A SYSTEM DYNAMICS APPROACH APPLIED TO WIND ENERGY SYSTEM SUSTAINABILITY

by

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Abstract

A SYSTEM DYNAMICS APPROACH APPLIED

TO WIND ENERGY SYSTEM

SUSTAINABILITY

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Sustainability of energy systems is one of the most important challenges currently facing humanity. Access to energy is critical to ensure economic and social development of a nation (UNDP et al., 2000); however, extraction, production and consumption of energy resources are also associated with high volumes of greenhouse gas (GHG) emissions, environmental damage and, in some cases, adverse health effects in communities where energy facilities are located. Renewable energy sources have been considered as an alternative to traditional energy sources to meet energy demand in a sustainable manner (Del Rio and Burguillo, 2008). Wind energy is considered to be one of the cleanest sources of energy. Furthermore, wind energy is one of the fastest growing energy sources worldwide. Wind energy systems are large complex systems that involve heterogeneous stakeholders as well as various system elements.

It is critical to better understand the sustainability of wind energy systems from a holistic perspective over the lifecycle of the system to ensure its favorable contribution to the sustainability of the energy system as a whole. Wind energy system sustainability focuses on a balance between economic, social and environmental objectives.

Systems thinking studies a system of interest as a whole, where all the system's parts interact with each other as well as with other systems. System dynamics, a systems thinking methodology, has been used to evaluate the sustainability of wind energy systems.

A wind energy system sustainability causal model has been developed to represent key factors and factor relationships related to wind energy system sustainability during the installation, operation and maintenance, and decommissioning phases. A system dynamics simulator was developed to represent causal model factors and model the behavior of these factors. The aim of the simulator is to help decision makers to understand the impacts of their decisions. A better understanding of factors and factor relationships associated with wind energy system sustainability would provide energy decision makers a way to assess sustainability of a wind energy system.

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Chapter 1

Introduction

Sustainability of energy systems has been identified as one of the most complex challenges for society (Cherp, Jewell, & Goldthau, 2011). An increasing energy demand, limited non-renewable resources, and the undesired energy byproducts generated as result of the processes and technologies to produce, convert and use energy resources, provide an illustration of the challenges associated with energy systems. Sustainability of energy systems implies balancing environmental, social, and economic requirements while meeting the increasing energy demand.

Sustainable development is defined as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). According to the United Nations, economic, social, and environmental aspects constitute the three pillars on which sustainability stands (United Nations, 2005).

Renewable energy sources have been perceived as an alternative to meet the world energy needs in a sustainable manner (Del Río & Burguillo, 2008). Renewable energy sources are considered a cleaner way to produce energy. Environmental change and a desire to increase energy security in conjunction with advances in renewable energy technology, and the uncertainty associated with oil prices have been drivers for the proliferation of renewable energy utilization.

Systems engineering plays an important role in dealing with uncertainties, risks, as well as the complexity of systems. Systems engineering is defined as “an interdisciplinary approach and means to enable the realization of successful systems” (INCOSE, 2011). System thinking is used by systems engineers to address complex problems. Systems thinking studies a system of interest as a whole, where all the system’s parts interact with each other as well as with other systems. The International Energy Agency (IEA) (2012a) has identified systems thinking as “essential to explore opportunities to leverage technology deployments within existing and new energy infrastructure”.

This research uses system dynamics, a system thinking methodology, to address the sustainability of wind energy systems. System dynamics is used to identify factors and factor relationships related to the sustainability of wind energy systems. System dynamics use causal models and simulation to represent the nonlinear relationships among factors to get a better understanding of the system as a whole and how sustainability could be achieved.

Motivation

Energy systems have to be economically profitable. However, profit is not the only key parameter to consider. Environmental and social requirements also have to be met over the whole system lifecycle from concept to disposal. Energy systems are required to be sustainable and meet all three aspects of sustainability.

Wind energy systems have to be sustainable. However, it is a challenge to balance the economic, environmental, and social factors. There is a need to characterize sustainability in wind energy systems and to know the main factors and their relationships that contribute to wind energy system sustainability.

This research focuses on understanding the factors and factor relationship related to the sustainability of a wind energy system and modeling the results of the interplay between these factors.

Research Questions

Key questions in this research are:

- What are the factors and factor relationships that affect wind energy system sustainability? The objective is to identify the economic, social, and environmental factors that have an effect on the sustainability of a wind energy system as well as their relationships.
- What are the impacts of decisions made related to the factors that affect wind energy system sustainability? The goal is to get a better understanding of the impacts of different decisions made during the installation, operation and maintenance and decommissioning of wind energy systems and to help decision makers to make more informed decisions while considering sustainability.

Research Objectives

The objective of this research is to develop a system dynamics model that helps systems engineers and energy decision makers to get a better understanding of the effects and relationships among various factors related to the sustainability of a wind energy system. Therefore, giving better insights on how to achieve more sustainable wind energy systems.

Scope

This research focuses on onshore wind energy systems, specifically during the installation, operation and maintenance and decommissioning phases. This research addresses the economic, social, and environmental factors related to system sustainability.

Contributions

Major contributions provided by the research are:

- A wind energy system sustainability causal model. A graphical representation of key factors and factor relationships that contribute to wind energy system sustainability.
- A simulator to model decisions to assess the system behavior by looking at the factors interactions during the installation, operational and decommissioning phases of wind energy systems. This simulator would help decision makers to evaluate effects of decisions through analysis of different scenarios before committing any kind of resources.

Chapters Organization

Chapter 1 presents an introduction to the dissertation research. It provides an overview of the research area, motivation for the research, primary research questions, research objectives, scope of the research, the research contributions, and an outline of the organization of the remaining chapters.

Chapter 2 is divided in two parts. The first part provides background information related to the research domain, such as sustainability, energy systems, and wind energy. The second part of this chapter provides background information related to the research methods used for this research.

Chapter 3 presents the research design and the methods used to answer the related research questions and develop the contributions. A detailed discussion of research tasks is presented.

Chapter 4 presents the results of the research. The wind energy system sustainability causal model, its validation, simulator architecture and simulator architecture validation are presented in this chapter. Furthermore, chapter 4 provides an overview of the simulator data collection and populated simulator. Simulation runs and verification and validation results of the simulator are presented. Results of the simulator and associated analysis are provided.

Chapter 5 provides a summary of the research contributions. Considerations about how this research could be expanded are also discussed.

Appendix A presents wind energy system sustainability causal model factors and factor definitions.

Appendix B presents the wind energy system sustainability causal model validation package.

Appendix C contains information on the inputs received from the validator from the causal model validation process. It also contains modifications that were made to the wind energy system sustainability causal model according to recommendations and inputs received from the validator.

Appendix D presents the elements of the simulator architecture. Definitions and units of measurement for each variable are also included.

Appendix E presents the wind energy system sustainability simulator code.

Appendix F presents the second iteration of the wind energy system sustainability causal model validation and simulator architecture validation package.

Appendix G contains information on the additional inputs received from validators for the wind energy system sustainability causal model and simulator architecture validation process. It also contains modifications that were made to the wind energy system sustainability causal model and simulator architecture according to recommendations and inputs received from the validators.

Appendix H presents the data collection package developed to request data to populate the simulator.

Appendix I contains information on the collected data for running the simulator.

Appendix J presents the wind energy system sustainability simulator validation package that include the results of running the simulator with the populated data.

Appendix K contains information on the inputs received from validators from the wind energy system sustainability simulator validation process.

Chapter 2

Literature Review

This chapter provides background information related to the research. The first part of the literature review provides information about the problem domain and includes relevant background information related to sustainability, energy systems and wind energy, all of which are associated with this dissertation. The second part provides information about research methods that is applied in this dissertation to develop the system dynamics model for wind energy system sustainability.

Problem Domain

The research objective is to develop a system dynamics model that helps systems engineers and decision makers to obtain a better understanding of the relationships among various factors related to the sustainability of wind energy systems. Hence, background information related to wind energy system sustainability defined in the scope of this research is presented.

Sustainability

Sustainability has become an increasingly vital global consideration. It has been subject to a large amount of studies and debates throughout the literature (Assefa & Frostell, 2007). The most widely accepted definition of sustainability is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Sustainable development can be historically categorized in three major periods Mebratu (1998): pre-Stockholm, including all precursor effort before Stockholm Conference on Environment and Development in 1972; from the Stockholm Conference on Environment and Development to the World Commission on Environment and Development (WCED) in 1987; and post-WCED, which includes the 2005 World Summit (UN, 2005) and still continues into the present.

Sustainable development represents a shift from the traditional economic perspective to a more holistic view (Harris & Goodwin, 2001). According to Harris and Goodwind (2001), for a system to be considered sustainable, it has to exhibit the following features: environmental sustainability, economic sustainability, and social sustainability. Environmental sustainability refers to maintaining a stable resource base where renewable resources exploitation is limited, up to a point where enough investment ensures adequate substitutes. Conservation of natural resources, stability of atmosphere and ecosystem function is the objective. Economic sustainability refers to the capability to produce goods and services on a continuing basis. Manageable levels of government and external debt as well as balanced industrial and agricultural production are key economic sustainability objectives for a country. Social sustainability refers to objectivity in distribution and opportunity among society, and adequate provision of basic social services including health and education, gender equity, and political accountability and participation.

The United Nations (2005) recognizes economic development, social development and environmental protection as “interdependent and mutually reinforcing pillars” of sustainable development. The social pillar relates to equitable resource access, empowerment, accessibility, participation, cultural identity, and institutional stability. Consideration of public concerns such as access to energy resources, public health and safety as well as advancement of the working population is covered by this pillar. Respect for public rights such as empowering communities in deciding what kind of industries are acceptable to be nearby, freedom to express opposition to certain regulations and, in general, the right to be heard during the decision making process related to decisions that impact the community are main goals of this pillar. Economic development focuses on economic security characterized by a fair and efficient allocation of resources. The environmental pillar relates to the protection of the natural environment and ensures the conservation and protection of natural ecosystems.

Sustainability is a dynamic concept (Mog, 2004) since it is not defined by fixed goals, or unique methods to achieve it. Instead it is contained in a continuous learning and adaptation cycle where balance is continuously pursue in shifting background conditions. As a result, understanding of sustainable development would be refined and modified by future generations to reflect their own perspectives, goals and objectives, and from a broader body of knowledge left by us as legacy (Kemmler and Spreng, 2007).

The need for a systems approach to address sustainable development has been recognized during the last United Nations Summit on Sustainable Development held in Rio de Janeiro, Brazil (United Nations, 2012). Given the nature and scope of the sustainability pillars and the interrelationships among them, a systems thinking approach is appropriate to address sustainability challenges.

Sustainability Assessment

Sustainability assessment provides decision-makers with a way for evaluating systems, from an integrated perspective, looking at environmental, economic and social factors from short- and long-term perspectives (Kates et al., 2001).

According to Stevens (2008) sustainability assessments are performed through various analyses. These are: relevance, scoping, impact, comparative, associative and political analysis. Relevance analysis refers to obtaining a better understanding if sustainability is relevant for the system under study. Scoping analysis refers to understanding the extent and depth of the various procedures and tools for the assessment. Impact analysis refers to getting a better understanding of the short and long term economic, environmental and social impacts of the system under study. Comparative analysis focuses on getting insights about major synergies, conflicts, and trade-offs of the system of interest and other systems. Associative analysis focuses on identifying the measures that have to be taken to mitigate negative impacts. Political analysis concentrates in finding the most suitable path (economic, environmental and social) to get a sustainable system.

According to Singh et al. (2009), sustainability assessment could be performed using two methodologies: monetary aggregation, mainly used by the mainstream economists, and physical indicators, which are used by scientist and researchers in other disciplines. Furthermore, giving equal attention to the three sustainability pillars, and adequate consideration to the longer-term, assigning monetary values to environmental and social aspects for comparisons, identifying trade-offs in the sustainability pillars on a comparable basis, reconciling conflicts between economic, environmental and social goals, and providing the basis for political decisions (Stevens, 2008) are the main difficulties that need to be overcome when performing sustainability assessments.

Energy System

Energy is the capacity of a physical system to perform work. Energy systems encompass the energy sources, and processes of extraction, production and transformation of raw energy materials into energy products that are delivered to the customer for their final use. The main energy products are electricity and fuels. With the development of electronics, information systems and technology, in general, the use of electricity has grown rapidly during the last decades. Therefore, development of the 21st century society is highly dependent on electricity. Fuels are physical energy products that can be stored and transformed into useful energy at a later time, such as petroleum, gas, and coal. The transportation industry and electricity generation industry are major users of this kind of energy products.

Energy sources can be classified as renewable and non-renewable energy sources (EIA, 2012a). Renewable energy sources are energy sources that can be sustained indefinitely. Renewable energy sources are wind, solar, biomass, water (hydropower) and geothermal. Non renewable energy sources are energy sources that cannot be replenished in a short period of time; they are a finite source of energy. Non renewable energy sources are oil and petroleum products, natural gas, coal and uranium.

According to the International Energy Agency (IEA) (IEA, 2015) projections, the world energy demand will grow by one-third between 2013 and 2040. Countries that are not part of OECD nations are driving the energy demand. By 2040, is expected a 9% decrease in the use of oil and coal, that will be replaced by 5% increase in renewables utilization and 2% each, in gas and nuclear use.

In the United States, renewable electricity generation is defined to increase by 72% from 2013 to 2040 according to the reference case developed by the U.S. Energy Information Administration (EIA, 2015). This growth is driven by rising long term natural gas prices, high capital cost of new coal and nuclear generation, government incentives for increasing renewable energy use, and cost reductions for renewable generation. Furthermore, the country's energy consumption is growing at a slower pace than previous years (EIA, 2015). This reduced growth (0.3% per year) is a result of structural changes in the economy, energy efficiency improvements and the adoption of policies that promote increased energy efficiency. Natural gas, renewable energy (excluding liquid biofuels) and nuclear energy have become the energy sources of choice for new energy system installations.

Energy System Sustainability

Leveraging the WCED (1987) sustainability definition, energy sustainability can be defined as an energy system that meets the needs of the present without compromising the ability of future generations to meet their own needs. One can consider energy sustainability to include environmental, social, and economic dimensions, the three pillars associated with sustainable development. While the environmental dimension focuses on conserving the current ecosystem, other important considerations are reducing or eliminating greenhouse gas emissions, managing hazardous wastes, optimal use and control of water and other natural resources, and reduction of environmental disruption, among others. The social dimension ensures that while producing / supplying the demanded energy products, negative effects on public health, safety, and other social concerns are minimized. The economic dimension ensures that energy businesses are still profitable while meeting the environmental and social dimensions.

The availability of energy is critical to ensure a thriving economy and society. For the most part, a country's development and economic growth is tied to its energy system (IAEA, 2005 and UNDP et. al. 2000). However, a dilemma is that energy systems are also currently associated with high volumes of greenhouse gas (GHG) emissions, environmental damage and, in some cases, adverse health effects in communities where energy facilities are located. Traditional energy resources are being depleted and there is increasing evidence of significant impacts on nature due to their use. Given this, energy sustainability is a growing major concern. The overall "global energy system" is currently facing various challenges related to all three sustainability pillars. Reaching a balance among social, economic, and environmental pillars is a key objective for today's society. It is critical to address energy sustainability in such a way that countries can further their economic growth while balancing important social and environmental concerns.

According to the World Energy Outlook (IEA, 2013), the energy sector is responsible for the largest amount of greenhouse gas emissions in the world. Furthermore, reducing these gas emissions is critical to limit the average global temperature increase to less than 2 degrees Celsius (IEA, 2013). Although nations are engaged on implementing emergency actions to achieve the set goal, world efforts as a whole are more and more distant from meeting the objective. Things like increasing energy demand as well as projected carbon dioxide emissions and use of fossil fuels as primary source of energy (nearly 80%) by 2035, growing dependence of countries on imported fuels, added to the fact that 1.3 billion people lack access to electricity, have been consistently the trend in energy systems during the last years (EIA, 2011; IEA, 2012b; UNE, 2010; and GEA, 2012). Moreover, the resurgence of oil and gas production in some countries and reevaluation of nuclear energy in some others could lead to a shifting in energy policies (IEA, 2012b). All these major issues are an illustration of the complexity and uncertainty associated with energy system development.

2017 has been set as the year when all the permissible carbon dioxide emissions will be “locked in” by the energy infrastructure existent at that point in time (IEA, 2013); this means that new energy facilities shall meet the energy demand without increasing carbon dioxide emissions. The proximity of the date, for this constraint to become effective, should be taken as a sign of urgency for finding a clear definition of what needs to be done and how it can be done, that could position humanity in a path of reaching a sustainable energy system while minimizing the uncertainty of potential negative effects.

Renewable Energy Sources

Renewable energy sources are energy sources that regenerate and can be sustained indefinitely (EIA, 2013). As the International Energy Agency (2002) states: “renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources”. Wind energy is the kinetic energy present in wind motion that can be converted to mechanical energy for driving pumps, mills, and electric power generators. Solar energy is the radiant energy of the sun. It can be converted into other forms of energy, such as heat or electricity. Biomass is organic nonfossil material of biological origin. Biomass materials can be used to create fuels and gas. Water (hydropower) energy is the kinetic energy stored in water. This energy can be converted to mechanical, similar to wind energy to perform a variety of uses. Geothermal energy is energy in the form of heat from within the Earth. Heat can be converted into steam, hot water or used to generate electricity (EIA, 2013).

Harvesting energy from renewable energy sources produces a reduced amount of greenhouse gases compared to traditional energy sources. This characteristic has been one of the main drivers for renewable energy sources utilization in recent years. Renewable energy sources are perceived as a key contributor to supply the world energy needs. Furthermore, renewable energy sources are spread over various geographical areas around the world. In contrast, traditional non renewable energy sources are concentrated in a limited number of countries. In the past, low prices of non-renewable energy sources made it difficult for renewable energy sources to compete. Nowadays, the stringency of environmental regulations to mitigate or avoid climate change has given a boost to renewable energy development.

According to the International Energy Agency (2012), accelerated deployment of renewable energy, energy efficiency, and technological diversification of energy sources would result in a significant increase of countries energy security and economic growth.

Renewable energy sources can perform the function of fossil fuels in four distinct markets (REN21, 2012): power generation, heating and cooling, transport fuels, and rural (off-grid energy service). According to REN21 (2015), from 2006 through 2014 the total installed capacity of renewable energy sources in the world grew rapidly; solar photovoltaic (PV) increase at a rate of 58% annually, concentrating solar thermal power (CSP) increased at a rate of 37%, and wind power increased 26%. Demand for renewable energy is also growing.

In the power generation market, renewable energy represented an estimated 58% of the net additions to global power capacity in 2014 (REN21, 2015). Total renewable power capacity worldwide exceeded 1,712GW in 2014. By the end of 2014 operating renewable capacity represented an estimated 27.7% of global power generating capacity (REN21, 2015).

Renewable Energy Trends

Renewable energy development has had an accelerated growth in the 2000s (REN21, 2013). Various international organizations have modeled different scenarios that depict possible paths for renewable energy development in the future. These scenarios range from a conservative perspective (15-20% growth) (WEO, 2012; EIA, 2011) to a very optimistic perspective (50-95% growth) (German Advisory Council on Global Change, 2004; European Renewable Energy Council (EREC), 2007). A moderate perspective (30-45% market share) is also considered (IEA, 2006). Despite the disparity of the market share forecast for renewable energy depicted in these scenarios, utilization and further development of renewable energy shows a trend of growth that is expected to continue for at least few decades more.

Furthermore, a steady interest and support to renewable energy growth has been seen. National governments are diligent in this area and have enacted policy targets for future shares of renewable energy to 2020, 2030 and 2050. By 2011, at least 20 countries already had targets for shares of renewable energy (REN21, 2013). This unity to supporting policy frameworks for renewable energy development could lead to a high renewable energy share in the same time frame.

Energy System and Sustainability Research

Table 2.1 defines different research done in the energy system domain to assess sustainability. Some of the work found in the literature has been focus in one or two of the sustainability pillars.

Table 2-1 Energy Systems and Sustainability Research

References	Contribution
Afgan & Carvalho (2000)	Development of multicriteria sustainability assessment of energy systems looking at technical aspects
Begic & Afgan (2007)	Bosnia and Herzegovina power system assessment to determine options for the selection of new capacity building through sustainability indicators
Elghali et al. (2007)	Development of a sustainability framework for assessment of bioenergy systems life cycles
Assefa & Frostell (2007)	Analysis of the sustainability of energy technologies with ORWARE, a Swedish technology assessment tool. They characterize a sustainable technical system by assessing its overall system health as a sustainably functioning system
Evans et al. (2009); Evans et al. (2010); Varun et al. (2009); Silva Laro et al. (2011); and Kowalski et al. (2009)	Assessment of renewable electricity generation technologies
Silva Laro et al. (2011), Bringezu et al. (2009a), Fargione et al. (2008), Eisentraut (2010); Hill et al. (2006); Gacez; Vianna (2009), and Bringezu et al. (2009b)	Sustainability assessment of biofuels

System Dynamics and Energy Systems

System dynamics has been employed for more than 35 years for strategic planning and policy analysis in energy systems. Table 2.2 defines different applications of system dynamics in energy systems and associated research domain. A separate section is discussing the work related to system dynamics application to wind energy.

Table 2-2 System Dynamics and Energy Systems Research

References	Contribution
Naill (1976 and 1977)	Development of COAL1 and COAL2 models. The models demonstrated that coal was the best fuel for the energy transition.
Bassi (2009)	Development of Threhold21 (T21) model, a holistic framework that represents the causal structure of the technology development
Alternative Energy Systems (AES) Corporation (1993)	Development of the Integrated Dinamic Energy Analysis Simulation (IDEAS) model

Backus et al (1979) and (1981)	An improved version of FOSSIL models
Sterman (1981)	Development of an energy transition model that captures the energy-economy interactions
Sterman et al. (988); Davidsen et al. (1990)	Development of the petroleum life cycle model
Fiddaman (1997)	Development of the Feedback-Rich energy economy model (FREE)
Powell (1990a, 1990b); Morecroft (1992);	The behavior of OPEC and world oil markets
Tan et al. (2009)	Use of binomial decision trees and real options theory to evaluate system dynamics models of risky projects, using the wind energy industry as a case study
Chan et al. (2004)	Examine the role of the systems modeling for sustainable policy analysis in Canada, using bioethanol as a case study
Musango (2012)	A Bioenergy Technology Sustainability Assessment, (BIOTSA) model
Flynn & Ford (2005)	A carbon cycling and electricity generation from energy crops model
Tesch et al. (2003)	Development of system dynamics model of global agricultural and biomass development
Bantz & Deaton (2006)	Use of system dynamics to envision possible growth scenarios for the US biodiesel industry
Scheffran et al. (2007)	Development of a spatial-dynamics model of energy crop introduction in Illinois
Hsu (2012)	Using a system dynamics model to assess the effects of capital subsidies and feed-in tariffs on solar PV installations
Mazhari et al. (2011)	A hybrid simulation and optimization-based design and operation of integrated photovoltaic generation, storage units, and grid
Jones (2008)	Development of a system dynamics model to get understanding of the energy system as a complex system so that policy can promote the renewable sources deployment
Vimmerstedt et al. (2012)	Analysis of a portion of the Biomass-to-Biofuels supply chain using system dynamics
Devore et al. (2006)	Understanding U.S. biodiesel industry growth using system dynamics modeling
Chu et al. (2012)	Analysis and control design of sustainable policies for greenhouse gas emissions.
Davies & Simonovic (2009)	Development of a system dynamics model for analyzing behavior of the social-economic-climatic model.
Jalal & Bodger (2010)	Development of a system dynamics model to evaluate electricity generation expansion in New Zealand

Wind Energy

Wind energy is a form of solar energy. It is air in motion. Two percent of the sun's radiation that reaches Earth is converted to wind energy through heating and cooling of the Earth's surface.

The use of wind energy for performing activities useful for societal development goes back more than 3000 years. In ancient times wind energy was used to propel boats, to pump water and grind grain (EIA, 2012a). Windmills were widely used for food processing during the 11th century. The Dutch adapted the technology to be used for draining lakes. Windmills entered the New World with Europeans settlers during the 19th century. However, the electric power generation from windmills has just 125 years of history. Prof. James Blyth was the first to generate electricity from a windmill in 1887 (Price, 2005).

Since its inception, wind energy generation has been associated with fluctuations of oil prices. During the 1970s decade, due to the oil crisis, there was a major interest on renewable energy sources development. However, during the 1980s wind energy was not emphasized due to lack of a policy framework to support its growth. Later, in the 1990s, environmental concerns related to the potential of climate change ignited the wind energy development again (EIA, 2012a). During the 2000s, wind energy development received a major boost, when many countries adopted an incentive-oriented policy towards the wind energy industry and efforts for wind energy technology development extended among countries (Hepbasli, 2004; Ackerman, 2002; and Xu et al., 2012). Since the beginning of the 21st century, the world wind electricity generation capacity has doubled approximately every three and a half years (Yang, 2012).

Another reason for the rapid growth of wind energy is the perception that this kind of energy is one of the cleanest sources of energy. Different policies have been put in place around the world to promote a more sustainable energy system. In 2010, the European commission set as a goal that renewable energy shall supply 20% of the energy demand by 2020 (European Commission, 2010). United Kingdom also set 20% of green power by 2020 as a target (Strbac et. al, 2007). In addition, United States set as a target that 20% of electricity demand shall be supplied from wind power by 2030 (DOE, 2008).

Wind energy projects can be categorized as onshore wind energy projects and offshore wind energy projects. An onshore wind energy project is a wind energy installation located on land. An offshore wind energy project is, as its name implies, a wind energy installation located in the sea.

Wind Energy Project

A typical onshore wind energy project requires two to three years from conception to its operational phase. The time varies depending on the amount of information related to wind resource, history of wind energy development, permitting and environmental assessment requirements of the prospecting region or state to locate the wind energy project (AWS Truewind, 2009).

Wind energy project lifecycle phases are: wind resource assessment, permitting, financing, construction (installation), operation and maintenance, and decommissioning and/or repowering (AWS Truewind, 2009 and Osborn, 1998). A brief explanation of each of the phases is presented in the following paragraphs.

Wind Energy Resource Assessment

Assessment of wind resource is critical for wind energy projects. This phase is decomposed into three subprocesses. These are prospecting, validation and micrositing (AWS Truewind, 2009). Prospecting refers to identification of potential sites for a wind energy project. Terrain maps, wind resource maps, climatologic information, and local wind speed data are key source of information during this phase. A preliminary decision on performing additional efforts to potentially develop a wind energy project in a location is taken from the analysis of gathered information. Validation follows prospecting and includes a more detail study of the wind resource to assess energy production estimates. In this subprocess, monitoring stations are installed to collect data for wind resource characterization. For accurate results of the validation process, data is collected for a minimum of a year. Concurrent with the validation process, leasing negotiations with land owners and interactions with local authorities are initiated. Micrositing starts when the validation process is complete and viability of a project has been confirmed. During this process, additional wind data is collected to define appropriate type and size of turbines for the site, identify turbine locations and optimize prospectus project layout.

Permitting

In this phase, developers pursue approval for construction and operation of wind energy projects from government agencies. Local and federal rules and regulations are researched to ensure compliance with pertinent rules and regulations. The number of agencies and the levels of involvement of each of them depend on the wind energy project location, transmission lines, substation, operation and maintenance facilities, access roads to be used, wind energy project installed capacity, land ownership; and project ownership and funding sources (AWS Truewind, 2009).

Installation / Construction

The installation phase includes all work required to get a wind energy project built. This phase usually requires a time between five and twelve months. The project schedule works around crane utilization. Minimization of crane operating time is key, due to the high operating cost of large capacity cranes (AWS Truewind, 2009). Table 2.3 below shows the major tasks and subtasks of the installation phase. A turbine could be transported in seven trailers, a large capacity crane required 60 trailers to be transported (AWS Truewind, 2009). Transportation is performed following all federal and state transportation regulations related to weight and size. Depending on the condition of access roads, infrastructure modifications may be required that would be reflected in project costs.

Table 2-3 Wind Energy Project Installation Phase Tasks and Subtasks

(AWS Truewind, 2009)

Task	Subtask
Site Preparation	Access Roads Construction
	Foundations Construction
	Power Collection System installation
	Substation installation / Grid interconnection
Turbine Installation	Receive Tower and Turbine Components
	Set Tower Based Sections
	Complete Tower Assembly
	Install Nacelle and Rotor
Construction completion	Complete Internal Turbine Assembly and Connections
	Energize Project Site
	Commission and Test Turbine Functions
	Performance Testing to Verify Proper Operation

Operation and Maintenance (O&M)

Operation of wind energy projects is automatic and independent (AWS Truewind, 2009). An automated control system, which is remotely monitored, controls and monitors wind turbines performance. It also starts alarms in presence of dangerous conditions. A high speed communication network between turbines is required for remote site operation. One operator for every 10 to 20 turbines is usually the staff size required to operate and maintain a wind energy project. Personnel shall have the minimum required training, including electrical and mechanical skills, to troubleshoot general turbine faults and operational problems. Much of the work requires a significant amount of climbing.

Wind energy projects are expected to operate for 20 to 25 years. On the other side, lease agreements between land owners and operators may be longer than this period of time. Therefore, if reevaluation and repowering are considered, the development process would be minimized.

Decommission / Repowering

Repowering wind energy projects refers to replacing old and more costly wind turbines for new ones, which are usually smaller, and more technologically advanced. Repowering is considered when projects are reaching the end of their operational phase and/or major technological advances have taken place that can significantly impact the wind energy project's performance. Repowering is usually a smooth process since wind resources and site conditions are known. Surrounding communities are already familiar with the project's presence.

Decommissioning involves total removal of a wind power project after it has reached the end of its design life. Restoration of the land to original conditions might be required depending on lease agreements and permit requirements. This process includes complete removal of turbines, tower foundations (down to a certain depth), cabling, substation equipment, power poles, other buildings, etc. (AWS Truewind, 2009). Regrading and replantation is required where turbines, access roads, and buildings were located.

Wind Energy Systems in the World

Wind power is expected to maintain continuous growth as technology becomes more competitive in terms of cost with conventional sources of electricity generation. The total wind energy capacity installed worldwide by the end of 2014 was 370GW. In 2014, 51GW of wind energy capacity was added worldwide. Following a slowdown in 2013, wind power had a record year with a 44% increase over previous year.

The market for offshore wind turbines is still under development. In 2014, an estimated 1.7GW was added offshore increasing the offshore global capacity to 8.5GW (REN21, 2015). 13 countries had offshore wind farms, eleven of them in Europe as well as two in Asia.

Wind Energy in U.S.

In order to develop a wind energy project it is required to have projections of wind energy resources from the desired location. Areas with annual average wind speeds around 6.5 m/s and greater at 80-m height are considered to have suitable wind resource for wind development (DOE, 2010)

High resolution wind resource maps, developed by the National Renewable Energy Laboratory (NREL) and AWS Truewind, LLC (2015) show an accurate depiction of the overall wind resources of the U.S. States have a land-based wind energy potential of 9,118GW capacity at 80m and 10.325GW at 110m heights at 35% capacity factor (DOE, 2015).

Government Intervention

The wind energy market receives support of the government through a policy framework that allows indirect and direct subsides. Energy subsidies are the way how governments shape the energy market in a particular way. Direct subsidies are production tax credits (PTC) applied to energy produced by wind energy projects. In United States PTC passed into law as part of the Energy Policy Act of 1992. It applies to the first ten years of a wind energy project operation. A feed in tariff is a government policy that ensures to renewable energy producers a minimum price for selling their power into the grid. A feed in tariff is paid by energy customers; therefore raising the electricity price to end users (Janardhan and Fesmire, 2011).

Wind Energy Challenges

The variable nature of wind represents a major challenge for wind energy systems. However since energy demand is constantly changing, various studies have shown that large energy systems can handle up to 20% of wind energy without causing serious effects (Janardhan & Fesmire, 2011; DOE, 2008; Villlafafila et.al, 2007).

The best sites for wind farms are often far from load centers, which causes a need to build transmission lines that add a cost constraint to wind energy projects. Given that wind energy systems generate just a fraction of the installed capacity at any given time, utilization of transmission lines is inefficient, which represents a less that attractive return of investment to transmission lines investors (Janardhan & Fesmire, 2011).

Bird and bat deaths, soil erosion at wind farms, aesthetic impacts and reduction of property values, and the need for back up generation (2MW per 100 MW (Goggin, 2009)) are the most widely known environmental drawbacks for wind energy system development and operation.

In order to make use of the full potential of wind and other renewable energies, it will be of crucial importance to strengthen the related frameworks, institutions and policies. The world community as well as national governments will have to set up additional policies in favor of wind energy. Incentives for a decentralized and integrated 100 % renewable energy supply need to be created, again especially but not exclusively for developing countries.

Another key issue for the prospects of wind power in this context will be social acceptance. Recent studies from Scotland, Germany, the USA and Australia suggest that social acceptance is significantly higher in the case of wind farms that are owned by the local community where the wind farm is located. Obviously in such cases opposition against wind power is also significantly lower. In general, acceptance of wind farms is high; however, people who see themselves as owners of a wind farm naturally have an even more positive attitude. Policymakers have to draw the right conclusions from such results and introduce legislation that favors community based ownership models of wind farms.

Benefits of Using Wind Power

The United States Department of Energy (2005) has identified a set of benefits of using and deploying wind energy projects. These are:

- Economic competitiveness. Technological advances have made wind energy an economically comparable solution with traditional sources of energy such as coal.
- Wind energy brings economic benefits to farmers and ranchers. Wind energy projects, usually located in rural areas, provide an increase in rural jobs that has a positive effect on the local area. Since wind energy projects are compatible with farming and livestock care, wind energy projects represents and additional revenue to farmers and ranchers as a result of land leases.
- Wind turbines don’t consume water. This is a high advantage since water is becoming scarcer.

- Wind energy contributes to national energy security. Given the various natural sites with favorable conditions for wind energy projects, wind energy contributes to increase the United States energy security.
- Wind energy is inexhaustible and infinitely renewable. Unlike traditional energy sources, wind energy is freely available to be harvested.
- Wind energy has environmental benefits. Wind energy exploitation does not produce greenhouse gas emissions or any other pollutants that are usually byproducts of traditional energy source exploitation. It does not produce hazardous liquids or solid waste, does not deplete natural resources, and does not cause environmental damage due to extraction and transportation of these resources (Janardhan & Fesmire 2011).
- Wind energy is unsusceptible to fossil fuel price volatility because wind is free.
- Wind energy is the fuel of today and tomorrow. With continuous technology advances, the expectation is that wind energy could become the cheapest source of energy.
- Wind energy has various applications. Some of them have been around since ancient times like water pumping; others could be powering telecommunication sites, electricity generation in microgrids (mainly in remote villages), among other uses.
- The people want wind energy. The more knowledge the population has related to wind energy, the more acceptance to renewable energy sources. Just in 2012 a total of 66 utilities bought or owned wind power in 2012 (AWEA, 2013), which is a reflection of the customer acceptance of using wind for powering America.

<u>System Dynamics in Wind Energy and Sustainability</u>

System dynamics can be applied to understand the dynamic behavior of factors and factor relationships related to wind energy project sustainability. System dynamics have been used for modeling different aspects related to wind power systems. Research found in the literature is presented in this section.

Pruyt (2004) developed system dynamics models to study the long term development of wind energy diffusion dynamics. In this work, Pruyt criticized the limitation of the Wind Force 12 Report (2002) and present a system dynamics model with added feedback relationships that were previously ignored.

This model covers economic factors, technical factors and a few environmental factors. Hamarat and Pruyt (2011) expanded Pruyt's (2004) previous work using the Exploratory Modeling and Analysis (EMA) methodology to deal with the uncertainty related to the future of wind power.

Sanchez et al. (2005) developed a system dynamics model to consider profitability of energy technology. More specifically, they focused on the development of wind power as dependent on investors' decisions. The study focused on economic factors.

Dyner (2006) developed a system dynamics model for power market in Colombia. This model studies the effects of policy incentives on the behavior of wind farms generators. This model goes beyond the wind industry and look at relationships of factors related to the entire electricity market. A system dynamics model was developed for studying the effects of price patterns for tradable green certificates on wind electricity generation (Ford, Vogstad and Flynn, 2007).

A system dynamics model for understanding the historic development of different countries (United States, Denmark, Germany, Portugal and Spain) wind energy markets was developed (Dykes and Sterman, 2010). The main purpose was to assess the effects of policy on the development of different national markets for wind power as well as the impacts of the development on the wind industry. This model provides understandings into the dynamics and relationships of policy, technology adoption and industry development as key considerations for wind power development. This study focused on the economic and social factors.

A long term system dynamics model for the electricity market, based on conventional generation resources and wind power generation as a renewable energy resource, was developed (Hasani-Marzoni and Hosseini, 2011). This model allows understanding how a hybrid electricity market may evolve in the long term run looking at policies and their effects on investors' behaviors.

Hosseini et al. (2012) presents a system dynamics model to study the current situation of wind power market in Iran. The objective is to understand the effects of policies in the development of wind power generation. The scope of this work includes government related factors, power market and economic factors, generation technology, general limitations and environmental factors.

A system dynamics model to investigate the effects of incentive mechanisms on wind power investments was developed by Alishahi, Parsa Moghaddam and Sheil El-Shami (2012). This model is based on long term expansion planning.

As can be seen, the study of wind power development, associated with policies and associated incentive mechanisms have been the indisputable inquiry on those models. This is understandable due to the high level of uncertainty associated with future energy system composition.

Furthermore, to ensure a transition to a more sustainable energy system, it is crucial to better understand the environmental, social and economic factors and how they relate. However, a system dynamics model assessing wind energy system sustainability that considers the three pillars has not been found in the literature. Table 2.4 categorizes the work previously presented based on coverage of sustainability pillars.

Table 2-4 Categorization of Wind Energy Research Based on Sustainability Pillar Coverage

Paper	Sustainability Pillar
Pruyt (2004), Hamarat & Pruyt (2011), Ford, Vogstad and Flynn (2007)	Economic, Environmental (limited coverage)
Sanchez et al (2005), Dyner (2006), Hasani-Marzooni & Hosseini (2011), Alishahi, Moghaddam, & Sheikh-El-Eslami (2012)	Economic
Dykes & Sterman (2010)	Economic, Social (Limited)
Hosseini, Shakouri, & Akhlaghi (2012)	Economic, Environmental (limited coverage), Social (limited coverage)

Research Methods

The section provides background information about different research methods that can be used for this research to be able to answer the research questions and provide the research contributions.

Systems Engineering

"Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems." (INCOSE, 2011). Systems engineering deals with large and complex systems and focuses on the system as a whole; considering the complete problem and solution. An objective of systems engineering is to better understand the structure of the system and its behavior looking at the elements and the interaction between elements within the system and with its environment. The energy system is a complex system of systems. Systems engineering can help to address the complex sustainability challenges related to energy systems. Snyder (2008) highlights the need to apply systems engineering to transition to sustainable energy systems.

Systems engineering approaches systems from a holistic perspective. Researches have started to use systems engineering methodologies to approach wind energy (Kühn et al., 1997; Ozkan & Duffey, 2011; and Dykes & Meadows, 2011).

<u>Systems Engineering and Wind Energy</u>

The National Renewable Energy Laboratory (NREL) is developing a Wind Energy Systems Engineering (WESE) framework and tool (Dykes and Meadows, 2011) to approach wind energy complexity from a systems engineering perspective. This framework considers the technical systems as a whole, including their performance criteria and non-technical concerns brought by human and societal impacts. The main objectives of the WESE framework and tools are twofold: 1) to offer the capability of performing comprehensive and detailed analysis of various aspect of wind energy systems by means of systems engineering methods and models, and 2) to be a flexible framework that could expand systematically to support the wind industry's approach to present challenges and to help in the design and development of future wind technologies at lower cost. WESE tool architecture is based on NASA's OPENMDAO and Sandia's DAKOTA software. The first stage of the WESE tool includes the integration of wind power plants cost models and engineering- based wind turbine component cost and sizing models into a Levelized Cost of Energy (LCOE) analysis framework (Dykes and Meadows, 2011). Integration with other wind energy models and further levels of fidelity will be added to the tool in the next phases of the initiative.

A system engineering approach for assessing sustainability of wind energy systems based on the social, economic and environmental impacts has not been found in the literature.

<u>Systems Thinking</u>

Systems thinking, an approach within systems engineering, enables us to better understand complex systems. Systems thinking is a method of placing the system in its context and observing the system's role within the whole (Gharajedaghi, 1999). Systems thinking provides a holistic world view where things are interconnected (Maani and Maharaj, 2004). Systems thinking approaches allow us to perceive the world as a complex system and supports understanding its interconnectedness and interrelationships (Sterman, 2000).

Systems Thinking and Wind Energy

Wind energy has become one of the fastest growing renewable energy technologies in the world. In the same manner that the number of wind energy projects has grown, complexity has increased due to the heterogeneous set of stakeholders, with different objectives and goals, who are involved; the various competing technologies, set of elements and subsystems that conforms wind power projects; and the impacts of those projects to the environment and communities where they are located on throughout their entire life cycle.

Systems thinking can be applied to understand energy sustainability by considering the system as a whole. This approach has been identified as "essential to explore opportunities to leverage technology deployments within existing and new energy infrastructure" (IEA, 2012a). Systems thinking allows us to focus on optimization of the entire energy system, instead of the individual parts, and could result in an increase of overall performance and benefits.

Understanding that the different parts of the systems do not act in isolation, and that overall outcome would be the result of the various interactions among system parts, allows us to have a broader perspective of the problem and potentially find solutions that would benefit the system as a whole. A system thinking approach can be used to address the sustainability of wind energy systems.

Systems thinking has been employed to approach multiple issues within wind energy. Kuhn et al. (1997) presented the Structural and Economic Optimization of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS), developed in a collaborative effort between Delft University of Technology, the University of Sunderland, and industrial partners. The study consisted of development of cost models for offshore turbines, including their foundations, balance of station, and operation and maintenance. Responses of turbine designs to extreme conditions were modeled using finite element analysis. Long term behaviors of turbines were modeled using combined wind-wave models. Site-specific design was developed using Geographic Information System (GIS) tools with a cost-of-energy model to evaluate cost of energy for offshore wind in shallow waters across Europe.

The Offshore Wind Integrated Cost (OFWIC) (Ozkan and Duffey 2011) model includes models for wind, wave, turbine, balance of station, operations and maintenance, environmental pollution impacts, financing, scheduling, and network integration to obtain cost optimization for a specific site.

Decision Support Systems

A Decision Support System (DSS) is an information system that helps and supports people in the decision making process (Power 2002). DSSs provide knowledge and/or a knowledge processing capability that is influential in making decisions (Holsapple 2008).The use of DSSs is associated with an increase of productivity, agility, innovation and reputability of the decision making process. This leads to a higher level of satisfaction of the different stakeholders involved in the decision making process (Holsapple 2008).

Simulation

According to Bratley et al. (1987) “simulation means driving a model of a system with suitable inputs and observing the corresponding outputs”. Different than other methods that focus on answering the “what, how and/or why” questions of a specific issue of interest, simulation focuses on the “what if” question. It allows us to consider alternative scenarios and assess the results.

Modeling and simulation approaches help to study and experiment with dynamically complex processes that have important short- and long-term effects, by providing insights into the problem structure. Models are an abstract representation of our understanding of reality. Model usefulness and quality depend on the level of uncertainty associated with the elements of the model and the structure of the system.

There are three main simulation research techniques (Dooley, 2005). They are: discrete event simulation, continuous simulation (system dynamics), and agent-based simulation. In discrete event modeling, model entities evolve over time, events trigger other events sequentially and probabilistically (Dooley, 2005). Process flow charts are used for discrete event modeling. Continuous modeling (system dynamics), as the name implies, is used when entities in the model can change continuously (Özgün & Barlas, 2009). This method is a top-down approach. This technique use differential equations to define key system variable and their interactions with one another (Dooley, 2005). In agent based simulation, the system is modeled by agents, which are a set of autonomous decision makers (Bonabeau, 2002), that interact with one another and the environment and learn (Dooley, 2005).This method is a bottom-up approach. Selection of a simulation technique depends on the purpose of the model, the type of results expected, and modeler preferences. Simulation provides the basis for making decisions (Page, 1994). Simulators can help users to explore risks and evaluate the dynamic consequences of various decisions without having to actually build the real system. Decision makers can use simulators to understand the system dynamics associated with a system.

System Dynamics Modeling

System dynamics, a method developed by Forrester (1961), is an interdisciplinary approach that supports understanding the dynamic behavior and structure in complex systems. System dynamics represents complex systems and analyses their dynamic behavior over time (Forrester, 1961). According to Coyle (1996): "system dynamics deals with the time dependent behavior of managed systems with the aim of describing the system, and understanding, through qualitative and quantitative models, how information feedback governs its behavior, and designing robust information feedback structures and control policy through simulation and optimization". System dynamics models are causal mathematical models (Barlas, 1996).

The main objectives of system dynamics modeling are (Barlas and Carpenter, 1990; Sterman, 2000, Auerhahn, 2008):

- To get a better understanding of the endogenous structure of a system of interest.
- To identify the element relationships within the system of interest.
- To analyze and evaluate policies and strategies to study the effects on the system of interest.

System dynamics modeling could be performed from two different methods (Dolado, 1992) qualitative and quantitative. Qualitative or conceptual modeling uses causal loop diagrams (Hodgson, 1992), to provide better system understanding. Quantitative or numerical modeling uses stock-and-flow models to further study and analysis, through simulation, of the effects of different policies on the system.

System dynamics can help in comprehending complicated relationships between key factors. To deal with the complexity, non-linear relationships as well as linear relationships must be considered. The main structural components of a system dynamics model are stocks (levels) and flows (rates) (Forrester, 1969; Hanneman, 1988). Stocks represent state of the model or system and flows represent changes in the state of the model or system.

System dynamics offers various advantages; Winz et al. (2009) classified these advantages as: 1.flexibility, 2.established methodology, ease of uptake, transparency and adaptability, and 3. foresighting, on-going testing and learning, and stakeholder participation. A system dynamics model is useful when it serves the purpose for which it was developed (Sterman, 2000).

System dynamics modeling is suitable to approach multi-domain problems. It is widely applied in control systems engineering. Furthermore, it has been used in other fields such as business management, environmental management, energy and healthcare.

System Dynamics Limitations and Challenges

One of the main limitations for system dynamics is that it does not provide exact solutions and answers. Well defined operational problems are out of the scope of utilization of system dynamics. Quantification of qualitative variables may be challenging, use of qualitative data collection and analysis methodologies could help in this process (Luna-Reyes and Anderson, 2003). The problem boundary definition is challenging (Sterman, 2000). Modelers should be careful to only include key variables that contribute to generating the problem behavior as close as possible to the real world experience (Sterman, 2000).

System dynamics mainly support analyses of dynamically complex problems, which are interdisciplinary with inherent uncertainty (Vennix, 1996). To ensure consistency throughout the process of developing a system dynamics model while dealing with the system complexity is a main challenge of this approach.

Causal Model

Causal models are graphical representation of the system structure. Causal models are a qualitative or conceptual modeling technique (Hodgson, 1992). Causal diagrams capture the major feedback mechanisms within a model. Causal models are more an art than a science in the sense of the effort to effectively capture the feedback relationships (Sterman, 2000). These diagrams represent dynamic hypotheses about factors. They can also simplify the representation of a system. Elements (factors) and arrows (causal links) are the components of a causal diagram. A sign (+ or –) is assigned on each link indicating an increasing or decreasing relationship between factors. Furthermore, a complete loop can also be given a sign reflecting a positive or negative feedback.

Verification and Validation (V&V) of Simulator

Validation and verification of system dynamics simulators are performed to ensure accuracy, completeness and usefulness of the model; in other words, the process ensures that the model meets the purpose and goals of the modeling effort. Validation confirms the usefulness of the model. Verification determines if the simulator runs as planned. The Richardson and Pugh (1981) verification and validation process includes testing for suitability (verification), consistency (validation) and utility and effectiveness. Suitability testing focuses on examining the model to ensure that it fits for the purpose and it addresses the problem for which it was built. Consistency testing focuses on examining how well the model represents the real system. Utility and effectiveness testing focuses the effectiveness of the model in accomplishing the purposes of the study. It also checks if the model or its results can be used. Table 2.5 summarizes the tests used for the model verification and validation process. A brief explanation of what is included on each test is presented.

Table 2-5 Verification and Validation Activities (Richardson and Pugh, 1981)

Test for	Structure	Behavior
Suitability (Verification)	Dimensional consistency Extreme conditions in equations Boundary adequacy	Parameter (in) sensitivity Structural (in) sensitivity
Consistency (Validation)	Face validity Parameter values	Replication of reference mode (boundary adequacy for behavior) Surprise behavior Extreme condition simulations Statistical tests
Utility and Effectiveness	Appropriateness of model characteristics for audience	Counterintuitive behavior Generation of insights

Tests for suitability:

- Dimensional consistency: It ensures that dimensions in every equation of the models are checked with the computation.
- Extreme condition tests in equations: The equations of the models are tested to ensure they make sense when subjected to extreme but possible values of its variables.

- Boundary adequacy tests for structure: The structure of the model is checked to verify it contains the variables and feedback effects necessary to address the problem and suit the purpose of the model.
- Parameter (in) sensitivity: The behavior of the model is checked to see if it's sensitive to reasonable variations in parameter values.
- Structural (in) sensitivity: The behavior of the model is checked to ensure the model is sensitive to reasonable alternative formulations.

Tests for consistency:

- Face validity: The model's structure is checked to verify it looks like the real system and represents the essential characteristics of the actual system.
- Parameter values: This includes two tests; first, the parameters are checked to ensure they are recognizable in terms of the real system. Second, the values selected for the parameters are selected to ensure they are consistent with the best information available for the real system.
- Replication of reference modes (boundary adequacy tests focusing on behavior): The model is checked to make sure it reproduces the various reference behavior modes, including the problematic behavior, any observed responses to past policies, and any conceptually anticipated behavior arising from hypothetical situations.
- Surprise behavior: The model is checked to see if it produces unexpected behavior under some test circumstances not observed in the real system.
- Extreme condition simulations: The model is checked to verify it does not behave unreasonably under extreme conditions or policies.
- Statistical tests: The model's output is checked to verify it behaves statistically like the data from the real system (if possible).

Tests for utility and effectiveness:

- Appropriateness of structure for audience: The model's size, simplicity or complexity, and level of aggregation or richness of detail are checked to ensure they are appropriate for the audience intended for the research.

- Counterintuitive behavior: The model's behavior is checked to see if it contradicts intuitions and later reflects a clear implication of the structure of the system.
- Generation of insights: The model is checked to see if it can generate new insights about the system's behavior.

Chapter 3

Research Design

This chapter provides an overview of the research design used to develop the research contributions identified in Chapter 1. Figure 3.1 provides a graphical representation of the main activities and corresponding sequence used to perform the research. The individual sections in this chapter discuss each of the main activities in detail.

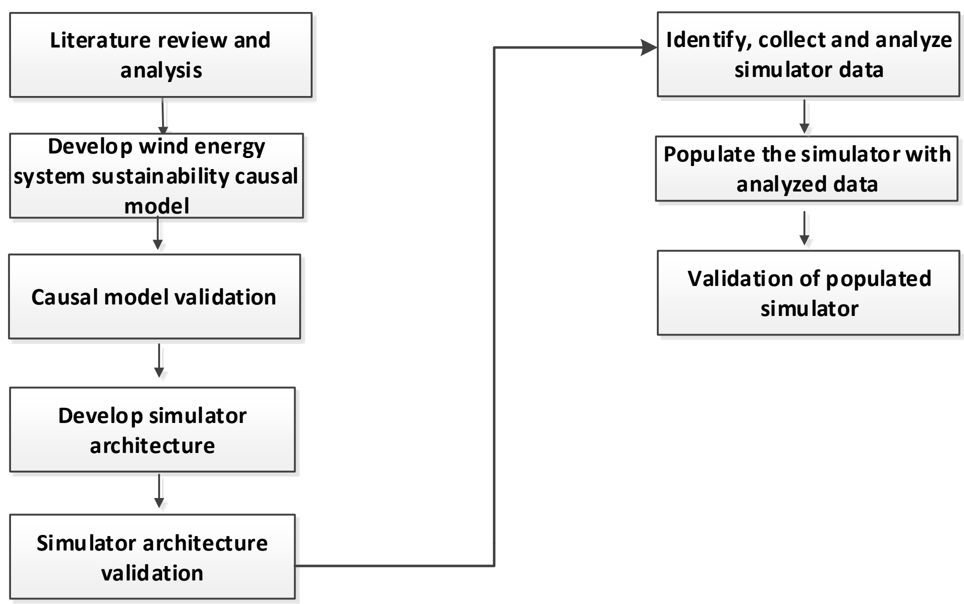

Figure 3-1 Research Design

Literature Review

A comprehensive literature review of sustainability, energy, wind energy systems, systems thinking, and system dynamics, related to wind energy system sustainability, was performed to better understand the current state of research. Literature searches were performed regularly to search for any relevant work to be added to the body of knowledge during the research development. The literature review is summarized in Chapter 2.

Analysis of literature reviews was performed to provide context for the research and understanding of how the problem domain was studied previously. Identification of energy system sustainability objectives that contribute to an understanding and identification of the factors and factor relationships associated with wind energy system sustainability were results of this task. Additionally, the literature review helped to identify data that was later used to populate the developed simulator.

A Systems Perspective of Energy System Sustainability

An understanding of energy system sustainability was developed to serve as a foundation to approach and comprehend the complexity of attaining sustainable wind energy systems. A categorization of energy system stakeholders, an understanding of the main energy system objectives related to sustainability, as well as the main functions performed in the energy system were part of this activity. This task was not part of the research design to answer the research questions, but it is listed because it was performed to converge on the specific topic.

After the energy system sustainability objectives were identified, a matrix that maps energy system stakeholders with energy system sustainability objectives was developed, followed by an IDEF0 diagram that represents the main functions performed within the energy system. These contributions helped to get a better understanding of energy system sustainability and served as a base for exploring wind energy system sustainability. These products are discussed in Chapter 4.

Wind Energy System Causal Model Development

The wind energy system has become an important component of the energy system given the continuous growth of the wind energy capacity within the new power generation capacity installed in United States. It is important to understand the impacts of the wind energy system to ensure its favorable contribution to the sustainability of the energy system as a whole.

Systems thinking, a core skill within systems engineering, has been employed to approach wind energy system sustainability. System dynamics modeling, a systems thinking approach, was utilized to help understand the complex factor relationships. System dynamics can help to visualize and explore the structure and behavior of factors related to wind energy system sustainability. As part of the system thinking approach, a causal model and a simulator were developed. Causal models are used in support of system dynamics to illustrate and capture the major feedback mechanisms within this system. Causal models can demonstrate various hypotheses about factors and factor relationships.

In developing the causal model, identification of the key factors and factor relationships were performed to get a better understanding of what drives sustainability during the installation, operation and maintenance, and decommissioning phases of a wind energy system. The causal model was developed using a Microsoft Visio diagram. Elements (factors) and arrows (relationships) are included in the causal diagram. A sign (either + or –) is assigned on each link indicating an increasing or decreasing relationship between factors The arrow heads also have a direction that indicates the sequence of the factors and the factor relationships. The causal model also includes feedback loops. The details about the causal model related to wind energy system sustainability are provided in Chapter 4.

Causal Model Validation

In order to ensure accuracy and completeness of the causal model, it needs to be validated. The main objective is to ensure that factors and factor relationships are a reasonable representation of the real system. This task ensures key factors, appropriate factor definitions and unit of measurement, factor relationships, and appropriate cause-effect direction between factors are validated.

The causal model was initially validated with the dissertation advisor through an iterative process of updating factors and brainstorming to make sure all the factors and their relationships were valid. The dissertation advisor provided comments and recommendations that helped with the validation process.

A wind energy system sustainability causal model validation package was then developed. With the assistance of the dissertation advisor, potential wind energy validators were identified. Validators were contacted to assist with the causal model validation. A validation presentation was made to a subject matter expert who had background expertise related to wind energy sustainability. The individual provided exceptional feedback regarding the model. The causal model validation package is provided in Appendix B. Based on the inputs that were received from the validator, an in-depth analysis was performed to see what changes would be reasonable to make. The list of feedback and inputs from the validator are provided in Appendix C. There were additional modifications to the causal model that were based on walkthroughs with the dissertation advisor and further analysis of the model and the literature. The modifications to the model and justification related to each change is provided in Appendix C. The validated causal model was used as an input to develop the simulator architecture.

Develop Simulator Architecture

Simulation is defined as the process of designing a model and performing experimentation with this model of a real system (Pritsker and O'Reilly, 1999). In the decision making process, simulation is a valuable aid to assess the impacts and evaluate implications of policies with no risk to the real system. Simulation enables 'what-if' analysis to consider alternative options. Simulation is the selected methodology that was used for the objective of developing a system dynamics model for wind energy system sustainability. Architecture is defined as "the organizational structure of a system or component" (IEEE, 1990). A system dynamics model simulator architecture includes a set of stocks, flows, and auxiliary variables, along with feedback. The wind energy system simulator architecture was developed using iThink simulation software. The iThink software provides a flexible platform for building simulation models.

The notation for the simulator architecture is shown below:

Stocks are representation of the state of the model or system. These are accumulations. (Figure 3.2).

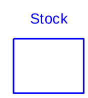

Figure 3-2 Stock

Flows (also called rates) represent changes in the state of the model or system. The job of flows is to fill and drain stocks. Inflows are represented by an arrow pointing to (adding to) a stock and outflows are represented by an arrow pointing out (subtracting from) of a stock. Rates control the flows. Rates are represented with valves (Figure 3.3).

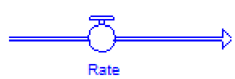

Figure 3-3 Flow (Rate)

Auxiliary variables represent combinations of information inputs. These can modify the flows. These hold values for constants, define external inputs to the model, calculate algebraic relationships, and serve as the repository for graphical functions. Auxiliary variables are shown with circles (Figure 3.4).

Figure 3-4 Auxiliary Variable

Clouds represent the sources and sinks for the flows (Figure 3.5). A source represents the stock from which a flow originates from outside the model scope. A sink represents the stock into which flows leaving the model scope drain. Sources and sinks are assumed to have infinite capacity and can never constrain the flow they support.

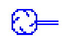

Figure 3-5 Cloud

Arrows represent causal dependencies in the model. They connect model elements.

An understanding of the factors and the relationships between factors can help in understanding what drives sustainability in wind energy systems. A wind energy system sustainability simulator can help users to explore risks and evaluate the dynamic consequences of various decisions without affecting the real system. The wind energy system sustainability simulator models the factors that relate to the wind energy system while considering the three pillars of sustainability (social, economic, and environmental). Energy decision makers can use the simulator to understand the system dynamics associated with wind energy and use this knowledge to make informed decisions.

The overall simulator architecture is discussed in Chapter 4. The simulator architecture represents the validated causal model using system dynamics simulator notation. Appendix D presents the simulator architecture entities including the stocks, flows, and auxiliary variables.

The variables in the simulator are established on equations. The equations are developed based on the relationships and the nature of the variables. Chapter 4 discusses the model equations in more detail. The equations are located in the equation layer and incorporated in the source code output of the simulator. The complete list of the iThink model listing is provided in Appendix E.

Simulator Architecture Validation

Validation of the system architecture was an iterative process. An initial level of validation was completed with the dissertation advisor to ensure preliminary simulator architecture appropriateness and completeness, the purpose of this step was to ensure that the simulator architecture is a reasonable representation of the system. Updates and changes to the model were made as a result of advisor feedback. The validation of the simulator is performed in two stages. In the first stage the simulator architecture is validated and in the second stage the populated simulator is validated. The overall approach for the model validation includes tests of the structure and behavior of the model. This strategy follows a framework of guidelines presented by Richardson & Pugh (1981) that builds confidence in the model and its results. The validation includes boundary structural adequacy, face validity, parameter validity, replication of reference modes, and appropriateness of structure tests. These tests build confidence in the model.

For the first stage, there was no data and the only test that was checked from the Richardson and Pugh framework was identified as "face validity". Face validity checks the model's structure to verify that it is a recognizable picture of the real system and represents the essential characteristics of the actual system.

The simulator validation architecture process was performed in a manner similar to the wind energy system sustainability causal model validation. A simulator architecture validation package was prepared and presented to validators to request feedback related to the simulator architecture. The simulator architecture validation package also contained a section to validate the causal model. Hence, additional feedback was received from subject matter experts related to the wind energy system sustainability causal model. The simulator architecture validation package is provided in Appendix F. Three validators, a wind energy researcher, an energy systems engineer expert, and a wind energy developer/operator were identified to assess the model in the first validation stage. The validation package was presented to the validators to acquire their feedback. The simulator architecture was updated based on recommendations and insights from the validators.

The validation results, assessments based on validator comments, and modifications to the simulator architecture are discussed in Appendix G.

Identify, Collect and Analyze Simulator Data

Identify Simulator Data

After the simulator architecture was validated, it was required to collect the data in order to populate and run the simulator. Utilization of proper data is crucial for obtaining accurate results from running the model. Identified data requirements were useful in requesting and gathering proper data from available resources.

At this stage, with the simulator architecture validated, the data requirements were clearer in terms of the model entities. Therefore, with better knowledge of what needed to be collected for the purpose, a data collection package was developed to elicit data from wind energy developers, operators, and organizations for the simulator.

Collect Simulator Data

Once data requirements were identified, data was collected to populate the simulator. A data collection package was developed to elicit information needed to populate the simulator. Various individuals were contacted and a data package was provided to two of them. The data collection package is presented in Appendix H. However, insufficient data was provided. Due to inability to collect data from individuals, data was instead obtained from the literature. Useful databases and government websites that have available information that was used in the model include: U. S. Department of Energy (DOE), National Renewable Energy Laboratories (NREL), U. S. Energy Information Administration (EIA), Database of State Incentives for Renewables & Efficiency (DSIRE) and American Wind Energy Association (AWEA). Some of the previous research materials reviewed included quantitative data that was also used.

Analyze Simulator Data

Some of the collected data could not be populated directly in the simulator. Evaluation of the information collected was performed to determine what information could be used. Data was analyzed to know if unit conversion was needed or any other data adjustment and justification was required to be performed before populating in the simulator. Information that was gathered through existing databases is presented in Appendix I.

Populate the Simulator with Analyzed Data

The simulation model was populated using the analyzed data. At this point the model was run. Simulator results and outputs were gathered and analyzed. Furthermore, the simulator operation was monitored closely to ensure the model ran properly. During this process all identified problems and issues that arose were corrected to ensure proper simulator performance.

Different scenarios were developed to analyze the results and behavior of the simulator runs. Results generated from these scenarios can be used to assess the impact of different policies associated with wind energy system sustainability. The scenarios and analysis of the simulator results are discussed in Chapter 4.

Validation of Populated Simulator

Once the preliminary model tests were performed to find and fix model problems, the populated simulator entered second stage of the validation process. The validation effort focuses on building confidence in the wind energy system sustainability simulator as a reasonable representation of the real system and in its usefulness in providing results.

Similar to the causal model and simulator architecture validation processes, a validation package for the simulator was developed. The dissertation advisor reviewed the simulator validation package and updates were made based on recommendations. Validators were identified to validate the simulator results. The validation package was provided to the validators. The simulator validation package is presented in Appendix J. Validator recommendations and assessment based on feedback are discussed in Appendix K. Individuals that served as validators throughout the research had a minimum of 9 years of wind energy experience as researchers, developers, or operators with understanding of the wind energy system and associated economic, social, and environmental factors.

The overall approach for the model validation includes tests of the structure and behavior of the model. This strategy follows a framework of guidelines presented by Richardson & Pugh (1981) that builds confidence in the model and its results. The tests focus on suitability, consistency, utility, and effectiveness. The framework examines if the model is suitable for its purposes. It also checks if the model is consistent with the portion of reality it tries to capture. It focuses on how effective the model is in achieving the purposes of the study. It also checks if the model or its results can be used. The framework determines if the simulator runs as planned.

The validation includes boundary structural adequacy, face validity, parameter validity, replication of reference modes, and appropriateness of structure tests. Table 3.1 summarizes the tests used in the framework for the model validation activities. Activities and tests presented on the table were defined in

Chapter 2. Some of these tests were performed by the validators and the remaining were performed by the dissertation author. Validator feedback was acquired with the validation package.

Table 3-1 Simulator Validation Activities

Test for	Structure	Behavior
Suitability (Verification)	Dimensional consistency Extreme conditions in equations Boundary adequacy	Parameter (in) sensitivity Structural (in) sensitivity
Consistency (Validation)	Face validity Parameter values	Replication of reference mode (boundary adequacy for behavior) Surprise behavior Extreme condition simulations Statistical tests
Utility and Effectiveness	Appropriateness of model characteristics for audience	Counterintuitive behavior Generation of insights

Chapter 4

Research Results

This chapter provides the dissertation research results and discussions of the results of the research design implementation. Results are used to answer research questions presented in Chapter 1.

The research results include a system perspective of energy system sustainability, the causal model for wind energy system sustainability, the causal model validation process and results, the simulator architecture, the simulator architecture validation process and results, data collection and simulator data population, and the validation process and results from runs of the populated simulator.

System Perspective of Energy System Sustainability

While the focus of the research was wind energy system sustainability, there was a need for an overall energy system sustainability perspective that could serve as a foundation to approach and comprehend the complexity of attaining sustainable wind energy systems. The energy system sustainability contribution was developed by performing a comprehensive literature review and through analyzing existing work. An energy system stakeholders' categorization, energy system sustainability objectives and a high level process model were iteratively developed.

An energy system stakeholder classification is depicted in Figure 4-1. The classification was developed looking at major energy system functions. Stakeholders are categorized into five groups: extractors of energy resources, producers of energy products, users, enabling stakeholders, and other stakeholders. These five groups were refined by considering main functions of the energy system and stakeholders related to these functions.

A categorization of energy system stakeholder objectives associated with the three pillars of sustainability was performed. Table 4.1 presents this categorization. The importance that an energy system objective has depends on the stakeholder and the stakeholder's function in the energy system. Table 4.2 shows the mapping between energy sustainability objectives and energy system stakeholders.

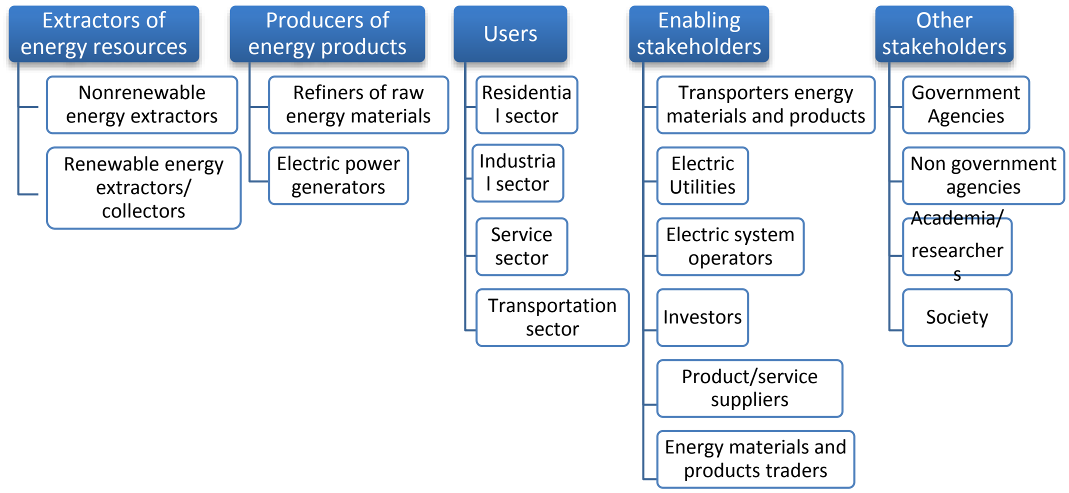

Figure 4-1 Energy System Stakeholder Classification

Table 4-1 Energy System Stakeholder Sustainability Objectives

Sustainability Pillar	Objective
Economic	• Increase corporate value • Increase energy efficiency • Reduce energy costs • Increase reliability of energy systems
Environmental	• Reduce environmental impact • Maximize resource conservation • Increase level of environmental restoration
Social	• Ensure energy availability • Ensure energy security • Establish positive stakeholder relationships

Table 4-2 Energy System Stakeholder to Energy Sustainability Objectives Mapping

	Objective									
	Economic				Environmental			Social		
Stakeholder	Increase Corporate Value	Increase Energy Efficiency	Reduce Energy Cost	Increase Reliability of Energy Systems	Reduce Environmental Impact	Maximize Resource Conservation	Increase Level of Environmental Restoration	Ensure Energy Availability	Ensure Energy Security	Establish Positive Stakeholder Relationships
Extractors of Energy Resources										
Nonrenewable Energy Resource Extractors	x				x		x	x	x	x
Renewable Energy Resource Extractors / Collectors	x			x	x		x	x	x	x
Producers of Energy Products										
Refiners of Raw Energy Materials	x	x	x		x		x	x		x
Electric Power Generators	x	x	x	x	x		x	x		x
Users										
Residential Sector		x	x		x		x	x		
Industrial Sector		x	x		x			x		
Service / Commercial Sector		x	x		x			x		
Transportation Sector		x	x		x			x		
Enabling Stakeholders										
Transporters of Energy Materials and Products	x				x			x	x	x
Electric Utilities	x	x		x	x			x	x	x
Electric System Operators	x	x	x	x	x			x	x	
Investors	x	x								
Enabling Product / Service Suppliers	x	x		x	x					
Energy Materials and Products Traders	x									
Other Stakeholders										
Government Agencies		x	x	x	x	x	x	x	x	x
Nongovernment Agencies		x	x	x	x	x	x	x	x	x
Academia / Researchers		x	x	x	x	x		x	x	x
Society		x	x	x	x	x	x	x	x	x

An energy system process model was developed based on analyzing important energy system stakeholder functions reviewed in the literature. A clear understanding of the main functions performed within the energy system helps one to better analyze and approach sustainability, taking into account the interactions among the different functions, and their effects on meeting sustainability objectives (economic, social and environmental) throughout the overall energy system. The developed process model is split into two figures given its size and shown in Figure 4-2 and Figure 4-3. Furthermore, given the amount of information presented, numbers have been used to represent inputs, outputs, controls and mechanisms. A legend for the values represented by each number is shown in Table 4.3.

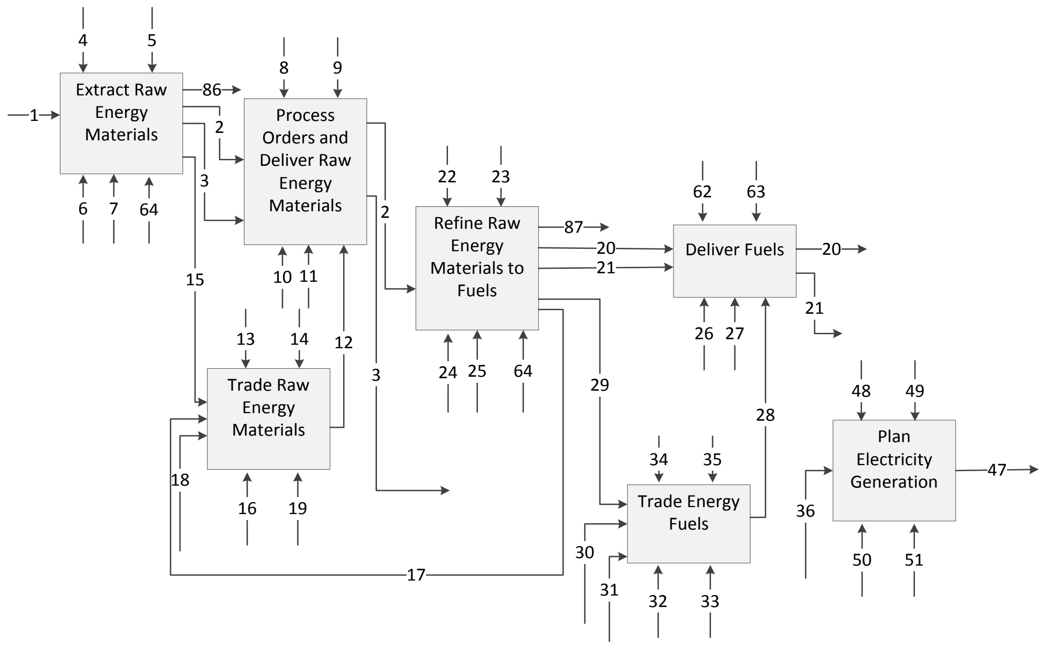

Figure 4-2 Energy System Process Model (Part A)

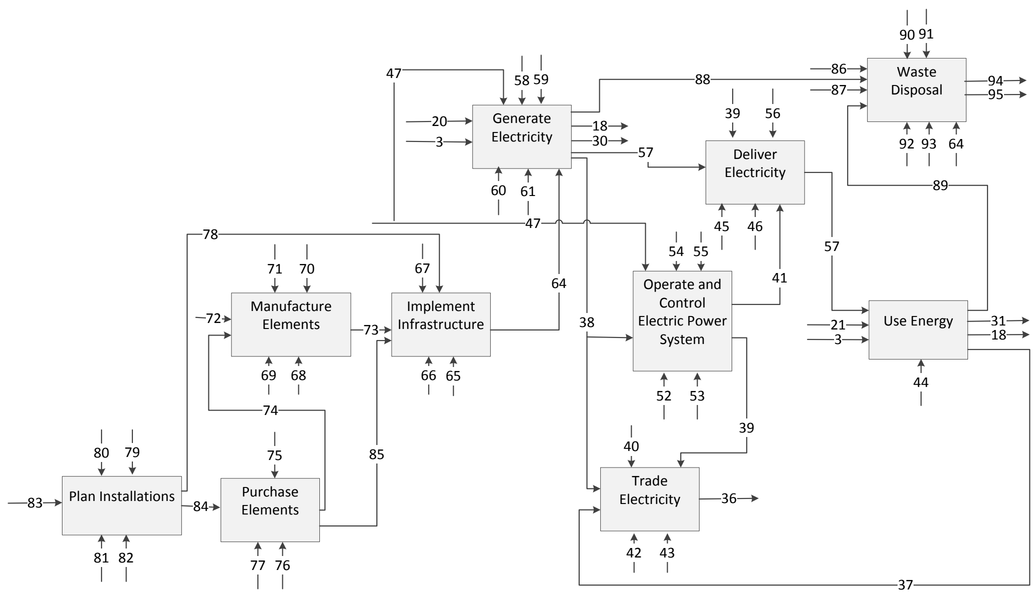

Figure 4-3 Energy System Process Model (Part B)

Table 4-3 Energy System Process Model Legend

1- Land natural footprint	49- Regulation for electricity planning
2-Raw Energy Materials (REMs) that require refinement	50- Tools for electricity planning
3-REMs that don't require refinement	51- Personnel for planning
4-Extraction guidelines	52- Equipment and tools to operate electric network
5-Extraction regulations	53- Personnel to operate and control electric network
6- Machines and tools required to make extraction	54- Regulation to operate and control electric networks
7-Personnel required to make extractions	55- Operation and control guidelines of electric networks
8- Order processing and transportation guidelines	56- Electricity transmission and distribution guidelines
9-Transportation regulations	57- Electricity generated
10- Machines and tools required to process orders and transport REMs	58- Electricity generation guidelines
11-Personnel required to process orders and transport REMs	59- Electric generation regulations
12- REMs sales contracts	60- Tools and machines to generate electricity
13-REMs market guidelines	61- Personnel to generate electricity
14-REMs regulations	62- Regulations for delivering fuels
15-Available REMs and price	63- Guidelines for delivering fuels
16- Personnel to do the trades in the REM market	64-Installations required to perform the extraction, refinement, generation, and disposal processes
17- Refineries demand of REMs	65-Personnel for implementing infrastructure
18- Demand of REMs that doesn't require refinement	66-Equipment and tools for implementing infrastructure
19- Tools for trading	67-Implementation regulations and permitting
20- Fuels used to generate electricity	68-Equipment and tools for elements manufacturing
21- Fuels used by energy end users	69-Personnel for manufacturing elements
22- Refinement guidelines	70-Manufacturing guidelines
23- Refining regulations	71-Elements manufacturing regulations
24- Machines and tools to refine REMs	72-Raw material for elements manufacturing
25 Personnel to make refinement	73-Manufactured elements
26- Machine and tools to deliver fuels	74-Elements purchase orders
27- Personnel to make deliveries (transport)	75-Purchasing guidelines
28- Fuel sales contracts	76-Personnel for purchasing elements
29- Available fuels and prices	77-Equipment and tools to be purchased
30- Fuel demand from generators	78-Implementation guidelines
31- Fuel demand from end users	79-Installation planning regulations
32- Personnel to make fuel trades	80-Installation planning guidelines
33- Tools for fuel trading	81-Tools for planning installation
34- Fuel trading guidelines	82-Personnel for planning installations
35- Fuel trading regulations	83- Energy product need
36- Electricity sales contracts	84-Elements for developing needed installations
37- Electricity demand	85-Off the shelf components
38- Available electric power and prices	86-Waste from REM extraction
39- Transmission and distribution regulations	87- Waste from refinement process
40- Electricity trading guidelines	88-Waste from electricity generation
41- Electricity dispatch	89-Waste from use of energy products
42- Personnel for electricity trade	90-Waste disposal guidelines
43- Tools for electricity trade	91- Waste disposal regulations
44-Energy powered devices	92-Personnel to dispose waste
45- Electricity transmission and distribution tools and networks	93-Tools for waste disposal
46-Personnel to enable delivering electricity	94-Waste bi-products
47- Plans and schedules of electric power generation	95-Other waste
48- Electricity planning guidelines	

Sustainability objectives could be assessed across the entire energy system lifecycle by function using the matrix presented in the Table 4.2, as well as assessing how the inputs, outputs, controls and mechanisms related to the function impact sustainability. Furthermore, the process model offers a graphical representation of the functions of the energy system that could be used to analyze prospective modifications that consider sustainability of the entire energy system.

Wind energy System Sustainability Objectives

A wind energy system is defined as an integrated set of elements, subsystems, and/or assemblies working together to produce and supply wind energy to end users. These elements can be geographically distributed. System elements include products (e.g., wind turbines and other hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. The complexity of the wind energy system is associated with the interactions among different stakeholders and their products to generate the electric power to satisfy the end user demand. The wind energy system requires interactions among wind project designers, wind turbine providers, electric system operators, land owners, electric equipment manufacturers, transporters, cable providers, utilities, local and federal agencies, investors and others.

The quest for a more sustainable energy system has been a major driving force for wind energy systems development and growth. The wind energy system has to be sustainable itself to adequately support the sustainability of the energy system as a whole. A well balanced set of objectives that include economic, environmental and social considerations are critical for healthy wind energy systems capable of contributing to a more sustainable energy system as a whole.

There are multiple considerations related to the economic objectives. It is critical for the wind energy system to spark interest in investors. The wind energy system has to be profitable to attract investors. This required attractiveness is the main reason why several federal incentives have been put in place to stimulate the wind industry growth over the past three decades (DOE, 2011; DOE, 2013). Various technological advances are making wind energy more efficient and reliable. Examples include the elevation of turbine mounting heights to 180 meters and above (Wind Aware Ireland, 2014), and the increase of turbine sizes, given that wind speeds increase with the height and are also more stable. Furthermore, installation of wind turbines offshore, where wind speeds are higher and more stable, makes wind energy a more reliable energy source.

Also, reduction of costs for wind energy systems is mainly associated with wind turbine installation, and operation and maintenance activities. Given that newer wind turbines are considerably larger than older generations, there is an economy of scale that has helped in decreasing maintenance costs, since wind turbine preventive maintenance (or service) doesn’t depend on the size of the turbine, it is based on hours of operation. Separately, the need for transmission line improvements in order to bring wind energy to load concentrations increases the cost of wind energy production (Wind Aware Ireland, 2014).

Among the environmental objectives associated with the wind energy system, reduction of bird and bat strikes as well as the noise perceived in communities closer to operating wind turbines are considered of high importance to successfully install and deploy wind energy systems. In order to mitigate the impact of wind turbine operation, careful site evaluation of birds, bats and other endemic animals living on site should be performed to assess the best location for wind turbine installation and operation. Modern turbine designs have reduced wind turbine noise during operation to a range of 35 to 45 dB at 350 meters away from wind turbine sites. Implementation and use of these new wind turbines reduce the overall noise from wind turbine operation perceived by neighboring communities. Additionally, the Environmental Protection Agency (EPA) has an ongoing initiative, the RE-Powering America's Land Initiative (EPA, 2015), which encourages renewable energy development on current and formerly contaminated land, landfills, and mine sites subjected to the community's approval. The initiative has given a purpose to reuse abandoned industrial sites for wind farms and other forms of renewable energy sources. One of the major objectives is to reduce the environmental impacts of energy systems in cases where restoration is out of the options.

Another important objective for wind energy systems is to increase the level of environmental restoration. Given the type of structures used for wind turbines installation, returning sites to their original condition is attainable in sites where wind farms have operated. However, for wind turbine manufacturing activities, this objective is still a work in progress, as in all manufacturing industries, given the use/reuse of natural resources to build the various wind energy system elements.

Relative to the social objectives, one of the main objectives of the wind energy system is to increase energy availability and security to avoid dependence on other countries' energy resources. Since wind is a "free" resource available worldwide, the growth of the wind energy sector strongly supports this objective.

The energy system sustainability objectives associated with the installation, operation and maintenance, and decommissioning phases of a wind energy system are to increase corporate value, minimize energy cost, minimize environmental impact, and establish positive stakeholder relationships. Other objectives related to the operational and maintenance phase include increasing reliability of energy systems and ensuring energy availability.

Wind Energy System Sustainability Causal Model

Detailed literature reviews and analysis of wind energy and other renewable energy sources (Pruyt, 2004; Sanchez et.al.,2005; Hasani-Marzoni and Hosseini, 2011; Dykes and Sterman, 2010), including previously developed wind energy causal models, and other renewable energy sources causal models, were used to identify key factors and factor relationships. Development of a wind energy system sustainability causal model was performed as part of this task.

Figure 4-4 represents the wind energy system sustainability causal model. The model presents key sustainability factors related to wind energy system sustainability. The aim of this causal model is to provide a better understanding of the factors and factor relationships associated with wind energy system sustainability during installation, operation and maintenance, and decommissioning phases. The factors in the causal model are listed in Appendix A with a definition of each factor and the unit of measurement.

Causal Model Factor Relationships

This section presents a detailed description of the relationships in the developed causal model. As the number of wind turbines installed increases, the number of operating wind turbines increases. As the number of operating wind turbines increases, the wind energy installed capacity increases. As the wind turbine rotor diameter increases, the wind turbine capacity increases. As the wind turbine capacity increases, the wind energy installed capacity increases. As the number of wind turbines installed increases, the quantity of skilled personnel needed during wind energy system installation increases. As the number of wind turbines installed increases, the quantity of skilled personnel needed during wind energy system operation also increases.

As the number of wind turbines installed increases, wind energy installed capital cost increases. As the wind turbine rotor diameter increases, wind energy installed capital cost increases. As the number of operating wind turbines increases, wind energy operation and maintenance cost also increases. As the wind turbines rotor diameter increases, wind energy operation and maintenance cost decreases. Volume of wind project water consumption, energy used for wind energy installation and operation, volume of waste from wind energy installation, and volume of waste from wind energy operation and maintenance are also expected to increase as a result of an increase in the number of wind turbines installed. As the number of wind turbines installed increases, the volume of excavation and trenching of the wind energy system increases. As the number of wind turbines installed increases, the amount of wind energy area available for other uses decreases.

As the number of decommissioned wind turbines increased, the quantity of skilled personnel needed during wind energy system decommission increases. As the quantity of skilled personnel needed during wind energy system installation increases, the employment rate increases. As the quantity of skilled personnel needed during wind energy system operation increases, the employment rate also increases. As the quantity of skilled personnel needed during wind energy system decommission increases, the employment rate also increases. As the employment rate increases, the wind energy population resistance decreases.

When the number of wind turbines installed increases, the number of accidents during installation and operation of wind projects are expected to increase. As the wind energy area increases, the available land decreases. As the distance between the wind energy system and community increases, the level of visual impact decreases. As the level of visual impact increases, the society awareness increases.

As the balance of station cost increases, the wind energy installed capital cost increases. As the soft cost increases, the wind energy installed capital cost also increases. When the wind energy installed capital cost increases, the wind energy total cost increases. An increase in wind energy system operation and maintenance cost also increases wind energy total cost. An increase in the wind energy total cost increases the electricity price. An increase in the wind energy integration cost also increases the utility resistance. As the electricity price increases, the utility electricity price increases. As the utility electricity price increases, the wind energy population resistance increases. As the wind energy installed capacity increases, the electrical energy reserves increases. As the number of wind turbines installed increases, the society awareness to wind energy also increases. As the society awareness increases, the wind energy population resistance decreases. An increase in the wind energy population resistance decreases the amount of economic incentives for implementing wind technology advances.

As the area of excavation and trenching increases, the ecological footprint increases. As the wind energy area increases, the available land for other uses decreases. As the available land increases, the ecological footprint decreases. As the volume of wind energy water consumption increases, the ecological footprint also increases. As the volume of waste from wind energy installation increases, the ecological footprint increases. As the volume of waste from wind energy operation and maintenance increases, the ecological footprint also increases. As the volume of waste from wind turbine decommissioning increases, the ecological footprint also increases. As the carbon footprint increases, the ecological footprint increases. As the ecological footprint increases, the wind energy population resistance increases.

As the energy used for wind energy installation increases, the carbon footprint increases. As the energy used for wind energy operation and maintenance increases, the carbon footprint also increases. As the energy used for wind turbine decommissioning increases, the carbon footprint also increases. Increases of wind power generated decreases the carbon footprint.

When the wind energy installed capacity increases, the wind power generated increases. As the wind turbine rotor diameter increases, the capacity factor increases. As the wind turbine hub height increases, the capacity factor also increases. As the site wind speed increases, the capacity factor also increases. As the capacity factor increases, the wind power generated also increases. As the wind power generated increases, the profits of the wind energy system increases. As the electricity price increases, the profit of the wind energy system also increases. As the profit of the wind energy system increases, the net present value increases. As interest rates for the resources required for installing and operating the wind project increases, the net present value decreases. As the wind power generated increases, the amount of electricity available for use increases. As the amount of electricity available for use increases, the level of energy security increases.

As the electrical energy reserves increases, the wind energy integration cost increases. As the utility resistance to wind energy increases, the level of reinforcement of government regulations, standards and policies for energy sustainability increases.

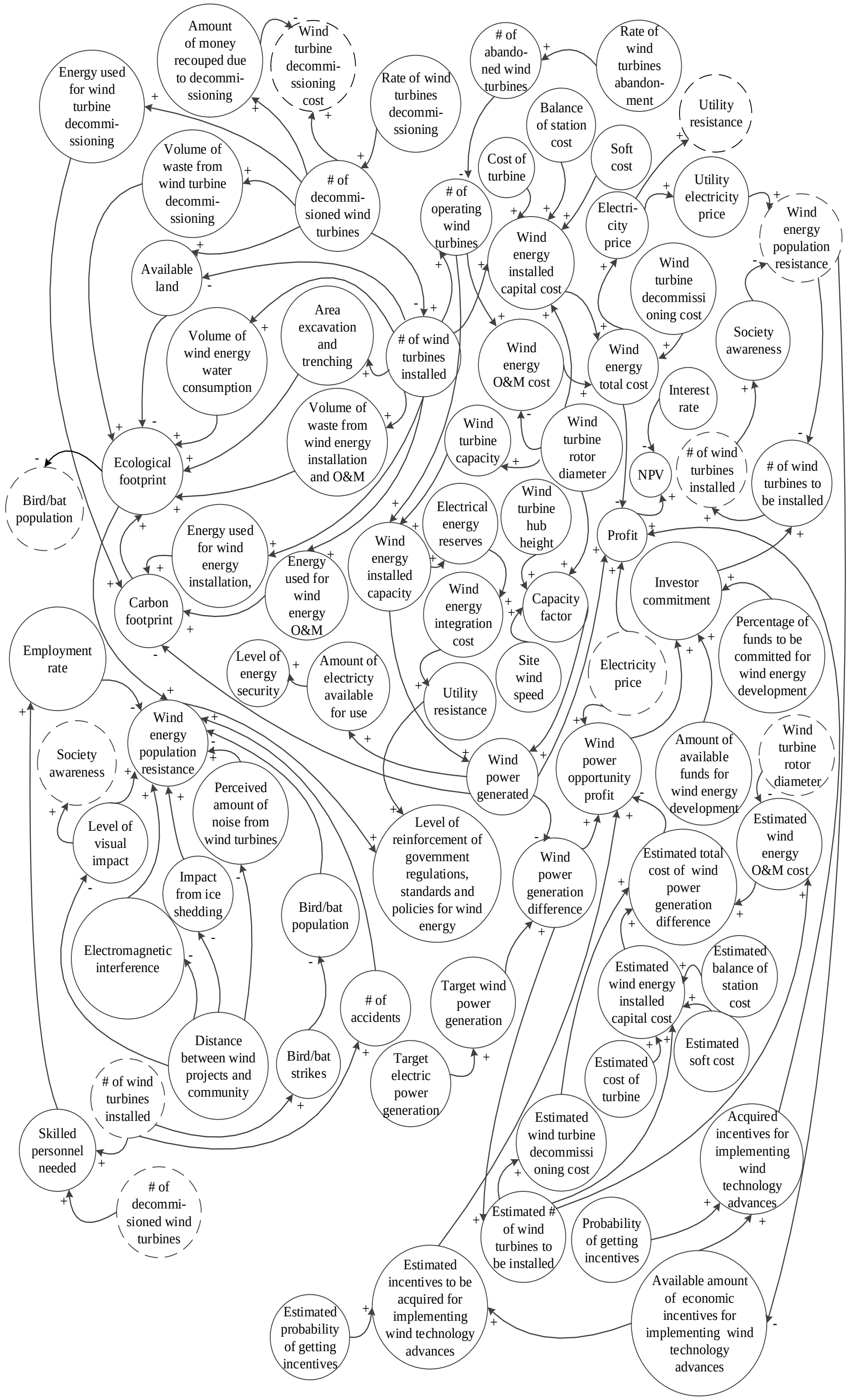

Figure 4-4 Wind Energy System Sustainability Causal Model

As the number of wind turbines installed increases, bird/bat strikes increases. An increase on bird/bat strikes results in a decrease of the bird/bat population. When the distance between the wind energy system and community increases, the impact from ice shedding, the electromagnetic interference, the perceived amount of noise from wind turbines, and the level of visual impact decrease.

As the number of accidents increases, the wind energy population resistance increases. As the impact from ice shedding, the electromagnetic interference, and the average temperature on the site increase, the wind energy population resistance also increases. As the volume of available water resources, the available land, and bird/bat population increase, the wind energy population resistance decreases.

As the wind energy population resistance increases, the level of reinforcement of government regulations, standards and policies for energy sustainability increases. As the amount of economic incentives for implementing wind technology advances increases, the acquired incentives for wind technology advances increases. As the probability of getting incentives increases, the acquired incentives for wind technology advances also increases. As the acquired incentives for wind technology advances increases, the number of wind turbines to be installed increases.

An increase in the wind energy population resistance decreases the available amount of economic incentives for implementing wind technology advances. An increase in the wind energy population resistance also decreases the number of wind turbines to be installed. An increase in the number of wind turbines to be installed increases the number of turbines installed. As the available amount of economic incentives for implementing wind technology advances increases, the estimated incentives to be acquired for implementing wind technology advances increases. As the estimated probability of getting incentives increases, the estimated incentives to be acquired for implementing wind technology advances also increases. As the target electric power increases, the target wind power generation increases. As the target wind power generation increases, the wind power generation difference increases. As the wind power generated increases, the wind power generation difference also decreases. As the wind power generation difference increases, the wind power opportunity profit increases. As the estimated incentives to be acquired for implementing wind technology advances increases, the wind power opportunity profit increases. As the wind power opportunity profit increases, the investor commitment to fund wind energy developments increases. As the percentage of funds to be committed for wind energy development increases, the investor commitment to fund wind energy developments also increases. As the investor commitment to fund wind energy developments increases, the number of wind turbines to be installed increases.

Wind Energy System Sustainability Feedback Loop Examples

Factors in the wind energy system sustainability causal model relate to the three pillars of sustainability. In order to help the reader to understand the model, a feedback loop related to each sustainability pillar is presented. A feedback loop associated with the environmental pillar is shown in Figure 4-5. This feedback loop includes the number of wind turbines to be installed, the number of wind turbines installed, the volume of wind energy water consumption, the ecological footprint, and the wind energy population resistance. As the figure illustrates, as the number of wind turbines to be installed increases, the number of wind turbines installed increases. As the number of wind turbines installed increases, the volume of wind energy water consumption increases. As the wind energy water consumption increases, the ecological footprint increases. As the ecological footprint increases, the wind energy population resistance increases. As the wind energy population resistance increases, the number of wind turbines to be installed decreases closing the feedback loop. This loop is a balancing loop.

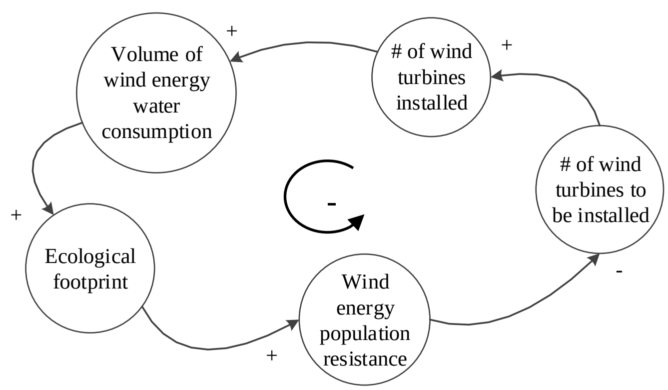

Figure 4-5 Environmental Pillar Feedback Loop

The feedback loop related to the economic pillar includes the number of turbines installed, the number of turbines to be installed, the wind energy installed capacity, the wind power generated, the wind power generation difference, the wind power opportunity profit and the investor commitment. This is also a balancing loop and is shown in Figure 4-6. Another loop includes the number of turbines installed, the number of turbines to be installed, the society awareness, and the wind energy population resistance. This feedback loop is related to the social pillar and is presented in Figure 4-7.

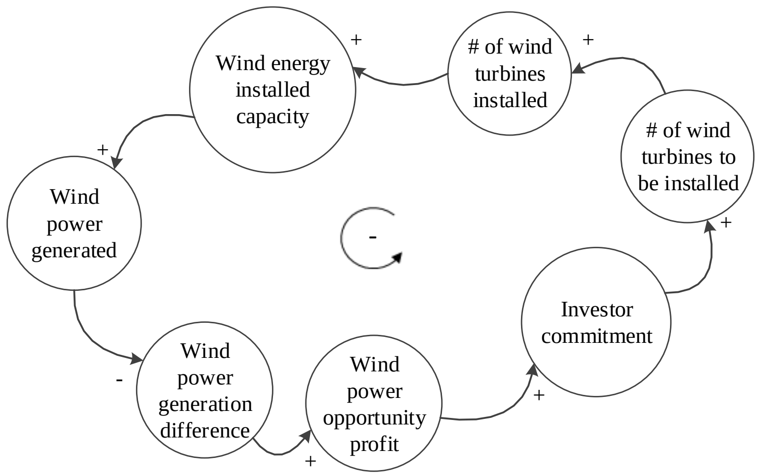

Figure 4-6 Economic Pillar Feedback Loop

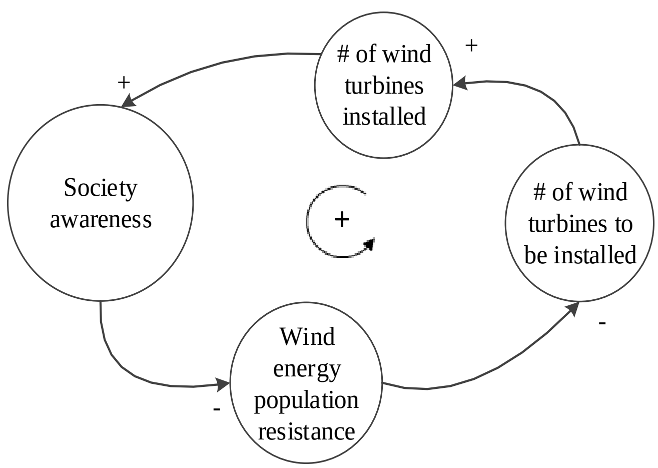

Figure 4-7 Social Feedback Loop

Causal Model Validation

The causal model was validated to ensure the model is a reasonable representation of the real system. Furthermore, the validation exercise ensures accuracy and completeness of the model. Factors and factor relationships were validated throughout an in-depth analysis of related previous research. Meetings were held with the dissertation advisor to discuss appropriateness and completeness of factors and factor relationships. Updates and changes to the model were made as a result of the advisor feedback.

Final drafts of the validation presentation and validation package were presented to the dissertation committee members. The committee members provided input after presentation of materials. Additional updates and changes were necessary to include committee recommendations. The final validation package included a validation purpose, a model introduction, the causal model, description on how to read the model and what the symbols mean, tables describing the factors, the definition of each factor, corresponding units of measurement, factor relationships, and a set of questions that validators were required to answer related to the model.

Individuals were selected and contacted to validate the model. A heterogeneous set of validators was desired for representing the different perspectives associated with the real system. The set of validators included decision makers in the policy sector, development, operation and maintenance of wind energy projects. These validators were contacted via phone or email. A validator responded to help with the causal model validation. A validation presentation was made and the validation package was provided to the validator. The validation package is presented in Appendix B. An analysis of validator inputs was performed to evaluate potential changes to the causal model after receiving inputs from the validator. The list of recommended inputs and changes from the validator are provided in Appendix C. This appendix also includes the modifications made to the causal model and the wind energy system sustainability factor tables. The validated causal model was used as an input to develop the wind energy system sustainability simulator architecture.

Wind Energy System Sustainability Simulator

A wind energy system sustainability simulator can help decision makers to explore risks and assess the dynamic consequences of various decisions without affecting the real system. The wind energy system sustainability simulator models the factors that relate to wind energy system while considering the three pillars of sustainability (social, economic, and environmental). Energy decision makers can use the simulator to understand the system dynamics associated with wind energy and use this knowledge to make informed decisions.

Wind Energy System Sustainability Simulator Architecture

The simulator architecture represents the validated causal model using system dynamics simulator notation. A set of the validated factors and factor relationships were used to develop the simulator architecture. Most of the factors in the causal model were used in the simulator architecture development and the factors that were not modeled were mainly the ones that were difficult to quantify. The wind energy system sustainability simulator architecture, presented in Figure 4-8, was developed using the iThink simulation software, version 9.1.4. To increase readability, the architecture has been divided into 4 sections presented in Figures 4-9 through 4-12.

This simulator is the final version of the system dynamics model after going through modifications based on recommendations received from validators for the architecture validation process. The elements of the simulator architecture are classified and listed in Appendix D. Definitions and unit of measurements for each variable are also included.

The simulator architecture includes a set of stocks, flows, and auxiliary variables linked through connectors. The variables in the simulator are established on equations. The equations are developed based on the relationships and the nature of the variables. Based on the data that was available to populate the simulator, the model is a deterministic model. Appendix E presents the complete iThink model listing.

Simulator Architecture Validation

Validation of the system architecture was an iterative process. An initial level of validation was completed with the dissertation advisor to ensure preliminary simulator architecture appropriateness and completeness. The purpose of this step was to ensure that the simulator architecture is a reasonable representation of the system. Updates and changes to the model were made as a result of advisor feedback. The validation of the simulator was performed in two stages. In the first stage the simulator architecture was validated and in the second stage the populated simulator was validated. The section focuses on the first stage of the validation. The overall approach for the model validation includes tests of the structure and behavior of the model. This strategy follows a framework of guidelines presented by Richardson & Pugh (1981) that builds confidence in the model and its results.

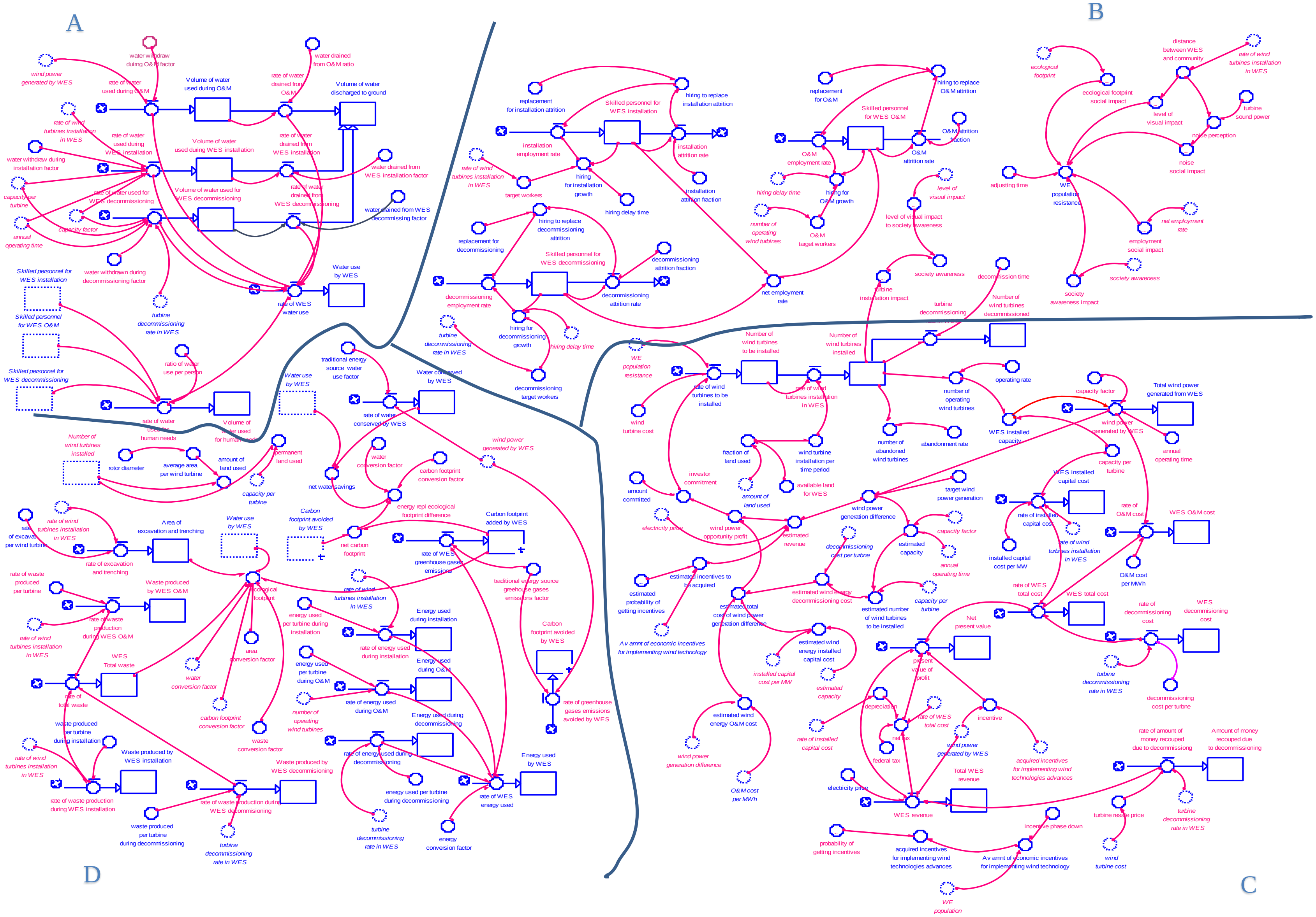

Figure 4-8 Wind Energy System Sustainability Simulator Architecture

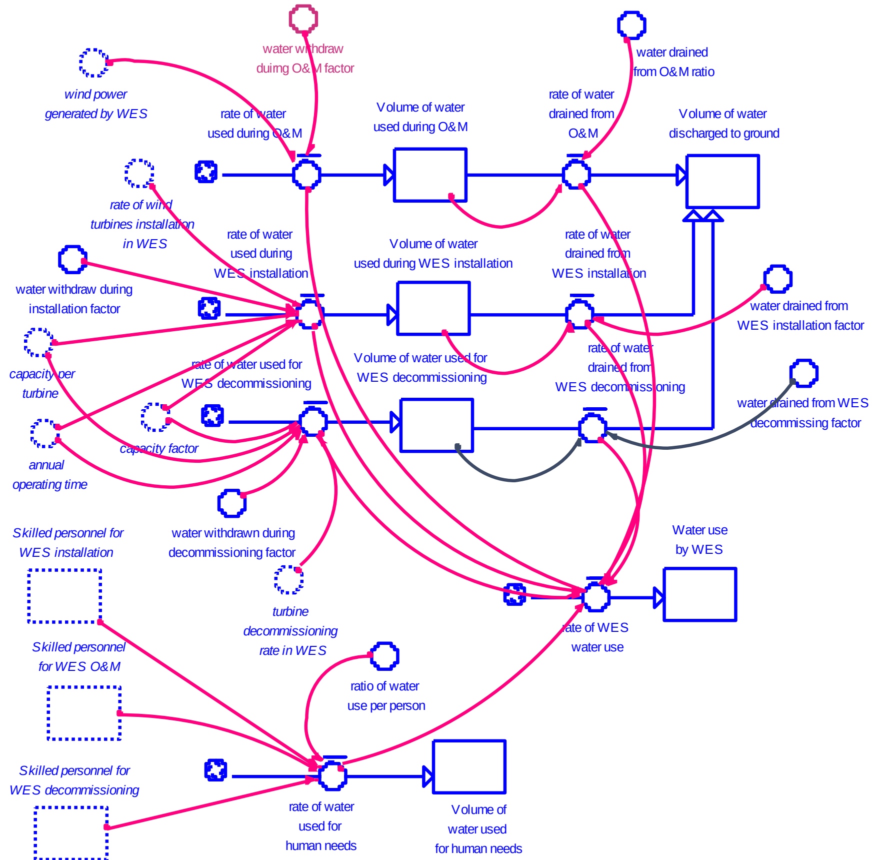

Figure 4-9 Wind Energy System Sustainability Simulator Architecture Subset A

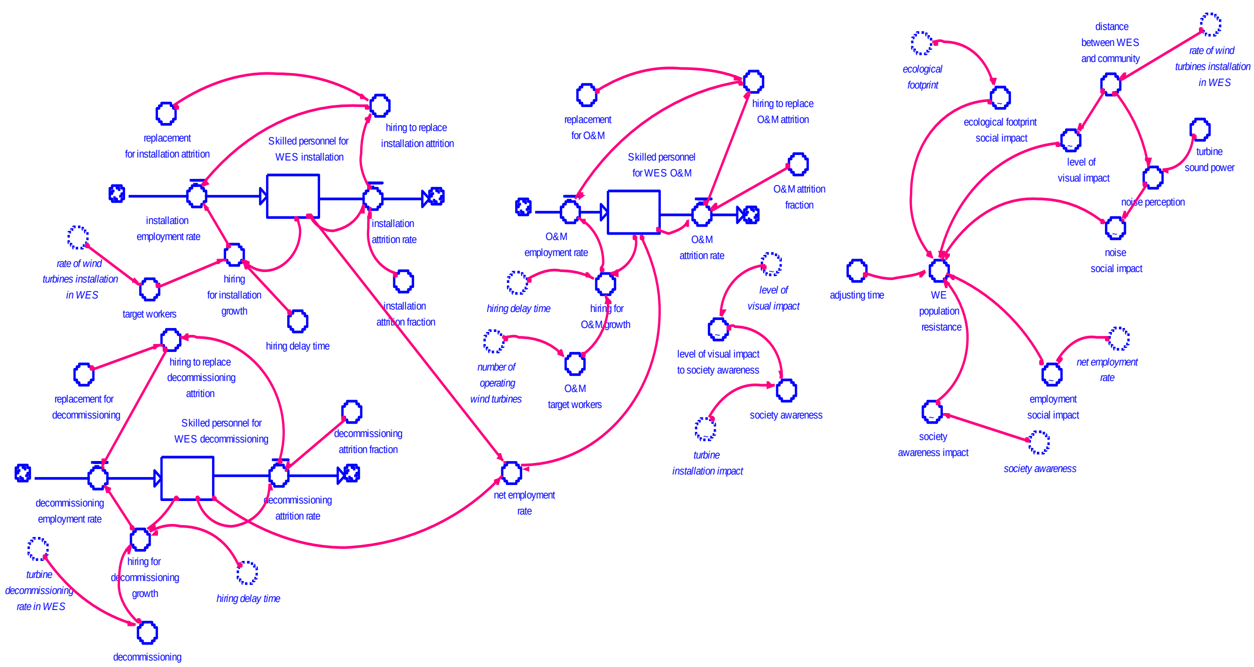

Figure 4-10 Wind Energy System Sustainability Simulator Architecture Subset B

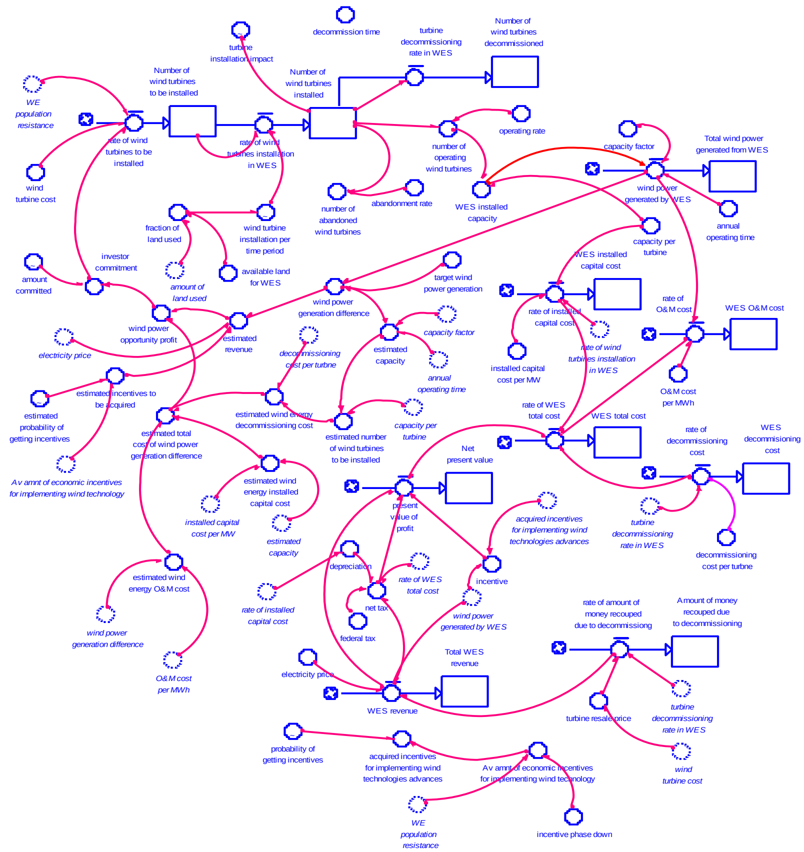

Figure 4-11 Wind Energy System Sustainability Simulator Architecture Subset C

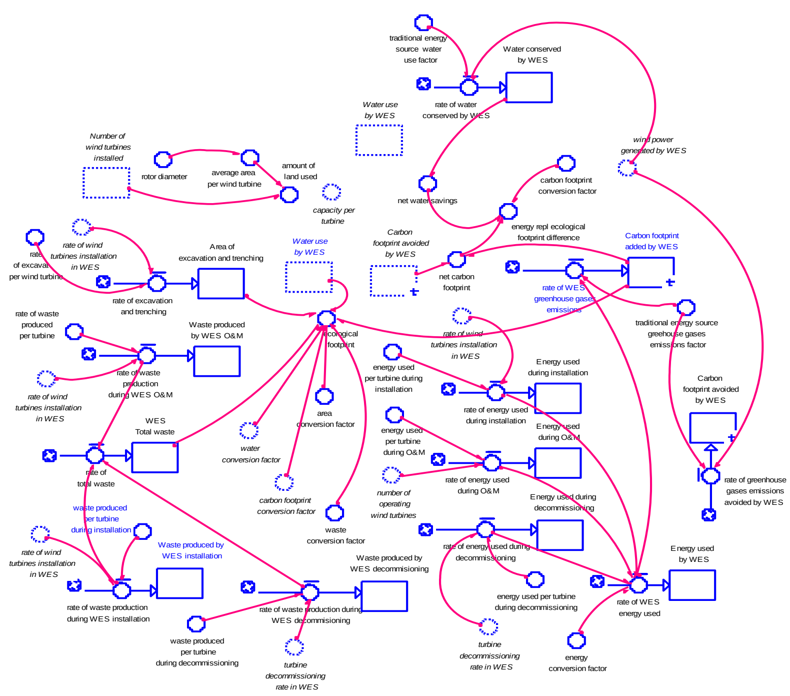

Figure 4-12 Wind Energy System Sustainability Simulator Architecture Subset D

For the first stage, there was no data and the only test that was checked from the Richardson and Pugh framework was identified as “face validity”. Face validity checks the model’s structure to verify that is a recognizable picture of the real system and represents the essential characteristics of the actual system.

The simulator validation architecture process was performed in a manner similar to the wind energy system sustainability causal model validation. A simulator architecture validation package was prepared and presented to validators and requested feedback related to the simulator architecture.

The simulator architecture validation package also contained a section to validate the causal model. Hence, additional feedback was received from subject matter experts related to the wind energy system sustainability causal model. The simulator architecture validation package is provided in Appendix F. Three validators provided results to assess the model in this stage. The simulator architecture was updated based on recommendations and insights obtained from the validators. The validation results, assessments based on validator comments, and modifications to the simulator architecture are provided in Appendix G.

Simulator Data Identification, Collection and Analysis

After the simulator architecture was validated, data identification and collection was performed in order to populate and run the simulator. Identification of data requirements was useful in gathering and requesting proper data from available resources. Utilization of proper data is crucial for obtaining accurate results from running the model.

A data collection package was developed to elicit data from wind energy developers, operators, and organizations for the simulator. The developed data collection package is presented in Appendix H.

Once the data collection package was developed to elicit information needed to populate the simulator, various data sources were contacted and the data collection package was provided to them. However limited input was received. Instead, data was obtained from literature given difficulty in obtaining data from individuals. Data was obtained from databases and government websites including U. S. Department of Energy (DOE), National Renewable Energy Laboratories (NREL), U. S. Energy Information Administration (EIA), Database of State Incentives for Renewables & Efficiency (DSIRE) and American Wind Energy Association (AWEA).

Some of the collected data could not be populated directly in the simulator. Evaluation of the information collected was performed to determine what information could be used in the simulator. Data was analyzed to assess if unit conversion was needed or any other data adjustment were required to be performed before populating in the simulator. Information that was gathered using existing databases is presented in Appendix I.

Simulator Runs and Results

A simulator is a decision making tool that helps decision makers to understand the impact of different decisions in the system of interest. Simulations have been run to understand how the different variables in the system influence particular outputs. Multiple scenarios may occur within the wind energy system associated with sustainability. Results generated from these scenarios can be used to assess the impact of different policies associated with wind energy system sustainability.

Information from three states, Texas, California and Iowa, was used to populate and run the simulator. For each of these states, three scenarios were evaluated: 1) a baseline case, 2) elimination of economic incentive after year 2019, and 3) a setback distance of 1000m between the wind energy system and the nearest community. These scenarios are discussed in greater detail in the scenarios section.

Input variables chosen to evaluate their impact in the simulator are (1) the acquired incentives for implementing wind technologies advances (relates to scenario 2 - elimination of economic incentive) and (2) the distance between the wind energy system and the nearest community. These inputs have an effect on the number of wind turbines that are added to the wind energy system. Different scenarios can be developed and tested to evaluate the impact of these two variables on some of the simulator outputs. The impact of these inputs can be evaluated analyzing the outputs related to variables in the three pillars of sustainability. Each scenario includes output results. Outputs that were analyzed include ecological footprint, energy replacement ecological footprint difference, net water savings, net carbon footprint, net present value, net employment rate, wind energy population resistance and society awareness. These factors are related to one or more of the sustainability pillars (environmental, economic and social).

Length of simulation runs was chosen in such a way that the dynamics of the factors can reflect dynamic behavior associated with the installation, operation and maintenance, and decommissioning activities that interact in a real system. Given that a wind turbine operating life is generally considered to be

20 years and the scope of the research included installation, operation and maintenance, and decommissioning activities, the length of the simulation runs for all scenarios was set to 30 years.

The turbine used to populate the simulator is a 1.5 MW nameplate capacity, 80 m rotor diameter, and 80 m hub height. The net capacity factor was set to 31.9%. The definitions of input and output factors are presented in Appendix D. In the following sections, the scenarios to be evaluated are described, and the results of the simulations runs are presented.

Scenarios

Multiple scenarios may occur within the wind energy system associated with sustainability. Energy policy makers can use the simulator to assess different wind energy system policies to understand the impact of their decisions on simulator outputs. Table 4.4 summarizes the scenarios simulated per state.

Table 4-4 Simulator Scenarios

Scenario 1	State baseline case
Scenario 2	Elimination of economic incentive (PTC)
Scenario 3	Minimum distance to nearest community set to 1000 m

Scenario 1 is the baseline case. In this scenario, The simulator is run without modifying the amount of economic incentives and/or the distance between wind energy system and nearest community.

The Renewable Electricity Production Tax Credit (PTC) has been used to represent the economic incentives since it has been historically shown to have an effect on new wind power capacity installation (AWEA, 2015). The Renewable Electricity Production Tax Credit (PTC) is an inflation-adjusted per-kilowatt-hour (kWh) tax credit for electricity generated by qualified energy resources and sold by the taxpayer to an unrelated person during the taxable year. The duration of the credit is 10 years after the date the facility is placed in service (DSIRE, 2015). The starting time, year "0", for the simulator represents a particular state (Texas, California, Iowa) wind energy system conditions by year 2000. Actual PTC incentive amounts as well as active and expiration periods have been included in the simulator from the simulation start, year 0 until end of year 19 (2019). For the rest of the simulation time (from year 20 to year 30), a 0.84 probability of acquiring the economic incentive has been assumed. This value was selected because it represents the current historical PTC incentive behavior from year 2000 until 2019 (3 expirations in 19 years (2002, 2004, and 2013)).The simulator also assumes that the amount of financial incentive to be acquired from year 20 to year 30 is the same amount that is projected to be acquired for year 2019, which is the year when last PTC extension is projected to expire (DSIRE, 2015).

The distance between the wind energy system and the nearest community has been defined as the average value of the distance between wind energy farms and the nearest community to them. This value is specific for each state. The distance value is kept constant for the rest of the simulation baseline case.

Scenario 2 represents the elimination of economic incentives (PTC). Similar to the baseline case, actual PTC incentive amounts as well as active and expiration periods have been included in the simulator for the first 19 years of simulation. This scenario includes elimination of economic incentives from year 20 through the end of the simulation. This scenario was chosen based on the historical impact that this factor has had in the wind energy system development and the actual downward trend that the incentive exhibits. The most recent extension is set to expire on December 31, 2019 for wind energy installations (DSIRE, 2015). This extension shows a yearly incentive phase down: year 2017 (20% reduction), year 2018 (40% reduction) and year 2019 (60% reduction). One can see the potential impact of the incentive elimination on the output parameters. Results can be compared with the baseline case or other scenarios that consider varying attributes related to the economic incentive.

Scenario 3 focuses on the change in the minimum distance between the wind energy system and the nearest community from the current minimum distance per state to 1000 m. In this scenario, the average distance between the wind energy system and the nearest community is the same as the baseline case scenario until year 14 (2014). Distance is set to 1000m from year 2015 through the rest of the simulation. The 1000m minimum distance has been chosen based on the tendency among cities across United States to establish this distance (calculated as an average) as the minimum set back distance to a residence. If wind energy systems continue to grow to meet the expected Department of Energy (DOE) goal by year 2030 (DOE, 2008, 2015), land based installations may get closer to communities. One can evaluate the impact of the minimum distance change presented in this scenario versus the baseline scenario on the output parameters.

Simulation results are provided per state. The following sections presents the results for Texas, California and Iowa State.

State of Texas

Scenario 1: Simulate Baseline Case

In this scenario, the simulator is run without modifying the amount of economic incentives and the distance between the wind energy system and the nearest community. Data from the state of Texas has been input for the simulation run. The results are shown after running the simulation for 30 years. Table 4.5 shows the values of output parameters in years 10, 20 and 30, followed by a discussion of the output behavior.

Table 4-5 Scenario 1 Simulation Outputs- State of Texas

	10	20	30
Ecological footprint (Global Hectares)	674,444.11	1,712,632.29	2,208,047.02
Energy replacement ecological footprint difference (Global Hectares)	9,936.75	102,967.96	221,358.66
Net water savings (Gallons)	2.089E+10	2.153E+11,	4.624E+11
Net carbon footprint (metric tons CO_2)	26,895,369.63	281,067,139.8	605,461,712.0
Net present value ($)	8.81E+17	3.36E+19	7.31E+19
Net employment rate (person)	311	713	1,475
WE population resistance (dimensionless)	0.233	0.356	0.383
Society awareness impact (dimensionless)	0.150	0.150	0.150

The legend for the outputs in the figures are shown as part of the figure, in the top part of the figure. The ecological footprint represents the amount of land and water area required for nature to regenerate the resources used by the wind energy system during installation, operation and decommissioning. The energy replacement ecological footprint difference is the algebraic sum of the net water savings and the net carbon footprint given wind energy system installation, operation and decommissioning. It represents the ecological footprint savings (related to water and carbon dioxide emissions) of using wind energy to supply energy demand instead of traditional nonrenewable sources.

The behavior of the ecological footprint is observed in Figure 4-13. The ecological footprint of the wind energy system increases as turbines are added to the system, operated, maintained and decommissioned. The figure shows a high growth in the ecological footprint magnitude between years 8 and 11. This growth is the result of the increase in turbine installations during the same period. After year 11 the figure shows a period of relative stability, given a less aggressive investment pattern for wind energy installations, and operation and maintenance activities. The simulator assumes that decommissioning activities will not start until year 20. The increase of the ecological footprint after year 20 is associated with decommissioning activities and operation and maintenance activities. Given the structure of the most recent PTC extension, that shows a yearly incentive phase down for years 2017, 2018 and 2019 (with a 20%, 40% and 60% reduction respectively), the investment attractiveness has decreased, resulting in a cease on investment commitment that consequently stops new turbine installations after year 17. The ecological footprint of the wind energy system relates to the environmental pillar. The ecological footprint of the Texas' wind energy system for the baseline case is 2,208,047.02 global hectares at the end of year 30. Additionally, the graph also depicts the energy replacement ecological footprint difference which accounts for the amount of the ecological footprint that is avoided against the ecological footprint generated by the wind energy system.

Figures 4-14 and 4-15 show the net water savings and the net carbon footprint of the wind energy system during the 30 years of the simulation run. As can be seen in Figure 4-14, the net water savings is overlapped with the water conserved by the wind energy system (WES). The water used by WES is negligible (also shown in the figure). The net carbon footprint, shown in Figure 4-15, represents the difference between the carbon footprint avoided for using wind energy instead of nonrenewable energy and the carbon footprint added by WES due to installation, operation and maintenance, and decommissioning activities. Both factors are also shown in Figure 4-15. The net water savings at the end of the simulation is 4.624E+11 gallons and the net carbon footprint is 605,461,712 metrics tons of CO_2.

The net employment rate represents the rate of employment during the wind energy installation, operation and maintenances, and decommissioning phases of the WES. Figure 4-16 depicts the net employment rate. The highest number of employees related to the installation, operation and maintenance and decommission of the wind energy system is, at the end of the simulation, 1,475 people in the system. Figure 4-16 also shows the behavior of the skilled personnel for WES installation, the skilled personnel for WES operation and maintenance, and the skilled personnel for WES decommissioning.

The net present value (NPV) relates to the economic pillar. The net present value of the state of Texas' wind energy system for the baseline case is presented in Figure 4-17. For the 30 years of simulation, the net present value is $7.31E+19 ($2014). The present value of profits, which represents the amount remaining after wind energy total costs are deducted from total revenue, is also depicted in the figure.

The wind energy population resistance and the society awareness are shown in Figure 4-18. These outputs relate to the social pillar. It can be observed that, for the baseline scenario, there is low population resistance to wind energy systems, from year 0 to year 8. It is after year 8, with the increase of wind turbine installation that the population resistance increases, similar to the ecological footprint behavior. The wind energy population resistance reaches a value of 38.3% in year 30. The society awareness, which refers to the knowledge accumulated in society due to experience with wind energy, shows a continuous growth between years 2 and 4 of the simulation run, given the increase of installation activities that increases the number of wind turbines installed in the system. Once the first 1000 turbines have been installed, the simulator assumes that communities near to wind energy system sites are aware of their existence, figure shows a constant value (0.150) to represent the accumulated knowledge of the society after year 4 and until the end of the simulation runs.

Given the simulator inputs and policies associated with the behavior of the simulator elements, the simulator equilibrium state is reached at year 34.

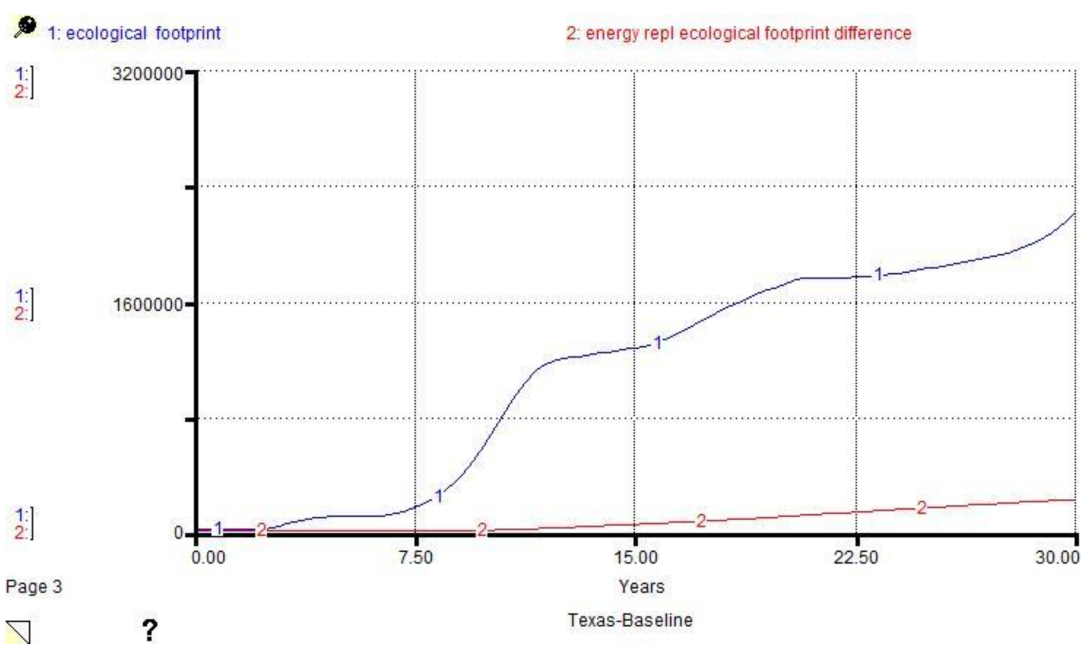

Figure 4-13 Texas Scenario 1- Ecological Footprint

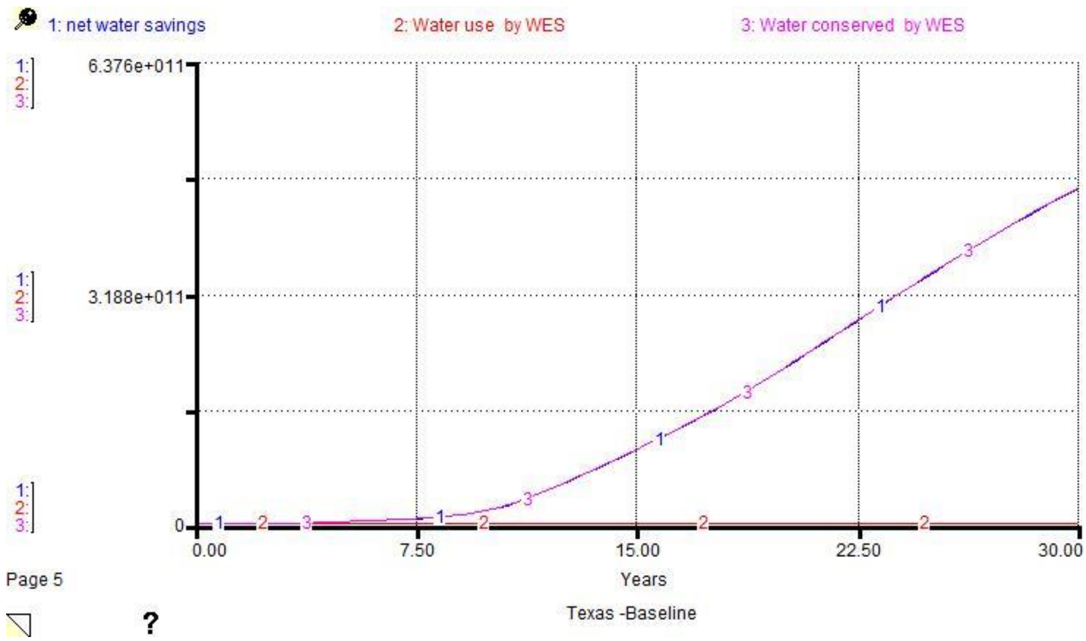

Figure 4-14 Texas Scenario 1- Water Savings

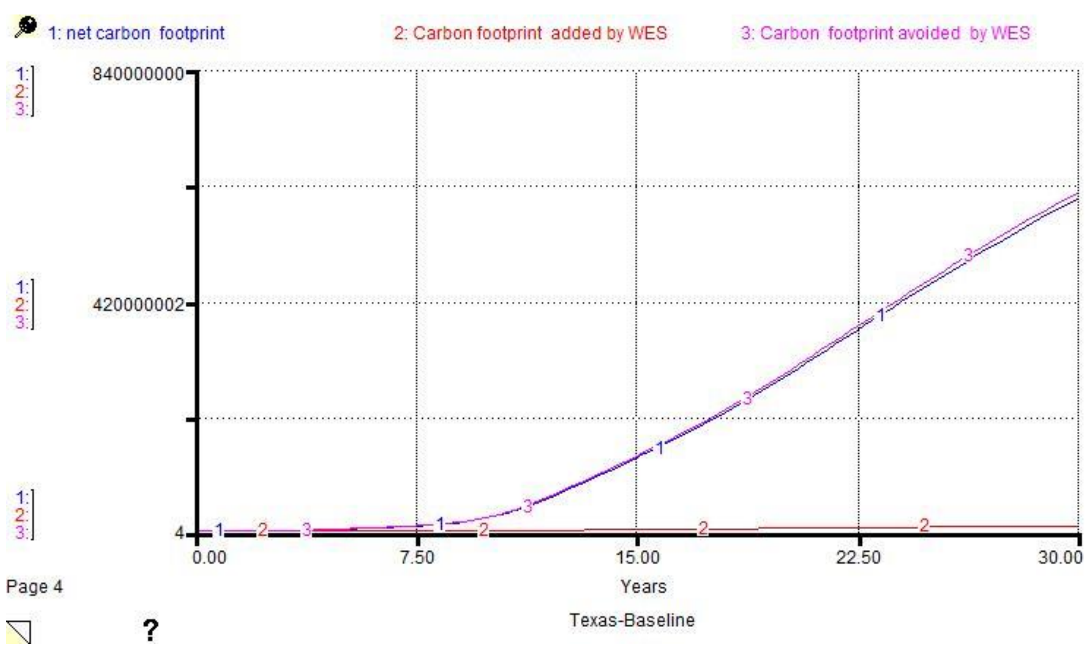

Figure 4-15 Texas Scenario 1- Carbon Footprint

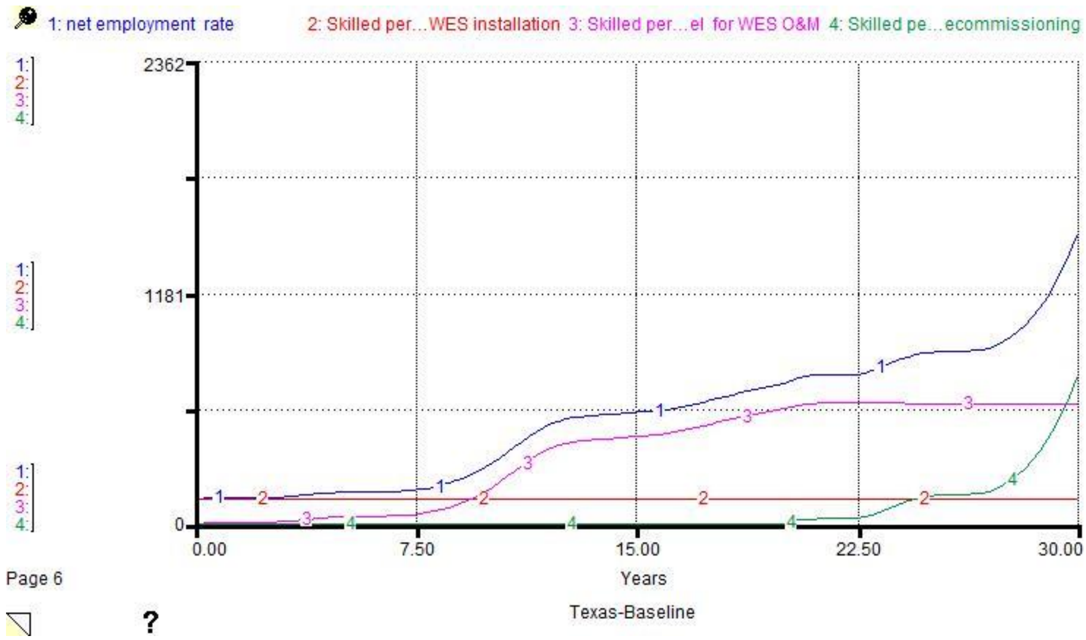

Figure 4-16 Texas Scenario 1- Employment

Figure 4-17 Texas Scenario 1- Net Present Value

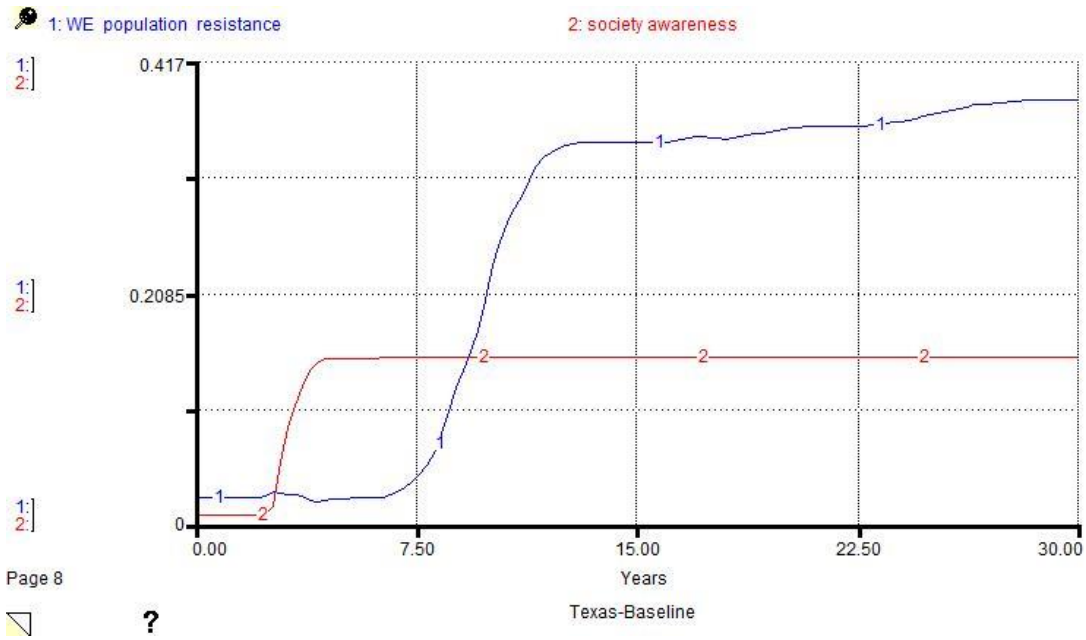

Figure 4-18 Texas Scenario 1- Wind Energy Population Resistance and Society Awareness

Scenario 2: Elimination of Economic Incentives

In this scenario, the PTC is eliminated at the end of year 19. The results can be compared with the baseline case. Effects of this variable can be seen on the output parameters. These outputs are associated with the three pillars of sustainability. Below, the simulation results for this scenario are presented in Table 4.6. Results are organized similar to the Table 4.5 shown for scenario 1.

Table 4-6 Scenario 2 Simulation Outputs- State of Texas

	10	20	30
Ecological footprint (Global Hectares)	674,444.11	1,712,632.29	2,208,047.02
Energy replacement ecological footprint difference (Global Hectares)	9,936.75	102,967.96	221,358.66
Net water savings (Gallons)	2.089E+10	2.153E+11	4.624E+11
Net carbon footprint (metric tons CO_2)	26,895,369.63	281,067,139.8	605,461,712
Net present value ($)	8.81E+17	3.36E+19	7.31E+19
Net employment rate (person)	311	713	1475
WE population resistance (dimensionless)	0.233	0.356	0.383
Society awareness impact (dimensionless)	0.150	0.150	0.150

When the economic incentives are eliminated, the investor commitment decreases; therefore, the number of wind turbines to be installed decreases. In the present scenario, outputs have the same behavior and values as the baseline case. The reason is that the elimination of economic incentives is set to start in year 20 through the end of the simulation. However, similar to the baseline scenario, given the structure of the most recent PTC extension, investment commitment is insensitive to this elimination, a cease on investment commitment after year 17 has already stopped new turbine installations. Outputs maintain the same behavior as the scenario 1, Figures 4-19 through 4-24 show the scenario output behavior.

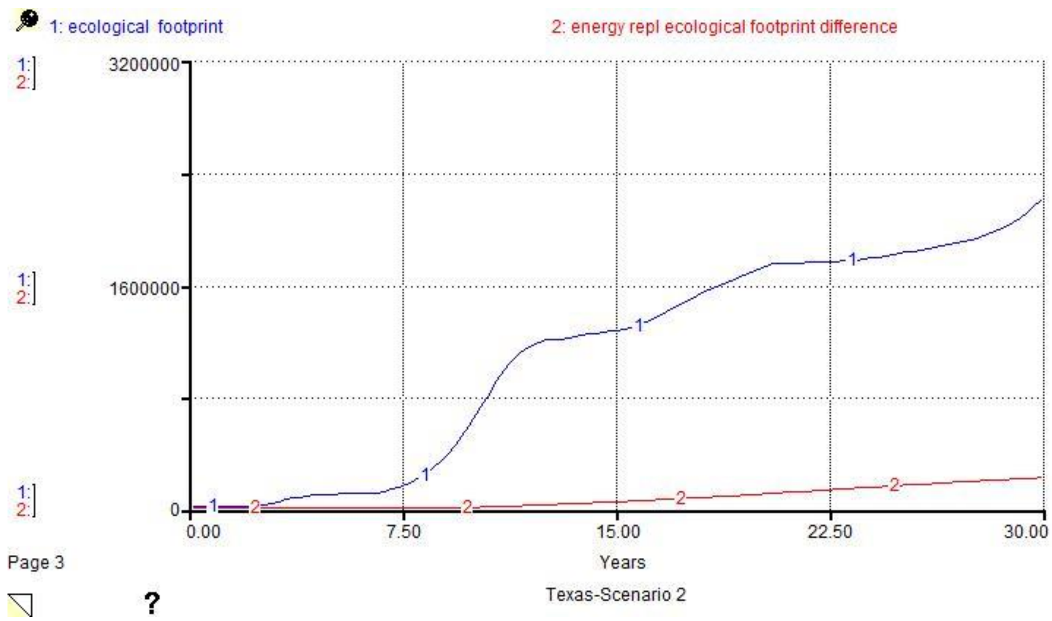

Figure 4-19 Texas Scenario 2- Ecological Footprint

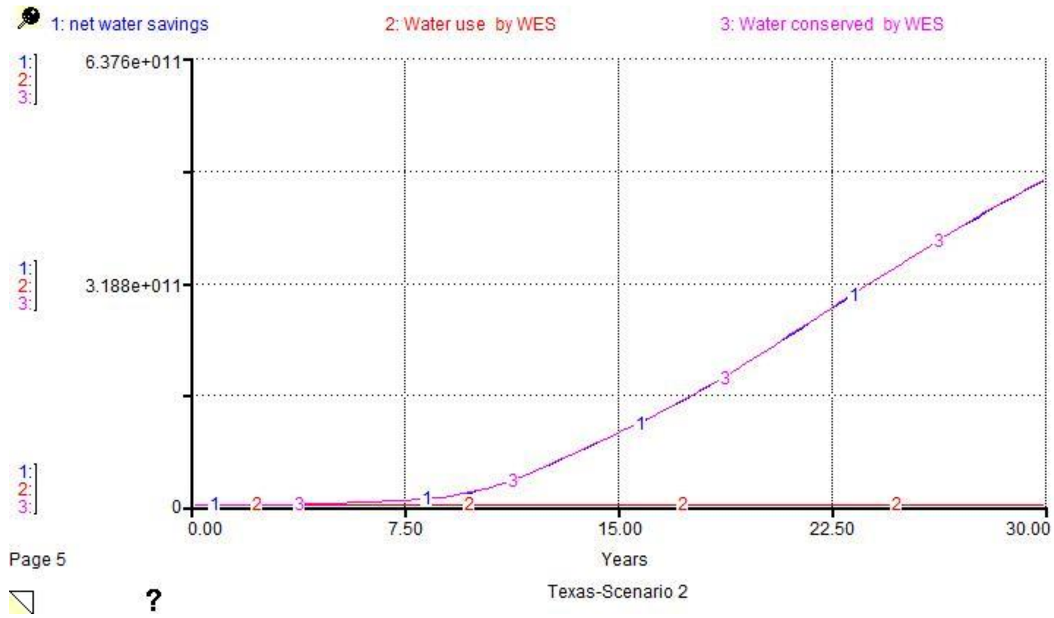

Figure 4-20 Texas Scenario 2- Water Savings

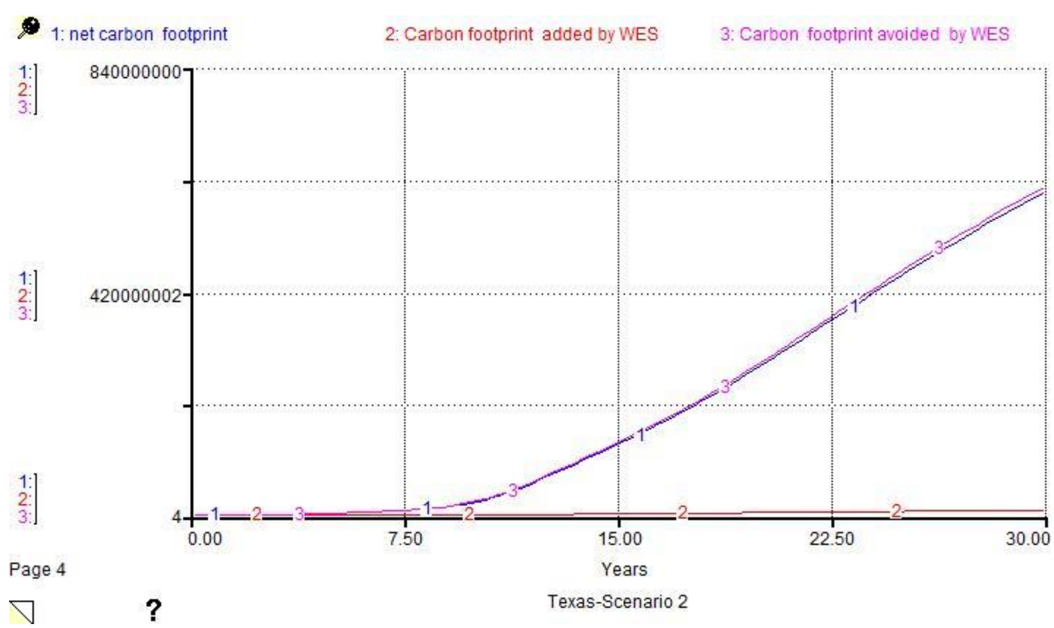

Figure 4-21 Texas Scenario 2- Carbon Footprint

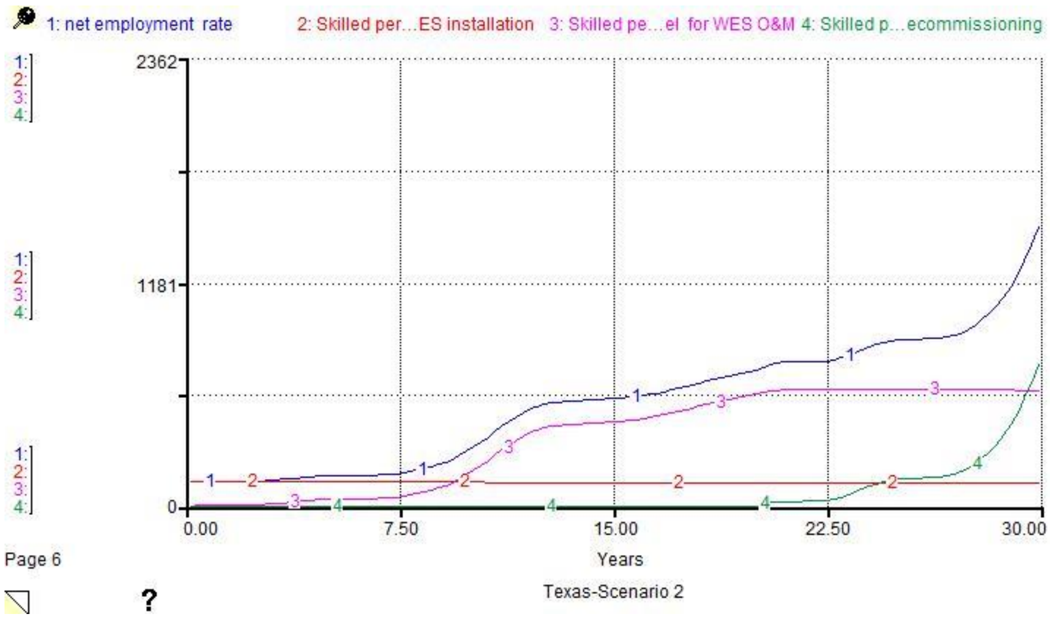

Figure 4-22 Texas Scenario 2- Employment

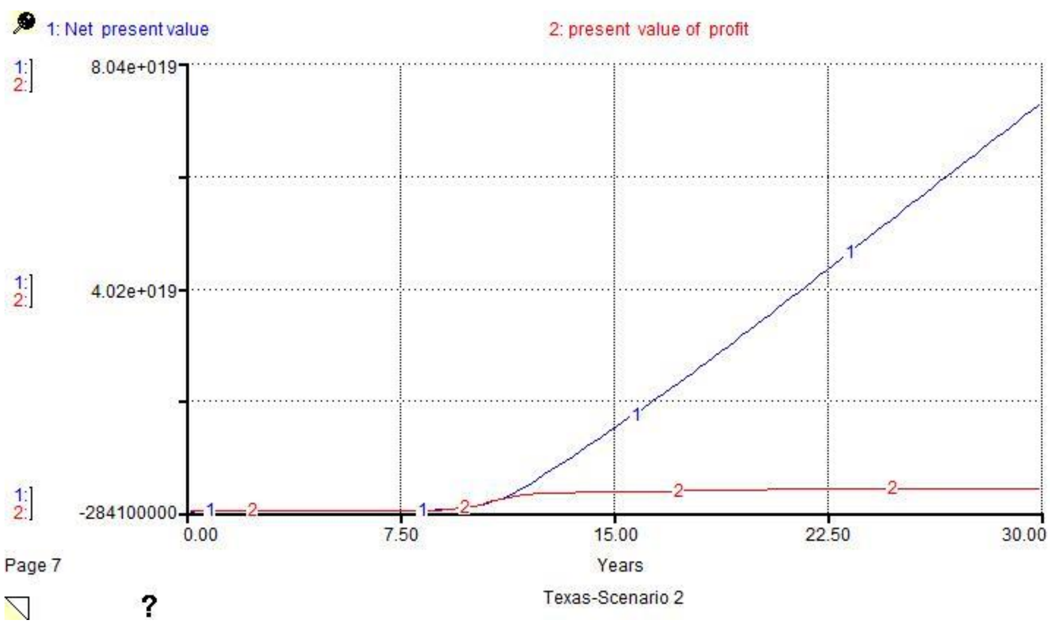

Figure 4-23 Texas Scenario 2- Net Present Value

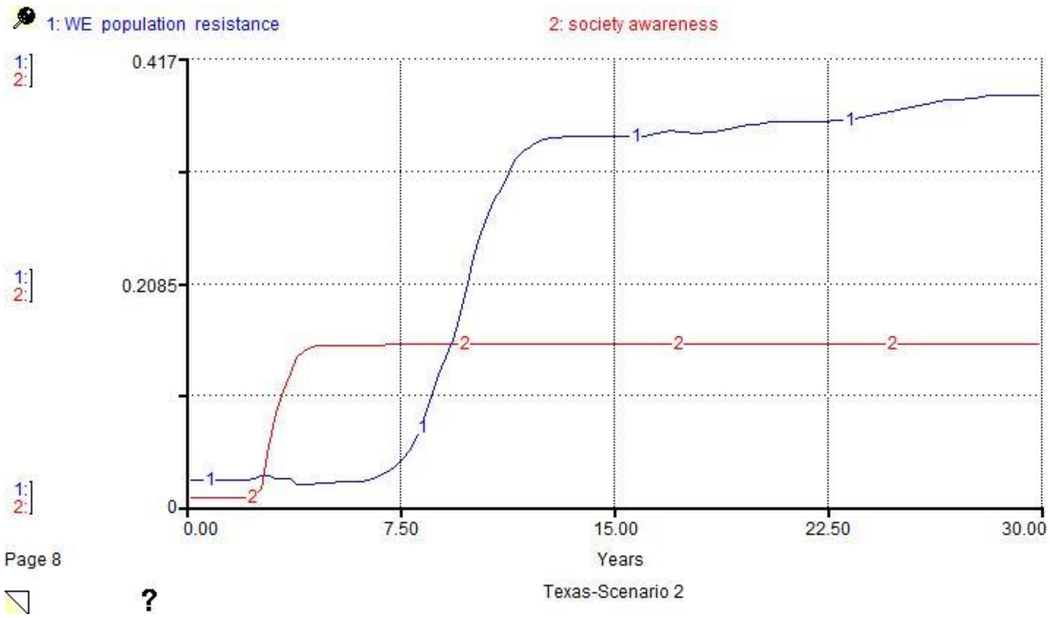

Figure 4-24 Texas Scenario 2- Wind Energy Population Resistance and Society Awareness

Scenario 3: Minimum Distance Between Wind Energy System and Nearest Community set to 1000 m.

In the scenario 3, a case that includes a reduction on the minimum distance between the wind energy system and the nearest community is run. The user can evaluate the impact of performing the baseline case versus the additional change to the minimum distance, which affects the output variables related to the three pillars of sustainability. Table 4.7 shows the values of output parameters in years 10, 20 and 30, followed by a discussion of the output behavior. In the case of Texas, baseline distance was in average 20 km from a sample size of 35 wind energy projects. The change on distance to 1000m is simulated to start happening at year 15. Figure 4-25 through 4-30 show the scenario output behavior.

Table 4-7 Scenario 3 Simulation Outputs- State of Texas

	10	20	30
Ecological footprint (Global Hectares)	674,444.11	1,661,796	2,149,986
Energy replacement ecological footprint difference (Global Hectares)	9,936.75	102,469.8	216,691.2
Net water savings (Gallons)	2.089E+10	2.14E+11	4.53E+11
Net carbon footprint (metric tons CO_2)	26,895,369.63	2.8E+08	5.93E+08
Net present value ($)	8.81E+17	3.35E+19	7.22E+19
Net employment rate (person)	311	698	1454
WE population resistance (dimensionless)	0.233	0.468	0.497
Society awareness impact (dimensionless)	0.150	0.241	0.241

When the distance between the wind energy system and the nearest community decreases, the noise perceived increases, and the level of visual impact increases. Therefore, the wind energy population resistance increases. The increase on the wind energy population resistance decreases the number of turbines to be installed, decreasing the overall set of outputs. The decrease on the output can be observed in the Figures 4-25 through 4-30, as well as in the summary of values presented in the Table 4.7. The change is observed starting in year 15 since it is the set up time to decrease the distance in the simulator.

The behavior of the ecological footprint is observed in Figure 4-25. The ecological footprint of the Texas' wind energy system for the scenario 3 is 2,149,986 global hectares at the end of year 30. Additionally, the graph also depicts the energy replacement ecological footprint difference. Figures 4-26 and 4-27 show the net carbon footprint and the net water savings of the wind energy system during the 30 years of the simulation run. The net water savings at the end of the simulation is 4.53 E+11 gallons and the net carbon footprint is 5.93E+8 metrics tons of CO_2. Figure 4-28 depicts the net employment rate. The highest number of employees related to the installation, operation and maintenance and decommission of the wind energy system is, at the end of the simulation, 1,454 people in the system. Figure 4-28 also shows the behavior of the skilled personnel for WES installation, the skilled personnel for WES operation and maintenance, and the skilled personnel for WES decommissioning. The net present value of the state of Texas' wind energy system for the scenario 3 is presented in Figure 4-29. For the 30 years of simulation, the net present value is $7.22E+19 ($2014). The present value of profits is also depicted in the figure. The wind energy population resistance and the society awareness are shown in Figure 4-30. These outputs relate to the social pillar. The wind energy population resistance and the society awareness values for year 30 are 49.7% and 24.1% respectively.

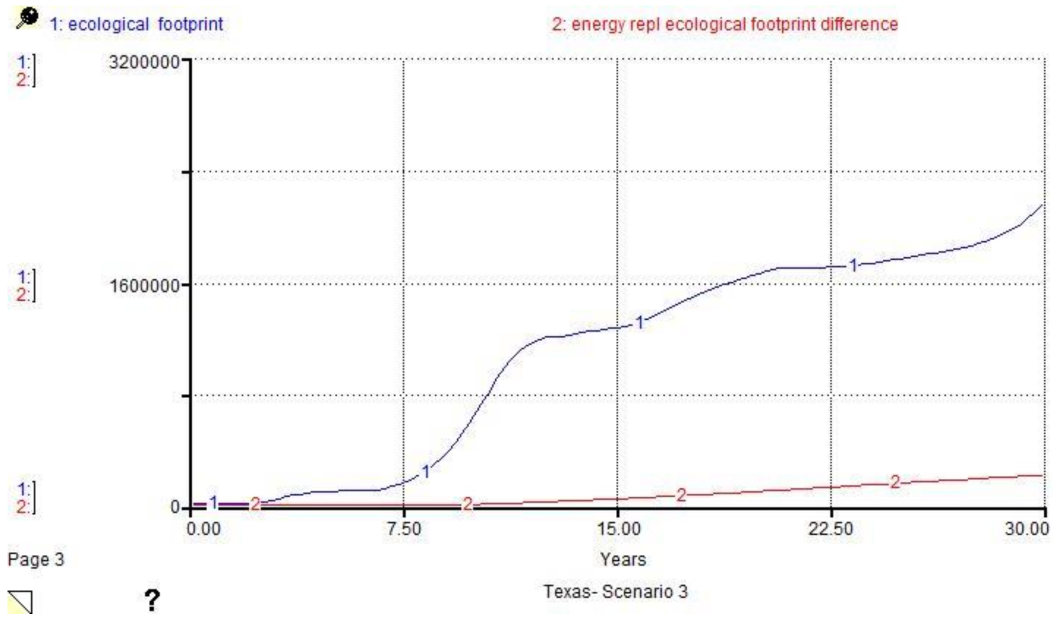

Figure 4-25 Texas Scenario 3- Ecological Footprint

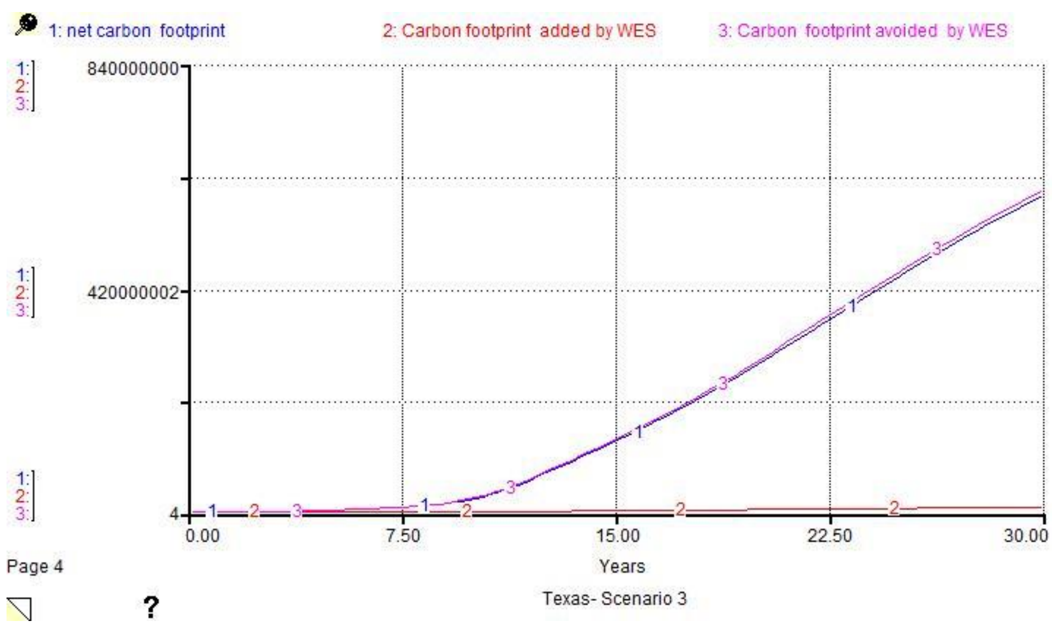

Figure 4-26 Texas Scenario 3- Carbon Footprint

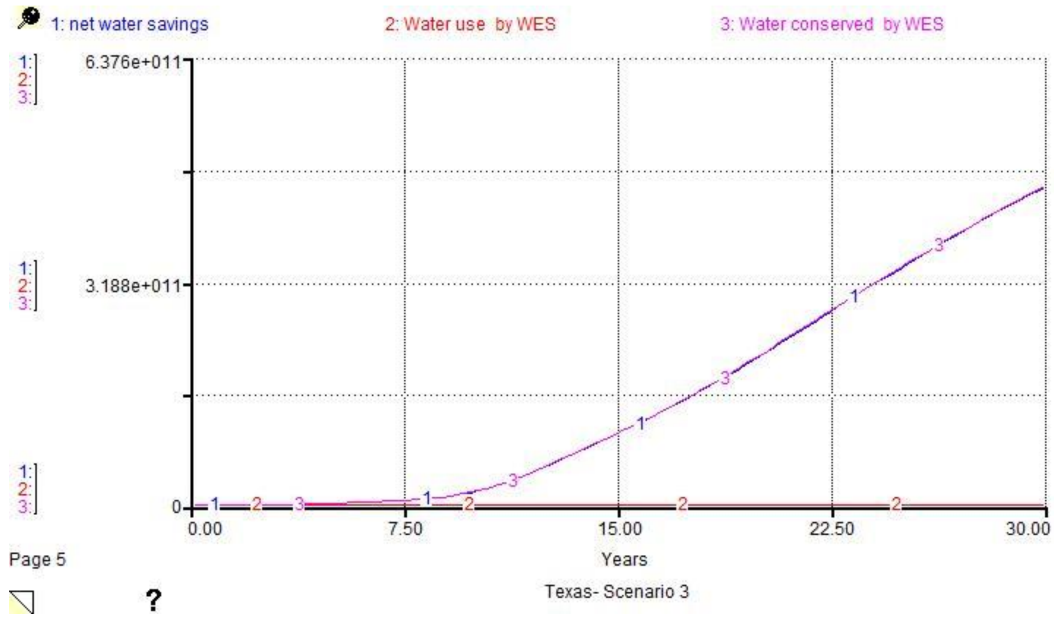

Figure 4-27 Texas Scenario 3- Water Savings

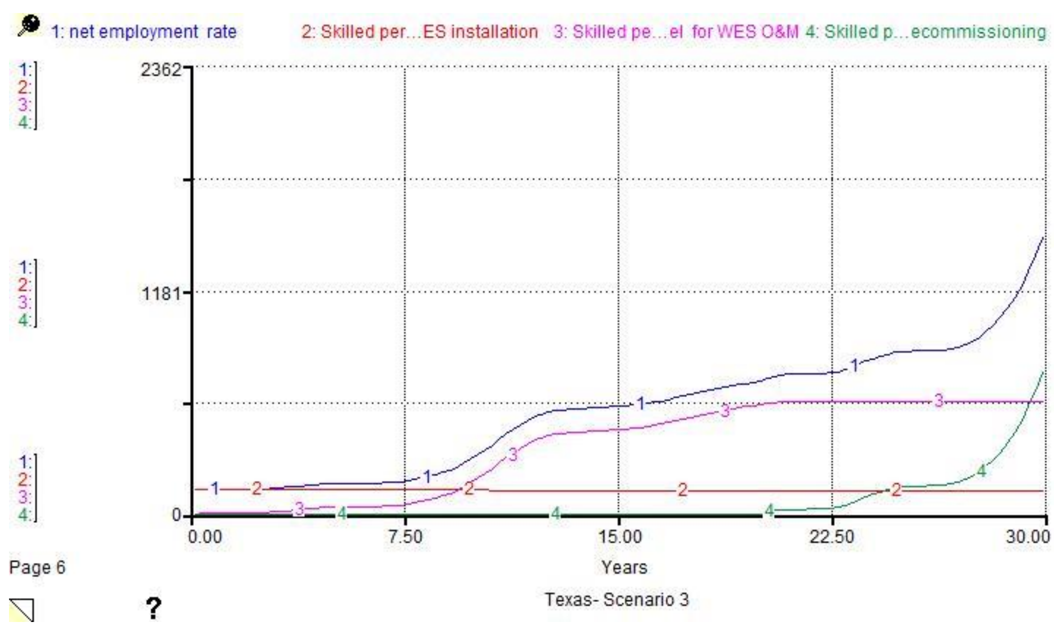

Figure 4-28 Texas Scenario 3- Employment

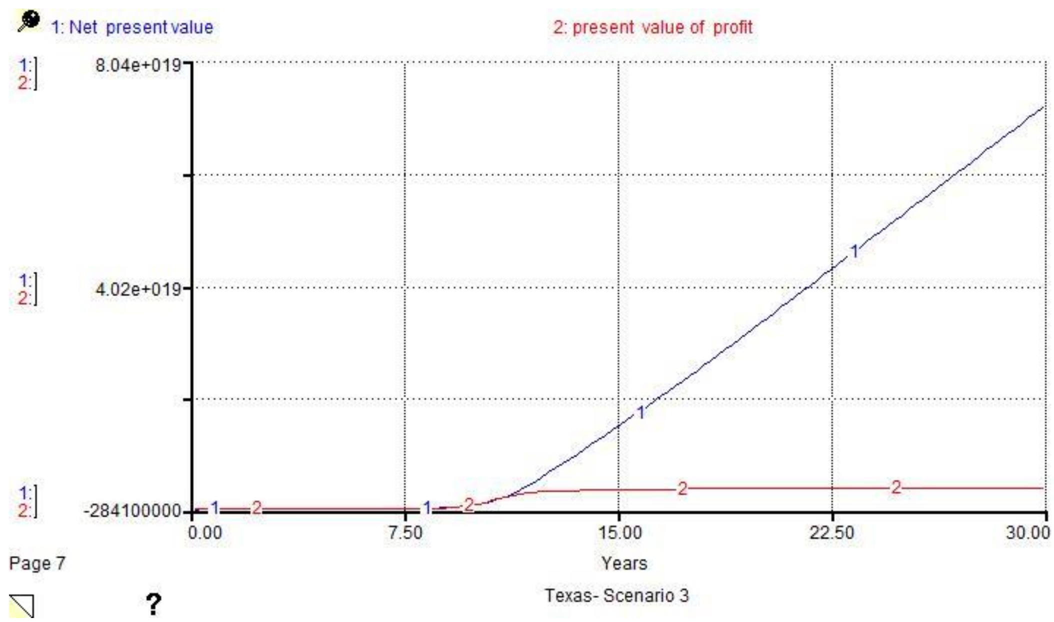

Figure 4-29 Texas Scenario 3- Net Present Value

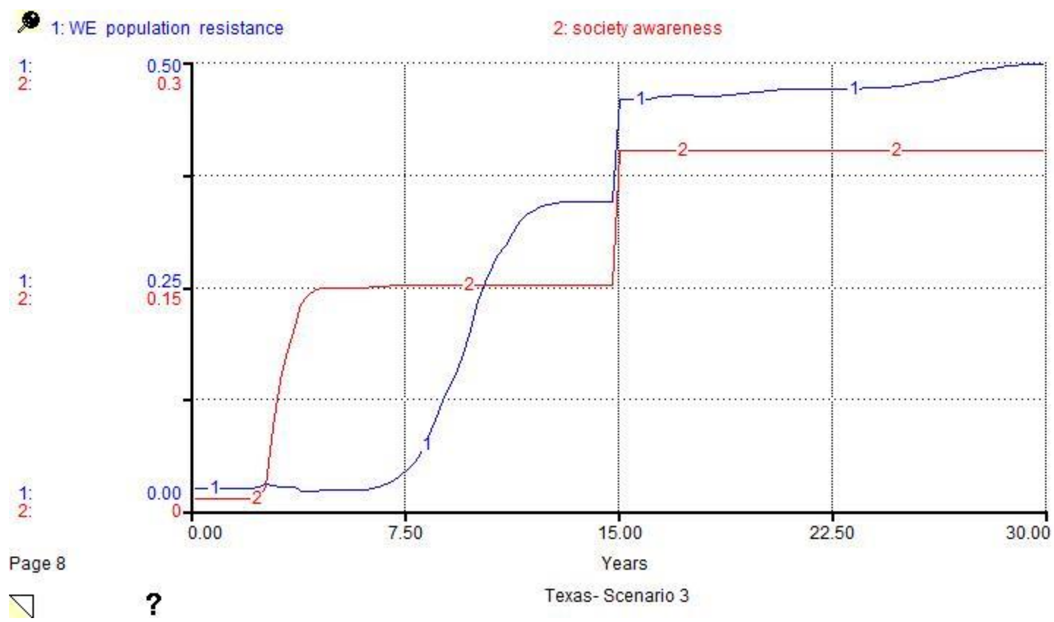

Figure 4-30 Texas Scenario 3- Wind Energy Population Resistance and Society Awareness

State of California

Scenario 1: Simulate Baseline Case

In this scenario, similar to Texas, the simulator is run without modifying the amount of economic incentives and the distance between wind energy system and the nearest community. The simulation is run as is. Data from the state of California has been used, as input for the simulation runs. The results are shown after running the simulation for 30 years, Table 4.8 shows the values of output parameters in years 10, 20 and 30, followed by a discussion of the output behavior presented in Figure 4-31 through 4-36.

Table 4-8 Scenario 1 Simulation Outputs- State of California

	10	20	30
Ecological footprint (Global Hectares)	258,288.3	743,615.8	1,649,439
Energy replacement ecological footprint difference (Global Hectares)	14,636.51	52,750.33	96,933.6
Net water savings (Gallons)	3.08E+10	1.1E+11	2.03E+11
Net carbon footprint (metric tons CO_2)	39,577,292	1.44E+08	2.65E+08
Net present value ($)	1.10E+17	2.66E+18	7.41E+18
Net employment rate (person)	1,177	1,335	1,678
WE population resistance (dimensionless)	0.079	0.252	0.351
Society awareness impact (dimensionless)	0.150	0.150	0.150

Figure 4-31 shows the behavior of the ecological footprint. The ecological footprint of the wind energy system increases as the number of turbines are added to the system, operated, maintained and decommissioned. The ecological footprint of the California's wind energy system at the end of the simulation for the baseline case is 1,649,439 global hectares. Additionally, the energy replacement ecological footprint difference is 96,933.6 global hectares. Figures 4-32 and 4-33 show the net water savings and the net carbon footprint of the wind energy system. The net water savings at the end of the simulation is 2.03E+11 gallons and the net carbon footprint is 2.65E+08 metrics tons of CO_2.

It is observed in Figure 4-34 that the highest number of employees related to the installation, O&M and decommission activities of the wind energy system in the state of California happens at the end of the simulation , this value is 1,678 people. Figure 4-34 also shows the behavior of the skilled personnel for WES installation, the skilled personnel for WES operation and maintenance, and the skilled personnel for WES decommissioning.

The net present value relates to the economic pillar. The net present value of the California's wind energy system, depicted in Figure 4-35, for the baseline case is $7.41E+18 ($2014). The wind energy population resistance and the society awareness are showed in Figure 4-36. It can be observed that at the beginning of the simulation the wind energy system has a major acceptance, the wind energy population resistance is only 7.9%. However, the wind energy population resistance increases to 35.1% by the end of the simulation due to the increase in the installation, operation and maintenance, and decommissioning activities. The society awareness keeps the same value during the entire simulation run. The reason is that the simulator considers that the society awareness is already established after more than 1000 turbines have been installed and are in service.

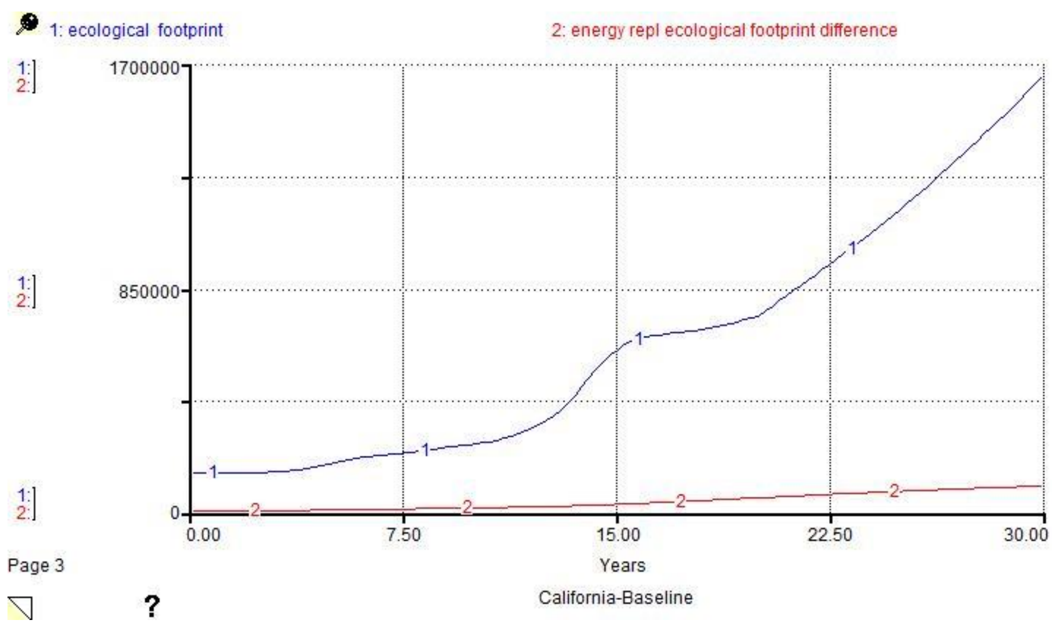

Figure 4-31 California Scenario 1- Ecological Footprint

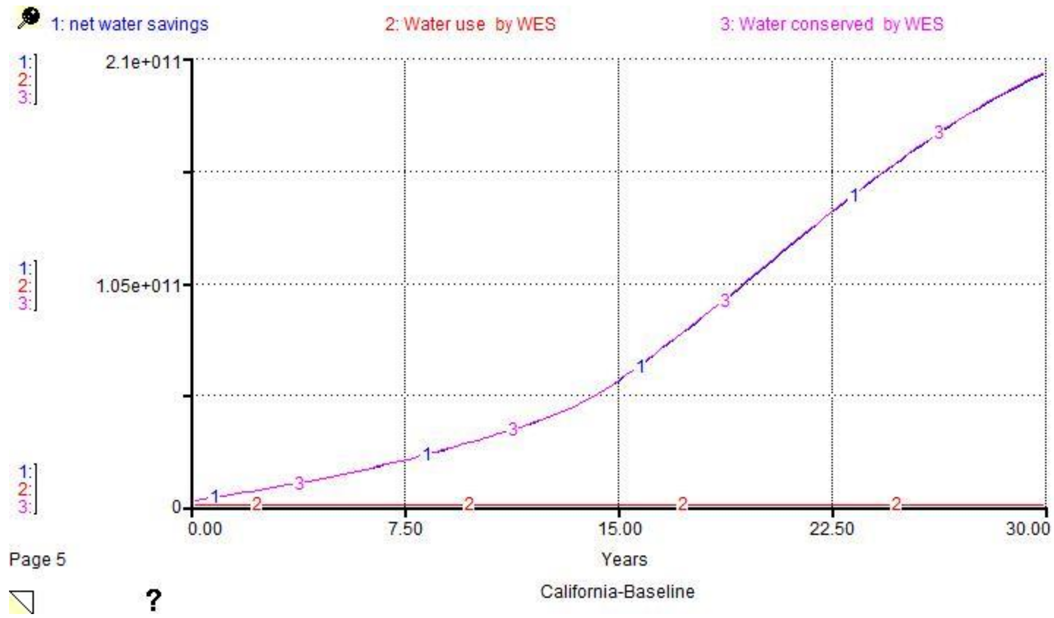

Figure 4-32 California Scenario 1- Water Savings

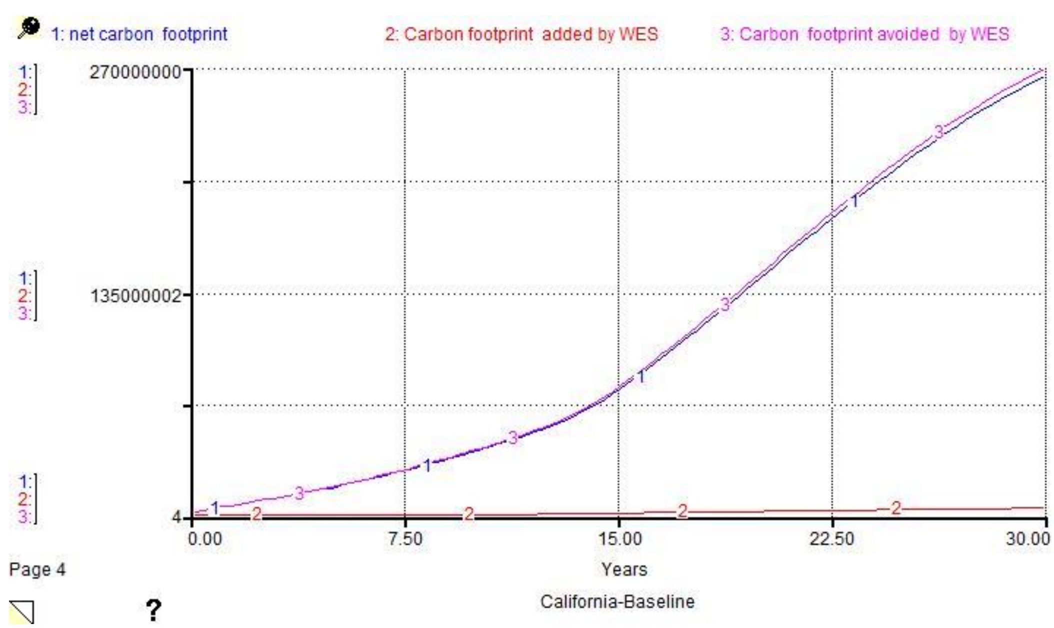

Figure 4-33 California Scenario 1- Carbon Footprint

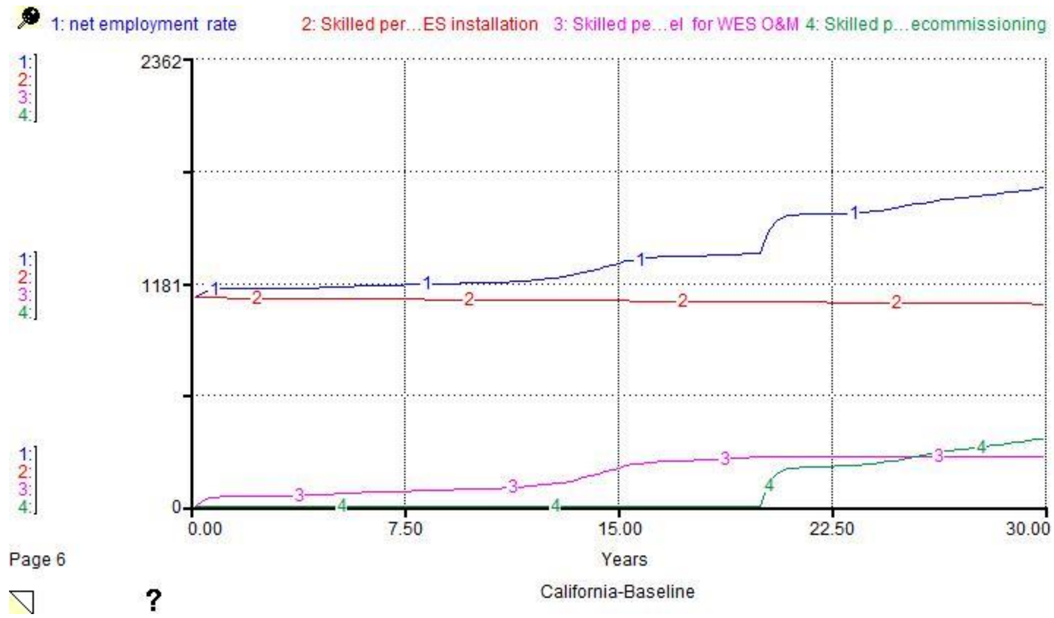

Figure 4-34 California Scenario 1- Employment

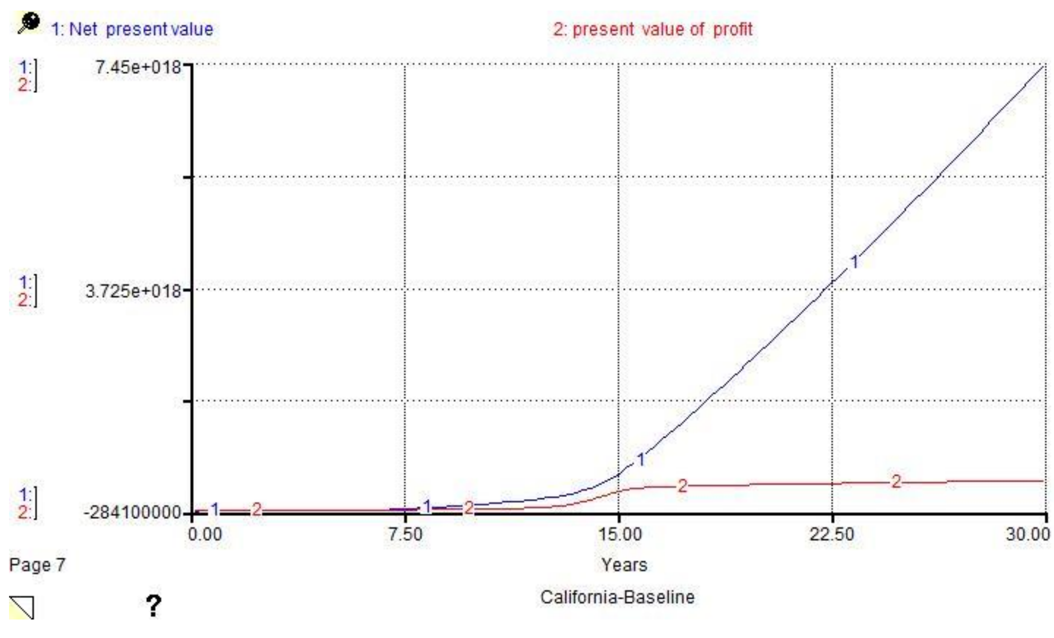

Figure 4-35 California Scenario 1- Net Present Value

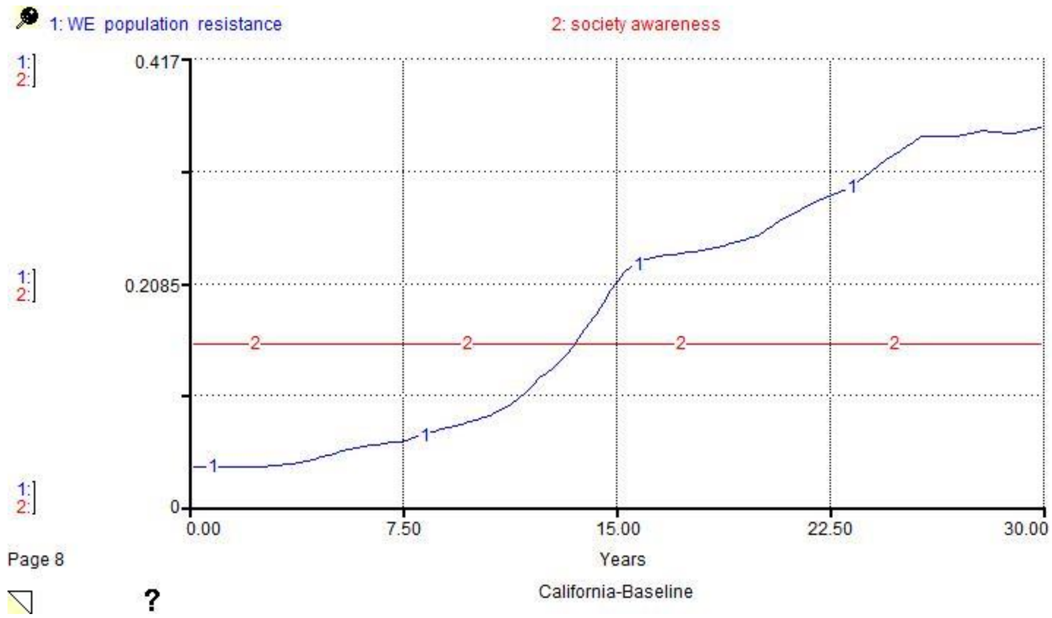

Figure 4-36 California Scenario 1- Wind Energy Population Resistance and Society Awareness

Scenario 2: Elimination of Economic Incentives

The simulator is run modifying only the amount of economic incentives (PTC) that can be obtained for wind energy implementation. In this scenario the amount of economic incentives is eliminated at the end of year 19. The results can be compared with the baseline case or other scenarios related to financial incentives. Effects of this variable can be seen on the output parameters. These outputs are from the three pillars of sustainability. The results are shown in Figures 4-37 through 4-42 after running the simulation for 30 years, Table 4.9 shows the values of output parameters in years 10, 20 and 30, followed by a discussion of the output behavior.

Table 4-9 Scenario 2 Simulation Outputs- State of California

	10	20	30
Ecological footprint (Global Hectares)	258,288.3	743,615.8	1,649,439
Energy replacement ecological footprint difference (Global Hectares)	14,636.51	52,750.33	96,933.6
Net water savings (Gallons)	3.08E+10	1.1E+11	2.03E+11
Net carbon footprint (metric tons CO_2)	39,577,292	1.44E+08	2.65E+08
Net present value ($)	1.10E+17	2.66E+18	7.41E+18
Net employment rate (person)	1,177	1,335	1,678
WE population resistance (dimensionless)	0.079	0.252	0.351
Society awareness impact (dimensionless)	0.150	0.150	0.150

As can be observed in Table 4.9 and the figures, this scenario outputs look similar to the baseline scenario. Given the high cost of electricity ($67.76/MWh average value for years 2000-2014 in the West region, against $37.70/MWh in the Central area (Wiser and Bolinger, 2015)), elimination of the PTC did not alter the behavior and values of the outputs.

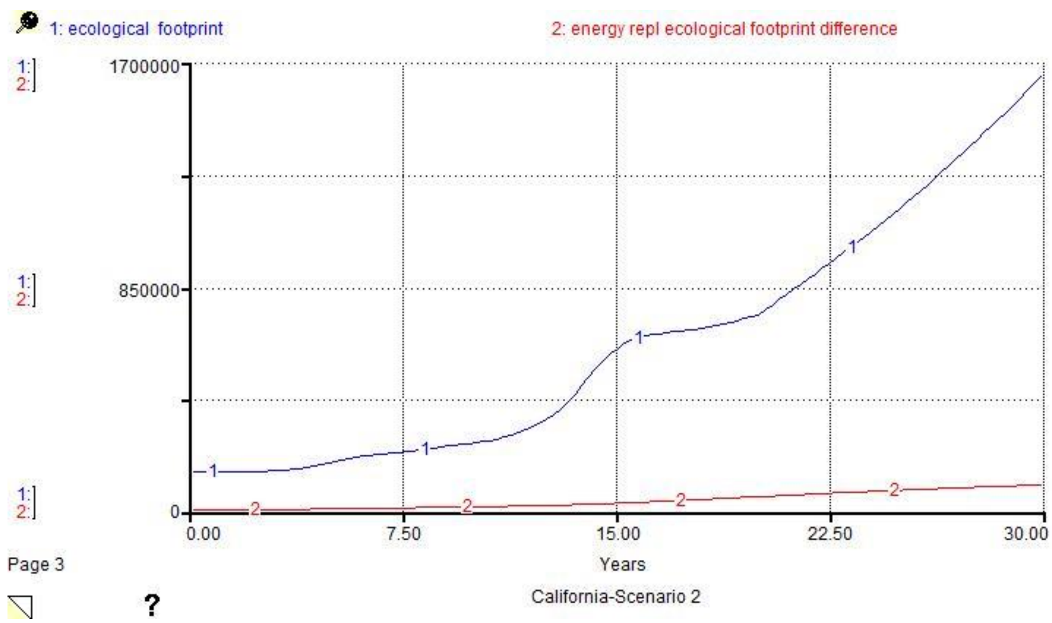

Figure 4-37 California Scenario 2- Ecological Footprint

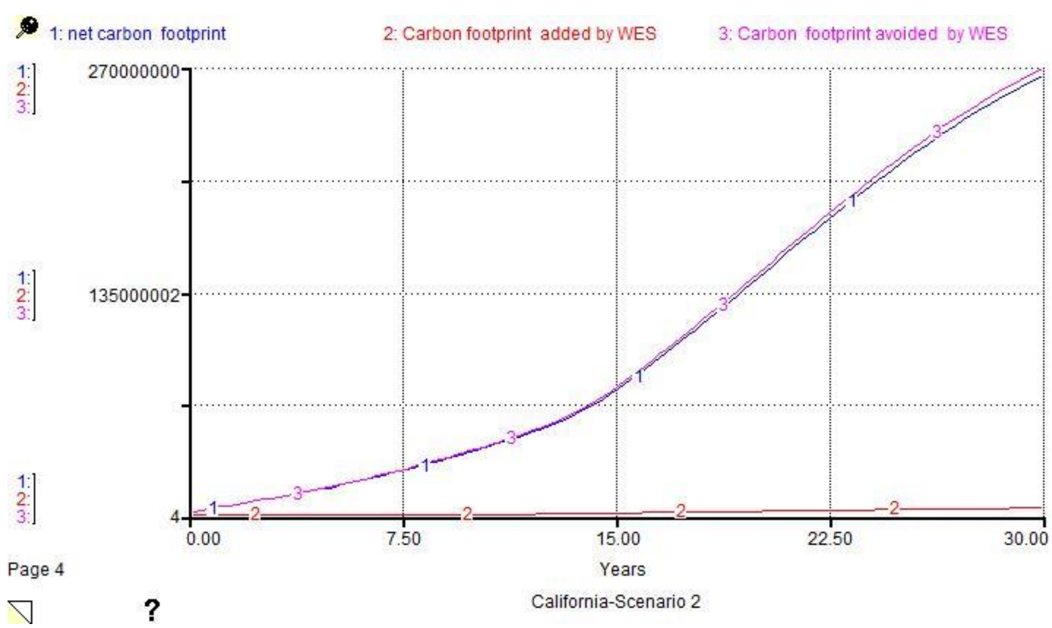

Figure 4-38 California Scenario 2- Carbon Footprint

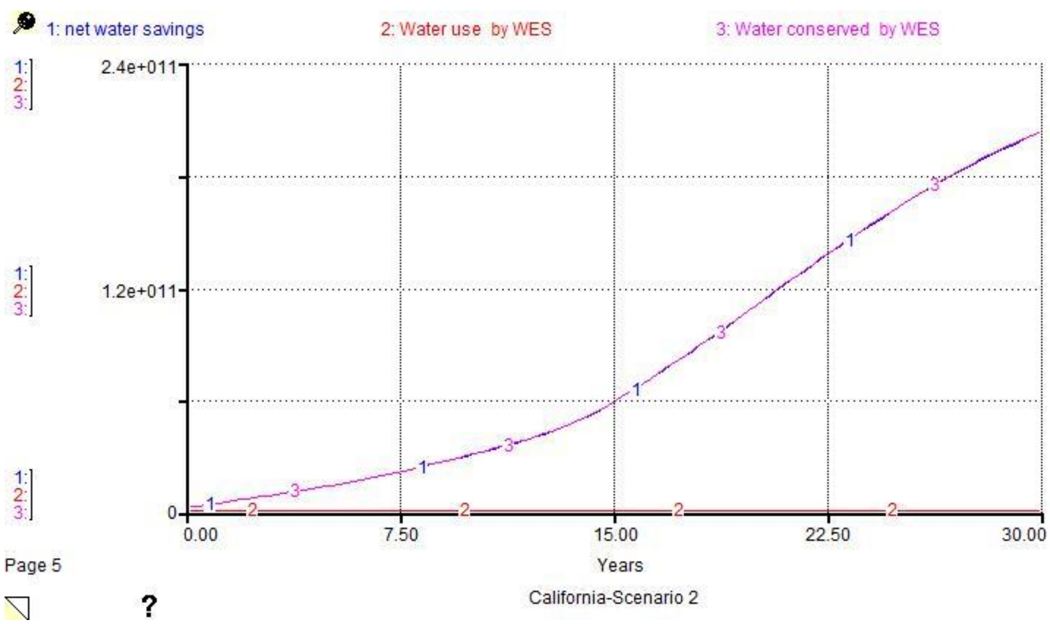

Figure 4-39 California Scenario 2- Water Savings

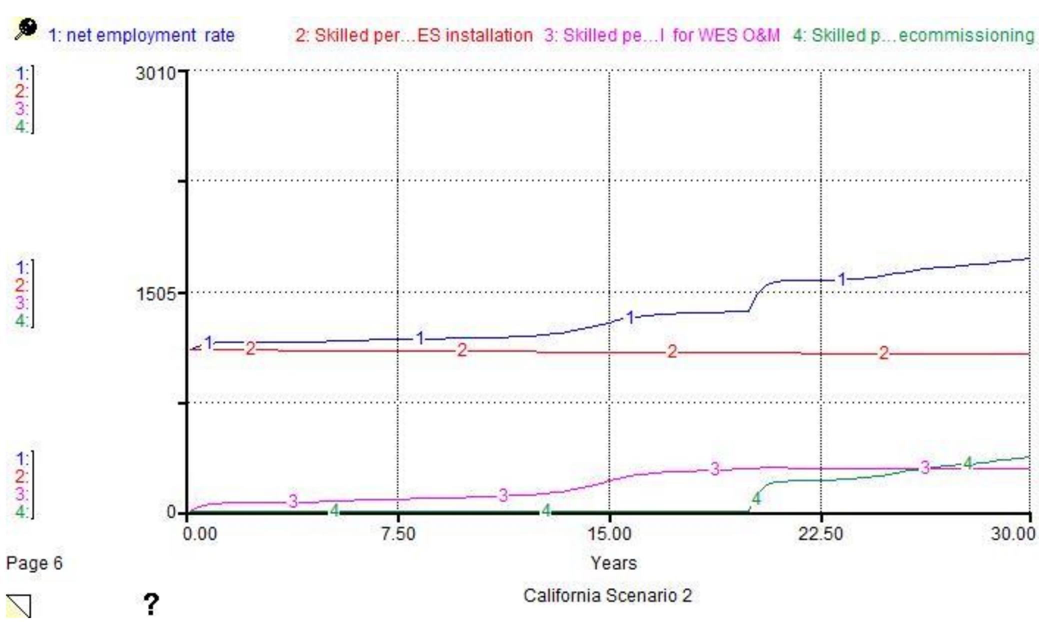

Figure 4-40 California Scenario 2- Employment

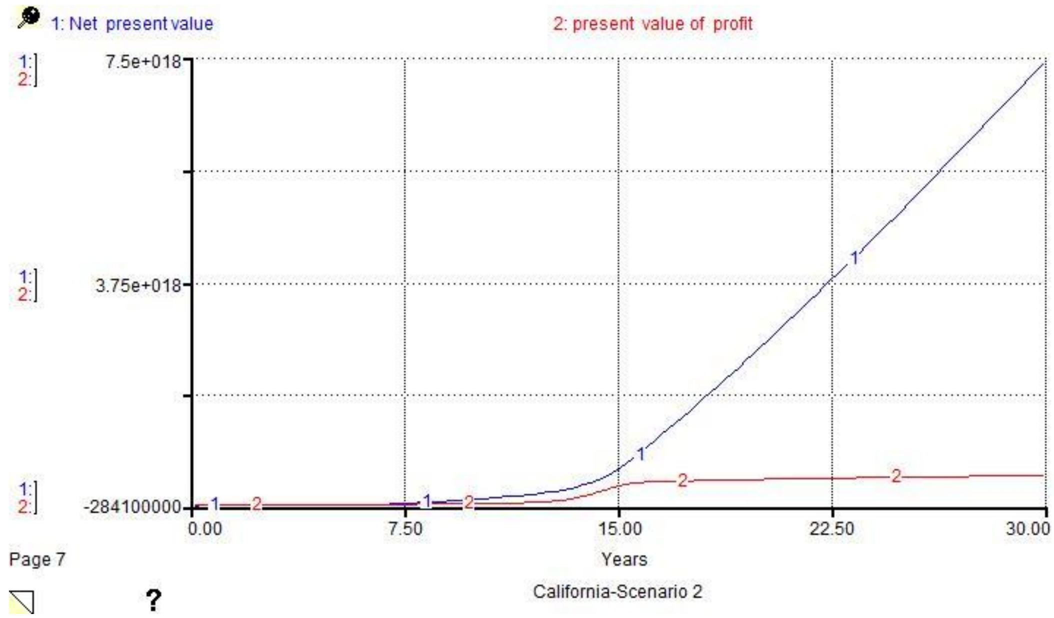

Figure 4-41 California Scenario 2- Net Present Value

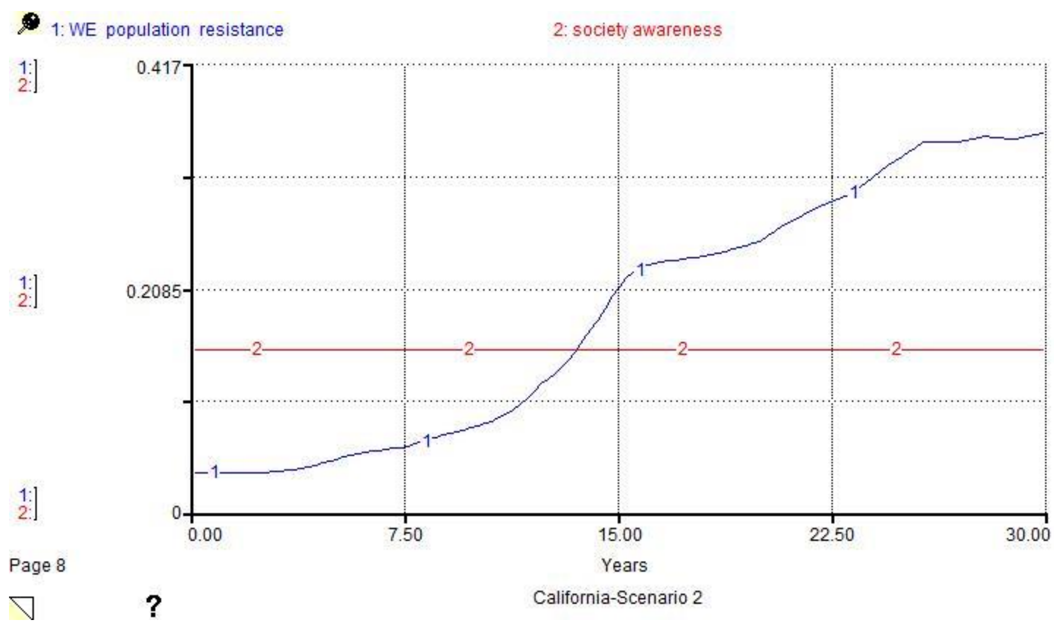

Figure 4-42 California Scenario 2- Wind Energy Population Resistance and Society Awareness

Scenario 3: Simulate Minimum Distance Between Wind Energy System and Nearest Community 1000 m

In this scenario the simulator is running a case that includes a reduction on the minimum distance between the wind energy system and the nearest community. The user can evaluate the impact of performing the baseline case versus the additional change on minimum distance on the output variables related to the three pillars of sustainability. The results are shown on Table 4-10, followed by a discussion of the output behavior shown in Figures 4-43 through 4-48. In the case of California, baseline distance was in average 13 km from a sample size of 30 wind energy projects. The change on distance to 1000m is simulated to start happening at year 15.

Table 4-10 Scenario 3 Simulation Outputs- State of California

	10	20	30
Ecological footprint (Global Hectares)	258,288.3	731,101.4	1,593,856
Energy replacement ecological footprint difference (Global Hectares)	14,636.51	52,632.07	94,395.78
Net water savings (Gallons)	3.08E+10	1.1E+11	1.97E+11
Net carbon footprint (metric tons CO_2)	39,577,292	1.43E+08	2.58E+08
Net present value ($)	1.10E+17	2.65E+18	7.23E+18
Net employment rate (person)	1,177	1332	1673
WE population resistance (dimensionless)	0.079	0.363	0.463
Society awareness impact (dimensionless)	0.150	0.241	0.241

When the distance between wind energy system and the nearest community decreases, the noise perceived increases and the level of visual impact increases. Therefore the wind energy population resistance increases. The increase of the wind energy population resistance decreases the number of turbines to be installed, decreasing the overall set of outputs, as can be observed in the Figures 4-43 through 4-48, as well as in the summary of values presented in the Table 4.10. The change is observed starting in year 15 since it is the set up time to decrease the distance in the simulator.

The behavior of the ecological footprint is observed in Figure 4-43. The ecological footprint of the California's wind energy system for the scenario 3 is 1,593,856 global hectares at the end of year 30. Additionally, the graph also depicts the energy replacement ecological footprint difference.The energy replacement ecological footprint difference is 94,395.78 global hectares by the end of the simulation. Figures 4-44 and 4-45 show the net carbon footprint and the net water savings of the wind energy system during the 30 years of the simulation run. The net water savings at the end of the simulation is 1.97E+11 gallons and the net carbon footprint is 2.58E+08 metrics tons of CO_2. Figure 4-46 depicts the net employment rate. The highest number of employees related to the installation, operation and maintenance and decommission of the wind energy system is, at the end of the simulation, 1673 people in the system. Figure 4-46 also shows the behavior of the skilled personnel for WES installation, the skilled personnel for WES operation and maintenance, and the skilled personnel for WES decommissioning. The net present value of the state of California's wind energy system for the scenario 3 is presented in Figure 4-47. For the 30 years of simulation, the net present value is $7.23E+18 ($2014). The present value of profits is also depicted in the figure. The wind energy population resistance and the society awareness are shown in Figure 4-48. These outputs relate to the social pillar. The wind energy population resistance and the society awareness values for year 30 are 46.3% and 24.1% respectively.

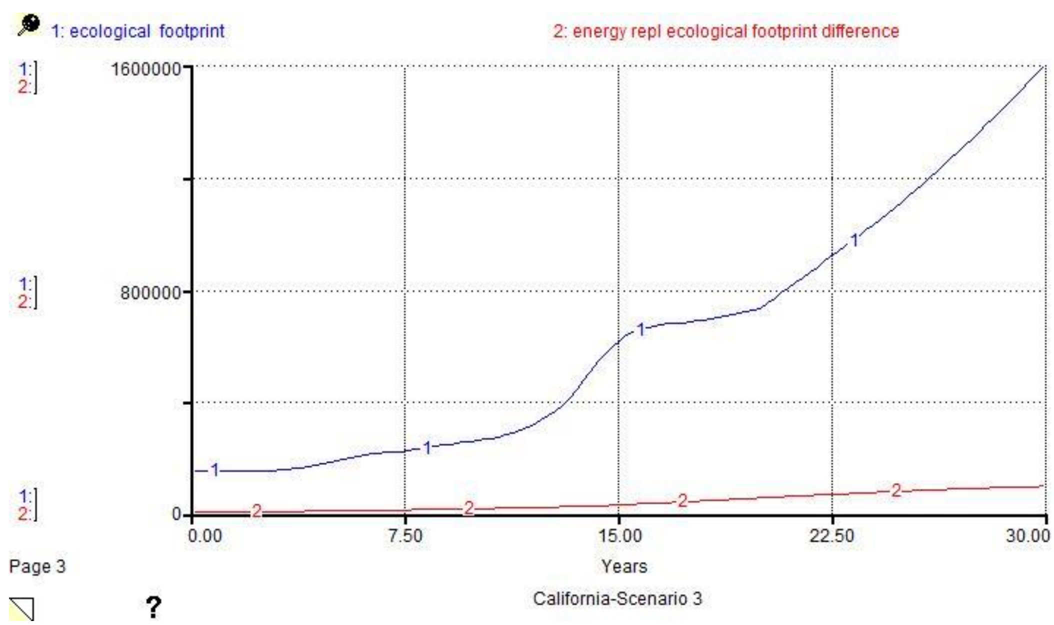

Figure 4-43 California Scenario 3- Ecological Footprint

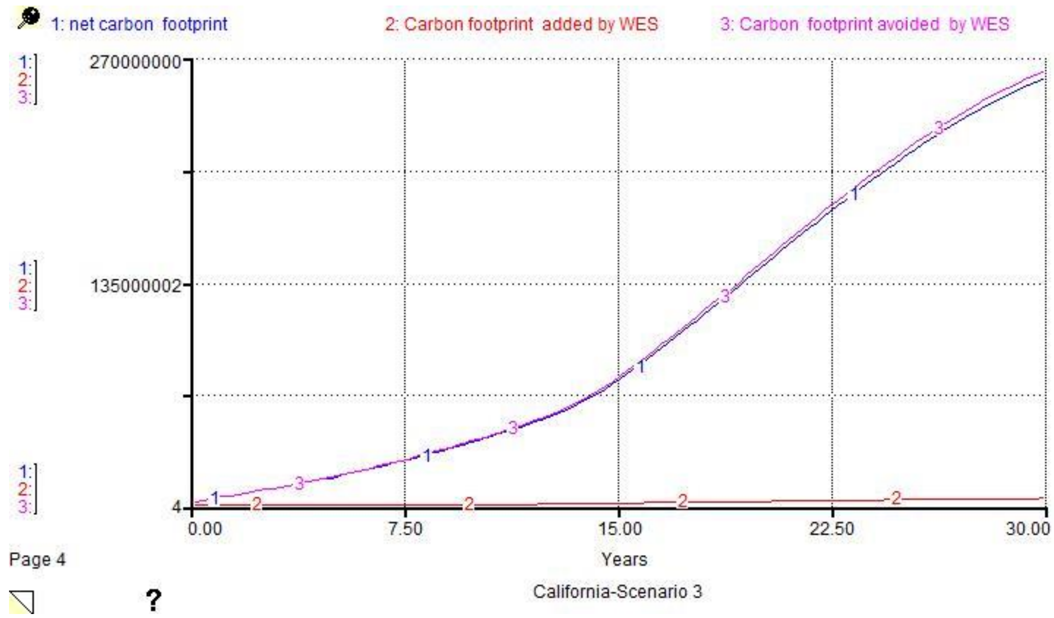

Figure 4-44 California Scenario 3- Carbon Footprint

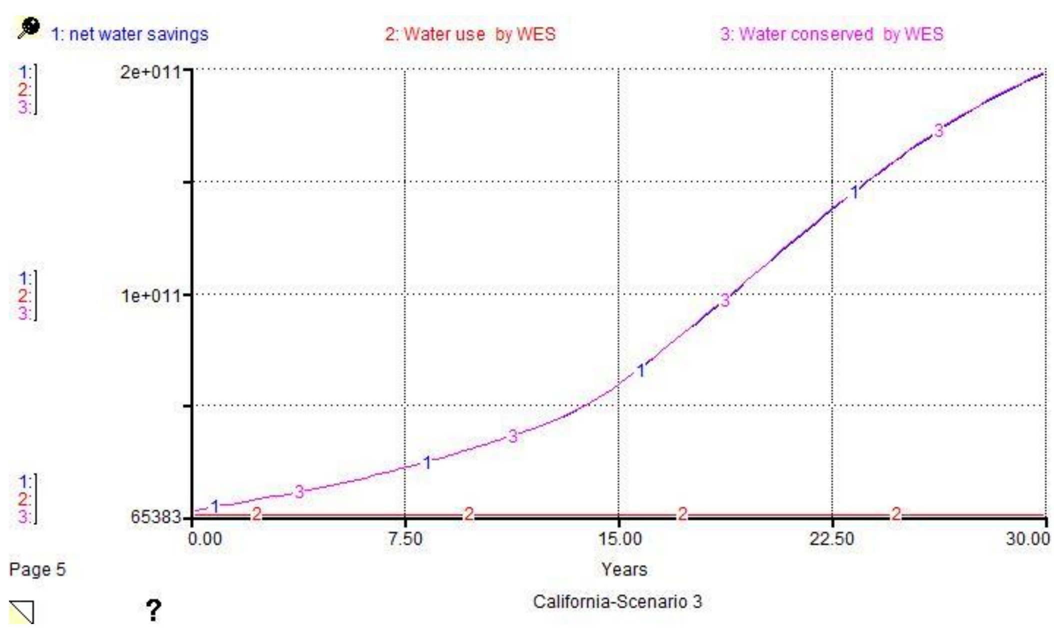

Figure 4-45 California Scenario 3- Water Savings

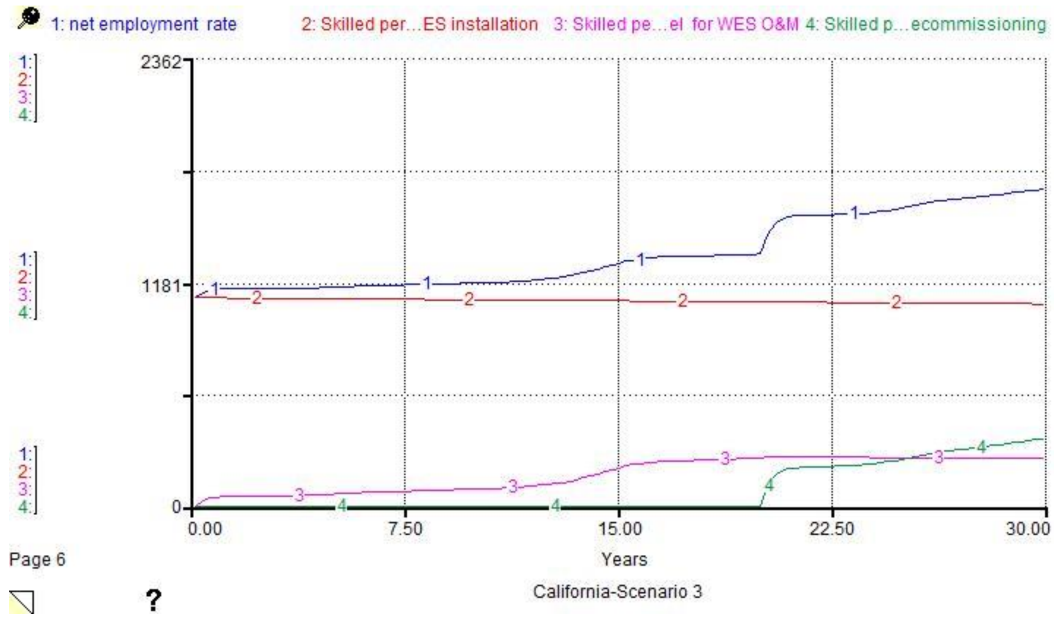

Figure 4-46 California Scenario 3- Employment

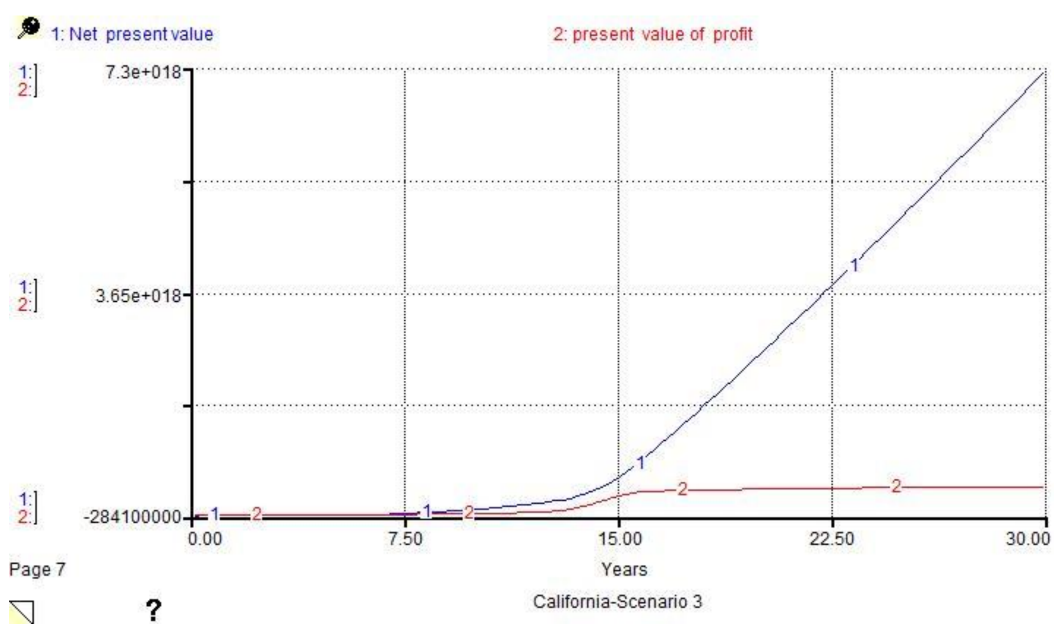

Figure 4-47 California Scenario 3- Net Present Value

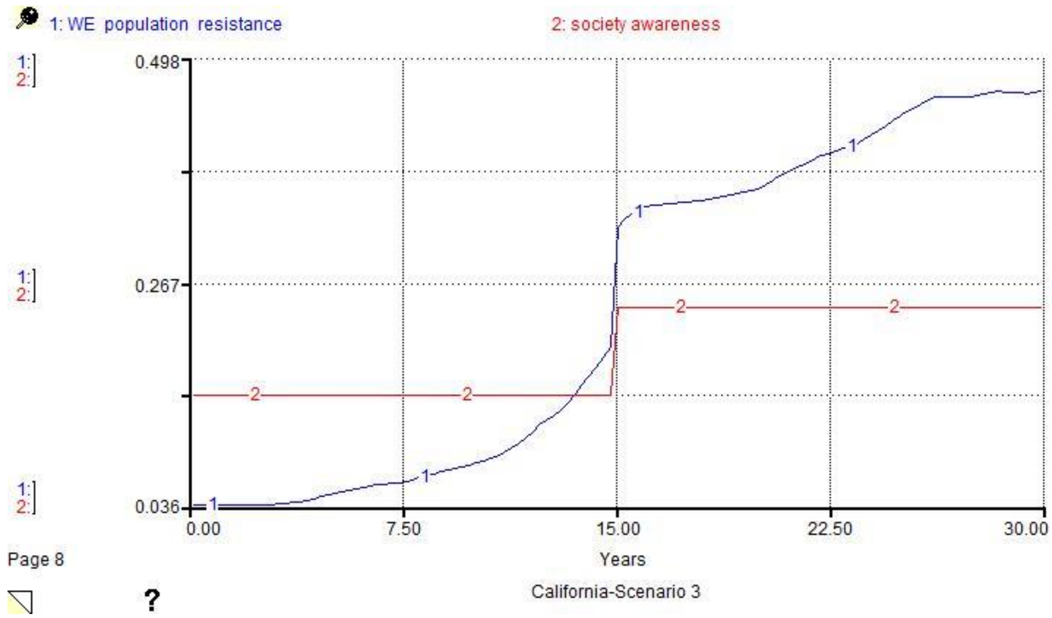

Figure 4-48 California Scenario 3- Wind Energy Population Resistance and Society Awareness

State of Iowa

Scenario 1: Simulate Baseline Case

In this scenario, as in the states of Texas and California, the simulator is run without modifying the amount of economic incentives and the distance between the wind energy system and the nearest community. The simulation is run as is. Data from the state of Iowa has been used as input for the simulation run. Figures 4-49 through 4-54 show the output behavior. Table 4.11 shows the values of output parameters in years 10, 20 and 30, followed by a discussion of the output behavior.

Table 4-11 Scenario 1 Simulation Outputs- State of Iowa

	10	20	30
Ecological footprint (Global Hectares)	213,574.1	564,237.1	717,592.13
Energy replacement ecological footprint difference (Global Hectares)	3,439.71	39,681.08	76,842.31
Net water savings (Gallons)	7.24E+09	8.3E+10	1.6051E+11
Net carbon footprint (metric tons CO_2)	9,291,722	1.08E+08	210,178,607
Net present value ($)	4.55E+16	5.43E+18	1.18E+19
Net employment rate (person)	217	361	571
WE population resistance (dimensionless)	0.057	0.187	0.241
Society awareness impact (dimensionless)	0.150	0.150	0.150

The behavior of the ecological footprint is observed in Figure 4-49. The ecological footprint of the wind energy system increases as the number of turbines are added to the system, maintained and decommissioned. Ecological footprint of the wind energy system relates to the environmental pillar. The ecological footprint of the Iowa's wind energy system at the end of the simulation, for the baseline case, is 717,592.13 global hectares. Additionally, the graph is also depicting the energy replacement ecological footprint difference with a value of 76,842.31 global hectares at year 30.

Figures 4-50 and 4-51 show the net water savings and the net carbon footprint of the wind energy system, during the 30 years of the simulation run. As can be seen, water savings and carbon footprint avoided are the major resultant in their respective category. The net water savings at the end of the simulation is 1.6051E+11 gallons and the net carbon footprint is 210,178,607 metrics tons of CO_2.

Figure 4-52 shows the number of employees in the wind energy system during installation, O&M and decommissioning. In the present scenario, the highest number of employees is reached at year 30, with 571 people as the number of employee related to the installation, O&M and decommissioning activities. Figure 4-52 also shows the behavior of the skilled personnel for WES installation, the skilled personnel for WES operation and maintenance, and the skilled personnel for WES decommissioning.

The net present value, shown in Figure 4-53, relates to the economic pillar. The net present value of Iowa's wind energy system at the end of the simulation, for the baseline case, is $1.18E+19 ($2014).

The wind energy population resistance and the society awareness are depicted in Figure 4-54. These outputs relate to the social pillar. It can be observed that at the beginning of the simulation the wind energy system development has a major acceptance in the state (5.7% resistance). In fact, Iowa is the first state to reach the 2030 - 20% wind energy production goal in year 2012 (IWEA, 2015). Additional state policies have kept this industry moving forward beyond the met goal. It is observed in Figure 4-55 that the target generation was reached in year 14 and the number of turbines to be installed decreased to 0 as the goal is met. Additionally, it can be observed in Figure 4-55 that even in the case that simulated generation is below the target generation after year 23, the installation of wind turbines does not increase. The main reason for this behavior is that the assumed incentive available (PTC) for those years is not sufficient to make the investment attractive. State policies would be the ones supporting the required revamp in wind energy installation.

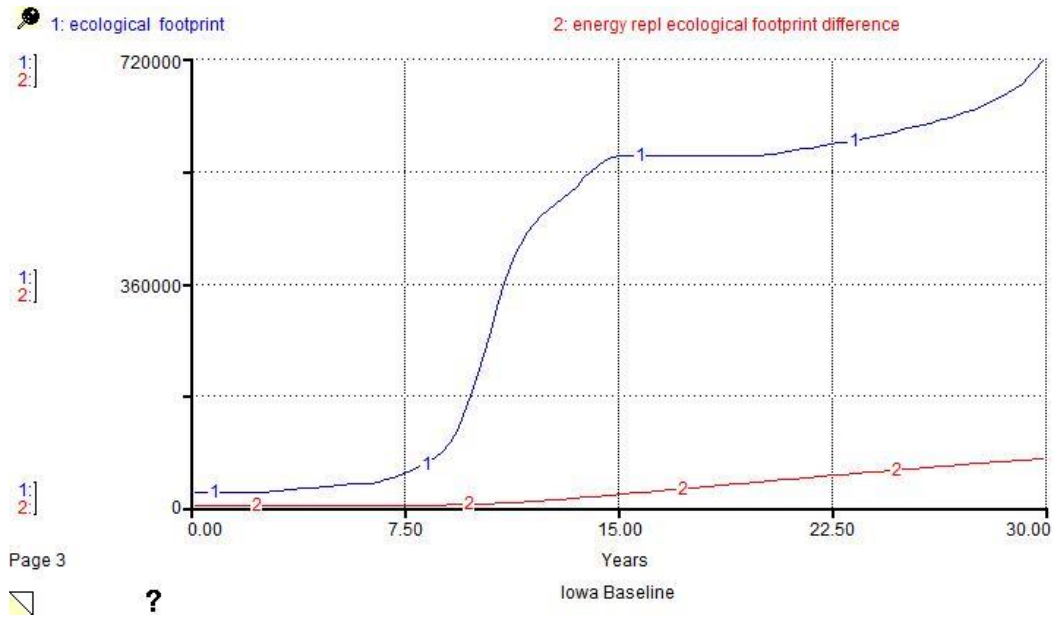

Figure 4-49 Iowa Scenario 1- Ecological Footprint

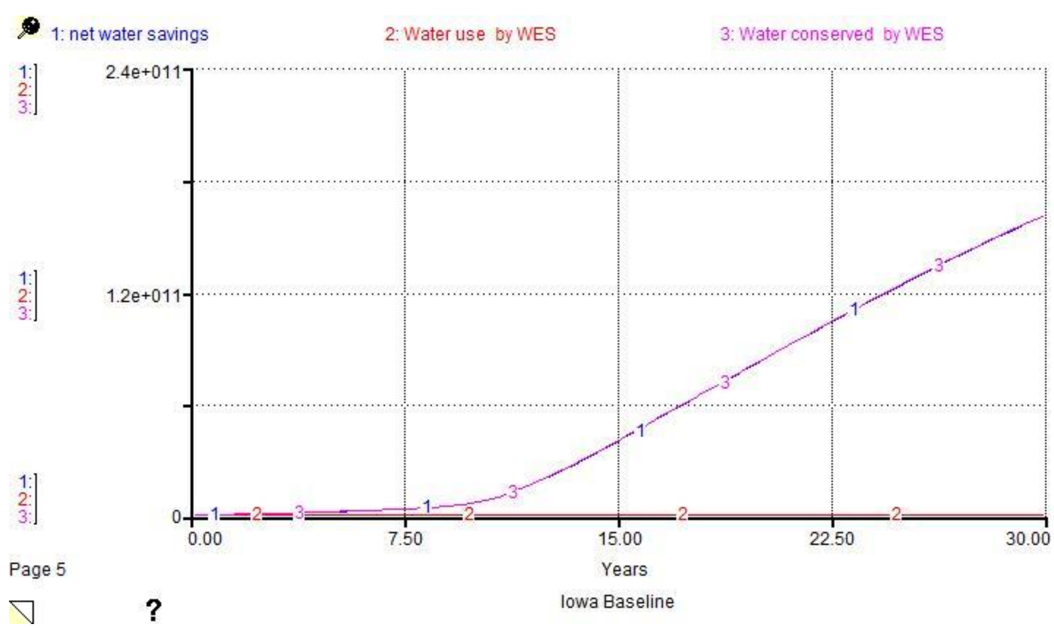

Figure 4-50 Iowa Scenario 1- Water Savings

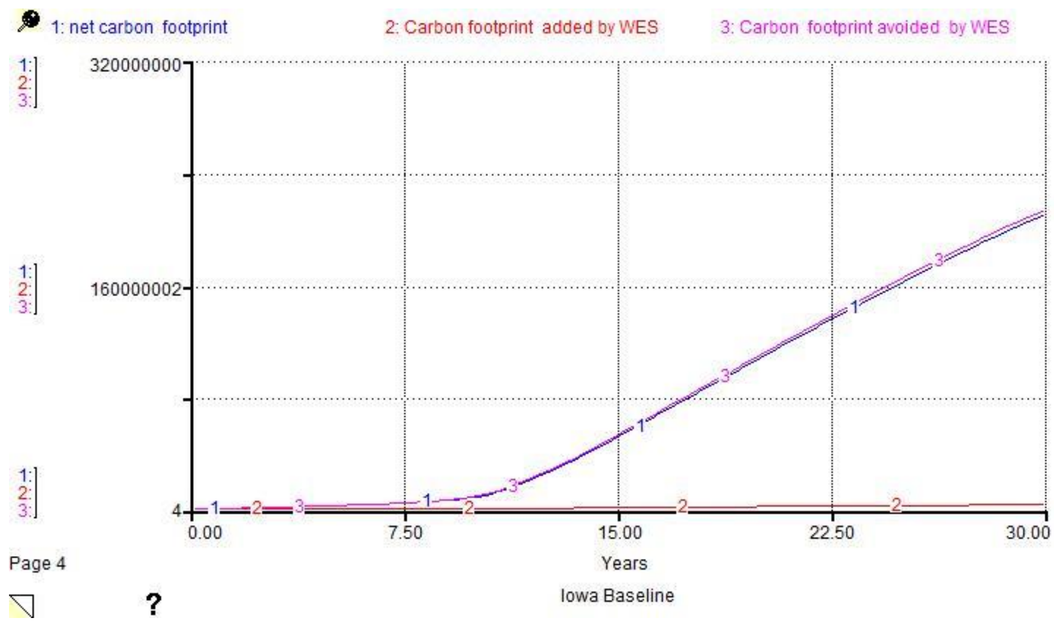

Figure 4-51 Iowa Scenario 1- Carbon Footprint

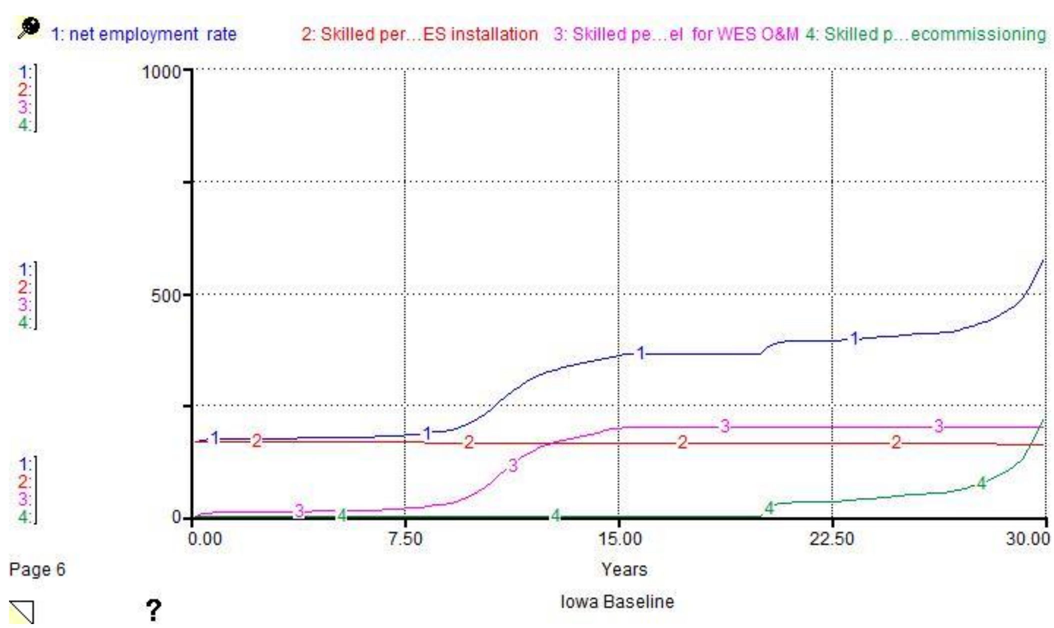

Figure 4-52 Iowa Scenario 1- Employment

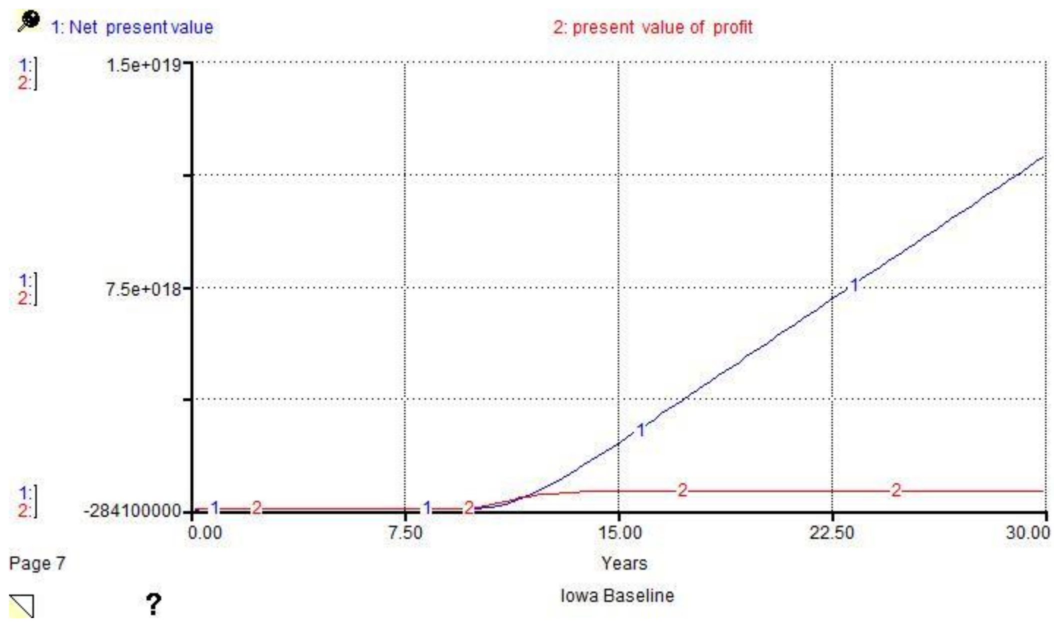

Figure 4-53 Iowa Scenario 1- Net Present Value

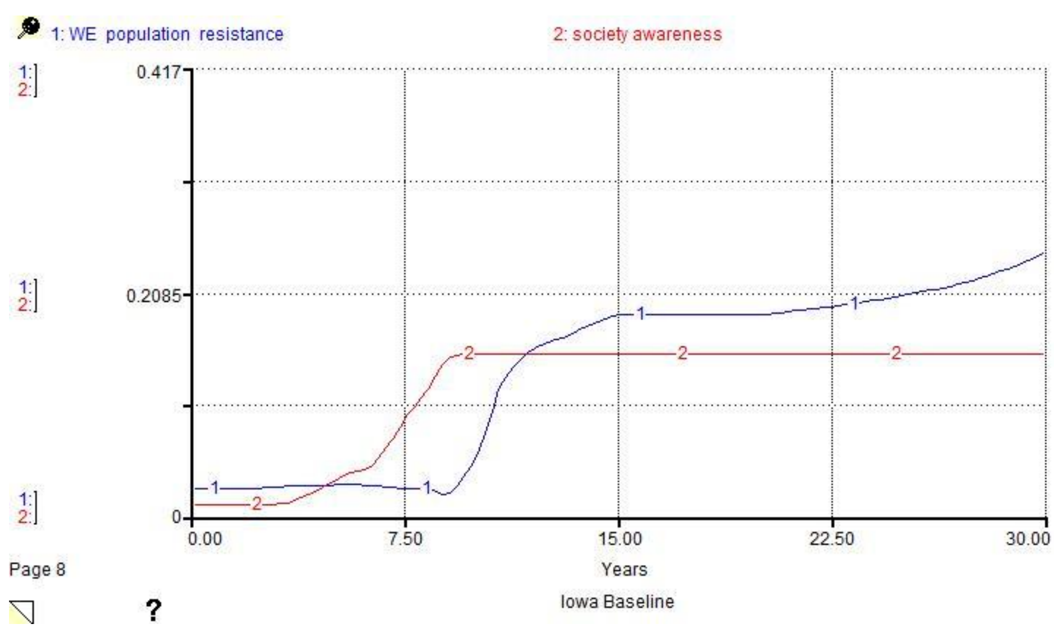

Figure 4-54 Iowa Scenario 1- Wind Energy Population Resistance and Society Awareness

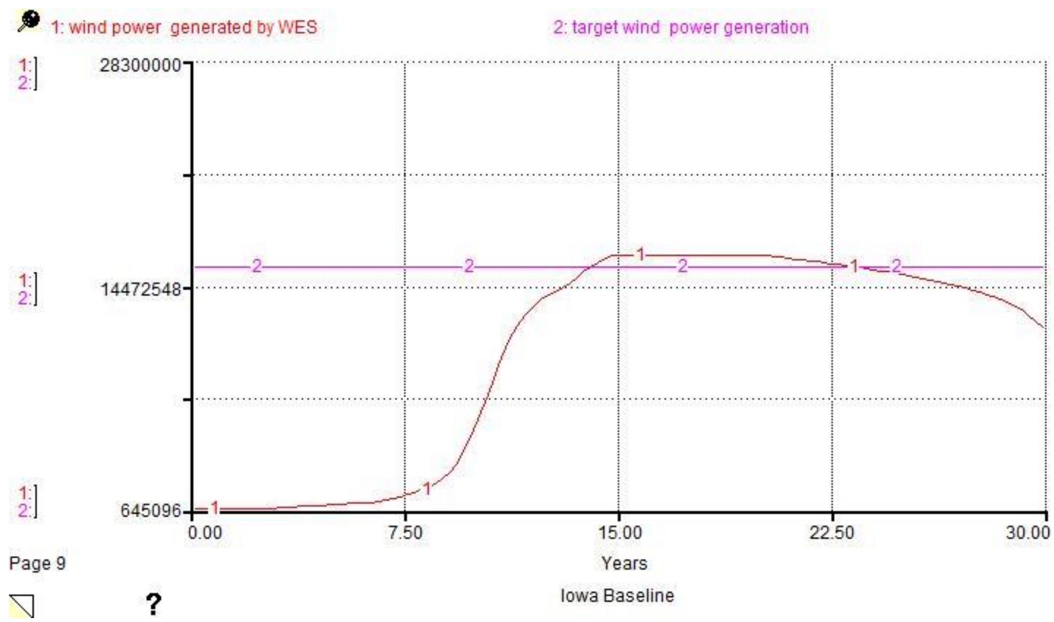

Figure 4-55 Iowa Scenario 1- Target Generation

Scenario 2: Elimination of Economic Incentives

The simulator is run modifying only the amount of economic incentives (PTC) that can be obtained for wind energy implementation. In this scenario the amount of economic incentives is eliminated at the end of year 19. The results can be compared with the baseline case or other scenarios related to financial incentives. Effects of this variable can be seen on the output parameters. These outputs are from the three pillars of sustainability. The results are shown below in Table 4.12, followed by a discussion of the output behavior presented in Figures 4-56 through 4-61.

Table 4-12 Scenario 2 Simulation Outputs- State of Iowa

	10	20	30
Ecological footprint (Global Hectares)	213,574.1	564,237.1	717,592.13
Energy replacement ecological footprint difference (Global Hectares)	3,439.71	39,681.08	76,842.31
Net water savings (Gallons)	7.24E+09	8.3E+10	1.6051E+11
Net carbon footprint (metric tons CO_2)	9,291,722	1.08E+08	210,178,607
Net present value ($)	4.55E+16	5.43E+18	1.18E+19
Net employment rate (person)	217	361	571
WE population resistance (dimensionless)	0.0576	0.187	0.241
Society awareness impact (dimensionless)	0.150	0.150	0.150

As it was discussed in the baseline scenario, Iowa met the 20% target early in the simulation (year 14). Since the changes in the incentives are happening after they meet the target, the simulator completes the installations and it does not add new wind turbines to the system. As expected, results from this scenario are similar to the baseline case.

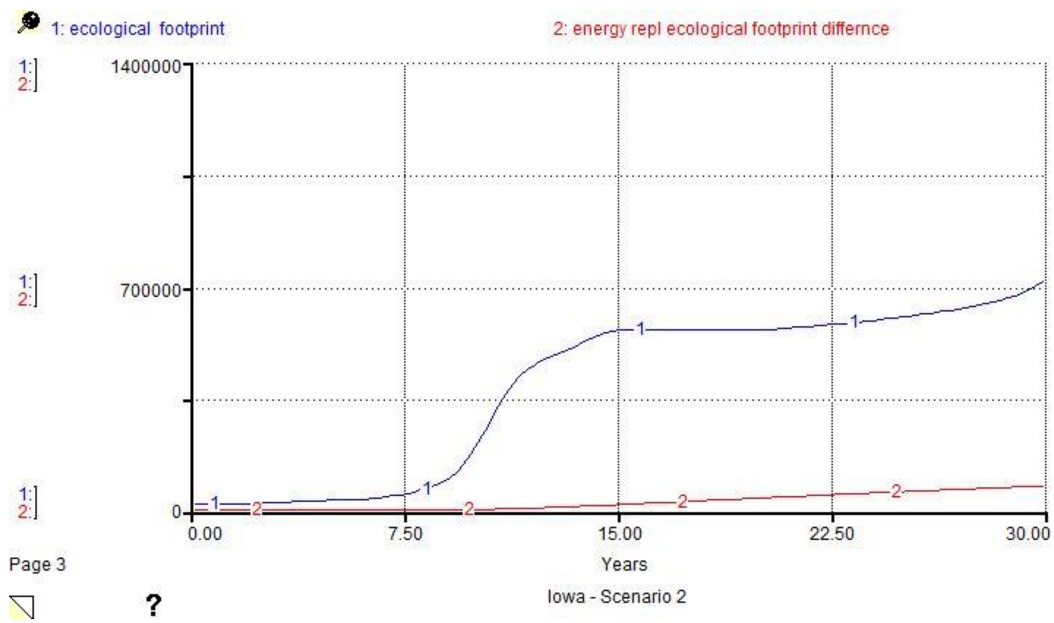

Figure 4-56 Iowa Scenario 2- Ecological Footprint

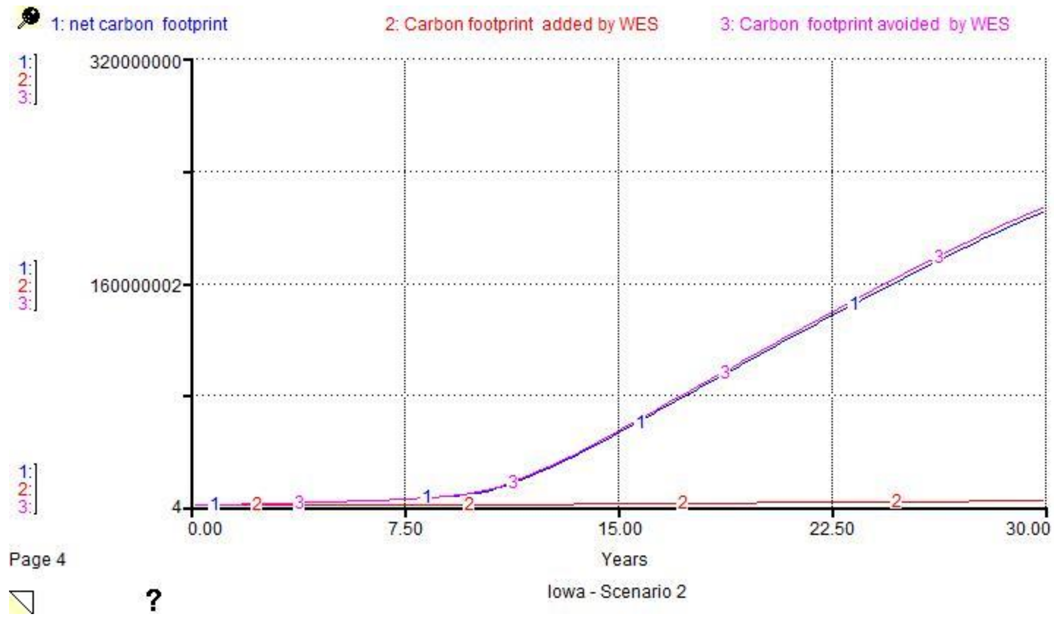

Figure 4-57 Iowa Scenario 2- Carbon Footprint

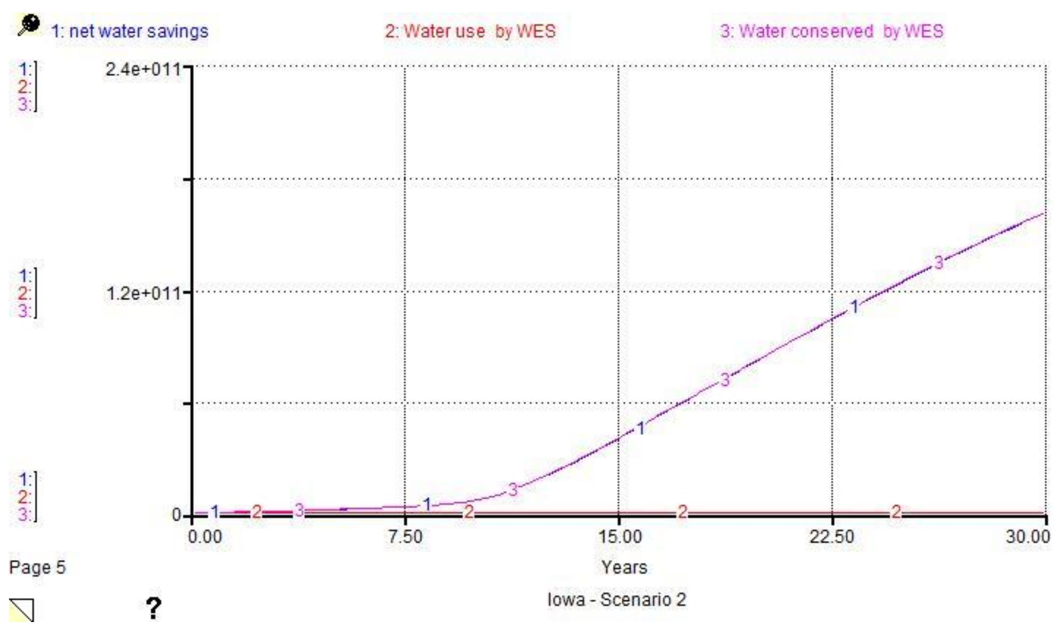

Figure 4-58 Iowa Scenario 2- Water Savings

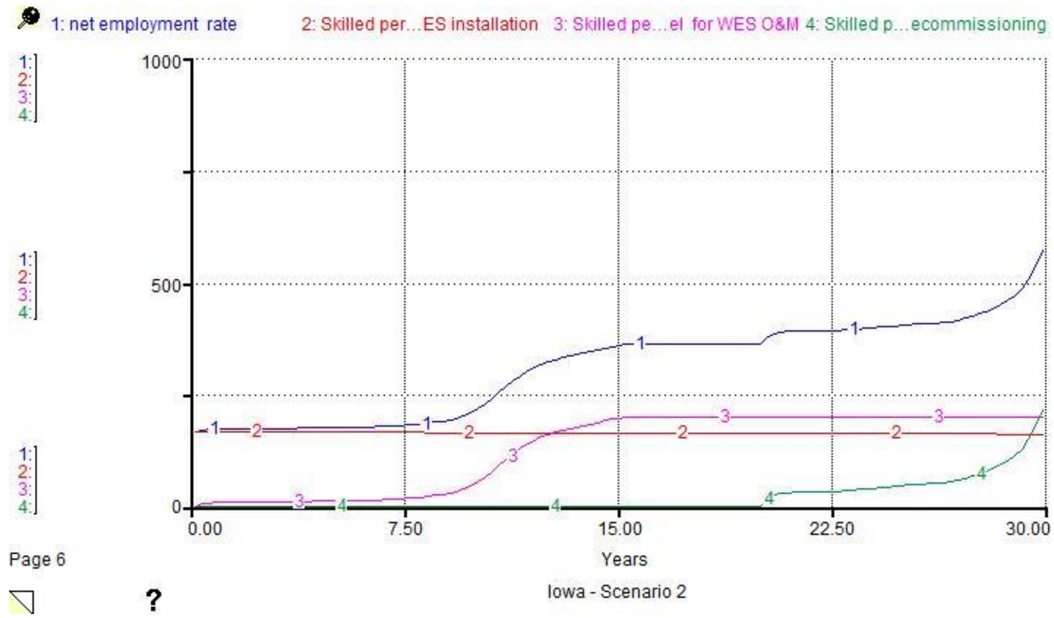

Figure 4-59 Iowa Scenario 2- Employment

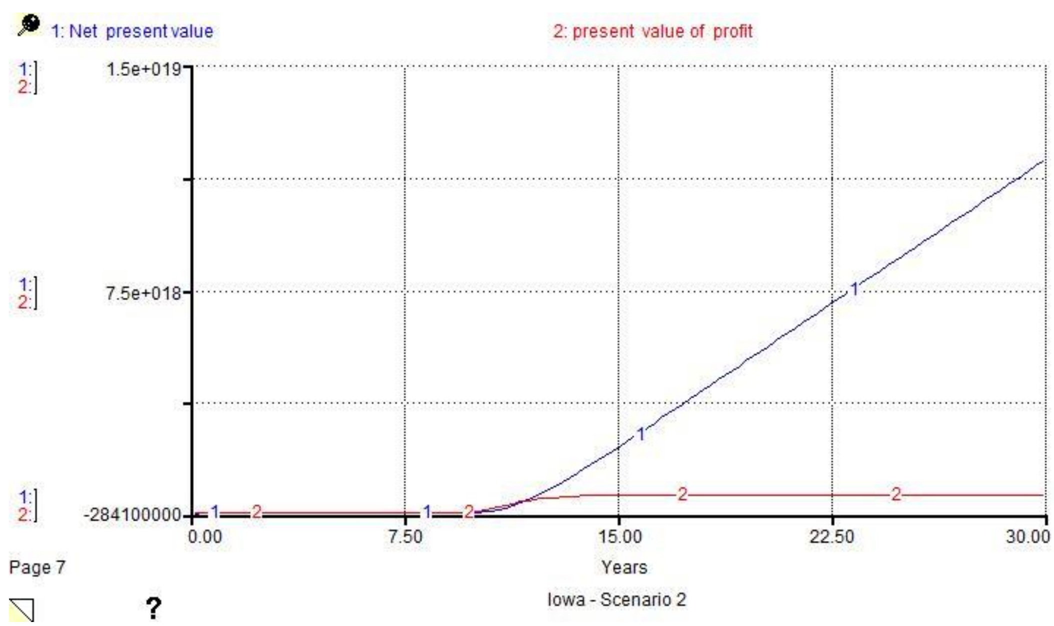

Figure 4-60 Iowa Scenario 2- Net Present Value

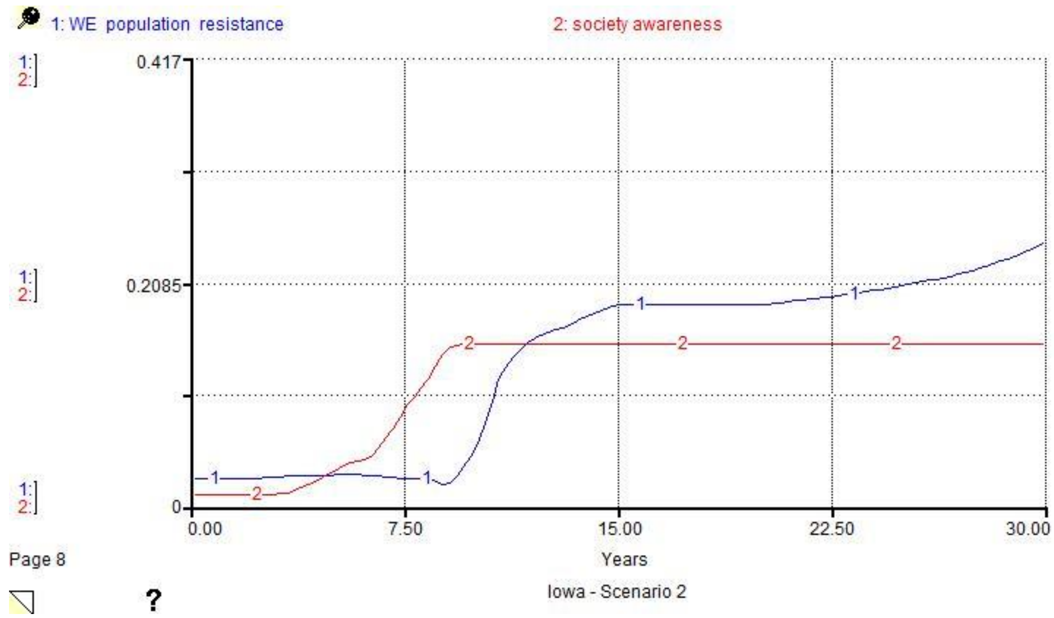

Figure 4-61 Iowa Scenario 2- Wind Energy Population Resistance and Society Awareness

Scenario 3: Simulate Minimum Distance Between Wind Energy System and Nearest Community 1000 m

In this scenario the simulator is running a case that includes a reduction on the minimum distance between the wind energy system and the nearest community. The user can evaluate the impact of performing the baseline case versus the additional change on minimum distance on the output variables related to the three pillars of sustainability. The results are shown after running the simulation for 30 years, Table 4.13 shows the output parameters in years 10, 20 and 30. Figures 4-62 through 4-67 show the output behavior. In the case of Iowa, baseline distance was, in average, 11km from a sample size of 20 wind energy projects. The change on distance to 1000m is simulated to start happening at year 15.

Table 4-13 Scenario 3 Simulation Outputs- State of Iowa

	10	20	30
Ecological footprint (Global Hectares)	213,574.1	564,237.1	717,592.13
Energy replacement ecological footprint difference (Global Hectares)	3,439.71	39,681.08	76,842.31
Net water savings (Gallons)	7.24E+09	8.3E+10	1.6051E+11
Net carbon footprint (metric tons CO_2)	9,291,722	1.08E+08	210,178,607
Net present value ($)	4.55E+16	5.43E+18	1.18E+19
Net employment rate (person)	217	360.9234	571
WE population resistance (dimensionless)	0.0576	0.187	0.241
Society awareness impact (dimensionless)	0.150	0.150	0.150

As it was discussed in the baseline scenario, Iowa met the 20% target back in year 14 (simulated model). Since the changes in the incentives are happening after they meet the target, the simulator completes the installations and it is no longer adding new generation to reach the target. Results from this scenario show the same behavior and values as the scenario 1.

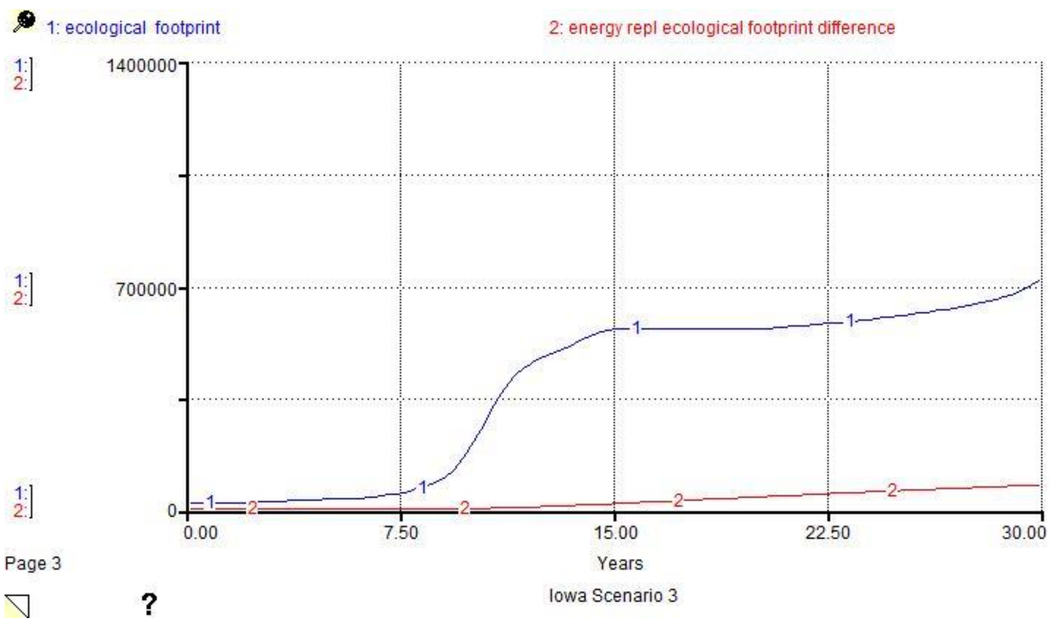

Figure 4-62 Iowa Scenario 3- Ecological Footprint

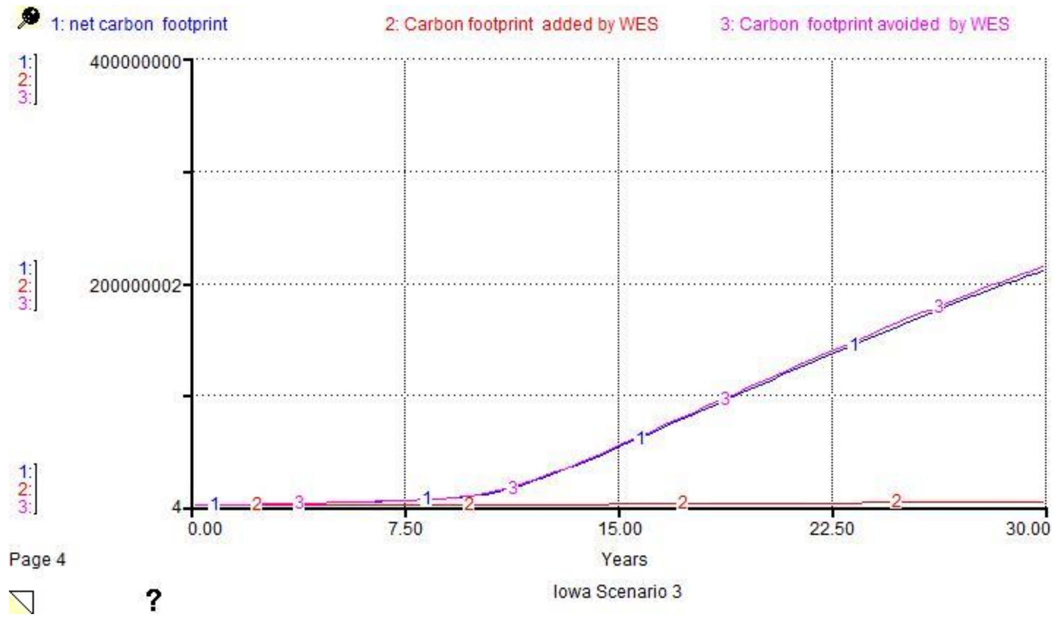

Figure 4-63 Iowa Scenario 3- Carbon Footprint

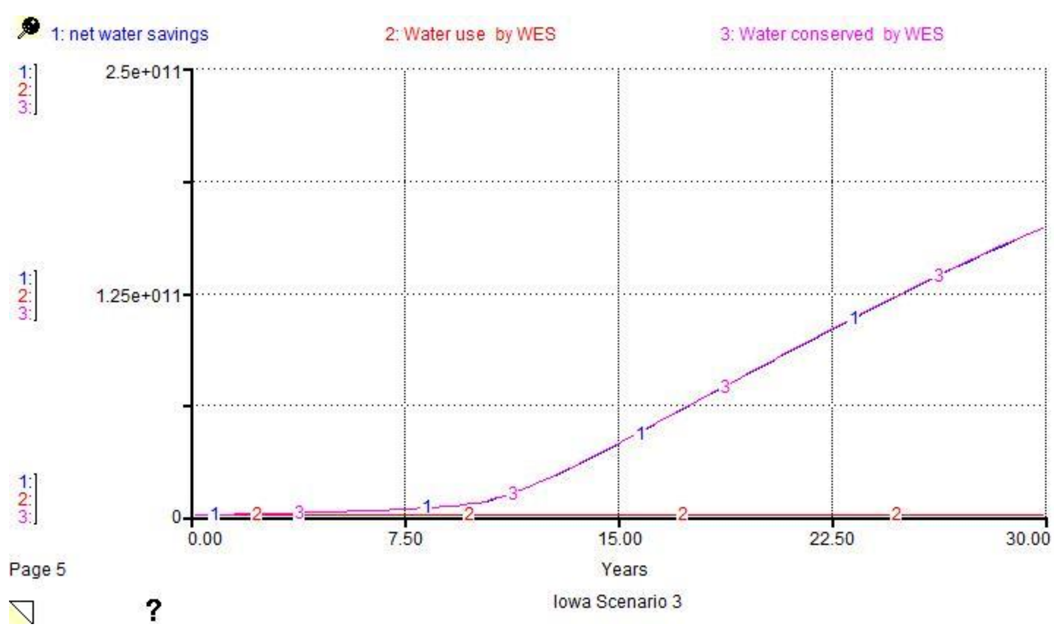

Figure 4-64 Iowa Scenario 3- Water Savings

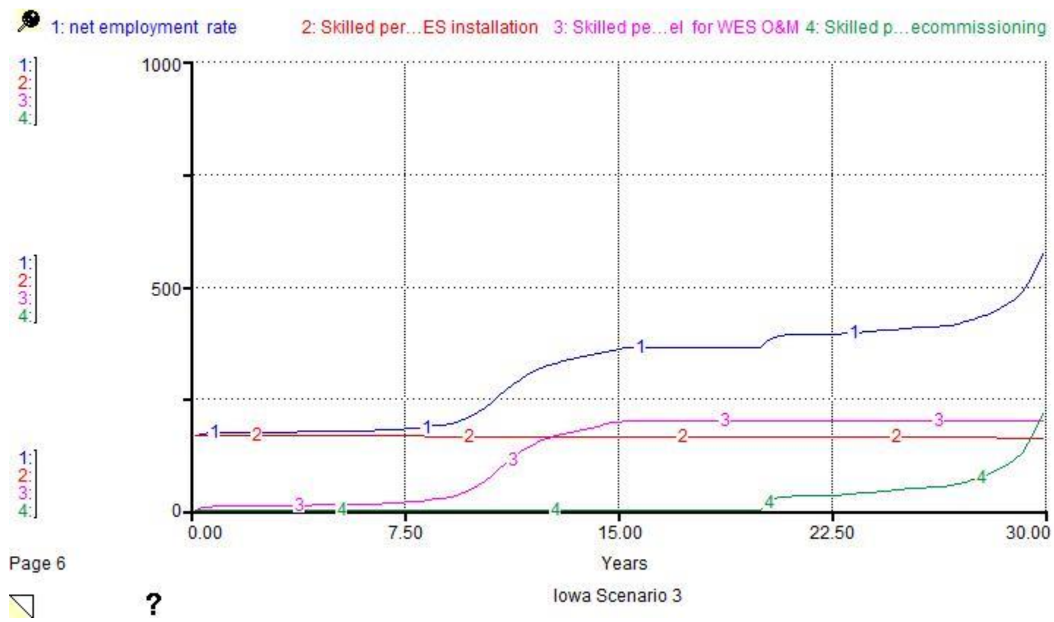

Figure 4-65 Iowa Scenario 3- Employment

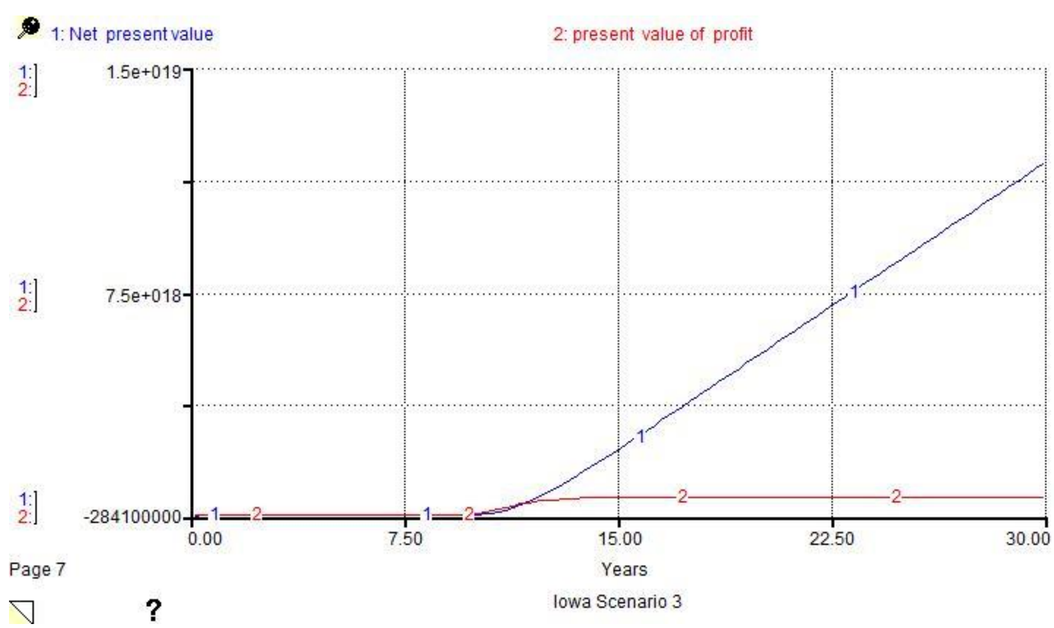

Figure 4-66 Iowa Scenario 3- Net Present value

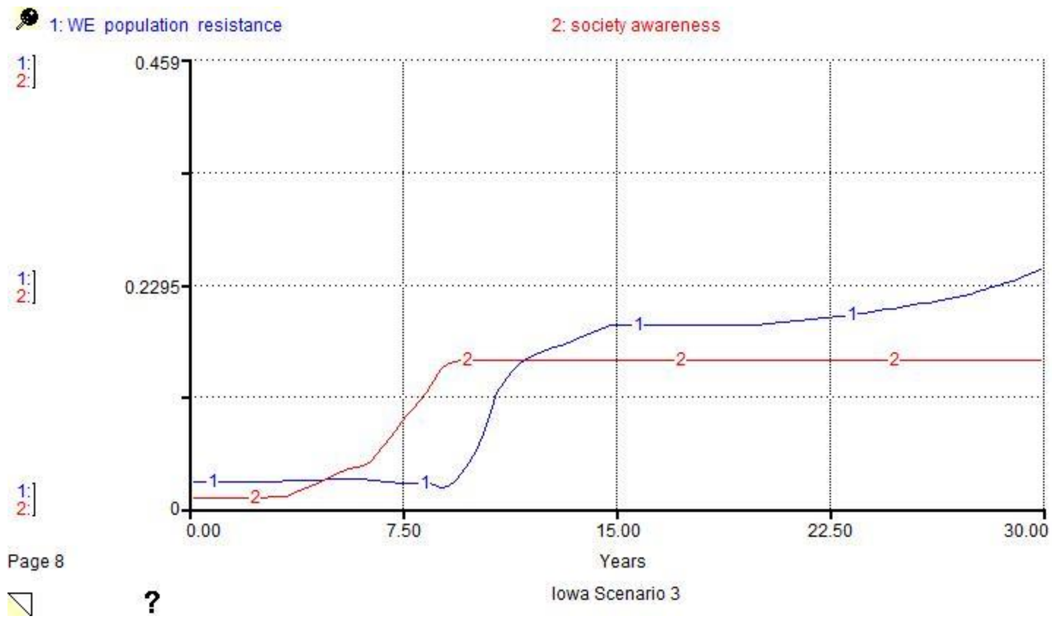

Figure 4-67 Iowa Scenario 3- Wind Energy Population Resistance and Society Awareness

Simulator Results Summary

Results from the simulation runs for Texas, California and Iowa have been presented. Table 4.14 summarizes the results of the three scenarios per state at year 30. In the state of Texas, a reduction of the PTC makes it unattractive to invest in the wind energy system beyond year 17. The impact of the PTC phase down is similar to the elimination of incentives impact that is shown in scenario 2. Results of scenario 1 and scenario 2 suggest the need for other policies at the state level to maintain the support of wind energy industry development to meet the 20% of wind national goal by 2030. Results from scenario 3 demonstrate the impact of reducing the minimum distance between the wind energy system and the nearest community. As expected, the distance reduction increases the wind energy population resistance and the society awareness. This is an important consideration when setting minimum setbacks for wind energy installations. The distance reduction limits the growth of wind turbine installations near the community as well as the growth of a city toward the turbine installation. This has an effect on social perception of the wind energy system.

For the state of California it has been noted that, given the high electricity prices in the region, the decrease and/or elimination of the PTC presented in scenario 1 and scenario 2 have similar behavior, given the assumption that installation and operation and maintenance cost are the same at the national level. Similar to Texas, the distance reduction, presented in scenario 3, increases the wind energy population resistance and the society awareness.

The state of Iowa reached the 20% wind by 2030 goal back in year 2012. It was shown in the baseline scenario and in the scenario 2 that PTC reduction or elimination has little impact on the dynamics of the wind energy system. Results are the same for the three scenarios given that the 20% goal by 2030 was reached earlier in the simulation. Additionally, when the number of turbines is reduced due to decommissioning, the small amount of economic incentives (PTC) makes it unattractive to invest in the wind energy system by year 23. The phase down of the PTC and the elimination of the PTC in scenario 2 suggest the need for other policies at the state level to ensure the state capability to maintain the 20% of wind goal beyond year 30. Results from scenario 3, demonstrate the impact of reducing the minimum distance between the wind energy system and the nearest community. As expected, the distance reduction increases the wind energy population resistance and the society awareness. Scenario 3 outputs are similar to the baseline due to same reasoning explained for scenario 2.

Table 4-14 Simulation Results by State at Year 30

State		Scenario 1 (Baseline)	Scenario 2 (Elimination of incentives)	Scenario 3 (Distance set 1000m)
Texas	Ecological footprint (Global Hectares)	2,208,047.02	2,208,047.02	2,149,986
	Energy replacement ecological footprint difference (Global Hectares)	221,358.66	221,358.66	216,691.2
	Net water savings (Gallons)	4.624E+11	4.624E+11	4.53E+11
	Net carbon footprint (metric tons CO_2)	605,461,712	605,461,712	5.93E+08
	Net present value ($)	7.31E+19	7.31E+19	7.22E+19
	Net employment rate (person)	1,475	1475	1454.487
	WE population resistance (dimensionless)	0.383	0.383	0.497
	Society awareness impact (dimensionless)	0.150	0.150	0.241
California	Ecological footprint (Global Hectares)	1,649,439	1,649,439	1,593,856
	Energy replacement ecological footprint difference (Global Hectares)	96,933.6	96,933.6	94,395.78
	Net water savings (Gallons)	2.03E+11	2.03E+11	1.97E+11
	Net carbon footprint (metric tons CO_2)	2.65E+08	2.65E+08	2.58E+08
	Net present value ($)	7.41E+18	7.41E+18	7.23E+18
	Net employment rate (person)	1,678	1,678	1673
	WE population resistance (dimensionless)	0.351	0.351	0.463
	Society awareness impact (dimensionless)	0.150	0.150	0.241
Iowa	Ecological footprint (Global Hectares)	717,592.13	717,592.13	717,592.13
	Energy replacement ecological footprint difference (Global Hectares)	76,842.31	76,842.31	76,842.31
	Net water savings (Gallons)	1.6051E+11	1.6051E+11	1.6051E+11
	Net carbon footprint (metric tons CO_2)	210,178,607	210,178,607	210,178,607
	Net present value ($)	1.18E+19	1.18E+19	1.18E+19
	Net employment rate (person)	571	571	571
	WE population resistance (dimensionless)	0.241	0.241	0.241
	Society awareness impact (dimensionless)	0.150	0.150	0.150

Validation of Simulator Results

This section discusses the second stage of the simulator validation effort: the validation of the populated simulator. The validation effort focuses on building confidence in the wind energy system sustainability simulator as a reasonable representation of the real system and in its usefulness in providing results. A validation package, similar to previous validations performed for the causal model and the simulator architecture, was developed and provided to validators. The validation checks if the simulation model runs as planned. The populated simulator validation package is presented in Appendix J. The validation focused on addressing four aspects including suitability, consistency, utility, and effectiveness (Richardson and Pugh, 1981).

Validators were required for a number of the validation activities including boundary structural adequacy, structural sensitivity, face validity, parameter validity, replication of reference modes, and appropriateness of structure tests. The validation package and simulator were provided to validators. Validators responded to the questions and their feedback and comments are provided in Appendix K. Validators found the simulator was a reasonable representation of the wind energy system sustainability.

Chapter 5

Summary and Future Work

This chapter presents a summary of the key contributions and findings of this research. The chapter concludes with possibilities for future work.

Summary

This study focuses on understanding the factors and factor relationships related to the sustainability of a wind energy system. The main objective of this research is to help energy decision makers to better understand the effects and relationships among various factors related to the sustainability of wind energy systems. Therefore, it will give a better insight on how to achieve more sustainable wind energy systems.

Major contributions of this study are the identification of factors and factor relationships related to wind energy sustainability, the development of a wind energy system sustainability causal model, and a system dynamics simulator. System dynamics was used to model key factors and factor relationships related to wind energy system sustainability. The causal model and simulator help to provide a better understanding of the wind energy system sustainability. The simulator provides energy decision makers with a deeper understanding of the impacts of their decisions related to wind energy system sustainability.

Wind Energy System Sustainability Causal Model

A causal model was developed to provide a graphical illustration of the factors and factor relationships related to wind energy system sustainability. A causal model helps decision makers to understand the dynamic hypothesis related to factors and factor relationships that contribute to wind energy system sustainability.

The causal model was validated with the help of subject matter experts and represents key factors and factor relationships associated with wind energy system sustainability. The validated causal model includes several feedback loops. The validated set of causal model factors and factor relationships were inputs to the wind energy system sustainability simulator.

Wind Energy System Sustainability Simulator

A system dynamics model was developed to address wind energy system sustainability. Energy decision makers can use the simulator to make more informed decisions. The simulator helps decision makers to understand the impact of their decisions, and gives them further insights related to the behavior of different model elements and their relationship with certain inputs.

As was discussed in chapter 4, information from three states, Texas, California and Iowa, was used to populate and run the simulator. For each of these states, three scenarios were evaluated: 1) a baseline case, 2) elimination of economic incentive after year 2019, and 3) a setback distance of 1000m between wind energy system and the nearest community. Simulator architecture, output behavior, and calculated results of simulator runs were validated by subject matter experts.

Future Work

This study can be considered a starting point for future research that includes other interesting views and research directions. Some of the future directions are listed in this section.

Firstly, the simulator scope has been limited to wind energy system installation, O&M, and decommissioning phases. To further understand wind energy system sustainability, the other phases from concept to disposal can be included in the model. Furthermore, a statistical analysis can be performed to identify the significant factors and reduce the set of modeled factors.

Currently, the simulator assumes a specific type of turbine during the simulation run time. As a future direction, turbine characteristics can be modified during runs to reflect the effect of technology change in the wind energy system sustainability model outputs.

Additional incentives, at the state level, can also be included in the model to get better insights associated with the overall incentive structure and its overall impact to wind energy systems sustainability. A better understanding of financial decisions associated with investment in a type of energy and the sustainability implications associated with it were beyond the scope of the present study. It can be interesting to further model the associated dynamics.

A subset of the causal model factors were used for the development of the simulator. The other factors not modeled in the simulator can be analyzed to find the appropriate way to model and include them in the simulator. Factors such as birds/bats population can also be further modeled to understand associated dynamics related wind energy system sustainability. The inclusion of energy storage for wind energy systems opens another research venue. The effect of minimizing wind generation variability, in addition to other social, environmental, and economic impacts associated with energy storage inclusion warrants further research.

Wind energy system population resistance is an important social factor. There is a significant opportunity to delve further into the social aspects of wind energy system sustainability. Ramifications of economic, social, and environmental factors related to wind energy population resistance, the psychological effects associated with the population exposure to wind energy systems, as well as other energy sources could be explored.

Moreover, a further understanding of the effects of the distance between wind energy systems and communities can be an important research contribution to the policy framework. The limitations and implications that this factor can impose to social development require additional understanding.

Finally, the model can also be further extended to other sources of energy and associated sustainability considerations. The developed model can be part of an effort to develop an overall energy system of systems sustainability model that includes other types of energy sustainability models already developed, and others to be developed.

Appendix A

Causal Model Factors, Definitions and Units

Table A-1 Causal Model Factors, Definitions, and Units

Factor	Definition	Unit
# of abandoned wind turbines	The number of wind turbines abandoned after end of useful life. End of useful life implies that turbine is not used to generate wind energy for the owner any longer. Abandoned turbines remain in their original installed location.	Number of turbines
# of accidents	# of human incidents fatal or not that occur in the wind energy system during installation, O&M and decommissioning.	Number of accidents
# of decommissioned wind turbines	The total number of wind turbines that are decommissioned from the wind energy system.	Number of turbines
# of operating wind turbines	Refers to the actual number of turbines operating in the wind energy system.	Number of turbines
# of wind turbines installed	The total number of wind turbines installed in the wind energy system.	Number of turbines
# of wind turbines to be installed	The total number of wind turbines to be installed based on investor's commitment.	Number of turbines
Acquired incentives for implementing wind technology advances	Refers to the actual amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Amount of available funds for wind energy development	Refers to the actual amount on financial markets available for wind energy investments	Dollars
Amount of electricity available for use	Refers to the total amount of electricity, independent of the type of source, available for use in the electric grid.	Gigawatts

Table A.1—*Continued*

Amount of money recouped due to decommissioning	Represents the amount of money recuperated due to decommissioning of wind turbines.	Dollars / year
Area of excavation and trenching	Amount of land excavated and trenched required for turbine tower installation, access roads, electric substation and O&M building construction.	Squared meter (m^2)
Available amount of economic incentives for implementing wind technology advances	Provides motivation in financial form to organizations that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Available land	Refers to the total land available that could be used for wind energy development or any other purpose.	Square meter (m^2)
Balance of station cost	Refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Balance of plant/station is the cost of all infrastructural and facilities of a wind project with an exception of the turbine and all its elements (Tegen et al., 2012).	Dollars
Bird/bat population	Average bird/bat population in the area where wind energy projects are located.	Number of birds / area
Bird/bat strikes	# of birds/bats that hit the wind turbines and die.	Number of birds / area

Table A.1—*Continued*

Capacity factor	The ratio of wind energy (assuming all turbines are same size) actual output over a period of time, to its potential output if it were possible for it to operate at full theoretical capacity indefinitely.	%
Carbon footprint	The demand on biocapacity required to sequester the carbon dioxide (CO_2) emissions from fossil fuel combustion (Global Footprint Network, 2012).	Metric Tons of carbon dioxide
Cost of turbine	Refers to the capital cost of a wind turbine.	Dollars
Distance between wind projects and community	Distance between wind project and closest surrounding community.	Kilometers
Ecological footprint	Represents the amount of land and water area required for nature to regenerate the resources used by the wind energy project development (Global Footprint Network, 2012).	Global hectares
Electrical energy reserves	Refers to the electric generation that has to be on reserve to cover any imbalance and intermittent operation of wind energy.	Megawatts
Electricity price	Represents the average sale price of electricity generated from a wind energy system to utilities.	Megawatts-hour / Dollars
Electromagnetic interference	Any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades the effective performance of electronics and electrical equipment. Refers to the interference of wind turbines with electromagnetic communication systems.	dBμV

Table A.1—*Continued*

Employment rate	Represents the rate of employment during the wind energy installation, O&M and decommissioning phases. % of direct jobs related to the development of the wind energy system.	%
Energy used for wind energy system decommissioning	Amount of electricity and other energy sources used during decommissioning activities.	Megawatts / hour
Energy used for wind energy system installation	Amount of electricity and other energy sources used during wind energy system installation.	Joules
Energy used for wind energy system O&M	Amount of electricity and other energy sources used during wind energy O&M.	Megawatts / hour
Estimated # of wind turbines to be installed	Refers to the estimated number of wind turbines that would be required to cover the total wind power generation difference.	Number of turbines
Estimated balance of station	Balance of station is the estimated cost of all infrastructural and facilities of a wind project with an exception of the turbine and all its elements.	Dollars
Estimated cost of turbine	Refers to the estimated unit cost of turbine.	Dollars
Estimated incentives to be acquired for implementing wind technology advances	Refers to the potential amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Estimated probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances to cover the total wind energy difference.	%

Table A.1—*Continued*

Estimated soft cost	Refers to the estimated costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars
Estimated total cost of wind power generation difference	Refers to the estimated cost of wind turbines installation, and O&M to cover total wind power generation difference.	Dollars
Estimated wind energy installed capital cost	Refers to the estimated amount of investment required to cover the total wind power generation difference.	Dollars
Estimated wind energy O&M cost	Represents the estimated operational and maintenance costs of the additional wind turbines required to cover the total wind power generation difference.	Dollars
Impact from ice shedding	Impact from ice that is shed from wind turbines.	Dollars
Interest rate	Refers to the cost of money required to pay to a lender to finance a wind energy project.	%
Investor commitment	Refers to investor interest in financing additional wind power installation.	Dollars
Level of energy security	Refers to equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed, and socially acceptable energy services to end users (Sovacool, 2012).	Index
Level of reinforcement of government regulations, standards, and policies for wind energy	Indicates the severity of government regulations, standards, and policies for wind energy efforts.	Level 1- Severe 2- Strong 3- Minimal 4- Negligible

Table A.1—*Continued*

Level of visual impact	Represents how well wind turbines can be seen from horizon.	Levels: 1-Visual dominate 2- Visual intrusive 3- Noticeable 4- Negligible
Net present value (NPV)	Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flow is the algebraic sum of money estimated to flow in and out of a wind energy system over some period of time as a result of a particular project (adapted from Stevens, 1994).	Dollars
Perceived amount of noise from wind turbines	Refers to the amount of noise perceived in the nearest communities during wind turbine operation.	Decibels
Percentage of funds to be committed for wind energy development	Refers to the fraction of available funds for wind energy development to be committed by investors.	%
Probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances.	%
Profit	The amount remaining after wind energy total costs are deducted from total revenue.	Dollars / year
Rate of wind turbine abandonment	Rate at which turbines are abandoned in the wind energy system once turbines end of useful life have been reached.	Number of turbines / year
Rate of wind turbine decommissioning	Represents the rate at which turbines are decommissioned once they have reached the end of useful life.	Number of turbines / year
Site wind speed	The actual wind speeds that flow in a site that could be useful for wind energy deployment.	Meters/ seconds

Table A.1—*Continued*

Skilled personnel needed for decommissioning	Represents the human resources needed with the skill level required for wind energy decommissioning.	Number of people
Skilled personnel needed for installation	Represents the human resources needed with the skill level required for wind energy installation.	Number of people
Skilled personnel needed for O&M	Represents the human resources needed with the skill level required for wind energy O&M.	Number of people
Society awareness	Refers to the knowledge accumulated in society due to experience with wind energy.	Levels: 1-Familiar to wind energy 2-Some familiarity to wind energy 3-No familiar to wind energy
Soft cost	Refers to costs that are not considered direct costs related to wind energy project construction. Includes construction	Dollars
Target electric power generation	Refers to the total amount of electric power expected to be generated in a defined time period.	Megawatt hour
Target wind power generation	Refers to the amount of electric power expected to be generated from wind energy in a defined time period.	Megawatt hour
Utility electricity price	Refers to the electricity sale price to end customers.	Dollars/ Megawatt hour
Utility resistance	Refers to opposition of utility companies to wind energy.	%
Volume of waste from wind turbine decommissioning	Represents the amount of solid waste, hazardous and industrial waste produced during the wind turbine decommissioning.	Cubic meter
Volume of waste from wind energy installation and O&M	Represents the amount of solid waste, hazardous and industrial waste produced during the wind energy installation and O&M.	Metric Tons

Table A.1—*Continued*

Volume of wind energy water consumption	Represents the total amount of water needed for installation, O&M and decommissioning of wind energy system.	Gallons/ turbine
Wind turbine decommissioning cost	Refers to the cost associated to decommissioning wind turbines and associated element once they have reach the end of their useful life.	Dollars/ year
Wind energy installed capacity	Theoretical maximum capacity of a wind energy system based on the number of wind turbines installed in the system.	Megawatts
Wind energy installed capital cost	The amount of investment required to develop a wind energy system. This includes wind turbines, balance of station and soft costs (Tegen et al., 2012).	Dollars/ year
Wind energy integration cost	Refers to the costs added to the electric grid operation for including intermittent sources of energy (wind energy) in its operation.	Dollars / year
Wind energy O&M cost	Represents the operation and maintenance costs of a wind energy system. It includes land lease cost, labor wages and material, and levelized replacement costs.	Dollars / year
Wind energy population resistance	Refers to the general population opposition to wind energy.	%
Wind energy total cost	Sum of initial wind energy installed capital cost, O&M cost and decommissioning costs.	Dollars/ year
Wind power generated	Amount of electric power generated by a wind energy system.	Megawatt hour / year

Table A.1—*Continued*

Wind power generation difference	Refers to the difference between the actual wind power generated and the target wind power generation.	Megawatt hour / year
Wind power opportunity profit	Refers to the perceived potential profit that could be generated from wind power investment to cover wind power generation difference.	Dollars
Wind turbine capacity	Refers to the nameplate capacity of a wind turbine.	Megawatt
Wind turbine hub height	Refers to the wind turbine hub height.	Meters
Wind turbine rotor diameter	Refers to the wind turbine rotor diameter.	Meters

Appendix B

Causal Model Validation Package

The wind energy system sustainability causal model validation package developed and presented to validators is provided below. This validation package includes an earlier version of the causal model. The references mentioned in the package are included in the Reference section.

Purpose

The purpose of the validation process is to ensure that the factors and factor relationships represented in the causal model are valid. This validation process should require approximately two hours of your time.

Causal Model Introduction

Renewable energy sources have become crucial for obtaining more sustainable energy systems. Their importance has been highlighted by society's increasing demand for energy, finite supply of traditional sources of energy and significant amount of greenhouse gas emissions when exploiting traditional energy sources. Wind energy is one of the fastest growing renewable energy sources worldwide. Wind energy project sustainability is an important challenge in energy systems. A goal of wind energy project sustainability is to develop and operate wind energy projects that don't cause negative social, environmental and economic impacts in the communities where they are located. Multiple factors contribute to wind energy project sustainability.

Causal models graphically illustrate the factors and factor relationships in a complex system. Literature review and analysis of wind energy project and other renewable energy sources factors, including previously developed wind energy causal models, and other renewable energy sources causal models, resulted in the identification of a set of factors and relationships represented in a causal model. Figure 1 shows the wind energy project sustainability causal model to be validated. The scope of the model encompasses the wind energy project installation phase through the operational phase.

Causal diagrams capture the major feedback mechanisms within a model. These diagrams can demonstrate various hypotheses about factors. Elements (factors) and arrows (relationships) are included in a causal diagram. A sign (either + or –) is assigned on each link indicating an increasing or decreasing relationship between factors. The positive or negative signs on the arrows indicate the nature of the relationship in the causal model. The arrow heads also have a direction that indicates the sequence of the factors and the factor relationships. Reviewers need to look at the sequence of the factors and relationships. Some factors have indirect relationships from other factors versus direct relationships. An understanding of the factors and the relationships between factors provides a better understanding of what drives wind energy project sustainability.

Causal Model Factors and Relationships

The factors in the causal model are listed in Table B-1 including a definition of each factor and the unit of measurement.

The causal model indicates that as the number of wind turbines increases, the wind project installed capacity increases. As the wind turbine size increases, the wind turbine capacity increases. As the wind turbine capacity increases, the wind project installed capacity increases. As the number of wind turbines increases, the quantity of skilled personnel needed during wind project installation increases. As the number of wind turbines increases, the quantity of skilled personnel needed during wind project operation also increases. As the quantity of skilled personnel needed during wind project installation increases, the employment rate increases. As the quantity of skilled personnel needed during wind project operation increases, the employment rate also increases. As the employment rate increases, the wind project population resistance decreases. An increase in employment rate decreases the quantity of skilled personnel available for installation and operation of a wind power project.

An increase in the number of wind turbines cause additional multiple effects. As the number of wind turbines increases, wind project installed capital cost increases. As the cost of turbine increases, wind project installed capital cost increases. As the number of wind turbines increases, wind project operation and maintenance cost increases. As the wind turbines size increases, wind project operation and maintenance cost increases. As the number of wind turbines increases, the wind turbine density increases. Volume of wind project water consumption, energy used for wind project installation and operation, volume of waste from wind project installation, and volume of waste from wind project operation and maintenance are also expected to increase as a result of an increase in the number of wind turbines. As the number of wind turbines increases, the volume of excavation and trenching in a wind project increases. As the number of wind turbines increases, the amount of wind project area available for other use decreases.

When the number of wind turbines increases, the number of accidents during installation and operation of wind projects are expected to increase. An increase in the experience of wind project employees decreases the number of accidents. As the wind project area increases, the wind turbine density decreases. As the wind project area increases, the available land for other uses decreases. As the number of wind projects increases, the available land for other uses decreases. As the available land increases, the distance between wind project and community increases. As the distance between wind project and community increases, the society awareness decreases.

As the balance of station cost increases, the wind project installed capital cost increases. As the soft cost increases, the wind project installed capital cost increases.. When the wind project installed capital cost increases, the wind project total cost increases. An increase in wind project operation and maintenance cost also increases wind project total cost. An increase in the wind project total cost increases the electricity price.

As the electricity demand increases, the electricity price increases. An increase in the cost of reserves operation also increases the electricity price. As the electricity price increases, the quantity of wind projects increases. As the electricity price increases, the wind project population resistance decreases. As the number of wind projects increases, the electrical energy reserves increases. As the number of wind projects increases, the society awareness to wind projects also increases. As the society awareness of wind projects increases, wind project population resistance decreases. As the society awareness of wind projects increases, wind project population resistance also decreases. An increase in the wind project population resistance decreases the amount of economic incentives for implementing wind technology advances.

As the volume of excavation and trenching increases, the ecological footprint increases. As the wind project area increases, the ecological footprint increases. As the volume of wind project water consumption increases, the ecological footprint also increases. As the volume of waste from wind project installation increases, the ecological footprint increases. As the volume of waste from wind project operation and maintenance increases, the ecological footprint also increases. When the amount of wind project area available for other use increases, the ecological footprint decreases. As the carbon footprint increases, the ecological footprint increases. As the ecological footprint increases, the volume of available water resources decreases. As the ecological footprint increases, the volume of available land also decreases. As the ecological footprint increases, the wind project population resistance increases.

Adams and Keith (2013) found that as wind turbine density increases, the site wind speed decreases. As a result of site wind speed increases, the average temperature in the area of the wind project increases. As the energy used for wind project development and operation increases, greenhouse gas emissions increase. Increases of wind power generated decreases greenhouse gas emissions. An increase in the amount of electric energy reserves used increases the greenhouse gas emissions. As greenhouse gas emissions increases, the carbon footprint increases. A greenhouse gas emissions increase, the average temperature in the area of the wind project increases.

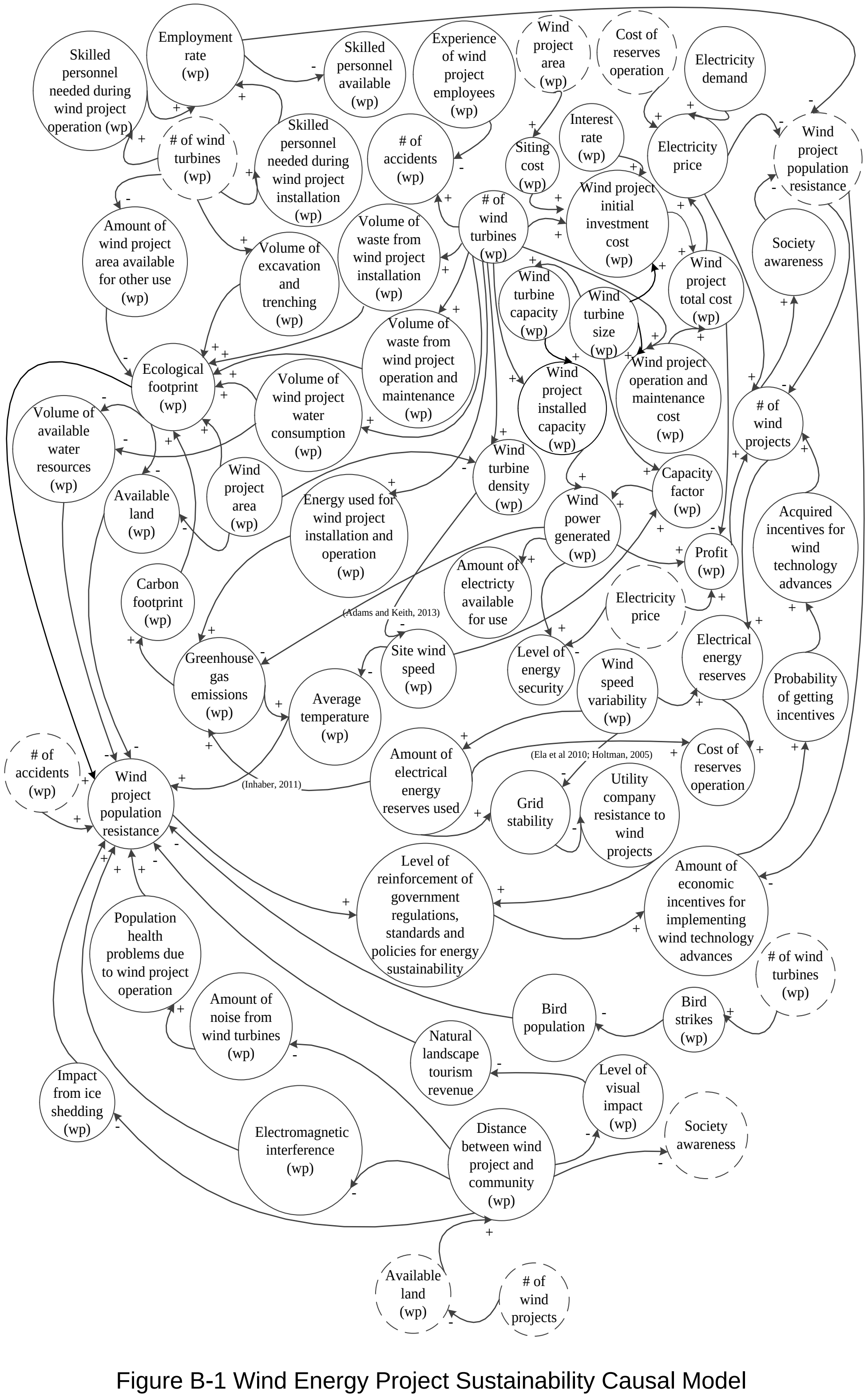

Figure B-1 Wind Energy Project Sustainability Causal Model

When the wind project installed capacity increases, the wind power generated increases. As the wind turbine size increases, the capacity factor increases. As the site wind speed increases, the capacity factor also increases. As the capacity factor increases, the wind power generated also increases. As the wind power generated increases, the profit of the wind project increases. As the electricity price increases, the profit of the wind project also increases. As the wind project total cost increases, the profit of the wind project decreases. As the profit of the wind project increases, the number of wind projects also increases. As the profit of the wind project increases the NPV increases. As the interest rate increases, the NPV also increases. As the wind power generated increases, the level of energy security increases. As the electricity price increases, the level of energy security decreases. As the wind power generated increases, the amount of electricity available for use also increases.

When the wind speed variability increases, the electrical energy reserves increases, and the amount of electrical reserves used also increases. An increase of wind speed variability decreases grid stability. As the amount of electrical reserves used increases, grid stability increases. An increase in grid stability decreases the utility company resistance to wind projects. As the electrical energy reserves increases, and the amount of electrical reserves used also increases, the cost of reserves operation increases. As the utility company resistance to wind projects increases, the level of reinforcement of government regulations, standards and policies for energy sustainability increases.

As the number of wind turbines increases, bird strikes increases. An increase on bird strikes results in a decrease of bird population. As the level of visual impact increases, the natural landscape tourism revenue decreases. As the level of visual impact increases, the wind project population resistance also increases. When the distance between wind project and community increases, the impact from ice shedding, the electromagnetic interference, the amount of noise from wind turbines, and the level of visual impact decrease. As the amount of noise from wind turbines increases, population health problems due to wind project operation increases. When population health problems due to wind project operation increases, the wind project population resistance increases.

As the number of accidents increases, the wind project population resistance increases. As the impact from ice shedding, the electromagnetic interference, and the average temperature on the site increase, the wind project population resistance also increases. As the volume of available water resources, the available land, the natural landscape tourism revenue, and bird population increase, the wind project population resistance decreases.

As the wind project population resistance increases, the level of reinforcement of government regulations, standards and policies for energy sustainability increases. As the level of reinforcement of government regulations, standards and policies for energy sustainability increases, the amount of economic incentives for implementing wind technology advances increases. As the amount of economic incentives for implementing wind technology advances increases, the probability of getting incentives increases. As the probability of getting incentives increases, the acquired incentives for wind technology advances increases. As the acquired incentives for wind technology advances increases, the number of wind projects increases.

Table B-1 Wind Energy Project Sustainability Factors and Metrics

Factor	Definition	Unit
# of accidents	# of human incidents fatal or not that occur in wind energy projects during installation, operation and maintenance	Number of accidents
# of wind projects	The number of wind energy projects in an specific region	Number of projects
#of wind turbines	The number of wind turbines in a project	Number of wind turbines
Acquired incentives for wind technology advances	Refers to the actual amount of incentives in financial form obtained by businesses and investors that implement new wind energy projects and/or technologies to make them more sustainable and efficient	Dollars

Table B.1—*Continued*

Amount of economic incentive for implementing wind technology advances	Provides motivation in financial form to businesses and investors that implement new wind energy projects and/or technologies to make them more sustainable and efficient	Dollars
Amount of electricity available for use	Refers to the total amount of electricity available for use in the electric grid	Gigawatts (GW)
Amount of electrical energy reserves used	Amount of electrical energy reserves used due to wind power variation	Megawatts per hour (MW/h)
Amount of noise from wind turbines	Represents the level of noise that wind turbines produce in operation	Decibels (dB)
Amount of wind project area available for other use	Area of a wind project that could be shared with some other human/economic activity	Square meter (m^2)
Available land	Refers to total land available that could be used for wind energy project development or any other purpose	Square meter (m^2)
Average temperature	The local temperature at a wind energy project site and nearby communities when wind energy project is operating	Fahrenheit (ºF)
Bird population	# of bird population in the area where wind energy projects are located	Number of birds /area
Bird strikes	# of birds that hit the wind turbines and die	Number of birds / area
Capacity factor	The ratio of wind energy project (assuming all turbines are same size) actual output over a period of time, to its potential output if it were possible for it to operate at full theoretical capacity indefinitely	%
Carbon footprint	The demand on biocapacity required to sequester the carbon dioxide (CO_2) emissions from fossil fuel combustion (Global Footprint Network, 2012)	hectares

Table B.1—*Continued*

Cost of reserves operation	Refers to the cost associated to have electric power reserves as a backup for wind generation when insufficient wind power is generated	Dollars
Distance between wind project and community	Distance between the wind power project and closest surrounding community	Kilometers (Km)
Ecological footprint	Represents the amount of land and water area required for nature to regenerate the resources used by the wind energy project development (Global Footprint Network, 2012)	Global Hectares
Electrical energy reserves	Refers to the electric generation that has to be on reserve to cover any imbalance and intermittent operation of a wind energy project	Megawatts (MW)
Electricity demand	Represents the amount of electricity demanded by population	Megawatts per hour (MW/h)
Electricity price	Represents the value of electricity	Kilowatts / Dollars
Electromagnetic interference	Any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades the effective performance of electronics and electrical equipment. Refers to the interference of wind turbines with electromagnetic communication systems	dBμV
Employment rate	Represents the rate of employment on the areas near wind energy projects during the installation and the operational phases of the project. % of direct jobs related to the development of wind energy projects	%

Table B.1—*Continued*

Energy used for wind project installation and operation	Amount of electricity and other energy sources used in a wind energy project. This include wind energy project installation and operation	Megawatts per hour (MW/h)
Experience of wind project employees	Represents the increasing capability of humans to perform all required work in wind energy projects	Hours worked/person
Greenhouse gas emissions	The amount of carbon dioxide that could be emitted by electricity generation and other sources of energy	Metric Tons of CO_2
Grid stability	A steady state balance between generation and consumption of electricity. Due to variability on wind speeds over time, wind power plants could create grid instability. Instability occurs when there is a change in frequency of +/- 5% from 60Hz	Hertz (Hz)
Impact from ice shedding	Impact from ice that is shed from wind turbines	Dollars
Interest rate	Refers to the cost of money required to pay to a lender to develop a wind energy project	%
Level of energy security	Equitable providing available, affordable, reliable, efficient, environmentally benign, proactively governed, and socially acceptable energy services to end users (Sovacool, 2012)	Index
Level of reinforcement of government regulations, standards, and policies for energy sustainability	Indicates the severity of government regulations, standards, and policies for energy sustainability efforts	Level
Level of visual impact	Represents how well wind turbines can be seen from horizon	Levels: 1-Visual dominate 2- Visual intrusive 3- Noticeable 4- Negligible
Natural landscape tourism revenue	Income due to tourism activity in the zones near to wind energy project area	Dollars

Table B.1—*Continued*

Population health problems due to wind project operation	The number of population health problems due to wind energy project operation	# of cases
Probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances	%
Profit	The amount remaining after wind energy project total costs are deducted from total revenue	Dollars/year
Site wind speed	The actual wind speeds that flow in a site that could be useful for wind energy deployment	Meters/seconds (m/s)
Siting cost	Refers to the cost of wind energy project site	Dollars
Skilled personnel available	Represents the human resources available that have the skill level required to install, operate and maintain the wind energy project	Number of people
Skilled personnel needed during wind project installation	Represents the human resources needed with the skill level required to install the wind energy project	Number of people
Skilled personnel needed during wind project operation	Represents the human resources needed with the skill level required to operate and maintain the wind energy project	Number of people
Society awareness	Refers to the knowledge accumulated in society due to experience with similar projects	Levels: 1-Familiar to wind energy projects 2-Some familiarity 3-No familiar to wind energy projects
Utility company resistance to wind projects	Refers to opposition of utility companies to wind energy projects	%
Volume of available water resources	Represents the total amount of available water resources accessible to humans	Cubic meter (m^3)
Volume of excavation and trenching	Amount of land excavating and trenching required for the turbine tower installation, access roads, electric substation and operations and maintenance building construction	Cubic meter (m^3)

Table B.1—*Continued*

Volume of waste from wind project installation	Represent the amount of solid waste, hazardous and industrial waste produced during the wind energy project installation	Cubic meter (m^3)
Volume waste from wind project operation and maintenance	Represent the amount of solid waste, hazardous and industrial waste produced during the wind energy project operation and maintenance	Cubic meter (m^3)
Volume of wind project water consumption	Represents the total amount of water needed to construct and install a wind energy project	Cubic meter (m^3)
Wind power generated	Amount of electric power generated by a wind energy project	Megawatts (MW)
Wind project area	Area of land that is used to construct the wind energy project	Square meter (m^2)
Wind project installed capacity	Theoretical maximum capacity of a wind energy project	Megawatts (MW)
Wind project initial investment cost	The initial investment required to develop a wind energy project. This includes wind turbines, foundations, and grid connection	Dollars
Wind project operation and maintenance cost	Represents the operation and maintenance costs of a wind energy project	Dollars/year
Wind project population resistance	Refers to population opposition to wind energy projects	%
Wind project total cost	Sum of initial wind energy project investment cost and operation and maintenance cost	Dollars
Wind speed variability	Refers to variation of wind speed that result in wind power output variation	%
Wind turbine capacity	Refers to the nameplate capacity of a wind turbine	Megawatts (MW)
Wind turbine density	Refers to the number of wind turbines encompassed in a wind energy project area	# turbines / m^2
Wind turbine size	Refers to the wind turbine rotor diameter	Meters (m)

Contact Information

The following contact information will only be used for authenticating an individual response to the validation exercise. All individual contact information and validation results will be kept confidential.

Name	
Role (Position)	
Location	
Experience (Years)	
Wind Project (s)	

Validation Process

Please review the set of factors, factor units, and factor relationships in the causal model. For each factor in Table 3, please answer these questions. Space is allocated in Table B.2 for your inputs related to the factors. Please consider the following questions:

- Is the factor valid and reasonable?
- Is the definition of the factor reasonable?
- Is the unit for this factor reasonable?

Table B-2 Factors & Units

(Please provide your comments here)

Factor	Comments
# of accidents	
# of wind projects	
# of wind turbines	
Acquired incentives for wind technology advances	
Amount of economic incentive for implementing wind technology advances	
Amount of electrical energy reserves used	

Table B.2—*Continued*

Amount of electricity available for use	
Amount of noise from wind turbines	
Amount of wind project area available for other use	
Available land	
Average temperature	
Bird population	
Bird strikes	
Cost of reserves operation	
Capacity factor	
Carbon footprint	
Distance between wind project and community	
Ecological footprint	
Electrical energy reserves	
Electricity demand	
Electricity price	
Electromagnetic interference	
Employment rate	
Energy used for wind project installation and operation	
Experience of wind project employees	
Greenhouse gas emissions	
Grid stability	

Table B.2—*Continued*

Impact from ice shedding	
Interest rate	
Level of energy security	
Level of reinforcement of government regulations, standards, and policies for energy sustainability	
Level of visual impact	
Natural landscape tourism revenue	
Population health problems due to wind project operation	
Probability of getting incentives	
Profit	
Site wind speed	
Siting cost	
Skilled personnel available	
Skilled personnel needed during wind project installation	
Skilled personnel needed during wind project operation	
Society awareness	
Utility company resistance to wind projects	
Volume of available water resources	
Volume of excavation and trenching	

Table B.2—*Continued*

Volume of waste from wind project installation	
Volume of waste from wind project operation and maintenance	
Volume of wind project water consumption	
Wind power generated	
Wind project area	
Wind project installed capacity	
Wind project initial investment cost	
Wind project operation and maintenance cost	
Wind project population resistance	
Wind project total cost	
Wind speed variability	
Wind turbine capacity	
Wind turbine density	
Wind turbine size	

Please answer the following questions related to the causal model. Table B.3 provides the relationships between the factors and the nature of the relationship. Please use this table to answer the following questions:

- Are the relationships between the factors in the model valid and realistic?
- Does the nature of the links (positive or negative signs) on the causal model reflect the interactions between factors?

Table B-3 Factor Relationships

Factor →	Factor	+/-	Comment
# of accidents	Wind project population resistance	+	
# of wind projects	Society awareness	+	
	Electrical energy reserves	+	
	Available land	-	
# of wind turbines	# of accidents	+	
	Amount of wind project area available for other use	-	
	Bird strikes	+	
	Energy used for wind project installation and operation	+	
	Skilled personnel needed during wind project installation	+	
	Skilled personnel needed during wind project operation	+	
	Volume of wind project water consumption	+	
	Volume of waste from wind project installation	+	
	Volume of waste from wind project operation and maintenance	+	

Table B.3—*Continued*

# of wind turbines	Volume of excavation and trenching	+	
	Wind project installed capacity	+	
	Wind project initial investment cost	+	
	Wind project operation and maintenance cost	+	
	Wind turbine density	+	
Acquired incentives for wind technology advances	# of wind projects	+	
Amount of economic incentives for implementing wind technology advances	Probability of getting incentive	+	
Amount of electrical energy reserves used	Cost of reserves operation	+	
	Grid stability	+	
	Greenhouse gas emissions	+	
Amount of noise from wind turbines	Population health problems due to wind project operation	+	
Amount of wind project area available for other use	Ecological footprint	-	
Available land	Distance between wind project and community	+	

Table B.3—*Continued*

Available land	Wind project population resistance	-	
Average temperature	Wind project population resistance	+	
Bird population	Wind project population resistance	-	
Bird strikes	Bird population	-	
Capacity factor	Wind power generated	+	
Carbon footprint	Ecological footprint	+	
Cost of reserves operation	Electricity price	+	
Distance between wind project and community	Amount of noise from wind turbines	-	
	Electromagnetic interference	-	
	Impact from ice shedding	-	
	Level of visual impact	-	
	Society awareness	-	
Ecological footprint	Available land	-	
	Volume of available water resources	-	
	Wind project population resistance	+	
Electrical energy reserves	Cost of reserves operation	+	
Electricity demand	Electricity price	+	

Table B.3—*Continued*

Electricity price	# of wind projects	+	
Electricity price	Level of energy security	-	
	Profit	+	
	Wind project population resistance	-	
Electromagnetic interference	Wind project population resistance	+	
Employment rate	Skilled personnel available	-	
	Wind project population resistance	-	
Energy used for wind project installation and operation	Greenhouse gas emissions	+	
Experience of wind project employees	# of accidents	-	
Greenhouse gas emissions	Carbon footprint	+	
	Average temperature	+	
Grid stability	Utility company resistance to wind projects	-	
Impact from ice shedding	Wind project population resistance	+	
Interest rate	Wind project initial investment cost	+	

Table B.3—*Continued*

Level of reinforcement of government regulations, standards, and policies for energy sustainability	Amount of economic incentives for implementing wind technology advances	+	
Level of visual impact	Natural landscape tourism revenue	-	
Natural landscape tourism revenue	Wind project population resistance	-	
Population health problems due to wind project operation	Wind project population resistance	+	
Probability of getting incentives	Acquired incentives for wind technology advances	+	
Profit	# of wind projects	+	
Site wind speed	Wind power generated	+	
Siting cost	Wind project initial investment cost	+	
Skilled personnel needed during wind project installation	Employment rate	+	
Skilled personnel needed during wind project operation	Employment rate	+	
Society awareness	Wind project population resistance	-	

Table B.3—*Continued*

Utility company resistance to wind projects	Level of reinforcement of government regulations, standards and policies for energy sustainability	+	
Volume of available water resources	Wind project population resistance	-	
Volume of excavation and trenching	Ecological footprint	+	
Volume of waste from wind project installation	Ecological footprint	+	
Volume of waste from wind project operation and maintenance	Ecological footprint	+	
Volume of wind project water consumption	Ecological footprint	+	
	Volume of available water resource	-	
Wind power generated	Greenhouse gas emissions	-	
	Amount of electricity available for use	+	
	Level of energy security	+	
	Profit	+	
Wind project area	Available land	-	
	Siting cost	+	
	Wind turbine density	-	
Wind project installed capacity	Wind power generated	+	

Table B.3—*Continued*

Wind project initial investment cost	Wind project total cost	+	
Wind project operation and maintenance cost	Wind project total cost	+	
Wind project population resistance	# of wind projects	-	
	Amount of economic incentives for implementing wind technology advances	-	
Wind project population resistance	Level of reinforcement of government regulations, standards and policies for energy sustainability	+	
Wind project total cost	Electricity price	+	
Wind speed variability	Grid stability	-	
Wind turbine capacity	Wind project installed capacity	+	
Wind turbine density	Site wind speed	-	
Wind turbine size	Capacity factor	+	
	Wind project initial investment cost	+	
	Wind project operation and maintenance cost	+	
	Wind turbine capacity	+	

Additional comments and insights are encouraged. Feel free to markup the causal model. Please use the notes section below to provide additional information on your recommendations including any suggestions for changes with:

- Missing factors or incorrect factors
- Missing or unidentified relationships between factors
- Factor definitions and associated units

Notes

Additional recommendations and notes may be provided here.

Appendix C

Causal Model Validation Feedback and Assessment

A validator provided initial validation inputs. Validation of the causal model was done again at a later stage. Additional causal model validation inputs are shown in Appendix G. Inputs received from the causal model validator are presented in this section. There are separate tables for the validator comments. Assessment based on the validator inputs are also provided in this Appendix. Table C.1 provides validator feedback and assessments based on validator comments related to the factor definition. Table C.2 provides validator feedback and assessments related to the factor relationships. Validator did not provide any additional notes related to missing factors or relationships.

Table C-1 Factor Definitions Validation Analysis

Factor	Comment Validator 1	Assessment
Amount of economic incentive for implementing wind technology advances	Not sure how different than “Acquired incentives”, reasonable definition, reasonable units	Comment from validator has been analyzed and the decision is that no modification was made to this factor. “Amount of economic incentive for implementing wind technology advances” factor refers to the financial incentives available to potential businesses and investors to implement new wind energy projects and/or technologies. “Acquired incentives for wind technology advances” factor refers to the actual amount of incentives in financial form obtained by particular businesses and investors to implement new wind energy projects and/or technologies. Factor definition for ”Amount of economic incentive for implementing wind technology advances” and “Acquired incentives for wind technology advances” have been modified as shown above to clarify why these factors are different.
Average temperature	Doesn’t seem like a factor that would have any impact, reasonable definition, reasonable units	Comment from validator has been analyzed and the decision is that no modification was made to the factor. According to Adams and Keith (2013) an increase in temperature in areas near large wind farms has been detected. In the long term, this could produce undesirable environmental effects.
Bird/Bat population	Reasonable factor, definition shouldn’t just be birds in the area but should include migrating bird patterns, reasonable units	Comment from validator has been considered and a modification was made to the definition to include validator recommendation.
Electrical energy reserves	Not sure how this is different from “Amount of electrical energy reserves used”, reasonable definition, reasonable units	Comment from validator has been analyzed and the decision is that no modification was made to this factor. Electrical energy reserves refer to the electric generation that has to be on reserve to cover any imbalance and intermittent operation of a wind energy project. Amount of electricity available for use refers to the actual amount of electrical energy reserves used due to wind power variation.
Employment rate	Reasonable factor, I would differentiate between effects during development, construction and operation because they differ greatly (construction employments is orders of magnitude higher than operation employment), reasonable units	Comment from validator has been analyzed. Differences between the employment rate during installation and operation will be taken into consideration when simulating the factor behavior over time.

Table C.1—*Continued*

Level of reinforcement of government regulations, standards, and policies for energy sustainability	Reasonable factor, reasonable definition, units not provided at top of p.8	Levels added to definition are listed below. Levels: 1- Severe 2- Strong 3- Minimal 4- Negligible
Volume of available water resources	How is the fixed amount of water resources available projected to change (up or down) over time?	Comment from validator has been analyzed. The causal loop model shows that as the volume of wind project water consumption decreases, the volume of available water resource for human use increases, mainly during wind project installation, as hypothesis. There may be variations in terms of water use during installation and operation.
Volume of excavation and trenching	Doesn't seem like an important factor, reasonable definition, reasonable units	Comment from validator has been analyzed and the decision is that no modification was made to this factor. Sustainability of wind energy project includes environmental impacts. Soil removal from an area changes the natural soil condition for future uses. However, it is understood that wind energy project location would define the type of effect of this factor. Natural pristine environments would be negatively impacted by soil extraction and removal; on the other hand, soil already damaged by other industrial activities would be neutral to this factor.
Volume of waste from wind project installation	Doesn't seem like a factor given there is no hazardous waste generated by wind project installation, reasonable definition, reasonable units	Comment from validator has been analyzed, factor definition has been modified to: Volume of waste from wind project installation, represents the amount of hazardous and nonhazardous waste, this includes industrial waste produced during the wind energy project installation. Sustainability of wind energy project includes environmental impacts. Waste from wind energy project has a negative effect in the environment.
Volume of waste from wind project operation and maintenance	Doesn't seem like a factor given there is no hazardous waste generated by wind project operation, reasonable definition, reasonable units	Comment from validator has been analyzed, factor definition has been modified to: Volume of waste from wind project operation and maintenance represents the amount of hazardous and nonhazardous waste; this includes industrial waste produced during the wind energy project operation and maintenance. Sustainability of wind energy project includes environmental impacts. Waste from wind energy project has a negative effect in the environment.
Wind power generated	Reasonable factor, reasonable definition, shouldn't it be MWh?	Comment from validator has been analyzed; as a result, factor unit in the model has been modified.

Table C.1—*Continued*

Wind turbine size	Reasonable factor, should differentiate between rotor diameter and size of the machine (that is, you could have a 1.5MW that produces more energy as the rotor diameter increases, or you could have a 2MW that produces more than a 1.5MW for the same rotor diameter), reasonable units	Comment from validator has been analyzed and factor name and definition have been modified. “Wind turbine size” factor has been change to “Wind turbine dimension” and refers to the physical dimension of a wind turbine. It is measure as the diameter of the turbine. This is the size of the machine.

Table C-2 Factor Relationships Validation Analysis

Factor →	Factor	+/-	Validator 1	Assessment
# of Accidents	Wind project population resistance	+	Doesn’t seem realistic	The relationship will remain the same. The factor that is related to was renamed as wind project local population resistance. After careful consideration population resistance related to “# of accidents” factor is more related to local effects than to global effects. This will address validator comment.
# of wind turbines	# of Accidents	+	Doesn’t seem realistic	The relationship will remain the same. Given that the amount of work required in a wind energy project will depend on the # of turbines the project is composed of. An increase in the number of turbine that has to be installed or served increases the probability of accident occurrence.
Amount of electrical energy reserves used	Cost of reserves operation	+	Only realistic if you think that you need 1 MW of reserves for every 1 MW of wind. There’s significant debate over that.	Validator comment has been analyzed. Given the significant debate, researcher judgment is to leave it in.

Table C.2—*Continued*

Amount of noise from wind turbines	Population health problems due to wind project operation	+	It is far from proven that noise causes health problems	Validator comment has been analyzed. The relationship will remain the same. There is a significant debate over this relationship (Hamilton, 2009), (Colby et. al, 2009), (Chapman, 2011), (Rourke, 2013) in the literature, and judgment of researcher to leave it in.
Bird population	Wind project population resistance	-	I don't think the amount of bird strikes influence the general population's view of wind projects	The relationship will remain the same. The factor that is related to was renamed as wind project local population resistance. After careful consideration population resistance related to "bird population" factor is more related to local effects than to global effects. This will address validator comment.
Distance between wind project and community	Amount of noise from wind turbines	-	Noise generated doesn't decrease, but perhaps noise affecting nearby people decreases	The relationship will remain the same. "Amount of noise from wind turbines" definition has been modified to address validator comment. Amount of noise from wind turbines, represents the level of noise that wind turbines produce in operation that is perceived by communities near to project.
Distance between wind project and community	Level of visual impact	-	Visual impacts are often cited where there are the least people to start with	The relationship will remain the same. Various sources in the literature (AWS Truewind, 2009)(Westerberg et al., 2013) (Ajayi, 2012)(Kondili & Kaldellis, 2012) have cited visual impacts as one of the major concerns related to wind energy project development.
Grid stability	Utility company resistance to wind projects	-	True, but utility resistance is more often to price of wind generation	The relationship will remain the same. Validator agrees with relationship.
Natural landscape tourism revenue	Wind project population resistance	-	This one doesn't make sense to me.	The relationship will remain the same. The factor that is related to was renamed as wind project local population resistance. . After careful consideration population resistance related to "natural landscape tourism revenue" factor is more related to local effects than to global effects. like Westerberg et al. (2013) discusses potential effects on tourism in a France coast.

Table C.2—*Continued*

Volume of available water resources	Wind project population resistance	-	Again, not sure how the amount of available water changes over time	The relationship will remain the same. The factor that is related to was renamed as wind project local population resistance. After careful consideration population resistance related to "volume of available water resources" factor is more related to local effects than to global effects This relationship is perceived mainly during installation, considered as short term effect.
Wind project population resistance	# of wind projects	-	I don't see the connection	The relationship will remain the same. The factor wind project population resistance has been decomposed into wind project local population resistance as a component of wind project population resistance.
Wind turbine density	Site wind speed	-	No. Wind speed should be independent. The amount of energy created by putting my turbines into the same area should decrease	The relationship will remain the same. Adam and Keith (2013) have validated this relationship.
Wind turbine size	Capacity factor	+	Not necessarily true	Validator comment has been analyzed. "Wind turbine size" factor has been renamed as "Wind turbine dimension". Relationship will remain the same. Wind turbine dimension factor definition has been modified to address validator concern.
Wind turbine size	Wind project operation and maintenance cost	+	O&M cost could decrease from using larger turbines	Validator comment has been analyzed. "Wind turbine size" factor has been renamed as "Wind turbine dimension". A decision has been made to change sign of relationship as result of validator comment.

In summary, as a result of analysis of validator inputs the following changes have been made to the model:

- Definitions of following factors have been modified.

    "Acquired incentives for wind technology advances" factor

    "Amount of economic incentive for implementing wind technology advances" factor

    "Amount of noise from wind turbines" factor

    "Bird/bat population" factor

    "Volume of waste from wind project installation" factor

    "Volume of waste from wind project operation and maintenance" factor

    "Wind turbine size" factor

- "Wind turbine size" factor name has been modified to "Wind turbine dimension".
- "Cost of turbine" factor has been added as a new factor to the model.
- Relationship between "Wind turbine dimension" factor and "Wind project operation and maintenance cost" factor changed sign. It is now decreasing (-) instead of increasing (+). Relationship direction remains the same.

Appendix D

Elements of the Simulator Architecture:

Definitions and Units of Measurement for Stocks, Rates and Auxiliary Variables

The following tables present the definitions and unit of measurement for the stocks

Table D-1 Stock Definitions and Units

Stock	Definition	Unit
Amount of money recouped due to decommissioning	Represents the accumulated amount of money recovered due to decommissioning of wind turbines.	Dollars
Area of excavation and trenching	Amount of land excavating and trenching required for turbine tower installation, access roads, electric substation and operations building construction.	Squared meter (m^2)
Carbon footprint added by WES (wind energy system)	Represents the greenhouse gases emissions caused to install, operate and /or decommission wind turbines and other elements of the system.	Tons of Carbon dioxide (CO_2)
Carbon footprint avoided by WES	Represents the greenhouse gases emissions avoided by generating electricity from wind energy system.	Tons CO_2
Energy used by WES	Represents the total energy used by WES during installation, operations and maintenance (O&M) and decommissioning.	Megawatts per hour (MWh)
Energy used during decommissioning	Represents the energy used during wind turbine decommissioning.	Joules
Energy used during installation	Represents the energy used during WES installation.	Joules
Energy used during O&M	Represents the energy used during WES operation and maintenance.	Joules
Net present value	Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flows is the algebraic sum of money estimated to flow in and out of an organization over some period of time as a result of a particular project (Stevens, 1994).	Dollars

Table D.1—*Continued*

Number of wind turbines decommissioned	The number of wind turbines decommissioned from the wind energy system.	Number of turbines
Number of wind turbines installed	The number of wind turbines installed in a wind energy system.	Number of turbines
Number of wind turbines to be installed	The number of wind turbines planned to be installed in a wind energy system.	Number of turbines
Skilled personnel for WES decommissioning	Represents the human resources needed with the skill level required for decommissioning.	Number of people
Skilled personnel for WES installation	Represents the human resources needed with the skill level required for wind energy system installation.	Number of people
Skilled personnel for WES O&M	Represents the human resources needed with the skill level required for wind energy O&M.	Number of people
Total WES revenue	Represents the total income received by wind energy system operation.	Dollars
Total wind power generated from WES	Represents the accumulated amount of electric power generated by a wind energy system.	MWh
Volume of water discharged to ground	Represents the total amount of water discharged to ground by WES during installation, O&M and decommissioning.	Gallons
Volume of water used during O&M	Represents the total amount of water used during operation and maintenance phase.	Gallons
Volume of water used during WES installation	Represents the total amount of water used during the installation phase.	Gallons
Volume of water used for human needs	Represents the total amount of water used for the personnel working on the installation, O&M and/or decommission of the wind energy system.	Gallons
Volume of water used for WES decommissioning	Represents the total amount of water used during the decommissioning phase.	Gallons

Table D.1—*Continued*

Waste produced by WES decommissioning	Represents the accumulated waste produced during WES decommission.	Metric Tons
Waste produced by WES installation	Represents the accumulated waste produced during WES installation.	Metric Tons
Waste produced by WES O&M	Represents the accumulated waste produced during WES O&M.	Metric Tons
Water conserved by WES	Represents the accumulated amount of water conserved for avoiding use of other energy sources due to wind power generation.	Gallons
Water used by WES	Represents the accumulated amount of water used by the wind energy system from installation phase through decommissioning phase.	Gallons
WES decommissioning cost	Represents the accumulated decommission cost of the wind energy system.	Dollars
WES installed capital cost	Represents the accumulated installed capital costs of a wind energy system.	Dollars
WES O&M cost	Represents the accumulated operation and maintenance costs of a wind energy system. It includes land lease cost, labor wages and material, and levelized replacement costs.	Dollars
WES total cost	Sum of initial wind energy installed capital cost, O&M cost and decommissioning cost.	Dollars
WES total waste	Sum of waste produced during wind energy installation, O&M and decommissioning phases.	Metric Tons

Table D-2 Rates Definitions and Units

Rate	Definition	Unit
Decommissioning attrition rate	Represents the rate of personnel exiting from the decommissioning activities.	Number of people per year
Decommissioning employment rate	Represents the rate of employment during the WES decommissioning phase.	Number of people per year
Installation attrition rate	Represents the rate of personnel exiting from the installation activities.	Number of people per year
Installation employment rate	Represents the rate of employment during the WES installation phase.	Number of people per year
O&M attrition rate	Represents the rate of personnel exiting from the O&M activities.	Number of people per year
O&M employment rate	Represents the rate of employment during the WES O&M.	Number of people per year
Present value of profit	The amount remaining after wind energy system total costs are deducted from total revenue.	Dollars per year
Rate of amount of money recouped due to decommissioning	Represents the rate at which money is recouped due to decommissioning of wind turbines.	Dollars per year
Rate of decommissioning cost	Represents the rate at which decommissioning expenditures are disbursed in the wind energy system.	Dollars per year
Rate of energy used during decommissioning	The rate at which energy is used during turbine decommissioning activities.	Joules per year
Rate of energy used during installation	The rate at which energy is used during turbine installation activities.	Joules per year
Rate of energy used during O&M	The rate at which energy is used during turbine O&M activities.	Joules per year
Rate of excavation and trenching	The rate at which land excavation and trenching required for turbine tower installation, access roads, electric substation and O&M building construction is performed.	m^2 per year

Table D.2—*Continued*

Rate of greenhouse gases emissions avoided by WES	The rate at which the greenhouse gases emissions is avoided by generating electricity from wind energy system.	Tons of CO_2 per year
Rate of installed capital cost	The amount of investment required to develop a wind energy system. This includes wind turbines, balance of station and soft costs. Balance of station cost refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Soft cost refers to costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars per year
Rate of O&M cost	The rate at which O&M costs are utilized.	Dollars per year
Rate of total waste	Represents the rate at which waste is produced by the wind energy system. This is the sum of WES waste produced during installation, O&M and decommissioning during a year.	Metric Tons per year
Rate of waste production during WES decommissioning	Represents the rate at which waste is produced during WES decommissioning.	Metric Tons per year
Rate of waste production during WES installation	Represents the rate at which waste is produced during WES installation.	Metric Tons per year
Rate of waste production during WES O&M	Represents the rate at which waste is produced during WES O&M.	Metric Tons per year
Rate of water conserved by WES	Represents the rate at which water is conserved due to wind energy consumption.	Gallons per year
Rate of water drained from O&M	The rate at which water is drained during WES O&M activities.	Gallons per year
Rate of water drained from WES installation	The rate at which water is drained during WES installation activities.	Gallons per year

Table D.2—*Continued*

Rate of water drained from WES decommissioning	The rate at which water is drained during WES decommissioning activities.	Gallons per year
Rate of water used for WES decommissioning	Represents the rate at which water is used during WES decommissioning phase.	Gallons per year
Rate of water used during O&M	Represents the rate at which water is used during WES O&M phase.	Gallons per year
Rate of water used during WES installation	Represents the rate at which water is used during WES installation phase.	Gallons per year
Rate of water used for human needs	The rate at which water is used for human consumption on the WES.	Gallons per year
Rate of WES energy used	The rate at which energy is used on the WES during installation, O&M and decommissioning	MWh per year
Rate of WES greenhouse gases emissions	The rate at which greenhouse gases emissions are produced due to wind energy system installation, O&M and decommissioning.	Tons CO_2 per year
Rate of WES total cost	Represents the WES total cost. This is the sum of installed capital cost, operation and maintenance cost, and decommissioning cost.	Dollars per year
Rate of WES water use	Represents the rate at which water is used in the WES during installation, O&M, and decommissioning activities.	Gallons per year
Rate of wind turbine installation in WES	The rate at which wind turbines are added to the WES.	Number of turbines per year
Rate of wind turbines to be installed	The rate at which wind turbines are planned to be installed post investor commitment.	Number of turbines per year
Turbine decommissioning rate in WES	Represents the rate at which wind turbines are decommissioned once they have reached the end of life.	Number of turbines per year
WES revenue	Represents the income received by WES operation.	Dollars per year
Wind power generated by WES	Represents the amount of wind power generated in an interconnected electric system.	MWh per year

Table D-3 Auxiliary Variable Definitions and Units

Auxiliary Variable	Definition	Unit
Abandonment rate	The ratio at which turbine are abandoned at the end of their useful life.	Number of turbines per year
Acquired incentives for implementing wind technologies advances	The actual amount of incentives in financial form obtained by particular businesses and investors to implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars per MWh
Adjusting time	Time required for the population to react to social impacts.	Year
Amount committed	Refers to the actual amount of funds available to be committed by investors for WES development.	Dollars/year
Available amount of economic incentives for implementing wind technology (In the model: Av amnt of economic incentives for implementing wind technology)	Provides motivation in financial form to businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars per MWh
Amount of land used	Refers to the amount of land already in used by WES.	Square meter (m^2)
Annual operating time	Refers to the amount of hours per year the wind energy system is expected to operate.	Hours per year
Area conversion factor	Area conversion factor from square meters to global hectares.	Global hectares/ m^2
Available land for WES	Represents the total available land that could be used for wind energy development.	m^2
Average area per wind turbine	Represents the amount of land required to install a wind turbine.	m^2 per turbine
Capacity factor	The ratio of wind energy (assuming all turbines are same size) actual output over a period of time, to its potential output if it were possible for it to operate at full theoretical capacity indefinitely.	% (dimensionless)

Table D.3—*Continued*

Capacity per turbine	Refers to the maximum rated output of a wind turbine under specific conditions designated by the manufacturer (modified from EIA glossary definition “nameplate capacity” (EIA, 2013)).	Megawatts per turbine
Carbon footprint conversion factor	Carbon footprint conversion factor from Metric Tons CO_2 to Global hectares.	Global hectares per Metric Tons of CO_2
Decommissioning attrition fraction	Represents the fraction of personnel leaving the wind energy system decommissioning activities.	Number of people per year
Decommissioning cost per turbine	Refers to the unit cost of turbine decommissioning.	Dollars
Decommissioning target workers	Represents the number of workers required to perform decommissioning activities in a given year.	Number of people
Decommission time	Represents the required time to decommission turbines from the wind energy system.	Year
Depreciation	Depreciation is an income tax deduction that allows a taxpayer to recover the cost or other basis of certain property. It is an annual allowance for the wear and tear, deterioration, or obsolescence of the property.	Dollars
Distance between WES and community	Average distance between the WES and the closest surrounding community.	Kilometers (Km)
Ecological footprint	Represents the amount of land and water area required for nature to regenerate the resources used by the WES.	Global hectares
Ecological footprint social impact	Represents the effect of the wind energy system ecological footprint on the population resistance.	dimensionless
Electricity price	Represents the average sale price of electricity generated from a wind energy system to utilities.	Megawatts hour per Dollars

Table D.3—*Continued*

Employment social impact	Represents the effect of the employment due to wind energy system installation, O&M and decommissioning activities on the population resistance.	dimensionless
Energy replacement ecological footprint difference	Algebraic sum of the net water savings and the net carbon footprint given wind energy system installation, operation and decommissioning. It represents the ecological footprint savings (related to water and carbon dioxide emissions) of using wind energy to supply energy demand instead of traditional nonrenewable sources. Focus is on water and energy.	Global hectares
Energy used per turbine during decommissioning	Refers to the amount of energy used for wind turbines decommissioning.	Joules per turbine
Energy used per turbine during installation	Refers to the amount of energy used for wind turbine installation.	Joules per turbine
Energy used per turbine during O&M	Refers to the amount of energy used for wind turbines to operate.	Joules per turbine
Energy conversion factor	Energy conversion factor from Joules to MWh.	Megawatts hour per Joules
Estimated incentives to be acquired	Refers to the potential amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars per year
Estimated number of wind turbines to be installed	Refers to the estimated number of wind turbines that would be required to cover the total wind power generation difference.	Number of turbines
Estimated total cost of wind power generation difference	Refers to the estimated cost of wind turbines installation, O&M and decommissioning to cover total wind power generation difference.	Dollars

Table D.3—*Continued*

Estimated wind energy decommissioning cost	Refers to the estimated amount of funds required to decommission wind turbines to be installed to cover wind power generation difference.	Dollars
Estimated wind energy installed capital cost	Refers to the estimated amount of investment required to cover the total wind power generation difference.	Dollars
Estimated wind energy O&M cost	Represents the estimated operational and maintenance costs of the additional wind turbines required to cover the total wind power generation difference.	Dollars
Estimated capacity	Represents the estimated energy capacity required to cover the wind power generation difference.	Megawatts
Estimated revenue	Represents the estimated income related to the wind power generation difference.	Dollars
Federal tax	A tax collected by the United States Internal Revenue Service (IRS) on the annual earnings of individuals, corporations, trusts and other legal entities.	% (dimensionless)
Estimated probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances to cover the total wind power generation difference.	% (dimensionless)
Fraction of land used	Refers to what fraction of the land allotted to wind turbines installed is actually built on.	% (dimensionless)
Hiring delay time	The amount of time required to hire personnel.	Year
Hiring for decommissioning growth	Refers to the human resource employment due to growth of decommissioning activities in the WES.	Number of people per year
Hiring for installation growth	Refers to the human resource employment due to growth of installation activities in the WES.	Number of people per year

Table D.3—*Continued*

Hiring for O&M growth	Refers to the human resource employment due to growth of operation and maintenance activities in the WES.	Number of people per year
Hiring to replace decommissioning attrition	Refers to the human resource employment due to decommissioning personnel attrition in the WES.	Number of people per year
Hiring to replace installation attrition	Refers to the human resource employment due to installation personnel attrition in the WES.	Number of people per year
Hiring to replace O&M attrition	Refers to the human resource employment due to operation and maintenance personnel attrition in the WES.	Number of people per year
Incentive	The actual amount of incentives in financial form obtained by particular businesses and investors to implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Incentive phase down	The actual amount of funds that could be received as an incentive per MWh generated in a given year	Dollars per MWh
Installation attrition fraction	Represents the fraction of personnel leaving the WES installation activities.	Number of people per year
Installed capital cost per MW	Refers to the unit cost of wind energy installation per MW. This includes wind turbines, balance of station and soft costs. Balance of station cost refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Soft cost refers to costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars/ MW

Table D.3—*Continued*

Investor commitment	Refers to amount of funds committed by investor to fund wind energy developments.	Dollars
Level of visual impact	Represents how well wind turbines can be seen from horizon.	% (dimensionless)
Level of visual impact to society awareness	Represents the effect of the WES level of visual impact on the population resistance.	% (dimensionless)
Net carbon footprint	The algebraic sum of the carbon footprint avoided and emitted during WES installation, operation and decommissioning.	Tons of CO_2 per year
Net employment rate	Represents the rate of employment during the wind energy installation, O&M and decommissioning phases.	Number of people per year
Net tax	The amount of money paid as tax due to revenue generation after total costs and depreciation credit have been subtracted.	Dollars
Net water savings	This is the algebraic sum of water used by WES and the water conserved by WES.	Gallons per year
Noise perception	Refers to the amount of noise perceived in the nearest communities during wind turbine operation.	Decibels
Noise social impact	Represents the effect of the noise perceived during wind turbine operation on the population resistance.	% (dimensionless)
Number of operating wind turbines	Represents the number of wind turbines operating in the WES.	Number of turbines
Number of abandoned wind turbines	Represents the number of wind turbines abandoned after end of operational life in the WES.	Number of turbines
O&M attrition fraction	Represents the fraction of personnel leaving the WES operational and maintenance activities.	Number of people per year
O&M cost per MWh	Refers to the unit cost of O&M activities per MWh.	Dollars per MWh per year
O&M target workers	Represents the number of workers required to perform O&M activities in a given year.	Number of people

Table D.3—*Continued*

Operating rate	The ratio at which turbine are operating during their useful life.	% (dimensionless)
Permanent land used	Amount of land that is impacted during the operational life of the wind turbines.	m^2
Probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances.	(%)dimensionless
Rate of excavation per wind turbine	Represents the rate at which land excavation and trenching is performed per turbine.	m^2 per year per turbine
Rate of waste produced per turbine	Refers to rate at which waste is produced per turbine during O&M.	Metric Tons per year
Ratio of water use per person	Refers to the amount of water use per person during the installation operation and maintenance, and decommissioning phases of the WES.	Gallons per person per year
Replacement for decommissioning	Represents the planned replacement of decommissioning personnel in the WES.	% per year
Replacement for installation attrition	Represents the planned replacement of installation personnel in the WES.	% per year
Replacement for O&M attrition	Represents the planned replacement of O&M personnel in the WES.	% per year
Rotor diameter	Refers to the wind turbine rotor diameter.	Meters
Society awareness	Refers to the knowledge accumulated in society due to experience with wind energy.	% (dimensionless)
Society awareness impact	Represents the effect of the society awareness on the population resistance related to WES.	% (dimensionless)
Target workers	Represents the number of workers required to perform installation activities in a given year.	Number of people
Target wind power generation	Refers to the amount of electric power expected to be generated from wind energy in a defined time period.	MWh per year

Table D.3—*Continued*

Traditional energy source greenhouse gases emissions factor	The greenhouse gases emissions factor of traditional sources of energy not operating due to wind power generation.	Tons of CO_2 per MWh
Traditional energy source water use factor	The average water use of traditional sources of energy not operating due to wind power generation.	Gallons per MWh
Turbine installation impact	Represents the effect of the number of turbines installed on the society awareness.	% (dimensionless)
Turbine resale price	Refers to the estimated value that a wind turbine will realize when is sold at the end of its useful life.	Dollars per turbine
Turbine sound power	It is a measure of the sound strength of a turbine.	Decibels
Waste conversion factor	Waste conversion factor from metric tons to Global hectares.	Global hectares per Metric Tons
Waste produced per turbine during decommissioning	Refers to the waste produced per turbine during WES decommissioning activities.	Metric Tons per turbine
Waste produced per turbine during installation	Refers to the waste produced per turbine during WES installation phase.	Metric Tons per turbine
Water drained from O&M ratio	Refers to the amount of water drained from the O&M activities during the O&M phase.	% (dimensionless)
Water drained from WES decommissioning factor	Refers to the amount of water drained from the decommissioning activities during the decommissioning phase.	% (dimensionless)
Water drained from WES installation factor	Refers to the amount of water drained from the installation activities during installation phase.	% (dimensionless)
Water withdraw during decommissioning factor	Refers to the amount of water withdraw for the decommissioning activities during the decommissioning phase.	% (dimensionless)
Water withdraw during O&M factor	Refers to the amount of water withdraw for the O&M activities during the O&M phase.	% (dimensionless)
Water withdraw during installation factor	Refers to the amount of water withdraw for the installation activities during installation phase.	% (dimensionless)

Table D.3—*Continued*

Water conversion factor	Water conversion factor from Gallons to Global hectares.	Global hectares per Gallons
WES installed capacity	Theoretical maximum capacity of a WES based on the number of wind turbines installed in the system.	MWh per year
WE population resistance	Refers to the general population opposition to the WES.	% (dimensionless)
Wind power generation difference	Refers to the difference between the actual wind power generated and the target wind power generation.	MWh per year
Wind power opportunity profit	Refers to the perceived potential profit that could be generated from wind power investment to wind power generation difference.	Dollars per year
Wind turbine cost	Refers to the unit cost of turbine.	Dollars per turbine
Wind turbine installation per time period	Refers to the percentage of wind turbines being added in the WES for a given year.	#/ #/ year

Appendix E

Wind Energy System Sustainability Simulator iThink Code

The simulator elements are part of the equations that represent the behavior of the system dynamics model and enable the model to be implemented properly. The following are the list of the equations related to the variables in the simulator and is extracted from the equation layer in the simulator for the state of Texas:

Amount_of_money__recouped_due__to_decommissioning(t) = Amount_of_money__recouped_due__to_decommissioning(t - dt) + (rate_of_amount_of__money_recouped__due_to_decommissiong) * dt

INIT Amount_of_money__recouped_due__to_decommissioning = 0

INFLOWS:

rate_of_amount_of__money_recouped__due_to_decommissiong = turbine_decommissioning__rate_in_WES*turbine_resale_price

Area_of__excavation_and_trenching(t) = Area_of__excavation_and_trenching(t - dt) + (rate_of_excavation__and_trenching) * dt

INIT Area_of__excavation_and_trenching = 183.52*10000

INFLOWS:

rate_of_excavation__and_trenching = rate__of_excavation__per_wind_turbine*rate_of_wind__turbines_installation___in_WES

Carbon__footprint_avoided__by_WES(t) = Carbon__footprint_avoided__by_WES(t - dt) + (rate_of_greenhouse__gases_emissions__avoided_by_WES) * dt

INIT Carbon__footprint_avoided__by_WES = 339359.7664

INFLOWS:

rate_of_greenhouse__gases_emissions__avoided_by_WES = wind_power__generated_by_WES*traditional_energy_source____greehouse_gases__emissions _factor

Carbon_footprint__added_by_WES(t) = Carbon_footprint__added_by_WES(t - dt) + (rate_of_WES__greenhouse_gases__emissions) * dt

INIT Carbon_footprint__added_by_WES = 19.85

INFLOWS:

rate_of_WES__greenhouse_gases__emissions =

rate_of_WES__energy_used*traditional_energy_source____greehouse_gases__emissions_facto

r

Energy_used__by_WES(t) = Energy_used__by_WES(t - dt) +

(rate_of_WES__energy_used) * dt

INIT Energy_used__by_WES = 286819.4364

INFLOWS:

rate_of_WES__energy_used =

((rate_of_energy_used_during_installation+rate_of_energy_used_during_decommissioning+rate

_of_energy_used__during_O&M)*energy__conversion_factor)

Energy_used__during_installation(t) = Energy_used__during_installation(t - dt) +

(rate_of_energy_used_during_installation) * dt

INIT Energy_used__during_installation = 9.15e14

INFLOWS:

rate_of_energy_used_during_installation =

energy_used__per_turbine_during__installation*rate_of_wind__turbines_installation___in_WES

Energy_used__during_O&M(t) = Energy_used__during_O&M(t - dt) +

(rate_of_energy_used__during_O&M) * dt

INIT Energy_used__during_O&M = 0

INFLOWS:

rate_of_energy_used__during_O&M =

energy_used__per_turbine__during_O&M*number_of__operating_wind_turbines

Energy_used_during_decommissioning(t) = Energy_used_during_decommissioning(t -

dt) + (rate_of_energy_used_during_decommissioning) * dt

INIT Energy_used_during_decommissioning = 0

INFLOWS:

rate_of_energy_used_during_decommissioning =

energy_used_per_turbine_during_decommissioning*turbine_decommissioning__rate_in_WES

Net__present_value(t) = Net__present_value(t - dt) + (present__value_of__profit) * dt

INIT Net__present_value = -284110752.39

INFLOWS:

present__value_of__profit = NPV((WES_revenue-rate_of_WES__total_cost-net_tax+incentive), 0.08)

Number_of__wind_turbines__installed(t) = Number_of__wind_turbines__installed(t - dt) + (rate_of_wind__turbines_installation___in_WES - turbine_decommissioning__rate_in_WES) * dt

INIT Number_of__wind_turbines__installed = 122

INFLOWS:

rate_of_wind__turbines_installation___in_WES = DELAY(Number_of__wind_turbines__to_be_installed*wind_turbine__installation_per__time_period, 1)

OUTFLOWS:

turbine_decommissioning__rate_in_WES = DELAY((Number_of__wind_turbines__installed/decommission_time),20,0)

Number_of__wind_turbines__to_be_installed(t) = Number_of__wind_turbines__to_be_installed(t - dt) + (rate_of_wind__turbines_to_be__installed - rate_of_wind__turbines_installation___in_WES) * dt

INIT Number_of__wind_turbines__to_be_installed = 0

INFLOWS:

rate_of_wind__turbines_to_be__installed = IF WE__population__resistance>=0 THEN ((investor__commitment*0.68)/wind__turbine_cost)*(1-WE__population__resistance) ELSE ((investor__commitment*0.68)/wind__turbine_cost)

OUTFLOWS:

rate_of_wind__turbines_installation___in_WES = DELAY(Number_of__wind_turbines__to_be_installed*wind_turbine__installation_per__time_period, 1)

Number_of__wind_turbines__decommissioned(t) = Number_of__wind_turbines__decommissioned(t - dt) + (turbine_decommissioning__rate_in_WES) * dt

INIT Number_of__wind_turbines__decommissioned = 0

INFLOWS:

turbine_decommissioning__rate_in_WES = DELAY((Number_of__wind_turbines__installed/decommission_time),20,0)

Skilled_personnel__for_WES_O&M(t) = Skilled_personnel__for_WES_O&M(t - dt) + (O&M__employment_rate - O&M__attrition_rate) * dt

INIT Skilled_personnel__for_WES_O&M = 0

INFLOWS:

O&M__employment_rate = hiring_for__O&M_growth+hiring_to_replace__O&M_attrition

OUTFLOWS:

O&M__attrition_rate = Skilled_personnel__for_WES_O&M*O&M_attrition__fraction

Skilled_personnel_for_WES_decommissioning(t) = Skilled_personnel_for_WES_decommissioning(t - dt) + (decommissioning__employment_rate - decommissioning__attrition_rate) * dt

INIT Skilled_personnel_for_WES_decommissioning = 0

INFLOWS:

decommissioning__employment_rate = hiring_for__decommissioning__growth+hiring_to_replace__decommissioning__attrition

OUTFLOWS:

decommissioning__attrition_rate = Skilled_personnel_for_WES_decommissioning*decommissioning_attrition_fraction

Skilled_personnel_for_WES_installation(t) = Skilled_personnel_for_WES_installation(t - dt) + (installation__employment_rate - installation_attrition_rate) * dt

INIT Skilled_personnel_for_WES_installation = 125

INFLOWS:

installation__employment_rate =

hiring_to_replace___installation_attrition+hiring__for_installation_growth

OUTFLOWS:

installation_attrition_rate =

Skilled_personnel_for_WES_installation*installation__attrition_fraction

Total_WES__revenue(t) = Total_WES__revenue(t - dt) + (WES_revenue) * dt

INIT Total_WES__revenue = 29873444.3

INFLOWS:

WES_revenue =

(wind_power__generated_by_WES*electricity_price)+rate_of_amount_of__money_recouped__due_to_decommissioning

Total_wind_power_generated_from_WES(t) =

Total_wind_power_generated_from_WES(t - dt) + (wind_power__generated_by_WES) * dt

INIT Total_wind_power_generated_from_WES = 492149

INFLOWS:

wind_power__generated_by_WES =

(WES_installed__capacity*capacity_factor*annual__operating_time)

Volume_of__water_used__for_human_needs(t) =

Volume_of__water_used__for_human_needs(t - dt) +

(rate_of_water__used_for__human_needs) * dt

INIT Volume_of__water_used__for_human_needs = 65382.6

INFLOWS:

rate_of_water__used_for__human_needs =

(Skilled_personnel_for_WES_decommissioning+Skilled_personnel_for_WES_installation+Skilled_personnel__for_WES_O&M)*ratio_of_water__use_per_person

Volume_of_water__used_during_O&M(t) = Volume_of_water__used_during_O&M(t - dt) + (rate_of_water__used_during_O&M - rate_of_water_drained_from__O&M) * dt

INIT Volume_of_water__used_during_O&M = 0

INFLOWS:

rate_of_water__used_during_O&M =

wind_power__generated_by_WES*water_withdraw_duirng_O&M_factor

OUTFLOWS:

rate_of_water_drained_from__O&M =

Volume_of_water__used_during_O&M*water_drained_from_O&M_ratio

Volume_of_water__used_during_WES_installation(t) =

Volume_of_water__used_during_WES_installation(t - dt) +

(rate_of_water__used_during__WES_installation -

rate_of_water_drained_from__WES_installation) * dt

INIT Volume_of_water__used_during_WES_installation = 492149

INFLOWS:

rate_of_water__used_during__WES_installation =

annual__operating_time*capacity_factor*capacity_per__turbine*rate_of_wind__turbines_installati

on___in_WES*water_withdraw_during_installation_factor

OUTFLOWS:

rate_of_water_drained_from__WES_installation =

Volume_of_water__used_during_WES_installation*water_drained_from__WES_installation_facto

r

Volume_of_water_discharged_to_ground(t) = Volume_of_water_discharged_to_ground(t

- dt) + (rate_of_water_drained_from__O&M + rate_of_water_drained_from__WES_installation +

rate_of_water__drained_from__WES_decommissioning) * dt

INIT Volume_of_water_discharged_to_ground = 123037250

INFLOWS:

rate_of_water_drained_from__O&M =

Volume_of_water__used_during_O&M*water_drained_from_O&M_ratio

rate_of_water_drained_from__WES_installation =

Volume_of_water__used_during_WES_installation*water_drained_from__WES_installation_facto

r

rate_of_water__drained_from__WES_decommissioning =

Volume_of_water_used_for_WES_decommissioning*water_drained_from_WES_decommissing_

factor

Volume_of_water_used_for_WES_decommissioning(t) =

Volume_of_water_used_for_WES_decommissioning(t - dt) +

(rate_of_water_used_for_WES_decommissioning -

rate_of_water__drained_from__WES_decommissioning) * dt

INIT Volume_of_water_used_for_WES_decommissioning = 0

INFLOWS:

rate_of_water_used_for_WES_decommissioning =

annual__operating_time*capacity_factor*capacity_per__turbine*turbine_decommissioning__rate_

in_WES*water_withdrawn_during_decommissioning_factor

OUTFLOWS:

rate_of_water__drained_from__WES_decommissioning =

Volume_of_water_used_for_WES_decommissioning*water_drained_from_WES_decommissing_

factor

Waste_produced_by_WES_O&M(t) = Waste_produced_by_WES_O&M(t - dt) +

(rate_of_waste__production__during_WES_O&M) * dt

INIT Waste_produced_by_WES_O&M = 0

INFLOWS:

rate_of_waste__production__during_WES_O&M =

rate_of_waste__produced_per_turbine*rate_of_wind__turbines_installation___in_WES

Waste_produced_by_WES_decommisioning(t) =

Waste_produced_by_WES_decommisioning(t - dt) +

(rate_of_waste_production_during_WES_decommisioning) * dt

INIT Waste_produced_by_WES_decommisioning = 0

INFLOWS:

rate_of_waste_production_during_WES_decommisioning =

turbine_decommissioning__rate_in_WES*waste_produced__per_turbine__during_decommission ing

Waste_produced_by_WES_installation(t) = Waste_produced_by_WES_installation(t - dt) + (rate_of_waste_production_during_WES_installation) * dt

INIT Waste_produced_by_WES_installation = 413580

INFLOWS:

rate_of_waste_production_during_WES_installation =

rate_of_wind__turbines_installation___in_WES*waste_produced__per_turbine__during_installati on

Water_conserved__by_WES(t) = Water_conserved__by_WES(t - dt) + (rate_of_water__conserved_by_WES) * dt

INIT Water_conserved__by_WES = 338106363

INFLOWS:

rate_of_water__conserved_by_WES =

wind_power__generated_by_WES*traditional_energy__source__water__use_factor

Water_use__by_WES(t) = Water_use__by_WES(t - dt) + (rate_of_WES__water_use) * dt

INIT Water_use__by_WES = 65382.6

INFLOWS:

rate_of_WES__water_use = (rate_of_water__used_during__WES_installation-rate_of_water_drained_from__WES_installation)+(rate_of_water__used_during_O&M-rate_of_water_drained_from__O&M)+(rate_of_water_used_for_WES_decommissioning-rate_of_water__drained_from__WES_decommissioning)+rate_of_water__used_for__human_ne eds

WES__decommisioning__cost(t) = WES__decommisioning__cost(t - dt) + (rate_of__decommissioning__cost) * dt

INIT WES__decommisioning__cost = 0

INFLOWS:

rate_of__decommissioning__cost = decommissioning__cost_per_turbne*turbine_decommissioning__rate_in_WES

WES__Total_waste(t) = WES__Total_waste(t - dt) + (rate_of__total_waste) * dt

INIT WES__Total_waste = 413580

INFLOWS:

rate_of__total_waste = rate_of_waste_production_during_WES_decommisioning+rate_of_waste_production_during_WES_installation+rate_of_waste__production__during_WES_O&M

WES_installed__capital_cost(t) = WES_installed__capital_cost(t - dt) + (rate_of_installed__capital_cost) * dt

INIT WES_installed__capital_cost = 311616960

INFLOWS:

rate_of_installed__capital_cost = rate_of_wind__turbines_installation___in_WES*capacity_per__turbine*installed_capital__cost_per_MW

WES_O&M_cost(t) = WES_O&M_cost(t - dt) + (rate_of__O&M_cost) * dt

INIT WES_O&M_cost = 0

INFLOWS:

rate_of__O&M_cost = wind_power__generated_by_WES*O&M_cost__per_MWh

WES_total_cost(t) = WES_total_cost(t - dt) + (rate_of_WES__total_cost) * dt

INIT WES_total_cost = 325748000

INFLOWS:

rate_of_WES__total_cost = rate_of_installed__capital_cost+(rate_of__O&M_cost)+(rate_of__decommissioning__cost)

abandonment_rate = STEP(0.01,10)

acquired_incentives__for_implementing_wind__technologies_advances = Av_amnt_of_economic_incentives__for_implementing_wind_technology*probability_of__getting_incentives

adjusting_time = 0.5

amount_committed = GRAPH(TIME)

(0.00, 0.00), (1.00, 1.6e+009), (2.00, 0.00), (3.00, 3.5e+008), (4.00, 0.00), (5.00, 1.2e+009), (6.00, 1.3e+009), (7.00, 2.9e+009), (8.00, 4.9e+009), (9.00, 4.1e+009), (10.0, 1.2e+009), (11.0, 5.4e+008), (12.0, 3.2e+009), (13.0, 2.5e+008), (14.0, 3.1e+009), (15.0, 1.8e+009), (16.0, 1.8e+009), (17.0, 1.8e+009), (18.0, 1.8e+009), (19.0, 1.8e+009), (20.0, 1.8e+009), (21.0, 1.8e+009), (22.0, 1.8e+009), (23.0, 1.8e+009), (24.0, 1.8e+009), (25.0, 1.8e+009), (26.0, 1.8e+009), (27.0, 1.8e+009), (28.0, 1.8e+009), (29.0, 1.8e+009), (30.0, 1.8e+009)

amount_of__land_used = Number_of__wind_turbines__installed*average_area__per_wind_turbine

annual__operating_time = 8760

area__conversion_factor = 1/10000

available_land__for_WES = 2.9066e11

average_area__per_wind_turbine = ((rotor_diameter^2)*3.1416/4)+((8*rotor_diameter)*(8*rotor_diameter))

Av_amnt_of_economic_incentives__for_implementing_wind_technology = IF WE__population__resistance> 0.5 THEN 0 ELSE incentive_phase_down

capacity_factor = 0.319

capacity_per__turbine = 1.5

carbon_footprint_conversion_factor = 0.0001365

decommissioning__cost_per_turbne = 100000

decommissioning__target_workers = turbine_decommissioning__rate_in_WES*0.578

decommissioning_attrition_fraction = 0.001

decommission_time = 3

depreciation = IF(TIME<8) THEN((0.5*rate_of_installed__capital_cost)*(0.20+(0.32*HISTORY(rate_of_installed__capital_cost,TIME-1))+(0.1920*HISTORY(rate_of_installed__capital_cost,TIME-2))+(0.1152*HISTORY(rate_of_installed__capital_cost,TIME-3))+(0.1152*HISTORY(rate_of_installed__capital_cost,TIME-4))+(0.0576*HISTORY(rate_of_installed__capital_cost,TIME-5)))) ELSE ((0.5*rate_of_installed__capital_cost)*((1+(0.20)+(0.32*HISTORY(rate_of_installed__capital_cost,TIME-1))+(0.1920*HISTORY(rate_of_installed__capital_cost,TIME-2))+(0.1152*HISTORY(rate_of_installed__capital_cost,TIME-3))+(0.1152*HISTORY(rate_of_installed__capital_cost,TIME-4))+(0.0576*HISTORY(rate_of_installed__capital_cost,TIME-5)))))

distance__between_WES__and_community = If rate_of_wind__turbines_installation___in_WES=0 THEN 7 else 7

ecological__footprint = Area_of__excavation_and_trenching*area__conversion_factor+(Carbon_footprint__added_by_WES*carbon_footprint_conversion_factor)+((WES__Total_waste*waste__conversion_factor))+(water__conversion_factor*Water_use__by_WES)

ecological_footprint_social_impact = GRAPH(ecological__footprint)

(0.00, 0.00), (110526, 0.023), (221053, 0.041), (331579, 0.0705), (442105, 0.087), (552632, 0.102), (663158, 0.126), (773684, 0.141), (884211, 0.152), (994737, 0.159), (1.1e+006, 0.173), (1.2e+006, 0.183), (1.3e+006, 0.183), (1.4e+006, 0.186), (1.5e+006, 0.185), (1.7e+006, 0.188), (1.8e+006, 0.191), (1.9e+006, 0.2), (2e+006, 0.203), (2.1e+006, 0.203)

electricity_price = 37.70

employment__social_impact = GRAPH(net_employment__rate)

(0.00, 0.00), (1.1e+010, 0.003), (2.2e+010, 0.00825), (3.3e+010, 0.0233), (4.4e+010, 0.0398), (5.5e+010, 0.0645), (6.6e+010, 0.093), (7.7e+010, 0.136), (8.9e+010, 0.148), (1e+011, 0.149), (1.1e+011, 0.148) energy__conversion_factor = 2.77777777778E-7 /1000

energy_repl_ecological_footprint_difference =

(net_carbon__footprint*carbon_footprint_conversion_factor)+(net_water_savings*water__conversion_factor)

energy_used__per_turbine__during_O&M = 2e11

energy_used__per_turbine_during__installation = 8.50e11

energy_used_per_turbine_during_decommissioning = 4.78e8

estimated__capacity =

wind_power__generation_difference/(capacity_factor*annual__operating_time)

estimated__probability_of__getting_incentives = GRAPH(TIME)

(0.00, 0.00), (1.00, 1.00), (2.00, 0.00), (3.00, 1.00), (4.00, 0.00), (5.00, 1.00), (6.00, 1.00), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 0.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 1.00), (18.0, 1.00), (19.0, 1.00), (20.0, 0.84), (21.0, 0.84), (22.0, 0.84), (23.0, 0.84), (24.0, 0.84), (25.0, 0.84), (26.0, 0.84), (27.0, 0.84), (28.0, 0.84), (29.0, 0.84), (30.0, 0.84)

estimated__revenue =

((wind_power__generation_difference*estimated_incentives_to_be_acquired)*(7.0236))+((wind_power__generation_difference*electricity_price)*10.5940)

estimated_incentives_to_be_acquired =

Av_amnt_of_economic_incentives__for_implementing_wind_technology*estimated__probability_of__getting_incentives

estimated_number__of_wind_turbines__to_be_installed =

estimated__capacity/capacity_per__turbine

estimated_total__cost_of_wind_power__generation_difference =

estimated_wind__energy_O&M_cost+estimated_wind__energy_installed__capital_cost+estimated_wind_energy_decommissioning_cost

estimated_wind__energy_installed__capital_cost =
estimated__capacity*installed_capital__cost_per_MW-(0.5*estimated__capacity*installed_capital__cost_per_MW)

estimated_wind__energy_O&M_cost =
O&M_cost__per_MWh*wind_power__generation_difference*10.5940

estimated_wind_energy_decommissioning_cost =
decommissioning__cost_per_turbne*estimated_number__of_wind_turbines__to_be_installed*0.2584

federal_tax = 0.35

fraction_of__land_used = IF amount_of__land_used<=available_land__for_WES THEN amount_of__land_used/available_land__for_WES ELSE 0

hiring__for_installation_growth = IF target_workers<=Skilled_personnel_for_WES_installation THEN 0 ELSE(Skilled_personnel_for_WES_installation-target_workers)/hiring_delay_time

hiring_delay_time = 0.5

hiring_for__decommissioning__growth = IF decommissioning__target_workers<=Skilled_personnel_for_WES_decommissioning THEN 0 ELSE (decommissioning__target_workers-Skilled_personnel_for_WES_decommissioning)/hiring_delay_time

hiring_for__O&M_growth = IF O&M__target_workers<=Skilled_personnel__for_WES_O&M THEN 0 ELSE(O&M__target_workers-Skilled_personnel__for_WES_O&M)/hiring_delay_time

hiring_to_replace__decommissioning__attrition =
decommissioning__attrition_rate*replacement_for__decommissioning

hiring_to_replace__O&M_attrition = O&M__attrition_rate*replacement__for_O&M

hiring_to_replace___installation_attrition =
installation_attrition_rate*replacement__for_installation_attrition

incentive =

(acquired_incentives__for_implementing_wind__technologies_advances*(wind_power__generated_by_WES-HISTORY(wind_power__generated_by_WES,TIME-1))+

(HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-1)*(HISTORY(wind_power__generated_by_WES,TIME-1)-HISTORY(wind_power__generated_by_WES, TIME-2))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-2)*(HISTORY(wind_power__generated_by_WES,TIME-2)-HISTORY(wind_power__generated_by_WES, TIME-3))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-3)*(HISTORY(wind_power__generated_by_WES,TIME-3)-HISTORY(wind_power__generated_by_WES, TIME-4))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-4)*(HISTORY(wind_power__generated_by_WES,TIME-4)-HISTORY(wind_power__generated_by_WES, TIME-5)) +

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-5)*(HISTORY(wind_power__generated_by_WES,TIME-5)-HISTORY(wind_power__generated_by_WES, TIME-6))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-6)*(HISTORY(wind_power__generated_by_WES,TIME-6)-HISTORY(wind_power__generated_by_WES, TIME-7))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-7)*(HISTORY(wind_power__generated_by_WES,TIME-7)-HISTORY(wind_power__generated_by_WES, TIME-8))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-8)*(HISTORY(wind_power__generated_by_WES,TIME-8)-HISTORY(wind_power__generated_by_WES, TIME-9))+

HISTORY(acquired_incentives__for_implementing_wind__technologies_advances,TIME-9)*(HISTORY(wind_power__generated_by_WES,TIME-9)-HISTORY(wind_power__generated_by_WES, TIME-10))))

incentive_phase_down = 23+ STEP (-4.6,17) + STEP(-4.6, 18)+STEP (-4.6, 19)

installation__attrition_fraction = 0.001

installed_capital__cost_per_MW = 1775000

investor__commitment = IF wind_power__opportunity_profit<1THEN 0 ELSE amount_committed

level_of__visual_impact = GRAPH(distance__between_WES__and_community)

(0.00, 0.1), (0.8, 0.0705), (1.60, 0.054), (2.40, 0.039), (3.20, 0.03), (4.00, 0.024), (4.80, 0.018), (5.60, 0.0165), (6.40, 0.0165), (7.20, 0.015), (8.00, 0.015)

level_of_visual_impact_to_society_awareness = GRAPH(level_of__visual_impact)

(0.00, 0.0025), (0.015, 0.0025), (0.03, 0.00375), (0.045, 0.00625), (0.06, 0.0675), (0.075, 0.129), (0.09, 0.205), (0.105, 0.235), (0.12, 0.244), (0.135, 0.245), (0.15, 0.246)

net_carbon__footprint = Carbon__footprint_avoided__by_WES-Carbon_footprint__added_by_WES

net_employment__rate = Skilled_personnel_for_WES_decommissioning+Skilled_personnel_for_WES_installation+Skilled_personnel__for_WES_O&M

net_tax = federal_tax*(WES_revenue-rate_of_WES__total_cost-depreciation)

net_water_savings = Water_conserved__by_WES-Water_use__by_WES

noise__social_impact = GRAPH(noise_perception)

(0.00, 0.00), (10.0, 0.00), (20.0, 0.00), (30.0, 0.00), (40.0, 0.1), (50.0, 0.15), (60.0, 0.2), (70.0, 0.2), (80.0, 0.2), (90.0, 0.2), (100, 0.2)

noise_perception = (turbine__sound_power-(10*LOG10(2*PI*(distance__between_WES__and_community*1000)^2))-(0.005*(distance__between_WES__and_community*1000)))+5 number_of__operating_wind_turbines = Number_of__wind_turbines__installed*operating_rate

number_of___abandoned__wind_turbines = Number_of__wind_turbines__installed*abandonment_rate

O&M__target_workers = number_of__operating_wind_turbines*0.051

O&M_attrition__fraction = 0.001

O&M_cost__per_MWh = 14.8

operating_rate = 0.95

permanent__land_used = 0.3*Number_of__wind_turbines__installed*capacity_per__turbine

probability_of__getting_incentives = GRAPH(TIME)

(0.00, 0.00), (1.00, 1.00), (2.00, 0.00), (3.00, 1.00), (4.00, 0.00), (5.00, 1.00), (6.00, 1.00), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 0.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 1.00), (18.0, 1.00), (19.0, 1.00), (20.0, 0.84), (21.0, 0.84), (22.0, 0.84), (23.0, 0.84), (24.0, 0.84), (25.0, 0.84), (26.0, 0.84), (27.0, 0.84), (28.0, 0.84), (29.0, 0.84), (30.0, 0.84)

rate__of_excavation__per_wind_turbine = 15000

rate_of_waste__produced_per_turbine = 0.07575

ratio_of_water__use_per_person = 523.060659

replacement__for_O&M = 0.001

replacement__for_installation_attrition = 0.001

replacement_for__decommissioning = 0.001

rotor_diameter = 80

society__awareness_impact = GRAPH(society_awareness)

(0.00, 0.00675), (0.04, 0.00825), (0.08, 0.0128), (0.12, 0.0173), (0.16, 0.0293), (0.2, 0.0607), (0.24, 0.11), (0.28, 0.134), (0.32, 0.143), (0.36, 0.148), (0.4, 0.148)

society_awareness = level_of_visual_impact_to_society_awareness+turbine__installation_impact target_wind__power_generation = 14.2e7

target_workers = rate_of_wind__turbines_installation___in_WES*0.578

traditional_energy__source__water__use_factor = 519

traditional_energy_source____greehouse_gases__emissions_factor = 0.689551

turbine__installation_impact = GRAPH(Number_of__wind_turbines__installed)

(0.00, 0.00), (100, 0.003), (200, 0.00975), (300, 0.057), (400, 0.093), (500, 0.113), (600, 0.134), (700, 0.145), (800, 0.147), (900, 0.147), (1000, 0.148)

turbine__sound_power = 107

turbine_resale_price = DELAY(wind__turbine_cost,20)*0.5

waste__conversion_factor = 0.04

waste_produced__per_turbine__during_decommissioning = 3390

waste_produced__per_turbine__during_installation = 3390

water__conversion_factor = 0.0000003

water_drained_from_O&M_ratio = 0

water_drained_from__WES_installation_factor = 0.65

water_drained_from_WES_decommissing_factor = 0.9231

water_withdraw_duirng_O&M_factor = 1

water_withdrawn_during_decommissioning_factor = 13

water_withdraw_during_installation_factor = 26

WES_installed__capacity = capacity_per__turbine*number_of__operating_wind_turbines

WE__population__resistance = ((ecological_footprint_social_impact+level_of__visual_impact+noise__social_impact)-(employment__social_impact+society__awareness_impact))/adjusting_time

wind__turbine_cost = 1296000

wind_power__generation_difference = If target_wind__power_generation<wind_power__generated_by_WES THEN 0 ELSE target_wind__power_generation-wind_power__generated_by_WES

wind_power__opportunity_profit = IF estimated__revenue>estimated_total__cost_of_wind_power__generation_difference THEN((estimated__revenue/estimated_total__cost_of_wind_power__generation_difference)) ELSE 0

wind_turbine__installation_per__time_period = GRAPH(fraction_of__land_used)

(0.00, 0.65), (0.1, 0.65), (0.2, 0.6), (0.3, 0.58), (0.4, 0.55), (0.5, 0.5), (0.6, 0.49), (0.7, 0.45), (0.8, 0.25), (0.9, 0.15), (1, 0.00)

Appendix F

Wind Energy System Simulator Causal Model and Simulator Architecture Validation Package

The wind energy system sustainability simulator architecture is presented in Chapter 4. The validation package provided to the subject matter experts is presented here. The validation package includes the causal model factors and factor relationships, the stocks, flows, and auxiliary variables in the simulator. This package includes the initial simulator architecture and sets of stocks, rates, and auxiliary variables. The package included references that are provided with all the other references in the Reference section. The following section provides the causal model and the simulator architecture validation package:

Causal Model and Simulator Architecture Validation Package

Renewable energy sources have become an alternative to meet energy demand in a more sustainable manner. Their importance has been highlighted by society's increasing demand for energy, finite supply of traditional sources of energy and significant amount of greenhouse gas emissions when exploiting traditional energy sources. Wind energy is one of the fastest growing renewable energy sources worldwide (Wind Energy Foundation, 2013). Wind energy sustainability is an important challenge in energy systems. A goal of wind energy sustainability is to develop, operate and maintain wind energy system that doesn't cause negative social, environmental and economic impacts in the communities where they are located.

A causal model and simulator architecture representing wind energy system sustainability have been developed. The causal model graphically illustrates key factors, factor relationships and major feedback loops of the wind energy system. This provides a better understanding of the wind energy sustainability behavior as a whole. The simulator architecture has been developed based on the wind energy sustainability causal model. The simulator architecture would allow simulating impacts of various decisions related to the sustainability of wind energy systems.

Purpose

The purpose of the validation process includes:

1. Ensure that the factors and factor relationships represented in the causal model are valid.

2. Ensure that the simulator architecture is valid and is a reasonable representation of the system.

This validation process should require approximately three hours of your time.

Potential Users of the Simulator

Potential users of the simulator are decision makers who could benefit from using the simulator. The simulator could help decision makers to assess the impacts of policies on the sustainability of wind energy system as a whole.

Scope of the Model

The scope of the model encompasses the installation, operation and maintenance (O&M), and decommissioning phases of the wind energy system.

Assumptions

1. A wind energy system is composed of various wind energy projects that are geographically located in the same country/state.
2. Wind energy projects considered in this research are utility scale projects. Utility scale projects produce a large amount of electricity to be sold in the electric grid.
3. Turbine technology is considered out of scope for this model since technical analysis for selecting appropriate type of turbine is done in previous phases of the system cycle.
4. The electric grid is out of the scope for the research. The dynamics under study for this research are related to understanding wind energy system sustainability. The electric grid is composed of different sources of energy, renewable and nonrenewable; therefore the dynamics involved in the electric grid should include the effects of all those kind of energy sources and will require additional study.

Wind Energy Sustainability Causal Model Validation Purpose

The purpose of the causal model validation process is to ensure that the factors and factor relationships represented in the causal model are a reasonable representation of factors and factor relationships related to sustainability of wind energy.

Causal Model Introduction

Causal models graphically illustrate the factors and factor relationships in a system. Literature review and analysis of wind energy systems and other renewable energy sources, including previously developed wind energy causal models, and other renewable energy sources causal models, resulted in the identification of a set of factors and relationships that are represented in a causal model. Multiple factors contribute to wind energy sustainability. Figure F.1 shows the wind energy sustainability causal model to be validated. The scope of the model encompasses the wind energy system installation, O&M and decommissioning phases.

Causal diagrams capture the major feedback mechanisms within a system. These diagrams can demonstrate various hypotheses about factors. Elements (factors) and arrows (relationships) are included in a causal diagram. A sign (either + or –) is assigned on each link indicating an increasing or decreasing relationship between factors. The positive or negative signs on the arrows indicate the nature of the relationship in the causal model. The arrow heads also have a direction that indicates the sequence of the factors and the factor relationships. Reviewers need to look at the sequence of the factors and relationships. Some factors have indirect relationships from other factors versus direct relationships. An understanding of the factors and the relationships between factors provides a better understanding of what drives wind energy sustainability.

Causal Model Factors and Relationships

The factors in the causal model are listed in Table F-1 including a definition of each factor and the unit of measurement.

The causal model indicates that as the number of operating wind turbines increases, the wind energy installed capacity increases. As the rate of wind turbine abandonment increases, the number of abandoned wind turbines increases. As the number of abandoned wind turbines increases, the number of operating wind turbines decreases. As the wind turbine dimension increases, the wind turbine capacity increases. As the wind turbine capacity increases, the wind energy installed capacity increases. As the number of wind turbines installed increases, the quantity of skilled personnel needed during wind energy system installation and O&M increases.

As the number of decommissioned wind turbines increases, the quantity of skilled personnel needed during wind turbine decommissioning also increases. As the quantity of skilled personnel needed during wind energy system installation, O&M and decommissioning increases, the employment rate increases. As the employment rate increases, the wind energy population resistance decreases.

An increase in the number of wind turbines installed cause additional multiple effects. As the number of wind turbines installed increases, the number of operating wind turbines increases. As the number of wind turbines installed increases, wind energy installed capital cost increases. As the cost of turbine increases, wind energy installed capital cost also increases. As the number of operating wind turbines increases, wind energy O&M cost increases. As the wind turbine dimension increases, wind energy O&M cost decreases. As the wind turbine dimension increases, the wind energy installed capital cost increases. Volume of wind energy water consumption, energy used for wind energy installation and O&M, volume of waste from wind energy installation and O&M, and volume of excavation and trenching are also expected to increase as a result of an increase in the number of wind turbines installed. As the number of wind turbines installed increases, the available land for wind energy projects decreases. When the number of wind turbines installed increases, the number of accidents during wind energy installation, and O&M are expected to increase.

As the balance of station cost increases, the wind energy installed capital cost increases. As the soft cost increases, the wind energy installed capital cost increases. When the wind energy installed capital cost increases, the wind energy total cost increases. An increase in wind energy O&M cost also increases wind energy total cost. As the wind turbine decommissioning cost increases, the wind energy total cost increases. An increase in the wind energy total cost increases the electricity price. An increase in the electricity price increases the utility electricity price. An increase in the electricity price also increases the utility resistance to wind energy integration.

As the utility electricity price increases, the wind energy population resistance increases. As the wind energy installed capacity increases, the electrical energy reserves increases. As the electrical energy reserves increases, the wind energy integration cost increases. As the wind energy integration cost increases, the utility resistance increases. As the number of wind turbines to be installed increases, the number of wind turbines installed increases. As the number of wind turbines installed increases, the society awareness to wind energy also increases. As the society awareness of wind energy increases, wind energy population resistance decreases. An increase in the wind energy population resistance decreases the amount of economic incentives for implementing wind technology advances.

As the volume of excavation and trenching increases, the ecological footprint increases. As available land for wind energy increases, the ecological footprint decreases. As the volume of wind energy water consumption increases, the ecological footprint also increases. As the volume of waste from wind energy installation and O&M increases, the ecological footprint increases. As the volume of waste from wind turbine decommissioning increases, the ecological footprint also increases. As the carbon footprint increases, the ecological footprint increases. As the ecological footprint increases, the wind energy population resistance increases.

As the energy used for wind energy installation and O&M increases, the carbon footprint increases. As the energy used for wind turbine decommissioning increases, the carbon footprint also increases. Increases of wind power generated, decreases the carbon footprint. When the wind energy installed capacity increases, the wind power generated increases. As the wind turbine dimension increases, the capacity factor increases. As the site wind speed increases, the capacity factor also increases. As the capacity factor increases, the wind power generated also increases.

As the target electric power generation increases, the target wind power generation increases. As the target wind power generation increases, the wind power generation shortage increases. As the wind power generated increases, the wind power generation shortage decreases. As the wind power generation shortage increases, the wind power opportunity profit increases. As the electricity price increases, the wind power opportunity profit also increases. As the wind power opportunity profit increases, the investor commitment increases. As the amount of available funds for wind energy development increases, the investor commitment also increases.

As the percentage of funds to be committed for wind development increases, the investor commitment also increases. As the investor commitment increases the number of wind turbines to be installed increases.

As the wind power generation shortage increases, the estimated number of wind turbines to be installed increases. As the estimated number of wind turbines to be installed increases, the estimated wind energy installed capital cost, estimated wind energy O&M cost, and the estimated wind turbine decommissioning cost increase. As the estimated wind energy installed capital cost, estimated wind energy O&M cost, and the estimated wind turbine decommissioning cost increase, the estimated total cost of shortage wind power generation increases. As the estimated cost of turbine increases, the estimated wind energy installed capital cost increases. As the estimated soft cost increases, the estimated wind energy installed capital cost increases. As the estimated balance of station increases, the estimated wind energy installed capital cost increases. As the wind turbine dimension increases, the estimated wind energy O&M cost decreases.

As the estimated total cost of shortage wind power generation increases, the wind power opportunity profit decreases. As the amount of economic incentives for implementing wind technology advances increases, the estimated incentives to be acquired for implementing wind technology advances increases. As the estimated probability of getting incentives increases, the estimated incentives to be acquired for implementing wind technology advances increases. As the estimated incentives to be acquired for implementing wind technology advances increases, the wind power opportunity profit increases.

As the wind power generated increases, the profit from wind energy increases. As the electricity price increases, the profit from wind energy sales also increases. As the wind energy total cost increases, the profit from wind energy decreases. As the profit from wind energy increases the net present value (NPV) increases. As the interest rate increases, the NPV decreases.

As the wind power generated increases, the amount of electricity available for use also increases. As the amount of electricity available for use increases, the level of energy security increases.

As the number of wind turbines installed increases, bird/bat strikes increases. An increase on bird/bat strikes results in a decrease of bird/bat population. As the level of visual impact increases, the society awareness increases.

As the level of visual impact increases, the wind energy population resistance also increases. As the distance between wind projects and community increases, the impact from ice shedding, the electromagnetic interference, the perceived amount of noise from wind turbines, and the level of visual impact decrease. As the perceived amount of noise from wind turbines increases, the wind energy population resistance increases. As the wind energy population resistance increases, the number of wind turbines to be installed decreases.

As the number of accidents increases, the wind energy population resistance increases. As the impact from ice shedding, and the electromagnetic interference increase, the wind energy population resistance also increases. As the bird/bat population increases, the wind energy population resistance decreases.

As the wind energy population resistance increases, the level of reinforcement of government regulations, standards and policies for wind energy increases. As the utility resistance increases, the level of reinforcement of government regulations, standards and policies for wind energy also increases.

As the number of accidents increases, the wind energy population resistance increases. As the impact from ice shedding, and the electromagnetic interference increase, the wind energy population resistance also increases. As the bird/bat population increases, the wind energy population resistance decreases.

As the rate of wind turbines decommissioning increases, the number of decommissioned wind turbines increases. As the number of decommissioned wind turbines increases, the number of wind turbines installed in the wind energy system decreases.

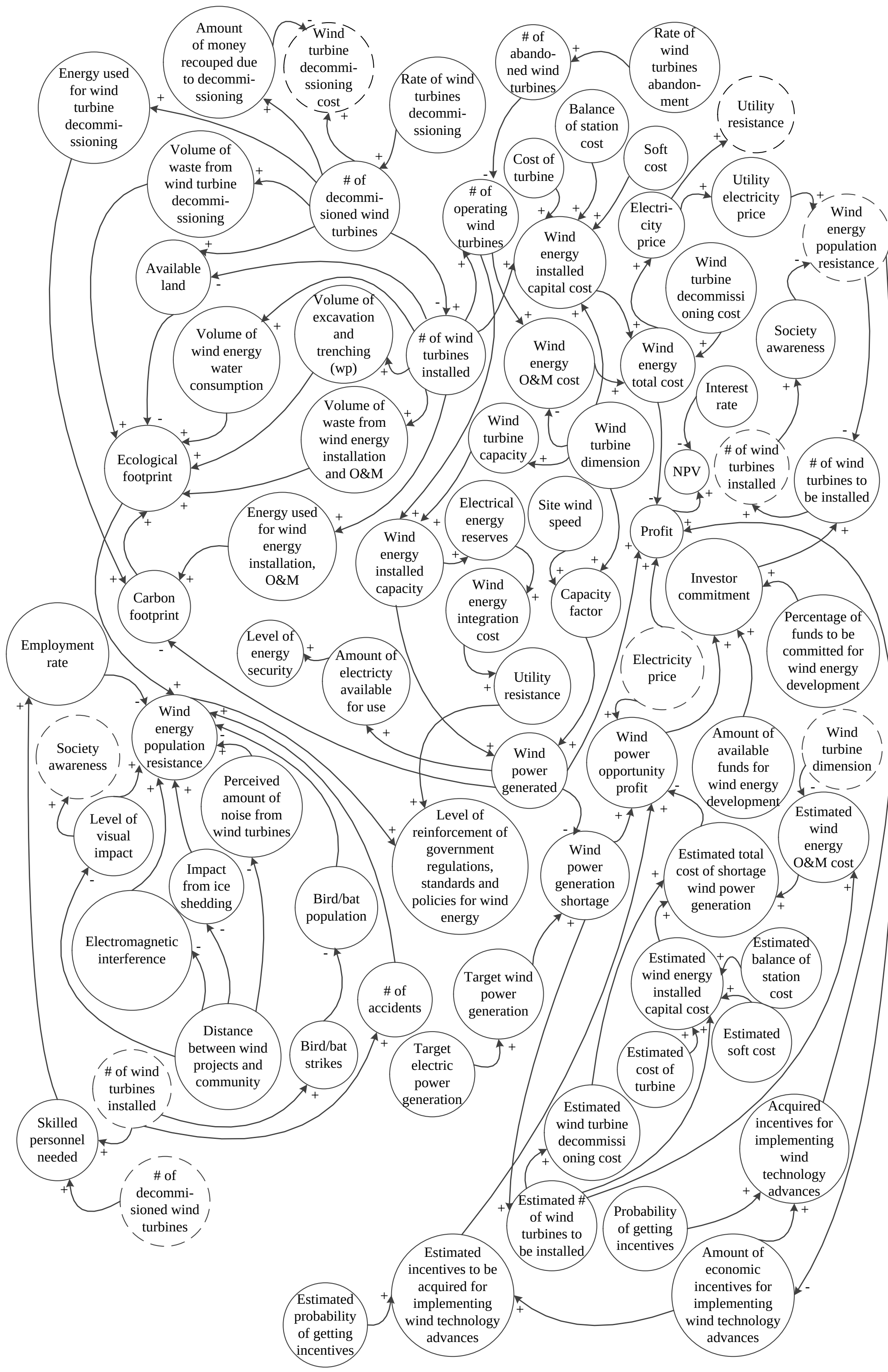

Figure F-1 Wind Energy System Sustainability Causal Model

As result of an increase on the number of decommissioned wind turbines, the wind turbine decommissioning cost, the amount of money recouped due to decommissioning, and the volume of waste from wind turbine decommissioning also increase. As the number of decommissioned wind turbines increases, the available land for wind energy increases. As the number of decommissioned wind turbines increases, the energy used for wind turbine decommissioning also increases.

As the amount of economic incentives for implementing wind technology advances increases, the acquired incentives for implementing wind technology advances increases. As the amount of economic incentives for implementing wind technology advances increases, profit increases. As the probability of getting incentives increases, the acquired incentives for implementing wind technology advances increases.

Table F-1 Wind Energy System Sustainability Factors and Metrics

Factor	Model Definition	Units
# of abandoned wind turbines	The number of wind turbines abandoned after end of useful life. Abandoned turbines remain in their original installed location.	Number of turbines
# of accidents	# of human incidents fatal or not that occur in the wind energy system during installation, O&M and decommissioning.	Number of accidents
# of decommissioned wind turbines	The total number of wind turbines that are decommissioned from the wind energy system. Decommissioning means turbines are removed from their installed site.	Number of turbines
# of operating wind turbines	Refers to the actual number of turbines operating in the wind energy system.	Number of turbines
# of wind turbines installed	The total number of wind turbines installed in the wind energy system.	Number of turbines
# of wind turbines to be installed	The total number of wind turbines to be installed based on investor’s commitment.	Number of turbines

Table F.1—*Continued*

Acquired incentives for implementing wind technology advances	Refers to the actual amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Amount of available funds for wind energy development	Refers to the actual amount on financial markets available for wind energy investments	Dollars
Amount of economic incentive for implementing wind technology advances	Provides motivation in financial form to businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Amount of electricity available for use	Refers to the total amount of electricity, independent of the type of source, available for use in the electric grid.	Gigawatts
Amount of money recouped due to decommissioning	Represents the amount of money recuperated due to decommissioning of wind turbines.	Dollars / year
Available land	Refers to the total land available that could be used for wind energy development or any other purpose.	Square meter (m^2)
Balance of station cost	Refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Balance of plant/station is the cost of all infrastructural and facilities of a wind project with an exception of the turbine and all its elements (Tegen et al., 2012).	Dollars
Bird/bat population	Average bird/bat population in the area where wind energy projects are located.	Number of birds / area
Bird/bat strikes	# of birds/bats that hit the wind turbines and die.	Number of birds / area

Table F.1—*Continued*

Capacity factor	The ratio of wind energy (assuming all turbines are same size) actual output over a period of time, to its potential output if it were possible for it to operate at full theoretical capacity indefinitely.	%
Carbon footprint	The demand on biocapacity required to sequester the carbon dioxide CO_2) emissions from fossil fuel combustion (Global Footprint Network, 2012).	Grams of carbon dioxide
Cost of turbine	Refers to the unit cost of turbine.	Dollars
Distance between wind projects and community	Distance between wind project and closest surrounding community.	Kilometers
Ecological footprint	Represents the amount of land and water area required for nature to regenerate the resources used by the wind energy project development (Global Footprint Network, 2012).	Global hectares
Electrical energy reserves	Refers to the electric generation that has to be on reserve to cover any imbalance and intermittent operation of wind energy.	Megawatts
Electricity price	Represents the average sale price of electricity generated from a wind energy system to utilities.	Kilowatts / Dollars
Electromagnetic interference	Any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades the effective performance of electronics and electrical equipment. Refers to the interference of wind turbines with electromagnetic communication systems.	dBMV
Employment rate	Represents the rate of employment during the wind energy installation, O&M and decommissioning phases. % of direct and indirect jobs related to the development of the wind energy system.	%

Table F.1—*Continued*

Energy used for wind turbine decommissioning	Amount of electricity and other energy sources used during decommissioning activities.	Megawatts / hour
Energy used for wind energy installation, and O&M	Amount of electricity and other energy sources used during wind energy installation, and O&M.	Megawatts / hour
Estimated # of wind turbines to be installed	Refers to the estimated number of wind turbines that would be required to cover the total wind energy shortage.	Number of turbines
Estimated balance of station	Balance of station is the estimated cost of all infrastructural and facilities of a wind project with an exception of the turbine and all its elements	Dollars
Estimated cost of turbine	Refers to the estimated unit cost of turbine.	Dollars
Estimated incentives to be acquired for implementing wind technology advances	Refers to the potential amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Estimated probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances to cover the total wind energy shortage.	%
Estimated soft cost	Refers to the estimated costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars
Estimated total cost of shortage wind power generation	Refers to the estimated cost of wind turbines installation, and O&M to cover total wind power shortage.	Dollars
Estimated wind energy installed capital cost	Refers to the estimated amount of investment required to cover the total wind power shortage.	Dollars

Table F.1—*Continued*

Estimated wind energy O&M cost	Represents the estimated operational and maintenance costs of the additional wind turbines required to cover the total wind power shortage.	Dollars
Impact from ice shedding	Impact from ice that is shed from wind turbines.	Dollars
Interest rate	Refers to the cost of money required to pay to a lender to develop a wind energy project.	%
Investor commitment	Refers to investor interest in financing additional wind power installation.	Dollars
Level of energy security	Refers to equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed, and socially acceptable energy services to end users (Sovacool, 2012).	Index
Level of reinforcement of government regulations, standards, and policies for wind energy	Indicates the severity of government regulations, standards, and policies for wind energy efforts.	Level 1- Severe 2- Strong 3- Minimal 4- Negligible
Level of visual impact	Represents how well wind turbines can be seen from horizon.	Levels: 1-Visual dominate 2- Visual intrusive 3- Noticeable 4- Negligible
Net present value (NPV)	Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flow is the algebraic sum of money estimated to flow in and out of a company over some period of time as a result of a particular project (Stevens, 1994).	Dollars
Perceived amount of noise from wind turbines	Refers to the amount of noise perceived in the nearest communities during wind turbine operation	Decibels
Percentage of funds to be committed for wind energy development	Refers to the fraction of available funds for wind energy development to be committed by investors.	%

Table F.1—*Continued*

Probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances.	%
Profit	The amount remaining after wind energy total costs are deducted from total revenue.	Dollars / year
Rate of wind turbine abandonment	Rate at which turbines are abandoned in the wind energy system once turbines end of useful life have been reached.	Number of turbines / year
Rate of wind turbine decommissioning	Represents the rate at which turbines are decommissioned once they have reached the end of useful life.	Number of turbines / year
Site wind speed	The actual wind speeds that flow in a site that could be useful for wind energy deployment.	Meters/seconds
Skilled personnel needed	Represents the human resources needed with the skill level required for wind energy installation, O&M and decommissioning.	Number of people
Society awareness	Refers to the knowledge accumulated in society due to experience with wind energy.	Levels: 1-Familiar to wind energy 2-Some familiarity to wind energy 3-No familiar to wind energy
Soft cost	Refers to costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs (Tegen et al., 2012).	Dollars
Target electric power generation	Refers to the total amount of electric power expected to be generated in a defined time period.	Megawatt hour
Target wind power generation	Refers to the amount of electric power expected to be generated from wind energy in a defined time period.	Megawatt hour
Utility electricity price	Refers to the electricity sale price to end customers.	Dollars/Megawatt hour
Utility resistance	Refers to opposition of utility companies to wind energy.	%

Table F.1—*Continued*

Volume of excavation and trenching	Amount of land excavating and trenching required for turbine tower installation, access roads, electric substation and O&M building construction.	Cubic meter
Volume of waste from wind turbine decommissioning	Represents the amount of solid waste, hazardous and industrial waste produced during the wind turbine decommissioning.	Cubic meter
Volume of waste from wind energy installation and O&M	Represents the amount of solid waste, hazardous and industrial waste produced during the wind energy installation and O&M.	Cubic meter
Volume of wind energy water consumption	Represents the total amount of water needed for installation, O&M and decommissioning of wind energy system.	Cubic meter
Wind turbine decommissioning cost	Refers to the cost associated to decommissioning wind turbines and associated element once they have reach the end of their useful life.	Dollars/ year
Wind energy installed capacity	Theoretical maximum capacity of a wind energy system based on the number of wind turbines installed in the system.	Megawatts
Wind energy installed capital cost	The amount of investment required to develop a wind energy system. This includes wind turbines, balance of station and soft costs (Tegen et al., 2012).	Dollars
Wind energy integration cost	Refers to the costs added to the electric grid operation for including intermittent sources of energy (wind energy) in its operation.	Dollars / year
Wind energy O&M cost	Represents the operation and maintenance costs of a wind energy system. It includes land lease cost, labor wages and material, and levelized replacement costs.	Dollars / year

Table F.1—*Continued*

Wind energy population resistance	Refers to the general population opposition to wind energy projects.	%
Wind energy total cost	Sum of initial wind energy installed capital cost, O&M cost and decommissioning costs.	Dollars
Wind power generated	Amount of electric power generated by a wind energy system.	Megawatt hour / year
Wind power generation shortage	Refers to the difference between the actual wind power generated and the target wind power generation.	Megawatt hour
Wind power opportunity profit	Refers to the perceived potential profit that could be generated from wind power investment to cover wind power generation shortage.	Dollars
Wind turbine capacity	Refers to the nameplate capacity of a wind turbine.	Megawatt
Wind turbine dimension	Refers to the wind turbine rotor diameter.	Meters

Contact Information

The following contact information will only be used for authenticating an individual response to the validation exercise. All individual contact information and validation results will be kept confidential.

Name	
Role (Position)	
Experience (Years)	
Organization	

Validation Process

Factors

Please review the set of factors, factor units, and factor relationships in the causal model. For each factor in Table F.1, please answer these questions.

Space is allocated in Table F.2 for your inputs related to the factors. Please consider the following questions:

- Is the factor valid and reasonable?
- Is the definition of the factor reasonable?
- Is the unit for this factor reasonable?

Table F-2 Factors & Units (Please provide your comments here)

Factor	Comments
# of abandoned wind turbines	
# of accidents	
# of decommissioned wind turbines	
# of operating wind turbines	
# of wind turbines installed	
# of wind turbines to be installed	
Acquired incentives for implementing wind technology advances	
Amount of available funds for wind energy development	
Amount of economic incentive for implementing wind technology advances	
Amount of electricity available for use	
Amount of money recouped due to decommissioning	
Available land	
Balance of station cost	
Bird/bat population	
Bird/bat strikes	
Capacity factor	
Carbon footprint	
Cost of turbine	
Distance between wind projects and community	

Table F.2—*Continued*

Ecological footprint	
Electrical energy reserves	
Electricity price	
Electromagnetic interference	
Employment rate	
Energy used for wind turbine decommissioning	
Energy used for wind energy installation, and O&M	
Estimated # of wind turbines to be installed	
Estimated balance of station	
Estimated cost of turbine	
Estimated incentives to be acquired for implementing wind technology advances	
Estimated probability of getting incentives	
Estimated soft cost	
Estimated total cost of shortage wind power generation	
Estimated wind energy installed capital cost	
Estimated wind energy O&M cost	
Impact from ice shedding	
Interest rate	
Investor commitment	
Level of energy security	
Level of reinforcement of government regulations, standards, and policies for wind energy	
Level of visual impact	
Net present value (NPV)	
Perceived amount of noise from wind turbines	

Table F.2—*Continued*

Percentage of funds to be committed for wind energy development	
Probability of getting incentives	
Profit	
Rate of wind turbine abandonment	
Rate of wind turbine decommissioning	
Site wind speed	
Skilled personnel needed	
Society awareness	
Soft cost	
Target electric power generation	
Target wind power generation	
Utility electricity price	
Utility resistance	
Volume of excavation and trenching	
Volume of waste from wind turbine decommissioning	
Volume of waste from wind energy installation and O&M	
Volume of wind energy water consumption	
Wind turbine decommissioning cost	
Wind energy installed capacity	
Wind energy installed capital cost	
Wind energy integration cost	
Wind energy O&M cost	
Wind energy population resistance	
Wind energy total cost	
Wind power generated	

Table F.2—*Continued*

Wind power generation shortage	
Wind power opportunity profit	
Wind turbine capacity	
Wind turbine dimension	

Factor Relationship

Please answer the following questions related to the causal model. Table 4 provides the relationships between the factors and the nature of the relationship. Please use this table to answer the following questions:

- Are the relationships between the factors in the model valid and realistic?
- Does the nature of the links (positive or negative signs) on the causal model reflect the interactions between factors?

Table F-3 Factor Relationships

Factor →	Factor	+/-	Comment
# of abandoned wind turbines	# of operating wind turbines	-	
# of accidents	Wind energy population resistance	+	
	# of wind turbines installed	-	
# of decommissioned wind turbines	Available land	+	
	Amount of money recuperated due to decommissioning	+	
# of decommissioned wind turbines	Energy used for wind turbine decommissioning	+	
	Volume of waste from wind turbine decommissioning	+	
	Wind turbine decommissioning cost	+	
	Skilled personnel needed	+	

Table F.3—*Continued*

# of operating wind turbines	Wind energy installed capacity	+	
	Wind energy O&M cost	+	
# of wind turbines installed	# of accidents	+	
	# of operating wind turbines	+	
	Available land	-	
	Bird/bat strikes	+	
	Energy used for wind energy installation, and O&M	+	
	Skilled personnel needed	+	
	Society awareness	+	
	Volume of waste from wind energy installation and O&M	+	
	Volume of wind energy water consumption	+	
	Volume of excavation and trenching	+	
	Wind energy installed capital cost	+	
# of wind turbines to be installed	# of wind turbines installed	+	
Acquired incentives for wind technology advances	Profit	+	
Amount of available funds for wind energy development	Investor commitment	+	

Table F.3—*Continued*

Amount of economic incentives for implementing wind technology advances	Acquired incentives for wind technology advances	+	
	Estimated incentives to be acquired for implementing wind technology advances	+	
Amount of electricity available for use	Level of energy security	+	
Amount of money recuperated due to decommissioning	Wind turbine decommissioning cost	-	
Available land	Ecological footprint	-	
Balance of station cost	Wind energy installed capital cost	+	
Bird/bat population	Wind energy population resistance	-	
Bird/bat strikes	Bird/bat population	-	
Capacity factor	Wind power generated	+	
Carbon footprint	Ecological footprint	+	
Cost of turbine	Wind energy installed capital cost	+	
Distance between wind projects and community	Electromagnetic interference	-	
	Impact from ice shedding	-	
	Level of visual impact	-	
	Perceived noise from wind turbines	-	
Ecological footprint	Wind energy population resistance	+	

Table F.3—*Continued*

Electrical energy reserves	Wind energy integration cost	+	
Electricity price	profit	+	
	Utility electricity price	+	
	Utility resistance	+	
	Wind power opportunity profit	+	
Electromagnetic interference	Wind energy population resistance	+	
Employment rate	Wind energy population resistance	-	
Energy used for wind installation, and O&M	Carbon footprint	+	
Energy used for wind turbine decommissioning	Carbon footprint	+	
Estimated # of wind turbines to be installed	Estimated wind turbine decommissioning cost	+	
	Estimated wind energy installed capital cost	+	
	Estimated wind energy O&M cost	+	
Estimated balance of station	Estimated wind energy installed capital cost	+	
Estimated cost of turbine	Estimated wind energy installed capital cost	+	
Estimated incentives to be acquired for implementing wind technology advances	Wind power opportunity profit	+	

Table F.3—*Continued*

Estimated probability of getting incentives	Estimated incentives to be acquired for implementing wind technology advances	+	
Estimated soft cost	Estimated wind energy installed capital cost	+	
Estimated total cost of shortage wind power generation	Wind power opportunity profit	-	
Estimated wind energy installed capital cost	Estimated total cost of shortage wind power generation	+	
Estimated wind energy O&M cost	Estimated total cost of shortage wind power generation	+	
Impacts from ice shedding	Wind energy population resistance	+	
Interest rate	NPV	-	
Investor commitment	# of wind turbines to be installed	+	
Level of visual impact	Society awareness	+	
	Wind energy population resistance	+	
Perceived amount of noise	Wind energy population resistance	+	
Probability of getting incentives	Acquired incentives for wind technology advances	+	
Profit	NPV	+	
Rate of wind turbine abandonment	# of abandoned wind turbines	+	
Rate of wind turbine decommissioning	# of decommissioned wind turbines	+	

Table F.3—*Continued*

Site wind speed	Capacity factor	+	
Skilled personnel needed	Employment rate	+	
Society awareness	Wind energy population resistance	-	
Soft cost	Wind energy installed capital cost	+	
Target electric power generation	Target wind power generation	+	
Target wind power generation	Wind power generation shortage	+	
Utility electricity price	Wind energy population resistance	+	
Utility resistance	Level of reinforcement of government regulations, standards and policies for energy sustainability	+	
Volume of excavation and trenching	Ecological footprint	+	
Volume of waste from wind turbine decommissioning	Ecological footprint	+	
Volume of waste from wind energy installation and O&M	Ecological footprint	+	
Volume of wind energy water consumption	Ecological footprint	+	
Wind turbine decommissioning cost	Wind energy total cost	+	

Table F.3—*Continued*

Wind energy installed capacity	Electrical energy reserves	+	
	Wind power generated	+	
	Wind energy total cost	+	
Wind energy integration cost	Utility resistance	+	
Wind energy O&M cost	Wind energy total cost	+	
Wind energy population resistance	# of wind turbines to be installed	-	
	Amount of economic incentives for implementing wind technology advances	-	
	Level of reinforcement of government regulations, standards and policies for wind energy	+	
Wind energy total cost	Electricity price	+	
	Profit	-	
Wind power generated	Carbon footprint	-	
Wind power generated	Amount of electricity available for use	+	
	Profit	+	
	Wind power generation shortage	-	
Wind power generation shortage	Estimated of wind turbines to be installed	+	
	Wind power opportunity profit		
Wind power opportunity profit	Investor commitment	+	
Wind turbine capacity	Wind energy installed capacity	+	

Table F.3—*Continued*

Wind turbine dimension	Capacity factor	+	
	Wind energy installed capital cost	+	
	Wind energy O&M cost	+	
	Wind turbine capacity	+	

Additional Comments

Additional comments and insights are encouraged. Feel free to mark up the causal model. Please use the notes section below to provide additional information on your recommendations including any suggestions for changes with:

- Missing factors or incorrect factors
- Missing or unidentified relationships between factors
- Factor definitions and associated units

Notes

Additional recommendations and notes may be provided here.

Wind Energy Sustainability Simulator Architecture Validation

Purpose

The purpose of the wind energy sustainability simulator architecture validation process is to ensure the simulator architecture is valid and the model is a reasonable representation of the system.

Simulator Purpose

A wind energy sustainability simulator can help users to explore risks and evaluate the dynamic consequences of various decisions without affecting the real system. The simulator helps to perform what-if analysis to assess alternative scenarios. The wind energy sustainability simulator models the factors that relate to wind energy sustainability while considering the three pillars of sustainability (social, economic, and environmental). Energy decision makers can use such a simulator to understand the system dynamics associated with wind energy and use this knowledge to make informed decisions.

Simulator Scope

The scope of the model encompasses the wind energy project installation, O&M and decommissioning phases.

Simulator Architecture Introduction

Simulation is defined as the process of designing a model and performing experimentation with this model of a real system (Pritsker and O'Reilly, 1999). In the decision making process, simulation is a valuable aid to assess the impacts and evaluate implications of policies with no risk to the real system. Simulation enables 'what-if' analysis to consider alternative options. Architecture is defined as "the organizational structure of a system or component" (IEEE, 1990). A system dynamics model simulator architecture includes a set of stocks, flows, and auxiliary variables along with feedback. The notation for the simulator architecture is shown below:

Stocks represent state of the model or system. They are accumulations. Stocks are shown using rectangles (Figure F.2).

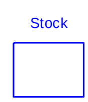

Figure F-2 Stock

Flows (also called rates) represent changes in the state of the model or system. Inflows are represented by an arrow pointing to (adding to) a stock and outflows are represented by an arrow pointing out (subtracting from) of a stock. Rates control the flows. Rates are represented with valves (Figure F.3).

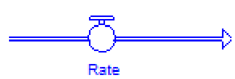

Figure F-3 Rate

Auxiliary variables are combinations of information inputs. They can modify the flows. Auxiliary variables are shown with circles (Figure F.4).

Figure F-4 Auxiliary variable

Clouds represent the sources and sinks for the flows. A source represents the stock from which a flow originates from outside the model scope. A sink represents the stock into which flows leaving the model scope drain. Sources and sinks are assumed to have infinite capacity and can never constrain the flow they support (Figure F.5).

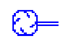

Figure F-5 Cloud

Arrows represent causal dependencies in the model. The simulator architecture is developed using the iThink simulation software. iThink software provides a flexible platform for building simulation models.

Simulator Architecture

The simulator architecture is based on the wind energy sustainability causal model. In order to better understand the simulator architecture, the wind energy sustainability causal model, illustrating factors included in the system dynamics architecture, is shown in Figure F.6. The shaded factors are those included in the simulator architecture. The factors definitions were presented in Table F.1. The wind energy simulator architecture is represented in Figure F.7. Definitions and units of measurements for the stocks, rates, and auxiliary variables for the simulator architecture are listed in Tables F.4, F.5 and F.6 respectively.

In order to allow the validator to more easily see the simulator architecture, Figure F.8 has been split to 4 sections as shown in Figure F.8 and is illustrated in Figures F.9, F.10, F.11 and F.12 respectively.

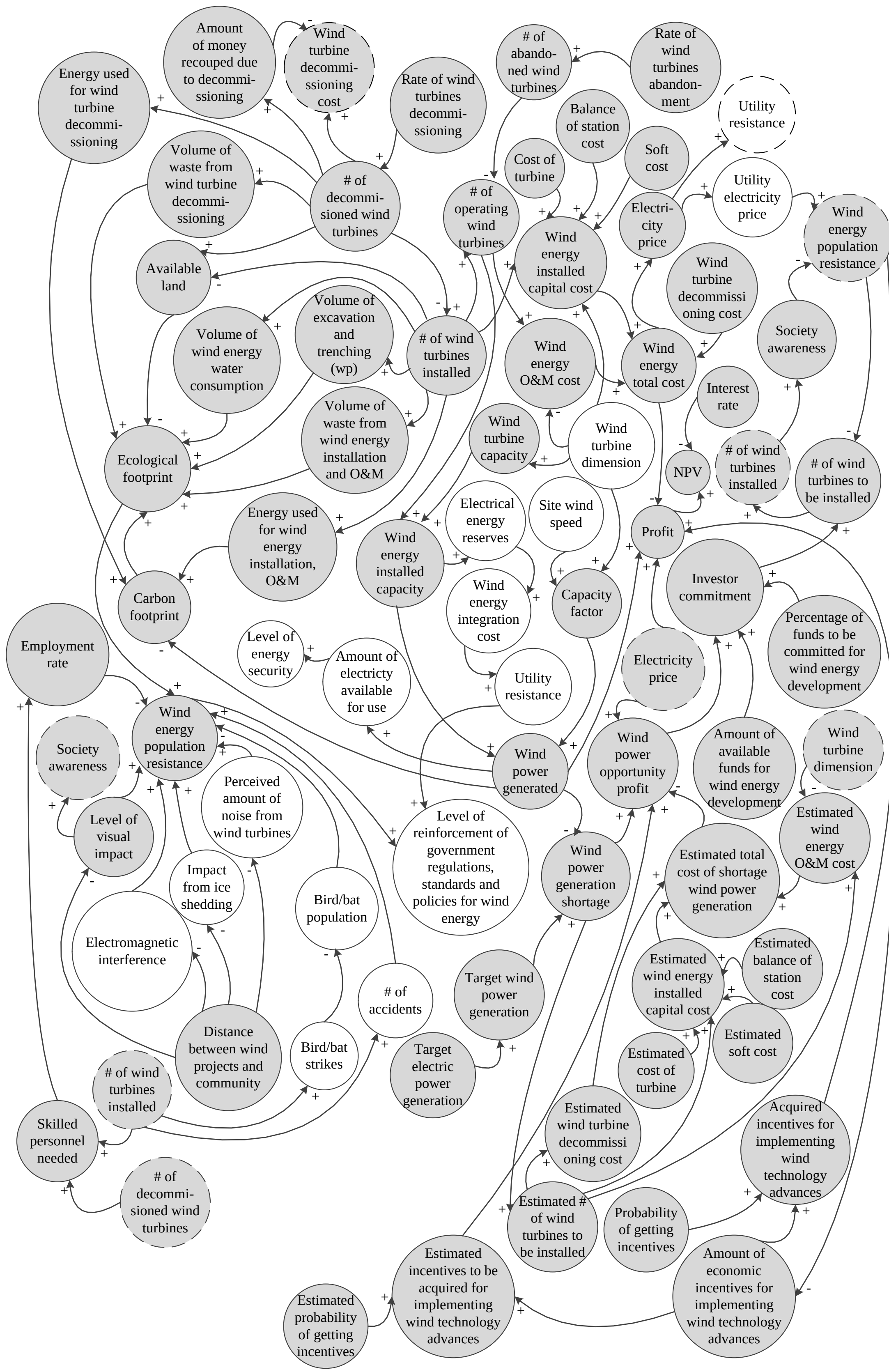

Figure F-6 Wind Energy System Sustainability Causal Model

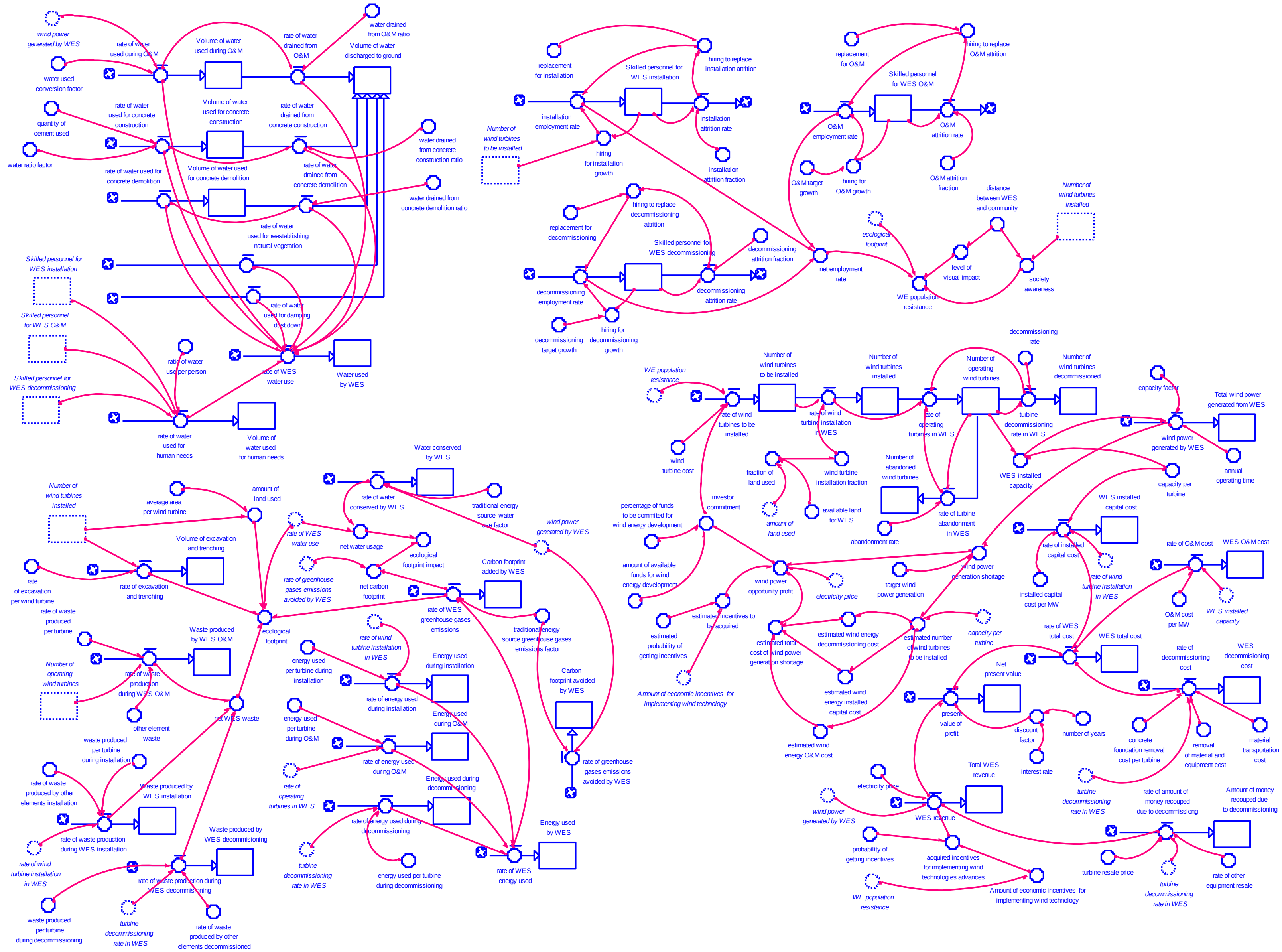

Figure F-7 Wind Energy System Sustainability Simulator Architecture

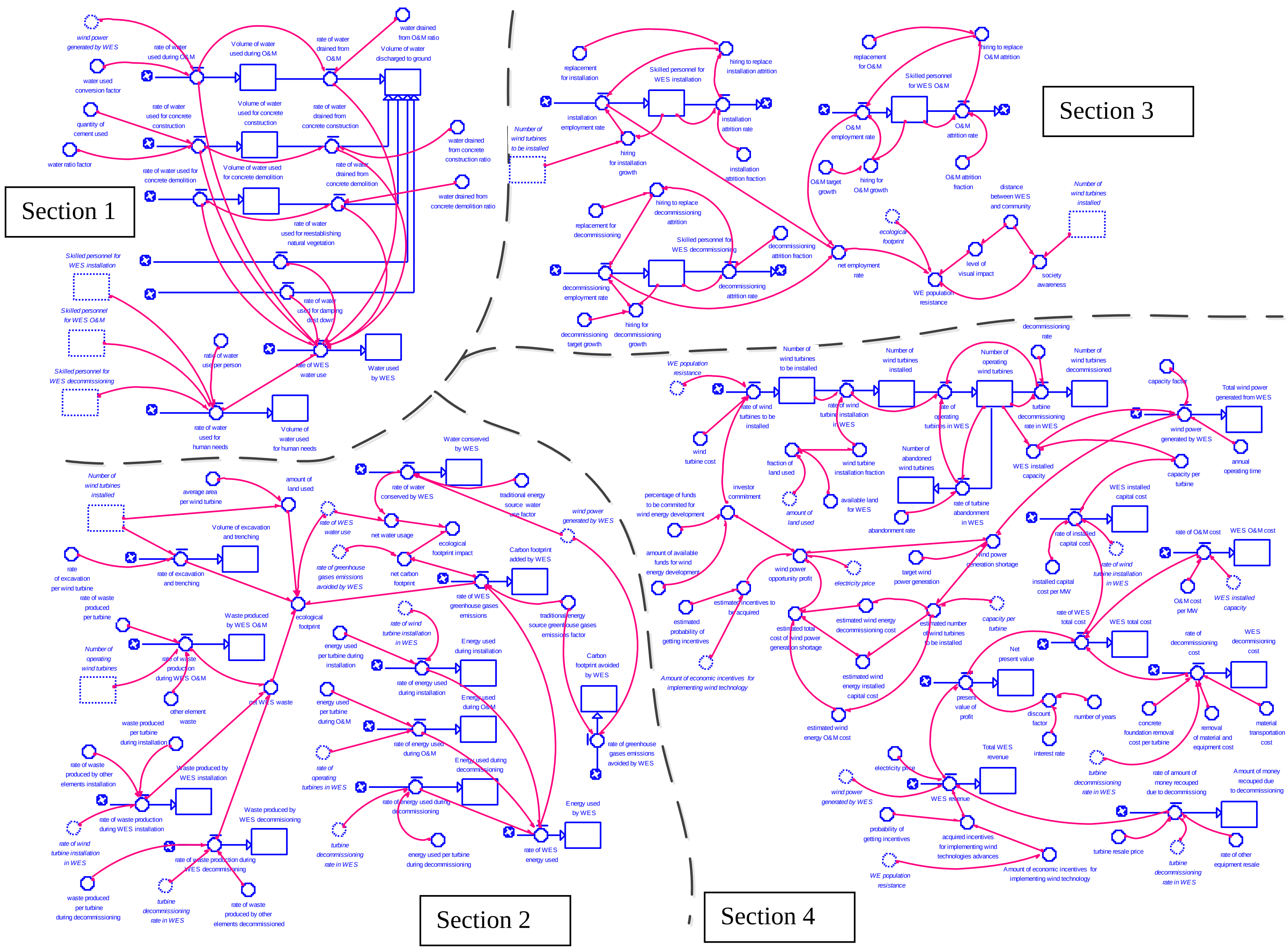

Figure F-8 Wind Energy System Sustainability Simulator Architecture Sections

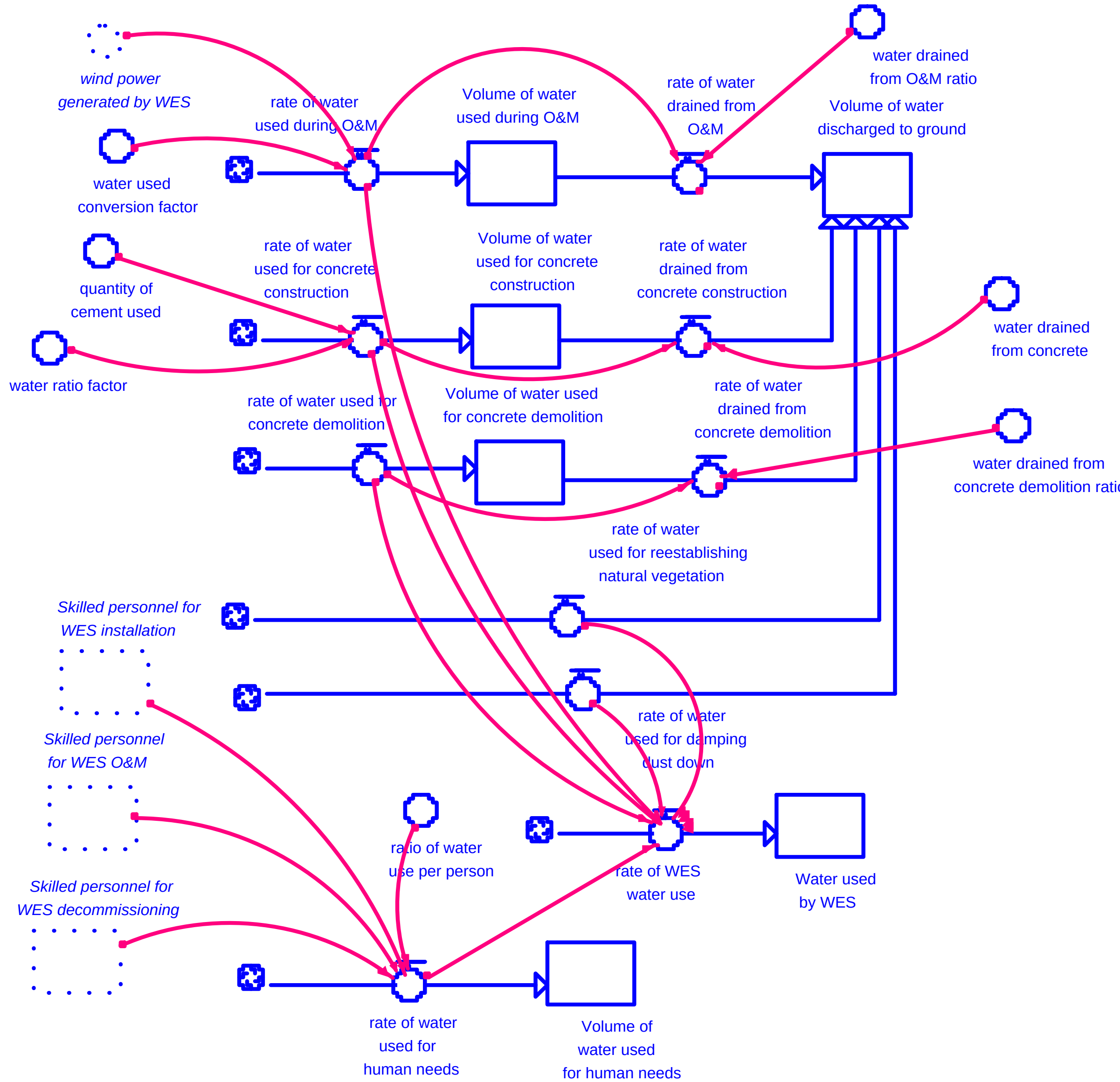

Figure F-9 Wind Energy System Sustainability Simulator Architecture Section 1

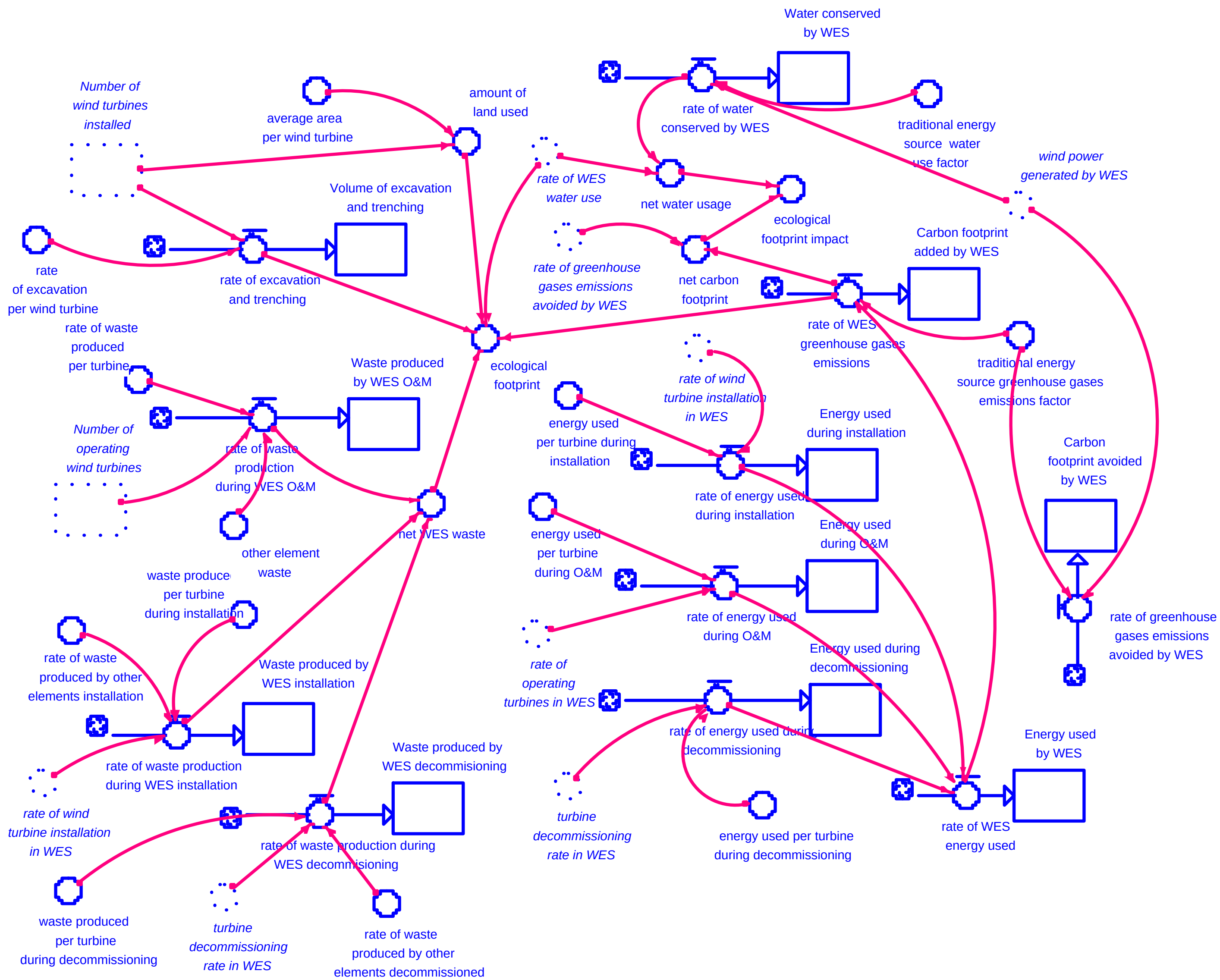

Figure F-10 Wind Energy System Sustainability Simulator Architecture Section 2

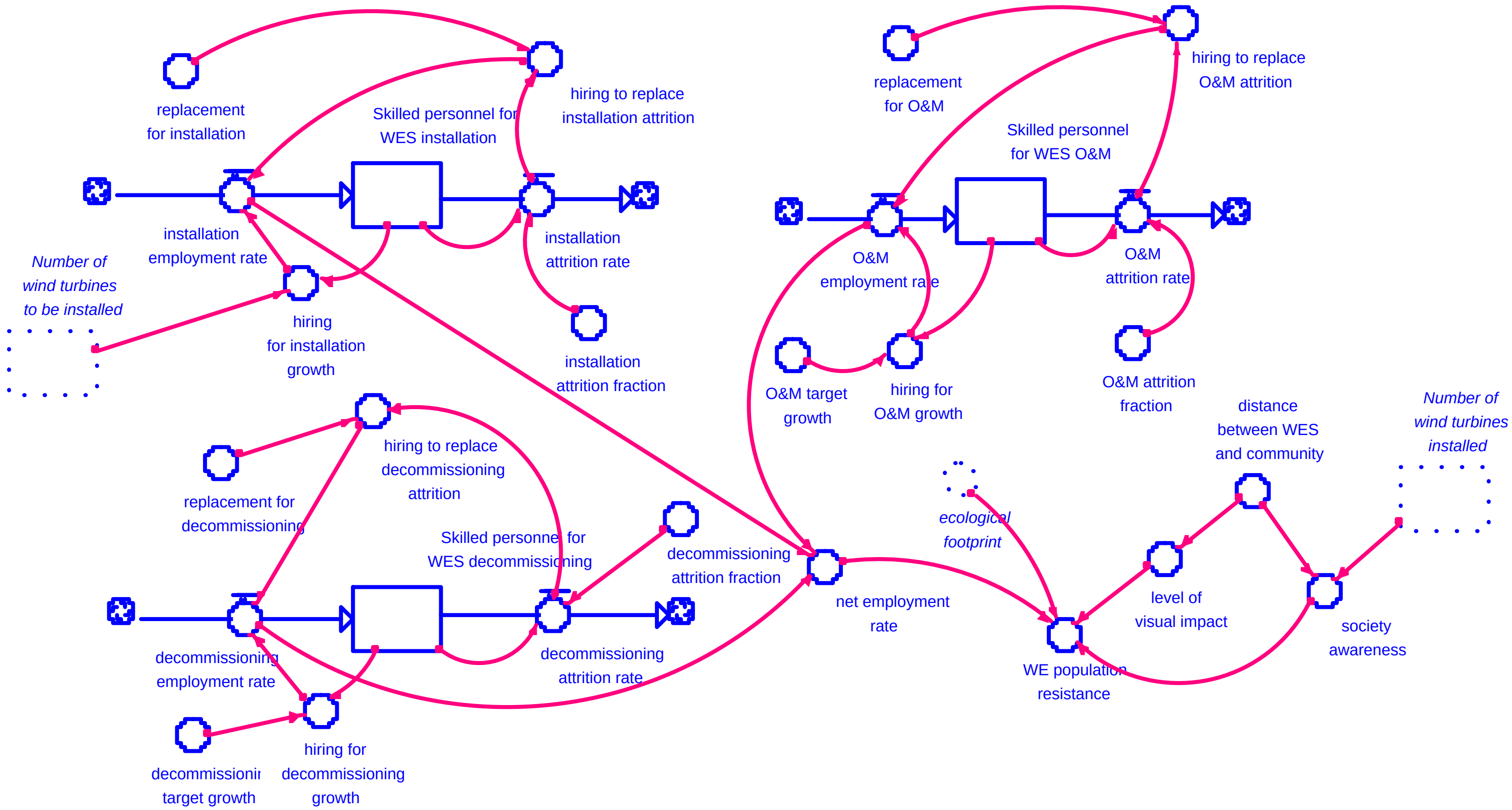

Figure F-11 Wind Energy System Sustainability Simulator Architecture Section 3

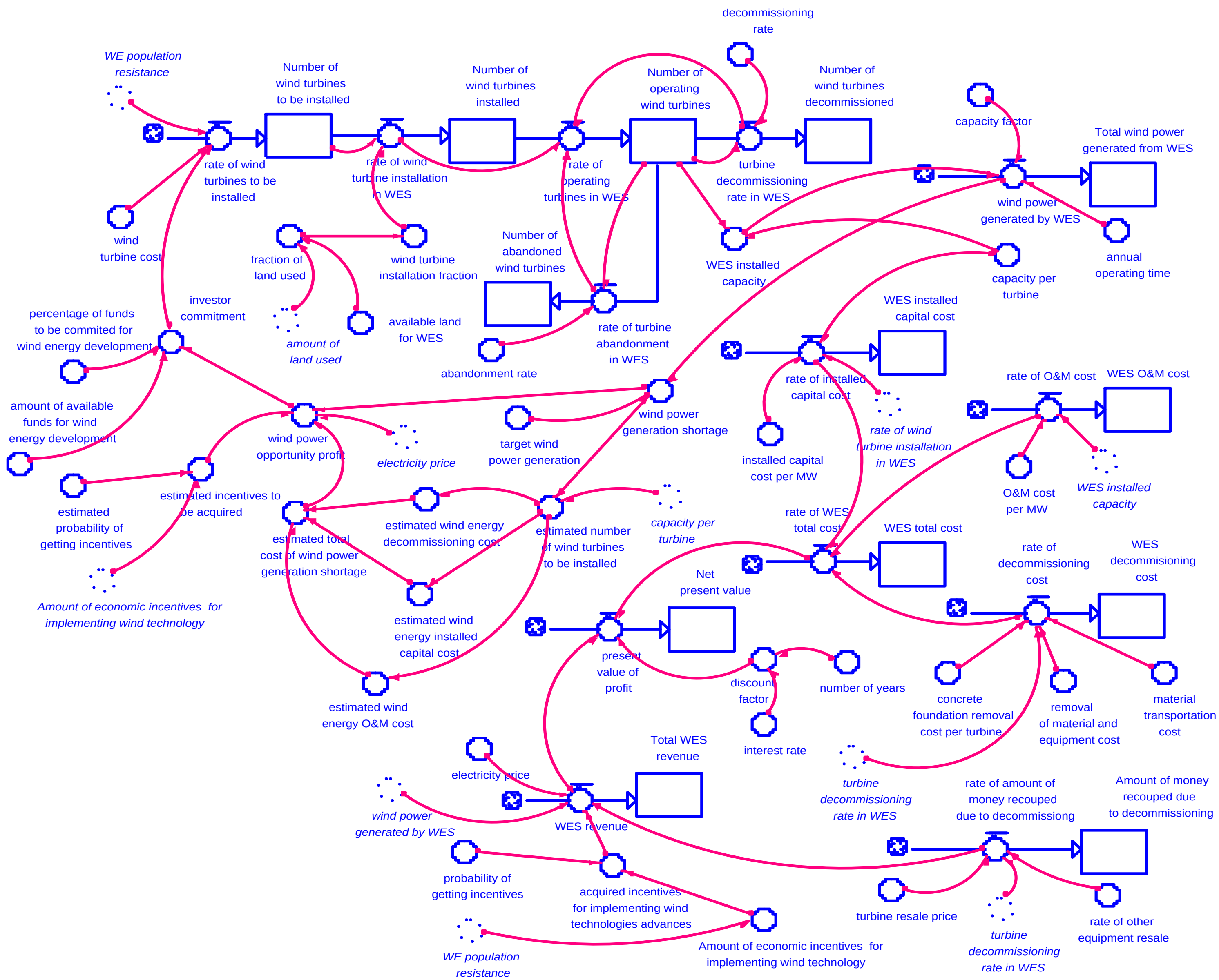

Figure F-12 Wind Energy System Sustainability Simulator Architecture Section 4

Table F.4 identifies the definition of each of the stocks in the simulator architecture along with a unit of measurement.

Table F-4 Stock Definitions & Units

Stock	Definition	Unit
Amount of money recouped due to decommissioning	Represents the accumulated amount of money recovered due to decommissioning of wind turbines.	Dollars
Carbon footprint added by WES (wind energy system)	Represents the greenhouse gases emissions caused to install, operate and /or decommission wind turbines and other elements of the system.	Grams of Carbon dioxide t (CO_2)
Carbon footprint avoided by WES	Represents the greenhouse gases emissions avoided by generating electricity from wind energy system.	Grams of Carbon dioxide (CO_2)
Energy used by WES	Represents the total energy used by WES during installation, O&M and decommissioning.	kWh
Energy used during decommissioning	Represents the energy used during wind turbine decommissioning.	kWh
Energy used during installation	Represents the energy used during WES installation.	kWh
Energy used during O&M	Represents the energy used during WES operation and maintenance.	kWh
Net present value	Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flows is the algebraic sum of money estimated to flow in and out of an organization over some period of time as a result of a particular project (Stevens, 1994).	Dollars
Number of abandoned wind turbines	Represents the number of wind turbines abandoned after end of operational life in the wind energy system.	Number of turbines
Number of operating wind turbines	Represents the number of wind turbines operating in the wind energy system.	Number of turbines

Table F.4—*Continued*

Number of wind turbines decommissioned	The number of wind turbines decommissioned from the wind energy system.	Number of turbines
Number of wind turbines installed	The number of wind turbines installed in a wind energy system.	Number of turbines
Number of wind turbines to be installed	The number of wind turbines installed in a wind energy system.	Number of turbines
Skilled personnel for WES decommissioning	Represents the human resources needed with the skill level required for decommissioning.	Number of people
Skilled personnel for WES installation	Represents the human resources needed with the skill level required for wind energy system installation.	Number of people
Skilled personnel for WES O&M	Represents the human resources needed with the skill level required for wind energy O&M.	Number of people
Total WES revenue	Represents the total income received by wind energy system operation.	Dollars
Total wind power generated from WES	Represents the accumulated amount of electric power generated by a wind energy system.	MWh
Volume of excavation and trenching	Amount of land excavating and trenching required for turbine tower installation, access roads, electric substation and O&M building construction.	Cubic meter
Volume of water discharged to ground	Represents the total amount of water discharged to ground by WES during installation, O&M and decommissioning.	Cubic meter
Volume of water used during O&M	Represents the total amount of water used during operation and maintenance phase.	Cubic meter
Volume of water used for concrete construction	Represents the total amount of water used for concrete construction during the installation phase.	Cubic meter

Table F.4—*Continued*

Volume of water used for concrete demolition	Represents the total amount of water used for concrete demolition during the decommissioning phase.	Cubic meter
Volume of water used for human needs	Represents the total amount of water used for the personnel working on the installation, O&M and/or decommission of the wind energy system.	Cubic meter
Waste produced by WES decommissioning	Represents the accumulated waste produced during wind energy decommission.	Cubic meter
Waste produced by WES installation	Represents the accumulated waste produced during wind energy installation.	Cubic meter
Waste produced by WES O&M	Represents the accumulated waste produced during wind energy O&M.	Cubic meter
Water conserved by WES	Represents the accumulated amount of water conserved for avoiding use of other energy sources due to wind power generation.	Cubic meter
Water used by WES	Represents the accumulated amount of water used by the wind energy system from installation phase through decommissioning phase.	Cubic meter
WES decommissioning cost	Represents the accumulated decommission cost of the wind energy system.	Dollars
WES installed capital cost	Represents the accumulated installed capital costs of a wind energy system.	Dollars
WES O&M cost	Represents the accumulated operation and maintenance costs of a wind energy system. It includes land lease cost, labor wages and material, and levelized replacement costs.	Dollars
WES total cost	Sum of initial wind energy installed capital cost, O&M cost and decommissioning cost.	Dollars

Table F.5 identifies the rates in the simulator architecture along with a definition and a unit of measurement for each.

Table F-5 Rate Definitions & Units

Rate	Definition	Unit
Decommissioning attrition rate	Represents the rate of personnel exiting from the decommissioning activities.	Number of people per year
Decommissioning employment rate	Represents the rate of employment during the wind energy decommissioning phase.	Number of people per year
Installation attrition rate	Represents the rate of personnel exiting from the installation activities.	Number of people per year
Installation employment rate	Represents the rate of employment during the wind energy installation phase.	Number of people per year
O&M attrition rate	Represents the rate of personnel exiting from the O&M activities.	Number of people per year
O&M employment rate	Represents the rate of employment during the wind energy O&M.	Number of people per year
Present value of profit	The amount remaining after wind energy total costs are deducted from total revenue.	Dollars per year
Rate of amount of money recouped due to decommissioning	Represents the rate at which money is recouped due to decommissioning of wind turbines.	Dollars per year
Rate of decommissioning cost	Represents the rate at which decommissioning expenditures are disbursed in the wind energy system.	Dollars per year
Rate of energy used during decommissioning	The rate at which energy is used during turbine decommissioning activities.	KWh per year
Rate of energy used during installation	The rate at which energy is used during turbine installation activities.	KWh per year
Rate of energy used during O&M	The rate at which energy is used during turbine O&M activities.	KWh per year

Table F.5—*Continued*

Rate of excavation and trenching	The rate at which land excavation and trenching required for turbine tower installation, access roads, electric substation and O&M building construction is performed.	Cubic meters/year
Rate of greenhouse gases emissions avoided by WES	The rate at which the greenhouse gases emissions is avoided by generating electricity from wind energy system.	Grams of Carbon dioxide (CO_2) per year
Rate of installed capital cost	The amount of investment required to develop a wind energy system. This includes wind turbines, balance of station and soft costs. Balance of station cost refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Soft cost refers to costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars / year
Rate of O&M cost	The rate at which O&M costs are utilized.	Dollars per year
Rate of operating turbines in WES	Represents the rate of operating turbines in the WES.	Number of turbines per year
Rate of turbine abandonment in WES	Rate at which turbines are abandoned in the wind energy system once turbines end of life have been reached.	Number of turbines per year
Rate of waste production during WES decommissioning	Represents the rate at which waste is produced during wind energy decommissioning.	Cubic meter per year
Rate of waste production during WES installation	Represents the rate at which waste is produced during wind energy installation.	Cubic meter per year

Table F.5—*Continued*

Rate of waste production during WES O&M	Represents the rate at which waste is produced during wind energy operation and maintenance.	Cubic meter per year
Rate of water conserved by WES	Represents the rate at which water is conserved due to wind energy consumption.	Cubic meter per year
Rate of water drained from concrete construction	The rate at which water is drained from concrete construction. The rate at which water is drained from concrete construction during installation phase.	Cubic meter per year
Rate of water drained from concrete demolition	The rate at which water is drained from concrete demolition. The rate at which water is drained from concrete demolition during decommissioning phase.	Cubic meter per year
Rate of water drained from O&M	The rate at which water is drained during wind energy O&M activities.	Cubic meter per year
Rate of water used during O&M	Represents the rate at which water is used during O&M phase.	Cubic meter per year
Rate of water used for concrete construction	Represents the rate at which water is used for concrete construction during wind energy installation.	Cubic meter per year
Rate of water used for concrete demolition	Represents the rate at which water is used during concrete demolition during the decommissioning phase.	Cubic meter per year
Rate of water used for damping dust down	Represents the rate at which water is used for damping dust during wind energy installation and decommissioning phases.	Cubic meter per year
Rate of water used for reestablishing natural vegetation	Represents the rate at which water is used for restoring natural vegetation during wind energy installation and decommissioning phases.	Cubic meter per year
Rate of water used for human needs	The rate at which water is used for human use on wind energy projects.	Cubic meter per year
Rate of WES energy used	The rate at which energy is used on the WES during installation, O&M and decommissioning	MWh per year

Table F.5—*Continued*

Rate of WES greenhouse gases emissions	The rate at which greenhouse gases emissions are produced due to wind energy system installation, O&M and decommissioning.	Grams of Carbon dioxide (CO_2) per year
Rate of WES total cost	Represents the wind project total cost. This is the sum of wind project installed capital cost, operation and maintenance cost, and decommissioning cost.	Dollars per year
Rate of WES water use	Represents the rate at which water is used in the wind energy system during installation, O&M, and decommissioning activities.	Cubic meter per year
Rate of wind turbine installation in WES	The rate at which wind turbines are added to the wind energy system.	Number of turbines per year
Rate of wind turbines to be installed	The rate at which wind turbines are planned to be installed post investor commitment.	Number of turbines per year
Turbine decommissioning rate	Represents the rate at which turbines are decommissioned once they have reached the end of life.	Number of turbines per year
WES revenue	Represents the income received by wind energy system operation.	Dollars per year
Wind power generated by WES	Represents the amount of wind power generated in an interconnected system.	Megawatts hour / year

Table F.6 identifies the auxiliary variables in the simulator architecture along with a definition and a unit of measurement for each.

Table F-6 Auxiliary Variable Definition & Units

Auxiliary Variable	Definition	Unit
Abandonment rate	The ratio at which turbine are abandoned at the end of their useful life.	#/year

Table F.6—*Continued*

Acquired incentives for implementing wind technologies advances	The actual amount of incentives in financial form obtained by particular businesses and investors to implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars / year
Amount of available funds for wind energy development	Refers to the actual amount on financial markets available for wind energy investments	Dollars / year
Amount of economic incentives for implementing wind technology	Provides motivation in financial form to businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Amount of land used	Refers to the amount of land already in used by WES.	Square meter (m^2)
Annual operating time	Refers to the amount of hours per year wind energy system is expected to operate.	Hours per year
Available land for WES	Represents the total available land that could be used for wind energy development.	Square meter (m^2)
Average area per wind turbine	Represents the amount of land required to install a wind turbine.	Square meter (m^2)
Capacity factor	The ratio of wind energy (assuming all turbines are same size) actual output over a period of time, to its potential output if it were possible for it to operate at full theoretical capacity indefinitely.	% (dimensionless)
Capacity per turbine	Refers to the maximum rated output of a wind turbine under specific conditions designated by the manufacturer (modified from EIA glossary definition “nameplate capacity” (EIA, 2013)).	Megawatts / turbine

Table F.6—*Continued*

Concrete foundation removal cost per turbine	Represents the unit cost of turbine concrete foundation removal during the decommissioning phase.	Dollars per turbine
Decommissioning attrition fraction	Represents the fraction of personnel leaving the wind energy system decommissioning activities.	#/ year
Decommissioning rate	Represents the rate at which turbines are decommissioned from wind energy system.	#/ year
Decommissioning target growth	Represents the projected growth of turbine decommissioning activities in the wind energy system.	#/ year
Discount factor	Single payment present worth factor.	Dimensionless
Distance between WES and community	Average distance between the wind power project and the closest surrounding community.	Kilometers (Km)
Ecological footprint	Represents the amount of land and water area required for nature to regenerate the resources used by the wind energy system.	Global hectares
Ecological footprint impact	Represents the impact of WES on the ecological footprint	Global hectares
Electricity price	Represents the average sale price of electricity generated from a wind energy system to utilities. Focus is on water and energy.	Megawatts hour / Dollars
Energy used per turbine during decommissioning	Refers to the amount of energy used for wind turbines decommissioning.	KWh per turbine
Energy used per turbine during installation	Refers to the amount of energy used for wind turbine installation	KWh per turbine
Energy used per turbine during O&M	Refers to the amount of energy used for wind turbines to operate.	KWh per turbine

Table F.6—*Continued*

Estimated incentives to be acquired	Refers to the potential amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars/year
Estimated number of wind turbines to be installed	Refers to the estimated number of wind turbines that would be required to cover the total wind energy shortage.	Number of turbines
Estimated total cost of wind power generation shortage	Refers to the estimated cost of wind turbines installation, and O&M to cover total wind power shortage.	Dollars
Estimated wind energy decommissioning cost	Refers to the estimated amount of funds required to decommission wind turbines to be installed to cover wind power shortage.	Dollars
Estimated wind energy installed capital cost	Refers to the estimated amount of investment required to cover the total wind power shortage.	Dollars
Estimated wind energy O&M cost	Represents the estimated operational and maintenance costs of the additional wind turbines required to cover the total wind power shortage.	Dollars
Estimated probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances to cover the total wind energy shortage.	%
Fraction of land used	Refers to what fraction of the land allotted to wind turbines installed is actually built on.	%
Hiring for decommissioning growth	Refers the human resource employment due to growth of decommissioning activities in the wind energy system.	Number of people per year

Table F.6—*Continued*

Hiring for installation growth	Refers the human resource employment due to growth of installation activities in the wind energy system.	Number of people per year
Hiring for O&M growth	Refers the human resource employment due to growth of operation and maintenance activities in the wind energy system.	Number of people per year
Hiring to replace decommissioning attrition	Refers the human resource employment due to decommissioning personnel attrition in the wind energy system.	Number of people per year
Hiring to replace installation attrition	Refers the human resource employment due to installation personnel attrition in the wind energy system.	Number of people per year
Hiring to replace O&M attrition	Refers the human resource employment due to operation and maintenance personnel attrition in the wind energy system.	Number of people per year
Installation attrition fraction	Represents the fraction of personnel leaving the wind energy system installation activities.	#/ year
Installation target growth	Represents the projected growth of turbine installation activities in the wind energy system.	#/ year
Installed capital cost per MW	Refers to the unit cost of wind energy installation per MW. This includes wind turbines, balance of station and soft costs. Balance of station cost refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Soft cost refers to costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars/MW

Table F.6—*Continued*

Interest rate	Refers to the cost of money required to pay to a lender to develop a wind energy project.	% (dimensionless)
Investor commitment	Refers to amount of funds committed by investor to fund wind energy developments.	Dollars
Level of visual impact	Represents how well wind turbines can be seen from horizon.	Level 1-Visual dominate 2- Visual intrusive 3- Noticeable 4- Negligible
Material transportation cost	Represents the cost to transport equipment and turbines removed during decommissioning activities.	Dollars per year
Net carbon footprint	The algebraic sum of the carbon footprint avoided and emitted during wind energy system installation, operation and decommissioning.	Grams of Carbon dioxide (CO_2) per year
Net employment rate	Represents the rate of employment during the wind energy installation, O&M and decommissioning phases.	Number of people per year
Net water usage	Represents the total wind energy water usage. This is the algebraic sum of water used, the water returned to natural environment and the water conserved due to wind power generation.	Cubic meter per year
Net WES waste	Represents the total waste produced by the wind energy system during installation, O&M and decommissioning.	Cubic meter per year
Number of years	Wind energy system time of interest.	Number of years
O&M attrition fraction	Represents the fraction of personnel leaving the wind energy system operational and maintenance activities.	#/ year
O&M cost per MW	Refers to the unit cost of operation and maintenance activities per megawatt.	Dollars/MW/year

Table F.6—*Continued*

O&M target growth	Represents the projected growth of operational and maintenance activities in the wind energy system.	% per year
Other elements waste	Refers to rate at which waste is produced by elements of the wind energy system excluding wind turbines waste during O&M.	Cubic meter per year
Percentage of funds to be committed for wind energy development	Refers to the fraction of available funds for wind energy development to be committed by investors.	%
Probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances.	%
Quantity of cement used	Refers to the amount of cement used for wind turbine base construction.	Kilograms (KGr)
Rate of excavation per wind turbine	Represents the rate at which land excavation and trenching is performed per turbine.	Cubic meter per year per turbine
Rate of other equipment resale	Represents the rate at which equipment removed during decommissioning are sold (excluding wind turbines)	Dollars per year
Rate of waste produced by other elements decommissioned	Refers to rate at which waste is produced during decommissioning activities of other elements in the wind energy system excluding wind turbines.	Cubic meter per year
Rate of waste produced by other elements installation	Refers to rate at which waste is produced during installation of other elements in the wind energy system different from wind turbines.	Cubic meter per year
Rate of waste produced per turbine	Refers to rate at which waste is produced per turbine during O&M.	Cubic meter per year
Ratio of water use per person	Refers to the amount of water use per person during the installation operation and maintenance, and decommissioning phases of the wind energy system.	Cubic meter per person per year

Table F.6—*Continued*

Removal of material and equipment cost	Represents the cost to remove equipment and turbines during decommissioning activities.	Dollars per year
Replacement for decommissioning	Represents the planned replacement of decommissioning personnel in the wind energy system.	% per year
Replacement for installation	Represents the planned replacement of installation personnel in the wind energy system.	% per year
Replacement for O&M	Represents the planned replacement of operational and maintenance personnel in the wind energy system.	% per year
Society awareness	Refers to the knowledge accumulated in society due to experience with wind energy.	Level 1-Familiar with wind energy 2-Some familiarity with wind energy 3-Not familiar with wind energy
Target wind power generation	Refers to the amount of electric power expected to be generated from wind energy in a defined time period.	Megawatt hour per year
Traditional energy source greenhouse gases emissions factor	The greenhouse gases emissions factor of traditional sources of energy not operating due to wind power generation.	Grams of carbon dioxide (CO_2) per MWh
Traditional energy source water use factor	The average water use of traditional sources of energy not operating due to wind power generation.	Cubic meters per MWh
Turbine resale price	Refers to the estimated value that a wind turbine will realize when is sold at the end of its useful life.	Dollars per turbine
Waste produced per turbine during decommissioning	Refers to the waste produced per turbine during wind energy decommissioning activities.	Cubic meter per turbine
Waste produced per turbine during installation	Refers to the waste produced per turbine during wind energy installation phase.	Cubic meter per turbine

Table F.6—*Continued*

Water drained from concrete demolition ratio	Refers to the amount of water drained from the concrete demolition activities during the decommissioning phase.	% (dimensionless)
Water drained from concrete construction ratio	Refers to the amount of water drained from the concrete construction activities during the installation phase.	% (dimensionless)
Water drained from O&M ratio	Refers to the amount of water drained from the operation and maintenance activities during the operation and maintenance phase.	% (dimensionless)
Water ratio factor	Refers to the amount of water required per quantity of cement during concrete foundation construction.	Cubic meter per cement pound
Water used conversion factor	Refers to the amount of water used per KWh generated for O&M activities.	Cubic meter per KWh
WES installed capacity	Theoretical maximum capacity of a wind energy system based on the number of wind turbines installed in the system.	Megawatts /year
WE population resistance	Refers to the general population opposition to the wind energy system.	#/year
Wind power generation shortage	Refers to the difference between the actual wind power generated and the target wind power generation.	Megawatt hour per year
Wind power opportunity profit	Refers to the perceived potential profit that could be generated from wind power investment to cover wind power generation shortage.	Dollars per year
Wind turbine cost	Refers to the unit cost of turbine.	Dollars per turbine
Wind turbine installation fraction	Refers to the percentage of turbines installed in a given year.	# / year

Simulator Architecture Validation Overview

The simulator architecture validation process follows the framework developed by Richardson and Pugh (1981) for building confidence in system dynamics models. The purpose of the simulator architecture validation process is to check the model's consistency with reality. The structure of the model is checked applying the Richardson and Pugh's "face validity" criterion.

Face validity checks the model's structure to verify it looks like the real system and represents the essential characteristics of the actual system.

Validation Questions

Questions will be asked about simulator architecture structure and essential characteristics.

Please use space below each section to answer the question:

1. Does the structure of the simulator architecture represent the real system? If so in what way? If not, why not?
2. Are the essential characteristics of the real system represented in the simulator architecture?

Please review the set of stocks, rates, auxiliary variables, and how they are structured in the simulator architecture.

<u>Stocks</u>

For each stock in Table F.4, please answer these questions. Space is allocated in Table F.7 for your inputs related to the stocks. Please enter "OK" or enter a checkmark in the spaces for the following questions if you are satisfied with an area and have no other comments about it. Please answer the following questions:

- Is the stock valid and reasonable?
- Is the definition of the stock reasonable?
- Is the unit for this stock reasonable?

Table F-7 Stocks (Please provide your comments here)

Stock	Comments
Amount of money recouped due to decommissioning	
Carbon footprint added by WES (wind energy system)	
Carbon footprint avoided by WES	
Energy used by WES	
Energy used during decommissioning	
Energy used during installation	
Energy used during O&M	
Net present value	
Number of abandoned wind turbines	
Number of installed wind turbines	
Number of operating wind turbines	
Number of wind turbines decommissioned	
Skilled personnel for WES decommissioning	
Skilled personnel for WES installation	
Skilled personnel for WES O&M	
Skilled personnel for WES installation, O&M and decommissioning	
Total WES revenue	
Total wind power generated from WES	
Volume of excavation and trenching	
Volume of water discharged to ground	
Volume of water used during O&M	
Volume of water used for concrete construction	
Volume of water used for concrete demolition	

Table F.7—*Continued*

Volume of water used for human needs	
Waste produced by WES decommissioning	
Waste produced by WES installation	
Waste produced by WES O&M	
Water conserved by WES	

<u>Rates</u>

For each rate in Table F.5, please answer these questions. Space is allocated in Table F.8 for your inputs related to the rates. Please answer the following questions:

- Is the rate valid and reasonable?
- Is the definition of the rate reasonable?
- Is the unit for this rate reasonable?

Table F-8 Rates (Please provide your comments here)

Rate	Comments
Decommissioning attrition rate	
Decommissioning employment rate	
Installation attrition rate	
Installation employment rate	
O&M attrition rate	
O&M employment rate	
Present value of profit	
Rate of amount of money recuperated due to decommissioning	
Rate of decommissioning cost	
Rate of energy used during decommissioning	

Table F.8—*Continued*

Rate of energy used during installation	
Rate of energy used during O&M	
Rate of energy used during decommissioning	
Rate of excavation and trenching	
Rate of greenhouse gases emissions avoided by WES	
Rate of installed capital cost	
Rate of O&M cost	
Rate of operating turbines in WES	
Rate of turbine abandonment in WES	
Rate of waste production during WES decommissioning	
Rate of waste production during WES installation	
Rate of waste production during WES O&M	
Rate of water conserved by WES	
Rate of water drained from concrete construction	
Rate of water drained from concrete demolition	
Rate of water drained from O&M	
Rate of water used during O&M	
Rate of water used for concrete construction	
Rate of water used for concrete demolition	
Rate of water used for damping dust down	
Rate of water used for reestablishing natural vegetation	
Rate of water used for human needs	
Rate of WES greenhouse gases emissions	
Rate of WES total cost	

Table F.8—*Continued*

Rate of WES water use	
Rate of wind turbine installation in WES	
Turbine decommissioning rate	
WES revenue	
Wind power generated by WES	

<u>Auxiliary Variables</u>

For each auxiliary variable in Table F.6, please answer these questions. Space is allocated in Table F.9 for your inputs related to the auxiliary variables. Please answer the following questions:

- Is the auxiliary variable valid and reasonable?
- Is the definition of the auxiliary variable reasonable?
- Is the unit for this auxiliary variable reasonable?

Table F-9 Auxiliary Variables (Please provide your comments here)

Auxiliary Variable	Comments
Abandoned rate	
Acquired incentives for implementing wind technologies advances	
Amount of available funds for wind energy development	
Amount of economic incentives for implementing wind technology	
Amount of land used	
Annual operating time	
Available land for WES	
Average area per wind turbine	
Capacity factor	

Table F.9—*Continued*

Capacity per turbine	
Carbon footprint conversion factor	
Concrete foundation removal cost per turbine	
Decommissioning attrition fraction	
Decommissioning rate	
Decommissioning target growth	
Discount factor	
Distance between WES and community	
Ecological footprint	
Ecological footprint impact	
Electricity price	
Energy used per turbine during decommissioning	
Energy used per turbine during installation	
Energy used per turbine during O&M	
Energy used other purposes	
Estimated incentives to be acquired for implementing wind technology advances	
Estimated number of wind turbines to be installed	
Estimated total cost of wind power generation shortage	
Estimated wind energy decommissioning cost	
Estimated wind energy installed capital cost	
Estimated wind energy O&M cost	
Estimated probability of getting incentives	
Fraction of land occupied	

Table F.9—*Continued*

Hiring for decommissioning growth	
Hiring for installation growth	
Hiring for O&M growth	
Hiring to replace decommissioning attrition	
Hiring to replace installation attrition	
Hiring to replace O&M attrition	
Installation attrition fraction	
Installation target growth	
Installed capital cost per MW	
Interest rate	
Investor commitment	
Level of visual impact	
Material transportation cost	
Net carbon footprint	
Net employment rate	
Net water usage	
Net WES waste	
Number of years	
O&M attrition fraction	
O&M cost per MW	
O&M target growth	
Other elements waste	
Percentage of funds to be committed for wind energy development	
Probability of getting incentives	

Table F.9—*Continued*

Quantity of cement used	
Rate of excavation per wind turbine	
Rate of other equipment resale	
Rate of waste produced by other elements decommissioned	
Rate of waste produced by other elements installation	
Rate of waste produced per turbine	
Ratio of water use per person	
Removal of material and equipment cost	
Replacement for decommissioning	
Replacement for installation	
Replacement for O&M	
Society awareness	
Target wind power generation	
Traditional energy source greenhouse gases emissions factor	
Traditional energy source water use factor	
Turbine resale price	
Volume of waste conversion factor	
Volume of water conversion factor	
Waste produced per turbine during decommissioning	
Waste produced per turbine during installation	
Water drained from concrete demolition ratio	
Water drained from concrete construction ratio	
Water drained from O&M ratio	

Table F.9—*Continued*

Water ratio factor	
Water used conversion factor	
WES installed capacity	
WE population resistance	
Wind power generation shortage	
Wind power opportunity profit	
Wind turbine cost	
Wind turbine installation fraction	

<u>Relationships</u>

Please answer the following question:

- Are the relationships between the stocks, rates, and auxiliary variables in the model reasonable? If not, please provide comments for recommended changes.

Additional comments and feedback are encouraged. Feel free to mark up the simulator architecture. Please use the notes section below to provide additional information on your recommendations including any suggestions for changes.

- Any missing stocks, rates, and auxiliary variables, or incorrect stocks, rates and auxiliary variables?
- Any missing or unidentified relationships between stocks, rates, and auxiliary variables?
- Any changes recommended to stock, rate, and auxiliary variable definitions and associated units?

<u>Notes</u>

Additional recommendations and notes may be provided here.

Appendix G

Causal Model and Simulator Architecture Validation Feedback and Assessment

The validation package was presented to subject matter experts and the results are shown in the following tables along with assessment of the inputs. Table G.1 presents causal model factor definitions. Table G.2 presents validation results for the factor relationships. Table G.3 presents causal model validation additional comments and notes. Table G.4 presents validation results for the stock definitions and units of measurement. Table G.5 presents validation results for the flows definitions and units of measurement. Table G.6 presents validation results for the auxiliary variables definitions and units of measurement. Table G.7 presents results from the face validity test, validation results for the relationship between the variables and additional notes and comments provided by validators.

Table G-1 Causal Model Validation-Factors, Definitions and Units of Measurement

Factors	Validator 1	Validator 2	Validator 3	Assessment
# of abandoned wind turbines	Factor Unreasonable, there will be few abandoned, too valuable as scrap.	Validator 2 only provided inputs in Causal model notes, additional comments section	Factor Ok. Def. “Useful life” unclear. Units Ok	Modification made to clarify what is meant by end of useful life. Modified definition: The number of wind turbines abandoned after end of useful life. End of useful life implies that turbine is not used to generate wind energy for the owner anymore. Abandoned turbines remain in their original installed location.
# of accidents	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok	No further action required based on validator comments.
# of decommissioned wind turbines	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok	No further action required based on validator comments.
# of operating wind turbines	Factor valid and reasonable		Factor Ok. Def. Units: consider MW operational	Number of turbines does reflect the actual turbines in operation. No further action required based on validator comments.
# of wind turbines installed	Factor valid and reasonable		Factor Ok. Def. Define “investor’s commitment” turbine contract signed? Units MW planned.	Investor commitment refers to investor interest in financing additional wind power installation. Number of turbines does reflect the actual turbines installed. No further action required based on validator comments.
# of wind turbines to be installed	Factor valid but speculative, Never really know the thoughts of developers until they BUILD it.		Why would this be different than operating? Units MW planned.	Turbines to be installed encompass turbines planned to be installed based on investor commitment and this is different from “operating wind turbines”. No further action required based on validator comments.
Acquired incentives for implementing wind technology advances	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok	No further action required based on validator comments.
Amount of available funds for wind energy development	Factor valid and reasonable		Factor seems strange. If the business case is there, so is the funding	Business case may be there but not necessarily the funding. No further action required based on validator comments.

Table G.1—*Continued*

Amount of economic incentives for implementing wind technology advances	Factor valid and reasonable but at mercy of federal whims on levels of support, so it will fluctuate CONSTANTLY over decades		Factor Ok. Def. should include Universities/National Labs. Units Ok.	Simulator can take variations over time into account. Factor name updated to "Available amount of economic incentives for implementing wind technology advances". Factor definition updated to generalize terms so that the researchers are also included.
Amount of electricity available for use	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok	No further action required based on validator comments.
Amount of money recouped due to decommissioning	Factor valid and reasonable		Factor Ok. Def. recuperated by whom? Someone pays. Units Ok.	Funding recuperated by group that performs decommissioning. No further action required based on validator comments.
Available land	Factor valid and reasonable		Factor Ok. Definition Ok. Units Ok. Fundamentally an economic?	No further action required based on validator comments.
Balance of station cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Bird/bat population	Factor valid and reasonable but means limiting Available land, if the land with bird/bats is avoided, then this factor is moot.		Factor Ok. Def. Ok. Units Ok. Ignores variability species	The weight of this factor might be small but it should remain in the causal loop model since it is a concern. No further action required based on validator comments.
Bird/bat strikes	Factor valid and reasonable but means limiting Available land, if the land with bird/bats is avoided, then this factor is moot.		Factor Ok. Def. Ok. Units Ok. Ignores variability in species	The weight of this factor might be small but it should remain in the causal loop model since it is a concern. No further action required based on validator comments.
Capacity factor	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Carbon footprint	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.

Table G.1—*Continued*

Cost of turbine	Factor valid and reasonable		Factor Ok. Def. should clarify Opex, Caexp or both. Units Ok.	Factor definition has been updated to include the capital cost. Modified definition: Refers to the capital cost of a wind turbine.
Distance between wind projects and community	Factor valid and reasonable but only if community does not grow TOWARD the wind area		Factor Ok. Def. what's community mean? Units Ok.	Simulator can represent distance changing over time. Community is defined as the nearest locality from wind energy projects where a group of people lives. No further action required based on validator comments.
Ecological footprint	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Electrical energy reserves	Odd, every turbine makes base load become more of a reserve, so ave capacity factor increases reserves (12 – 14 % of rated on average)		Factor Ok. Def. ignores timing and variability. Units Ok.	This is a valid comment; timing and variability are important considerations. These are not part of the simulator model in an attempt to keep the model simpler. Given the complexity of these elements, they could be addressed as future research. No further action required based on validator comments.
Electricity price	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MWh	Simulator outputs related to factor can also be represented in $/MW. No further action required based on validator comments.
Electromagnetic interference	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Employment rate	Factor valid and reasonable but VERY variable during life of wind plant		Factor Ok. Def. Ok. Units- ignore % employment changes during project life.	Varying employee rate can be modeled in simulator. No further action required based on validator comments.
Energy used for wind turbine decommissioning	Factor valid and reasonable		Factor Ok. Def. Ok. Units-MWh's? Joules ?	Units: MWh. Factor name changed to "Energy used for wind energy system decommissioning". No further action required based on validator comments.

Table G.1—*Continued*

Energy used for wind energy installation, and O&M	Factor valid and reasonable		Factor Ok. Def. Separate installation from O&M. Units- MWh's? Joules (installation) MWh/MWh- for O&M?	Factor separated in two factors: Energy used for wind energy system installation [joules] and Energy used for wind energy system O&M[MWh]
Estimated # of wind turbines to be installed	Factor Not valid and reasonable, how do we know what is possible until it is done?		? Lost. Wind energy shortage is confusing	"Wind power generation shortage" has been renamed to "Wind power generation difference". When simulating, we will clarify that this factor is based on other factors external to the model. No further action required based on validator comments.
Estimated balance of station	Factor valid and reasonable		How is this different than balance of station cost?	This factor is based on the estimated number of wind turbines to be installed; balance of station cost is based on the actual number of wind turbines installed. No further action required based on validator comments.
Estimated cost of turbine	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW.	Simulator outputs related to factor can be represented in $/MW. No further action required based on validator comments.
Estimated incentives to be acquired for implementing wind technology advances	Factor valid and reasonable but at whim of society support for renewables and funding availability for support		If this is different than amount of funds, call one factor "incentives secured" & the other "incentives available"	To address concern, will change name of "amount of economic incentives for implementing wind technology advances" factor to "available amount of economic incentives for implementing wind technology advances". We will clarify that this factor is based on other factors. No further action required based on validator comments.
Estimated probability of getting incentives	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.

Table G.1—*Continued*

Estimated soft cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW.	Simulator outputs related to factor can also be represented in $/MW. No further action required based on validator comments.
Estimated total cost of shortage wind power generation	Factor valid and reasonable		Again, I do not understand wind power shortage.	"Estimated total cost of shortage wind power generation" has been renamed to "Estimated total cost of wind power generation difference". We will clarify that this factor is based on other factors external to the model. No further action required based on validator comments.
Estimated wind energy installed capital cost	Factor valid and reasonable		Check what you put for definition.	Definition has been modified to reflect changes to "Wind power generation shortage" This factor was renamed to "Wind power generation difference". Modified definition: Refers to the estimated amount of investment required to cover the total wind power generation difference.
Estimated wind energy O&M cost	Factor valid and reasonable		Again, I do not understand wind power shortage.	Factor will remain in the model. Definition has been modified to reflect changes to "Wind power generation shortage". This factor was renamed to "Wind power generation difference". Modified definition: Represents the estimated operational and maintenance costs of the additional wind turbines required to cover the total wind power generation difference.

Table G.1—*Continued*

Impact from ice shedding	Factor valid and reasonable, very regional dependant, so available lands will be controlling factor.		Do you mean icing downtime or damage caused by shed ice?	This impact is from shed ice. No further action required based on validator comments.
Interest rate	Factor valid and reasonable		Rename Factor Ok. Def. use the terms: “finance a wind project”	This definition was updated to include word “finance”. Modified definition: Refers to the cost of money required to pay to a lender to finance a wind energy project.
Investor commitment	Factor valid and reasonable		Commitment is difficult to define/measure. Units : $/MW	Simulator outputs related to factor can also be represented in $/MW. No further action required based on validator comments.
Level of energy security	Factor valid and reasonable but will be societal controlled not industry, it has to be a perceived value not a real cost		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Level of reinforcement of government regulations, standards, and policies for wind energy	Factor valid and reasonable but again will be varied over the next decades, will not be a static value		Factor Ok. Def. Ok. Units Ok.	Varying level of reinforcement of government regulations, standards, and policies for wind energy can be represented in the simulator. No further action required based on validator comments.
Level of visual impact	Too hard to determine, it is like proving that chocolate is the best ice cream, someone always points to vanilla, and then the arguing starts.		Does not recognize that some views sheds are worth more than others. Units OK	It is a key factor/concern defined in the literature. Validator 3 comment is valid. Effect is related to location. No further action required based on validator comments.

Table G.1—*Continued*

Net present value (NPV)	Factor valid and reasonable		Factor Ok. Def. NPV of what? The industry, cumulatively? Units Ok.	This is NPV of actual profits of the wind energy system at state/country level. Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flow is the algebraic sum of money estimated to flow in and out of a wind energy system over some period of time as a result of a particular project (adapted from Stevens, 1994). No further action required based on validator comments.
Perceived amount of noise from wind turbines	Factor valid and reasonable		Factor Ok. Def. Ok. Units Decibels generated/Decibels background	No further action required based on validator comments.
Percentage of funds to be committed for wind energy development	Factor valid and reasonable		Factor Ok. Def.: Available relative to what? Units: % of what?	Funds available relative to the total amount of funds available for renewable energy development. No further action required based on validator comments.
Probability of getting incentives	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Profit	Factor valid and reasonable		Factor Ok. Def. Ok. Units: $ need a reference year, like $2015	The reference year for $ is whenever the year simulation is run. No further action required based on validator comments.
Rate of wind turbine abandonment	Changes historically, usually dependent on the materials value at end of design life.		I guess I really think of an abandoned turbine as a turbine in need of repair	Simulator can represent rate of wind turbine abandonment changing over time during simulation. Assume constant for year simulation run. No further action required based on validator comments.
Rate of wind turbine decommissioning	Factor valid and reasonable			No further action required based on validator comments.

Table G.1—*Continued*

Site wind speed	Factor valid and reasonable		Generally Ok but recognize that this number depends not just on wind but also hub height	No further action required based on validator comments.
Skilled personnel needed	Factor valid and reasonable		Factor Ok, Def. Ok. Would consider separate categories for installations vs. O&M	Factor has been split in three factors: decommissioning, installation and O&M in the simulator.
Society awareness	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Soft cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units: $/MW	Simulator outputs related to factor can also be represented in $/MW. No further action required based on validator comments.
Target electric power generation	Factor valid and reasonable		Factor Ok. Def. Ok. Understand that generation ≠ consumption -> transmission losses [Validator crossed out Target and substituted with expected]	This factor is intended to be a strategic objective. No further action required based on validator comments.
Target wind power generation	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok. [Validator crossed out Target and substituted with expected]	This factor is intended to be a strategic objective. No further action required based on validator comments.
Utility electricity price	Factor valid and reasonable		Usually customers are broken down into subcategories, like residential, commercial, industrial	Given simulator purpose factor will remain as is. No further action required based on validator comments.

Table G.1—*Continued*

Utility resistance	Factor valid and reasonable		?	Given simulator purpose factor will remain as is. No further action required based on validator comments.
Volume of excavation and trenching	Factor valid and reasonable		Probably the land disturbance concern is more m^2 than m^3	Factor changed to “area of excavation and trenching”, units: m^2.
Volume of waste from wind turbine decommissioning	Factor valid and reasonable		? what type of waste was produce would be an important distinction	Factor definition states types of waste considered in the model. No further action required based on validator comments.
Volume of waste from wind energy installation and O&M	Factor valid and reasonable		See previous comment	Factor definition states types of waste considered in the model. No further action required based on validator comments.
Volume of wind energy water consumption	Factor valid and reasonable		Factor Ok. Def. Ok. Units m^3/MW	Units change gallons/turbine. Simulator outputs related to factor can also be represented in gallons/MW. No further action required based on validator comments.
Wind turbine decommissioning cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW.	Calculated value will be $/yr. based on factor inputs. Simulator outputs related to factor can be also be represented in $/MW. . No further action required based on validator comments.
Wind energy installed capacity	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Wind energy installed capital cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW to account for inflation $ should have a reference year, like $2012	Calculated value will be $/yr. based on factor inputs. No further action required based on validator comments.

Table G.1—*Continued*

Wind energy integration cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW note that increased wind penetration might lead to higher $/MW integration costs	Calculated value will be $/yr. based on factor inputs. . No further action required based on validator comments.
Wind energy O&M cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW	Calculated value will be $/yr. based on factor inputs. Simulator outputs related to factor can be also be represented in $/MW. No further action required based on validator comments.
Wind energy population resistance	Factor valid and reasonable, but the EDGE areas are the big resistance (when they do not get a wind turbine then they are upset, but far away from view shed it is way less arguing.		Factor Ok. Def. Ok. Units: % of what? Maybe an index?	Refers to % of total population impacted by wind energy system. No further action required based on validator comments.
Wind energy total cost	Factor valid and reasonable		Factor Ok. Def. Ok. Units $/MW? $/MWh?	Calculated value will be $/yr. based on factor inputs. Simulator outputs related to factor can also be represented in $/MW. No further action required based on validator comments.
Wind power generated	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Wind power generation shortage	Factor valid and reasonable, and variable		Factor Ok. Def. Ok. Units MWh/yr.	“Wind power generation shortage” has been renamed to “Wind power generation difference”.

Table G.1—*Continued*

Wind power opportunity profit	Factor valid and reasonable		Too complicated. I don't get this.	Modified definition to reflect change in factor "wind power generation shortage": Refers to the perceived potential profit that could be generated from wind power investment to cover wind power generation difference. No further action required based on validator comments.
Wind turbine capacity	Factor valid and reasonable		Factor Ok. Def. Ok. Units Ok.	No further action required based on validator comments.
Wind turbine dimension	Factor valid and reasonable, but will grow, we have seen it over past decades that the 3 -5 MW will be the new standard once they show it is economical.		Factor Ok. Def. Ok. Units Ok. (Hub height is also important) [Validator crossed out dimension substitute with rotor].	Factor has been changed for two factors: wind turbine hub height and wind turbine rotor diameter. Simulator can represent wind turbine hub height and rotor diameter changing over time during simulation.

[Information enclosed in brackets was made by validator in another location of the validation package]

Table G-2 Causal Model Validation- Factor Relationships

Factor →	Factor	+/-	Validator 1	Validator 2	Validator 3	Assessment
# of abandoned wind turbines	# of operating wind turbines	-	There will be few abandoned turbines,	Validator 2 only provided inputs in Causal model notes, additional comments section	Valid	No further action required based on validator comments.
# of accidents	Wind energy population resistance	+	No relation I think		Valid	No further action required based on validator comments.
# of decommissioned wind turbines	# of wind turbines installed	-	Factor valid and reasonable		Valid	No further action required based on validator comments.
	Available land	+	Factor valid and reasonable		Negligible-not a big concern	No further action required based on validator comments.
	Amount of money recuperated due to decommissioning	+	Factor valid and reasonable		Recuperated to whom? This could be a cost to a wind project owner.	No further action required based on validator comments.
	Energy used for wind turbine decommissioning	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
	Volume of waste from wind turbine decommissioning	+	Factor valid and reasonable		Valid, but small	No further action required based on validator comments.
	Wind turbine decommissioning cost	+	Factor valid and reasonable		Valid	No further action required based on validator comments.

Table G.2—*Continued*

# of decommissioned wind turbines	Skilled personnel needed	+	Factor valid and reasonable		Negligible	"Skilled personnel" factor will be divided in three factors for decommissioning, installation and O&M in simulator.
# of operating wind turbines	Wind energy installed capacity	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
	Wind energy O&M cost	+	Factor valid and reasonable		Strange, if this is measured in $/MW, learning curve should make this a negative correlation	No further action required based on validator comments.
# of wind turbines installed	# of accidents	+	Factor valid and reasonable		Not valid. Accidents on a #/MW basis used to be more frequent	Factors relationship can also be represented as # accidents/MW. Relationship remains the same.
	# of operating wind turbines	+	Factor valid and reasonable but highly correlated to O&M		Valid	No further action required based on validator comments.
	Available land	-	Factor valid and reasonable		Not necessary. New transmission lines can open more sites	Available land refers to the total amount of land available that could be used for wind energy development. No further action required based on validator comments.
	Bird/bat strikes	+	Factor valid and reasonable		Valid. But wildlife monitoring is getting better and operational practices can improve	No further action required based on validator comments.

Table G.2—*Continued*

# of wind turbines installed	Energy used for wind energy installation, and O&M	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
	Skilled personnel needed	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
	Society awareness	+	Factor valid and reasonable, but is self-inflating, as more turbine, then more awareness when they get placed locally.		Valid	No further action required based on validator comments.
	Volume of waste from wind energy installation and O&M	+	Factor valid and reasonable		Valid, but there is not much waste	No further action required based on validator comments.
	Volume of wind energy water consumption	+	Factor valid and reasonable, but should be VERY LOW for production		Valid, but relative to what? Wind uses less water than other forms of generation	Water consumption refers to the actual amount of water consumed during installation, O&M and decommissioning, its value is not relative to any other source of energy. No further action required based on validator comments.
	Volume of excavation and trenching	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
	Wind energy installed capital cost	+	Factor valid and reasonable		Decreases if units of $/MW are used	Factor can also be represented in $/MW. No further action required based on validator comments.

Table G.2—*Continued*

# of wind turbines to be installed	# of wind turbines installed	+	Valid but hard to tell, again, intent does not lead to 100% results, so no way to know for sure how many they intend to install.		Valid	No further action required based on validator comments.
Acquired incentives for wind technology advances	Profit	+	The profit plan will be made before the installation starts, if they can't prove profit potential then it never starts. So it is more of a neutral than a +/-		Disagree. Most decisions are made on project economic hurdle rates	The profit considered in the model are profits calculated during a simulation run. No further action required based on validator comments.
Amount of available funds for wind energy development	Investor commitment	+	Factor valid and reasonable		Too nebulous	This relationship represents that as the amount of available funds for wind energy development increases, the Investor commitment increases. No further action required based on validator comments.
Amount of economic incentives for implementing wind technology advances	Acquired incentives for wind technology advances	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Estimated incentives to be acquired for implementing wind technology advances	+	Factor valid and reasonable		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Amount of electricity available for use	Level of energy security	+	Factor valid and reasonable but need to make it a time of day comparison and not based on total electrical generation potential, it is not how much I can make as it is how much can I deliver as the day changes (meeting demand as it fluctuates hourly)		Disagree. Security is proportional to energy availability relative to demand	The purpose of the model is to show only the effect of what happens in the level of energy security due to wind energy. No further action required based on validator comments.
Amount of money recuperated due to decommissioning	Wind turbine decommissioning cost	-	Factor valid and reasonable but remember it will ALWAYS pay to decommission after useful life of turbine is reached		Again, recuperated by whom?	Funding recuperated by group that performs decommissioning. No further action required based on validator comments.
Available land	Ecological footprint	-	Factor valid and reasonable but needs refining, the footprint matters Not how much space is taken compared to how much disturbances is made to the land to place the turbines. Out of 40 acres for a big turbine only 1-2 acres is disturbed, rest is fallow and used for original use.		Disagree, wind farms use 1-2% of a site	It is understood that land effect ifs reduced in comparison to other uses of the land. No further action required based on validator comments.
Balance of station cost	Wind energy installed capital cost	+	Factor valid and reasonable		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Bird/bat population	Wind energy population resistance	-	Factor valid and reasonable but insect population control will be the major factor that leads to recognizing this as a problem, if impact is severe.		Agree	No further action required based on validator comments.
Bird/bat strikes	Bird/bat population	-	Factor valid and reasonable		Not sure I agree. Other population controls could be more significant habitat loss, disease, etc.	The relationship has been identified in the literature as a major concern that could have a negative effect on bird/bat population. No further action required based on validator comments.
Capacity factor	Wind power generated	+	Factor valid and reasonable and based on rated power and O&M, how many are online for the period.		Agree	No further action required based on validator comments.
Carbon footprint	Ecological footprint	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Cost of turbine	Wind energy installed capital cost	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Distance between wind projects and community	Electromagneti c interference	-	Not a factor, dampers at substation will counter any EM affect		Agree, but negligible except for radar	Level of electromagnetic interference can be modified to reflect available technology that reduces the effects. No further action required based on validator comments.

Table G.2—*Continued*

Distance between wind projects and community	Impact from ice shedding	-	Factor valid and reasonable		Climate and location dependent, flawed	Validator 3 comments are correct. The ice shedding effect is location dependent. While in some areas effect could be critical, in others may not exist. No further action required based on validator comments.
	Level of visual impact	-	Factor valid and reasonable		Location dependent, flawed	The farther a wind development is from population eye sight, the level of visual impact decreases. No further action required based on validator comments.
	Perceived noise from wind turbines	-	Factor valid and reasonable		Location dependent	This relationship represents that as the distance between wind energy development and community increases, the perceived noise reduces. No further action required based on validator comments.
Ecological footprint	Wind energy population resistance	+	Not a factor, real results of eco cost has nothing to do with complaints of anti- wind nuts.		Disagree. Should be assessed relative to other forms of generation	The model is trying to represent the population reaction to actual ecological effects on their environment. Relationship remains the same.
Electrical energy reserves	Wind energy integration cost	+	Factor valid and reasonable		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Electricity price	profit	+	Factor valid and reasonable		Depends. Someone profits probably agree	No further action required based on validator comments.
	Utility electricity price	+	It is the same, what it costs is what it is worth.		Agree	No further action required based on validator comments.
	Utility resistance	+	Factor valid and reasonable		Disagree, depends on the price of wind relative to other electricity	The relationship is exploring the effect of an increase of generated electricity cost by wind energy systems have on utility resistance by itself. No further action required based on validator comments.
	Wind power opportunity profit	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Electromagnetic interference	Wind energy population resistance	+	Not a factor, they will never see it, but will still complain		I think this is mostly a concern w/radar	No further action required based on validator comments.
Employment rate	Wind energy population resistance	-	Slight factor valid and reasonable, if complaints keep a farm from being built then jobs for that area are reduced, but still grow some where else, wind farms will not stop, just adjust		Agree	No further action required based on validator comments.
Energy used for wind installation, and O&M	Carbon footprint	+	Factor valid and reasonable		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Energy used for wind turbine decommissioning	Carbon footprint	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Estimated # of wind turbines to be installed	Estimated wind turbine decommissioning cost	+	Factor valid and reasonable		No relationship	Relationship remains the same. If the number of turbines increases over the course of time decommissioning increases, increasing decommissioning costs.
	Estimated wind energy installed capital cost	+	Factor valid and reasonable		Could decrease if units are in $/MW	Factor can also be represented in $/MW. No further action required based on validator comments.
	Estimated wind energy O&M cost	+	Factor valid and reasonable		Same comment (as previous one)	No further action required based on validator comments.
Estimated balance of station	Estimated wind energy installed capital cost	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
Estimated cost of turbine	Estimated wind energy installed capital cost	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
Estimated incentives to be acquired for implementing wind technology advances	Wind power opportunity profit	+	Factor valid and reasonable		Valid	No further action required based on validator comments.

Table G.2—*Continued*

Estimated probability of getting incentives	Estimated incentives to be acquired for implementing wind technology advances	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
Estimated soft cost	Estimated wind energy installed capital cost	+	Factor valid and reasonable		Valid	No further action required based on validator comments.
Estimated total cost of shortage wind power generation	Wind power opportunity profit	-	Factor valid and reasonable		? I don’t really get this	Factor name has been changed to Estimated total cost of wind power generation difference. Relationship still exists.
Estimated wind energy installed capital cost	Estimated total cost of shortage wind power generation	+	Factor valid and reasonable		?	No further action required based on validator comments.
Estimated wind energy O&M cost	Estimated total cost of shortage wind power generation	+	Factor valid and reasonable		?	No further action required based on validator comments.
Impacts from ice shedding	Wind energy population resistance	+	Factor valid and reasonable		I don’t think this is a big population resistance issue	No further action required based on validator comments.
Interest rate	NPV	-	Factor valid and reasonable		Not necessarily	No further action required based on validator comments.
Investor commitment	# of wind turbines to be installed	+	Factor valid and reasonable but will change over time, so watch for long term simulation		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Level of visual impact	Society awareness	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Wind energy population resistance	+	Factor valid and reasonable		Not necessarily neutral?	No further action required based on validator comments.
Perceived amount of noise	Wind energy population resistance	+	Factor valid and reasonable		Not necessarily a big population resistance issue- v. local	No further action required based on validator comments.
Probability of getting incentives	Acquired incentives for wind technology advances	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Profit	NPV	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Rate of wind turbine abandonment	# of abandoned wind turbines	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Rate of wind turbine decommissioning	# of decommissioned wind turbines	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Site wind speed	Capacity factor	+	Factor valid and reasonable		Disagree. Related, but rotor diameter, hub height etc. also play a role	Relationship remains the same. Turbine dimension factor also has a positive relationship to capacity factor.
Skilled personnel needed	Employment rate	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Society awareness	Wind energy population resistance	-	Factor valid and reasonable		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Soft cost	Wind energy installed capital cost	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Target electric power generation	Target wind power generation	+	Factor valid and reasonable		Disagree. No relation market driven	The long term objective has been 20% of electricity generated by wind by 2030. No further action required based on validator comments.
Target wind power generation	Wind power generation shortage	+	Factor valid and reasonable		I still don't get wind power generation shortage	"Wind power generation shortage" factor has been renamed to "Wind power generation difference" Relationship remains the same.
Utility electricity price	Wind energy population resistance	+	Factor valid and reasonable		Disagree. What matters is wind power price vs. average electricity price	The effect represented here is social. An increase in utility electricity price increases wind energy population resistance. No further action required based on validator comments.
Utility resistance	Level of reinforcement of government regulations, standards and policies for energy sustainability	+	Factor valid and reasonable		Disagree. This isn't the utilities problem rather the problem of wind developers/owners /operators	Utility resistance contributes to an increase in the level of reinforcement of government regulations, standards and policies for energy sustainability. No further action required based on validator comments.
Area of excavation and trenching	Ecological footprint	+	Factor valid and reasonable		Minimal	No further action required based on validator comments.

Table G.2—*Continued*

Volume of waste from wind turbine decommissioning	Ecological footprint	+	Factor valid and reasonable		Maybe. We can recycle steel	No further action required based on validator comments.
Volume of waste from wind energy installation and O&M	Ecological footprint	+	Factor valid and reasonable		Minimal	No further action required based on validator comments.
Volume of wind energy water consumption	Ecological footprint	+	Factor valid and reasonable		Agree but should be compared to other forms of generation	No further action required based on validator comments.
Wind turbine decommissioning cost	Wind energy total cost	+	Factor valid and reasonable		Disagree. So late in project life, sort of a non-issue	Relationship remains the same. Even though it is happening late in the project life, if decommissioning is part of the land lease contracts and permits, it must be considered in the total project cost.
Wind energy installed capacity	Electrical energy reserves	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Wind power generated	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Wind energy installed capital cost	Wind energy total cost	+	Factor valid and reasonable		Agree	No further action required based on validator comments.

Table G.2—*Continued*

Wind energy integration cost	Utility resistance	+	Factor valid and reasonable but Utility will try to get developers to bear the cost, then becomes un noticed by Utility		Agree	No further action required based on validator comments.
Wind energy O&M cost	Wind energy total cost	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Wind energy population resistance	# of wind turbines to be installed	-	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Amount of economic incentives for implementing wind technology advances	-	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Level of reinforcement of government regulations, standards and policies for wind energy	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Wind energy total cost	Electricity price	+	Factor valid and reasonable		Disagree. Wind is not the marginal producer	Relationship remains the same. Factor refers to the cost of the electricity generated by the wind energy system and sold in the wholesale market.

Table G.2—*Continued*

Wind energy total cost	Profit	-	Factor valid and reasonable		No relationship	Profits are calculated as the difference between revenues and wind energy total cost. No further action required based on validator comments.
Wind power generated	Carbon footprint	-	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Amount of electricity available for use	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
	Profit	+	Factor valid and reasonable		No relation. Just because power is produced doesn't mean it is profitably produced	Relationship remains the same. For the purpose of the model, simulator could calculate negative profit (which means losing money).
	Wind power generation shortage	-	Factor valid and reasonable		I do not get wind power generation shortage	No further action required based on validator comments.
Wind power generation shortage	Estimated of wind turbines to be installed	+	Factor valid and reasonable		I do not get wind power generation shortage	Wind power generation shortage factor has been renamed as wind power generation difference. No further action required based on validator comments.

Table G.2—*Continued*

Wind power generation shortage	Wind power opportunity profit	+	Needs to be -, shortage leads to less profit		I do not get wind power generation shortage	In the causal model wind power generation factor represents the amount of wind power needed to fulfill the target wind energy contribution. Factor has been renamed to: "Wind power generation difference". Relationship remains the same.
Wind power opportunity profit	Investor commitment	+	Factor valid and reasonable		Agree	No further action required based on validator comments.
Wind turbine capacity	Wind energy installed capacity	+	Factor valid and reasonable		No relation	In a wind energy system, an increase in wind turbine capacity increases wind energy installed capacity. No further action required based on validator comments.
Wind turbine dimension	Capacity factor	+	Factor valid and reasonable		No relationship. Ignores the significance of wind speed	Relationship remains the same. See site wind speed factor relationship to capacity factor.
	Wind energy installed capital cost	+	Factor valid and reasonable		No relationship. Manufacturers are doing great things	Relationship remains the same. Wind turbine dimension factor has been changed to two factors: wind turbine rotor, and wind turbine hub.
	Wind energy O&M cost	-	Factor valid and reasonable		No relationship. See previous comment	Relationship remains the same. Wind turbine dimension factor has been changed to two factors: wind turbine rotor, and wind turbine hub.

Table G.2—*Continued*

Wind turbine dimension	Wind turbine capacity	+	Factor valid and reasonable		Not necessarily	Relationship remains the same. Wind turbine dimension factor has been changed to two factors: wind turbine rotor, and wind turbine hub.

Table G-3 Notes, Additional Comments

Validator 1	Validator 2	Validator 3	Assessment
	1.System architectures are generally determined by a small number of causal factors, some of us call them design drivers. You have logically identified many causal factors, all of them valid, but many of them (like employment) not very important for determining structural relationships, the system architecture. 2.A primary wind system design driver is intermittency. Consumers want power on demand and wind turbines produce only when the wind blows. Wind production tends to be low when demand is high. What this means is that wind farms and coal plants are not interchangeable. it is not possible to plug in a wind farm and un-plug a coal plant and retain reliability. A reliable system needs both. Wind reduces the consumption of coal but the system still needs the coal plant. The wind industry still does not fully understand these relationships 3.The energy marketplace will eventually change to better reflect system costs. Wind will be more costly than it appears to be today. For example, if the system needs storage to manage wind, storage costs are likely to be charged to wind when wind competes with generators that do not require storage (like geothermal). 4.In my opinion, the dominant environmental factor is noise. Informed consumers will not be willing to live near wind turbines. This will seriously constrain the ultimate deployment of onshore wind. 4.It all comes down to cost. Most of what is advocated is technically feasible but as the expense of redundancy and rarely used hardware. Large scale wind is technically feasible but likely at substantially higher cost (~10x) than say geothermal-electric.		The wind energy system sustainability simulator architecture includes environmental, economic and social factors associated with the wind energy system. Employment is associated with two sustainability pillars: the social and the economic pillar. No further action due to this comment. Model does not identify wind power as the only source to supply electricity. Other factors can be included in the model to reflect the changes in the market place. Future iterations of the system dynamics model should take those into consideration. Perceived noise factor is included in the simulator. Model scope includes wind energy system installation, operation, maintenance and decommissioning phases. Research can be extended, in the future, to look at other renewable energy sources.

Table G-4 Simulator Architecture Validation – Stock Definitions

Stocks	Validator 1	Validator 2	Validator 3	Assessment
Amount of money recouped due to decommissioning	OK	Validator 2 only provided inputs in Causal model notes, additional comments section	Again, recouped by whom?	Stock will remain in the model. Funding recuperated by group that performs decommissioning.
Carbon footprint added by WES (wind energy system)	OK		Valid, Def. Reasonable, Units reasonable	No further action required based on validator comment.
Carbon footprint avoided by WES	OK		Valid, Def. Reasonable, Units reasonable	No further action required based on validator comment.
Energy used by WES	OK		Valid, Def. Reasonable, Units Ok	No further action required based on validator comment.
Energy used during decommissioning	OK		Problematic, what about recycled components	Factor will remain in the model. Energy is used in disassemble, installed equipment.
Energy used during installation	OK		Duplicate w/energy used by WES	Stock will remain in the model. It is a component of the total energy used by WES that represents the fractions of the Energy Used during installation.
Energy used during O&M	OK		Duplicate w/energy used by WES	Stock will remain in the model. It is a component of the total energy used by WES that represents the fractions of the energy used during O&M.

Table G.4—*Continued*

Net present value	OK		NPV of what? Problematic $ should be expressed in a reference year and discount rate specified	Stock will remain in the model. This is NPV of actual profits of the wind energy system at state/country level. Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flow is the algebraic sum of money estimated to flow in and out of a wind energy system over some period of time as a result of a particular project (adapted from Stevens, 1994).
Number of abandoned wind turbines	OK		I don't think there is that much societal difference between abandoned and decommissioned WTG's except that abandonment is irresponsible ownership.	Stock will remain in the model. Besides, abandoned wind turbines are left behind in the field after the end of useful life, decommissioned wind turbines are demounted and possibly sold in a secondary market.
Number of installed wind turbines	OK		Valid, Def. Reasonable, Units – MW installed	No further action required based on validator comments.
Number of operating wind turbines	OK		Same as above	No further action required based on validator comments.
Number of wind turbines decommissioned	OK		Valid, Def. Reasonable, MW decommissioned	No further action required based on validator comments.

Table G.4—*Continued*

Skilled personnel for WES decommissioning	OK		Valid, Def. Ok, Units Ok	No further action required based on validator comments.
Skilled personnel for WES installation	OK		See above	No further action required based on validator comments.
Skilled personnel for WES O&M	OK		See above	No further action required based on validator comments.
Skilled personnel for WES installation, O&M and decommissioning	OK		See above	No further action required based on validator comments.
Total WES revenue	OK		Valid, Def. Ok, specify yr. for $	Stock will remain in the model. The reference year for $ is whenever the year simulation is run.
Total wind power generated from WES	OK		Valid. Def Ok. Units Ok	No further action required based on validator comments.
Volume of excavation and trenching	OK		Valid, Def. Ok, consider m² (area)	Factor name and definition modified. New name: "Area of excavation and trenching" .
Volume of water discharged to ground	OK		? Why is this important?	Stock will remain in the model. It is a component of the total water used by WES.
Volume of water used during O&M	OK		Is minimal	No further action required based on validator comments.
Volume of water used for concrete construction	OK		Valid, Def. Ok. Units Ok	No further action required based on validator comments.
Volume of water used for concrete demolition	OK		Do we do this? I have no clue.	No further action required based on validator comments.

Table G.4—*Continued*

Volume of water used for human needs	OK		This is so complicated to measure. Total water used for society>>>>>>>Wind energy plus a lot of water we use is then put back in to the earth system	No further action required based on validator comments.
Waste produced by WES decommissioning	OK		For all this depending on waste material, all m^3 are not created equal.	No further action required based on validator comments.
Waste produced by WES installation	OK			No further action required based on validator comments.
Waste produced by WES O&M	OK			No further action required based on validator comments.
Water conserved by WES	OK		Valid, Def Ok, Units Ok but people do not agree how measure water from other generation sources- ex is once – third cooling of combustion turbine water use? Or mostly a temperature change?	Stock will remain in the model. Assumptions related to how this stock is calculated will be identified in the simulator.

Table G-5 Simulator Architecture Validation- Rate Definitions

Rates	Validator 1	Validator 2	Validator 3	Assessment
Decommissioning attrition rate	OK	Validator 2 only provided inputs in Causal model notes, additional comments section	I don't think there are WTG decommissioning specialists	Rate will remain in the model. Rate represents the personnel that perform decommissioning.
Decommissioning employment rate	OK		See above	No further action required based on validator comment.
Installation attrition rate	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
Installation employment rate	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
O&M attrition rate	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
O&M employment rate	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
Present value of profit	OK			No further action required based on validator comment.
Rate of amount of money recuperated due to decommissioning	OK		See other comments on this	No further action required based on validator comment.
Rate of decommissioning cost	OK		Problematic	No further action required based on validator comment.
Rate of energy used during decommissioning	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
Rate of energy used during installation	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
Rate of energy used during O&M	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
Rate of energy used during decommissioning	OK			No further action required based on validator comment.
Rate of excavation and trenching	OK		Def. Ok, consider m^2	Rate will remain in the model. Factor name changed to area of excavation and trenching. Units changed to m^2

Table G.5—*Continued*

Rate of greenhouse gases emissions avoided by WES	OK		Def. Ok, Unit Ok	No further action required based on validator comment.
Rate of installed capital cost	OK		Is this a rate?	Yes. Over the course of installation time installed capital costs is spent. Rate will remain in the model.
Rate of O&M cost	OK		$/MW/yr	Rate will remain in the model. Calculated in the simulator as $/yr. Output can also be represented as $/MW/yr.
Rate of operating turbines in WES	OK		Is this a rate?	Yes. The number of operating turbines increases at a specific rate, given industry growth. Rate will remain in the model.
Rate of turbine abandonment in WES	OK		Combine abandoned & decommissioned	No further action required based on validator comment.
Rate of waste production during WES decommissioning	OK		Small flow, not all m^3 created equal	No further action required based on validator comment.
Rate of waste production during WES installation	OK		Not all m^3 created equal. Not a big factor in wind sustainability	No further action required based on validator comment.
Rate of waste production during WES O&M	OK		Not all m^3 created equal. Not a big factor in wind sustainability	No further action required based on validator comment.
Rate of water conserved by WES	OK		Conserved as a function of offsetting other generation types?	Yes, rate represents water conserved as a function of offsetting other generation types. No further action required based on validator comment.
Rate of water drained from concrete construction	OK		? Not important	Factor will remain in the model. Value could be minimal; sustainability is the focus of the model that is the reason to represent this factor.

Table G.5—*Continued*

Rate of water drained from concrete demolition	OK		All this water stuff. Is it really that big a deal?	Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.
Rate of water drained from O&M	OK			Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.
Rate of water used during O&M	OK			Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.
Rate of water used for concrete construction	OK			Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.
Rate of water used for concrete demolition	OK			Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.
Rate of water used for damping dust down	OK			Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.
Rate of water used for reestablishing natural vegetation	OK		Only 1-2% of total land area is disturbed- this probably a minimal / negligible rate	Rate will remain in the model. Simulator is capturing the actual use of water in the wind energy system, even if is minimal given model purpose.

Table G.5—*Continued*

Rate of water used for human needs	OK		Not clear. Probably not important	Rate will remain in the model. Rate represents the rate at which the water is used for human needs during installation, O&M and decommissioning.
Rate of WES greenhouse gases emissions	OK		Better tied to manufacture & installation	Rate will remain in the model. Simulator is considering the installation phase.
Rate of WES total cost	OK		Needs to be broken into Capex /Opex	Rate will remain in the model. Installation and O&M cost are included in the model, see rates above.
Rate of WES water use	OK			No further action required based on validator comment.
Rate of wind turbine installation in WES	OK		Def. Ok, Units – MW installed/yr.	No further action required based on validator comment.
Turbine decommissioning rate	OK		Def. Ok, Units MW decommissioned/yr.	No further action required based on validator comment.
WES revenue	OK		Def Ok, Specify year of $	The year reference will be the year of calculation. No further action required based on validator comment.
Wind power generated by WES	OK		Def Ok, Units Ok	No further action required based on validator comment.

Table G-6 Simulator Architecture Validation- Auxiliary Variables Definitions and Units

Auxiliary Variables	Validator 1	Validator 2	Validator 3	Assessment
Abandoned rate	OK	Validator 2 only provided inputs in Causal model notes, additional comments section	Combined w/decommissioned? MW/yr.	Auxiliary variable will remain in the model. Abandoned turbines are not combined with decommissioned turbines.
Acquired incentives for implementing wind technologies advances	OK		Def. measurable, specify yr. of $	No further action required based on validator comment.
Amount of available funds for wind energy development	OK		In theory, infinite (investment attractiveness)	No further action required based on validator comment.
Amount of economic incentives for implementing wind technology	OK		Is this for R&D or deployment?	Auxiliary variable name changed to "Available amount of economic incentives for implementing wind technology advances" to reflect changes in Factor definitions validator inputs assessment table. This is deployment.
Amount of land used	OK		Does this include full site or only disturbed land? Also called availability	It just includes the disturbed land. No further action required based on validator comment.
Annual operating time	OK		Def. reasonable, Units reasonable	No further action required based on validator comment.
Available land for WES	OK		Can change. (how much it cost to connect to the grid)	No further action required based on validator comment.
Average area per wind turbine	OK		m^2/MW Area disturbed (a couple of acres) total site (80+acres/MW)	No further action required based on validator comment.

Table G.6—*Continued*

Capacity factor	OK		Def. reasonable, Units reasonable	No further action required based on validator comment.
Capacity per turbine	OK		Def. reasonable, Units reasonable	No further action required based on validator comment.
Carbon footprint conversion factor	OK		Not in Def. list	This was inadvertently included in the list and not shown in the architecture.
Concrete foundation removal cost per turbine	OK		Could vary greatly per turbine and by soil type. $/MW	Factor units can also be represented as $/MW. No further action required based on validator comment.
Decommissioning attrition fraction	OK		Not aware of dedicated decommissioning specialists	No further action required based on validator comment.
Decommissioning rate	OK		MW/yr	Factor units can also be represented as MW/yr. No further action required based on validator comment.
Decommissioning target growth	OK		MW/yr	Factor units can also be represented as MW/yr. No further action required based on validator comment.
Discount factor	OK		Ok	No further action required based on validator comment.
Distance between WES and community	OK		Community is difficult to define	No further action required based on validator comment. Community definition has been updated, see same factor in the Factors definition validator inputs assessment.
Ecological footprint	OK		Ok Hectares/MW	Factor units can also be represented as Hectares/MW. No further action required based on validator comment.
Ecological footprint impact	OK		Ok	No further action required based on validator comment.

Table G.6—*Continued*

Electricity price	OK		Wholesale Wholesale electricity price. $/MWh specify yr of $	No further action required based on validator comment.
Energy used per turbine during decommissioning	OK		Comments provided in other sections	No further action required based on validator comment.
Energy used per turbine during installation	OK			No further action required based on validator comment.
Energy used per turbine during O&M	OK			No further action required based on validator comment.
Energy used other purposes	OK		Not in definitions list	Factor added to factor definition list.
Estimated incentives to be acquired for implementing wind technology advances	OK		Incentives for deployments or for R&D?	Auxiliary variable will remain in the model. Incentives for deployment.
Estimated number of wind turbines to be installed	OK		Wind power shortage doesn't make sense to me	Auxiliary variable will remain in the model. "Wind power generation shortage" has been renamed to "Wind power generation difference".
Estimated total cost of wind power generation difference	OK		Wind power shortage doesn't make sense to me	Auxiliary variable will remain in the model. "Wind power generation shortage" has been renamed to "Wind power generation difference".
Estimated wind energy decommissioning cost	OK		$/MW	Factor units can also be represented as $/MW. No further action required based on validator comment.
Estimated wind energy installed capital cost	OK		$/MW	Factor units can also be represented as $/MW. No further action required based on validator comment.
Estimated wind energy O&M cost	OK		$/MW	Factor units can also be represented as $/MW. No further action required based on validator comment.

Table G.6—*Continued*

Estimated probability of getting incentives	OK		I don’t get the shortage	Auxiliary variable will remain in the model. “Wind power generation shortage” has been renamed to “Wind power generation difference”.
Fraction of land occupied	OK		How one would calculate the denominator is not clear	Auxiliary variable will remain in the model. This auxiliary variable is calculated as the amount of land used divided by the available land for WES.
Hiring for decommissioning growth	OK		Include in total people employed /yr-Why break out HR?	Auxiliary variable will remain in the model. HR has been broken out to differentiate among different phases. Factor units can also be represented as $/MW.
Hiring for installation growth	OK			Auxiliary variable will remain in the model. HR has been broken out to differentiate among different phases. Factor units can also be represented as $/MW.
Hiring for O&M growth	OK			Auxiliary variable will remain in the model. HR has been broken out to differentiate among different phases. Factor units can also be represented as $/MW.
Hiring to replace decommissioning attrition	OK			Auxiliary variable will remain in the model. HR has been broken out to differentiate among different phases. Factor units can also be represented as $/MW.
Hiring to replace installation attrition	OK			Auxiliary variable will remain in the model. HR has been broken out to differentiate among different phases. Factor units can also be represented as $/MW.
Hiring to replace O&M attrition	OK			Auxiliary variable will remain in the model. HR has been broken out to differentiate among different phases. Factor units can also be represented as $/MW.

Table G.6—*Continued*

Installation attrition fraction	OK		Not a fraction as described	Auxiliary variable will remain in the model. Factor represents the fraction of personnel leaving the installation activities.
Installation target growth	OK		MW installed/yr.	Factor units can also be represented as $/MW.
Installed capital cost per MW	OK		Specify year of $	No further action required based on validator comment.
Interest rate	OK		Varies w/time- does not depend on wind project, more on borrower creditworthiness, current business conditions, etc.	No further action required based on validator comment.
Investor commitment	OK		Define commitment- signed a WTG contract?	Auxiliary variable will remain in the model. Represents the amount of money an investor(s) is willing to invest in a wind energy system.
Level of visual impact	OK		Subjective	Auxiliary variable will remain in the model; it has been identified as one of the major causes of NYMB.
Material transportation cost	OK		From where to where? How would you know?	Auxiliary variable will remain in the model. It includes transportation of decommissioned materials outside from wind energy areas.
Net carbon footprint	OK		Ok	No further action required based on validator comment.
Net employment rate	OK		Ok	No further action required based on validator comment.
Net water usage	OK		Ok	No further action required based on validator comment.
Net WES waste	OK		Sort of Ok. Can't we recycle some components?	No further action required based on validator comment. Some component can be recycled; however that phase is out of the scope of simulator.

Table G.6—*Continued*

Number of years	OK		Ok-length of model run?	Yes, this is the time the simulation will run.
O&M attrition fraction	OK		#/yr. not a fraction	Auxiliary variable will remain in the model. This is the name of the factor. Factor represents the fraction of personnel leaving the O&M activities in a given year.
O&M cost per MW	OK		Ok	No further action required based on validator comment.
O&M target growth	OK		OK	No further action required based on validator comment.
Other elements waste	OK		This must be negligible on a societal scale	No further action required based on validator comment.
Percentage of funds to be committed for wind energy development	OK		Not sure what this means	Auxiliary variable will remain in the model. This factor will have predefined values since factor is associated with other factors that are out of the scope of the model.
Probability of getting incentives	OK		Ok	No further action required based on validator comment.
Quantity of cement used	OK		Kg/MW	Auxiliary variable will remain in the model. Units can also be represented as Kg/MW.
Rate of excavation per wind turbine	OK		Again, consider m^2	Auxiliary variable will remain in the model. Units have been modified.
Rate of other equipment resale	OK		$ or m^3? are you turning an old turbine into cash or volume?	It is Dollars; Auxiliary variable will remain in the model. Unit of measure is dollars ($). Factor represents the translation of equipment into cash.
Rate of waste produced by other elements decommissioned	OK		Negligible, surely?	This factor is quantified given the purpose of the model. No further action required based on validator comment.

Table G.6—*Continued*

Rate of waste produced by other elements installation	OK		Negligible, surely?	This factor is quantified given the purpose of the model. No further action required based on validator comment.
Rate of waste produced per turbine	OK		Really what is expended during O&M is energy-moving heavy equipment	Simulator can handle null values if no waste is produced during O&M.
Ratio of water use per person	OK		???	No further action required based on validator comment.
Removal of material and equipment cost	OK		From where to where/	Auxiliary variable will remain in the model. If decommission is performed a transportation cost is defined, from installation to a predefined location outside the installation.
Replacement for decommissioning	OK		Not sure we have decommissionin g personnel	Auxiliary variable will remain in the model. This factor represents the personnel utilized to perform decommissioning activities.
Replacement for installation	OK		Ok	No further action required based on validator comment.
Replacement for O&M	OK		Ok	No further action required based on validator comment.
Society awareness	OK		Ok	No further action required based on validator comment.
Target wind power generation	OK		Ok	No further action required based on validator comment.
Traditional energy source greenhouse gases emissions factor	OK		Varies hugely by region	This factor will be defined based on data entered to simulator. Including geographical location and electric system.
Traditional energy source water use factor	OK		How do you think about hydro? Use or not?	Auxiliary variable will remain in the model. Water used discussed here is in traditional energy sources that use water to operate, but it does not include hydropower.

Table G.6—*Continued*

Turbine resale price	OK		End of useful life implies value=0	Auxiliary variable will remain in the model. End of useful life refers to salvage value.
Volume of waste conversion factor	OK		Not defined in the list	This was inadvertently included in the list and not shown in the architecture.
Volume of water conversion factor	OK		Not defined in the list	This was inadvertently included in the list and not shown in the architecture.
Waste produced per turbine during decommissioning	OK			No further action required based on validator comment.
Waste produced per turbine during installation	OK			No further action required based on validator comment.
Water drained from concrete demolition ratio	OK			No further action required based on validator comment.
Water drained from concrete construction ratio	OK			No further action required based on validator comment.
Water drained from O&M ratio	OK			No further action required based on validator comment.
Water ratio factor	OK		Ok	No further action required based on validator comment.
Water used conversion factor	OK		Ok	This was inadvertently included in the list and not shown in the architecture.
WES installed capacity	OK		How would this possibly be calculated?	Auxiliary variable will remain in the model. It is calculated as the number of turbines multiplied by turbine capacity.
WE population resistance	OK		Better as an index	Auxiliary variable will remain in the model. Factor is represented as a percentage.

Table G.6—*Continued*

Wind power generation shortage	OK		The problem I have with this is that I don't understand the target. If the wind doesn't show up or the equipment has problems, that's it	Auxiliary variable will remain in the model. For clarification purposes "Wind power generation shortage" has been renamed to "Wind power generation difference".
Wind power opportunity profit	OK		See above	Auxiliary variable will remain in the model. For clarification purposes "Wind power generation shortage" has been renamed to "Wind power generation difference".
Wind turbine cost	OK		$/MW	Auxiliary variable will remain in the model. Units can also be represented as $/MW.
Wind turbine installation fraction	OK		#/yr. is not a fraction	Change auxiliary variable name to "Wind turbine installation per time period".

Table G-7 Simulator Architecture Validation- Additional Notes and Comments

Validator 1	Validator 2	Validator 3	Assessment
Face Validity Test: Many of the major factors and how they interrelate have been covered, but many rates are controlled by areas outside the wind turbine planning/ development process, these rates need to be shown that they are not controlled by developers but by outside forces with multiple reasoning for accept/reject of wind development. Again review the steps for development, see if any areas there can be added or clarified in the model storages / rate/ clouds.	Validator 2 only provide inputs in Causal model notes, additional comments		Based on Validator 1 comments: No further action required based on validator comment. Simulator scope includes installation, operation, maintenance and decommissioning phases. Factors exogenous to the model take values associated with the development phase and areas that are related. An analysis of the wind energy system sustainability including all phases of the systems can be further study in the future.
Relationship between variables: The set of rates stocks and auxiliary factors are well considered for a wind development and external push and pulls that a developer would see, but the values themselves will NOT be STATIC for many of the rates, so the model will have to deal with changing values over time as a planned wind farm is designed, planned, constructed, operated and decommissioned. The values at day -780 will not be the same as the day that digging starts or the day the 10th year commissioning anniversary is held, or the 25th year decommissioning party, so needs to be some flexibility in simulation for that time of life change in model results based on WHEN you are looking at the results.			No further action required based on validator comment. Simulator can take into account the different input value to show the dynamics during simulation runs.

Table G.7—*Continued*

Additional Notes and Comments: I could not sit and think about all the factors that you have already placed in consideration, means you have spent a lot of time already on it, but the true development values will have to be determined and seen to be near to real world installations to also validate the model results. So be watching for opportunity to work with any developers / operators that will be willing to share the costs and considerations they have for project planning.		I cannot believe the amount of effort that has gone into this – recognition to some hard work done. I understand that you are between a rock and a hard place w/the need to generalize while understanding that wind projects, opportunities and problems are themselves quite variable. Broadly, I think it would help to really tighten down on most of the economic rate/stacks/variables definitions. Wind sustainability is an economic question first and an ecological /societal question second. The economic indicators/ rates chosen don't really relate clearly to wind project economics. I recognize this is a really hard problem. Also-wind target production setting is simple, wind operator try to make as much power as they can-there is no "target" so there is no "shortage". There are too many things flowing around this model- people, $, m³of waste, water, carbon, energy, etc. Could $ be converted to energy? Or something? It is a bit overwhelming the $ flows are particularly confusing which is why I suggested possibly considering them to be energy flows.-->$ is a claim on energy or resources anyway. This is a very ambitious project. Best wishes	No further action required based on validator 1 comment. Addressing Validator 3 comments: Changes have been made to the model elements after careful analysis of validator inputs, changes are included in Tables G.4, G.5 and G.6. In the present research sustainability takes into consideration economic, environmental and social factors. Definition of outputs associated with the three pillars of sustainability in terms of energy flows or other unit of measurement can be further analyzed in the future.

Appendix H

Wind Energy System Simulator Data Collection Package

The data collection package that was provided to the potential data sources is provided below:

Purpose:

The purpose of this package is to obtain information and necessary data to populate the wind energy sustainability simulator. The simulator will help energy decision makers in the decision making process.

A wind energy system is composed of various wind energy projects that are geographically located in the same country/state. Wind energy projects are utility scale projects.

Data should be from a wind energy project. This could be an individual wind farm. Aggregated data could also be used as long as the wind energy projects are in the same geographical location (collocated), serving and impacting the same community.

Data is currently requested by year, week or quarter, depending on the variable. If data is not constant within unit (year, quarter, week, etc.) please identify any variation and when this happened, in order we can simulate the correct behavior.

The data time frame includes installation, operation and maintenance (O&M), and decommissioning (if available) phases. Several years of data is needed to simulate dynamic behavior change of outputs. While we are interested in long term installation, O&M, and decommissioning, we realize that you may not have all this data. Please provide the data you can.

Contact Information

All individual contact information will be kept confidential. No individual respondent name or organization will be tied to data. The contact information will only be used for authenticating an individual response.

Name	
Role (Position)	
Experience (Years)	
Organization	
Wind Energy Project (s) Location (State(s))	

Data Collection

Please answer the following questions in the space given in the following table (Table H.1). Definitions for each factor are in Table H.2 (factor definitions). If you don’t have the items in the particular identified units of measure, please provide the data with the units you normally use. We will convert the data to the specific units. For data which do not apply to your organization please indicate ‘Does not apply’. If data is not available, please indicate ‘Not available or N/A’.

Table H-1 Characteristics of Provided Data

Identify which years correspond to installation, O&M, and decommissioning	
How many phases (wind energy projects) are included?	

Table H-2 Data Collection Table

<table>
<tr><th>Question</th><th>Factor</th><th>Unit of Measure</th><th>Data</th></tr>
<tr><td>What is the wind turbines abandonment rate?</td><td>Abandonment rate</td><td>Number of turbines / quarter</td><td><table><tr><td>Quarter</td><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr. 10</td><td>Yr. 11</td><td>Yr. 12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)</td></tr>
<tr><td>What is the amount of available funds for wind energy development?</td><td>Amount of available funds for wind energy development</td><td>Dollars/ quarter</td><td><table><tr><td>Quarter</td><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr. 10</td><td>Yr. 11</td><td>Yr. 12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)</td></tr>
<tr><td>What is the available amount of economic incentives for implementing wind technologies?</td><td>Amount of economic incentives for implementing wind technology</td><td>Dollars/ KWh/ quarter</td><td><table><tr><td>Quarter</td><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr. 10</td><td>Yr. 11</td><td>Yr. 12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)</td></tr>
<tr><td>What is the amount of land used by the wind energy system?</td><td>Amount of land used</td><td>Square meter (m^2)</td><td><table><tr><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr.10</td><td>Yr. 11</td><td>Yr.12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>If factor is changing more frequently than yearly, please specify units and quantitative value.</td></tr>
<tr><td>What is the available land that could be used by the wind energy system?</td><td>Available land for WES</td><td>Square meter (m^2)</td><td><table><tr><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr.10</td><td>Yr. 11</td><td>Yr.12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>If factor is changing more frequently than yearly, please specify units and quantitative value.</td></tr>
<tr><td>What is the average area required per wind turbine?</td><td>Average area per wind turbine</td><td>Square meter (m^2)</td><td><table><tr><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr.10</td><td>Yr. 11</td><td>Yr.12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>If factor is changing more frequently than yearly, please specify units and quantitative value.</td></tr>
<tr><td>What is the average capacity factor?</td><td>Capacity factor</td><td>Dimensionless (%)</td><td><table><tr><td>Yr. 1</td><td>Yr. 2</td><td>Yr. 3</td><td>Yr. 4</td><td>Yr. 5</td><td>Yr. 6</td><td>Yr. 7</td><td>Yr. 8</td><td>Yr. 9</td><td>Yr.10</td><td>Yr. 11</td><td>Yr.12</td><td>Yr. 13</td><td>Yr. 14</td><td>Yr. 15</td><td>Yr. 16</td><td>Yr. 17</td><td>Yr. 18</td><td>Yr. 19</td><td>Yr. 20</td></tr><tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr></table>If factor is changing more frequently than yearly, please specify units and quantitative value.</td></tr>
</table>

What is the average capacity per turbine?	Capacity per turbine	Megawatts/ turbine

Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20

If factor is changing more frequently than yearly, please specify units and quantitative value.

What is the concrete foundation removal cost per turbine?	Concrete foundation removal cost per turbine	Dollars/ turbine

Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20

If factor is changing more frequently than yearly, please specify units and quantitative value.

What is the average decommissioning attrition fraction?	Decommissioning attrition fraction	# of people/ quarter

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the average decommissioning rate?	Decommissioning rate	# of turbines/ quarter

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the decommissioning target growth?	Decommissioning target growth	# of turbines / quarter

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the average distance between the WES and community?	Distance between WES and community	Miles (m)

Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20

If factor is changing more frequently than yearly, please specify units and quantitative value.

What is the wind energy electricity price?	Electricity price	Dollars / MWh/ week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average amount of energy used per turbine during decommissioning?	Energy used per turbine during decommissioning	KWh/ turbine / week	(see table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average amount of energy used per turbine during installation?	Energy used per turbine during installation	KWh/ turbine / week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average amount of energy used per turbine during O&M?	Energy used per turbine during O&M	KWh /turbine / week	(see table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the estimated wind energy decommissioning cost?	Estimated wind energy decommissioning cost	Dollars/ quarter	

Quarter	Yr. 1	Yr . 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the estimated wind energy installed capital cost?	Estimated wind energy installed capital cost	Dollars/ quarter	

Quarter	Yr. 1	Yr . 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the estimated wind energy O&M cost?	Estimated wind energy O&M cost	Dollars/ quarter	

Quarter	Yr. 1	Yr . 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the estimated probability of getting incentives?	Estimated probability of getting incentives	%/ quarter	

Quarter	Yr. 1	Yr . 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the average installation attrition fraction?	Installation attrition fraction	# of people / quarter	

Quarter	Yr. 1	Yr . 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the average installed capital cost per MW?	Installed capital cost per MW	Dollars/ MW/ week	

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average interest rate?	Interest rate	%	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
			If factor is changing more frequently than yearly, please specify units and quantitative value.																			
What is the average level of visual impact?	Level of visual impact	Level 1-Visual dominant 2- Visual intrusive 3- Noticeable 4- Negligible	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
			If factor is changing more frequently than yearly, please specify units and quantitative value.																			

What is the average material transportation cost during decommissioning?	Material transportation cost	Dollars/ week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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<td>What is the average O&M attrition fraction?</td>
<td>O&M attrition fraction</td>
<td># of people/ quarter</td>
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What is the average O&M cost per MW?	O&M cost per MW	Dollars/ MW/ week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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<td>What is the expected O&M target growth?</td>
<td>O&M target growth</td>
<td>% / quarter</td>
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What is the average waste produced by other elements (other than wind turbines) during O&M?	Other elements waste	m³/ week	(see weekly table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average probability of getting incentives?	Probability of getting incentives	%/ quarter	

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

What is the average quantity of cement used for wind turbines bases construction?	Quantity of cement used	Pounds/ week	(see table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average amount of excavation per wind turbine?	Rate of excavation per wind turbine	m²/ turbine / week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average rate of other equipment resale?	Rate of other equipment resale	Dollars/ week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average amount of waste produced by other elements decommissioned?	Rate of waste produced by other elements decommissioned	m³/ week	See weekly table below

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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What is the average amount of waste produced by other elements installation?	Rate of waste produced by other elements installation	m³/ week	(see table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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What is the average amount of waste produced per turbine?	Rate of waste produced per turbine	m^3/ week	See table below

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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What is the average amount of water used per person?	Ratio of water used per person	m^3/ week	See weekly table below

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average cost of removal of material and equipment?	Removal of material and equipment cost	Dollars /week	

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What percentage of people that have left employment for decommissioning will be replaced?	Replacement for decommissioning	% / quarter	Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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What percentage of people that have left employment for installation will be replaced?	Replacement for installation	% / quarter	Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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What percentage of people that left employment for O&M will be replaced?	Replacement for O&M	% / quarter	Provide information below (what happened, when in the quarter and for how long) about special events that occurred into a quarter that modified the factor. Please specify which quarter was affected. (If factor is changing more frequently than quarterly, please specify units and quantitative value)

Quarter	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Level of awareness of wind energy systems	Society awareness	Level 1-Familiar with wind energy 2-Some familiarity with wind energy 3-Not familiar with wind energy	If factor is changing more frequently than yearly, please specify units and quantitative value.

Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20

What is the average turbine resale price?	Turbine resale price	Dollars/ turbine	If factor is changing more frequently than yearly, please specify units and quantitative value.

Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr.10	Yr. 11	Yr.12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20

What is the average waste produced per turbine during decommissioning?	Waste produced per turbine during decommissioning	m^3/ turbine / week	See weekly table below

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average waste produced per turbine during installation?	Waste produced per turbine during installation	m³/ turbine/ week	(see weekly table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average percentage of water drained from concrete demolition?	Water drained from concrete demolition ratio	% of water used for concrete demolition/ week	

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average percentage of water drained from O&M?	Water drained from O&M ratio	% of water used for O&M/ week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average percentage of water drained from concrete construction?	Water drained from concrete construction	% of water used for concrete construction/ week	(see weekly table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average wind energy project(s) operating time?	Weekly operating time	Hours/ week

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

What is the average wind turbine installation proportion?	Wind turbine installation per time period	#/ # / week	(see weekly table below)

Week	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Yr. 11	Yr. 12	Yr. 13	Yr. 14	Yr. 15	Yr. 16	Yr. 17	Yr. 18	Yr. 19	Yr. 20
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Provide information below (what happened, when in the week and for how long) about special events that occurred into a week that modified the factor. Please specify which week was affected. (If factor is changing more frequently than weekly, please specify units and quantitative value)

Appendix I

Simulator Data Collected

The wind energy system sustainability data collection package was presented and provided to potential data sources but minimal inputs were received. Therefore data from government databases were used to populate the simulator. Texas, California and Iowa state information was collected to run the simulator. At situations where the data was not available in government databases, other resources in the literature were used to extract the information necessary to populate the simulator with the data. Data used as input for the simulator is presented in Table I.1.

Table I-1 Simulator Initial Inputs per State

Input	Units	Texas	California	Iowa	Comments
Abandonment rate	Number of turbines per year	0.01	0.01	0.01	(Gray, 2013)
Adjusting time	year	0.5	0.5	0.5	It is assumed that installation of new capacity takes a year. The simulator assumes it takes 1/2 for affecting social perception due to installation, O&M and decommissioning activities.
Amount of money recouped due to decommissioning	Dollars	0	0	0	Assume all installation starts at year 2000. Existing data is not available prior to this time. This means decommissioning is also = 0.
Annual operating time	Hour/year	8760	8760	8760	Total number of hours in a year
Area of excavation and trenching	Square meter	1835200	16159930	2404200	Data calculation is based on the quantity of MW installed in the state. Year 2000 is year 0. Initial value is calculated at year 0. Mean value used for calculation (Denholm et al., 2009)
Available land for WES	Square meter	2.9066E+11	3280000000	9.52E+10	(NREL and AWS True Power, 2015).
Capacity factor	Dimensionless	0.319	0.319	0.319	Average value year 2000-2014 (Wiser and Bolinger, 2015)
Capacity per turbine	Megawatt	1.5	1.5	1.5	Most common turbine installed between 200-2014 (Wiser and Bolinger, 2015).
Carbon footprint avoided by WES	Metric Ton CO_2	339359.766	2425856.278	340514.1	6.89551 × 10-4 metric tons CO_2 / kWh (EPA, 2014) State Generation year 2000 (EIA, 2015)

Table I.1—*Continued*

Carbon footprint added by WES	Metric Ton CO2	19.85	175.29	26.2	Installation 2% of 27158 GJ= 543.16GJ, and 2230GJ/20y=111.5 GJ O&M (Crawford, 2009). Assume all installation starts at year 2000. This means O&M is = 0
Decommission time	Year	3	3	3	Assumed it would take three years after 20 years of operation to decommission wind turbines installed.
Decommissioning cost per turbine	Dollars	100000	100000	100000	(Ferrel, 2013)
Decommissioning attrition fraction	Number of people per year	0.001	0.001	0.001	No data available. For modeling purposes assume 0.1%.
Electricity price	Megawatts hour per Dollars	37.7	67.76	37.7	Average electricity price (PPA) from year 2000 to year 2014 (Wiser and Bolinger, 2015)
Energy used by WES	Megawatt-hour	286819.436	430002.7657	450672.2	Assume all installation starts at year 2000. This means O&M or decommissioning. Use Installed Capacity to calculate the energy used (EIA,2015)
Energy used during installation	Joules	9.15E+14	1.37E+15	1.44E+15	850KW- Installation 2% of 27158GJ 3MW- Installation 2% of 84237GJ Using interpolation between energy values- energy installation is approx. =850 GJ (Crawford, 2009) Assume all installation starts at year 2000. For simulator we will use as Turbine capacity=1.5 MW.

Table I.1—*Continued*

Energy used during O&M	Joules	0	0	0	Installation starts at year 0. This means O&M is = 0
Energy used per turbine during O&M	Joules per turbine	2E+11	2E+11	2E+11	Interpolation (Crawford,2009)
Energy used per turbine during installation	Joules per turbine	8.5E+11	8.5E+11	8.5E+11	Interpolation (Crawford,2009)
Energy used during decommissioning	Joules	0	0	0	Assume installation starts at year 2000. This means decommissioning is = 0.
Energy used per turbine during decommissioning	Joules per turbine	478000000	478000000	4.78E+08	Interpolation (Crawford,2009)
Federal tax	Dimensionless	0.35	0.35	0.35	(IRS, 2015)
Hiring delay time	year	0.5	0.5	0.5	For modeling purposes assume 0.5 year.
Installation attrition fraction	Number of people per year	0.001	0.001	0.001	For modeling purposes assume 0.1%
Installed capital cost per MW	Dollars	1775000	1775000	1775000	Average installation cost from year 2000 to year 2014 (Wiser and Bolinger, 2015)
Net present value	Dollars	-284110752	-298099817	-4.2E+09	Assume year 2000 = year 0
Number of wind turbines decommissioned	Number of turbines	0	0	0	Assume all installation starts at year 2000. This means decommissioning is also = 0
Number of wind turbines installed	Number of turbines	122	1077	162	Assume all installation starts at year 2000.This means abandoned and decommissioned turbines=0 MW. Use installed capacity at year 2000 as initial value (Wiser and Bolinger, 2015)

Table I.1—*Continued*

Number of wind turbines to be installed	Number of turbines	0	0	0	Assume initial value zero (0)
O&M attrition fraction	Number of people per year	0.001	0.001	0.001	For modeling purposes assume 0.1%
O&M cost per MWh	Dollars per MWh per year	14.8	14.8	14.8	Average O&M cost from year 2000 to year 2014 (Wiser and Bolinger, 2015)
Operating rate	Dimensionless	0.95	0.95	0.95	For modeling purposes assume 95% of all turbines installed in a state are operating.
Rate of excavation per wind turbine	Square meter per year per turbine	15000	15000	15000	(Denholm et al., 2009)
Rate of waste produced per turbine	Metric Tons per year	0.07575	0.07575	0.07575	(Ardente et al., 2008)
Ratio of water use per person	Gallons per person per year	523.060659	523.060659	523.0607	(World Health Organization, 2015)
Replacement for installation attrition	% per year	0.001	0.001	0.001	For modeling purposes assume 0.1%
Replacement for O&M	% per year	0.001	0.001	0.001	For modeling purposes assume 0.1%
Replacement for decommissioning	% per year	0.001	0.001	0.001	For modeling purposes assume 0.1%
Rotor diameter	Meter	80	80	80	Average rotor diameter from year 2000 to year 2014 (Wiser and Bolinger, 2015)
Skilled personnel for WES installation	People (Person)	125	1099	165	68 people/100MW-JEDI Model (NREL,2015)

Table I.1—*Continued*

Skilled personnel for WES decommissioning	People (Person)	0	0	0	Assume initial value zero (0). Assume all installation starts at year 2000. This means decommissioning is = 0
Skilled personnel for WES O&M	People (Person)	0	0	0	Assume initial value zero (0). Assume all installation starts at year 2000.This means O&M is = 0
Target wind power generation	MWh per year	142000000	78100000	15600000	Calculated using Wind Generation year 2000 as a base (EIA, 2015) Target= 20% generation by year 30.
Total WES revenue	Dollars	29873444.3	319295767.5	1.32E+08	Calculated using electricity price average for the region between years 2000 and 2014 (Wiser and Bolinger, 2015) and year 2000 generation (EIA, 2015)
Total wind power generated from WES	Megawatt-hour	492149	3518023	493820	Wind Generation Year 2000 (EIA, 2015)
Traditional energy source water use factor	Gallons per MWh	519	519	519	It depends on what fuel type and technology is replaced. For this calculation we consider coal/tower replacement (687) which is 519 gal/MWh (Macknick et al., 2011)
Traditional energy source greenhouse gases emissions factor	Tons of CO_2 per MWh	0.689551	0.689551	0.689551	(EPA, 2014)
Volume of water discharged to ground	Gallons	123037250	87950575	12345500	Assume all installation starts at year 2000. This means O&M is = 0 and decommissioning is also = 0. (Meldrum et al., 2013)

Table I.1—*Continued*

Volume of water used during O&M	Gallons	0	0	0	Assume all installation starts at year 2000. This means O&M is = 0 and decommissioning is also = 0. (Meldrum et al., 2013)
Volume of water used during WES installation	Gallons	492149	3518023	493820	Assume all installation starts at year 2000. This means O&M is = 0 and decommissioning is also = 0. (Meldrum et al., 2013)
Volume of water used for human needs	Gallons	65382.6	133648.2075	204252.3	Assume all installation starts at year 2000. This means O&M is = 0 and decommissioning is also = 0. (World Health Organization, 2015)
Volume of water used for WES decommissioning	Gallons	0	0	0	Assume all installation starts at year 2000. This means O&M is = 0 and decommissioning is also = 0. (Meldrum et al., 2013)
Waste conversion factor	Global hectares per Metric Tons	0.04	0.04	0.04	
Waste produced per turbine during decommissioning	Metric Tons per turbine	3390	3390	3390	Assumed similar to installation (Ardente et al., 2008)
Waste produced per turbine during installation	Metric Tons per turbine	3390	3390	3390	(Ardente et al., 2008)
Waste produced by WES decommissioning	Metric Tons	0	0	0	Assume all installation starts at year 2000. This means decommissioning is also = 0

Table I.1—*Continued*

Waste produced by WES installation	Metric Tons	413580	413580	547869	Assume all installation starts at year 2000. Calculate based on the amount of waste per turbine(Ardente, 2008)
Waste produced by WES O&M	Metric Tons	0	0	0	Assume all installation starts at year 2000.
Water conserved by WES	Gallons	338106363	2416881801	3.39E+08	It depends on what fuel type and technology is replaced. For this calculation we consider coal/tower replacement (Macknick et al. 2011). Assume all installation starts at year 2000.
Water drained from WES installation factor	Dimensionless	0.65	0.65	0.65	(Meldrum et al., 2013)
Water drained from O&M ratio	Dimensionless	0	0	0	(Meldrum et al., 2013)
Water drained from WES decommissioning factor	Dimensionless	0.9231	0.9231	0.9231	(Meldrum et al., 2013)
Water use by WES	Gallons	65382.6	574843.6642	65382.6	Water used during installation.
Water withdraw during installation factor	Dimensionless	26	26	26	(Meldrum et al., 2013)
Water withdraw during O&M factor	Dimensionless	1	1	1	(Meldrum et al., 2013)
Water withdrawn during decommissioning factor	Dimensionless	13	13	13	(Meldrum et al., 2013)

Table I.1—*Continued*

WES decommissioning cost	Dollars	0	0	0	Assume all installation starts at year 2000. Decommissioning cost year 0 = 0
WES Total waste	Metric Tons	413580	3649900	547869	Total waste=Installation waste
WES installed capital cost	Dollars	311616960	2868387575	4.3E+08	Assume all installation starts at year 2000. Use installed wind power project cost yr 2000 to make calculation (Wiser and Bolinger, 2015).
WES O&M cost	Dollars	0	0	0	Assume all installation starts at year 2000.
WES total cost	Dollars	311616960	2868387575	4.3E+08	Total cost is equal to installed cost, based on the assumption that the installation starts at year 2000.
Wind turbine cost	Dollars	1296000	1296000	1296000	Average Turbine Cost (>100MW) from year 2000 to year 2014 (Wiser and Bolinger, 2015)

Table I-2 Conversion Factors

Input	Units	Conversion factor
Area conversion factor	Global Hectares/ m^2	0.0001
Carbon footprint conversion factor	Global hectares per Metric Tons of CO_2	0.000137
Energy conversion factor	Megawatts hour per Joules	2.78E-10
Waste conversion factor	Global hectares per Metric Tons	0.04
Water conversion factor	Global hectares per Gallons	3.00E-07

Appendix J

Populated Simulator Validation Package

This section includes the populated simulator validation package that was provided to the subject matter experts. The validation package included references that are provided with all the other references in the Reference section. The validation package of the populated simulator provided to the validators is as following:

Validation Package Purpose

The purpose of the validation package document is to facilitate the model validation effort. The validation effort focuses on building confidence in the wind energy system sustainability simulator as a reasonable representation of the real system and in its usefulness in providing results. The package checks if the simulation model runs as planned. According to Pritsker et al. (1997), model validation determines whether a model is a "useful or reasonable representation of the system". The validation focuses on addressing four aspects including suitability, consistency, utility, and effectiveness (Richardson and Pugh, 1981). Questions such as the following are related to these aspects:

- Is the model suitable for its purpose and the problem it addresses?
- Is the model consistent with the slice of reality it tries to capture?
- How effective is the model in achieving the purpose of the study?
- Can the model or its results be used?

System Represented

The system the simulator is representing is the wind energy system at the state (Texas, California, Iowa) level. The wind energy system is an integrated set of elements including wind turbines, assemblies, and other resources working together to harvest wind energy. These elements can be geographically distributed. However, all elements of the wind energy system taken together offer their output to the same electric system.

Simulation Model Purpose and Scope

The purpose of the simulation model is to help energy decision makers at all levels to understand the system dynamics associated to wind energy system sustainability and use this knowledge to make informed decisions. The wind energy system sustainability simulator models the factors that relate to wind energy system sustainability and include those related to the three pillars of sustainability: social, economic, and environmental. A simulator can help users to explore risks and evaluate the dynamic consequences of various decisions without having to interrupt or affect the existing system. The simulator helps decision makers to perform what-if analysis to assess alternative decisions. The scope of the research is limited to factors related to the installation, operation and maintenance, and decommissioning phases of wind energy systems. The research considers a wind energy system within a particular geographical location. Texas, California and Iowa were chosen as geographical locations. The focus is on understanding onshore wind energy system sustainability.

Contact Information

All individual contact information will be kept confidential. No individual respondent name will be tied to particular validation results. The contact information will only be used for authenticating an individual response.

Name	
Role (Position)	
Experience (Years)	

This document will contain your comments about the model for validation tests you are being asked to perform.

The overall approach for the model validation includes tests of the structure and behavior of the model. This strategy follows a framework of guidelines presented by Richardson & Pugh (1981) that builds confidence in the model and its results. The tests focus on suitability, consistency, utility, and effectiveness.

The validation includes boundary structural adequacy, face validity, parameter validity, replication of reference modes, and appropriateness of structure tests. Table J.1 presents the subset of tests, in the context of the Richardson & Pugh framework, where your help is required:

Table J-1 Validation Activities

Activity Type	Structure	Behavior
Suitability	Boundary structural adequacy	Structural (in)sensitivity
Consistency	Face validity	Replication of reference modes
	Parameter validity	
Model Utility & Effectiveness	Appropriateness of structure	

Each of the tests in Table 1 will be handled separately in this document. The individual model test sections include an introductory section that identifies questions to consider and how to perform the test. The introductory section for each question is followed by a space for you to place comments. Please enter “OK” or enter a checkmark in the spaces for the tests if you are satisfied with an area and have no other comments about it.

Other information supplied to assist in the model validation activities include the wind energy system sustainability simulator architecture (Figure 1), the factor definitions that explains the model’s variables in detail, the model Runtime files that includes the simulation runs, and the simulator runs and results discussion (in a separate document). Table 2 includes a legend for figure J.1. Please review the information in order to understand the model's purpose, usage, and particulars in order to perform your validation activities.

The validation activities required to support tests in Table J.1 follow:

(1) Structure – Boundary structural adequacy

Questions: Does the structure of the simulator include the elements (inputs, variables and feedback loops) and level of detail that is necessary to address the model's scope and purpose?

Test process: Review the model's structure (Figure 1) against its purpose and scope as stated in the model purpose and scope section of this document.

(2) Behavior – Structural sensitivity test

Questions: Are there details missing in the model's structure that would critically influence the model's behavior and results? Are there inappropriate model details that introduce improper model behavior or unduly influence model behavior? Would minor changes to the model's structure/alternative structural formulations make a difference in the model's behavior?

Test process: Run the model and review the model's behavior by looking at model outputs.

(3) Structure – Face validity test

Questions: Does the model's structure represent reasonable and adequate characteristics of wind energy system sustainability? Are the essential characteristics of the real system represented? Is the model a recognizable picture of the real system?

Test process: Review the model's structure (Figure J.1).

(4) Structure – Parameter validity test

Questions: Are the model elements (factors) recognizable in terms of wind energy system sustainability? The wind energy system sustainability simulator models the factors that relate to wind energy sustainability including the three pillars of sustainability: social, economic, and environmental. Are the values selected for the model elements consistent with information available about wind energy system sustainability? Do the values make sense?

Test process: Review model elements (Figure J.1) and values (wind energy system sustainability simulator runs and results document).

(5) Behavior – Replication of reference modes (consistency of model behavior with real system)

Question: Does the model reproduce behavior seen in a real system or anticipated behavior arising from potential situations?

Test process: Run the model and review model outputs.

(6) Structure – Appropriateness of structure test

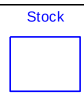
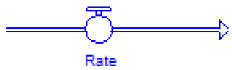
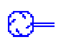
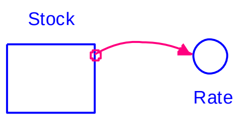
Question: Are the model's characteristics (level of complexity, simplicity, size, and level of aggregation or detail) appropriate for the model's purpose and potential users?

Test Process: Review the model's structure.

Notes

Additional notes and recommendations may be provided here:

Table J-2 Legend for Figure J.1

Symbol	Symbol name	Definition
	Stock (also called accumulation)	Represents state of the model or system. These are accumulations.
	Flow (also called rate)	Represents changes in the state of the model or system. The job of flows is to fill and drain stocks.
	Auxiliary variables	Represents combinations of information inputs. These can modify the flows. These hold values for constants, defines external inputs to the model, calculates algebraic relationships, and serves as the repository for graphical functions.
	Cloud	Represents the sources and sinks for the flows. A source represents the stock from which a flow originates from outside the model scope. A sink represents the stock into which other variables flow and leave the model.
	Arrow	Represents causal dependencies in the model. The job of the connector is to connect model elements.

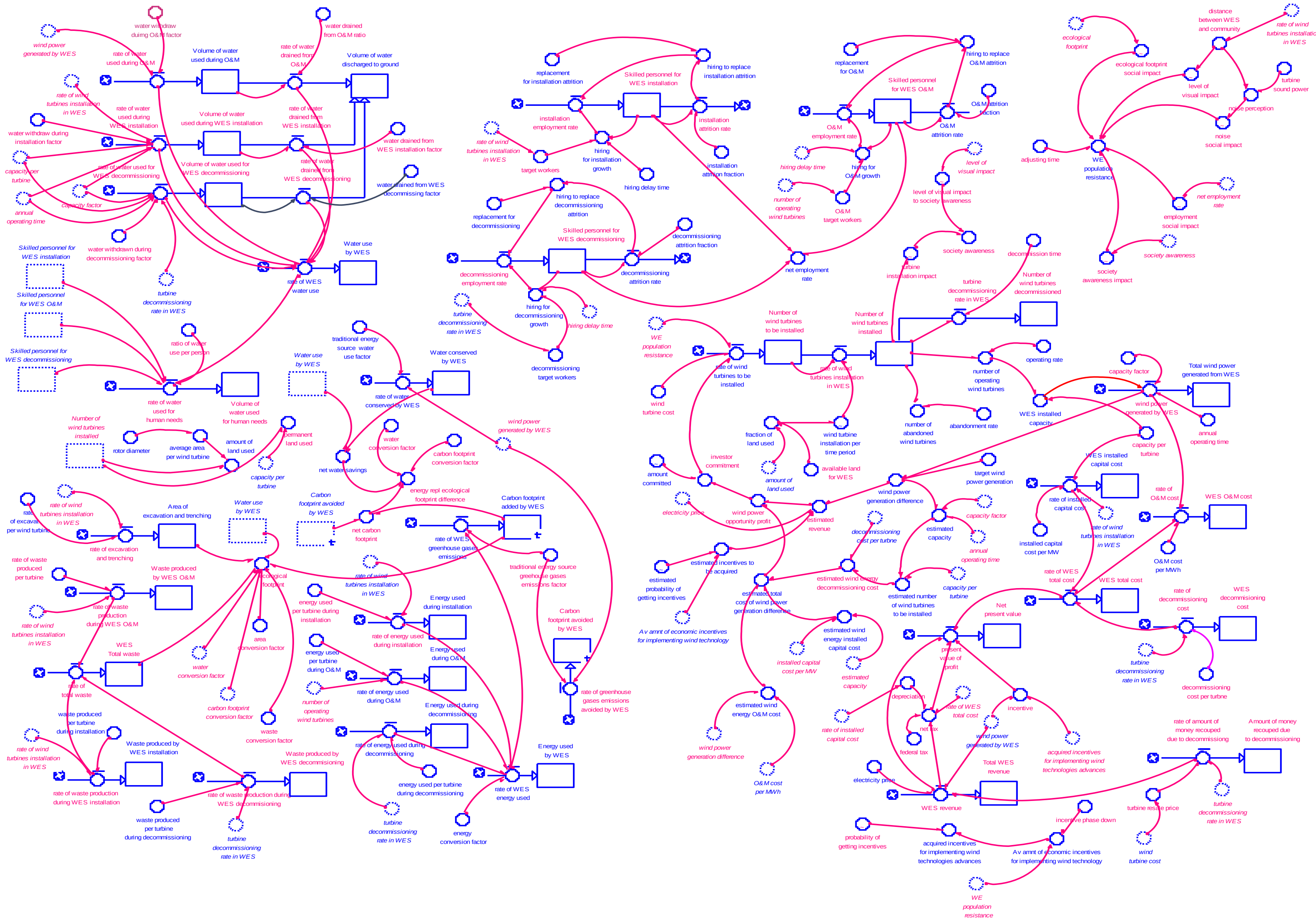


Figure J-1 Wind Energy System Sustainability Simulator Architecture

Wind Energy System Sustainability Simulator Stock, Rate and Auxiliary Variable Definitions

Table J-3 Stock Definitions

Stock	Definition	Unit
Amount of money recouped due to decommissioning	Represents the accumulated amount of money recovered due to decommissioning of wind turbines.	Dollars
Area of excavation and trenching	Amount of land excavating and trenching required for turbine tower installation, access roads, electric substation and operations building construction.	Squared meter (m^2)
Carbon footprint added by WES (wind energy system)	Represents the greenhouse gases emissions caused to install, operate and /or decommission wind turbines and other elements of the system.	Tons of Carbon dioxide (CO_2)
Carbon footprint avoided by WES	Represents the greenhouse gases emissions avoided by generating electricity from wind energy system.	Tons CO_2
Energy used by WES	Represents the total energy used by WES during installation, operations and maintenance (O&M) and decommissioning.	Megawatts per hour (MWh)
Energy used during decommissioning	Represents the energy used during wind turbine decommissioning.	Joules
Energy used during installation	Represents the energy used during WES installation.	Joules
Energy used during O&M	Represents the energy used during WES operation and maintenance.	Joules
Net present value	Net present value is the algebraic sum of the net cash flows discounted at the minimum acceptable rate of return, to present time. Net cash flows is the algebraic sum of money estimated to flow in and out of an organization over some period of time as a result of a particular project (Stevens, 1994).	Dollars
Number of wind turbines decommissioned	The number of wind turbines decommissioned from the wind energy system.	Number of turbines
Number of wind turbines installed	The number of wind turbines installed in a wind energy system.	Number of turbines
Number of wind turbines to be installed	The number of wind turbines planned to be installed in a wind energy system.	Number of turbines
Skilled personnel for WES decommissioning	Represents the human resources needed with the skill level required for decommissioning.	Number of people
Skilled personnel for WES installation	Represents the human resources needed with the skill level required for wind energy system installation.	Number of people
Skilled personnel for WES O&M	Represents the human resources needed with the skill level required for wind energy O&M.	Number of people
Total WES revenue	Represents the total income received by wind energy system operation.	Dollars

Total wind power generated from WES	Represents the accumulated amount of electric power generated by a wind energy system.	MWh
Volume of water discharged to ground	Represents the total amount of water discharged to ground by WES during installation, O&M and decommissioning.	Gallons
Volume of water used during O&M	Represents the total amount of water used during operation and maintenance phase.	Gallons
Volume of water used during WES installation	Represents the total amount of water used during the installation phase.	Gallons
Volume of water used for human needs	Represents the total amount of water used for the personnel working on the installation, O&M and/or decommission of the wind energy system.	Gallons
Volume of water used for WES decommissioning	Represents the total amount of water used during the decommissioning phase.	Gallons
Waste produced by WES decommissioning	Represents the accumulated waste produced during WES decommission.	Metric Tons
Waste produced by WES installation	Represents the accumulated waste produced during WES installation.	Metric Tons
Waste produced by WES O&M	Represents the accumulated waste produced during WES O&M.	Metric Tons
Water conserved by WES	Represents the accumulated amount of water conserved for avoiding use of other energy sources due to wind power generation.	Gallons
Water used by WES	Represents the accumulated amount of water used by the wind energy system from installation phase through decommissioning phase.	Gallons
WES decommissioning cost	Represents the accumulated decommission cost of the wind energy system.	Dollars
WES installed capital cost	Represents the accumulated installed capital costs of a wind energy system.	Dollars
WES O&M cost	Represents the accumulated operation and maintenance costs of a wind energy system. It includes land lease cost, labor wages and material, and levelized replacement costs.	Dollars
WES total cost	Sum of initial wind energy installed capital cost, O&M cost and decommissioning cost.	Dollars
WES total waste	Sum of waste produced during wind energy installation, O&M and decommissioning phases.	Metric Tons

Table J-4 Rates Definitions

Rate	Definition	Unit
Decommissioning attrition rate	Represents the rate of personnel exiting from the decommissioning activities.	Number of people per year
Decommissioning employment rate	Represents the rate of employment during the WES decommissioning phase.	Number of people per year

Rate	Definition	Unit
Installation attrition rate	Represents the rate of personnel exiting from the installation activities.	Number of people per year
Installation employment rate	Represents the rate of employment during the WES installation phase.	Number of people per year
O&M attrition rate	Represents the rate of personnel exiting from the O&M activities.	Number of people per year
O&M employment rate	Represents the rate of employment during the WES O&M.	Number of people per year
Present value of profit	The amount remaining after wind energy system total costs are deducted from total revenue.	Dollars per year
Rate of amount of money recouped due to decommissioning	Represents the rate at which money is recouped due to decommissioning of wind turbines.	Dollars per year
Rate of decommissioning cost	Represents the rate at which decommissioning expenditures are disbursed in the wind energy system.	Dollars per year
Rate of energy used during decommissioning	The rate at which energy is used during turbine decommissioning activities.	Joules per year
Rate of energy used during installation	The rate at which energy is used during turbine installation activities.	Joules per year
Rate of energy used during O&M	The rate at which energy is used during turbine O&M activities.	Joules per year
Rate of excavation and trenching	The rate at which land excavation and trenching required for turbine tower installation, access roads, electric substation and O&M building construction is performed.	m^2 per year
Rate of greenhouse gases emissions avoided by WES	The rate at which the greenhouse gases emissions is avoided by generating electricity from wind energy system.	Tons of CO_2 per year
Rate of installed capital cost	The amount of investment required to develop a wind energy system. This includes wind turbines, balance of station and soft costs. Balance of station cost refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Soft cost refers to costs that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	Dollars per year
Rate of O&M cost	The rate at which O&M costs are utilized.	Dollars per year
Rate of total waste	Represents the rate at which waste is produced by the wind energy system. This is the sum of WES waste produced during installation, O&M and decommissioning during a year.	Metric Tons per year
Rate of waste production during WES decommissioning	Represents the rate at which waste is produced during WES decommissioning.	Metric Tons per year

Rate	Definition	Unit
Rate of waste production during WES installation	Represents the rate at which waste is produced during WES installation.	Metric Tons per year
Rate of waste production during WES O&M	Represents the rate at which waste is produced during WES O&M.	Metric Tons per year
Rate of water conserved by WES	Represents the rate at which water is conserved due to wind energy consumption.	Gallons per year
Rate of water drained from O&M	The rate at which water is drained during WES O&M activities.	Gallons per year
Rate of water drained from WES installation	The rate at which water is drained during WES installation activities.	Gallons per year
Rate of water drained from WES decommissioning	The rate at which water is drained during WES decommissioning activities.	Gallons per year
Rate of water used for WES decommissioning	Represents the rate at which water is used during WES decommissioning phase.	Gallons per year
Rate of water used during O&M	Represents the rate at which water is used during WES O&M phase.	Gallons per year
Rate of water used during WES installation	Represents the rate at which water is used during WES installation phase.	Gallons per year
Rate of water used for human needs	The rate at which water is used for human consumption on the WES.	Gallons per year
Rate of WES energy used	The rate at which energy is used on the WES during installation, O&M and decommissioning	MWh per year
Rate of WES greenhouse gases emissions	The rate at which greenhouse gases emissions are produced due to wind energy system installation, O&M and decommissioning.	Tons CO_2 per year
Rate of WES total cost	Represents the WES total cost. This is the sum of installed capital cost, operation and maintenance cost, and decommissioning cost.	Dollars per year
Rate of WES water use	Represents the rate at which water is used in the WES during installation, O&M, and decommissioning activities.	Gallons per year
Rate of wind turbine installation in WES	The rate at which wind turbines are added to the WES.	Number of turbines per year
Rate of wind turbines to be installed	The rate at which wind turbines are planned to be installed post investor commitment.	Number of turbines per year
Turbine decommissioning rate in WES	Represents the rate at which wind turbines are decommissioned once they have reached the end of life.	Number of turbines per year
WES revenue	Represents the income received by WES operation.	Dollars per year
Wind power generated by WES	Represents the amount of wind power generated in an interconnected electric system.	MWh per year

Table J-5 Auxiliary Variable Definitions

Auxiliary Variable	Definition	Unit
Abandonment rate	The ratio at which turbine are abandoned at the end of their useful life.	Number of turbines per year
Acquired incentives for implementing wind technologies advances	The actual amount of incentives in financial form obtained by particular businesses and investors to implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars per MWh
Adjusting time	Time required for the population to react to social impacts.	Year
Amount committed	Refers to the actual amount of funds available to be committed by investors for WES development.	Dollars/year
Available amount of economic incentives for implementing wind technology (In the model: Av amnt of economic incentives for implementing wind technology)	Provides motivation in financial form to businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars per MWh
Amount of land used	Refers to the amount of land already in used by WES.	Square meter (m^2)
Annual operating time	Refers to the amount of hours per year the wind energy system is expected to operate.	Hours per year
Area conversion factor	Area conversion factor from square meters to global hectares.	Global hectares/ m^2
Available land for WES	Represents the total available land that could be used for wind energy development.	m^2
Average area per wind turbine	Represents the amount of land required to install a wind turbine.	m^2 per turbine
Capacity factor	The ratio of wind energy (assuming all turbines are same size) actual output over a period of time, to its potential output if it were possible for it to operate at full theoretical capacity indefinitely.	% (dimensionless)
Capacity per turbine	Refers to the maximum rated output of a wind turbine under specific conditions designated by the manufacturer (modified from EIA glossary definition "nameplate capacity" (EIA, 2013)).	Megawatts per turbine
Carbon footprint conversion factor	Carbon footprint conversion factor from Metric Tons CO_2 to Global hectares.	Global hectares per Metric Tons of CO_2
Decommissioning attrition fraction	Represents the fraction of personnel leaving the wind energy system decommissioning activities.	Number of people per year
Decommissioning cost per turbine	Refers to the unit cost of turbine decommissioning.	Dollars
Decommissioning target workers	Represents the number of workers required to perform decommissioning activities in a given year.	Number of people
Decommission time	Represents the required time to decommission turbines from the wind energy system.	Year

Auxiliary Variable	Definition	Unit
Depreciation	Depreciation is an income tax deduction that allows a taxpayer to recover the cost or other basis of certain property. It is an annual allowance for the wear and tear, deterioration, or obsolescence of the property.	Dollars
Distance between WES and community	Average distance between the WES and the closest surrounding community.	Kilometers (Km)
Ecological footprint	Represents the amount of land and water area required for nature to regenerate the resources used by the WES.	Global hectares
Ecological footprint social impact	Represents the effect of the wind energy system ecological footprint on the population resistance.	dimensionle ss
Electricity price	Represents the average sale price of electricity generated from a wind energy system to utilities.	Megawatts hour per Dollars
Employment social impact	Represents the effect of the employment due to wind energy system installation, O&M and decommissioning activities on the population resistance.	dimensionle ss
Energy replacement ecological footprint difference	Algebraic sum of the net water savings and the net carbon footprint given wind energy system installation, operation and decommissioning. It represents the ecological footprint savings (related to water and carbon dioxide emissions) of using wind energy to supply energy demand instead of traditional nonrenewable sources. Focus is on water and energy.	Global hectares
Energy used per turbine during decommissioning	Refers to the amount of energy used for wind turbines decommissioning.	Joules per turbine
Energy used per turbine during installation	Refers to the amount of energy used for wind turbine installation.	Joules per turbine
Energy used per turbine during O&M	Refers to the amount of energy used for wind turbines to operate.	Joules per turbine
Energy conversion factor	Energy conversion factor from Joules to MWh.	MWh per Joules
Estimated incentives to be acquired	Refers to the potential amount of incentives in financial form obtained by businesses and investors that implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars per year
Estimated number of wind turbines to be installed	Refers to the estimated number of wind turbines that would be required to cover the total wind power generation difference.	Number of turbines
Estimated total cost of wind power generation difference	Refers to the estimated cost of wind turbines installation, O&M and decommissioning to cover total wind power generation difference.	Dollars
Estimated wind energy decommissioning cost	Refers to the estimated amount of funds required to decommission wind turbines to be installed to cover wind power generation difference.	Dollars

Auxiliary Variable	Definition	Unit
Estimated wind energy installed capital cost	Refers to the estimated amount of investment required to cover the total wind power generation difference.	Dollars
Estimated wind energy O&M cost	Represents the estimated operational and maintenance costs of the additional wind turbines required to cover the total wind power generation difference.	Dollars
Estimated capacity	Represents the estimated energy capacity required to cover the wind power generation difference.	Megawatts
Estimated revenue	Represents the estimated income related to the wind power generation difference.	Dollars
Federal tax	A tax collected by the United States Internal Revenue Service (IRS) on the annual earnings of individuals, corporations, trusts and other legal entities.	% (dimensionless)
Estimated probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances to cover the total wind power generation difference.	% (dimensionless)
Fraction of land used	Refers to what fraction of the land allotted to wind turbines installed is actually built on.	% (dimensionless)
Hiring delay time	The amount of time required to hire personnel.	Year
Hiring for decommissioning growth	Refers to the human resource employment due to growth of decommissioning activities in the WES.	Number of people per year
Hiring for installation growth	Refers to the human resource employment due to growth of installation activities in the WES.	Number of people per year
Hiring for O&M growth	Refers to the human resource employment due to growth of operation and maintenance activities in the WES.	Number of people per year
Hiring to replace decommissioning attrition	Refers to the human resource employment due to decommissioning personnel attrition in the WES.	Number of people per year
Hiring to replace installation attrition	Refers to the human resource employment due to installation personnel attrition in the WES.	Number of people per year
Hiring to replace O&M attrition	Refers to the human resource employment due to operation and maintenance personnel attrition in the WES.	Number of people per year
Incentive	The actual amount of incentives in financial form obtained by particular businesses and investors to implement new wind energy additions and/or technologies to make them more sustainable and efficient.	Dollars
Incentive phase down	The actual amount of funds that could be received as an incentive per MWh generated in a given year	Dollars per MWh
Installation attrition fraction	Represents the fraction of personnel leaving the WES installation activities.	Number of people per year
Installed capital cost per MW	Refers to the unit cost of wind energy installation per MW. This includes wind turbines, balance of station and soft costs. Balance of station cost refers to the cost of engineering permits, foundations, roads and civil work, electrical interface, turbine transportation, assembly and installation. Soft cost refers to costs	Dollars/ MW

Auxiliary Variable	Definition	Unit
	that are not considered direct costs related to wind energy project construction. Includes construction finance and contingency costs.	
Investor commitment	Refers to amount of funds committed by investor to fund wind energy developments.	Dollars
Level of visual impact	Represents how well wind turbines can be seen from horizon.	% (dimensionless)
Level of visual impact to society awareness	Represents the effect of the WES level of visual impact on the population resistance.	% (dimensionless)
Net carbon footprint	The algebraic sum of the carbon footprint avoided and emitted during WES installation, operation and decommissioning.	Tons of CO_2 per year
Net employment rate	Represents the rate of employment during the wind energy installation, O&M and decommissioning phases.	Number of people per year
Net tax	The amount of money paid as tax due to revenue generation after total costs and depreciation credit have been subtracted.	Dollars
Net water savings	This is the algebraic sum of water used by WES and the water conserved by WES.	Gallons per year
Noise perception	Refers to the amount of noise perceived in the nearest communities during wind turbine operation.	Decibels
Noise social impact	Represents the effect of the noise perceived during wind turbine operation on the population resistance.	% (dimensionless)
Number of operating wind turbines	Represents the number of wind turbines operating in the WES.	Number of turbines
Number of abandoned wind turbines	Represents the number of wind turbines abandoned after end of operational life in the WES.	Number of turbines
O&M attrition fraction	Represents the fraction of personnel leaving the WES operational and maintenance activities.	Number of people/ per year
O&M cost per MWh	Refers to the unit cost of O&M activities per MWh.	Dollars per MWh per year
O&M target workers	Represents the number of workers required to perform O&M activities in a given year.	Number of people
Operating rate	The ratio at which turbine are operating during their useful life.	% (dimensionless)
Permanent land used	Amount of land that is impacted during the operational life of the wind turbines.	m^2
Probability of getting incentives	Refers to the likelihood of getting economic incentives for implementing wind technology advances.	(%)dimensionless
Rate of excavation per wind turbine	Represents the rate at which land excavation and trenching is performed per turbine.	m^2 per year per turbine
Rate of waste produced per turbine	Refers to rate at which waste is produced per turbine during O&M.	Metric Tons per year

Auxiliary Variable	Definition	Unit
Ratio of water use per person	Refers to the amount of water use per person during the installation operation and maintenance, and decommissioning phases of the WES.	Gallons per person per year
Replacement for decommissioning	Represents the planned replacement of decommissioning personnel in the WES.	% per year
Replacement for installation attrition	Represents the planned replacement of installation personnel in the WES.	% per year
Replacement for O&M attrition	Represents the planned replacement of O&M personnel in the WES.	% per year
Rotor diameter	Refers to the wind turbine rotor diameter.	Meters
Society awareness	Refers to the knowledge accumulated in society due to experience with wind energy.	% (dimensionless)
Society awareness impact	Represents the effect of the society awareness on the population resistance related to WES.	% (dimensionless)
Target workers	Represents the number of workers required to perform installation activities in a given year.	Number of people
Target wind power generation	Refers to the amount of electric power expected to be generated from wind energy in a defined time period.	MWh per year
Traditional energy source greenhouse gases emissions factor	The greenhouse gases emissions factor of traditional sources of energy not operating due to wind power generation.	Tons of CO_2 per MWh
Traditional energy source water use factor	The average water use of traditional sources of energy not operating due to wind power generation.	Gallons per MWh
Turbine installation impact	Represents the effect of the number of turbines installed on the society awareness.	% (dimensionless)
Turbine resale price	Refers to the estimated value that a wind turbine will realize when is sold at the end of its useful life.	Dollars per turbine
Turbine sound power	It is a measure of the sound strength of a turbine.	Decibels
Waste conversion factor	Waste conversion factor from metric tons to Global hectares.	Global hectares per Metric Tons
Waste produced per turbine during decommissioning	Refers to the waste produced per turbine during WES decommissioning activities.	Metric Tons per turbine
Waste produced per turbine during installation	Refers to the waste produced per turbine during WES installation phase.	Metric Tons per turbine
Water drained from O&M ratio	Refers to the amount of water drained from the O&M activities during the O&M phase.	% (dimensionless)
Water drained from WES decommissioning factor	Refers to the amount of water drained from the decommissioning activities during the decommissioning phase.	% (dimensionless)
Water drained from WES installation factor	Refers to the amount of water drained from the installation activities during installation phase.	% (dimensionless)
Water withdraw during	Refers to the amount of water withdraw for the decommissioning activities during the decommissioning phase.	% (dimensionless)

Auxiliary Variable	Definition	Unit
decommissioning factor		
Water withdraw during O&M factor	Refers to the amount of water withdraw for the O&M activities during the O&M phase.	% (dimensionless)
Water withdraw during installation factor	Refers to the amount of water withdraw for the installation activities during installation phase.	% (dimensionless)
Water conversion factor	Water conversion factor from Gallons to Global hectares.	Global hectares per Gallons
WES installed capacity	Theoretical maximum capacity of a WES based on the number of wind turbines installed in the system.	MWh per year
WE population resistance	Refers to the general population opposition to the WES.	% (dimensionless)
Wind power generation difference	Refers to the difference between the actual wind power generated and the target wind power generation.	MWh per year
Wind power opportunity profit	Refers to the perceived potential profit that could be generated from wind power investment to wind power generation difference.	Dollars per year
Wind turbine cost	Refers to the unit cost of turbine.	Dollars per turbine
Wind turbine installation per time period	Refers to the percentage of wind turbines being added in the WES for a given year.	#/ #/ year

Appendix K

Populated Simulator Validation Feedback and Assessment

The populated simulator validation package was presented to subject matter experts and the results are shown in Table K.1 along with assessment of the inputs.

Table K-1 Simulator Validation Feedback and Assessment

Validator 1	Validator 2	Validator 3	Assessment
Boundary structural adequacy			
The model shown does incorporate the basics of wind energy development and shows the resources and remains once wind development continues based on the current known needs and production of product and wastes from existing wind plants. The model seems to be adequate to show and predict the possible growth of wind energy for the state (Texas) that was best known for this reviewer.	I don't see air pollution or water pollution. "Waste" means solid waste-it doesn't include air emissions or water pollution. There would be air pollution from equipment used during the installation phase for digging, preparing the foundation, etc. I am also surprised by the emphasis on water use. It's not something I would traditionally associate with installation or operation of an energy system. The structure is so complex, it's hard for me to imagine the flows/inputs, etc. Would actually represent a real system. How are you calculating the "ecological footprint"? Please round your numbers in the scenarios tables to 3 significant digits. When you show "0.15028125" it implies that you know that the value is not "0.15028124". These are model estimates-accurate to 2 or 3 significant digits, not 8. Also, the 2 on CO2 should be sub-scripted.	Is forecasting wind MW installations resulting from policy changes one of the goals of the model? If so, how does the model predict the wind MW that will be installed without comparing the cost of wind power to its competition (gas, solar, etc.)? That would be a complicated model so perhaps it is not the intent. The summary on page 21 indicates that Iowa results are kept the same for the three scenarios given that the 20% goal by 2030 was reached earlier in the simulation. This assumption is not realistic since each state will have its own goals independent of the U.S. goal. The PTC will result in more wind installations in all states (to the extent that there is any wind energy development in those states) regardless of whether those states have reached the 20% goal.	**Validator 1:** No change required. **Validator 2 comments response**: Air pollution and water pollution are not included in the simulator. Further research can be done in this area. These factors can be included in future iterations of the model. Water consumption is one of the main challenges of traditional energy systems, according to the United State Geological Survey (USGS) (2005), traditional electricity generation accounts for nearly 50% of U.S. water withdrawals. The ecological footprint is calculated as the sum of the ecological footprint of the water, land, and energy used to install, operate, maintain and decommission wind energy systems. Output values representation have been modified. All outputs are round it to 3 significant digits. The 2 on CO_2 have been modified as a sub-script through the entire document. **Validator 3 comments response**: The simulator shows the dynamics of wind turbine installation during the simulation run. The simulator analyze the wind energy system dynamics, it does not include dynamics associated with other types of energy sources. While developing the scenarios to be simulated, it was assumed the 20% goal by 2030 for each of the states. Goals are inputs in the simulator and can be easily change to represent the behavior.

Table K.1—*Continued*

Structural sensitivity test			
This has been the most difficult part of the review process, the limited version of the ISEE model software did not allow for easy viewing of the nodes titles or results, the ZOOM feature was not applicable and so portions of the model results could not be easily accessed or read, the graphical analysis box (yellow inset on the right hand side of the model area) could not be viewed or re positioned to use its information.	See response to question #1. I have no way to gauge how changing details would influence model behavior. You'd have to run a sensitivity test. Inputting different numerical values for the different inputs.		**Validator 1 comments response:** A meeting was held with the validator to explain how to get required information from the simulator. **Validator 2 comments response:** See validator 2 comments response for boundary structural adequacy test.
Face validity test			
OK, the model has shown the ability to incorporate past wind industry growth profiles and register wind energy potential and sustainability.	See response to question #1		**Validator 1:** No change required. **Validator 2 comments response:** See validator 2 comments response for boundary structural adequacy test.

Table K.1—*Continued*

Parameter validity test			
The comparison to 10, 20 and 30 year predictions listed in the Case Studies PDF file would be much easier to review if digital grouping or exponential notation (10000 = 10 * 10^3) were used throughout. There is also no potential for the social-political support for wind energy as a counteraction to the loss of the Federal economic support of the PTC loss. As Carbon emissions are further penalized then the value to energy providers of non polluting wind energy will show as a rise in energy valuation and even without PTC support would lead to more development of wind energy plants.	Social sustainability and economics look ok. For environmental, see comments on question #1. As far as values are concerned, what was the setback distance for the baseline case? I can't really comment on other values because I have no idea how you are calculating ecological footprint, water use, greenhouse gas emissions avoidance, etc.	The parameters that were chosen to summarize the scenario results are not easily recognizable or particularly useful when they are presented in isolation. For example, one scenario has a Net Carbon Footprint of 2.81E+08 metric tons CO_2. That sounds like a large number, but compared to what? It could be compared with a base case to calculate a % difference, or it could be normalized by dividing it by the population of the state. That would allow for comparison to other states. The two dimensionless parameters in the summary table (WE Population Resistance and Society Awareness Impact) address the above concern. If these parameters are going to be highlighted, it would be useful to describe them more fully so the user can better interpret the values. For example, does a Society awareness impact of 0.15 mean that 15% of the population are aware of wind power? If so, that sounds low. One parameter that may not need to be normalized is Net Employment Rate (person). The number of jobs resulting from policy changes is always a favorite among policymakers. Here are some commonly used parameters that you might consider highlighting: • Levelized Cost of Energy (LCOE) of wind power, in $/MWh • Wind Installations (MW) • % of total MWh from wind power	**Validator 1 comments response:** Penalization due to carbon emissions will have an effect in the dynamics of the wind energy system. Further research needs to be done in this area. This factor can be included in future iterations of the model. **Validator 2 comments response:** See validator 2 comments response for boundary structural adequacy test. Values for the setback distance are specific for each state. Setback for each state baseline use: Texas-20 km California-13km Iowa-11 km All equations are included in the Appendix E. **Validator 3 comments response:** Outputs can be transformed to allow comparisons. The 15% represents the society awareness component associated with installation, operation, maintenance and decommissioning activities only. Levelized Cost of Energy (LCOE) of wind power can be included in future versions of the model. Wind installations (MW) is included in the model. % of total MWh from wind power is not part of the model since it does not consider the overall electric power generation. This can be included as part of future work in a model that includes other sources of energy.

Table K.1—*Continued*

Replication of reference modes			
OK, it ran as expected and we were able to coordinated that the system gave consistent responses to the program in the developers full ISEE system.	Sorry-I have no idea whether the model reproduces behavior of a real system.		No change required
Appropriateness of structure test			
OK, but it is a very complex interlinked system already, and real LIFE is like that also, do we have enough interactions and understanding to model what WILL happen, the answer is no, but we can be at least encouraged that the predictions made using this beginning profile estimator will improve as comparisons to real industry growth to the model estimates are show to coincide or diverge.	Way too complex if users are like me. I think I would understand a table better than Fig. 1.		**Validator 1:** No change required. **Validator 2 comments response:** System dynamics diagrams use stocks, rates and auxiliary variables to represent a system.

Table K.1—*Continued*

Additional notes and recommendations			
This is a VERY GOOD attempt at predicting the potential of wind energy growth based on the valid assumptions and rates that are inputted. But there is no better proof than the results form industry advancing and reaching its targets and then comparing that to the model. The refinements that will have to be made to this complex and intricate network of inter related factors will not known until we reach some of these years of real industry productivity. It is the opinion of this reviewer that the model is very valid so far, and has been well constructed and shows to give results that feel in line with past REAL values that history has shown us, as well as reasonable expectations of results that we will be able to show in the next 5 years. The best request would be the table of opening values for the Texas case study be summarized in a table that matches with the definition / units table shown in this document. While adding all information for all case studies from al the states would be cumbersome in this report, having an Excel Spreadsheet of side by side comparable values may be a suitable method for reviewing the starting numbers and expected rates without having to interrogate the ISEE model layout before running a simulation. I think that with a better end result display (yellow graphics box) that many planners could SEE and easily review what the potential development pro and cons for wind energy could be in a region or economic area. This will have the potential to lead to better focused local support and planning for the projects as they go on line across a known time frame as well as prepare the region for the realities of wind farm growth compared to the resources needed for this plant increase.	None	As we discussed, I have reviewed a significant portion of the inputs to the Texas Simulator Baseline. Of those that I reviewed, they are all within the range of reasonable values. The model appears to be well constructed and consistent with real life conditions. My only comments or suggestions for improvement are contained in the Wind Energy System Sustainability Validation Package. You have addressed all of the questions that I posed in that document during our discussion today. Congratulations on completing a successful, realistic, and meaningful analysis tool.	**Validator 1 comments response:** Additional tables can be included that summarize all the initial values for each state as well as expected values for simulation runs. Input values are presented in Appendix I. Simulator purpose is to help decision makers to understand better the impact of their decisions related to wind energy system sustainability. The graphical display has been modified to facilitate use of the simulator. **Validator 2:** No change required. **Validator 3:** No change required.

Based in validators' comments the simulator is a reasonable representation of the real system.

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