fuel resources are not diverse enough. There are many areas around the globe with no access to adequate fossil fuel reserves, where demands are fulfilled with imports. This makes national energy supply plans highly uncertain and insecure as fossil fuel supply quantities are a function of many variables including but not limited to the political relations, economic situations, laws and regulations, and the national development plans of the involved countries. Moreover, climate change resulting from the concentration of greenhouse gas emissions from burning of fossil fuels has been recognized as one of the obstacles to sustainable development and planning (USAID, 2011; McDonald, 2006), resulting in different health and environmental problems.

Because of the aforementioned reasons, various countries all around the world have been developing policies in an attempt to control climate change and preserve the national energy security. As a result, national energy policy plans are promoting the more easily accessible renewable energy sources, among which the most popular technologies are hydropower plants, onshore and offshore wind power plants, solar thermal and photovoltaic energy, ocean energy,

biomass and biofuels, and geothermal power plants. Figure 1.1 shows the past and projected generation capacities for different renewable and nonrenewable energy sources under different EIA scenarios (EIA, 2011): reference (R); high oil prices (HOP); traditional high oil prices (THOP); low oil prices (LOP); traditional low oil prices (TLOP).
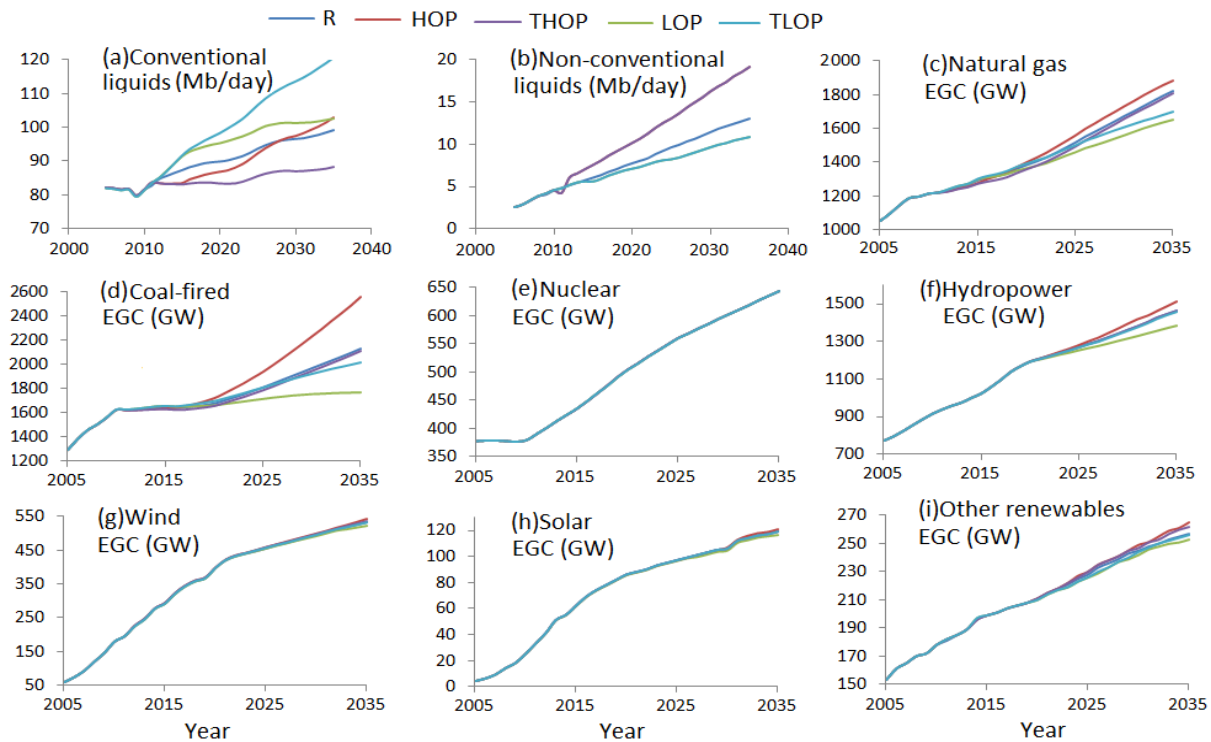
Figure 1.1: Energy generation capacity, 2005-2035 (adapted from Mirchi et al., 2012)

As illustrated in Figure 1.1, the renewables' share of total energy production is increasing rapidly on a global scale. In comparison with fossil energy sources, such renewables are known to be environmental- friendly because of lower emissions. Hence, the immediate substitution of renewables for fossil fuels is encouraged by most of the recent energy polices. Emerging policies are more inclined toward renewables in the future, so the energy mix resulting from those policies includes a combination of both fossil fuels and renewables, with the share of the renewables increasing gradually over time. Nevertheless, such policies largely ignore unintended

consequences, especially with respect to their effects on other valuable natural resources (e.g., water and land) in the long run.

Moving toward a sustainable future requires the actions taken to solve environmental problems be rich enough to address the problem, taking into account these actions' shortcomings and possible undesirable feedbacks. In the case of renewable sources of energy, how could it be justified to invest on a technology that produces close to zero carbon dioxide yet demands considerable amounts of natural resources and huge financial backup over a long time? Although such policies might be effective to reduce greenhouse gas emissions and the resulting global warming in the long run, they might have secondary impacts on other components of the ecosystem, namely water and land. Some renewables such as hydropower and biomass consume more water than others and some of them such as the ethanol and biomass require large land areas to produce energy. These secondary impacts are barriers to sustainable development as the pressure on a component of the ecosystem yields to the failure of that component and eventually, the collapse of the whole system. This is especially true for those ecosystem components that have already been under pressure because of other human activities. The secondary impacts on other ecosystem components might be so severe to nullify the advantages of the aforementioned policies. As a result, the general policy of substituting renewables for fossil fuels might not be effective unless the other impacts are also taken into consideration. In fact, we need to replace conventional energy sources with renewables ultimately, as the current world's energy profile is unsustainable in terms of energy security and environmental impacts. However, developing an efficient future energy mix that addresses energy security, climate change, environmental impacts, and energy diversity all together is an objective that best supports the needs of society.

The main question to be answered in this research becomes "***how to develop a sustainable energy portfolio with respect to the economic and environmental criteria, data and performance uncertainties, and risk attitudes and expected utilities?***"

1.2   Research Objectives

This research focuses on measuring the resource use efficiency of different energy sources with respect to sustainability indicators in the presence of uncertainty, evaluating the variability of energy sources efficiency based on resource limitations, measuring the variability of resource use efficiency scores due to existing uncertainties, evaluating the regionalized resource use efficiency of energy alternatives, and developing a sustainable energy portfolio development framework. The detailed objectives were achieved by the following main procedures:

1. Collecting the energy sources performance values under sustainability criteria; carbon footprint, water footprint, land footprint, and costs of energy production. Data are represented in ranges to reflect the technological and regional variations of energy sources performance values.

2. Measuring the impacts of current energy policies and future projections on global water resources.

3. Developing a system of systems framework for multi-criteria evaluation of energy sources efficiency:

    a. Developing a stochastic multi-criteria assessment framework for measuring the resource use efficiency scores of the energy sources;

b. Evaluating the sensitivity of energy source resource use efficiency scores for varying resource limitation conditions.

c. Evaluating the robustness of resource use efficiency scores for performance uncertainties of existing energy sources'.

4. Evaluating the resource use efficiency of the energy sources under different regional resource limitation patterns:

a. Collecting the states' carbon emissions, freshwater withdrawals, available land, and GDP values;

b. Weighting the resource use efficiency analysis criteria based on the availability of resources in each state;

c. Calculating the resource use efficiency of energy sources within the U.S.

5. Developing Energy portfolios with consideration of sustainability;

a. Developing sustainable energy portfolios based on Modern Portfolio Theory (MPT);

b. Developing sustainable energy portfolios based on Post-Modern Portfolio Theory (PMPT).

1.3   Dissertation Organization

The dissertation is organized as follows: following this overview chapter, chapter 2 investigates the impacts of the current energy policies and future energy projections on global water resources. Chapter 3 presents the fundamentals of resource use efficiency analysis based on sustainability measures in uncertain conditions. This chapter provides details of the efficiency assessment method as well as the sensitivity and robustness analyses of resource use efficiency

of energy sources'. Chapter 4 discusses the impacts of regional resource availability and limitation conditions on the preference toward different energy sources from a resource use perspective. In this chapter, the resource use efficiency scores are calculated for the states within United States of America based on the resource limitations in each state. Chapter 5 presents the proposed solutions to sustainable energy portfolio development based on the resource use efficiency scores and associated risks. This chapter discusses different portfolio theories (Modern Portfolio Theory and Post-Modern Portfolio Theory) to develop energy portfolios. Finally, chapter 6 concludes the research efforts, findings, and future recommendations of this work.

1.4   References

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CHAPTER 2: THE WATER DEMAND OF ENERGY

2.1   Introduction

Population growth is one of the main (if not the main) drivers of energy demand in the future. In the last century, water use rate almost doubled the population growth rate (World Bank, 2010). Under business-as-usual scenarios, the global energy consumption is estimated to rise from 77 million BTU per capita in 2012 to 91 million BTU per capita in 2035. So, the energy required for food production, water extraction, treatment, and transfer, education, industrial, residential, and commercial purposes, etc. is estimated to increase by more than 40% over the next 23 years (EIA, 2011). In addition to the potential technological, socioeconomic, political, and geographic challenges for generation, transmission, and supply of energy, substantial quantities of environmental resources required for producing energy are becoming a major concern for policy makers. Currently, human activities demand for natural resources such as freshwater, forests, fisheries and other ecosystems more than any other time in history (UNEP, 2007). As a result of such activities, ecological footprint exceeded biocapacity by 44% in 2006 and is estimated to exceed the biocapacity by 100% in 2030 (Global Footprint Network, 2010), meaning that the available environmental resources are approaching the breaking point (Wolf, 2010), leading to scarcity of such resources with reasonable quality.

With the experience of global warming as an unintended consequence of poorly developed energy production policies, reducing greenhouse gas (GHG) emissions has become an important priority in energy policy development, shifting the focus towards low-carbon energy production through alternative sources. The political and economic importance of energy security and

independence has been another incentive for investment in alternative sources of energy worldwide. While most renewable energy sources can help reducing GHGs, they also have some disadvantages (Brower, 1992; Abbasi and Abbasi, 2000; Madani et al., 2011, Hadian et al., 2012; Clarke, 2012). For example, some renewable energy sources require a considerable amount of valuable natural resources such as water and land. Hence, the potential impacts of energy generation on the environment and natural resources should be taken into account in developing global, national, and sub-country level energy policies and regulations to protect the already stressed ecosystem components more wisely while producing sufficient energy.

Water is an essential element in many human-driven processes, including energy generation. The agricultural water sector currently has the highest water demand at the global scale, followed by the energy and industrial sector that is responsible for 20% of the total water withdrawals (U.N. Water, 2012a). In the U.S., the energy sector is expected to be the fastest growing water consuming sector, being responsible for 85% of the increase in domestic water consumption in the 2005-2030 period (Carter, 2010). U.S. Governmental ethanol subsidies and mandates in the U.S. lead to considerable use of biofuels that have 70-400 times higher water footprint compared to traditional energy sources (Gerbens-Leenes et al., 2009). In some regions such as California, expanding the energy production from bioenergy requires 1,000 times more water than gasoline production (Fingerman et al., 2010). Hydrofracking, as another popular energy supply alternative, has been recognized as a high water-intensive series of actions that impact the surface water and ground water in both site creation and drilling processes (EPA, 2012). Regular oil and gas production processes also require water for drilling and extraction of resources (DOE, 2006). Large-scale hydroelectric power as one of the oldest renewable energy sources has a

relatively high water footprint (Gerbens-Leenes et al., 2009), mostly pertaining to the evaporation from large reservoir areas (Mekonnen and Hoekstra, 2012). The amount of water that is evaporated on a daily basis from hydroelectric reservoirs across the U.S. is enough to meet demands of 50 million people (Wilson and Leipzig, 2012). In coal and nuclear power plants, a large amount of water is circulated for cooling purposes, part of which goes back to the energy production system for reuse (World Nuclear Association, 2013) and the rest is evaporated or discharged into the original source, causing a range of environmental issues such as fish mortality and algae growth. Nuclear, coal, and natural gas power plants are the fastest growing freshwater users in the U.S., being responsible for more than half of the total freshwater withdrawals from different sources (Wilson, 2012). Concentrating Solar Power (CSP) also requires a considerable amount of water to spin steam turbines (Carter and Campbell, 2009). Other energy sources or energy production processes also require different levels of water supply. For instance, wind power and solar photovoltaic are generally known to be very environmentally friendly with no water footprint. However, the amount of water required in the manufacturing process may become considerable with large-scale implementation of these energy technologies, especially in places where technology is still immature or inefficient. In addition, these technologies require coal, nuclear, or natural gas backup to guarantee the sufficient supply of energy when wind or sun is not available (Schlesinger and Hirsch, 2009; Vartabedian, 2012) leading to more water use for cooling purposes.

Water is a global resource, distributed unevenly throughout the planet. This makes effective management of this valuable resource very complex at the national scale, especially with consideration of the virtually imported and exported water through global economic trades

(Hoekstra and Hung, 2012). International trade of energy in different forms such as oil, natural gas, coal, and biofuels, as well as the exchange of energy production technologies such as wind turbines and solar panels place pressure on global water resources. Quantifying the amount of water that goes into the energy sector at a global scale can help us better understand the risks associated with developing myopic energy management plans that ignore the effects of energy production on valuable natural resources. Water footprint is a reliable measure for this purpose and represents the amount of freshwater used to produce one unit of energy from a given energy source (Hoekstra and Hung, 2012). The components of water footprint are: blue water footprint, which is the volume of surface and ground water consumed in the energy production process; green water footprint, which represents the volume of rainwater consumed during the production process (related to evapotranspiration and the rainwater incorporated in crop or wood); and grey water footprint, which represents the amount of freshwater required to dilute the pollutants such that the quality of water remains above water quality standards. In fact, the water footprint index can take into account the direct and indirect water consumption in the energy production lifecycle. Past studies have acknowledged the necessity for calculating the water impact of different energy technologies. Gleick calculated the water consumption of different forms of energy, and his findings were the basis for many recent studies on the water footprint of energy (Gleick, 1994). Jacobson estimated the impacts of different renewable and nonrenewable energy technologies including their water footprint, based on which a multi-criteria decision making model was created to evaluate the efficiency of different energy sources (Jacobson, 2009). Gerbens-Leenes et al. calculated the water footprint of different types of biomass and concluded that large-scale production of biomass requires extensive amounts of water, leading to

unintended competition between "water for energy" and "water for food" (Gerbens-Leenes, 2009).

Considering the water footprint of various energy sources, Cooper and Sehlke suggested that developing a sustainable energy policy is not feasible unless the water footprint and cost of energy production are considered in addition to carbon footprint (Cooper and Sehlke, 2012). Some studies have been focusing on the water use of the energy sector in different regions across the globe. For instance, Wilson et al. estimated the water footprint of electricity sector in the U.S. and concluded that an average kWh of electricity from different sources in the U.S. in 2009 required almost 42 gallons of water, more than 95 percent of which was gray water footprint, associated with water quality effects of electricity production (Wilson and Leipzig, 2012). Macknick et al. reviewed the existing literature on water consumption and withdrawal for the U.S. electricity generating technologies and concluded that solar thermal and coal have the highest water consumption while non-thermal renewables such as wind and solar photovoltaic have the lowest water consumption (Macknick et al., 2012). Meldrum et al. reviewed and classified the existing literature of electricity's water withdrawal and water consumption for different energy technologies and concluded that the water used for cooling purposes dominated the life cycle water use of electricity generation. They also reported solar photovoltaic and wind as the lowest water consuming energy technologies, and thermoelectricity as the highest water consuming energy (Meldrum et al., 2013). Averyt et al. evaluated the water withdrawal and consumptive use of power plants in the U.S. (including ocean and fresh water) and observed substantial difference between the obtained results and EIA estimations, mostly due to imperfect assumptions and misreported information regarding power plants (Averyt, 2013).

In fact, estimation of future water demands of the global energy sector comes with numerous uncertainties and limitations and is contingent upon many parameters, including but not limited to future international and national regulations, global warming, energy security issues, and technological and economic development of nations. In fact, even energy scenarios from different sources yield different energy mix projections due to different assumptions, projection scope, and purposes. Hence, calculation of the water that goes to the energy sector depends on what energy supply scenario and calculation assumptions are considered. For instance, according to the World Energy Council (WEC), the water consumption of energy sector rises from 1775 BCM in 2005 to 2012 BCM in 2035 (less than 15% increase) (WEC, 2010). However, according to the International Energy Agency (IEA), 66 BCM of water was consumed by energy sector in 2012, whereas this number changes to 135 BCM in 2035 (more than 100% increase) (IEA, 2012). The main reason for such a gap between these estimations is the different definitions of water consumption as well as different water impact measurement methods used by these sources. Hence, water consumption of the energy sector, is not a reliable measure for estimation of the total water impacted by the energy sector, leading to inconsistent misinforming estimations. Water footprint (Hoekstra and Hung, 2012), on the other hand, represents the total direct and indirect water use of the energy sector and yields more robust understanding of the water-energy nexus and associated policy insights.

In this chapter, five energy scenarios developed by the International Energy Outlook of the U.S. Energy Information Administration (EIA) and water footprint of different energy technologies are set as bases for estimating the total global water footprint of energy production processes over the 2012-2035 period.

2.2   Methods and Data

The water footprint of global energy is estimated for 10 categories of energy sources including conventional and unconventional liquids, biofuels, natural gas, coal, nuclear, hydroelectric power, solar, wind, geothermal, and other renewable energy sources under five EIA energy mix scenarios for the 2005-2035 period. These scenarios generally project energy consumption based on the conditions of current laws and regulations as well as the effects of oil prices on the global energy market (EIA, 2011).

The reference scenario (REF) represents a "business-as-usual" assumption for oil prices, demographic trends, and technology. It assumes a baseline world economic growth of 3.5% per year from 2008 to 2015 and 3.3% from 2015 to 2035. This scenario assumes that a barrel of light sweet crude oil will cost $125 in 2035 (EIA, 2012). The high oil price (HOP) and low oil price (LOP) scenarios consider the impacts of high and low non-OECD demand conditions. The high oil price scenario assumes a higher demand for liquid fuels with a lower global supply when compared to the reference scenario. This scenario assumes that a barrel of light sweet crude oil will rise to $200 (in 2009 U.S.D.) in 2035, making it 60% more expensive than the reference scenario. The low oil price scenario assumes a lower demand for liquid fuels and a higher global supply when compared to the reference scenario. This scenario assumes that a barrel of light sweet crude oil will decrease to $50 (in 2009 U.S.D.) in 2035, making it 60% less expensive than the reference scenario. The traditional high oil price (THOP) and low oil price (TLOP) scenarios assume the same economic growth as the reference scenario but account for the impact of alternative supply conditions (EIA, 2011). The key assumptions for these scenarios are summarized in Table 2.1.

Table 2.1: Summary of EIA energy scenarios

Scenario	Oil price per barrel in 2035 (2009 dollars)	Assumptions
REF	$125	OPEC's oil production remains about 42% of world's total liquid fuel production.
HOP	$200	Higher oil prices result from high demand for liquid fuels in non-OECD countries due to high economic growth.
LOP	$50	Lower oil prices result from low demand for liquid fuels in non-OECD countries due to low economic growth.
THOP	$200	OPEC countries reduce their production from the current rate, resulting in higher oil prices.
TLOP	$50	OPEC countries increase their production from the current rate, resulting in lower oil prices.

The water footprints of different energy sources are presented in Table 2.1. Some of the values in Table 2.1 are given as intervals due to the technological and other regional conditions, resulting in different estimations of water footprints. For instance, the solar energy might be produced using different technologies (solar thermal and solar photovoltaic) with different water footprint. Moreover, the efficiency of different production can be affected by local conditions (e.g. solar radiation), resulting in some estimation uncertainties.

Table 2.2: Water footprint of different energy sources

Energy Source	Water Footprint (m^3/GJ)
Conventional/ Unconventional Liquids	4.29-8.6 (Hill and Younos, 2007)
Biofuels	37-42 (Gerbens-Leenes et al., 2009)
Natural Gas	0.1 (Gleick, 1994)
Coal	0.15-0.58 (Hill and Younos, 2007)
Nuclear	0.42-0.76 (Jacobson, 2009)
Hydroelectric	22[a] (Gerbens-Leenes et al., 2009)
Solar	0.037-0.78 (Jacobson, 2009)
Wind	0.001 (Jacobson, 2009)
Geothermal	0.005 (Jacobson, 2009)
Other Renewables	78 (Gerbens-Leenes et al., 2009)

[a] Some studies estimate the water footprint of hydropower plants to be three times higher than this amount (Mekonnen and Hoekstra, 2002).

The EIA scenarios do not provide a detailed estimation of the shares of different energy sources from total energy production. Hence, a set of assumptions is required to calculate the shares of the energy alternatives from total energy production, as follows:

- "Conventional liquids" include crude oil and lease condensate, natural gas plant liquids, and refinery gain; "Unconventional liquids" include oil sands, extra-heavy oil, coal-to-liquids, gas-to-liquids, and shale oil (not including biofuels);

- "Solar energy" includes solar thermal and solar photovoltaic technologies;

- "Wind energy" includes wind onshore and offshore technologies;

- "Hydroelectric" energy is produced by large hydropower systems associated with large reservoirs only. While small and run-of-the-river run-of-the river hydropower systems have smaller water footprint, they have been excluded from the study due to lack of reliable information on their water footprint

- "Other renewables" include wave and tidal, municipal waste, and ethanol. The water footprint of "other renewables" is assumed to be equal to that of ethanol as it is more prevalent than others;

- The energy production values are assumed to be equal to the energy consumption values; and

- If neither production, nor consumption of energy is provided for a given renewable energy, the generating capacity share for that type of energy is considered to be equal to energy production/consumption share of that energy.

To determine the water footprint of conventional liquids, unconventional liquids, and biofuels, the world's total liquids production values given by EIA are used as a basis to calculate the shares of these energy sources from the future energy supply portfolios (EIA, 2011). In 2005, the world's total liquid production was 84.6 million barrels per day (mbpd), while the world's conventional liquids production in that year was 82.1 mbpd (97 % of conventional liquids production). To find the amount of conventional liquids consumed (165.75 quadrillion BTU), the percentage of conventional liquids production was multiplied by the total liquids energy consumption (170.8 quadrillion BTU). The values for unconventional liquids (including biofuels) and biofuels were also found to be 2.6 and 0.7 mbpd, respectively.

The energy production from hydroelectric power, solar energy, wind energy, geothermal, and other renewable energy sources are not explicitly listed in EIA tables and were calculated similar to the liquid energy sources. Due to absence of the production or consumption values of renewable energies, generation capacities were assumed to represent the shares of these resources. Hydropower, solar energy, wind energy, geothermal, and other renewables have 773,

4, 60, 8, and 145 GW of generation capacities, respectively. The percent installed generation capacity for each renewable source was found by dividing the installed generation capacity of that renewable by the total installed generation capacity of all renewables. The total renewable energy consumption value (45.4 quadrillion BTU) was multiplied by the percent installed generation capacity of the aforementioned energy sources to calculate the energy production from each source. The values of energy consumption from natural gas, coal, and nuclear energy were explicitly listed in the EIA tables, so no additional calculation was needed. Once the shares of different energy sources from the world's total energy production were calculated for different scenarios, the water footprint of energy mixes for EIA scenarios were estimated based on the water footprint of different energy technologies to examine how energy policies are evolving over time in terms of water consumption.

2.3   Results and Discussion

The main oil supply forecast classes, i.e., peak forecasts and quasi-linear forecasts identified by (Bentley et al., 2009) have been the basis for development of low and high oil production forecasts (Sorrell et al., 2010). Both forecast types indicate an increasing share for renewable energy sources in the future, but comparing to high oil production forecasts, low oil production scenarios assume a larger share of energy coming from renewables. According to Sorrell et al., EIA forecasts fall into the high oil production category in which the global oil production will continue to rise or will plateau around year 2030 (Sorrell et al., 2010). Table 2.3 shows the percent increase in total energy production from 2012 to 2035 based on EIA estimates (EIA, 2011).

Table 2.3: Percent increase in energy production for different energy sources from 2012 to 2035

Energy Source	% Increase from 2012 to 2035				
	REF	HOP	LOP	THOP	TLOP
Conventional Liquids	17	23	21	5	42
Biofuels	114	210	75	209	75
Unconventional Liquids	180	217	128	216	129
Natural Gas	45	57	31	46	42
Coal	38	68	15	38	33
Nuclear	71	72	70	72	70
Hydroelectric	64	77	51	67	64
Solar	212	231	198	220	212
Wind	154	167	142	157	154
Geothermal	124	143	109	127	115
Other Renewables	44	55	38	50	44

According to Table 2.3, energy production from all energy sources experiences a significant increase, implying the considerable energy demand increase in period of 2012-2035. Energy production from all sources except oil has the highest and lowest increase rates under high and low oil price scenarios, respectively. Although the energy production from most of the energy sources increases dramatically, the shares of different energy sources from the world's total energy production do not change exceedingly in the 2012-2035 period due to increase in total energy production. Figure 2.1 illustrates the estimated shares of energy sources from total energy production in 2012 and 2035 based on the reference scenario.
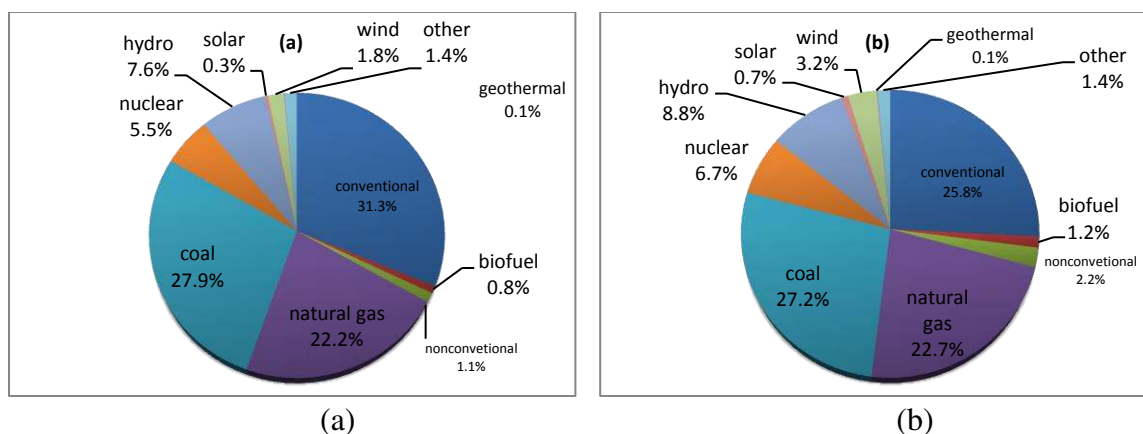
Figure 2.1: Shares of energy sources in world's total energy supply based on EIA reference scenario (a) 2012; (b) 2035.

In addition, Table 2.4 shows the estimated shares of different energy sources from the world's total energy production in 2012 and 2035 based on other energy scenarios (HOP, LOP, THOP, TLOP). Although the shares of energy sources under different scenarios do not vary significantly, as illustrated in Table 2.3, they have considerably different production magnitudes.

Table 2.4: Shares of energy sources in world's total energy supply based on EIA scenarios

Energy Source	HOP (%)		LOP (%)		THOP (%)		TLOP (%)	
	2012	2035	2012	2035	2012	2035	2012	2035
Conventional	31.0	24.2	31.3	28.8	31.1	23.3	31.3	30.4
Biofuels	0.7	1.5	0.7	1.0	0.7	1.6	0.7	0.9
Unconventional	1.5	3.1	1.2	2.1	1.5	3.4	1.2	1.8
Natural Gas	22.1	21.9	22.2	22.2	22.1	22.9	22.2	21.4
Coal	27.9	29.6	28.0	24.5	27.9	27.4	27.9	25.4
Nuclear	5.5	6.0	5.5	7.2	5.5	6.7	5.5	6.4
Hydroelectric	7.6	8.5	7.6	8.7	7.6	9.0	7.6	8.5
Solar	0.3	0.7	0.3	0.7	0.3	0.7	0.3	0.7
Wind	1.8	3.0	1.8	3.3	1.8	3.3	1.8	3.1
Geothermal	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1
Other Renewables	1.4	1.3	1.4	1.4	1.4	1.5	1.4	1.3

Figure 2.2 illustrates the global energy sector's water footprint in 2012. Figure 2.3 illustrates the percent increase in the world's total water footprint of energy consumption in 2020 and 2035 with respect to base values in 2012. The importance of year 2020 is that the energy targets and mandates for some regions such as member countries of the European Union are set for this year. Figure 2.3 indicates the future water use impacts of implemented energy policies in the future. In 2012, almost all scenarios have the same water footprint. In 2035, however, varying water use impact of different scenarios is noticeable, among which the HOP scenario has the highest impact in the future with 59%-66% higher water footprint than 2012. This is because under this scenario, the share of water-intensive energy sources such as hydropower, biofuels, and unconventional energy sources in the overall energy supply portfolio due to higher oil prices.
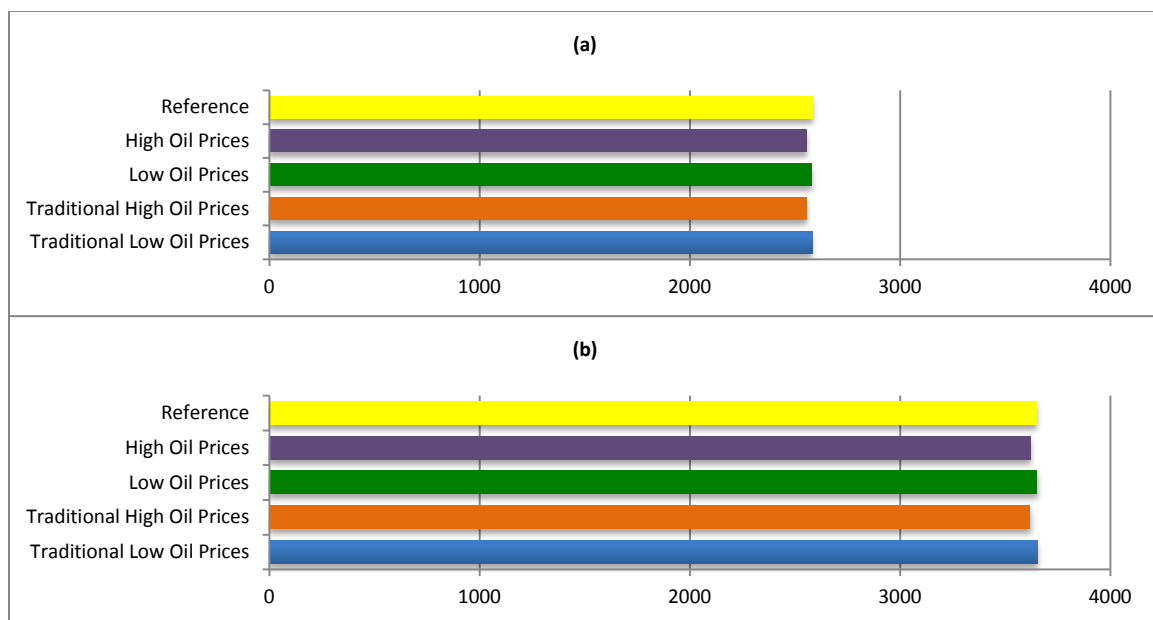
Figure 2.2: World's water footprint of energy consumption in billion cubic meters (BCM) (a) 2012 low estimation; (b) 2012 high estimation

According to Figure 2.3, the water footprint of the world's energy sector is projected to increase by at least 37% (LOP) and at most 66% (HOP) over the next two years, while the

available water resource for energy is shrinking due to increasing population and climatic changes.

Currently, the agricultural and domestic water sectors are responsible for 70% and 10% of the world's freshwater consumption, respectively, leaving 20% of the total available freshwater for the industry-energy sector (U.N. Water, 2012b). The increasing world population of 80 million people per year together with economic development implies increased freshwater demand in the future, putting more pressure on water resources worldwide. Based on this analysis, the amount of world's renewable water resources required by the energy sector increases from 4-7% in 2012 to 8-11% in 2035. This is of particular importance, if the world's renewable water resources remain unchanged and almost equal to the current 50,000 km^3 (Gleick, 1998; CIA, 2013) and the world needs more water and food for its increasing population. The estimated quantities, however, depend extensively on the shares of different energy sources, especially renewables, from the total energy production, which are not clear due to the uncertainties that exist with regard to the long-term evolution of different energy technologies.
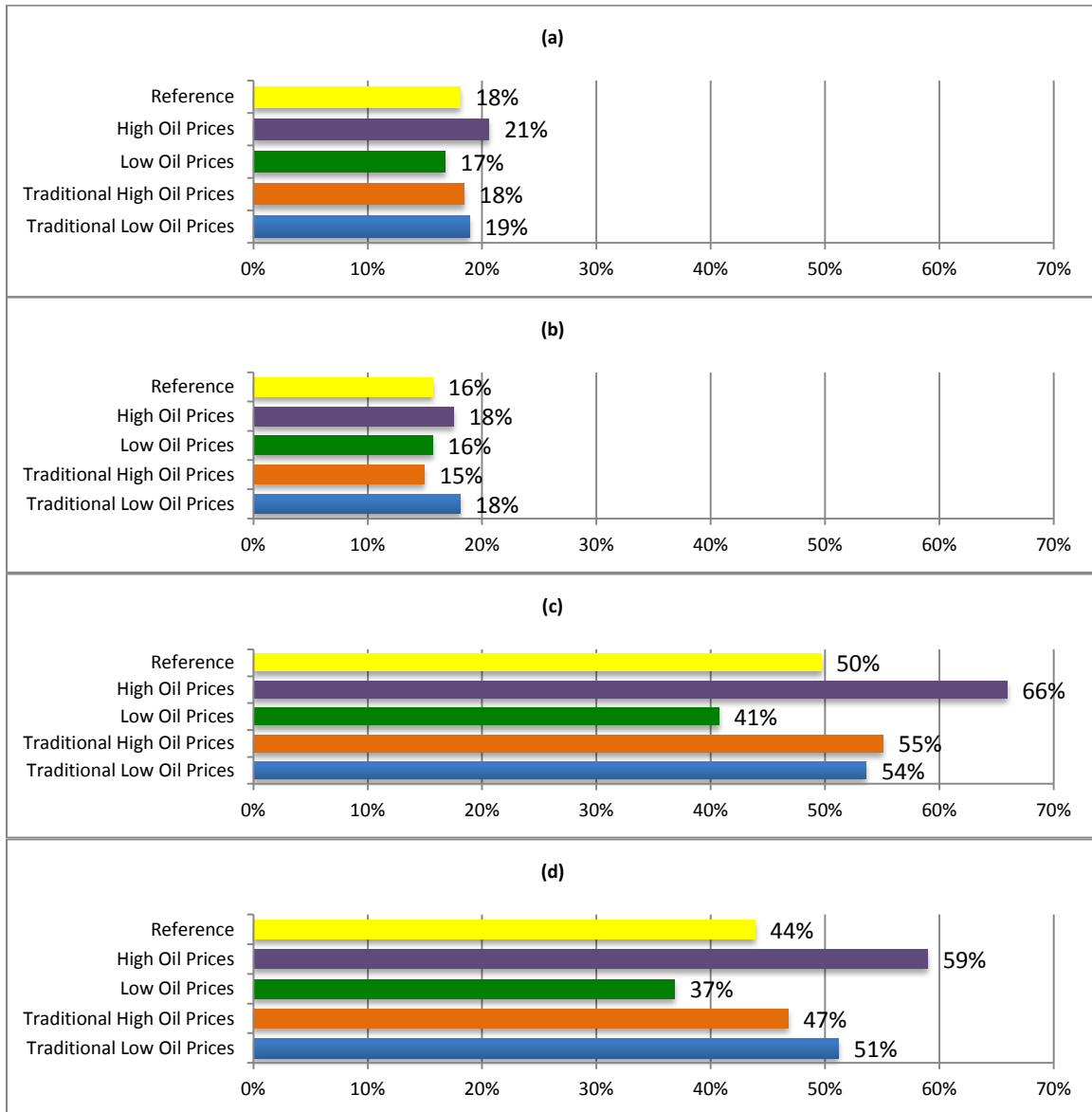
Figure 2.3: Percent increase in the World's water footprint of energy consumption compared to 2012: (a) 2020 low estimation; (b) 2020 high estimation; (c) 2035 low estimation; (d) 2035 high estimation

Figure 2.4 illustrates growth of per capita water footprint of the global energy consumption over the 2012-2035 period. For most scenarios, per capita energy's water footprint growth rate (13%-38%) surpasses the population growth rate (20%) and per capita energy consumption

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growth rate (18%), implying a steeper trend in per capita water footprint of global energy production.
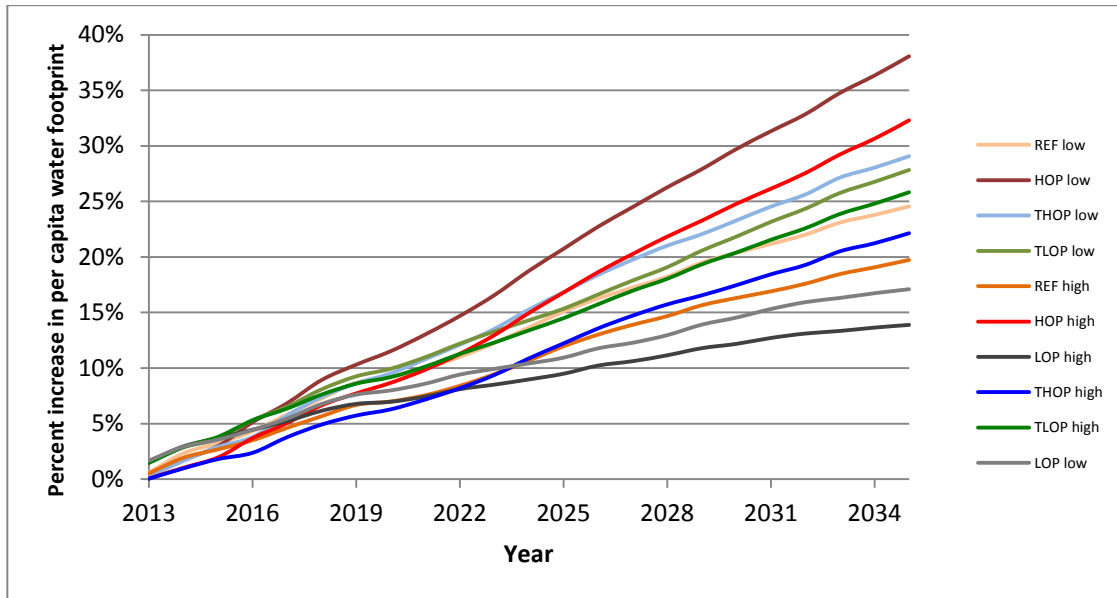
Figure 2.4: Percent increase in per capita water footprint of global energy production compared to 2012 based on different EIA scenarios.

2.4   Conclusion

The results indicate that if the 2012 energy sources proportionally keep the same shares of energy production in the future, the global water footprint of energy production will be lower by 1-10% from the water footprint of other future energy portfolio projections. This is mainly due to the fact that the 2012 energy portfolio excludes high shares of the water-intensive renewable energy sources that are expected to replace today's fossil fuels in the future. Hence, the undeniable fact that global energy portfolios are experiencing a gradual shift toward higher shares of renewables to reduce emissions and combat global warming is not sufficient to secure a sustainable future (Mirchi et al., 2012). In other words, the general policy of "energy production from renewables" is not sustainable unless accompanied by detailed analysis of the energy

policies' water use impacts. If the policies shift the future energy production scenarios toward investment in more renewable energy sources with relatively high water consumption such as biofuels and hydropower, energy-related water footprint might surpass the aforementioned levels, leading to severe water shortage that eventually has negative feedback to energy production. It is important to note that reduction in share of water-intensive energy resources from the total energy production does not necessarily lead to reduction in water footprint of the energy policies as the energy production from such resources is increasing over time.

Although the water footprint of different energy technologies varies for each power plant and depends on the geographic variations and climate (Mekonnen and Hoekstra, 2012), the fact that more water is needed to feed future thirsty energy sector is undeniable. The analysis shows that projected energy policies' water-energy ratio rises by 5%-10% in the 2012-2035 period, implying that more water is required for generating one unit of energy. This means an increase of 37-66% during the next two decades in the amount of water required for total energy production in the world. The amount of water that goes to the energy sector will be much higher if low oil production scenarios are realized in the future due to higher shares of water-intensive energy sources such as hydropower and biofuels. Hence, optimizing the energy policies with regard to the water usage besides reducing emissions should be an important concern for policy makers and necessary actions should be taken before water shortage becomes another global barrier to sustainable development, if it has not become already. The energy produced from water-intensive energy sources such as hydropower is not as 'green' as the energy produced from low water consumption energy sources such as wind energy although they both have emissions far less than fossil fuels. Therefore, future energy mix should rely more on the energy resources that

not only have controllable emissions, but also consume less water. In addition, future research should focus on improving the water use of different energy technologies, especially the ones with higher negative impacts on water resources.

The energy sector's water footprint calculations in this chapter had some major limitations that can be addressed in future studies. Despite its limitations, however, this study can provide some valuable insights, if its simplifying assumptions are not overlooked, especially when advising policy (Madani, 2013). The energy related water footprint calculations in this study were conducted based on the limited data from EIA and did not consider technological evolutions that result in reduction of water consumption in energy production processes over the next decades. Therefore, it is likely that the total water footprint of global energy production falls below or over the values suggested in this study, mostly due to variations in technology and energy efficiency and water use policies and regulations. Furthermore, technology advancements can contribute to improved water recycling and reuse in the energy sector, reducing the lifecycle water footprint of energy production processes. In addition, the shares of different forms of energy in a category was not clear from EIA databases, leading to some precision loss in calculations of this study. For instance, the likely shares of solar thermal, solar photovoltaic, wind onshore, and wind offshore were not specified by EIA. To overcome this ambiguity, the water footprint of such categories were defined as ranges to address the water requirements of different technologies within one category such as solar energy or wind energy. Here, hydroelectricity was assumed to be produced by large hydropower systems only, ignoring the portion of hydroelectricity supplied by small and run-of-the-river hydropower systems. This might result in overestimation of the water footprint of hydropower as large hydropower

reservoirs have significant water footprints due to evaporative losses. A more detailed

composition of the world's future energy mix provides a more reliable basis for study of the

water-energy nexus, policy analysis and management. In this study, the analysis is based on the

scenarios developed by EIA in order to cover a broad range of possible futures. Future studies

might focus on measuring the energy production's water footprint based on the portfolios

developed by other sources such as IEA, WEC, OPEC, etc.

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CHAPTER 3: A SYSTEM OF SYSTEMS APPROACH TO ENERGY SUSTAINABILITY ASSESSMENT

3.1   Introduction

Conventional fossil fuels, including oil, coal, and natural gas, have been the major sources of energy production worldwide. These fossil fuels, however, are becoming increasingly inaccessible in terms of extraction and reserves are gradually becoming harder to find. Many areas around the world do not have access to sufficient fossil energy reserves and, thus, must meet their demands through imports. This makes national energy supply plans uncertain and insecure, due to unreliability of fossil energy availability, which can be affected by different factors, including political stability, economic conditions, laws and legislations, and national development plans of fossil fuel suppliers. Also, the powerful energy suppliers such as OPEC members could affect the global energy security through their future energy production policies (Mirchi et al., 2012). As a result, the dependency of current energy systems on the limited fossil fuel resources endangers national energy security in many countries (UNEP, 2011).

Global warming, resulting from the concentration of the greenhouse gas (GHG) emitted from burning fossil fuels, has been recognized as one of the obstacles to sustainable development and planning (McDonald, 2006; USAID, 2011). Climate warming is expected to create a range of issues, including but not limited to health and environmental problems (EPA, 2011; NRDC, 2011), rising sea levels (NCDC, 2011), changing rainfall and temperature patterns (Dore, 2005; Mirchi et al., 2013), manipulated ecosystem productivity (Doll and Zhang, 2010), agricultural productivity deterioration (Gohari et al., 2013), increased energy demand and prices (Guégan et al., 2012), and limited availability of water-dependent energy sources such as hydropower

(Madani and Lund, 2010; Jamali et al., 2013). Many countries around the world have been developing policies in an attempt to preserve the national energy security and to adapt to climate change. The emerging policies are more inclined to use renewables in the future, so the ideal future energy supply portfolios include a combination of both fossil fuels and renewables, with the share of the renewables increasing gradually over time. For example, in the U.S., many states have renewable portfolio standards or goals (Zonis, 2011) that require the timely increasing production of energy from renewable sources to certain levels; in their 20/20/20 energy strategy, European countries have set an overall mandatory target of 20% for the portion of renewable energy in gross domestic consumption by 2020 (European Union, 2011); Denmark aims to cover 50% and 100% of the electricity demand through renewables by 2020 and 2050, respectively (The Danish Government, 2012); and Scotland plans to fully satisfy electricity demand via renewables by 2020 (The Scottish Government, 2012).

Sustainable development mandates establishing equilibrium between biocapacity, i.e. the area of productive land and water available to produce resources and absorb carbon dioxide wastes, and ecological footprint, i.e. the area of productive land and water required to produce resources and absorb carbon dioxide wastes (GFN, 2010). According to GFN (2010), the ecological footprint exceeded biocapacity by 44% in 2006 and is expected to surpass the biocapacity by 100% by the late 2030s, as a result of population growth and economic development, associated with increased consumption of goods and services and natural resource exhaustion. Continuation of this trend leads to natural resources unsustainability and eventually to ecosystem collapse (Holmberg et al., 1999; Wackernagel et al., 2002; Foley et al., 2005; UN, 2005). In comparison with fossil energy sources, the renewables are known to be more environmental-friendly and

'green', as they produce less carbon dioxide and other greenhouse gases. This has been the significant motivation for proposing the immediate substitution of fossil fuels with renewables to combat global warming. Nevertheless, what is largely ignored by such policies is the unintended consequences emerging from the increased use of renewables, especially with respect to their effects on other valuable natural resources (e.g., water and land) in the long run. Some renewable energy sources, such as hydropower and biomass, consume more water than others. Additionally, production of some of them like ethanol and biomass requires large land areas. These secondary impacts on water and land can establish barriers to sustainable development as the pressure on a major component of the ecosystem (e.g., land, water) can eventually yield to the failure of that the collapse of the whole system due to interrelations of ecosystem components.

Moving toward a sustainable future requires policy actions that solve existing problems without creating new ones (Gohari et al., 2013; Hjorth and Madani, accepted). Thus, it is essential to consider the byproducts of our climate change solutions, affecting other valuable natural resources. In the case of renewable energies, it is unjustifiable to invest in an energy production method that produces minimal GHGs, yet demands considerable amounts of natural resources (e.g. water and/or land) as well as significant financial backup in the long run. Although active use of renewable energies might be effective in reducing greenhouse gas emissions and the resulting climate change effects, secondary impacts on the other components of the ecosystem, namely water and land, are inevitable if carbon footprint is the only decision driver. As a result, the general policy of substituting fossil fuels with renewables might not be effective unless the other aspects of the policy are also taken into consideration. Ultimately, there is no alternative other than replacing the conventional energy sources with renewables, as the

current world's energy supply profile is unsustainable in terms of energy security and environmental impacts. However, tradeoffs should be seriously considered and the secondary impacts on other natural resources should be minimized.

Assessment of the sustainability of energy sources must be done through a hierarchical systems procedure that minimizes the impacts of energy production on each complex resource system (lower level consideration) with respect to the trade-offs involved and the aggregate impacts (higher level consideration). Because we are dealing with a larger system which itself is composed of independent but interacting systems (water, land, climate, economy, etc.), the hierarchical sustainability assessment procedure can be best developed within a system of systems framework (Hipel et al., 2008; Phillis et al., 2010; Hjorth and Madani, accepted). The schematic of this framework is shown in Figure 3.1. The objective of this chapter is to develop a quantitative procedure within the system of systems framework (Ackoff, 1971) to estimate the resource use efficiency of energy sources. A new resource use efficiency index is proposed which can be used to evaluate the aggregate impact of energy sources on different resources systems considering the existing uncertainties in estimated impacts of energy sources on each system. The resource use efficiency scores of different energy sources are calculated to indicate how a holistic view of energy production impacts can change the desirability of some of the 'green' energy sources.
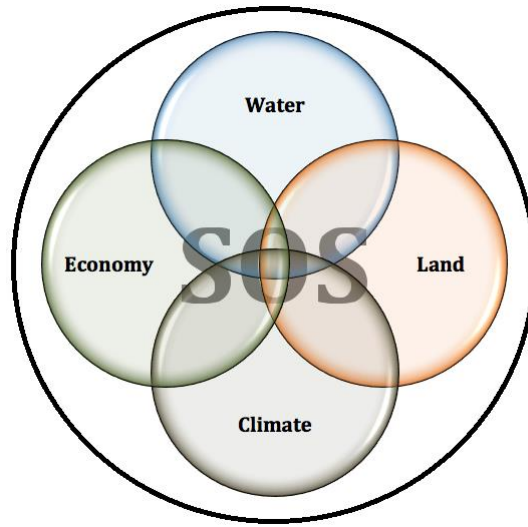
Figure 3.1: Energy sustainability assessment as a system of systems (SOS) framework

3.2 Energy Production Impacts: Selecting Lower Level Indicators

One of the most notable secondary effects of the energy production processes is water resources depletion. Energy is required for extraction, treatment, and distribution of water and water is needed to produce energy (Dennen et al., 2007). While the water becomes less available, the global water demand of the energy sector is expected to grow by 60-70% in the 2005-2035 period. Introduction of renewable energy to substitute conventional fossil energies can create competition over water (Gerbens-Leenes and Hoekstra, 2007), especially between the food and energy sectors with the potential to increase food prices and decrease food security (Gerbens-Leenes and Hoekstra, 2011a). For some renewable energy sources, the amount of freshwater used to produce a unit of energy is so high that makes them inefficient and unreliable sources of energy in comparison to traditional sources, when water consumption is considered as a sustainability criterion. For example, the amount of water needed to produce one unit of some bioenergies is between 70 to 400 times larger than the water needed to produce energy from the

conventional primary energy sources (Gerbens-Leenes et al., 2009a). A significant amount of freshwater (estimated to be 68 m3/GJ by Mekonnen and Hoekstra (2012)) is lost through evaporation for hydropower, the most prevalent renewable energy source. Other renewable energy technologies also show a large variability in direct and indirect water consumption (Spang, 2012).

Decarbonizing the current energy systems may be the most important step in battling climate change, but excluding water-energy nexus in energy policy evaluations results in unsustainable solutions to climate change that create other issues such as water shortage. Given the important role of water resources in sustainable development and considering the fact that nearly half of the world's population will be living in conditions of severe water stress by 2030 (OECD, 2008), the water use efficiency of energy sources must be taken into account in energy efficiency analyses and sustainable energy planning. This is of particular importance for countries with high water usage such as the U.S. with an average per capita water footprint of 2,842 cubic meters per year—105% more than world's average water footprint (Mekonnen and Hoekstra, 2011a).

Water footprint, defined as the total amount of freshwater used to produce products (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2007, 2008), is a reliable metric for water use efficiency. Water footprint for products and services including energy sources, energy applications, and energy utilization modes have been explored in a number of studies. Gleick (1994) calculated the consumptive water use of energy production for different energy sources and concluded that energy planning is highly dependent on the available regional water resources. Gerbens-Leenes and Hoekstra (2011a) studied water footprints of different modes of transport based on first generation biodiesel, bio-ethanol and bio-electricity and concluded that

electricity is much more efficient than biofuels in terms of water footprint. Gerbens-Leenes et al. (2009a) calculated the water footprint of energy from biomass for fifteen crops, emphasizing that the large difference between the average water footprint of biomass and the average water footprint of primary energy carriers makes bioenergies inefficient in terms of water use. Mekonnen and Hoekstra (2012) estimated the blue water footprint (the volume of surface and ground water consumed in the energy production process) of electricity from hydropower for a number of hydropower plants to be equivalent to 10% of global blue water footprint of crop production, concluding that hydropower is a significant water consumer. Other studies of water use of energy sources include Gerbens-Leenes et al. (2008 and 2009b), Fader et al. (2011), Gerbens-Leenes and Hoekstra (2011b), and Mekonnen and Hoekstra (2010, 2011b and 2011c). Table 3.1 indicates the water footprint of different energy sources.

Similar to water, as one of the principal ecosystem components, land also plays a significant role in maintaining a balanced ecosystem state and if deteriorated, can endanger the ecological cycles. Examples of negative land use impacts on the ecosystem include ecosystem productivity degradation (Vitousek, 1997), biodiversity loss (Pimm and Raven, 2000), soil erosion (Tidman et al., 2001), carbon cycle disruption and climate change (Houghton et al., 2002; Pielke et al., 2002), and water quality deterioration (Matson et al., 1997; Bennet et al., 2001). Similar to the water-energy nexus, the land-energy nexus must be considered in developing sustainable energy plans as they affect land use and the global ecological footprint. Some energy sources such as nuclear have comparatively small land footprints, while others, such as biomass and ethanol, have large land footprints when compared to others. Indeed, improving energy efficiency and

energy conservation can both decrease the land footprint of energy by reducing the need for further energy production infrastructure (Outka, 2011).

Land use practices are highly affected by the energy lifecycle including the location of extraction and travel distances between different energy production and transportation steps. Similarly, energy production can be influenced by land use patterns. For example, energy production from energy crops requires suitable land, resulting in competition with food crops with implications for food prices (Dale et al., 2011). Satisfying the U.S. 2005 electricity demand via wind power, for example, would need an area equal to the combined area of Texas and Louisiana. Using biofuels to generate the same amount of energy that can be produced by a 1,000 MW nuclear powerplant would require 2,500 square kilometers of land (Ausubel, 2007).

Recognizing land use as another energy sustainability criterion might make some energy production options inefficient and unsustainable. In its 20/20/20 energy policy, for instance, the European Union (EU) determined a minimum target of 10% for biofuels in 2020 (EU, 2011). In the U.S., according to Energy Independence and Security Act of 2007, 136 billion liters (36 billion gallons) of biofuel from corn and cellulosic crops should be produced in 2022 (Pimentel, 2009). According to a study by Shell (2008), a 200% increase in the usage of biomass as an energy source is expected by 2050, accounting for 15% of the total energy use. Given the significant land use impacts of biofuels, their sustainability as a solution to global warming is questionable. A number of studies have been focusing on the land use intensity of energy sources, including McDonalds et al. (2009), Fthenakis and Kim (2009), and Lovins (2011). Table 3.1 shows the values for the land footprint of different energy sources, defined as direct and indirect amount of land used for energy production purposes (Lugschitz et al., 2011).

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While environmental impacts of energy production has received attention in the recent decades, economics of energy remains to be a determinant parameter in developing sustainable energy plans. This is especially true in the face of growing energy prices at the global scale with energy producers trying to maximize their profit by maximizing the least-cost energy production. Several studies have investigated the cost of various energy sources. Energy costs are usually expressed as levelized costs, reflecting the capital costs, fuel costs, fixed and variable operation and maintenance costs, financing costs, and utilization rate for each energy option (ICCEPT, 2002; Cosijns and D'haeseleer, 2007; Lazard, 2009; EPRI, 2011; EIA, 2011a). Table 3.1 shows the levelized cost of different energy sources.

Life cycle-based energy production impact indicators such as levelized cost, carbon footprint, water footprint, and land footprint provide invaluable information about the effects of energy production on different interacting systems (economy, climate, water, and land) within a coupled human-natural system of systems. Nevertheless, individually, they fail to provide sufficient information for evaluating the overall resource use efficiency of energy sources and their sustainability. Thus, a system of systems perspective is required to develop a holistic understanding of the aggregate effects of energy sources on the larger human-natural system. The lack of such perspective has been the major cause of our rushed movements to replace fossil energy sources with the renewable and green energy sources. This research intends to bridge the gap in our understanding of the overall impacts of energy sources on human-natural systems to re-evaluate the sustainability of our energy production policies. As a proof-of-concept study, this work considers levelized cost, carbon footprint, water footprint, and land footprint as lower level system indicators and proposes a method for aggregating them at the system of systems level.

Table 3.1 indicates the average global-scale performances of different energy sources under the four lower level criteria considered in this study. The provided information is based on an extensive review of the information in the literature. Some of the table values are given in intervals, reflecting the uncertainties involved in the energy performances resulting from technological, geographic, geologic, and other variations at the global scale. The carbon footprint values are based on Life Cycle Assessment (LCA) studies, which take into account emissions during life cycle of the energy production. The values for water footprint reflect the water used during different production phases to produce one unit of energy. Where data were taken from different sources, the values were checked for consistency with respect to different assumptions behind estimations in each study. The levelized cost values for different energy sources in this study are primarily chosen from ICCEPT (2002) and Cosijns and D'haeseleer (2007). Given the assumptions used in these studies, their numbers are more applicable globally than at a regional basis. In order to account for the uncertainties involved in the long term cost estimations, the ranges used in this study are based on the interest rate used in the original studies (10%). It is also assumed that all technologies become mature after 2020, so the levelized cost of one unit of energy from different sources becomes almost constant over a long period. When required, the euro to dollar conversion rate was assumed to be 1.30. When cost data were extracted from different studies, they were adjusted for the differences between measures, such as currency and the year of calculation. The levelized cost of electricity from various biomass and ethanol sources were not clear in the reference studies.

Table 3.1: Carbon footprint, water footprint, land footprint, and cost of energy sources

Energy Type	Carbon Footprint (g CO_2/kWh)	Water Footprint (m^3/GJ)	Land footprint (m^2/GWh)	Cost (cent/kWh)
Ethanol from corn	81-85 (Hill, 2006)	78 (Gerbens-Leenes et al., 2009)	10667-12500 (McDonald et al., 2009)	2-4 (ICCEPT, 2002)
Ethanol from sugar cane	19 (Oliveira, 2008)	99 (Gerbens-Leenes et al., 2009)	9520 (McDonald et al., 2009)	2-4 (ICCEPT, 2002)
Biomass: wood-chip	25 (Parliamentary Office of Science and Technology, 2006)	42 (Gerbens-Leenes et al., 2009)	14433-21800 (McDonald et al., 2009)	4-10 (ICCEPT, 2002)
Biomass: miscanthus	93 (Parliamentary Office of Science and Technology, 2006)	37 (Gerbens-Leenes et al., 2009)	14433-21800 (McDonald et al., 2009)[*]	4-10 (ICCEPT, 2002)
Solar thermal	8.5-11.3 (Jacobson, 2009)	0.037-0.780 (Jacobson, 2009)	340-680 (McDonald et al., 2009)	4-10 (ICCEPT, 2002)
Solar photovoltaic	12.5-104 (World Energy Council, 2004)	0.042 (Jacobson, 2009)	704-1760 (McDonald et al., 2009)	10.9-23.4 (Cosijns and D'haeseleer, 2007)
Wind: onshore	6.9-14.5 (World Energy Council, 2004)	0.001 (Jacobson, 2009)	2168-2640 (McDonald et al., 2009)	4.16-5.72 (Cosijns and D'haeseleer, 2007)
Wind: offshore	9.1-22 (World Energy Council, 2004)	0.001 (Jacobson, 2009)	2168-2640[**]	3.64-8.71 cent/kWh (Cosijns and D'haeseleer, 2007)
Wave and tidal	14-119 (Jacobson, 2009)	0.001 (Jacobson, 2009)	33-463[**]	5-15 (ICCEPT, 2002)
Hydropower	2-48 (NEI, 2012)	22 (Gerbens-Leenes et al., 2009)	538-3068 (McDonald et al., 2009)	3.25-12.35 (Commission of European Communities, 2007)
Coal	834-1026 (World Energy Council, 2004)	0.15-0.58 (Hill and Younos, 2007)	83-567 (McDonald et al., 2009)	3.77-5.85 (Cosijns and D'haeseleer, 2007)
Oil	657-866 (World Energy Council, 2004)	4.29-8.6 (Hill and Younos, 2007)	1490 (McDonald et al., 2009)	8-10 (ICCEPT, 2002)
Natural gas	398-499 (World Energy Council, 2004)	0.1 (Gleick, 1994)	623 (McDonald et al., 2009)	5.46-11.96 (Cosijns and D'haeseleer, 2007)
Nuclear	9-70 (Jacobson, 2009)	0.42-0.76 (Jacobson, 2009)	63-93 (McDonald et al., 2009)	4.55-5.46 (Cosijns and D'haeseleer, 2007)
Geothermal	15.1-55 (Jacobson, 2009)	0.005 (Jacobson, 2009)	33-463 (McDonald et al., 2009)	1-8 (ICCEPT, 2002)

*Assumed to be the same as biomass woodchip.

**Assumed to be the same as geothermal (Jacobson, 2009)

3.3 Energy Resource Use Efficiency

In essence, the complexity of energy planning resulting from social, political, technological, economic, and ecosystem interactions requires a system of multiple criteria that should be evaluated and included in energy policy making. Thus, a systems approach to energy planning has been encouraged in several studies. Sims et al. (2003) analyzed the efficiency of different energy sources for their economic and carbon mitigation potential and concluded that nuclear, wind, hydropower and bioenergy technologies are efficient, while solar and carbon sequestration technologies are not. The World Energy Council (2004) compared energy systems using the LCA method, emphasizing the importance of considering different criteria in energy systems analysis, such as energy accessibility (representing costs of energy), energy availability (representing reliability of energy), and energy acceptability (representing environmental impacts). This study concluded that emissions from renewables and nuclear energy are comparable, while environmental impacts of fossil fuels could be decreased significantly if advanced technologies are applied. Abulfotuh (2007) emphasized the importance of considering the links between energy use, economic growth, and the environmental impacts of excessive use of energy in energy and environmental problems. Wang et al. (2009) reviewed published literature on Multi-Criteria Decision-Making (MCDM) applications in sustainable energy planning and concluded that efficiency, investment cost, CO2 emissions and job creation criteria, associated with technical, economic, environmental and social attributes, have been the main focus of previous research. Zhao et al. (2009) evaluated various power supply technologies based on the Analytic Hierarchy Process (AHP) and concluded that from a sustainability perspective,

hydropower and solar power are the best and the worst alternatives, respectively. Jacobson (2009) reviewed the possible solutions to climate change, air pollution, and energy security, taking into account the unintended effects on water supply, land use, wildlife, resource availability, thermal pollution, water chemical pollution, nuclear proliferation, and under-nutrition. He ranked a range of nonrenewable and renewable energy sources based on the aforementioned criteria without considering cost as a determining factor and concluded that wind, concentrated solar power (CSP), geothermal, tidal, solar, wave, and hydropower are the best options for electricity generation, while biofuels are the worst. Roth et al. (2009) studied sustainability of current and future electricity supply technologies from the environmental, social and economic points of view and reported hydropower, geothermal, and biogas technologies as the best energy alternatives. Chatzimouratidis et al. (2009a) evaluated powerplants based on technological, sustainability, and economic criteria using AHP and suggested renewable energy and fossil fuel powerplants as the best and the worst options among ten different alternatives. Oberschmidt et al. (2010) evaluated energy alternatives for electricity and heat supply using a Modified PROMETHEE method and concluded that renewable sources are more promising. Kahraman et al. (2009), Kahraman and Kaya (2010), and Kaya and Kahraman (2010) ranked different renewable energies that are best suited for future investment in Turkey, taking into account their technical, economic, environmental, political, and social aspects and suggested wind power as the best alternative. San Cristobal (2011) investigated various renewable energy sources in Spain based on different criteria, such as power, investment ratio, implementation period, operating hours, useful life, operation and maintenance costs, and tons of CO_2 avoided. He found biomass, wind, and solar energies to be the best alternatives.

The relatively high number of systems methods applications in energy planning reflects the fact that the field has correctly realized the complexity of the problem and identified the proper framework for problem analysis. However, significant differences between the study results indicate the inconsistency in the assumptions and methods applied in previous studies due to three major limitations:

a) Notion of optimality: Given the difference in the notion of optimality, various multi-criteria assessment methods produce different 'optimal' outcomes and rankings of different energy alternatives. This makes the study results highly sensitive to the choice of multi-criteria assessment method. Therefore, there is a need to develop a more robust assessment method, which minimizes the sensitivity of results to the analyst choice of multi-criteria assessment method.

b) Performance variability and uncertainty: Performance of energy production options under different assessment criteria (carbon footprint, water footprint, cost, etc.) depends on a variety of factors, including regional conditions and technology maturity. Therefore, estimation of the performance values at a large scale (e.g. global) becomes challenging and controversial. While some studies have suggested different methods to consider uncertainty in energy planning (Rylatt et al., 2001; Gamou et al., 2002; Borges and Antunes, 2003; Mavrotas et al., 2008; Chen et al., 2007; Cai et al., 2011b; Li et al., 2011b; Wang et al., 2010; Zang et al., 2012; Zhou et al., 2012) most of the literature overlooks the high level of uncertainty in performance values at different geographical scales. Conventionally, energy planning studies use deterministic performance values and/or use different methods which provide deterministic outputs despite the stochastic

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input information, hiding the risks associated with the study results. Therefore, there is a need to develop a method, which considers the uncertainties involved and informs the decision makers about the uncertainties impacts on assessment results and their robustness.

c) Lack of a reliable aggregating index: As discussed, different system level life-cycle indicators (water footprint, carbon footprint, etc.) provide valuable information, but the literature lacks a reliable aggregating indicator, which can provide useful quantitative information to the decision maker. Normally, performance aggregation is done using one of the multi-criteria decision making methods, which makes the aggregation process highly sensitive to the choice of method, while the final output provides meaningless quantitative information to the decision maker. Therefore, there is a need to develop a robust aggregating indicator at the appropriate level (system of systems level) which conveys useful quantitative information to decision makers with respect to performance uncertainness and the lower level indicators.

In this dissertation, a quantitative method is developed which addresses these limitations. To counterbalance the bias toward definition of optimality by a single analysis method and increase the robustness of results, this study employs multiple MCDM methods. Among the many methods available for multi-criteria analysis, five MCDM methods (Table 3.2) are applied here to investigate the resource use efficiency of different energy sources. The selected methods are mostly suitable for social planner problems (Linkov et al., 2004, 2005; Madani et al., 2013), in which a central decision maker is interested in identifying the system-wide optimal solution. To account for performance uncertainties (Table 3.1), multi-criteria assessment is combined with a

Monte-Carlo selection. This type of problem analysis, common in multi-criteria assessment under uncertainty (Madani and Lund, 2011; Madani et al., 2011; Shalikarian et al., 2011; Rastgoftar et al., 2012; Read et al., 2013) maps the stochastic decision making problem into numerous (100,000 in this case) deterministic problems by generating random numbers from the uncertainty intervals for all the energy sources. Each deterministic decision making problem is then solved and the energy sources are ranked using each MCDM method with respect to the four lower level criteria (carbon footprint, water footprint, land footprint, and cost). The winning probability of each alternative at each rank under each MCDM method is then calculated based on the results of 100,000 deterministic MCDM analyses. The winner alternative at each rank is selected to establish the final ranking under each MCDM method. Further details about this procedure can be found in Mokhtari et al. (2012) and Mokhtari (2013). For detailed mathematical descriptions of the five MCDM methods used in this study (Table 3.2), readers are referred to Madani et al. (2013).

Given that the overall rankings of the alternatives under each MCDM method are not necessarily identical (due to their different notions of optimality) there is a need for an aggregation method for establishing the overall ranking method, which is more robust. "Resource use efficiency" is proposed as a system of system index to evaluate the overall resource use efficiency of energy alternatives with respect to the four evaluation criteria and the performance uncertainties. The value of this index can be identified for each alternative using the following equation:

$$RUE_i = 100(\frac{C.N - B_i}{N(C-1)}) \tag{1}$$

where:

C: number of alternatives; N: number of MCDM methods; B$_i$: Borda score of alternative i (Borda score is the sum of the scores (ranks) given to each energy alternative by each MCDM methods (Sheikhmohammadi and Madani, 2008)); and RUE_i: resource use efficiency of alternative i. RUE_i varies from 0 to 100, where 0 is given to the absolute worst and 100 is given to the absolute best alternative.

Table 3.2: MCDM methods

Method	Notion of Optimality
Dominance	Selects the non-dominated option based on Pair-wise comparisons of the alternatives
Maximin	Selects the alternative with the maximum lowest performance under all criteria
Lexicographic	Selects the most desirable alternative for the most important criterion
TOPSIS	Selects the alternative with the minimum distance from the ideal performance
SAW	Selects the alternative with the highest weighted performance

3.4   Results

Table 3.3 shows the overall ranking of energy alternatives based on different MCDM methods. These rankings are based on the winning probabilities calculated using the Monte-Carlo MCDM method (Mokhtari et a., 2012; Mokhtari, 2013) with 100,000 rounds of selection. In this chapter, the four lower level resource use efficiency criteria are assumed to be equally important to the central energy planner. This assumption is not true in case of regional restriction in availability of one or more of the main resources (e.g. water and land). So, the weights can be adjusted accordingly considering the decision maker(s)' preferences at the local level. The results reported here are based on a global scale analysis with equally weighted criteria.

As expected, the rankings under different MCDM methods are not identical. A more robust ranking can be established based on the resource use efficiency scores of the energy alternatives,

which can be calculated based on the ranking results (Table 3.3) using Equation 1. Figure 3.2 shows the value of resource use efficiency for each energy alternative. In this figure, energy sources have been categorized into three groups (highly efficient, efficient, inefficient) based on their resource use efficiency scores. While the first group does not include any fossil energy sources, reflecting the desirability of most renewable energy sources, biofuels belong to the inefficient energy group with low efficiency scores together with coal and oil. This finding proves that renewable energies are not necessarily 'green' when a system of systems perspective is adopted. On the other hand, some energy sources such as nuclear and natural gas can be competitive with most renewable energies based on their overall resource use efficiency. The fact that no energy resource has received an efficiency score of 100 or 0 shows that there is no strictly dominant (best) and strictly dominated (worst) energy supply option, due to the performance value uncertainties.

Table 3.3: Ranking of the energy sources based on different MCDM methods

Energy Type	Dominance	Maximin	SAW	Lexicographic	TOPSIS
Ethanol from corn	12	9	15	13	15
Ethanol from sugar cane	10	12	12	7	13
Biomass: wood-chip	15	13	10	10	10
Biomass: miscanthus	14	11	13	15	11
Solar thermal	3	5	2	5	2
Solar photovoltaic	9	14	7	6	7
Wind: onshore	1	2	4	1	5
Wind: offshore	4	4	6	2	6
Wave and tidal	6	8	5	3	4
Hydropower	8	6	8	12	8
Coal	7	15	11	9	14
Oil	13	10	14	14	12
Natural gas	11	7	9	11	9
Nuclear	5	3	3	8	3
Geothermal	2	1	1	4	1
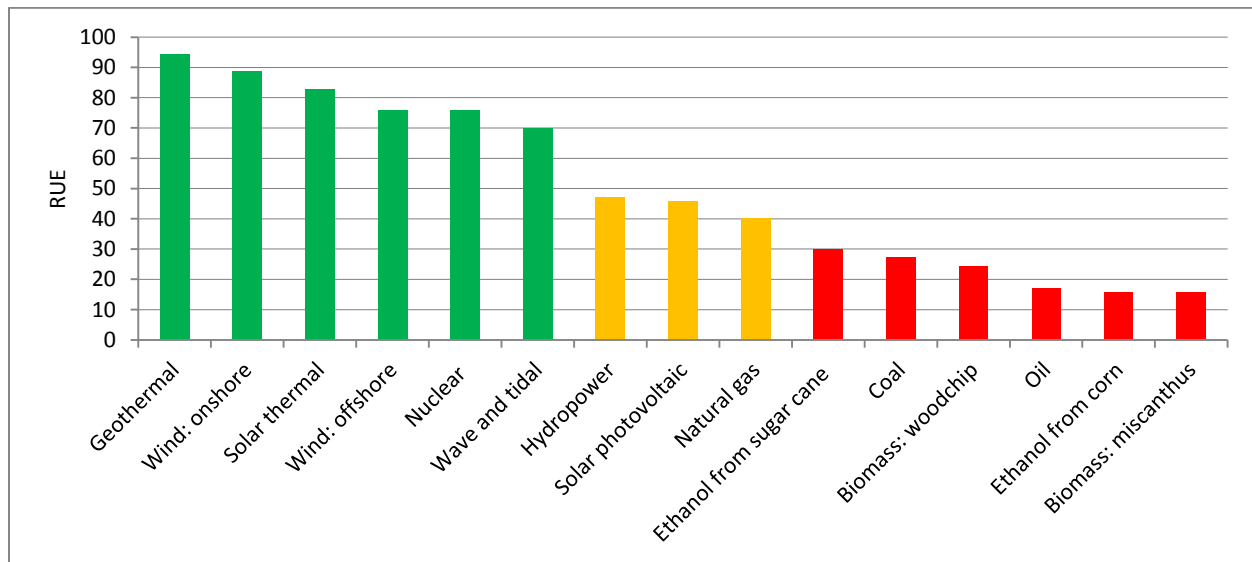
Figure 3.2: Resource use efficiency scores of different energy sources (0-100)

EIA (2011b) only foresees a 0.06% increase in share of geothermal in the global energy supply portfolio in the period of 2011-2035. However, while geothermal is not the best energy option in terms of energy production costs or emissions, it has the highest resource use efficiency

score (94) based on the four efficiency criteria considered in this analysis. This clearly shows how a holistic view of energy production effects on different resources using a system of systems approach can change desirability of an energy source, which is not highly desirable based on one or two specific criteria. While expansion of geothermal energy is encouraged based on the results here, different conditions and limitations exist in increasing the geothermal energy supply such as the availability and deepness of geothermal vents as well as the required technologies.

Similar to geothermal energy, wind (onshore and offshore) is one of the most efficient energy sources (resource use efficiency score=88) based on a system of systems perspective. However, the share of wind energy is supposed to increase by only 1.5% in the next two decades (EIA, 2011b). The small increase in the share of wind from the world's total energy production could be related to the geographic limitations as well as the cost of energy production from wind in countries in which this energy source is still immature. In many advanced economies, however, the energy production from wind is increasing rapidly. For instance, wind energy has had a growth of more than 2,000% in the U.S. during the 1995-2009 period (EIA, 2012b).

Solar thermal is the next most resource use efficient energy source (resource use efficiency score=83). Compared to solar photovoltaic (resource use efficiency score=46), solar thermal is more efficient due to lower carbon, land, and economic footprints, whereas solar photovoltaic is gaining more popularity due to accessibility of this technology and its ease of use without serious concerns about its overall resource use efficiency. From a resource use perspective, the efficiency of solar photovoltaic could be increased by improving the production technology and recycling PV materials after their useful life (Fthenakis, 2000). This yields a lower emission,

cost, and land use per unit of energy production and makes this energy alternative more resource use efficient.

According to Figure 3.2, nuclear energy with the resource use efficiency score of 76 is the most attractive nonrenewable energy source. Although safety issues, international laws and regulations, nuclear waste, and the lack of required technologies and materials could be the main barriers to further development of this energy, when looked at from a resource use perspective, nuclear energy is more efficient compared to some renewables such as hydropower, solar photovoltaic, ethanol, and biofuels.

Wave and tidal energies are renewable energy sources with a relatively high resource use efficiency score (70). Despite their power generation inefficiency, that yields fairly high carbon footprint and cost, their low water use and land use make them more efficient compared to more popular renewable power sources such as hydropower, solar photovoltaic and biofuels. However, technological barriers, production costs, and limitations in large-scale implementation of these technologies, are the main reasons for small share of such wave and tidal technologies from the world's total energy supply.

Hydropower has been the most commonly used renewable energy source for a long time. However, it has a resource use efficiency score of 47 because of its considerable water footprint (due to evaporative losses from hydropower reservoirs) and land footprints (due to the area of land required for the reservoir and other hydropower facilities). While this study uses the average performance values for evaluating the overall resource efficiencies, it must be noted that high water and land footprints are not concerning issues in case of small and run-of-river hydropower.

Therefore, these energy sources are expected to have higher resource use efficiencies under considered sustainability indicators in this study.

Natural gas (resource use efficiency score=40) is the most resource use efficient fossil fuel. Compared to coal (resource use efficiency score=27) and oil (resource use efficiency score=17), natural gas has lower carbon and water footprints. Resource use efficiency of natural gas is very close to some renewable energy sources such as hydropower and solar photovoltaic. Also, it is more efficient than biofuels, whereas it is not a competitive energy option if climate change or low-cost energy production are the only concerns. Among all types of fossil fuels, natural gas is capable of becoming more competitive to other renewables if its cost and carbon emissions are lowered.

Despite their relatively low costs, biofuels (resource use efficiency scores of 24 and 16) and different types of ethanol (resource use efficiency scores of 30 and 16) are among the least efficient alternatives from resource use perspective. This is mainly because of the considerable land and water footprints of these energy sources. While the current energy policies in different parts of the world promote biofuel and ethanol as reliable energy alternatives to fossil fuels (European Union, 2011; Pimentel et al., 2009), the results suggest that a system of systems perspective that considers their secondary impacts on land and water resources, makes these energies very inefficient overall.

Overall, the obtained results suggest that not all renewable energy sources are necessarily 'green' as they are generally perceived when the evaluation is based on system of systems perspective. However, this does not mean that our current reliance upon fossil fuels should be continued to avoid ecosystem damages by excluding renewables in the energy supply mix.

Instead, we need to invest in technological improvements that make renewable energy sources more efficient, mostly in terms of land and water use efficiency. Some renewables such as solar photovoltaic, hydropower, biofuels, and ethanol need more attention if we do not like to mitigate climate change by exhausting other valuable natural resources. A system of systems approach helps us understand the trade-offs involved between the effects of energy production on different components of the complex human-natural system that we are part of.

3.5   Robustness And Sensitivity

The method used here orders energy alternatives under each MCDM method based on their winning probabilities at each rank. Once the option with the highest winning probability is determined as the best alternative (rank 1) based on a given MCDM method, this option is removed from the alternatives set and the winning probabilities are calculated for the remaining options by repeating the same process. While the input performance values are certain, the overall resource use efficiency scores are deterministic. This might hide the uncertainty associated with the calculations from the decision makers. To inform the decision makers about the risks associated with selection of different alternatives, the standard deviation of the efficiency score of each energy alternative can be reported. Standard deviation of efficiency score of each alternative is calculated based on the ranking distribution (probability distribution of getting selected at different ranks) and reflects the degree of robustness of calculated efficiency scores (Madani et al., in review).

Table 3.4 presents the standard deviation of the resource use efficiencies of different energy alternatives calculated based on the proposed Monte-Carlo MCDM method with 100,000 rounds

of sampling. Relatively low standard deviation values imply a high degree of robustness in the calculated resource use efficiency scores. Among all sources, hydropower, nuclear, as well as wave and tidal energies have the least robust resource use efficiency sources under the existing performance values, while solar thermal, onshore wind, and ethanol have the most robust efficiency scores.

Table 3.4: Energy sources' standard deviation of resource use efficiency scores

Energy Type	Standard deviation (%)
Ethanol from corn	2.84
Ethanol from sugar cane	2.70
Biomass: wood-chip	3.96
Biomass: miscanthus	4.13
Solar Thermal	1.63
Solar Photovoltaic	3.82
Wind: Onshore	2.25
Wind: Offshore	3.32
Wave and Tidal	4.03
Hydropower	4.87
Coal	3.29
Oil	3.00
Natural Gas	3.06
Nuclear	4.16
Geothermal	3.70

In addition to information on degree of robustness, decision makers can benefit from learning about the sensitivity of efficiency scores to exclusion/inclusion of different criteria from the analysis. Sensitivity analysis helps with understanding the drawbacks of different energy sources that make them inefficient overall and the need to address them in order to improve the efficiency score significantly. For example, learning the fact that the high water footprint of biofuels is one of the main reasons for their inefficiency would encourage decision makers to invest in technological improvements that can help to minimize the biofuels water footprint.

Moreover, given that the importance of different resource use efficiency criteria (carbon footprint, water footprint, etc.) varies among regions depending on the availability of local resources, sensitivity analysis information can help selecting the best local energy supply sources. For example, hydropower could be a desirable renewable resource where water and land availability is not a limitation (e.g., Canada).

To examine the sensitivity of resource use efficiency scores of different energy sources to the four criteria in this study (carbon footprint (C), water footprint (W), land footprint (L), and cost ($)) the analysis was repeated using all subsets of these equally weighted criteria. Figure 3.3 shows how the energy alternatives' resource use efficiency scores vary depending on the criteria considered. Generally, efficiency scores are highly sensitive to the set of evaluation criteria. However, the degree of sensitivity varies among different energy options. For example, while oil shows a lower degree of sensitivity (difference between the maximum and minimum efficiency scores obtained), ethanol has a high degree of sensitivity. This means that desirability of geothermal is less dependent than the desirability of ethanol on local resource availability conditions.
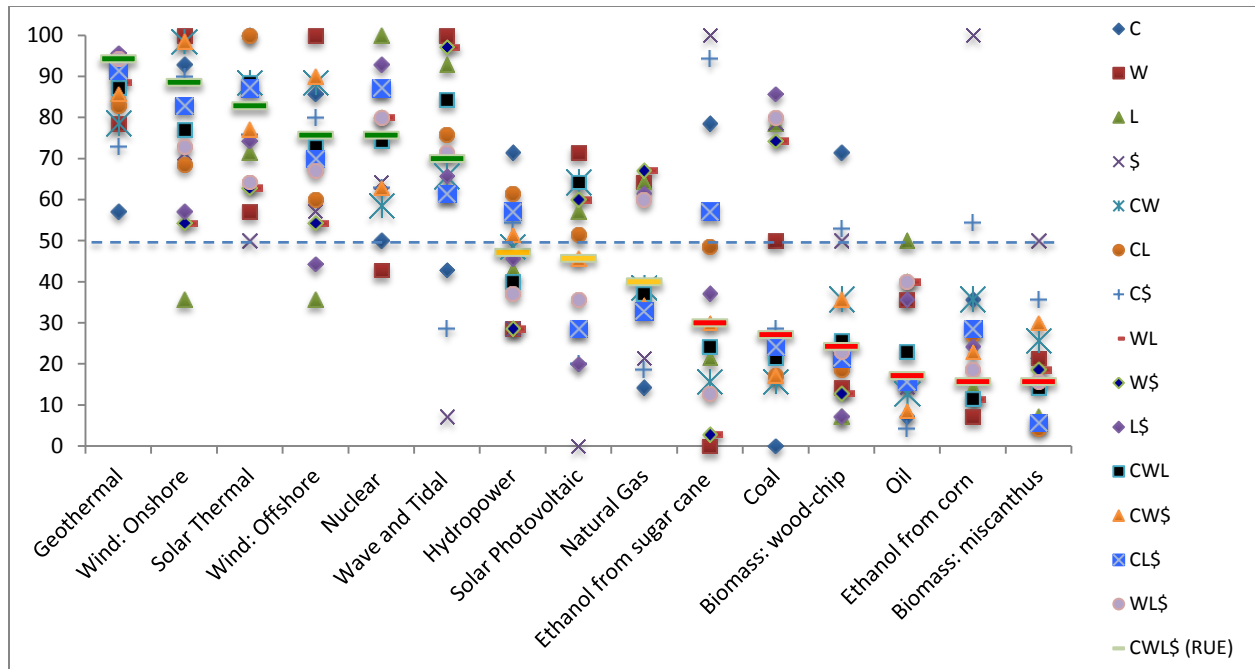
Figure 3.3: Sensitivity of energy sources' resource use efficiency to uncertainties in resource availabilities and limitations

Generally, the resource use efficiency sensitivity scores (Figure 3.3) are independent of the resource use efficiency values (Figure 3.2). Desirability of energy sources might be or not be highly sensitive to local resource availability conditions irrespective of their overall efficiency scores. Geothermal energy shows the lowest sensitivity (minimum difference between the maximum and minimum efficiency scores obtained) to resource availability conditions (the considered criteria).. High resource use efficiency score coupled with low sensitivity makes geothermal energy both efficient and reliable, if the required geographic and geological conditions for implementing this energy option are available. Although onshore and offshore wind energy sources have high efficiency scores, their scores are fairly sensitive to resource availability conditions, making these options undesirable where land availability is an important concern for the decision makers. Contrary to solar photovoltaic, solar thermal shows low resource use efficiency sensitivity to different resource availability constraints. The resource use

efficiency of solar thermal, however, is highly sensitive to the cost criterion, meaning that solar thermal is not a competitive energy option in poor economies. Nuclear energy shows a lower sensitivity to different resource availability conditions when compared to some renewable sources like wind, solar photovoltaic, and wave and tidal. With the lowest land use among all energy sources as well as low costs, the nuclear energy could become more resource use efficient if its water footprint is improved significantly. Nevertheless, with the Fukushima experience, future studies need to carefully reconsider the land footprint estimations for nuclear energy, as a significantly larger land use might be required (e.g. required expansion of protected/undeveloped zone around nuclear plants) to increase the safety of nuclear facilities. Similar to wind energy, wave and tidal energies show high resource use efficiency sensitivity and lose as energy production cost becomes more important to the decision maker. Hydropower has one of the lowest sensitivity values among all energy sources, meaning that the resource use efficiency of this energy source is not considerably dependent on resource limitation conditions. Natural gas shows a relatively low sensitivity. Although natural gas is not an appropriate energy option when GHG emissions are the main concern, its overall resource use efficiency score coupled with its fairly low sensitivity, could make natural gas an appropriate energy resource in some parts of the world depending on the local resource availability conditions. Oil has a low efficiency score sensitivity to resource availability, as the major source of energy in industrial and transportation sectors in many countries despite its significant environmental impacts. Desirability of biofuels is highly dependent on resource availability conditions, except for biomass from miscanthus, which has a fairly low sensitivity range. The resource use efficiency score of biofuels can improve significantly by improving their water use efficiency (lowering their water footprint).

3.6   Conclusions

Current energy production systems are extensively dependent on continued supply of natural resources such as water and land, as well as economic resources, while producing considerable amount of greenhouse gas emissions that result in climate warming. To achieve a sustainable energy mix that addresses the increasing energy demand and energy security with minimal impacts on our scarce resources, we need to consider the interactions of energy production with such independent systems (water, land, climate, economy) under existing uncertainties. Hence, a higher level system (system of systems) that accounts for the trade-offs between lower level components. In this chapter, a system of systems framework was proposed to measure the resource use efficiency of energy sources with respect to such trade-offs. For this purpose, a stochastic multi-criteria analysis framework is created to calculate the resource use efficiency scores under different sustainability criteria, e.g. carbon footprint, water footprint, land footprint, and costs of energy production under performance uncertainties. Such assessment framework is based on utilization of different MCDM methods to eliminate the bias toward specific energy sources, resulting from optimality definitions by different MCDM methods. Based on the proposed method, geothermal and biomass from miscanthus are the best and worst energy options, respectively. This, however, does not guarantee that high resource use efficient energy sources (geothermal, wind, solar thermal, nuclear, and wave and tidal energies) are attractive under all resource limitation conditions as these sources might be dominated by other energy sources in presence of certain conditions. Hence, a sensitivity analysis is performed to measure the variability of resource use efficiency scores of energy sources under different resource limitation scenarios. The sensitivity analysis results indicate that geothermal and ethanol from

sugarcane show the lowest and highest sensitivity to availability and limitation of resources. The impacts of existing performance uncertainties on the energies resource use efficiency scores are also measured to determine the robustness of the resource use efficiency scores. The results of the robustness analysis indicates that hydropower and solar thermal are the most and least robust energy sources under existing performance uncertainties.

The results clearly indicate that from a resource use perspective, some of the renewable energy sources such as hydropower and solar photovoltaic are not green in the current form and biofuel and ethanol have lower resource use efficiency comparing to natural gas, mainly due to high water and land footprints. Such sources should be improved in terms of emissions, water consumption, land use, and production costs to make them more resource use efficient and avoid more environmental losses in large scale energy production. In fact, use efficiency sensitivity analysis outcomes also provide decision makers with valuable insights into potential improvements in the efficiency of the energy technologies. This gives direction to future investment for bettering the resource use efficiency of a certain technology by improving its performance under one or more criteria.

This study had some limitations that could be addressed in future studies. First, the sustainability criteria in this study were weighted equally and did not clearly reflect the efficiency of energy sources for different regions. Although sensitivity analysis determined the variability of the resource use efficiency scores under different resource limitation conditions, there is still a need to consider the regional resource availability and limitations to develop a more reliable energy plan for different regions. In addition, the feasibility of energy alternatives in different regions should be taken into account, as not all energy sources are appropriate for all

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regions. Furthermore, other sustainability criteria should be added to the analysis to achieve a more reliable understanding of energy sources efficiency. Such criteria could be the energy return on investment (EROI), safety, and other indices that reflect the social and political impacts of energy production processes. Also, the analysis in this study was based on the assumption that the energy sources performance under different sustainability indicators does not change over time, while technology improvements could potentially lead to improving the performance values used in this study. Such performance improvements could be addressed in future studies.

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CHAPTER 4: ENERGIES' RESOURCE USE EFFICIENCY ANALYSIS UNDER REGIONAL RESOURCE AVAILABILITY AND LIMITATIONS: IMPLICATIONS FOR THE UNITED STATES OF AMERICA

4.1 Introduction

Increasing the share of renewable energy sources in the global energy mix is a key component of energy policies worldwide for alleviating global warming (Hvelplund and Lund, 1998; Lund et al., 2000, 2003; Perdan and Clift, 2004; Duic and da Graça Carvalho, 2004; Hennicke, 2004; Lund et al., 2005) and energy insecurity (Awerbuch, 2006; Yergin, 2006; Flavin et al., 2006). For instance, Denmark's energy policy calls for sourcing 100% of the energy from renewables by 2050 (Lund and Matheisen, 2009). The Scottish government will strive to produce 40% of its electricity from renewable energies by 2020 (Scottish Executive, 2003). Similarly, European Union Energy Council (2008) aims to provide 20% of its energy from renewables by 2020, while in China the share of renewables will increase to 16% of total primary energy (Martinot et al., 2007). To date, the U.S. has no federally defined renewable energy target (Delmas and Montes-Sancho, 2011). However, mandates such as Renewable Portfolio Standard (RPS) and the Mandatory Green Power Option (MGPO) have been implemented in some states, enforcing the use of renewable energy sources to specified levels. Furthermore, the US Energy Security and Independence Act of 2007 mandates production of 36 billion gallons of biofuel per year by 2022 (US Congress, 2007).

Comprehensive assessment of diverse energy technologies with different characteristics, limitations, and requirements is a critical challenge for effective energy policy. It is difficult, if not impossible, to determine the optimal share of different energy sources in the energy portfolio, in order to meet disparate sectorial energy demands (e.g., society, economic sector,

environmental agencies, and political parties) with maximum stakeholder satisfaction. As an important step in this process, effective energy policy should recognize the requirements, limitations, and efficiency of different energy technologies. Despite potentially significant impacts on energy production scheme, regional limitations such as economic and natural resource availability and potential environmental impacts of energy production are not explicitly incorporated in integrated regional energy planning frameworks. Jacobson (2009) investigated the energy solutions to global warming and energy security by simultaneously considering different criteria such as water use, land use, thermal pollution, concluding that wind, solar thermal and geothermal are the most efficient energy sources while biofuels are relatively inferior. As discussed in Chapter 3, the resource use efficiency of different energy alternatives were evaluated with respect to the energy sources' carbon, water, and land footprints, as well as cost of energy production and it was concluded that geothermal, wind, and solar thermal technologies are among the superior options, outperforming biofuels and oil. Accounting for regional limitations is especially critical for renewable energy sources causing energy sprawl (McDonald et al., 2009) because of appreciable natural resource footprint (Bryce, 2011), coupled with the need for fallback energy sources due to intermittency of renewables.

Regional energy production capacity and limitations affect the efficiency of energy sources of different types. For instance, onshore wind is an efficient energy source with close to zero emissions, fairly low prices, and availability in many areas, gaining increasing popularity in many countries (Herbert et al., 2007). However, wind turbines require considerable land, which may not be accessible in many areas (Mayerhoff et al, 2010). Alternatively, a low-efficiency less land intensive energy source may be preferred. Similarly, a large amount of water is required in

the lifecycle of energy production from biomass (Gerbens-Leenes et al., 2009) and hydropower (Mekonnen, M., Hoekstra, 2012). Hence, the energy mix of a water-scarce region with vast open lands is different from that of a water-abundant region with limited accessible land. Understanding these important environmental tradeoffs can illuminate energy planning.

A number of studies in the literature investigate the solutions to energy planning at regional scale. Examples include Beccali et al. (2003), Cormio et al. (2003), Terrados et al. (2007), Hiremath et al. (2007), Dicorato et al. (2007, 2008), Cai et al. (2009a, 2009b), Arnette and Zobel (2011), Derakhshan and Fogelholm (2011), Dzene et al. (2012), and Jebaraj et al. (2012). Most of these studies focus on developing analytical frameworks to deal with the complexity of energy planning and management problems with an emphasis on economic factors and greenhouse gas reduction. The literature is unclear as to how the preference toward different energy options is affected in the face of variable economic, environmental, and natural resource availability and/or constraints. The links between geographically variable resource availability and limitations and favorability of a specific energy source need to be better understood. This is especially important because expansion of some energy sources, mostly renewables (e.g., biofuel and ethanol), is widely advocated as a pathway to sustainability in energy production despite their high water and land footprint.

It is critical to determine the suitability of different renewable and nonrenewable energy sources from a regional-scale resource use perspective. Following Chapter 3, a statewide analysis is performed in this chapter to determine the resource use efficiency of energy alternatives across the U.S. under resource availability and limitations such as regional freshwater resources, available land, emissions cap, and GDP (as a measure of states' economic power). This chapter

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is structured as follows. First, the performance ranges of different renewable and nonrenewable energy sources under a set of sustainability criteria are presented, followed by description of the stochastic multi-criteria analysis framework to evaluate the resource use efficiency scores of the energy sources. Then, the states' resource limitations are discussed along with the outcomes of the analysis. Finally, the counterintuitive results are discussed.

4.2   Method and Data

A stochastic multi-criteria decision making framework is developed in this chapter to evaluate the resource use efficiency scores of energy alternatives, considering a suite of sustainability criteria. The framework facilitates energy planning using a set of multi-criteria analysis methods (MCDM) that evaluate energy sources' efficiency with reference to specific optimization objective functions. Input data, MCDM methods, and the resource use efficiency evaluation framework are discussed in this section.

4.2.1   Sustainability criteria

The sustainability criteria considered in the analysis include carbon footprint, water footprint, land footprint, and cost of energy production. The criteria are selected to create a holistic image of environmental impact, regional resource use efficiency, and capital requirement of energy production from different energy sources. Carbon, water, and land footprints, respectively, represent the amount of CO_2 equivalent (Wiedmann and Minx, 2007; Baldwin, 2006), life-cycle fresh water use (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2007 and 2008), and land requirement (Lugschitz et al., 2011) associated with production of one unit of energy (KWh) from a given energy source. Similarly, cost of energy production is considered in terms of the

budget required to produce one unit of energy. These sustainability criteria are given varying weights based on the greenhouse gas emissions, available budget, available land, and water resources in each state.

Many studies have attempted to quantify the carbon and resource use footprint, as well as cost implication of energy production, providing footprint and cost values that vary depending on the case-specific assumptions and methodologies employed (see for example World Energy Council, 2004; Gerbens-Leenes et al., 2009, McDonald et al., 2009). For instance, the land footprint of onshore wind technology is estimated to be trivial by some studies, mainly due to excluding the inter-turbine space from land footprint calculation, assuming that the land could be used for cultivation and grazing purposes (Lovins, 2011). By contrast, other studies consider inter-turbine space as part of the wind technologies' land footprint, arguing that wind farms cannot be used effectively for other human uses (Brand, 2010). The ranges of footprint values under the aforementioned sustainability criteria for renewable and nonrenewable energy sources are summarized in Table 4.1. The values reported in Table 4.1 have been compiled through a synthetic review of the existing literature on lifecycle analysis of energy production, which is discussed in the previous chapter. In case of significant discrepancy between literature values, the more common values are selected for this analysis. Furthermore, necessary adjustments are applied to the cost values to account for varying value of dollar over different periods of time and different monetary units (e.g., Euro) used to represent energy production cost.

Table 4.1: Performance of energy alternatives under different sustainability criteria

Energy Source Type	Carbon Footprint (g CO$_2$/kWh)	Water Footprint (m^3/GJ)	Land footprint (m^2/GWh)	Cost (cent/kWh)
Ethanol from corn	81-85	78	10667-12500	2-4
Ethanol from sugar cane	19	99	9520	2-4
Biomass: wood-chip	25	42	14433-21800	4-10
Biomass: miscanthus	93	37	14433-21800	4-10
Solar Thermal	8.5-11.3	0.037-0.780	340-680	4-10
Solar Photovoltaic	12.5-104.0	0.042	704-1760	10.9-23.4
Wind: Onshore	6.9-14.5	0.001	2168-2640	4.16-5.72
Wind: Offshore	9.1-22.0	0.001	2168-2640	3.64-8.71
Wave and Tidal	14-119	0.001	33-463	5-15
Hydropower	2-48	22	538-3068	3.25-12.35
Coal	834-1026	0.15-0.58	83-567	3.77-5.85
Oil	657-866	4.29-8.60	1490	8-10
Natural Gas	398-499	0.1	623	5.46-11.96
Nuclear	9-70	0.42-0.76	63-93	4.55-5.46
Geothermal	15.1-55.0	0.005	33-463	1-8

As can be seen in Table 4.1, performance values come with uncertainties that originate from regional and technological variations of energy production processes from different energy technologies. For instance, the carbon footprint of solar photovoltaic ranges from 12.5 to 104 gCO$_2$/KWh, mainly due to the efficiency of the materials, maturity of the energy technology, and sunlight availability in different locations that result in different energy production rates for a given level of emissions. Furthermore, Table 4.1 shows that there are tradeoffs between performance values of energy sources under different criteria. For instance, ethanol from corn is a more favorable energy source than natural gas in terms of carbon emissions and production costs. However, this energy source is extremely more water-intensive and has larger land footprint. Due to such tradeoffs, no energy source is strictly dominating others under all sustainability criteria.

4.2.2 *Stochastic Multi criteria Resource Use Efficiency Evaluaion*

To evaluate the resource use efficiency of the energy sources under such uncertainties, the stochastic MCDM framework, introduced in Chapter 3, is applied here. As discussed earlier, the framework consists of a set of MCDM methods, namely Lexicographic, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Simple Additive Weighting (SAW). These methods, which are discussed in length in Madani et al. (2013), are briefly described in Table 4.2). As the notion of optimality is not the same in different MCDM methods, this approach uses multiple MCDM methods to offset the bias toward optimality.

Table 4.2: Multi criteria decision making methods

Method	Description
Lexicographic	Identifies the most desirable alternative for the most important criterion
TOPSIS	Identifies the alternative with minimum distance from the ideal performance
SAW	Identifies the alternative with highest weighted performance

Due to existing uncertainties in the performance of energy sources under different sustainability criteria, random numbers are generated using a Monte-Carlo selection technique by sampling the footprint ranges of the sustainability criteria, which are weighted based on the availability of resources. A multi-criteria assessment is performed based on the generated random numbers to obtain the most efficient option after 100,000 runs of the model. The most efficient option is then removed from the energy list, followed by re-running the model to identify the next best energy source in an iterative ranking process with 100,000 generations. This process is repeated until the ranking of energy sources under each MCDM method is obtained. Finally, the resource use efficiency scores of alternative energy sources are calculated

by aggregating the outcomes of MCDM methods (equation 1). Scores range from 0 to 100 with larger scores representing higher resource use efficiency.

$$RUE_p = 100(\frac{45 - B_p}{42}) \tag{1}$$

where:

RUE_p: The resource use efficiency score of alternative p; B_p: The overall Borda score of alternative p.

4.3   Regional Resource Availability and Limitations

Criteria weights are determined based on the resource availability and limitations in the states. Table 4.3 provides the states' per capita values of carbon emissions, freshwater withdrawal, available land, and GDP for example US states. Per capita values are measures of the resource availability (freshwater, land, and budget) and emissions within states. According to this table, the availability of resources varies significantly for different locations. For instance, compared to Texas, Colorado has 185% and 100% more water and land availability, respectively. Such variations in resource availability in different locations affect the preference toward energy alternatives with different resource demands.

Table 4.3: States available resources

State	Carbon emissions (metric tons per capita) (EIA, 2013)	Freshwater withdrawal (1000 cubic meters per capita)(USGS, 2005)	Available land (square kilometers per capita) (U.S. Census Bureau, 2013)	Available funds (GDP in 1000 dollars per capita) (Bureau of Economic Analysis, 2012)
Alabama	28.05	2.93	0.03	32
Alaska	55.05	1.73	2.12	62
Arizona	14.50	1.31	0.04	34
Arkansas	22.91	5.46	0.05	32
California	10.03	1.23	0.01	46
Colorado	19.01	3.75	0.05	46

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Connecticut	10.52	0.34	0.00	56
Delaware	13.74	0.99	0.01	64
Florida	13.19	0.51	0.01	35
Georgia	17.60	0.76	0.02	37
Hawaii	14.37	0.48	0.01	45
Idaho	10.56	17.47	0.14	33
Illinois	17.87	1.62	0.01	44
Indiana	33.60	2.02	0.01	37
Iowa	30.00	1.55	0.05	42
Kansas	25.97	1.85	0.08	40
Kentucky	34.82	1.39	0.02	33
Louisiana	46.97	3.51	0.02	46
Maine	14.05	0.49	0.06	34
Maryland	12.39	0.33	0.00	46
Massachusetts	11.10	0.26	0.00	52
Michigan	16.62	1.62	0.01	33
Minnesota	17.70	1.06	0.04	46
Mississippi	22.25	1.33	0.04	29
Missouri	22.63	2.03	0.03	36
Montana	35.69	14.29	0.39	33
Nebraska	26.63	9.68	0.11	44
Nevada	14.40	1.25	0.11	42
New Hampshire	12.78	0.46	0.02	42
New Jersey	13.58	0.31	0.00	49
New Mexico	27.06	2.29	0.16	35
New York	8.90	0.73	0.01	51
North Carolina	15.15	1.67	0.01	40
North Dakota	75.36	2.86	0.28	49
Ohio	21.48	1.38	0.01	36
Oklahoma	27.96	0.58	0.05	36
Oregon	10.54	2.61	0.06	46
Pennsylvania	20.13	1.04	0.01	39
Rhode Island	10.59	0.18	0.00	41
South Carolina	18.68	2.38	0.00	31
South Dakota	18.64	0.85	0.24	42
Tennessee	17.19	2.37	0.02	36
Texas	26.36	1.32	0.03	45
Utah	22.79	2.40	0.08	38
Vermont	9.70	1.16	0.04	37
Virginia	13.92	1.24	0.01	48
Washington	11.50	1.16	0.03	46
West Virginia	54.21	3.65	0.03	29
Wisconsin	17.53	2.10	0.02	39
Wyoming	119.08	11.21	0.46	59

The U.S. average regional freshwater resources and available land, emissions and GDP are assumed to be the benchmark for calculating weights using the method developed by Journel and Rao (1996). The Kriging weighting method, through the following equations, calculates the weights of decision criteria based on the numerical distance of the states' values from the benchmark.

$$v_{ij} = \begin{cases} \frac{S_i - V_{ij}}{S_i}, & i\ representing\ water, land, or\ budget \\ \frac{V_{ij} - S_i}{S_i}, & i\ representing\ emissions \end{cases} \quad (2)$$

$$\eta_j = \begin{cases} 0, & v_{ij} \geq 0 \\ \left|min\ v_{ij}\right|, & \exists i\ |\ v_{ij} < 0 \end{cases} \quad (3)$$

$$\omega_{ij} = \frac{v_{ij} + \eta_j}{\sum_i(v_{ij} + \eta_j)} \quad (4)$$

where:

S_i: Standard value for criterion i; V_{ij}: Existing value for criterion i in state j; v_{ij}: Relative weight for criterion i in state j; η_j: Correction factor for state j; ω_{ij}: Weight of criterion i in state j;

For states' available resources, namely per capita of freshwater, land, and GDP, the values that are greater than benchmark are desirable, representing excess of such resources in the state, while lower than benchmark values imply resource shortage. As for carbon emissions, lower than benchmark values are favorable. Desirable condition for a given resource in a state is represented as negative relative weight (v_{ij}) for corresponding criterion, reflecting the non-criticality of such resource in that state, which results in a zero weight upon applying the correction factor (η_j) to the relative weights. In the State of Colorado, for example, the land availability is the most critical limitation (higher weight) for energy production purposes,

followed by available budget and emissions cap. The water availability is not a limiting parameter for energy production in Colorado, as the amount of available water resources (3760 m^3 per capita) in this state exceeds the benchmark (2504 m^3 per capita). Hence, the energy sources with large land footprints are expected to have lower resource use efficiency scores when compared to the case with no resource limitations. Table 4.4 shows the calculated criteria weights for selected states.

Table 4.4: States weights of resource use efficiency assessment criteria

State	Carbon emissions	Freshwater withdrawal	Available land	Available funds
Alabama	0.19	0.00	0.49	0.32
Alaska	0.34	0.33	0.00	0.33
Arizona	0.00	0.37	0.41	0.22
Arkansas	0.24	0.00	0.37	0.39
California	0.29	0.35	0.37	0.00
Colorado	0.16	0.00	0.52	0.32
Connecticut	0.00	0.38	0.41	0.21
Delaware	0.00	0.29	0.38	0.33
Florida	0.19	0.40	0.42	0.00
Georgia	0.06	0.44	0.50	0.00
Hawaii	0.00	0.33	0.35	0.32
Idaho	0.30	0.00	0.31	0.38
Illinois	0.21	0.34	0.45	0.00
Indiana	0.27	0.13	0.56	0.05
Iowa	0.16	0.23	0.31	0.30
Kansas	0.08	0.22	0.22	0.48
Kentucky	0.22	0.21	0.36	0.21
Louisiana	0.44	0.00	0.37	0.19
Maine	0.00	0.37	0.25	0.38
Maryland	0.00	0.42	0.44	0.14
Massachusetts	0.00	0.46	0.48	0.06
Michigan	0.00	0.36	0.63	0.01
Minnesota	0.00	0.41	0.43	0.15
Mississippi	0.00	0.28	0.34	0.38
Missouri	0.00	0.20	0.63	0.17
Montana	0.41	0.00	0.15	0.44
Nebraska	0.32	0.00	0.30	0.38
Nevada	0.00	0.41	0.15	0.44
New Hampshire	0.00	0.34	0.34	0.33
New Jersey	0.07	0.45	0.48	0.00
New Mexico	0.27	0.24	0.00	0.49

New York	0.23	0.37	0.39	0.00
North Carolina	0.05	0.36	0.59	0.00
North Dakota	0.48	0.20	0.00	0.32
Ohio	0.17	0.34	0.49	0.00
Oklahoma	0.09	0.39	0.27	0.25
Oregon	0.00	0.22	0.40	0.38
Pennsylvania	0.19	0.37	0.45	0.00
Rhode Island	0.00	0.34	0.35	0.32
South Carolina	0.00	0.12	0.56	0.31
South Dakota	0.21	0.37	0.00	0.41
Tennessee	0.00	0.18	0.61	0.21
Texas	0.30	0.34	0.36	0.00
Utah	0.00	0.08	0.28	0.63
Vermont	0.00	0.29	0.32	0.39
Virginia	0.02	0.41	0.57	0.00
Washington	0.00	0.40	0.48	0.12
West Virginia	0.42	0.00	0.27	0.30
Wisconsin	0.00	0.23	0.55	0.22
Wyoming	0.63	0.01	0.00	0.37
Georgia	0.06	0.44	0.50	0
Texas	0.30	0.34	0.36	0
Utah	0	0.08	0.28	0.64

4.4   Results And Discussion

4.4.1   Resource Use Efficiency Evaluation of the U.S. Energy Sources

In Chapter 3, the resource use efficiency scores of different energy alternatives in the U.S. were reported assuming unlimited resources for energy production. In this hypothetical case, the four sustainability criteria were considered to be equally important, each having a criterion weight of 25%. The results are shown in Figure 4.1 where energy sources are classified into three major categories; energy sources with high (green), medium (yellow), and low (red) resource use efficiency scores. The figure illustrates that when the regional resource availability and limitations are left out from the analysis, geothermal, wind, solar thermal energies top the list of the most resource use efficient energy sources, whereas coal, biomass, ethanol, and oil lie at the bottom.
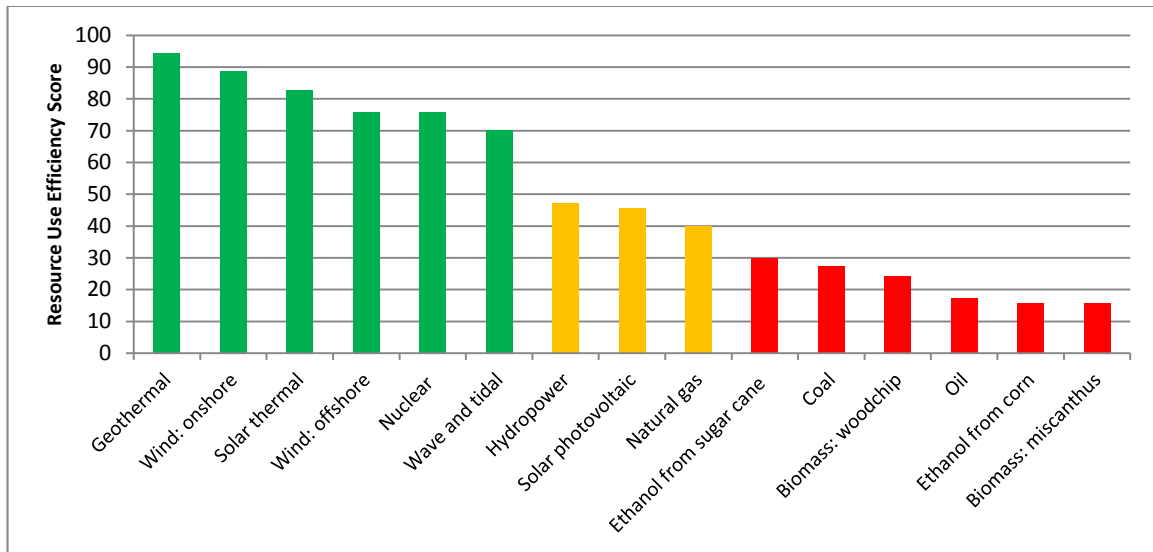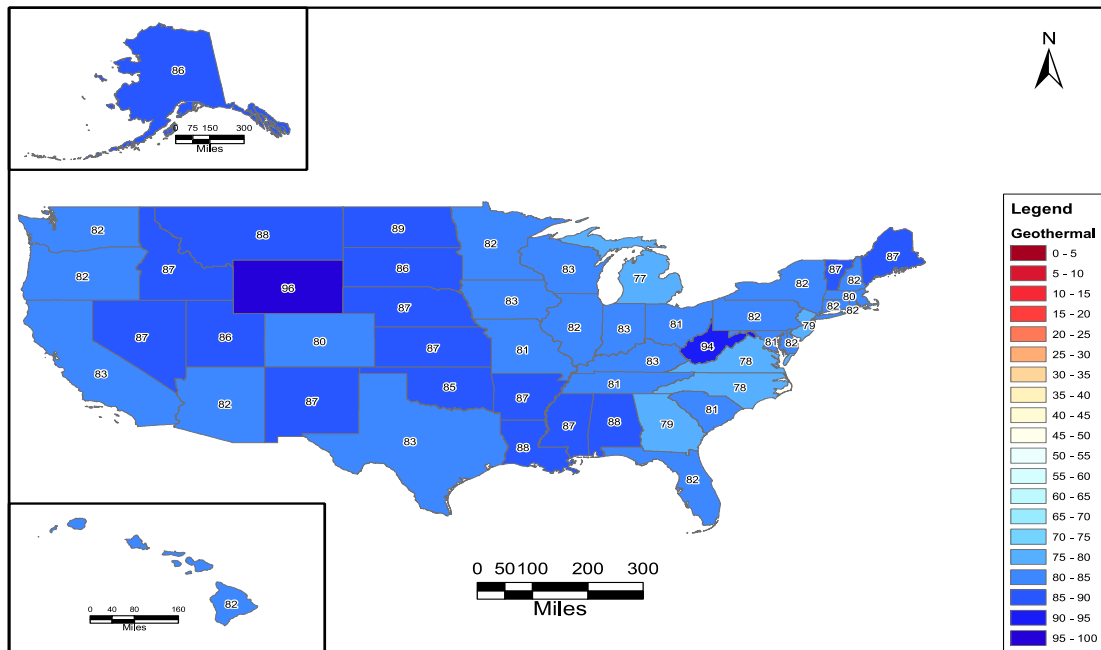
Figure 4.1: Resource use efficiency scores of different energy sources (0-100)

Figure 4.2 illustrates the statewide resource use efficiency maps for the energy sources with high resource use efficiency scores in the absence of resource limitations. According to this figure, geothermal is the most efficient energy source for most states. This energy source has fairly small water and land footprints and cost, but considerable carbon emission compared to other green energy sources. From a resource use perspective, geothermal energy efficiency ranges from 77 to 96, depending mainly on the state's emission caps. Also, wind onshore is one of the cheapest renewable energy sources, mostly due to relatively low capital investments as well as transportation and maintenance costs. Taking into account the available resources in different states, as shown in figure 4.2, onshore wind is one of the most attractive energy sources across the U.S., with higher resource use efficiency scores in the northeastern states. Onshore wind has minimal water and carbon footprints. However, the occupied land by wind farms is significant if the spaces between turbines are also taken into account. The resource use efficiency of onshore wind ranges from 60 to 95, depending on the land use limitations within each state.

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Compared to onshore wind technology, offshore wind has higher carbon footprint and cost values, mainly due to transportation. Although offshore wind is not feasible for most states, according to Figure 4.2, it is still potentially one of the most resource use efficient energy sources. The resource use efficiency of offshore wind ranges from 56 to 86 over the U.S. and largely depends on the budget availability and emissions cap in a given state.

Disregarding effects of temperature, solar thermal has a high resource use efficiency value across the U.S., with mid-eastern states such as Louisiana, Arkansas, and Missouri having higher values compared to other states (Figure 4.2). The resource use efficiency of solar thermal ranges from 69 to 90, mostly due to variations in the availability of water resources in different states. Emissions cap is not a limiting factor in the resource use efficiency of this technology due to low carbon footprints. However, relatively high operating cost of the system surpasses the benchmark, lowering the resource use efficiency of solar thermal technology for states with tight budgets. Nuclear energy is the most resource use efficient nonrenewable energy source for most states, having the smallest land footprint among all energy sources, as well as relatively low cost. The carbon and water footprints of this technology, however, surpass those of renewables such as wind and solar technologies. Hence, nuclear energy has a large resource use efficiency score for the states with significant land inaccessibility or budget constraint, whereas it has a lower score for states with emission caps or water shortage. The resource use efficiency score of nuclear ranges from 74 to 90. Similar to offshore wind energy, wave and tidal energies require the availability of a body of water to operate. The low electricity output of these technologies yield large carbon footprint and cost values, leading to low resource use efficiency scores for locations with emissions cap or budget constraints. Assuming all required conditions exist for all
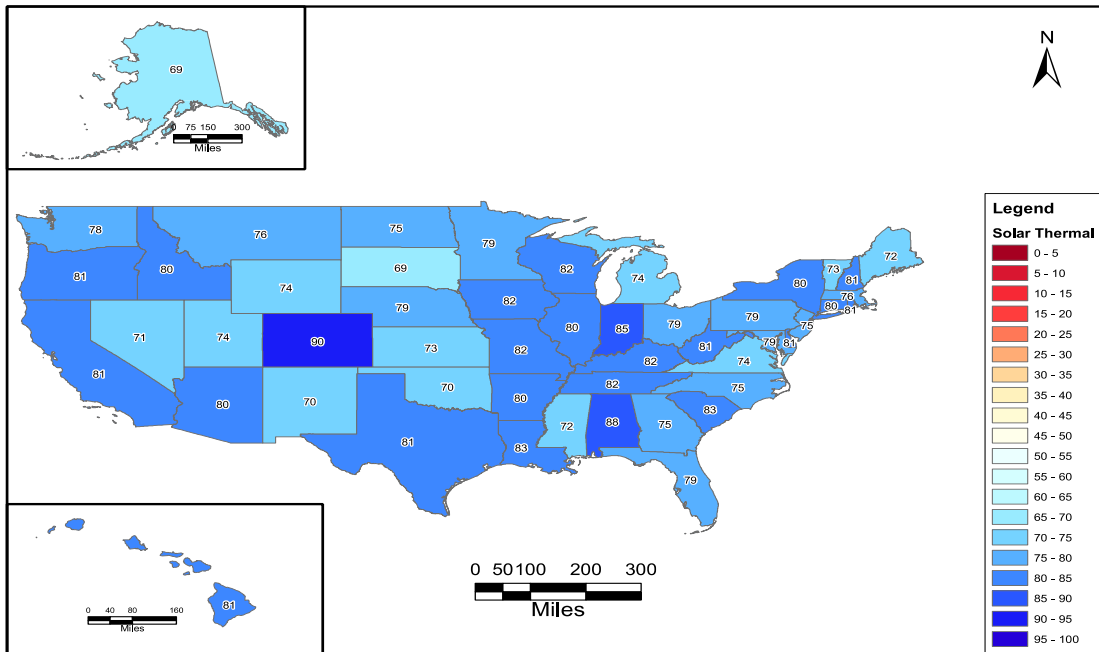
states, from a resource use perspective, the efficiency of wave and tidal energy sources range from 49 to 82.

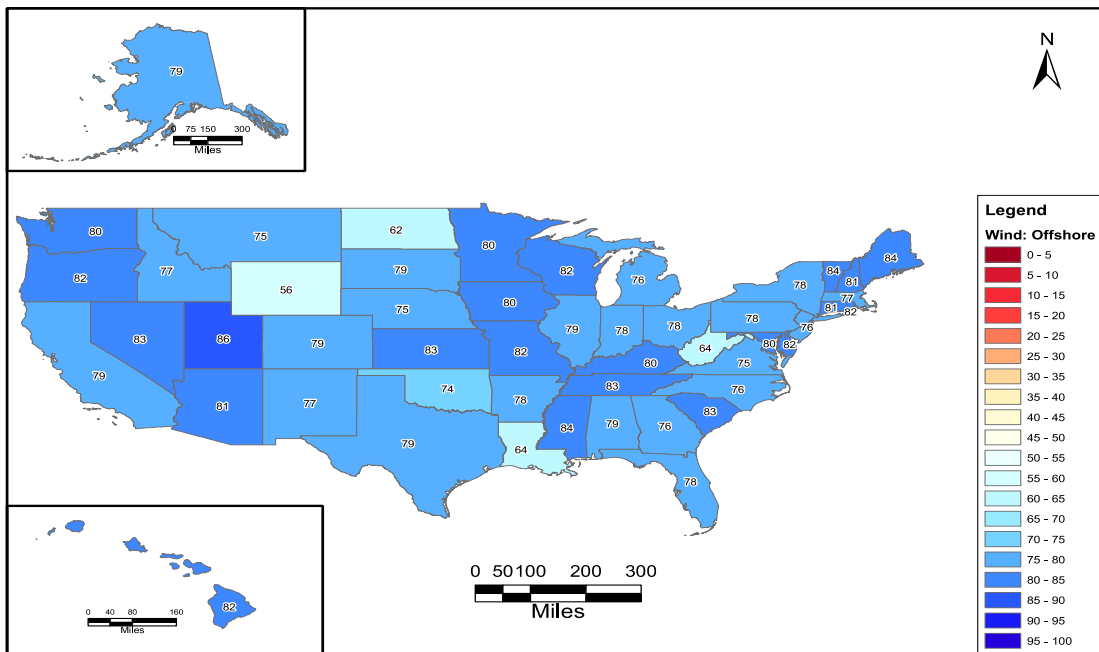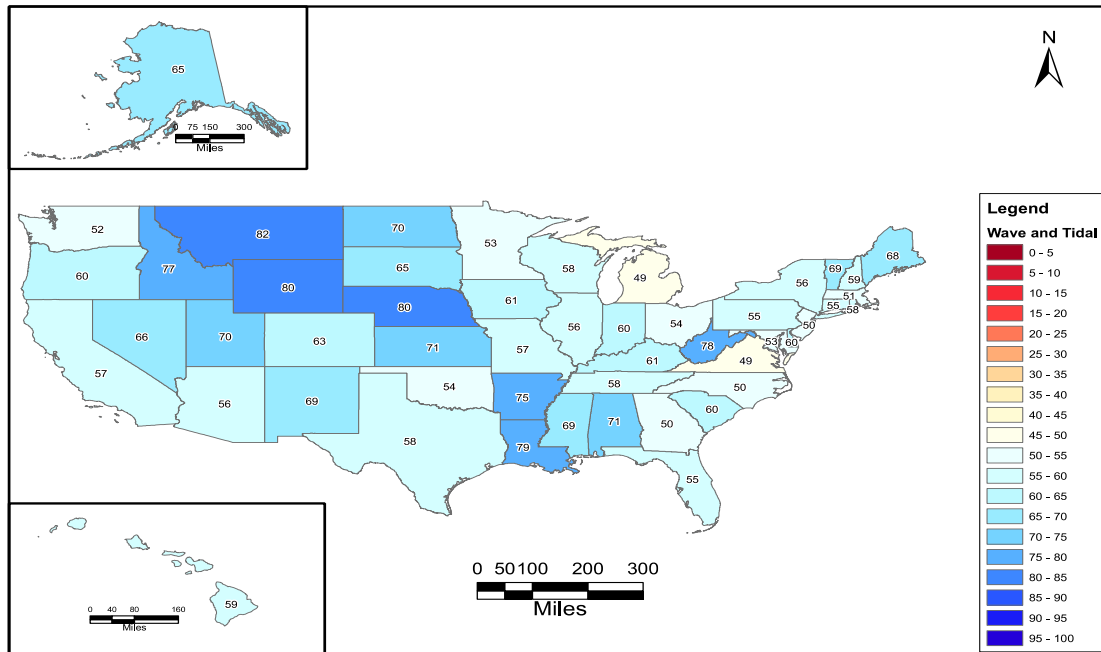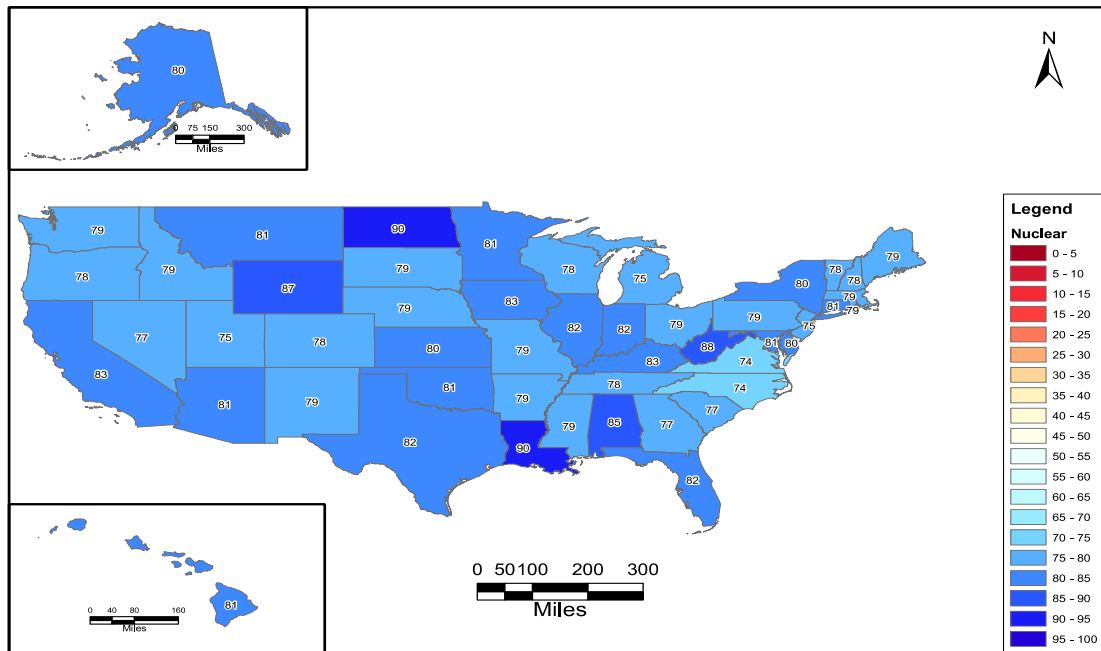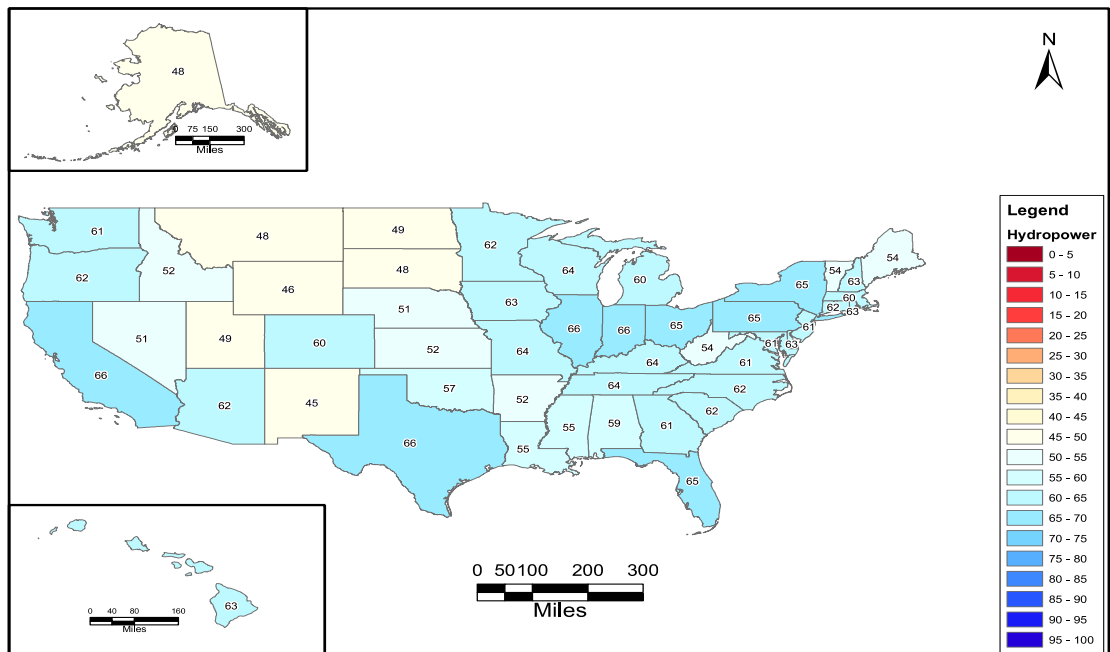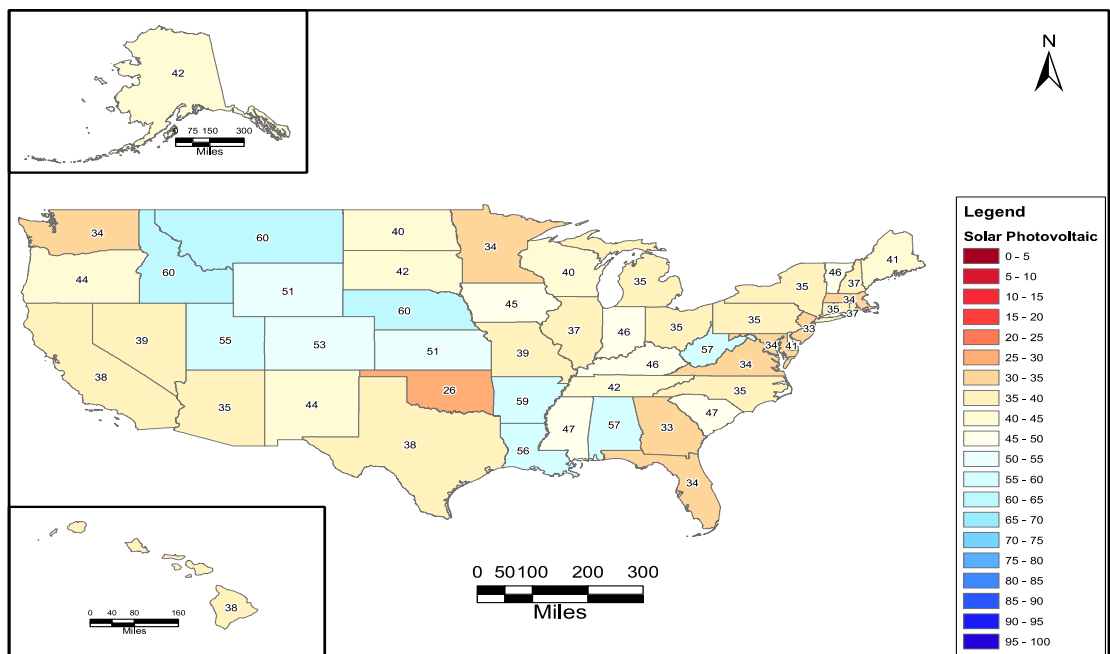

(a)
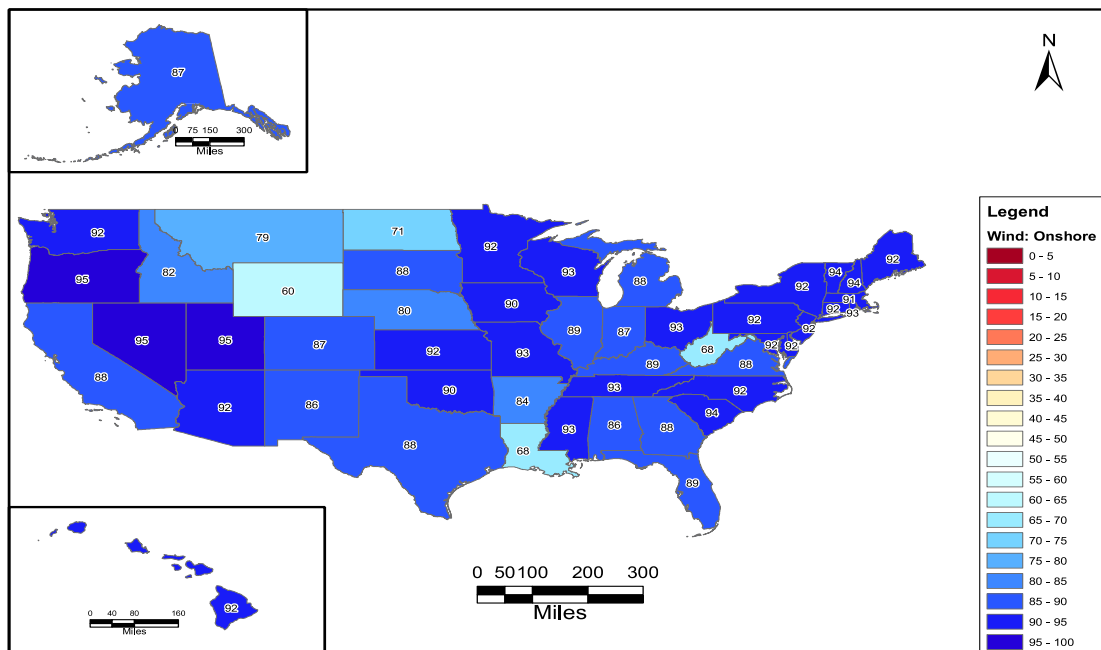
(b)

(c)

(d)

(e)

(f)

Figure 4.2: Statewide resource use efficiency maps for energy sources with high resource use efficiency: (a) Geothermal, (b) Onshore wind, (c) Solar thermal, (d) Offshore wind, (e) Wave and tidal, (f) Nuclear.
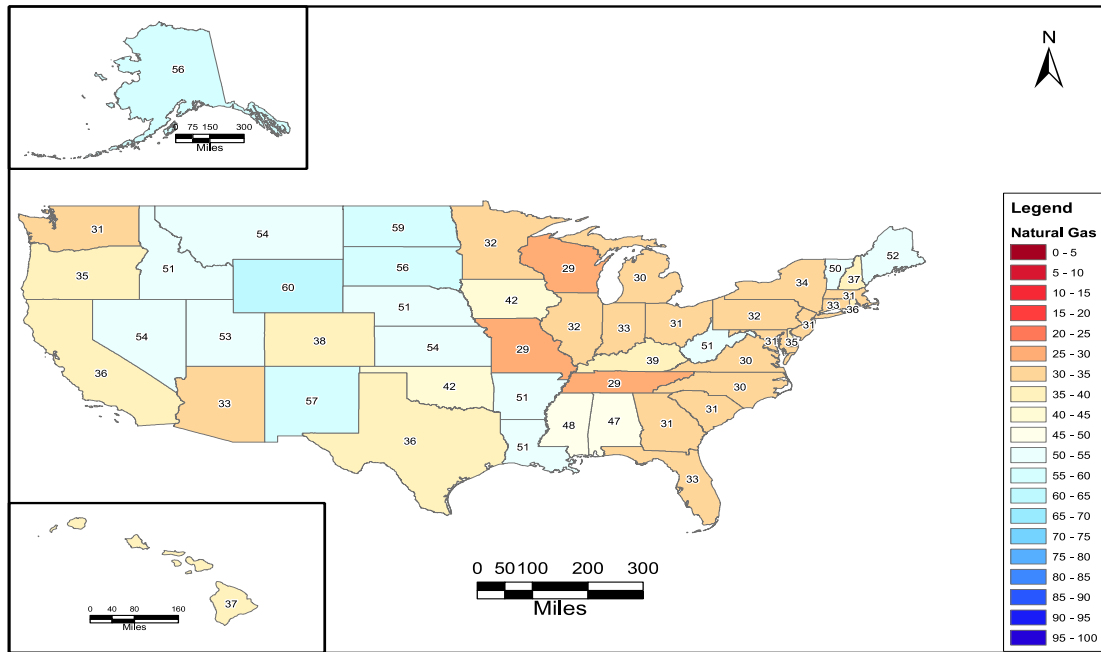
The resource use efficiency maps for energy technologies with medium resource use efficiency scores are shown in Figure 4.3. These include hydropower, solar photovoltaic, and natural gas. Hydropower is the most prevalent renewable energy source in the U.S., being responsible for almost 6% of electricity generation in the nation (NRDC, 2013). From a resource use perspective, hydropower has considerable water and land footprints as well as cost. It also has higher carbon footprints compared to wind and solar energy technologies. Assuming the presence of required conditions in any given state, the resource use efficiency of hydropower ranges from 45 to 66. The sensitivity of hydropower's resource use efficiency score comes mostly from water resources and land availability limitations coupled with budget constraints in most states. Compared to solar thermal (CSP), photovoltaic (PV) technology has lower water footprint but relatively higher than benchmark cost value followed by relatively large land footprint and carbon emissions, leading to lower resource use efficiency for most states. The resource use efficiency score of solar photovoltaic ranges from 26 to 60. This variation is mainly due to different budget limitations in states as well as various emission caps and land accessibility. Despite coal and oil, natural gas is seen as a green energy source due to lower carbon emissions. In fact, natural gas is a more appropriate energy source in most states compared to other forms of fossil fuels. The resource use efficiency of natural gas ranges from 29 to 54, with lower scores for eastern states, mostly due to the existing emissions limitations for those states.

(a)

(b)

(c)

Figure 4.3: Statewide resource use efficiency maps for energy sources with medium resource use efficiency: (a) Hydropower, (b) Solar photovoltaic, (c) Natural gas.

Figure 4.4 presents the resource use efficiency maps of the energy sources with low resource use efficiency scores. These energy sources include different types of ethanol and biofuel, coal, and oil. With large land and water footprints, ethanol from corn is an inferior energy source for many locations with low water and land availability such as some mid-western states, aggravating water stress in the long run. In addition, states with high water availability but restricted land such as West Virginia and Delaware in the East Coast are less favorable for ethanol production from corn compared to states with high water and land accessibility such as Michigan and Virginia. Unlike corn, production of ethanol from sugarcane is deemed to be more justified. Furthermore, the carbon emissions from processing the sugarcane to ethanol are lower than corn because sugarcane does not require fermentation (Shapouri and Salassi, 2006). However, as an energy crop, sugarcane has a slightly higher water footprint compared to corn.

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As demonstrated in the maps, sugarcane has a higher resource use efficiency score than corn in most states, while the lower score in other states such as Alabama is mostly because of the water scarcity and low emission caps.

Similar to ethanol, the amount of water required for cooling purposes in coal power plants is a significant issue. However, high carbon emissions are the most important limitation of power generation from coal in most states. In fact, out of all the energy sources, coal has the highest carbon footprint, leading to very low resource use efficiency score in most states, especially eastern states with low emission caps. According to Figure 4.4, North Dakota, South Dakota, New Mexico, Wyoming, and Alaska are the states where coal has the highest efficiency score due to relatively low emissions. Like coal, availability of oil reserves in a given region does not necessarily guarantee high resource use efficiency for oil in that region. The resource use efficiency score of oil ranges from 19 to 58, depending on the availability of resources in a given state. Compared to coal, oil has higher water footprint values, land footprint, and cost. However, in most states oil is a more attractive energy source than coal, mainly due to lower carbon emissions that is the most important limitation in majority of the states.

Energy production from both miscanthus and wood-chips have large land footprints and low costs, whereas miscanthus has a much larger carbon footprint as it requires harvest by machinery, but a lower water footprint due to its low moisture requirements for growth. As shown in Figure 4.4, miscanthus has a lower resource use efficiency score than wood-chips in most states, primarily because of the carbon emission constraints in different U.S. regions. Unless fund availability is a major concern in energy production, these energy sources are not competitive with other energy sources with regards to carbon and land footprints. The resource

use efficiency score ranges from 18 to 38 for biomass from miscanthus, while it ranges from 19

to 47 for wood-chips, implying wood-chip's higher sensitivity to resource availability variations.

(a)

(b)

(c)

(d)

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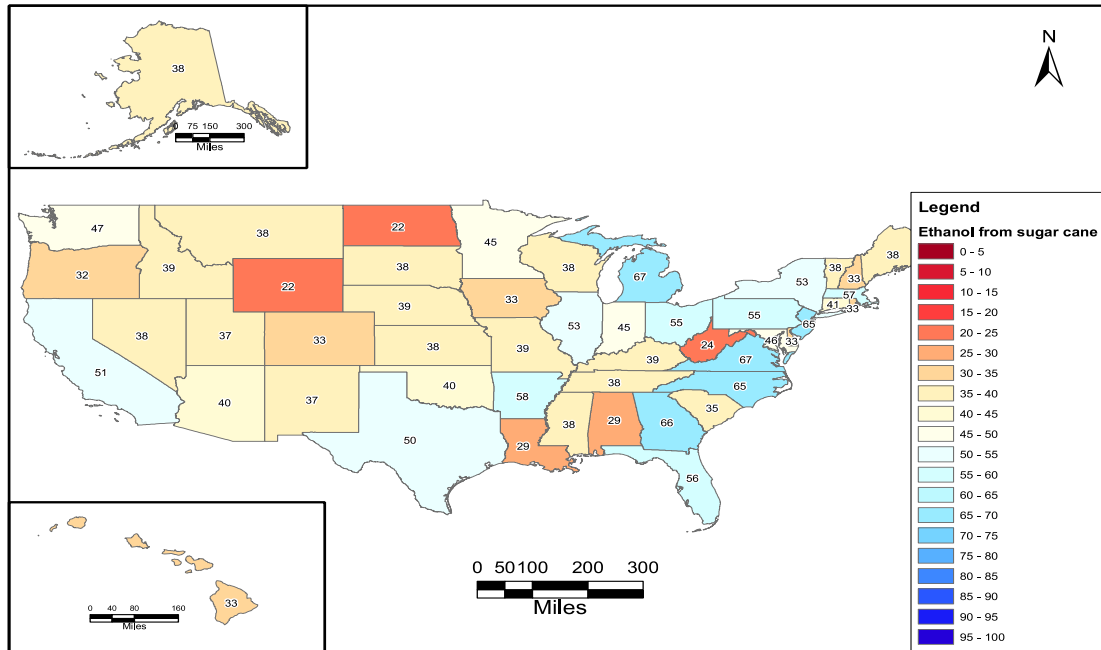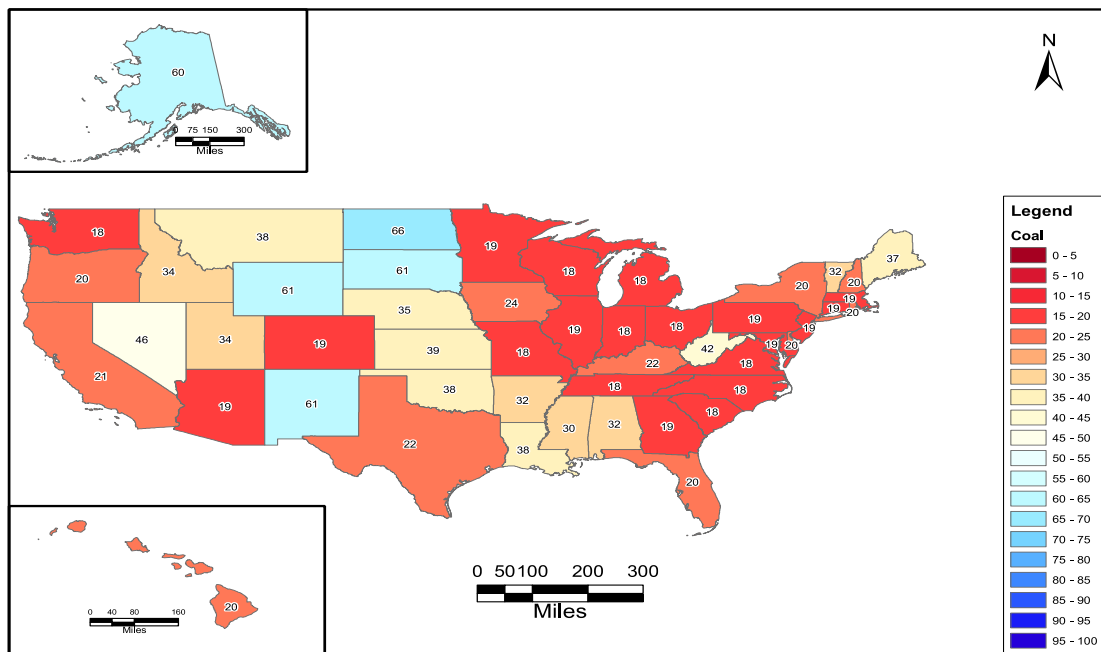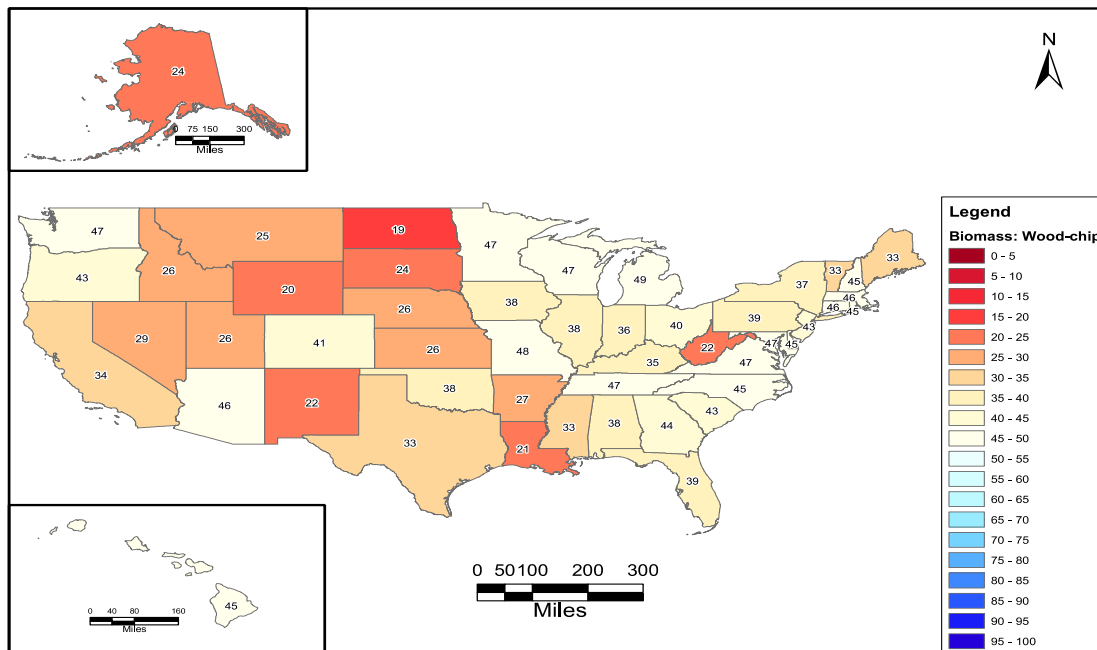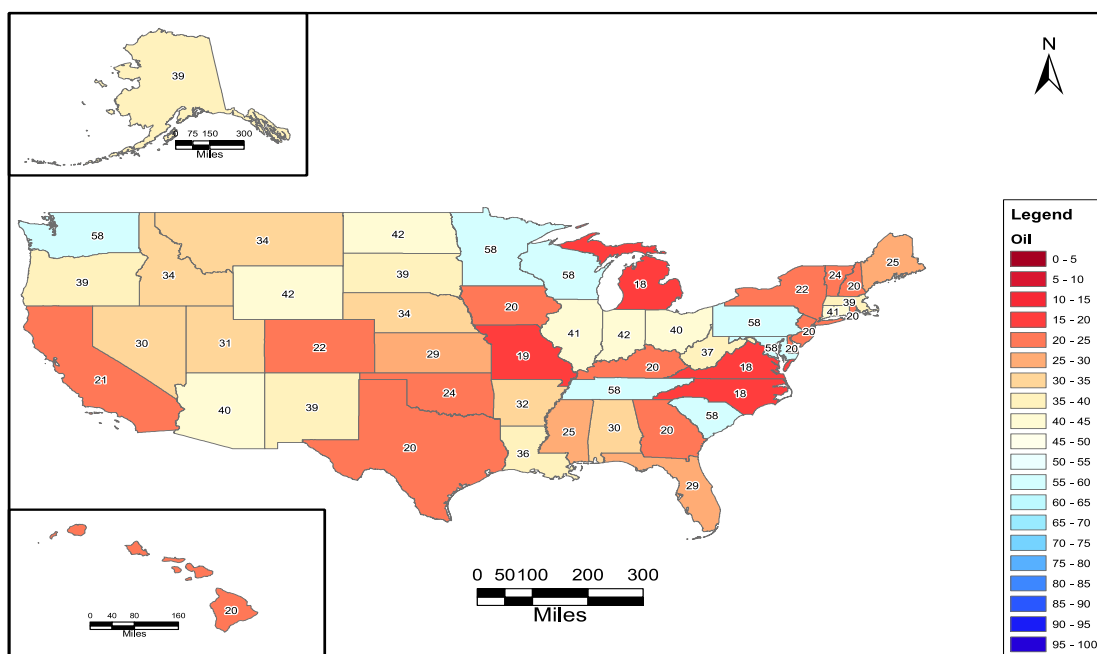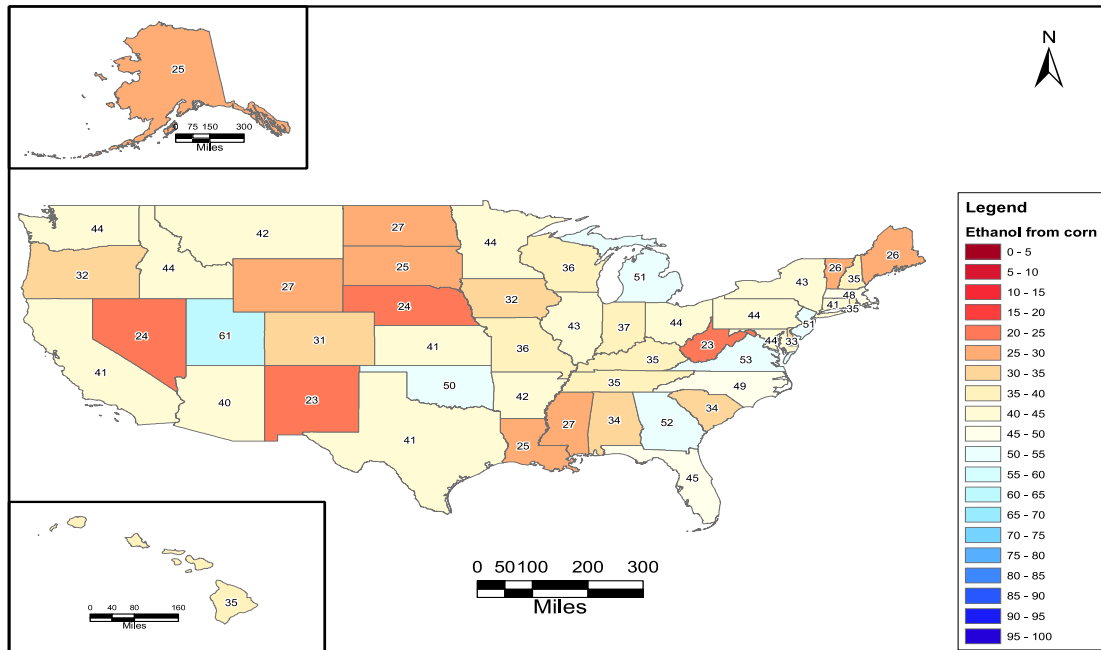
(e)
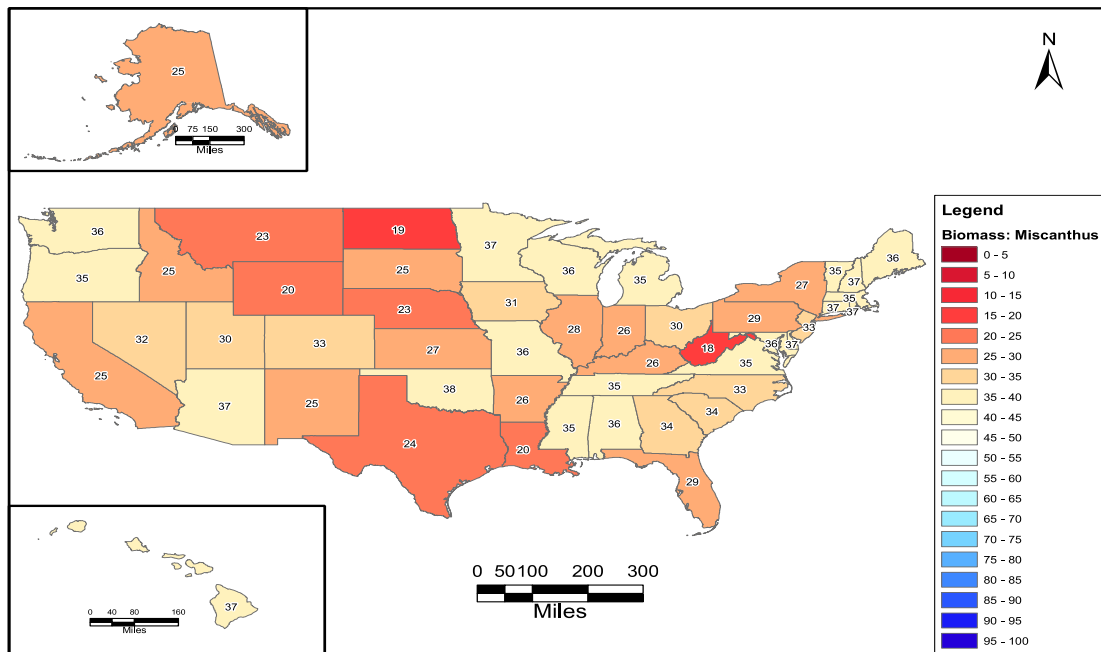
(f)

Figure 4.4: Statewide resource use efficiency maps for energy sources with low resource use efficiency: (a) Ethanol from Sugarcane, (b) Coal, (c) Biomass: woodchip, (d) Oil, (e) Ethanol from corn, (f) Biomass: Miscanthus.

4.4.2   State-Level Energy Production Planning

The heterogeneity of the ranking of different energy sources arising from regional resource availability and limitations bears important implications for state-level energy production planning as well as the U.S. energy production outlook. This point is discussed by taking a closer look at the resource use efficiency ranking of energy sources for the states of California, Wyoming, and Maryland.

Figure 4.5 illustrates the resource use efficiency scores of the energy technologies for California. According to Figure 4.5, the most resource use efficient energy technology is onshore wind, followed by nuclear energy. Indeed, the preference toward energy alternatives considering sustainability criteria does not follow the same order as in the analysis under no resource limitation conditions for the state. For instance, ethanol from corn and sugarcane are more attractive than solar photovoltaic energy technology, mainly due to budget limitations in the State of California. In addition, hydropower is 40% more attractive in this state compared to no resource limitation conditions. Despite its growing popularity in the State of California, solar photovoltaic is 16% less efficient from a resource use perspective. Furthermore, wave and tidal energies are 18% less efficient in this state and are not found to be among energy sources with high resource use efficiency. Also, biomass from miscanthus is 67% more resource use efficient and is more attractive than coal and oil.
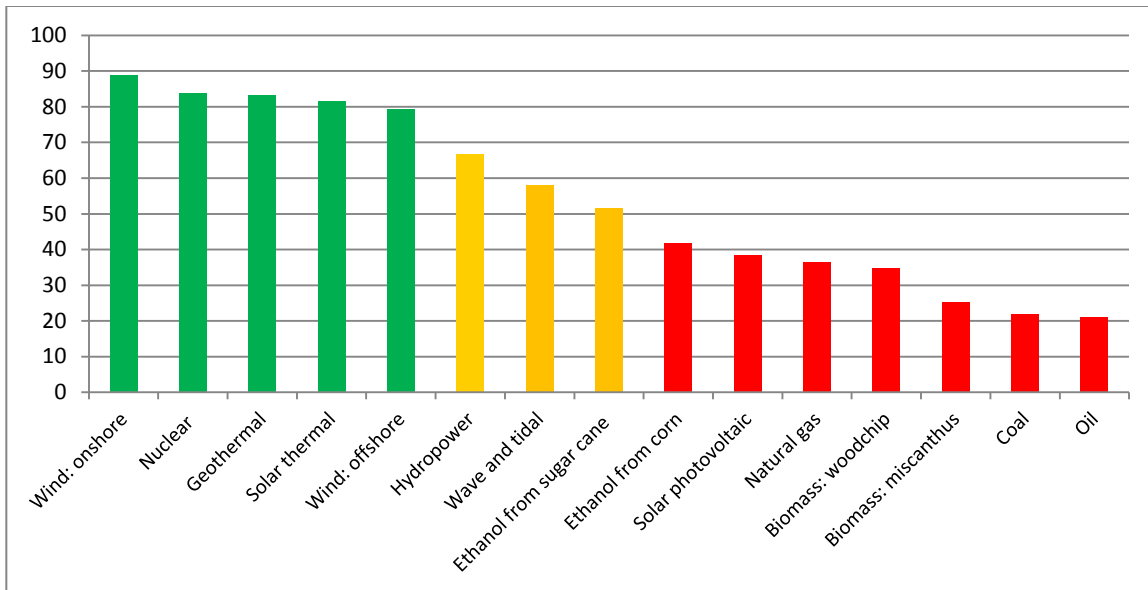
Figure 4.5: Resource use efficiency scores of different energy sources for California

The resource use efficiency scores of energy alternatives for the State of Wyoming are shown in Figure 4.6. In this state, wind energy technologies are not considered options with high resource use efficiency scores. In fact, traditional fossil fuels such as coal and natural gas are more efficient than wind energy in this state. Compared to the analysis with no resource limitations, coal is 130% more efficient in Wyoming from a resource use perspective. Also, natural gas is 50% more resource use efficient in this state. This is mostly due to the high emissions cap that allows for production of energy from fossil fuels with high carbon emissions. On the other hand, the resource use efficiency score of onshore wind energy technology is 32% lower compared to no resource limitation conditions. The reason for low resource use efficiency of wind energy is the low land availability that limits the implementation of wind energy with relatively large land footprint. Unlike the State of California, hydropower does not have a significant resource use efficiency score in Wyoming. Similarly, solar photovoltaic has a lower resource use efficiency score than coal and natural gas. In addition, different ethanol and biomass

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types are among the least resource use efficient energy sources in Wyoming. The main reason for this is that such energy sources demand for considerable amount of water resources, which is typically a scarce resource in that state.
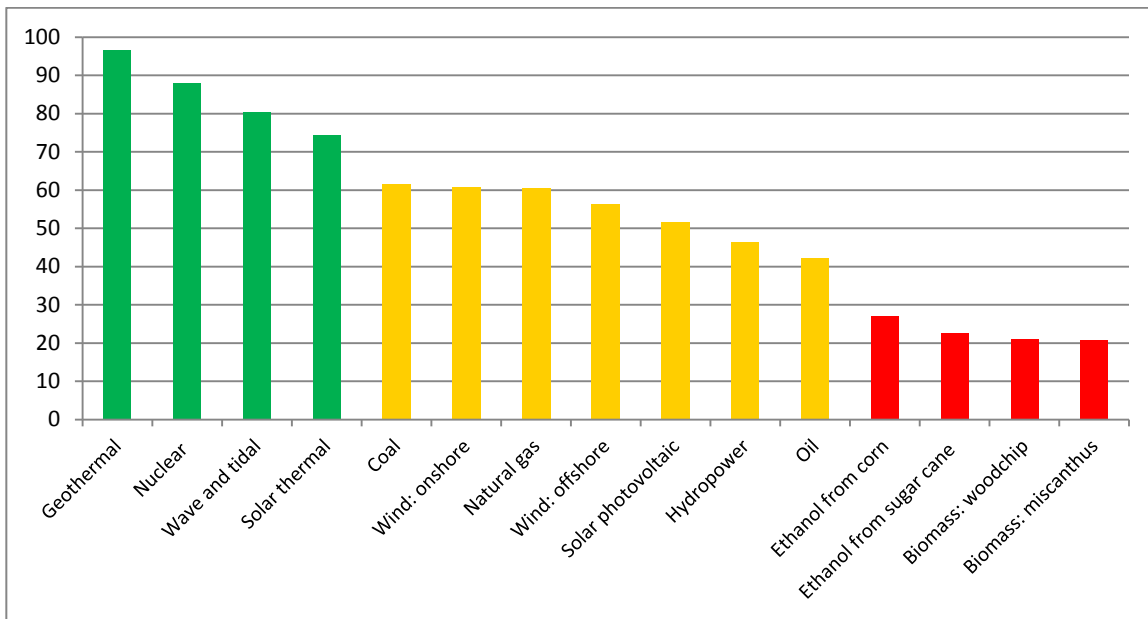
Figure 4.6: Resource use efficiency scores of different energy sources for Wyoming

Figure 4.7 shows the resource use efficiency map for the State of Maryland. Our analysis indicates that from a resource use perspective, the efficiency score of oil increases by 240% compared to the case with no resource limitations conditions (Figure 4.1). In this state, oil is found to be more resource use efficient than other fossil fuel types, ethanol, biomass, and solar photovoltaic. Similarly, when the sustainability criteria are taken into account, the resource use efficiency of hydropower in Maryland is over 30% higher than the U.S. hydropower resource use efficiency under no resource limitation condition. On the other hand, the resource use efficiency of solar photovoltaic technology drops by almost 25%. The main reason for low resource use efficiency score of solar photovoltaic is the significant budget limitations in Maryland. Despite

the relatively high resource use efficiency score of coal in Wyoming, this energy source is the

least resource use efficient energy option among all in Maryland.
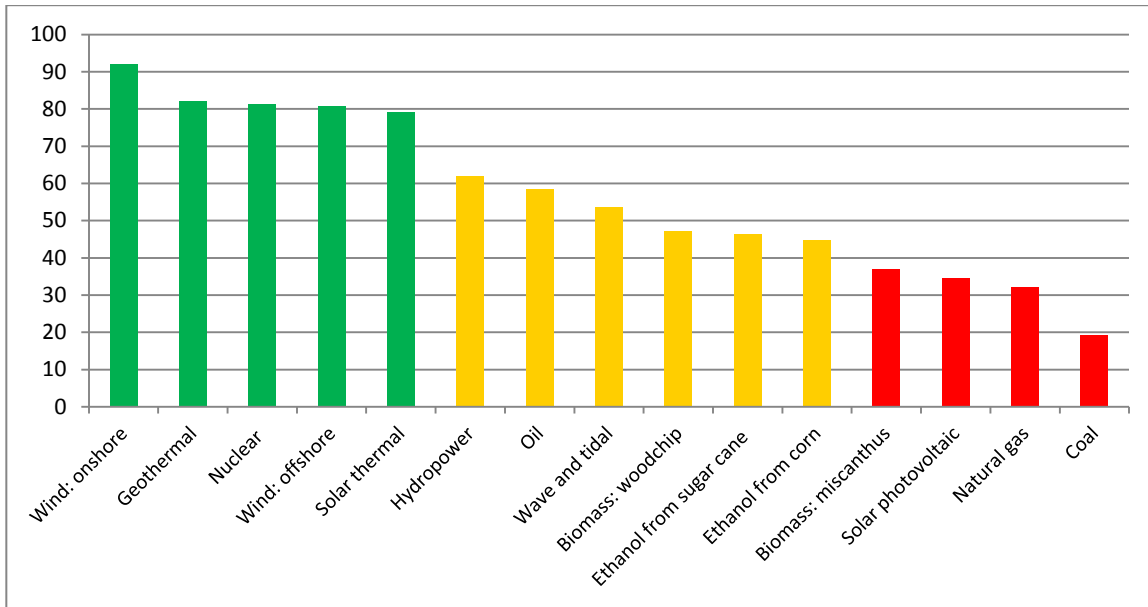
Figure 4.7: Resource use efficiency scores of different energy sources for Maryland

4.4.3 Implications for the U.S. Energy Production Outlook

Our results clearly indicate that the resource use efficiency of the energy sources is extremely

sensitive to availability of resources and existing limitations within a specific location. In fact,

various resource availabilities and limitations affect the preference toward different energy

options. The above examples indicate that not only the energy planning for cost or carbon

emissions reduction alone cannot be sustainable, but it also clarifies that not all renewable energy

sources with high resource use efficiency scores in the absence of resource constraints are

appropriate for all locations. In fact, high-level energy enterprise resource planning provides

valuable insights for decision makers to establish the appropriate goals and milestones to meet

future energy demand and secure a continuous energy supply, but it is unable to prescribe

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appropriate localized energy mix. For this purpose, the large scale energy resource planning should be downscaled to account for the local environmental and economic resource availabilities and limitations.

In the U.S., for instance, the production of 36 billion gallons of biofuel by 2022 requires extensive amounts of water and land. This policy could be questioned based on the water resources and land limitations in different states, especially those with limited water and land resources. 95% of ethanol is produced in 3 farm-production regions; region 5 (Iowa, Indiana, Illinois, Ohio, and Missouri), Region 6 (Minnesota, Wisconsin, and Michigan), and Region 7 (North Dakota, South Dakota, Nebraska, and Kansas) (RFA, 2007). Ethanol production in these regions demand for 10, 17, and 324 gallons of water per one gallon of ethanol, respectively (Wu, 2008). Our analysis indicates that corn-based ethanol production in the States of Iowa, North Dakota, South Dakota, and Nebraska is not efficient from resource use perspective. This is especially true for the last three states in region 7 with significant corn production water demand. Such policies will eventually leave significant negative impacts on the environment. Indeed, the effects of ethanol production from corn on the water resources have already been seen in particular states, leading to severe drought conditions in production zones.

California, Arizona, Nevada, and New Mexico are the top producers of energy from solar photovoltaic technology as a part of their renewable portfolio standards, although this energy source is one of the low efficiency energy sources for these states from a resource use perspective. As another example, disregarding the safety issues as a major constraint in further development of nuclear energy in the U.S., based on our analysis, it is one the most resource use efficient energy sources for most states. In fact, nuclear energy is preferable over some

renewable energy sources for most locations. Nevertheless, the investment on this energy source is trivial when compared to some renewables such as biofuels.

4.5   Conclusions

The efficiency of energy technologies is tied to the amount of resources they use to produce energy. The availability of such resources might vary for different locations, constraining the production of energy from specific energy sources that demand for extensive use of limited local resources. The results of our analysis indicate clearly that the localized energy efficiency assessment affects the preference toward energy alternatives. This means that some green energy sources might not be attractive for specific locations where implementation of such energy technologies may pose environmental, social, or economic risks in the long run. A good example is the onshore wind energy, which turned out to be one of the most attractive energy sources among all options in the absence of local resource constraints. However, considering the regional resource availabilities and limitations, onshore wind was not the best energy source for some of the states. On the other hand, fossil fuels were not efficient options from a resource use perspective in resource abundant conditions, whereas some of them such as coal and natural gas are as resource use efficient as renewables such as onshore wind and solar thermal in presence of specific resource limitations in some states. Solar photovoltaic technology, as another renewable energy with ever-increasing popularity in energy policies, is dominated by fossil fuels for some states.

Analysis of resource use efficiency of energy alternatives for a specific location with certain resource availability and limitation conditions should be a significant part of feasibility study of energy investments that seek sustainability. For this purpose, multi-criteria evaluation of energy sources with respect to long-term natural and economic resource limitations could provide invaluable insights to decision makers. Simultaneous consideration of environmental and economic parameters under existing local limitations as well as involved uncertainties reveals the efficiency, sensitivity, robustness, and reliability of different energy sources' performance in different conditions.

Despite its valuable insights for the resource use efficiency of different energy options under regional resource limitations, this study has some limitations that may be addressed in future studies. First, it is assumed in this study that all energy sources are technologically feasible in all locations. This limitation could be addressed through elimination of infeasible energy alternatives for a specific location besides implementing appropriate proxies to restrict the option for a certain region with particular geographic and geologic conditions that is suitable for only some of the available energy technologies. In addition, it is assumed that all the energy sources for a given state are produced within borders of that state and no transfer of energy or materials take place. In other words, it is assumed that energy technologies utilize the available resources in the region where they are implemented. In reality, however, there are resource trades for the purpose of energy production. To address this limitation, a comprehensive resource allocation map is required to demonstrate the amount of required internal and external resources for different sources of energy. Also, an analysis based on more accurate magnitudes for availability

and limitation of water, land, budget, and emissions could provide more reliable insights for

energy production investment or expansion projects.

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CHAPTER 5: ENERGY PORTFOLIO ANALYSIS AND DEVELOPMENT BASED ON SUSTAINABILITY CONSIDERATIONS

5.1   Introduction

Energy planning is one of the challenges facing governments at all times. Adequate energy resources should be available to support economic development, to maintain high living standards, and to provide national security. In the meantime, global warming resulting from human activities is tied to energy production and consumption processes, enforcing more restrictive laws and regulations at the energy planning level. Also, energy security considerations push the energy policies toward reliance upon inland energy sources and diversification of energy choices, which adds to the complexity of energy planning. Scarcity of natural resources is another challenge, as considerable environmental resources such as water and land are required to produce enough energy to meet demand. Needless to say, the resulting energy mix should be economically feasible, as energy production processes require significant financial support.

Traditionally, energy planning was simply adoption of the least-cost energy technologies. Such policies could address the energy demand effectively in an era with constant energy prices in the absence of competitive energy markets, advanced technologies, and cost uncertainty (Awerbuch, 1993, 1995a). However, with the evolution of diverse energy technologies and more competitive energy markets, the cost of energy production has been experiencing a rise in volatility, leading to revocation of past policies that failed to capture the uncertainty and dynamicity within evolving energy markets. Hence, energy planning began to be seen as an investment decision problem, evaluated from a portfolio perspective to manage risks and maximize returns of the portfolio instead of the energy options individually (Awerbuch, 2006).

For this purpose, the mean-variance portfolio theory, also called Modern Portfolio Theory (MPT), is applied to energy planning problems to create efficient portfolios. Previous research indicates that MPT can be applied to a range of energy planning problems in order to maximize return for a given risk level or minimize the risk for any expected return. For instance, Awerbuch and Yang (2007) applied the MPT to the European Union (EU) energy market and concluded that greater shares of nuclear and wind added to the EU energy portfolio lowered the risk and cost of the portfolio and carbon emissions while maximizing the energy security. Roques et al. (2008) studied the liberalized electricity markets to identify efficient electricity portfolios and concluded that incentives such as long-term power purchase contracts and low capital costs lead to more diversified electricity portfolios with greater shares of coal and nuclear energies. Madlener et al. (2009) applied the MPT for energy planning in Germany, Sweden, and United Kingdom and concluded that more efficient portfolios could be generated if shares of renewables went up. Other studies include Domingues et al. (2001), Lesbirel (2004), Beltran (2009), Rodoulis (2010), Delarue et al. (2011), Allan et al. (2011), Bhattacharya and Kojima (2012), and Arnesano et al. (2012).

Energy planning based on the risk-return relationship outputs diversified energy portfolios with a lower risk of return for any expected return. Compared to traditional energy mixes, such portfolios included larger shares of non-fossil fuel sources in terms of both the number of sources and energy production from each source, resulting in reduction of GHG emissions. Besides capital costs, operation and maintenance costs, and fuel costs, some studies have also considered carbon emissions costs for each asset in the portfolio as an indication of environmental effects pertaining to each energy source, and eventually, the portfolio. Examples

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include Awerbuch and Yang (2007), Roques et al. (2008), Bhattacharya and Kojima (2012), and Arnesano et al. (2012).

The past research acknowledges the necessity and advantage of energy portfolio analysis and development with focus on energy planning within specific locations. Although this is promising, there is still a lack of global energy analysis with sustainability considerations. Based on the previous chapter, despite the fact that energy policies are developed based on regional specifications, they should be consistent with global objectives, specifically when sustainability is desired on the global scale. Also, whether CO_2 costs in the literature represent either CO_2 trading costs or social cost of carbon (SCC), they underestimate the true resulting damages (Bernstein et al., 2008; Ackerman and Stanton, 2011) as not all negative effects could be explicitly and thoroughly represented by monetary units, especially when sustainability is a concern in energy portfolio development. In addition, previous studies fail to address other adverse effects resulting from energy production processes. Such impacts include but are not limited to water resources drainage and pollution, land use change, agricultural production loss, and biodiversity deterioration. Diversification of the energy portfolio might yield more secure energy supplies and lower emissions both due to increase in shares of renewable energy sources, but it does not necessarily guarantee minimal negative impacts on other components of the ecosystem. In other words, the notion of sustainability would not be acknowledged based solely on a diversified, decarbonized energy portfolio, unless the aforementioned secondary impacts are also taken into account in energy planning. Such sustainability concerns are neglected in the literature mainly because they are incomputable based on the common price measures. For instance, the dollar value of the water amount allocated to produce one unit of energy from a

particular energy source, although measurable, does not reveal its true value when it is looked at as a scarce natural resource. Even if the monetary value of water is to be used as a reliable measure for quantification of its true value, it cannot be added to costs corresponding to other energy production processes due to inconsistency within the nature of such costs. In addition, assuming that natural resources dollar values are a reasonable representation of secondary impacts of energy production, a traditional definition of investment risk as a measure of price fluctuations is not applicable to measure a portion of risk associated with such resources' prices. The reason is that natural resources prices do not respond as quickly to market demands and associated changes as fuel prices do. As a result, if moving toward sustainability is a concern in energy policy development, monetary units are not reliable and cannot reflect the actual costs and benefits. Hence, a new scale is required based on which the efficiency of energy production of natural resources are measured along with corresponding costs.

In this dissertation, the efficiency of energy production processes in terms of environmental impacts as well as associated costs are integrated into a resource use efficiency index, which is measure of sustainability. In summary, the resource use efficiency of an energy source is calculated based on a systems approach that takes into account the performance of the energy sources under multiple sustainability criteria, which are carbon emissions, water footprint, land footprint, and cost of energy production shown in this study. The resource use efficiency score is represented by a dimensionless number scale of 0 to 100 with larger numbers being more favorable. In the lack of a reliable sustainability measure, the resource use efficiency index accounts for the tradeoffs existing among different sustainability criteria when they are considered simultaneously for performance evaluation of an energy source. In other words, the

resource use efficiency score for an energy alternative could be interpreted as the investment returns estimated by a consistent measure that not only encompasses the costs of energy production and CO_2 emissions, but also other environmental impacts. Furthermore, it is worth mentioning that the performance of the energy sources considered in this study are measured mostly in ranges, due to the uncertainties that exist as a result of technological and regional variations. As discussed in Chapter 3, such performance uncertainties result in uncertain outcomes, leading to a distribution of resource use efficiency scores for a given energy source. As discussed later, a statistical analysis of the resulting distribution yields measures such as risk.

The main objective in this chapter is to construct global energy portfolios based on resource use efficiency (as a measure of sustainability) and related fluctuations (as a measure of risk). The energy sources considered in this study along with their performance under four sustainability criteria are shown in Table 5.1. Among the pool of data available in the literature, the values in Table 5.1 are selected in attempt to capture the current performance values for different technologies on the global scale. This chapter considers two methods of portfolio analysis and development: Modern Portfolio Theory (MPT) and Post-Modern Portfolio Theory (PMPT). These theories differ in their definition of risk. The former considers the standard deviation from the expected return as a measure of risk, while the latter employs the concept of downside risk as a measure of investment risk.

This chapter is structured as follows. The next two sections explain the fundamentals of sustainable energy planning based on MPT and PMPT, respectively. Then, the results from the two analyses are presented and a discussion of how the analysis based on the resource use

efficiency scores and associated risks clarifies sustainability of energy portfolios. Also, a discussion of how a more realistic measure of risk yields more efficient portfolios.

Table 5.1: Energy sources performance measures under four sustainability criteria

Energy Source Type	Carbon Footprint (g CO_2/kWh)	Water Footprint (m^3/GJ)	Land footprint (m^2/GWh)	Cost (cent/kWh)
Ethanol from corn	81-85	78	10667-12500	2-4
Ethanol from sugar cane	19	99	9520	2-4
Biomass: wood-chip	25	42	14433-21800	4-10
Biomass: miscanthus	93	37	14433-21800	4-10
Solar Thermal	8.5-11.3	0.037-0.780	340-680	4-10
Solar Photovoltaic	12.5-104.0	0.042	704-1760	10.9-23.4
Wind: Onshore	6.9-14.5	0.001	2168-2640	4.16-5.72
Wind: Offshore	9.1-22.0	0.001	2168-2640	3.64-8.71
Wave and Tidal	14-119	0.001	33-463	5-15
Hydropower	2-48	22	538-3068	3.25-12.35
Coal	834-1026	0.15-0.58	83-567	3.77-5.85
Oil	657-866	4.29-8.60	1490	8-10
Natural Gas	398-499	0.1	623	5.46-11.96
Nuclear	9-70	0.42-0.76	63-93	4.55-5.46
Geothermal	15.1-55.0	0.005	33-463	1-8

5.2   Sustainable Energy Planning Based On MPT

Developed by Markowitz (1952), the Modern Portfolio Theory (MPT) is considered the basis for modern economics (Rubinstein, 2002), helping investors and decision makers manage the risks associated with investments and make better decisions. According to MPT, a portfolio compounded by diverse, less than perfectly correlated securities may reduce the risk compared to individual securities, known as the portfolio effect.   In MPT, an efficient portfolio takes no unnecessary risk with respect to its expected return, meaning that the risk is minimized for any expected return or the expected return is maximized for any risk level (Beltran, 2009). In fact, portfolio selection in MPT is implemented based on tradeoffs between expected returns and risk attitudes of decision makers, as higher returns are generally associated with higher risks and vice

versa. In MPT, the expected return and risk of the portfolio are quantified based on the expected return and risk of the securities, given that the securities past returns follow normal distribution.

As discussed earlier, most of the energy portfolio studies have been dealing with the electricity sector investment risks in terms of monetary values. However, a systems approach is required in the energy policy analysis and development, in order to account for the environmental effects of the energy production besides the production costs. Hence, the expected return in this research is not defined as the expected return of assets based on dollars. Rather, it is defined as a function of the performances of the alternatives under environmental and economic criteria. The multi-criteria assessment of energy alternatives input data with associated uncertainties (Table 5.1) yields stochastic outputs. Goodness-of-fit normality tests show that the outcomes fit a normal distribution for all energy sources. As a result, the resource use efficiency and corresponding standard deviation for the energy sources are calculated in Chapter 3 based on the statistical analysis of distributions and are shown in Table 5.2.

The portfolio's resource use efficiency and risk are calculated based on the following equations:

$$(RUE)_p = \sum_{i=1}^{n} W_i (RUE)_i \tag{1}$$

$$(SD)_p = \sqrt{Var(\sum_{i=1}^{n} W_i (RUE)_i)} = \sqrt{\sum_{i=1}^{n} W_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} W_i W_j \sigma_i \sigma_j \rho_{ij}} \tag{2}$$

where:

$(RUE)_p$: Expected resource use efficiency of the portfolio; W_i: Proportion of energy source i in the portfolio; $(RUE)_i$: Expected resource use efficiency of energy source i; $(SD)_p$: Standard

deviation of the portfolio; σ_i, σ_j: Standard deviation of energy sources i and j; ρ_{ij}: The correlation between energy sources i and j.

Although generation costs of energy sources such as fossil fuels are correlated and usually move together in the market (Beltran, 2009; Awerbuch and Yang, 2007), emissions and other environmental impacts of a given energy source are almost independent of other energy sources. Hence, it is safe to assume that correlations between energy sources environmental impacts are zero, which results in close to zero correlation factors between resource use efficiency of the energy sources. In other words, the effect of cost correlations is trivial in the total correlation factor and assumed to be zero. Numerous portfolios are generated based on different asset allocation patterns. Not all of the generated portfolios are optimal however. In other words, there are a large number of portfolios with equal risk magnitudes but varying resource use efficiency scores. Similarly, there are numerous portfolios with equal resource use efficiency scores but varying risk magnitudes. Generated portfolios are illustrated in Figure 5.1. In fact, rational decision makers choose the least risky portfolio among those with equal resource use efficiency scores, or they choose the one with the largest resource use efficiency score between those with the same risk magnitude. Hence, the optimal portfolios for different risk and resource use efficiency values occur at the boundary of the feasible solutions (efficient frontier). Efficient frontier, shown on Figure 5.2, represents the optimal feasible portfolios, each of which is appropriate for an investor with a specific risk aversion degree. In MPT, selection between different efficient portfolios is made based on the highest modified Sharpe ratio (Rom and Ferguson, 1994), which signifies the risk-adjusted performance of the portfolio. The modified Sharpe ratio is calculated based on equation 3:

$$Modified\ Sharpe\ ratio = \frac{(RUE)_p}{(SD)_p} \tag{3}$$

5.3   Sustainable Energy Planning Based On PMPT

In MPT, the variance of returns for each asset in the portfolio is considered as a symmetric measure of risk associated with that asset, contributing to the portfolio variance (portfolio risk). However, the variance is not a perfect metric for measuring risk, because it captures positive volatility in addition to negative volatility. In fact, investors care more about avoiding loss than gaining profit, meaning that risk is not symmetrical and is severely skewed (Rom and Ferguson, 1994). Hence, the normal distribution is not necessarily a perfect simulation of a real world investor behavior. In addition, MPT fails to address the investor's goals by assuming the "mean" to be the expected return of assets and the portfolio. However, high efficiency portfolios should reflect investor objectives and expectations as the risk averseness of different investors affects their bias toward a given feasible alternative. To overcome these limitations, Post Modern Portfolio Theory (PMPT) was developed by Rom and Ferguson (1994) and yields a more realistic view of investment risk and return by proposing "downside risk" (Bawa, 1982; Fishburn, 1977; Sortino and Van Der Meer, 1991; Clarkson, 1989) and "minimum acceptable return". Downside risk (DR) represents the volatility below a target return, whereas any outcome greater than target return is favorable and should not be considered as the risk of investor but investment return uncertainty. Downside risk is the standard deviation of lower than expected returns, or the probability weighted below target returns with consideration of investor's risk attitude. In other words, downside risk addresses the probability of below target returns as well as the distance from the target return (Sortino, 2001). Minimum acceptable return (MAR)

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captures the investor's expectations and is defined as the minimum return to be earned to avoid failing to meet investor's objectives (Rom and Ferguson, 1994). Table 5.2 illustrates the skewness of resource use efficiency scores for the considered energy sources in this study. Positive skewness values represent right-skewed distributions, indicating more returns occurring above the median, which means that gains are larger and losses are smaller when they occur. Negative skewness values represent left-skewed distributions, indicating more returns occurring below the median, which means that gains are smaller and losses are larger when they occur (Nawrocki, 1997). In fact, positive skewness is a result of controlled risks and avoided losses that limit unfavorable outcomes, but allows for extended upside returns. As a result, normal distribution is not a perfect fit for resource use efficiency of the energy sources. A log-normal distribution, on the other hand, allows for both positive and negative skewness (Rom and Ferguson, 1994). Hence, a three-parameter log-normal distribution formulation, suggested by Forsey (2001), is used in this study to represent the resource use efficiency score of portfolios compounded by different energy options. Mean, standard deviation, and extreme value, used in Forsey-Sortino model (Sortino and Satchell, 2001), are used as a basis to create three-parameter log-normal distributions for the considered energy alternatives. These values are represented in Table 5.2.

Table 5.2: Resource use efficiency, standard deviation, extreme value and skewness

Energy Source Type	Resource use efficiency	Standard deviation	Extreme value	Statistical skewness
Ethanol from corn	15.7	2.8	7.2	0.2
Ethanol from sugar cane	30.0	2.7	10.6	0.4
Biomass: wood-chip	24.3	4.0	2.7	0.1
Biomass: miscanthus	15.7	4.1	17.8	0.0
Solar Thermal	82.9	1.6	54.1	0.1
Solar Photovoltaic	45.7	3.8	19.0	0.1
Wind: Onshore	88.6	2.2	68.1	0.3
Wind: Offshore	75.7	3.3	53.9	0.1
Wave and Tidal	70.0	4.0	38.2	0.2
Hydropower	47.1	4.9	20.5	0.3
Coal	27.1	3.3	2.6	0.1
Oil	17.1	3.0	0.9	0.0
Natural Gas	40.0	3.1	24.9	0.2
Nuclear	75.7	4.2	47.6	0.1
Geothermal	94.3	3.7	56.6	0.4

In this research, the method suggested by Forsey (2001) is adapted to fit a log-normal distribution to portfolios. Similar to MPT, the mean and standard deviation of the portfolio is calculated based on the means and standard deviations of the assets in the portfolio. The portfolio's extreme value (τ) is estimated based on the weighted average of the assets' extreme values that are calculated from equation (4) and shown in Table 5.2. Based on the following equations, some auxiliary parameters are required to calculate the lognormal distribution for the portfolio:

$$(\tau)_i = \min(RUE)_i - 4(SD)_i \tag{4}$$

$$(\tau)_p = \sum_{i=1}^{n} W_i(\tau)_i \tag{5}$$

$$Dif = |RUE - \tau|_p \tag{6}$$

$$\sigma = \ln\left(\left(\frac{SD}{Dif}\right)^2 + 1\right) \tag{7}$$

$$\mu = \ln(Dif) - \sigma^2 \tag{8}$$

$$\alpha = \frac{1}{\sqrt{2\pi}.\sigma} \tag{9}$$

$$\beta = \frac{-1}{2\sigma^2} \tag{10}$$

$$f(x) = \frac{\alpha}{x-\tau}\exp(\beta.(\ln(x-\tau)-\mu)) \tag{11}$$

$$(DR)_p = \sqrt{\int_{-\infty}^{MAR}(MAR - x)^n f(x)dx} \tag{12}$$

where:

τ_i, τ_p: Extreme values of energy source i and portfolio p, respectively; Dif, σ, μ, α, and β: Auxiliary parameters for calculating portfolio's lognormal distribution; $f(x)$: Lognormal distribution of portfolio's resource use efficiency scores; $(DR)_p$: Downside risk of the portfolio (Fishburn, 1977; Sortino and Van der Meer, 1991); n: Degree of investor's risk averseness.

In the downside risk equation, parameter "n" is the adjustment proxy for penalizing below target returns. Following Sortino and Van der Meer (1991), this research adopts a magnitude of 2 for n. The advantage of n=2 is that it makes DR comparable to standard deviation as the risk measure in MPT. Similar to MPT, the correlations between the resource use efficiency scores of the assets in a portfolio are assumed to be zero. Unlike MPT that yields one efficient frontier for all investors with diverse risk attitudes, PMPT gives a unique efficient frontier for any given MAR value, representing the efficient portfolios with respect to the investor's specific risk attitude. Hence, a portfolio might have different risk magnitudes depending on investors' expectations and project goals. Efficient frontiers for four investors with MAR of 50, 60, 70, and

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80 are shown in Figure 5.3. In PMPT, the comparison between efficient portfolios from a particular investor's perspective is calculated by the returns adjusted for downside risk and MAR, referred to as Sortino ratio (Sortino and Price, 1994). The Sortino ratio is calculated based on the following equation:

$$Sortino\ ratio = \frac{(RUE)_p - MAR}{(DR)_p} \qquad (15)$$

5.4   Results

Figure 5.1 shows the feasible portfolios generated based on MPT. As mentioned earlier, the optimal portfolios are located on the upper edge of the feasible region, contributing to a unique efficient frontier that is shown in Figure 5.2 (show in green). However, the lower edge (shown in blue) is also illustrated to compare the status of current energy portfolios with more efficient ones. The model is stopped running when a reasonable quantity of portfolios is generated, mainly due to a huge number of feasible and efficient portfolios that need considerable computational capacity to be found. The overlapped circles in the efficient frontier indicate diverse portfolios for a given set of resource use efficiencies and risk magnitudes. In other words, there might be more than one portfolio with equal or very close resource use efficiency and risk values.
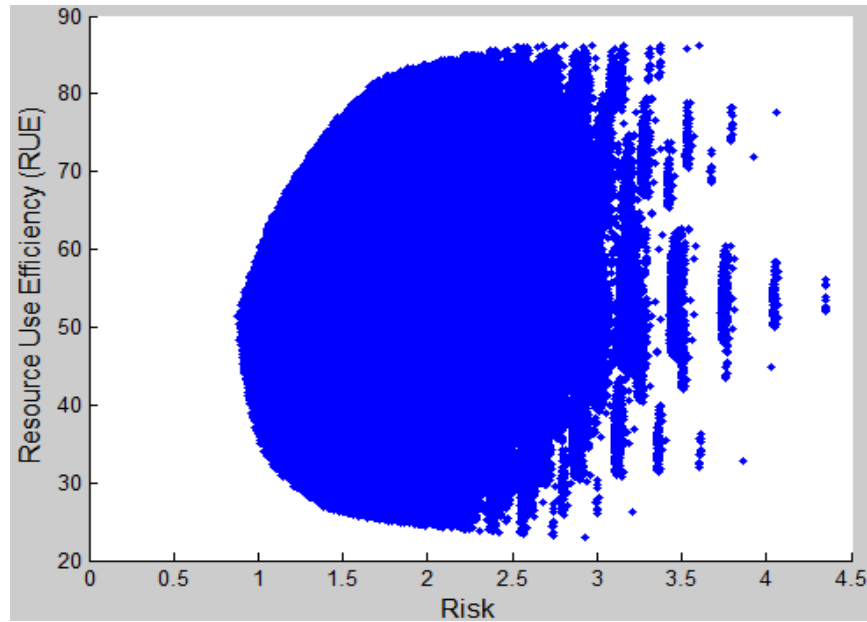
Figure 5.1: Feasible energy portfolios based on MPT

Illustrated in Figure 5.2 is the 2012 energy mix and the 2035 business as usual energy mix projection, shown as P0 and P1, respectively. The least risk-least RUE is shown as P2. Also, P2' represents the least RUE non-optimal portfolio with the same risk level as the 2035 projected energy mix. P3 indicates the optimal portfolio for RUE of 60. In addition, P4 represents the most efficient portfolio with the same risk level as 2035 projected energy mix.
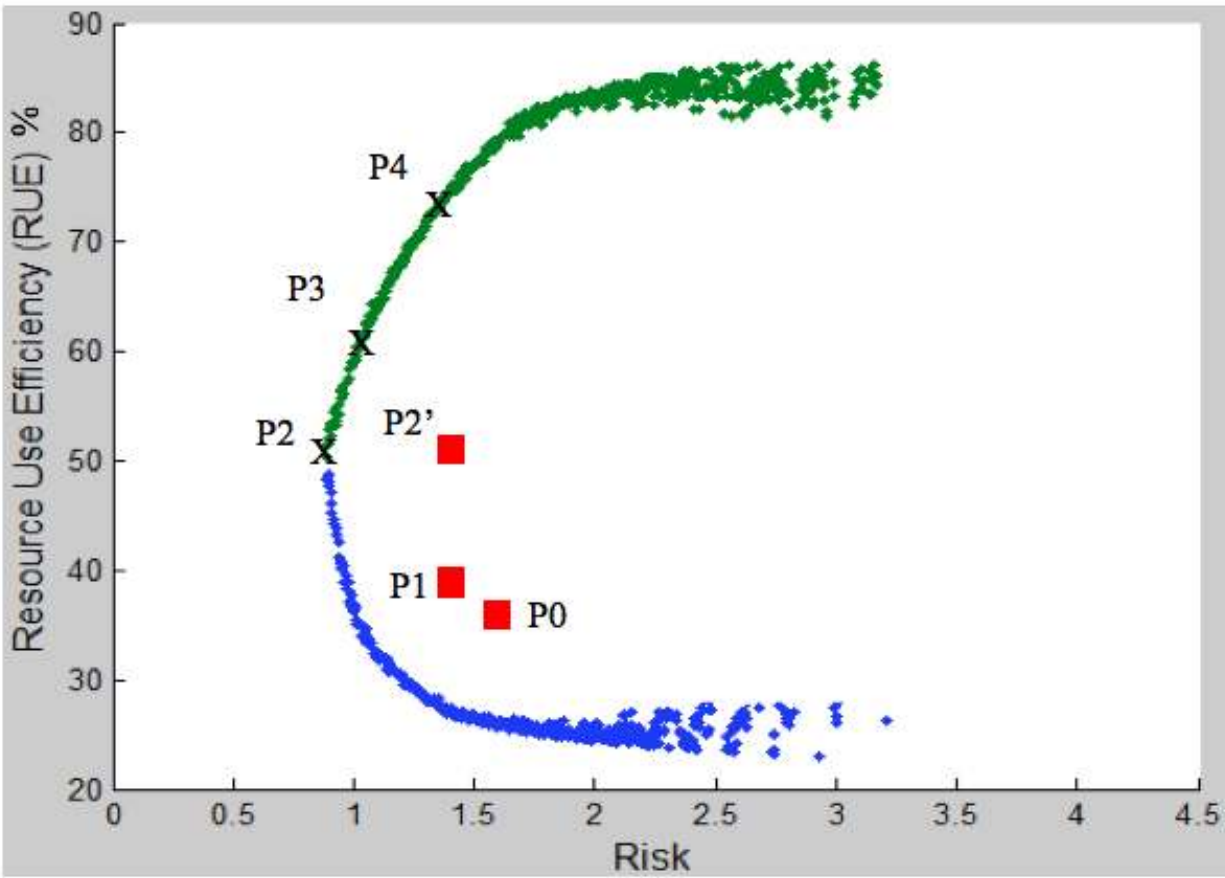
Figure 5.2: MPT efficient frontier and portfolios; P0: 2012 energy mix; P1: 2035 projected energy mix; P2: optimal energy mix with minimum risk and RUE; P2': potential energy mix with minimum RUE and 2035 equal risk; P3: optimal energy mix with RUE=60; P4: optimal energy mix with 2035 equal risk.

Figure 5.3 depicts the efficient frontiers for the analysis based on PMPT for four decision makers with MARs 50 (black), 60 (cyan), 70 (purple), and 80 (blue). As shown in this figure, optimal portfolios have different risk magnitudes for investors with diverse risk attitudes. In other words, a portfolio becomes riskier for a risk taker investor than a risk averse investor. Despite P2' which has a quantifiable downside risk and is shown on the graph, the 2012 energy mix (P0) and the projected 2035 energy mix (P1) have lower than expected returns and are not situated on the efficient frontiers for decision makers with MAR 50, 60, 70, and 80. In this figure, P5 and P6 represent the minimum risk efficient portfolios for MARs 50 and 60,

respectively. Also, P7 and P8 represent the efficient portfolios corresponding to RUE of 70 for

MARs 50 and 60.
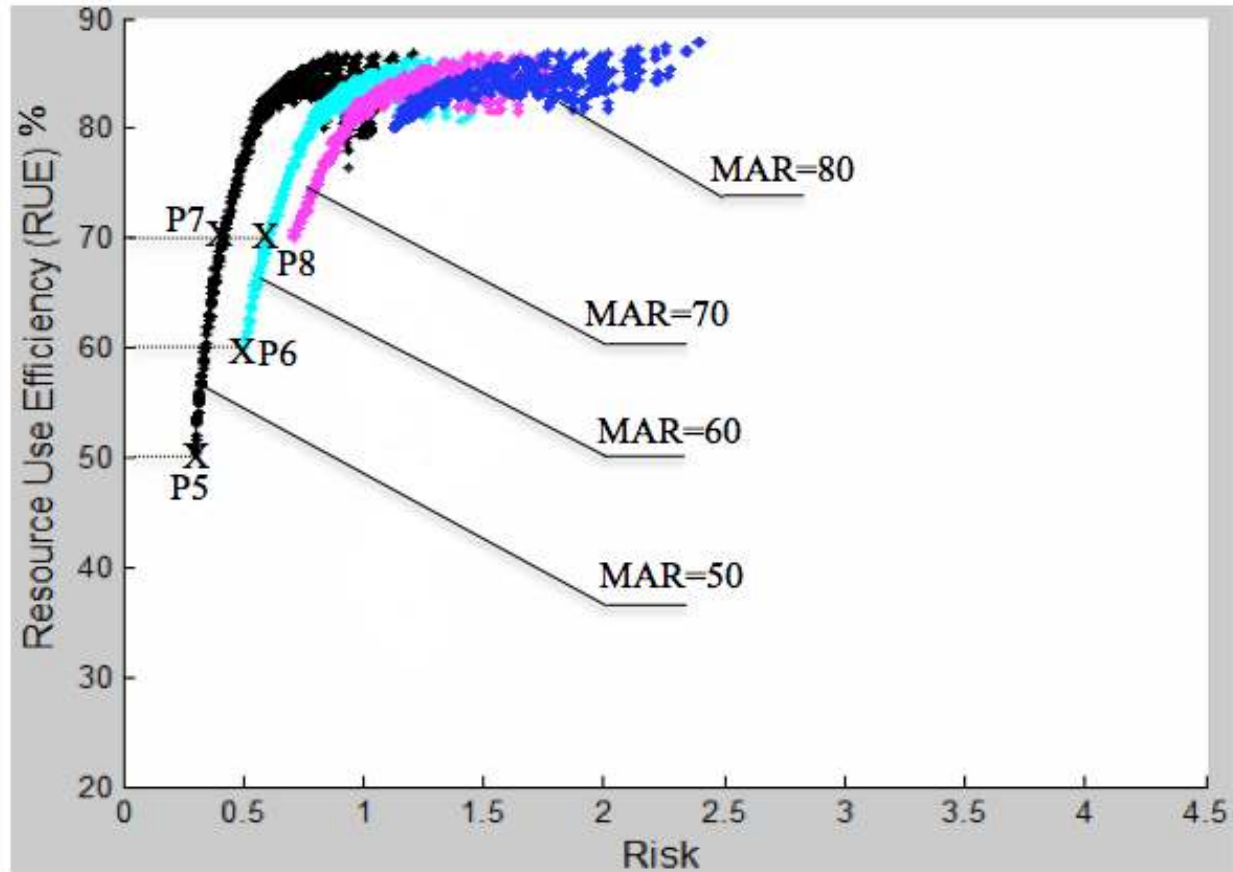
Figure 5.3: Efficient frontiers for decision makers with MAR=50 (black), MAR=60 (cyan), MAR=70 (purple), and MAR=80 (blue); P5: optimal energy mix with MAR=50 and minimum risk and RUE; P6: optimal energy mix with MAR=60 and minimum risk and RUE; P7: optimal energy mix with MAR=50 and RUE=70; P8: optimal energy mix with MAR=60 and RUE=70;

In addition to shares of different energy sources for selected portfolios, the resource use efficiency (RUE), downside risk (DR), and standard deviation (SD) of the portfolios are also calculated and shown in Table 5.3. The Sharpe and Sortino ratios are calculated for the chosen portfolios where applicable, in order to compare the efficiency and desirability of the portfolios from investment perspective.

Table 5.3: Energy mix components for different scenarios based on MPT and PMPT

		Energy portfolio									
		0	1	2	2'	3	4	5	6	7	8
		%									
Energy sources	Ethanol from corn	1.68	1.20	9.94	1.14	1.26	0.29	3.66	1.26	3.17	3.17
	Ethanol from sugar cane	0.49	1.00	8.29	0.80	0.68	0.64	3.25	1.68	2.38	2.38
	Biomass: wood-chip	0.20	0.60	0.55	0.67	0.42	0.21	0.41	0.42	0.24	0.24
	Biomass: miscanthus	0.60	0.63	2.76	2.01	1.68	0.57	6.10	1.68	1.58	1.58
	Solar Thermal	0.12	0.20	8.29	1.34	10.50	5.00	4.88	10.50	5.54	5.54
	Solar Photovoltaic	0.20	0.51	3.87	3.35	4.20	3.57	8.13	4.20	3.96	3.96
	Wind: Onshore	1.48	2.50	11.05	9.37	18.49	42.89	8.94	18.49	38.00	38.00
	Wind: Offshore	0.30	0.70	2.76	1.34	4.20	5.72	2.03	4.20	7.92	7.92
	Wave and Tidal	1.35	1.39	1.10	0.67	0.84	2.14	0.81	0.84	2.38	2.38
	Hydropower	7.51	8.77	5.52	23.09	7.56	21.09	12.20	7.56	13.46	13.46
	Coal	27.68	27.17	12.15	14.73	12.61	2.86	16.26	12.61	3.17	3.17
	Oil	30.92	25.84	11.05	13.39	8.40	1.43	10.16	8.40	2.38	2.38
	Natural Gas	21.90	22.70	13.26	16.73	14.71	4.29	16.26	14.71	5.54	5.54
	Nuclear	5.47	6.65	6.08	10.04	9.24	6.43	4.47	9.24	7.13	7.13
	Geothermal	0.09	0.15	3.31	1.34	4.20	2.86	2.44	4.20	3.17	3.17
(RUE)$_p$		37.11	39.47	51.1	51.1	60.00	72.38	50.00	60.00	70.00	70.00
(SD)$_p$		1.53	1.47	0.92	1.47	1.03	1.47	1.12	1.00	1.20	1.20
(DR)$_p$		--	--	0.31	0.49	0.34	0.49	0.37	0.45	0.40	0.53
Sharpe ratio		24.25	26.85	55.54	34.76	58.25	49.24	44.65	60	58.33	58.33
Sortino ratio		--	--	--	--	--	--	0	0	50.10	19.01

5.5 Discussion

According to Table 5.3, the 2012 energy mix (P0) and the 2035 business as usual energy mix (P1) get low RUE scores versus the risk taken. In fact, the resource use efficiency scores and risk magnitudes of these portfolios are close, meaning that compared to the 2012 energy mix, the 2035 projected energy mix does not experience a significant improvement from a resource use perspective. As shown in Figure 5.2, P0 and P1 are close to the curve representing the least efficient portfolios (the lower curve). This implies that these portfolios are not optimal when sustainability measures such as water use and land use are considered in addition to carbon emissions and cost of energy production, mainly due to the considerable shares of fossil fuels in the mix with their adverse environmental impacts. In Figure 5.2, P4 represents an efficient

portfolio with the same risk level as P1 but with 85% more efficiency. P4 compounds large shares of renewable energy sources, particularly wind and hydropower, while leaving less than 10% for fossil fuels. Regardless of unavailability of infrastructures required to meet targets in P4 as well as the current reliance upon fossil fuels, P4 implies that a portfolio with sustainable resource use efficiency carries considerable shares of specific renewable energy sources among available alternatives.

Based on the outcomes of MPT analysis, P2 represents an efficient portfolio with minimum risk and RUE. Compared to P0 and P1, P2 is less dependent on a specific energy source, yielding a more diversified portfolio with fossil fuels being responsible for only 36% of the energy production. P2 has 30% more RUE while 37% less risk than P1. P1 might be cheaper and more feasible given existing infrastructures, but it lacks considerable potential to address sustainability due to resource use inefficiency. In addition, compared to P1, P3 has 52% higher efficiency in terms of the resource use, while the risk is 30% lower. P3 has even lower shares of renewable and fossil fuels comparing to P2, but relies more upon specific energy sources such as wind and nuclear while holding substantially lower shares of biofuels.

P2' has the same resource use efficiency score as P2 but it has slightly higher risk value. However, as shown in Table 5.3, these portfolios hold notably different shares of available energy options. This shows that the shares of the energy sources in a portfolio are highly sensitive to the risk magnitude of the portfolio and change significantly in response to a small change in the risk. P2' has the same risk level as the 2035 projected energy mix (P1), but it has 30% more resource use efficiency. Figure 5.4 shows the energy production from different energy sources in the 2012 energy mix (P0) and the 2035 potential energy mix (P1). According to

Figure 5.4, the energy production from fossil fuels such as oil, coal, wave and tidal energy, and ethanol from corn decrease, whereas the energy production from most renewables experience significant rise, especially in the case of solar photovoltaic, geothermal, solar thermal, and onshore and offshore wind energies. This means that the projected 2035 energy mix might address the increasing energy needs, but it is not resource use efficient due to large shares of fossil fuels and fairly small shares of renewables.
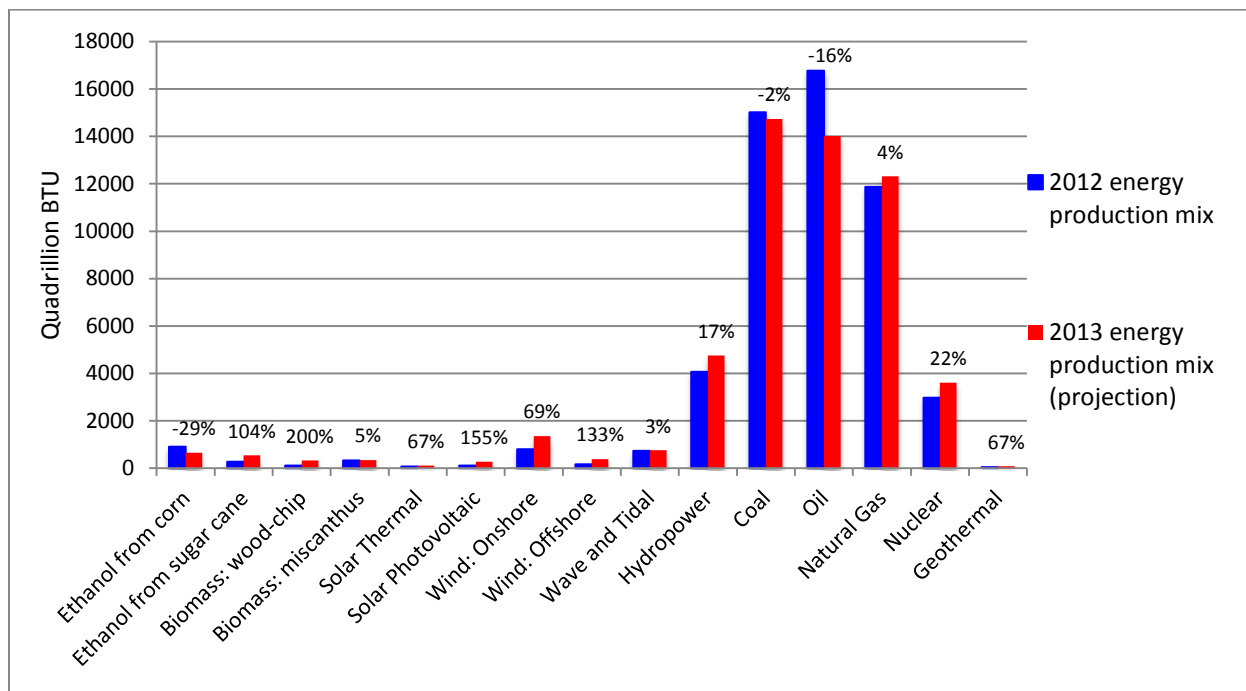
Figure 5.4: Energy production from different energy sources for 2012 energy mix (P_0) and 2035 potential energy mix (P_1)

Efficiency analysis based on PMPT yields different outcomes depending on decision maker's risk attitudes and MAR. However, as illustrated in Figure 5.5, efficient portfolios developed from PMPT analysis are less risky compared to those constructed based on mean-variance theory. P5, for instance, represents a portfolio with the least RUE score and risk magnitude for a decision maker with MAR of 50. P5 is comparable to P2 in terms of RUE, whereas it has 60%

less risk. Similarly, the least risky efficient portfolio for MAR of 60, P6, has the same RUE as P3, but 56% less risk. This indicates that a certain portfolio is more attractive from the more realistic downside risk perspective. P7 and P8, respectively developed for MARs 50 and 60, are comparable to P4 as they have close RUEs. It is obvious from Table 5.3 and Figure 5.5 that P7 and P8 have significantly lower risks, making them more attractive for decision makers adopting PMPT for portfolio analysis and development. Both portfolios have the same energy mix. However, P8 has a higher magnitude of downside risk when compared to P7, implying the fact that decision makers with higher MARs are adopting higher risk magnitudes for the same portfolio versus higher gained RUE.

According to Figure 5.3, P5 and P7 are both developed based on MAR of 50. As mentioned earlier, selection between diverse efficient portfolios developed for a particular decision maker is a tradeoff between adopting higher magnitudes of risk and gaining more RUE. Sortino ratio is developed to help with more robust decisions. In this case, P7 has a higher Sortino ratio, meaning that it is worth taking more risk for higher RUE. Similarly, P8 is more desirable compared to P6 developed for MAR of 60. Similar to Sortino ratio, Sharpe ratio helps decision makers select more desirable portfolios in presence of tradeoffs between higher efficiency and higher risk magnitudes. For instance, P4 has greater RUE and risk values compared to P3, but its Sharpe ratio is lower, meaning that the excess RUE is not worth the additional risk of P4. In other words, P3 is more desirable based on Sharpe ratio. However, P4 is more attractive if portfolios are compared based on Sortino ratio, implying that selection based on the more realistic downside risk yields different results.

As it is clear in Figure 5.5, PMPT yields a lower magnitude for risk of a certain portfolio than its standard deviation. In fact, PMPT's downside risk is a more realistic measure of risk compared to MPT's standard deviation. Hence portfolios developed based on PMPT are more reliable in terms of addressing decision makers' expectations and risk at
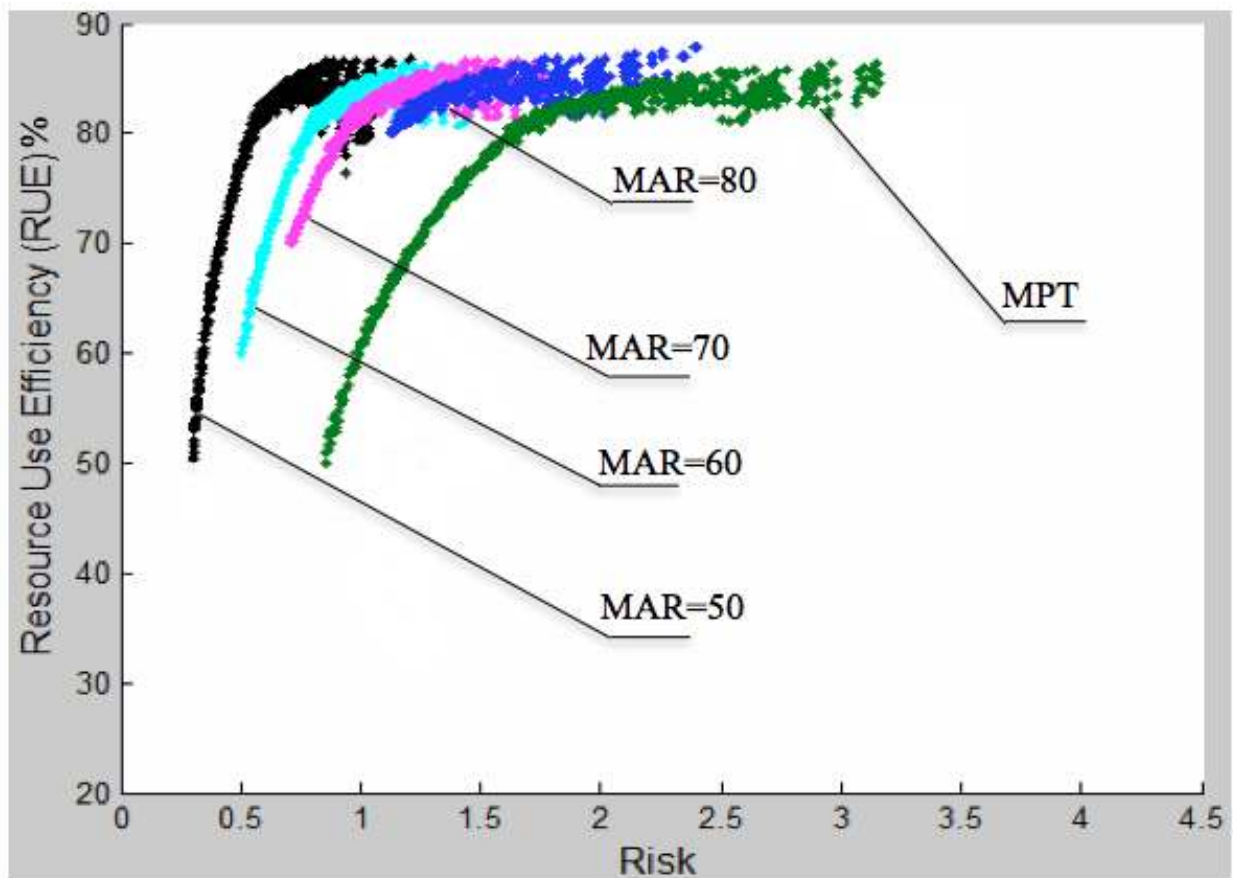
Figure 5.5: Efficient frontiers based on MPT and PMPT

The outcomes of the analysis indicate clearly that a potential efficient portfolio in terms of resource usage does not necessarily comprise considerable shares of renewable energy sources of all kinds. As indicated by Sortino and Satchell (2001), what matters at the end is the return and risk of the portfolio, not those of individual assets. From a sustainability perspective, portfolios with higher shares of the energy sources with relatively low overall environmental and economic

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impacts and risks have the most contribution in the portfolio. In addition, an efficient portfolio with large RUE or low risk is not necessarily attractive. In fact, the risk-RUE tradeoff of a portfolio for a specific decision maker determines the desirability of the portfolio.

The main message of this study is that energy planning based solely on cost simply ignores the adverse effects of energy production processes on the environment. Global warming is a clear example of such practices. Even taking into account the cost of emissions control and reduction does not save the environment. Increasing demand for energy along with secondary impacts of energy production processes on environmental resources such as water and land leave no space for single criterion energy planning. The results indicate clearly that the expected future energy status is highly unsustainable in terms of resource use efficiency, leading to severe consequences such as natural resource depletion and pollution. This analysis demonstrates how the concepts of resource use efficiency (RUE), developed based on a systems approach, addresses different environmental and economic concerns and could replace the traditional cost based energy planning in attempt to develop portfolios that are not only cost effective, but also environmentally friendly. It is worth mentioning that an efficient portfolio for a decision maker with specific goals and risk attitude is not necessarily unique. In other words, there might be numerous portfolios with varying shares of different energy sources that yield the same RUE and risk magnitude. In reality, technological, political, and economic considerations play a major role in development and implementation of energy portfolios. In this study, feasibility of constructed portfolios is not considered. In fact, more robust energy solutions could be developed if different aspects of feasibility are also considered. The developed model in this study is capable of addressing such concerns by adding more decision-making criteria that represent available

infrastructures as well as regional capacities and limitations. In addition, embodied energy for sources could also be considered as another important index in developing more reliable energy portfolios. For this purpose, energy return on investment (EROI) could also be taken into account as another sustainability criterion in evaluating the overall efficiency of individual energy sources that contribute to the portfolio. A systems approach toward energy planning is capable of considering multiple conflicting criteria in evaluating the overall efficiency of the energy sources, yielding a single and easy to understand measure to be fed into energy portfolio analyses and development frameworks.

5.6   Conclusion

Ecosystem failures usually emerge because of a human's willingness to succeed immediately, regardless of long-term impacts of his actions. A look into the past reveals many situations in which a particular action had been considered a reasonable solution to address a concern effectively, but it was regarded as a threat once its drawbacks and downsides were disclosed. One example of this could be the utilization of fossil fuels as primary energy sources to provide goods and services at the beginning of the industrial revolution. Despite the fact that our life in the current form would not have been possible without relying on fossil fuels over the past decades, the consequences of such reliance are so severe that immediate actions are required to regulate them. These actions should be designed and implemented in such a way that they have minimal effects on the already stressed ecosystem as we do not want our policies, especially environmental policies, to be a "today's solution and tomorrow's disaster" anymore. Energy sources typically require tremendous amounts of various natural resources. So, their effects on

such resources should be investigated. Recognizing the nexus between energy, economy, and natural resources subsystems provides the opportunity to move toward a more sustainable future. The point is, with a policy developed without a systems view to the energy planning problem, threats to our scarce natural resources are likely to emerge in the long run.

Least-cost energy planning neglects all negative impacts of energy production processes on the environment by encouraging unsustainable methods of energy production that either produce considerable amount of greenhouse gasses, consume a lot of water, or demand for significant amounts of land. The model illustrates how sustainability could be addressed in energy planning by applying the Modern Portfolio Theory (MPT) and Post Modern Portfolio Theory (PMPT) to resource use efficiency (RUE) of the energy sources with associated fluctuations (risk). Regardless of technological and regional limitations in energy planning, as indicated in the results, there is a significant gap between EIA's projected 2035 energy mix and a sustainable energy portfolio. Such energy production policies will eventually leave considerable negative impacts on our scarce natural resources and should be improved in terms of addressing sustainability concerns by reducing shares of fossil fuels to lower levels. However, an appropriate portfolio for a particular decision maker does not necessarily comprise considerable shares of renewable energy sources of all kinds. In other words, the risk-RUE of a portfolio is tied to a decision maker's expectations and risk attitudes, leading to various shares of the energy sources in the portfolio. A Systems approach toward evaluating energy sources overall efficiency in extremely helpful in this regard.

5.7   References

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATION

This dissertation incorporated the analysis of sustainable energy portfolios based on a resource use efficiency perspective. Different portfolio theories, namely Modern Portfolio Theory (MPT) and Post-Modern Portfolio Theory (PMPT) were implemented to create sustainable portfolios and illustrate the more reliable energy solutions. Different resource use sustainability indicators such as carbon footprint, water footprint, land footprint, and costs of energy production were taken into account, based on which resource use efficiencies of energy sources were measured. Various data (performance measures of renewable and nonrenewable energy sources under sustainability criteria and resource limitations across the U.S.) have been obtained, processed and utilized in this study. For the methodology part, this dissertation employed a system of systems approach that incorporated a set of stochastic multi-criteria assessment models to address different notions of optimality. This chapter discusses the critical findings, conclusions, and recommendations of the three major research aspects: (1) energy production secondary impacts analysis, (2) multi-criteria assessment of energy production efficiency, (3) energy planning based on resource use sustainability considerations.

6.1 Energy Production Secondary Impacts Analysis

Energy production processes demand considerable resources of different types, including, water, land, and money. To illustrate the impacts of global energy production on such resources, the impacts on water resources are calculated for different Energy Information Administration (EIA) energy scenarios for different oil price projections. The water footprint is selected as a

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reliable measure for this purpose as it accounts for all direct and indirect water use in the energy production lifecycle.

The water footprint values of different energy technologies are represented in ranges to represent the existing technological and regional uncertainties. In addition to water footprint values, the shares of different energy sources are extracted from EIA databases for five energy mix scenarios: Reference, High Oil Prices, Low Oil Prices, Traditional High Oil Prices, and Traditional Low Oil Prices. Based on these data, the amount of water that goes to the global energy sector is calculated under each scenario.

The results of this analysis indicates that the water footprint of future energy production grows faster than the amount of energy production itself, meaning that the global energy sector is becoming thirstier. This is found to be especially true for energy scenarios that predict high oil prices in the future, mostly due to larger shares of renewable energy sources in the future. In fact, the amount of water that goes to the energy sector is found to increase by 37-66% over the 2012-2035 period, while energy production and population are projected to grow by 40% and 20% over the same period, respectively. In fact, if the 2012 energy source shares continue into the future, the water footprint of the energy sector will be 1-10% less than the future energy projections developed by EIA. It is also found that the water to energy ratio increases by 5-10% over the 2012-2035 period, meaning that more water is required to produce one unit of energy. This implies that increasing the share of renewable energy sources in the energy mix might alleviate the climate change and improve the energy security, but it might have secondary impacts on our scarce natural resources such as water and land.

6.2   Multi-Criteria Assessment Of Energy Efficiency

To identify the resource use impacts of different renewable and nonrenewable energy sources, a new measure of efficiency is defined as resource use efficiency, representing the efficiency of different energy sources in terms of their demand for water, land, economic resources, as well as their carbon emissions in production of one unit of energy over their lifecycle. To calculate the resource use efficiency, the interactions of independent yet interacting climate systems, water systems, land systems, and economy systems are captured by a system of systems framework that consists of multiple multi-criteria assessment methods. The resource use sustainability analysis criteria are defined as carbon footprint, water footprint, land footprint, and costs of energy production. The performance values of energy sources under sustainability indicators are collected from a thorough literature review and adjusted (where needed) in accordance with the purpose of this study. One of the major contributions of this study is to consider the existing uncertainties of different energy technologies, which are reflected in the performance ranges of the energy sources under resource use efficiency criteria. To account for such uncertainties, a stochastic multi-criteria assessment framework is developed that consists of five MCDM methods, each of which has a unique definition of optimality. Criteria weights are also considered to be the same and equal to 25%, addressing the equivalent significance of all secondary impacts in a sustainable manner.

The results of this analysis indicate that not all renewable energy sources are resource use efficient based on simultaneous consideration of water impact, land impact, climate impact, and costs. Geothermal is recognized as the most resource use efficient energy source, followed by onshore wind, solar thermal, offshore wind, nuclear, and wave and tidal energies. These energy

sources are classified as sources with high resource use efficiency. Energy sources with medium resource use efficiency are hydropower, solar photovoltaic, and natural gas. Finally, low resource use efficient energy sources are different types of ethanol and biomass, coal, and oil. The results shows that some renewable energy sources such as ethanol and biofuels are less resource use efficient than some nonrenewable energy sources such as natural gas when a holistic view of the unintended consequences of energy production is employed.

To clarify the sensitivity of the obtained resource use efficiency scores under varying resource limitation conditions, sensitivity analysis is performed based on which extreme resource availability patterns are implemented in the model. Hence, the weight of different sustainability criteria varies from 0 to 100 to reflect resource limitation scenarios. Based on sensitivity analysis outcomes, geothermal and ethanol from sugarcane energy sources are the most and least sensitive energy sources under varying resource availability conditions.

In addition to the sensitivity analysis, robustness analysis is performed to investigate the effects of performance uncertainties on the resource use efficiency of the energy sources. In fact, the uncertainty intervals yield uncertain outcomes. In this analysis, all energy source resource use efficiency scores follow normal distribution. The standard deviation of such distributions is treated as an indication of resource use efficiency robustness in the face of performance uncertainties. The results of this analysis show that solar thermal and hydropower energy technologies are the most and least robust energy sources, respectively, meaning that the existing performance uncertainties have the smallest and largest impacts on the resource use efficiency of these energy sources, respectively.

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Furthermore, the impacts of regional resource limitations on the preference toward different energy sources are investigated. For this purpose, appropriate data are gathered from federal agencies for the availability of water, land, economic resources, and emissions in each state within the United States of America. Per capita emissions, freshwater withdrawals, land area, and GDP are chosen to represent such resource limitations across the United States. The resource use sustainability measures are weighted for each state based on the resource limitations in that state. The results of regionalized stochastic multi-criteria assessment illustrate that energy sources resource use efficiency scores are extremely sensitive to resource availability conditions. In fact, for some states, fossil fuels such as coal and oil are more resource use efficient than renewables such as solar and wind energy technologies. In other words, the high resource use efficient energy sources under "no resource limitation" conditions are not necessarily appropriate for all locations with different resource limitation patterns. Hence, although renewable energies have lower emissions and provide more diversity in the energy portfolio, they are not all appropriate for all locations with different characteristics.

6.3   Energy Planning Based On Resource Use Sustainability Considerations

Portfolio theories are utilized to develop energy portfolios that address global warming, energy security, and sustainability considerations discussed in this study. Based on portfolio theories, efficient portfolios have the largest possible return versus the lowest possible risk. In this study, portfolio returns are not defined as the expected return of assets based on monetary values that only reflect the economic aspect of sustainability. However, it is defined as the weighted average of energy sources resource use efficiency scores that consider both economic

and environmental sustainability aspects. In the Modern Portfolio Theory (MPT), portfolio risks are obtained based on energy alternatives standard deviation of resource use efficiency scores, meaning that any deviation (positive or negative) from expected resource use efficiency should be regarded as portfolio risk. In Post-Modern Portfolio Theory (PMPT), portfolio downside risk should be implemented, considering only the below target resource use efficiency scores as the risk of the portfolio. The results from both portfolio theories indicate that 2012 energy portfolio and 2035 energy projection based on the EIA reference scenario are not sustainable from a resource use perspective, as more efficiency could be obtained with the same risk level. In fact, these portfolios are similar in their risk and resource use efficiency scores. Another counterintuitive outcome of this analysis is that increasing the share of all renewables in the portfolio would not necessarily lead to more resource use efficient portfolios. In fact, only a few renewable energy sources contribute to portfolio high resource use efficiency and low risk levels.

Although the results of this study demonstrate the significance of simultaneous consideration of energy production impacts in energy planning and policy analysis, limitations do exist in the analysis. First, the outcomes of this research are obtained based on data from EIA scenarios, which are considered to be high oil production scenarios with lower shares for renewable energy sources in the future. To obtain more reliable solutions to the energy planning problem, future studies may focus on scenarios developed by other sources such as International Energy Agency (IEA), World Energy Council (WEC), Organization of the Petroleum Exporting Countries (OPEC), etc.

In addition, the performance measures of the energy sources in this study are based on the assumption that performance values of energy sources under different sustainability criteria do

not experience substantial alteration over time. However, future technology improvements could significantly affect the performance of energy sources, ultimately leading to different energy solutions. Also, the regional energy efficiency analysis in this study is performed based on the states total available water, land, GDP, and emissions. A more precise analysis could incorporate the limitations of such resources within each state (on smaller scale). Furthermore, more reliable energy efficiency outcomes could be reached based on the availability and limitation of such resources for the energy sector in each region.