MINIMIZING WATER REQUIREMENTS FOR ELECTRICITY GENERATION IN WATER SCARCE AREAS

by

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A Dissertation
Submitted to the Faculty
of the
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree of Doctor of Philosophy
in
Mechanical Engineering
April 2015

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Abstract

Renewable energy technologies are infrequently evaluated with regard to water use for electricity generation; however traditional thermoelectric power generation uses approximately 50% of the water withdrawn in the US. To address problems of this water-energy nexus, we explore the replacement of existing electricity generation plants by renewable technologies, and the effect of this replacement on water use. Using a binary mixed integer linear programing model, we explore how the replacement of traditional thermoelectric generation with renewable solar and wind technologies can reduce future water demands for power generation. Three case study scenarios focusing on the replacement of the J.T. Deely station, a retiring coal thermoelectric generation plant in Texas, demonstrate a significant decrease in water requirements. In each case study, we replace the generation capacity of the retiring thermoelectric plant with three potential alternative technologies: solar photovoltaic (PV) panels, concentrated solar power (CSP), and horizontal axis wind turbines (HAWT). The first case study, which was performed with no limits on the land area available for new renewable energy installations, demonstrated the water savings potential of a range of different technology portfolios. Our second case study examined the replacement while constrained by finite available land area for new installations. This demonstrated the trade-off between land-use efficient technologies with water-use efficiency. Results from our third case study, which explored the replacement of a gas-fired plant with a capacity equivalent to the J. T. Deely station, demonstrated that more water efficient thermoelectric generation technologies produce lower percentages of water savings, and in two scenarios the proposed portfolios require more water than the replaced plant. Comparison of multiple aspects of our model results with those from existing models shows comparable values for land-use per unit of electricity generation and proposed plant size. An evaluation of the estimated hourly generation of our model's proposed solution suggests the need for a trade-off between the intermittency of a technology and the required water use. As we estimate the "costs" of alternative energy, our results suggest the need to include in the expression the resulting water savings.

Acknowledgements

I would like to take this opportunity to thank the many individuals without whom this work would not have been completed: Prof. Bar-On, Prof. Bergendahl, and Prof. Trapp for this wonderful opportunity and their guidance and support. I would also like to thank the members of my dissertation committee for their time and assistance.

While there are far too many to list, I would like to thank everyone at WPI who helped encourage me, including Prof. Holly Ault, Prof. John Sullivan, Dr. Adriana Hera, and Dr. Raffaele Potami. I would also like to thank Sia Najafi for selecting me as his TA all those years ago, and for his help and support. I am also grateful to all the staff in the ME office, who helped me navigate throughout my time here at WPI.

I would like to thank my family and friends for supporting me during the long hibernation I needed to complete this work.

Finally, I would like to give long due acknowledgement to those individuals whose enthusiasm for education has inspired me, especially Jane Ostlund, David Brewster, Tom Vendetti, Neil McCarthy, and Bob Ferrante.

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List of Acronyms

CBC: COIN-OR branch and cut
COIN-OR: Computational Infrastructure for Operations Research
CSP: concentrated solar power
EFOM: Energy Flow Optimization Model
ERCOT: Electric Reliability Council of Texas
ETR: extraterrestrial radiation
HAWT: horizontal axis wind turbine
IECM: Integrated Environmental Control Board
MARKAL: Market Allocation
MILP: mixed integer linear programming
NETL: National Energy Technology Laboratory
NREL: National Renewable Energy Laboratory
NSRDB: National Solar Radiation Database
PV: photovoltaic
SAM: System Advisor Model
SM: solar multiple
TES: thermal energy storage
TIAM-FR: TIMES Integrated Assessment Model
TIMES: The Integrated MARKAL-EFOM System
TWDB: Texas Water Development Board
USGS: United States Geological Survey
VFR: visual flight rules

Nomenclature

A_j = direct area land use available in location j

a_c = required land area for CSP thermal storage and power block

a_p = land area required for one solar PV panel

a_w = land area required for one HAWT

b = width of solar PV panel

C_p = coefficient of power for HAWT

d = perpendicular distance between installed solar PV panels

E = total energy demand

e_{ij} = total energy technology i can produce in location j

h = height of installed solar PV panel

I = set of available technologies, indexed by i

J = set of potential locations, indexed by j

L = solar insolation at location j

l = length of solar PV panel

S_A^P = exposed PV panel surface area

S_A^w = swept area of HAWT

v_j = wind speed at location j

w_i = water volume used by technology i

x_{ij} = decision variable representing the percentage of technology i in location j

y_{ij} = binary decision variables to place technology i in location j

α = solar altitude angle

η_p = total solar PV efficiency

η_c = total CSP efficiency

θ = angle of installed solar PV panel

ρ = air density

φ = solar azimuth angle

1. Introduction

Renewable energy technologies are most frequently evaluated with respect to the savings in fossil fuels, reduction of carbon emissions, land requirements, and cost [1, 2]. Rarely is the focus placed on potential water savings that result from the use of alternative energy technologies for electricity generation.

Water is used in significant quantities for electricity generation, while electricity is used for clean water technologies such as desalination and water purification. The supply of water as well as the supply of conventional fuels used in electricity generation are both constrained and the demand for both is increasing worldwide [3]. Thus it is becoming ever more apparent that water availability and electricity generation are closely intertwined [3-8].

Nearly all traditional thermoelectric power production methods require significant amounts of water [9]. Thermoelectric electricity generation uses approximately 41% of the freshwater withdrawn in the United States [10] and is the single largest water category of withdrawal [4]. Meeting increasing electricity demands with thermoelectric electricity generation will require additional water supplies. The water sources used to satisfy the existing demand at times fail to meet the needed demand already today, and could limit supply for critical applications such as agricultural and domestic use in the future.

This stress on the water supply has been showing its effects for many years. For example, the demands on the Colorado River show the strain of energy generation on a diminished water supply. The region's rapid growth has resulted in allocating more rights to water withdrawals than there is water in the river [11, 12]. In 2009, the Navajo Generating Station in Arizona came perilously close to shutting down due to the low water levels in Lake Powell. It was saved only by the completion of a newly installed water inlet, 45 meters below the original. Without intervention, another reservoir of the Colorado River, Lake Mead, has a 50% chance of running dry by 2021. [13] This situation is not unique to the Colorado River, as almost one fifth of the world's population live in water scarce areas [14].

Environmental factors can have a significant impact on the interconnection between water and electricity. Droughts have put strains on already water constrained areas, such as the aforementioned Southwest United States. The record high-temperatures of 2012 further reduced availability of water, forcing several electricity generation plants to either ramp down production or receive a variance to operate above approved discharge temperatures [15].

Despite being deeply intertwined, the planning processes, data collection and reporting for energy and water systems have typically been considered and arranged separately [6]. Available and actual use generation data for individual power plants regarding final energy generation and fuel consumption is often reported on an annual basis, but may be obtained for shorter time frames [6]. Water use, consumption and withdrawal are reported in far less detail, and far less frequently [6]. Information is reported on a 3-5 year basis on the national level, in an aggregated or incomplete dataset; USGS reports only include withdrawal, not consumption [10, 16, 17].

In addition to usage reporting, planning decisions for water and energy are also made separately. Whereas energy planning decisions are typically made by private firms according to state restrictions, water planning decisions are often made by public municipalities or state governments. One of the outcomes of our modeling exercise is to highlight the importance of water requirement considerations for energy generation during the energy planning process [16, 17].

In this work, we explored the replacement of current electricity generation methods using nonrenewable fuels with alternative electricity generation technologies, specifically solar and wind. We investigated if this replacement will result in a reduction in water requirements for electricity generation. We modeled the water demands of a renewable electrical electricity generation system and optimized the renewable technology portfolio for minimum water requirements, while also considering the available land and land use. We show that considering water and energy use together during planning stages can inform decisions based on the combined benefit that derives not only from decreased use of fossil fuels, but also decreased water use in water constrained areas, thereby freeing up more water for alternative uses.

We developed a flexible and adaptable model that can aid in the analysis of these technology portfolios. It provides quantitative information of water reduction for a case study based on actual data for replacement of a retiring coal plant.

1.1 Contributions

- This work considers water requirements explicitly for different renewable energy based power generation portfolios.
- The work shows that the consideration of water requirements can affect the selection of a renewable energy portfolio and vice versa.
- We developed a model for the selection of a renewable energy technology portfolio that minimizes water use. The model uses solar and wind characteristics and location of existing transmission lines as input data.
- The model can use technologies and location as granular as the local level.
- We show that renewable energy technologies can result is significant water savings.
- We show that there may be a trade-off between land and water use.

This is a novel solution to evaluating requirements for electricity generation, as water requirements are not typically considered explicitly in models for changing electricity production methods. Existing models and evaluations tend to focus on broad regions, limiting the granular approach that can be taken with case studies at a local level. This type of analysis enables planners to make better informed decisions when selecting new power plants.

2. Background

Large-scale changes to the existing electricity generation infrastructure have been considered as a means to combat climate change. Replacing existing technologies with renewable energy based technologies has been studied with respect to air pollution, water pollution, energy security and cost, but not with respect to water consumption. This work investigates the use of renewable energy technologies on water use for specific examples based on specific data.

2.1 Energy transition studies

Several analyses have considered the transition to renewable energy technologies on the global scale and its effect on climate stabilization and economic development. Hoffert (2002) suggested that a course towards stabilization of climate change will require development of primary energy sources that do not emit carbon [18]. The technologies investigated in this study include solar and wind energy, nuclear technologies, and fossil fuels with carbon sequestering. Pacala (2004) also suggested solutions to climate change problems with, among other solutions, an increase in the use of renewable energy technologies [19]. In the case of both investigations, the motivations for such a change stem from problems related to climate change and energy stability, but do not address water requirements.

Regional contributions to climate stabilization were discussed by Jacobson (2001) and Cleetus (2009). Jacobson (2009) suggest a switch from coal to wind power throughout the US. This would address challenges of climate change and energy insecurity. They show that replacing 1,890 terawatt-hour per year of coal power with wind would satisfy the 1997 Kyoto Protocol [20]. Cleetus (2009) proposed a strategy to reduce US heat-trapping emissions by 26% of 2005 levels by 2020, and by 56% by 2030 [21]. This plan relies heavily on the conversion to renewable energy technologies, and is motivated by a drive toward a clean energy economy.

2.1.1 Feasibility of large scale renewable energy systems

The feasibility of these increases in renewable capability has been investigated and discussed from many view points, but with a lesser focus on water requirements, if at all. On a global scale, Delucchi (2011) suggested a plan for a system of global energy generation powered entirely by renewable wind, water, and solar technologies, with no biofuels, nuclear power, or coal, and addressed feasibility primarily with respect to cost [22, 23]. In Europe and near proximity Asia and Africa, Czisch (2006) suggests a conversion to renewable energy technologies as strategy for climate policy, with respect to economic feasibility and carbon costs [24].

Collectively, these studies have confirmed that a sizeable increase in the deployed use of renewable energy technologies for electricity generation is not only possible, but advantageous in many ways. Within the U.S., feasibility of a large scale renewable energy system was investigated in papers such as those by Fthenakis (2009) and Sovacool (2009). Fthenakis (2009) has investigated the technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US [25]. Sovacool (2009) investigated if a complete renewable electricity generation system is possible and desirable, with respect to technological and economic feasibility, as well as thermodynamic efficiency [26]. They looked at the benefits of a renewable power supply to determine desirability. It is within these examples that we see the first suggestions of interconnectivity between water and energy. Fthenakis (2009) mentions that water allocation for certain renewable energy technologies such as Concentrated Solar Power (CSP) is an issue, and suggests the need further study. Sovacool (2009) argues that “one of the most important, and least discussed, environmental issues facing the electricity industry is its water-intensive nature”, and that movement towards certain renewable technologies can provide benefits in both water and electricity sectors.

2.1.2 Inclusion of water requirements in conversion assessment

Recently, some authors have acknowledged the connection between power generation and water use, but quantitative assessments are still very limited. As some of these investigations into large scale conversation have begun to acknowledge the need for interconnection, the argument for a better connection between energy and water supply and demand has been growing in various regions through the world. Articles such as those by Dubreuil (2013) and Siddiqi (2011) show the existence of a close link between water and energy in the Middle East [4, 8]. In the U.S., Reports to Congress (2006, 2014) have discussed water requirements for operation of electricity generation technologies and discuss the link between water and energy

[27, 28] With a focus on the U.S. South West, Carter (2009) discussed water issues of CSP electricity, and identified water resource data gaps in existing reports [29]. The California Energy Commission also investigated the connections between water and energy, and discussed the effects of such a connection on the state of California [30]. While these studies and many more have established that water and energy are linked, they did not calculate actual water use for real case scenarios and for different technology portfolios. This is the gap that this thesis addresses.

2.2 Existing models for renewable electricity generation and/or water use

We could find only a limited number of models that evaluate the performance of renewable power plants and only with an added module that address water use. The U.S. Department of Energy and National Renewable Energy Laboratory's System Advisor Model (SAM) (version 2014.1.14, released on January 14th, 2014) [31] calculates financial and operational parameters for one technology at a time. It is a computer model designed to allow policy makers, project developers, equipment manufactures, and researchers to investigate and evaluate the financial, technological, and incentive options for renewable energy projects. This model calculates the performance and financial metrics of photovoltaic, concentrating solar power, solar water heating, wind, geothermal, biomass, and conventional power systems. Statistical analyses are available for Monte Carlo simulation, weather variability, as well as parametric and sensitivity analyses.

SAM is used to evaluate one electricity generation plant or technology installation at a time, giving a wide range of calculated information, including anticipated array size, hourly electricity production, and annual cash flow. The installations can range in size from a single wind turbine to a utility scale CSP plant; however the model is limited to one technology at a time. The operational water requirements of the evaluated system are not calculated.

Whereas SAM is designed for detailed analysis at a local level, for individual plants or installations, The National Energy Modeling System (NEMS) is a model designed to analyze U.S. energy use and emissions at the national level [21]. The model forecasts the production, imports, conversion, consumption, and prices of energy, and is used to examine the impact of new energy programs and policies. NEMS focuses on several sectors of supply and demand, including residential, commercial, transportation, electricity generation, and refining, however does not calculate or include water requirements for electricity generation.

The Integrated MARKAL-EFOM System (TIMES) world energy model utilizes an approach based on linear programming to estimate the economic equilibrium of the entire extended energy system [32, 33]. The TIMES model addresses a set of 42 demands for energy services spanning the entire energy sector: agriculture, residential, commercial, industry, and transportation. Parameters include energy service demands, resource potentials, policy settings, and the description of a set of technologies. Data, such as information on population, GDP, family units, etc., are obtained from other models or accepted outside sources.

The user provides estimates of end-use energy service demands, such as car road travel, residential lighting, steam heat requirements, etc., as well as estimates of the existing stock of energy related equipment in all sectors. The user also provides any necessary characteristics of existing or future technologies for energy supply, as well as the required resources. The model then computes an economic equilibrium for supply and demand in the 42 sectors with the objective of minimizing the system cost.

Dubreuil (2013) developed a water module for the TIMES Integrated Assessment Model (TIAM-FR) [4] to incorporate the energy demand of water utilities into the equilibrium calculated by the TIMES model. The module addresses the electricity demand for water uses, such as pumping, desalination, transportation, treatment, and irrigation, and incorporates this increase in energy demands into the TIAM-FR optimization. Parameters include the quantity of raw water resource, the energy resource to produce feedwater sources, and the water demand per sector. Results from this module show that electricity demand estimated with the TIMES model can be underestimated by up to 40% without the inclusion of the energy cost of water services. This module, however, focuses on the energy intensity of water, rather than the water intensity of energy, which is focus of this thesis.

2.3 Renewable energy technologies evaluated in this work

The studies mentioned in Section 2.1 have suggested a range of technologies [18, 22-24, 34], incorporating diversity into the grid. Solar based electricity generation technologies are highly desirable because the energy resource is very large compared to other known electricity generation methods [35, 36]. Wind technologies such as modern wind turbines have advantages including minimal downtime [37], distributed generation, and minimal water requirements during operation. Wind technologies also complement solar technologies; wind speeds are often greater in conditions such as night hours, or during stormy weather, when solar energy wouldn't be available [38].

The optimization model described in this paper includes a portfolio of technology choices available in given locales. While the optimization model is broadly applicable, for the purpose of the case study we focused on three technologies: one solar photovoltaic technology, one solar thermal technology, and one wind power technology. The power per land area is calculated for each technology in each location, limited to the percentage of the area selected by the model.

2.3.1 Solar Photovoltaic

Solar photovoltaic (PV) devices generate electricity directly by converting photons from sunlight to electricity. The PV used in the model was an average representation of a polycrystalline solar module. Varying panel dimensions were collected from various polycrystalline solar modules, and the average size was used to determine resultant electricity generation and required land area.

Table 1: Polycrystalline PV Panel Dimensions

	Width (*b*) (inches)	Length (*l*) (inches)	
Schott PERFORM 245	66.34	39.09	[39]
Hyundai 230W Poly Solar Module	64.76	38.70	[40]
Komaes Solar	64.96	38.98	[41]
New Energy 230W	64.57	39.06	[42]
ERA Solar ESPMC 230-250W	64.57	39.06	[43]
Average	65.04	38.98	

To calculate the land required per solar panel, it is important to consider not only the dimensions of the panel, but also the type of solar array, and the solar altitude and azimuth at the installation location. The array chosen was a fixed axis flat plate PV installation, with each location containing only one array. The panels were oriented at an angle of 25 degrees from horizontal, and mounted in landscape orientation. This angle installation and panel orientation were selected from commonly used values in existing solar PV installations.

The spacing required between each row of installed PV panels is dependent upon the maximum expected length of the shadow cast by the preceding row of panels, as shown in Figure 1. To calculate the length of this shadow, the solar altitude and azimuth must be determined for the anticipated installation location. Solar altitude (α) is the vertical angle of the sun from the horizon, and solar azimuth (ψ) is the angle of the sun's position relative to true south. An average solar altitude and solar azimuth for geographic boundaries of the model was used for all locations. These values were measured from data collected on December 21st, 2010, at 10 am and 2 pm, to space the panels to account for the longest projected shadows.

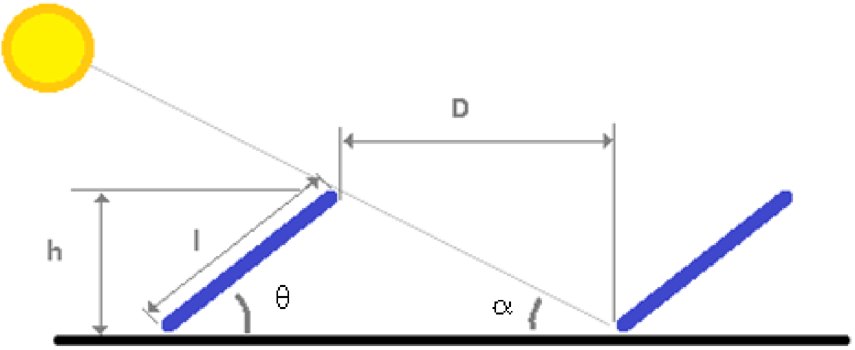


Figure 1: Row spacing for solar PV installations

To determine row spacing, the obstruction height (h) of the installed PV panels is dependent on the length of the panel and the installation angle, shown by equation (1). With this height, the solar altitude and solar azimuth, the required distance between installed panel rows is shown by equation (2). The area required per installed panel (a_p), dependent on the distance between rows, the dimensions of panels, and the angle of installation is then calculated by equation (3).

$$h = l * \sin(\theta) \tag{1}$$

$$D = \frac{h}{tan(\alpha)} cos(180 - \varphi) \tag{2}$$

$$a_p = (l * cos(\theta) + D) * b \tag{3}$$

The number of panels that could be installed in the direct use area of location j was calculated by dividing the total available area of location j (A_j) by the area required per panel (a_p). Final energy generation from location j was a function of the average surface area of a PV panel, the efficiency of the panel, and the efficiency of the system. The system efficiency (η_p) includes average expected losses from the transmission of light through the atmosphere. For technology $i = p$, where L is the solar insolation at location j and S_A^p is the surface area per PV panel, we estimated electricity generation equal to:

$$e_{p,j} = \frac{A_j}{a_p} L\, S_A^p \eta_p \tag{4}$$

2.3.2 Concentrated Solar Power

The concentrated solar power (CSP) technologies selected in our model use focused sunlight as a heat source to drive traditional steam turbine generation. The CSP technology included in our model was parabolic trough, which uses a series of long, curved reflectors to concentrate sunlight on receivers running the length of the mirrors. The sunlight heats a fluid in the receiver, which is used to boil water for steam-turbine generators to produce electricity.

In many instances, a thermal storage system is incorporated into the plant to extend energy generation beyond daylight hours. In our model, occupied land area and generation from molten salt thermal storage (a_c) is included in the energy and land area availability requirements for CSP in each location, and does not scale with installation capacity. Occupied land area for both the thermal storage and the steam plant were measured from aerial photographs of three operational CSP plants, and this total land area was subtracted from the total available land area in each location j.

Conversion efficiency for parabolic trough CSP was calculated from field area and generation data from existing CSP plants. The average electricity generation from three plants was divided by the field area of each respective plant, to calculate the generation expected per unit of field area. This expected average generation per area was then divided by the average solar insolation at the existing plant location to calculate a conversion efficiency (η_c) for CSP parabolic trough. This conversion efficiency incorporates peak optical efficiency, average reflector cleanliness, and the thermal efficiency of the technology, and produces a total energy output that scales linearly with available land area, less the land set aside for the power block and thermal storage [44]. For technology *i* = *c*, we have estimated electricity generation equal to:

$$e_{c,j} = L\,(A_j - a_c)\eta_c \tag{5}$$

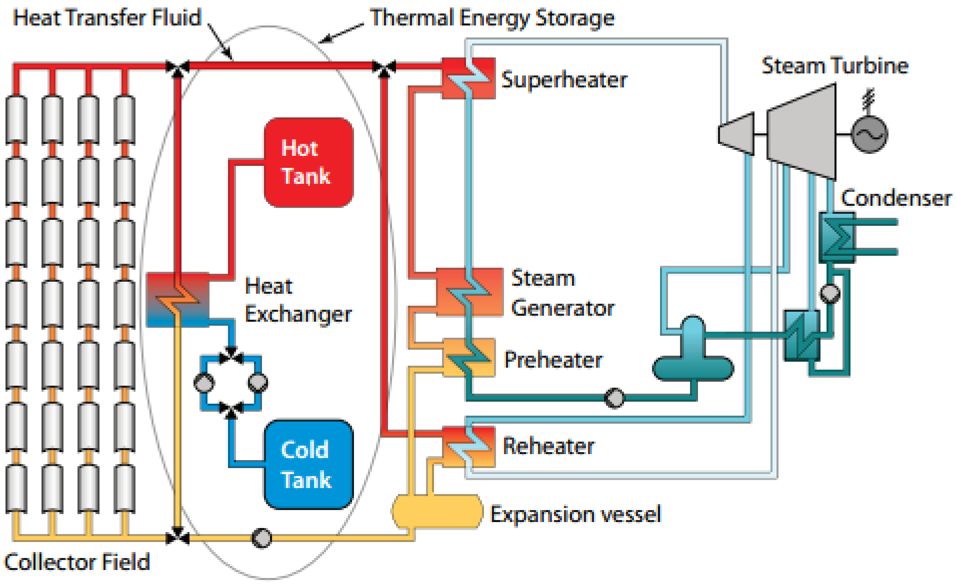


Figure 2: Diagram of CSP plant [45]

2.3.3 Wind

The wind energy generation included in the model was from horizontal axis wind turbine (HAWT) installations. Turbine height and blade size averaged across several commercially available models were used. For technology *i* = *w*, we estimated electricity generation equal to:

$$e_{w,j} = \frac{A_j}{a_w}\frac{1}{2}C_p S_A^w \rho v_w^3 \tag{6}$$

High-quality wind turbines typically have a power coefficient between 35-45%; a value of 40% was used for C_p in the calculations [46] [47].

The direct land area required for each wind turbine is dependent upon the height of the tower and the length of the blades. The total available land area was divided by the area required per turbine to determine the number of turbines installed at each location *j*.

2.4 Transmission losses

Transmission losses were calculated based on the linear distance between the new installation and existing high-power transmission lines. Losses were calculated for the added distance between the location *j* and the existing lines based on an average loss of 0.05 MW/mile. The 765 kV transmission lines, the use of which is assumed in this study, suffers from reduced system losses as compared to 500 kV and 345 kV systems [48].

2.5 Water requirements

For the purpose of discussing water requirements for energy generation, a distinction must be made in the terminology of water withdrawal and water consumption. Water withdrawal includes all water removed from the source for use, while consumption is water that is not available to return to the source, such as due to evaporation. Water withdrawal must always be greater than or equal to consumption. Thermal electricity generation plants use water for cooling in two ways; once-through cooling or closed loop. During once-through or open-loop cooling, water is withdrawn from the source, used for cooling within the plant, after which the majority of the water is returned to the source. The water requirements for this cooling technology have high withdrawals, with very low consumption. By comparison, closed-loop cooling recirculates water for cooling, and has comparatively low water withdrawal, but proportionally more consumption than once-through. The water use referenced in this work refers to all water withdrawals for energy generation; total water withdrawals represent the entire volume of water that must be available for plant operation.

The renewable technologies included in our model have widely varying water requirements. Solar CSP uses water in much the same way as traditional thermo-electric power plants. In wet cooling, steam turbines are generally cooled using water, whereas dry cooling utilizes air blown over networks of steam pipes and cooling fins [29]. A third cooling technology, hybrid cooling, employs a combination of the two. All three of these cooling technologies will also require water to wash reflectors in the solar field. Solar PV requires water for panel washing only, while water requirements for HAWT are negligible.

2.6 Optimization modeling

Our model utilizes a type of mathematical optimization known as mixed integer linear programming (MILP). Linear programming is used for the optimization of linear systems having both continuous and integer variables, in which the value of the objective function is optimized by changing the values of the decision variables, subject to a set of constraints that include these decision variables [49]. A model is considered binary mixed integer when at least one decision variable can take only the values 0 or 1, in addition to having continuous variables.

Our water-energy optimization model is a technology-location selection problem with a combinatorial structure. Explicitly enumerating all of the combinations leads to as many as $2^{|I||J|}$ possibilities (I is the set of all included technologies, and J is the set of possible locations). This quantity grows quickly with the sizes of |I| and |J|, and even without the additional side constraints of the model, it rapidly becomes prohibitive to evaluate all possible combinations explicitly in order to find one that optimizes the objective function.

The optimization problem was modeled and solved in Excel using OpenSolver using the open source COIN-OR branch-and-cut (CBC) optimization solver. Branch-and-bound (B&B), and its variants such as branch-and-cut (B&C), are one of the most commonly used methods for solving mixed integer linear programs. Rather than explicit enumeration, it is carried out implicitly, which is beneficial because exhaustive search quickly becomes intractable.

The B&B algorithm solves mixed integer linear programs by solving a sequence of simpler problems, one per node, on a rooted tree structure. These simpler problems are the mixed integer linear programs themselves, with their integer variable restrictions relaxed to continuous, and possibly additional restrictions based on the depth of the tree. After solving the relaxed problem at any node, a “branch” may be discarded, or "pruned" if the branch cannot produce a better solution then the best found so far by the algorithm. When solving, the set of possible solutions is split into two smaller sets, the union of which covers the original set, as shown in Figure 3. In the case of minimization, the lower bound of the function to be minimized is calculated for each of the two subsets by solving the LP formed by relaxing the integer restrictions to continuous.

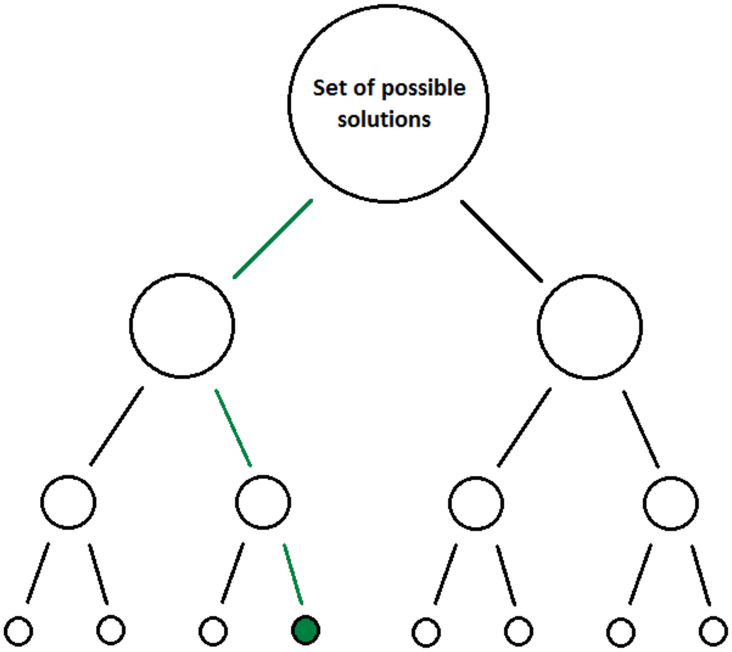


Figure 3: Branch and Bound rooted tree structure

This branch and bound process is repeated until the set of possible solutions is reduced to a single solution, or the upper and lower bounds of a set are equal [50]. This process ensures that the solution found by the model is a global minimum, rather than a heuristic solution that gives an approximate solution. The benefit afforded by the branch and bound method is the ability to obtain a provably global optimal solution to the model.

3. Water-energy optimization model design

We developed a model to represent the portfolio of technology choices available to given locales. It can be used to determine the percentage of technologies to locate in a given plant locations, capacities, and water requirements. Optimal plant locations can replace varying percentages of the projected plant closures and energy demand increases in a set region.

Several assumptions were made within the program:

- All data (i.e. technology efficiencies, transmission losses, energy generation requirements, solar insolation, and wind speed) were known with certainty [51].
- The increase in available energy generation in each location is assumed to be directly proportional to the land available.

- No minimum size limits were set on any installation.
- The coefficient of power (C_P) was assumed to be constant, rather than a function of wind speed.
- As expressed in equation (9), each location was limited to one technology, installed in a single array [52].
- The electricity demand E set in the model assumed direct replacement of the rated capacity of selected coal power plants that are scheduled to close.
- Distinctions were not made between base load and intermittent electricity generation technologies within the optimization model.

3.1 Water-energy optimization model

We modeled the problem as a binary mixed-integer program. Let I be the set of technologies available within the model, and Let J be the set of viable locations available to be selected within the model. There are two sets of variables: non-negative, continuous variables x_{ij}, representing the percentage of technology *i* used in location *j*, and the binary decisions y_{ij} representing placement of technologies in locations:

$$y_{ij} = \begin{cases} 1, \; if \; plant \; i \in I \; in \; location \; j \in J \\ 0, \; otherwise \; . \end{cases} \tag{7}$$

These variables were subject to the following constraints. The value of x_{ij} must be less than or equal to the value of y_{ij}, which constrains the total capacity in each location to less than or equal to 100% of the maximum capacity:

$$x_{ij} \leq y_{ij} \qquad \text{…for all i} \in \text{I and all j} \in \text{J.} \tag{8}$$

At most one technology *i* can be selected per location *j*:

$$\textstyle\sum_{i \in I} y_{ij} \leq 1 \qquad \text{…for all j} \in \text{J.} \tag{9}$$

The total electricity generated must meet or exceed the set average demands,

$$\sum_{i \in I} \sum_{j \in J} e_{ij} x_{ij} \geq E, \tag{10}$$

while minimizing the water requirements of the electricity generation system:

$$\min \sum_{i \in I} \sum_{j \in J} w_i x_{ij}. \tag{11}$$

The water requirements for each technology (w_i) is directly proportional to the energy generated by technology i in location j, dependent upon the water requirements per MWh. The calculation of energy generated in each location, e_{ij}, is described in the following sections.

This model has a discrete, discontinuous, “combinatorial structure” that makes it prohibitive to assess each variable assignment individually. The optimization model was implemented in Excel using OpenSolver with the open source COIN-OR branch and cut (CBC) optimization solver. This method, commonly used to solve NP-hard optimization problems, relies on an implicit enumeration to locate a globally optimal solution.

3.2 Data

The data required for model operation includes mean annual solar insolation in the modeled region, mean annual wind speeds in the modeled region, high powered transmission line locations, water requirements for the selected technologies, and available land for new installations. The geographical bounds of the model are controlled by the geographical bounds of this input data. In each scenario, the model will select the solar insolation measurement, wind speed measurement, and transmission tower geographically closest to the new installation location, so the size of the region is limited only by the input data.

4. Case study scenarios

The case studies analyzed with the model focused on replacing the electricity generation capacity of a retiring coal plant in Texas with renewable technologies, varying the land availability for replacement and the generation technology of the existing plant. The plant considered in the analysis is the J.T. Deely Station in San Antonio, Texas, with a nameplate capacity of 932 MW. The plant closure, which was announced in 2011, is scheduled for 2018 in an effort to switch to more renewable energy by 2020 [53]. The primary use of water for this station is recirculating cooling, using the San Antonio River as a source. In each instance of the analysis, the model is used to replace this nameplate capacity with the anticipated energy output from the various renewable technologies, while minimizing water requirements for the system.

The resultant water requirements produced by the model were compared to the existing water requirements for the J.T. Deely station. This data was collected from three sources: the National Energy Technology Laboratory (NETL), the Texas Water Development Board (TWDB), and the Integrated Environmental Control Board (IECM). The estimated value from the TWDB includes some data that represents use rather than consumption, accounting for the higher value. The water requirement included by IECM is estimated water usage based on technologies used within the station and environmental conditions. In all three cases, the estimated volume of water required was weighed against the annual plant generation from 2005 to determine an estimated water requirement of 1,065 gallons per MWhr.

Table 2: Water requirements for J.T.Deely Station in 2005 (gallons/MWHr)

NETL	TWDB	IECM
746	1,413	1,035
gal/MWhr	gal/MWhr	gal/MWhr

4.1 Input data

The geographical limit of all data collected was the borders of Texas. Whenever possible, all recorded data and estimates used in the model were from database records and models made in 2010. The state of Texas was chosen both for diverse resource availability, with its varying wind speeds and solar insolation across the states, and for its separate electricity grid interconnect, shown in Figure 4.

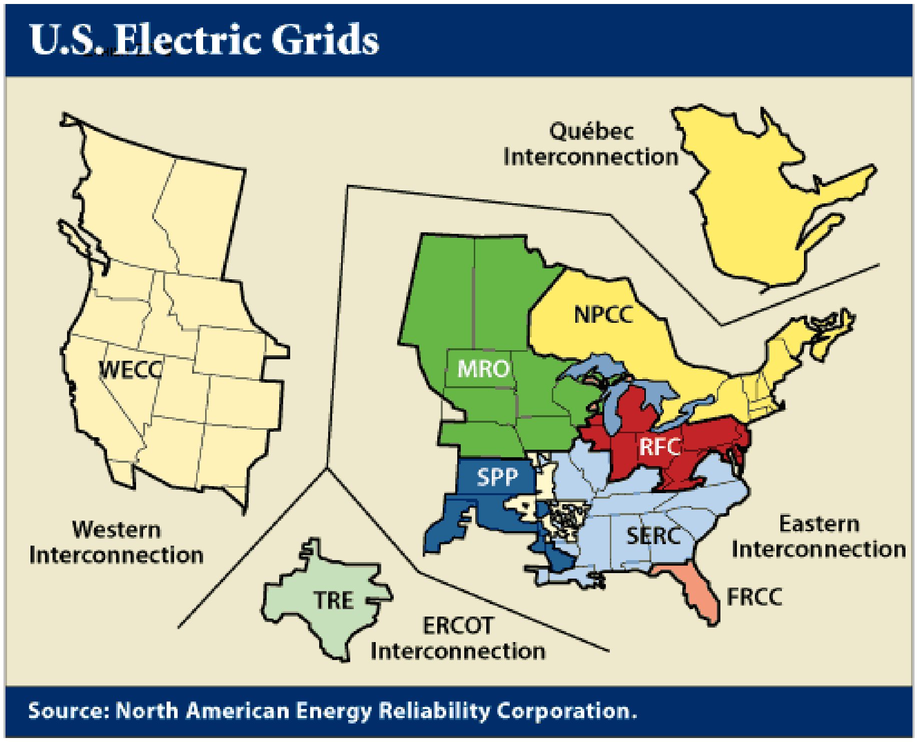


Figure 4: Diagram of US electricity interconnects [54]

4.1.1 Solar data

Measured solar insolation data was collected from the National Renewable Energy Laboratory (NREL) National Solar Radiation Database (NSRDB) [55]. This data included hourly measurements of solar insolation from 1,454 sites across Texas, shown in Figure 5. The solar insolation used in all model equations is the average hourly extraterrestrial radiation (ETR) from January 1, 2010 to December 31, 2010.

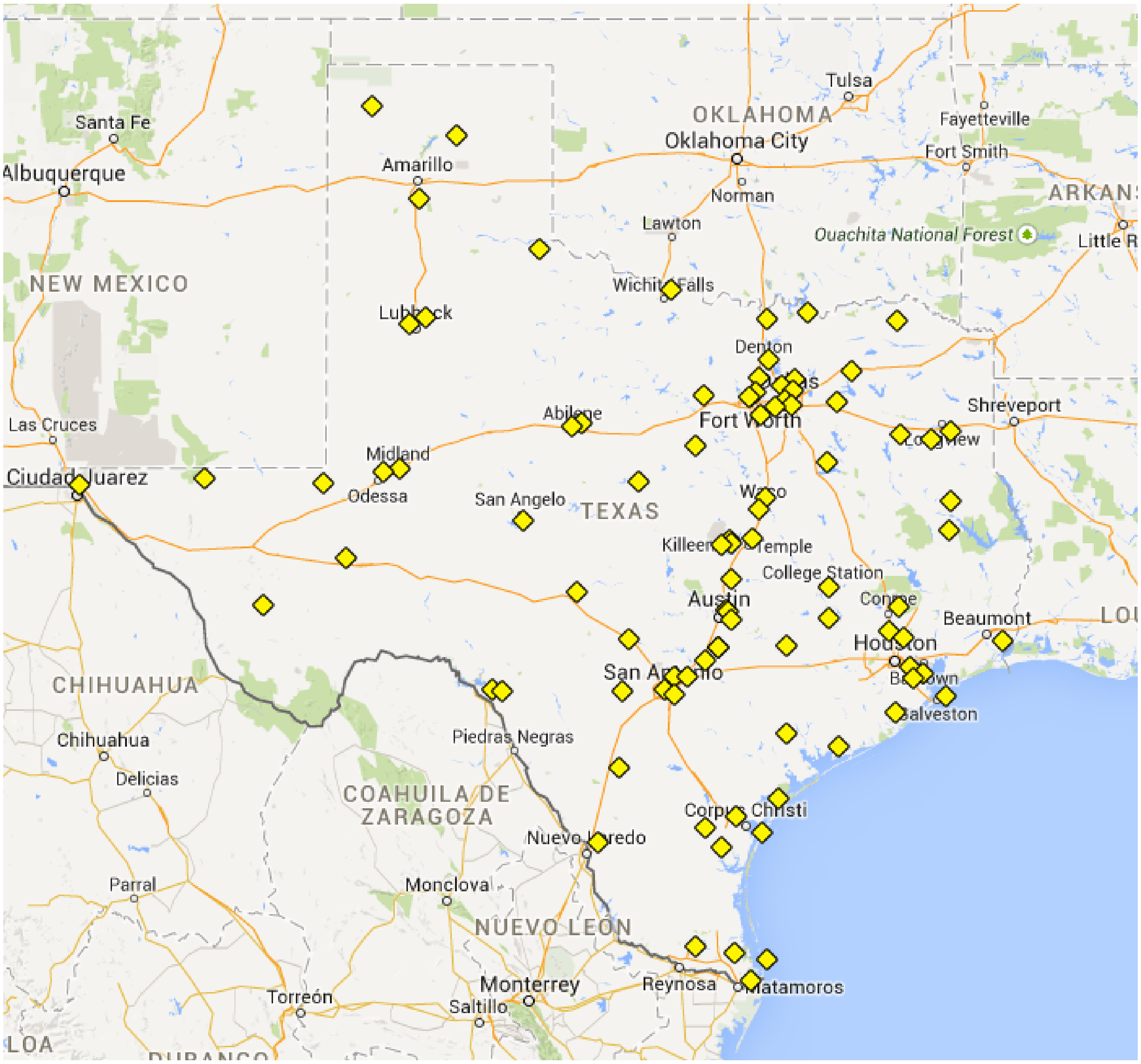


Figure 5: Solar data collection locations

4.1.2 Wind data

Wind speed data was collected from the NREL Wind Energy Resource Atlas of the United States, which accumulated wind data from 975 stations in the National Climatic Data Center [56]. This data included average annual wind speed from 40 unique locations within Texas, shown in Figure 6.

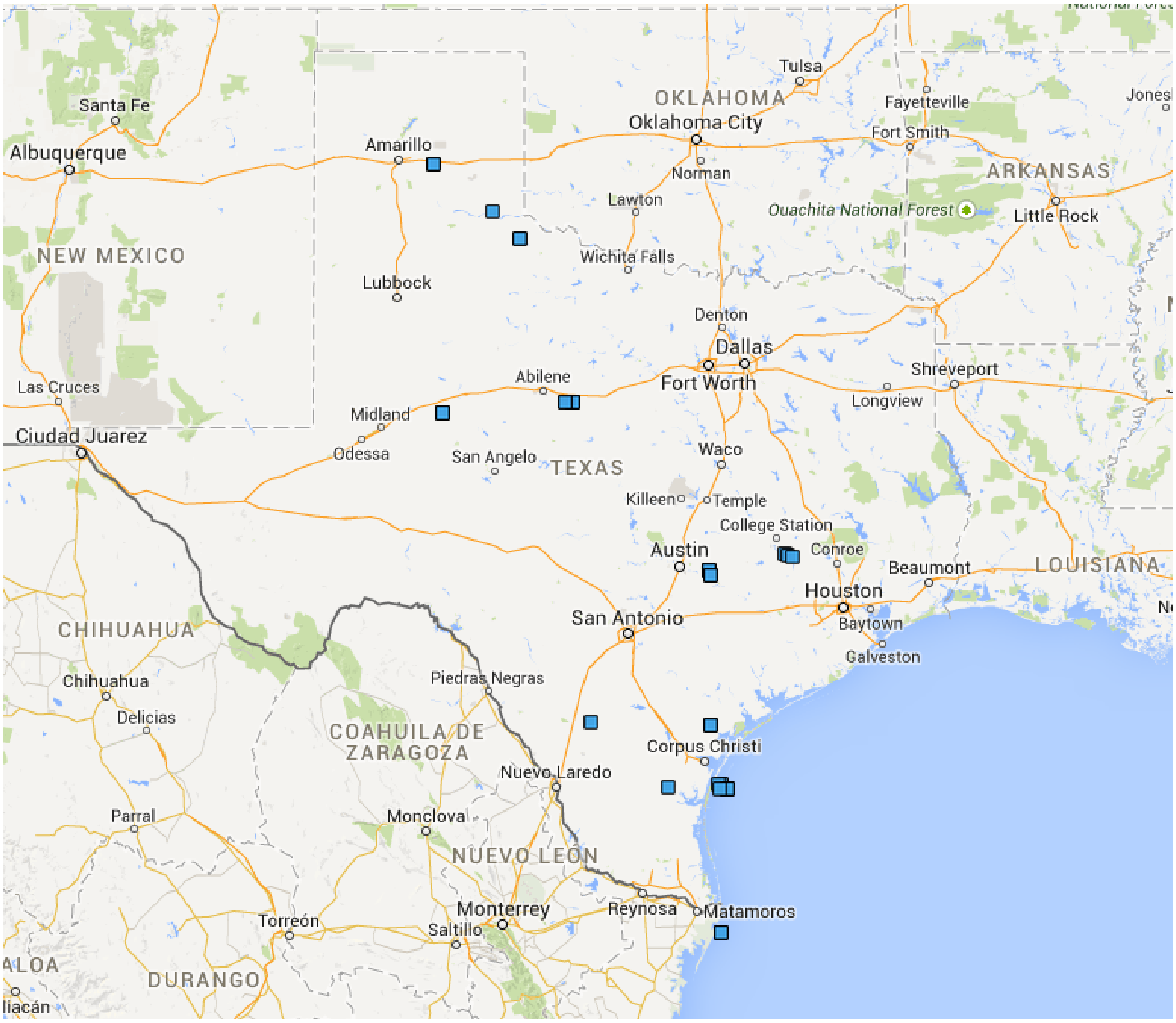


Figure 6: Wind data collection locations

4.1.3 Transmission data

The latitude and longitude of existing high power transmission lines were obtained from visual flight rules (VFR) aeronautical charts. A total of 1,469 transmission tower locations were noted within the model, shown in Figure 7.

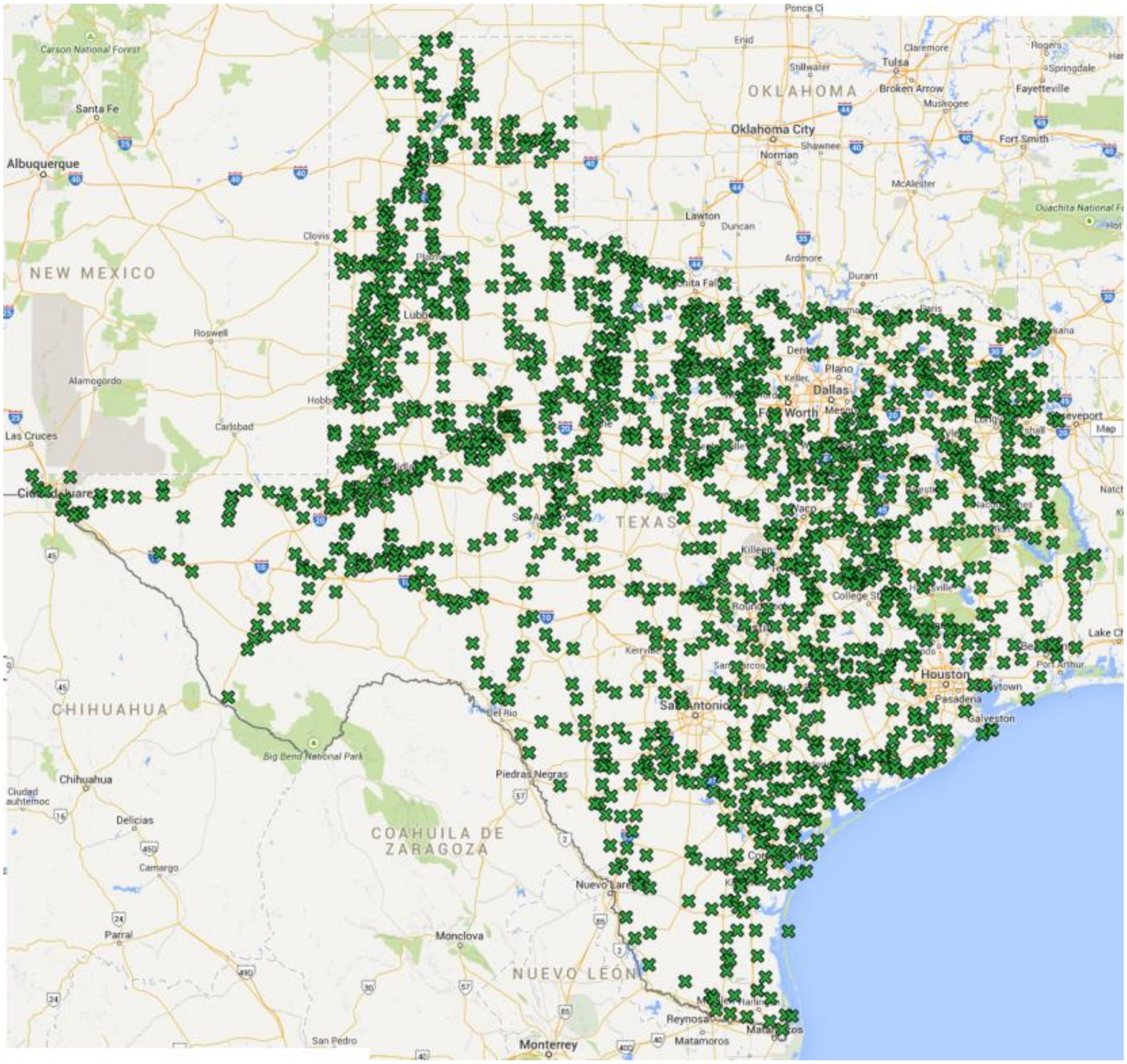


Figure 7: Existing transmission tower locations

4.1.4 Water requirements

Estimated water requirements were gathered from multiple sources, shown in Table 3, and the average of these estimated requirements was employed in the model calculations.

Table 3: Water requirement estimates for each technology (gallons/MWhr)

Fuel Type	Leitner (2002) [57]	DOE (2009) [29]	Cohen (1999) [58]	Stoddard (2006) [59]	Carter (2009) [29]	Fthenakis (2010) [60]	Hardberger (2009) [6]	**Average**
PV	4.4				5	4	30	10.9
Wind					0		0	0
CSP Wet	772	800	1,006.6	776.7	920	897.5	800	853.1
CSP Dry		80				79.2	80	79.1
CSP Hybrid		338					400	369

4.1.5 Land data

Available locations were selected from undeveloped land currently for sale in Texas. Zoning of these land parcels was not considered, and land parcels are examples only of the land area that could be devoted to energy generation.

4.2 Case Study I – Retiring coal plant with infinite land availability

In a preliminary analysis, the replacement of the J.T. Deely station was evaluated given infinite available land for the replacement technologies. The infinite land scenario allows the user to examine the water savings across a wide spread of technology distributions.

In the infinite land case, the solar insolation and wind speed used in all calculations are the average values from across all collection locations. As there is no set specific location for the new installations in this model, the transmission losses were ignored.

When minimizing the water requirements of the system, the model selected technologies from lowest to highest water requirements. If no land constraints are given on the system, the model will select 100% HAWT generation in each case. To assess the results of a diverse technological portfolio, the model was constrained to vary the allowable HAWT and PV generation capacity from 0% to 100% each and then evaluated for each of the three CSP cooling technologies.

Figure 1 shows the resultant water savings of the various technology portfolios, given only hybrid cooling for CSP plants. At point A the model is constrained to allow no generation from either HAWT or PV. When all electricity in the model is produced from CSP with Hybrid cooling, the percentage of water saved from that used by the original coal plant is 65%. This represents the minimum water savings possible by this technology portfolio.

As allowable generation from HAWT or PV is increased, the percentage of water saved by the system also increases. The plateau reached at curve B-C represents the diagonal at which all generation in the model can be satisfied by a combination of HAWT and PV. As the least water intensive technologies included in the model, this plateau varies from 99% water savings at 100% PV generation, and 100% water savings with all generation from HAWT.

When evaluated for wet (shown in Figure 9) and dry cooling (shown in Figure 10) CSP technologies, the results vary by the absolute minimum percentage of water reduction from the coal plant requirements, as shown by point A in Figure 8-Figure 10. The minimum water savings capable with all generation from CSP with dry cooling is 93%, while the minimum for CSP with wet cooling is 20% water savings.

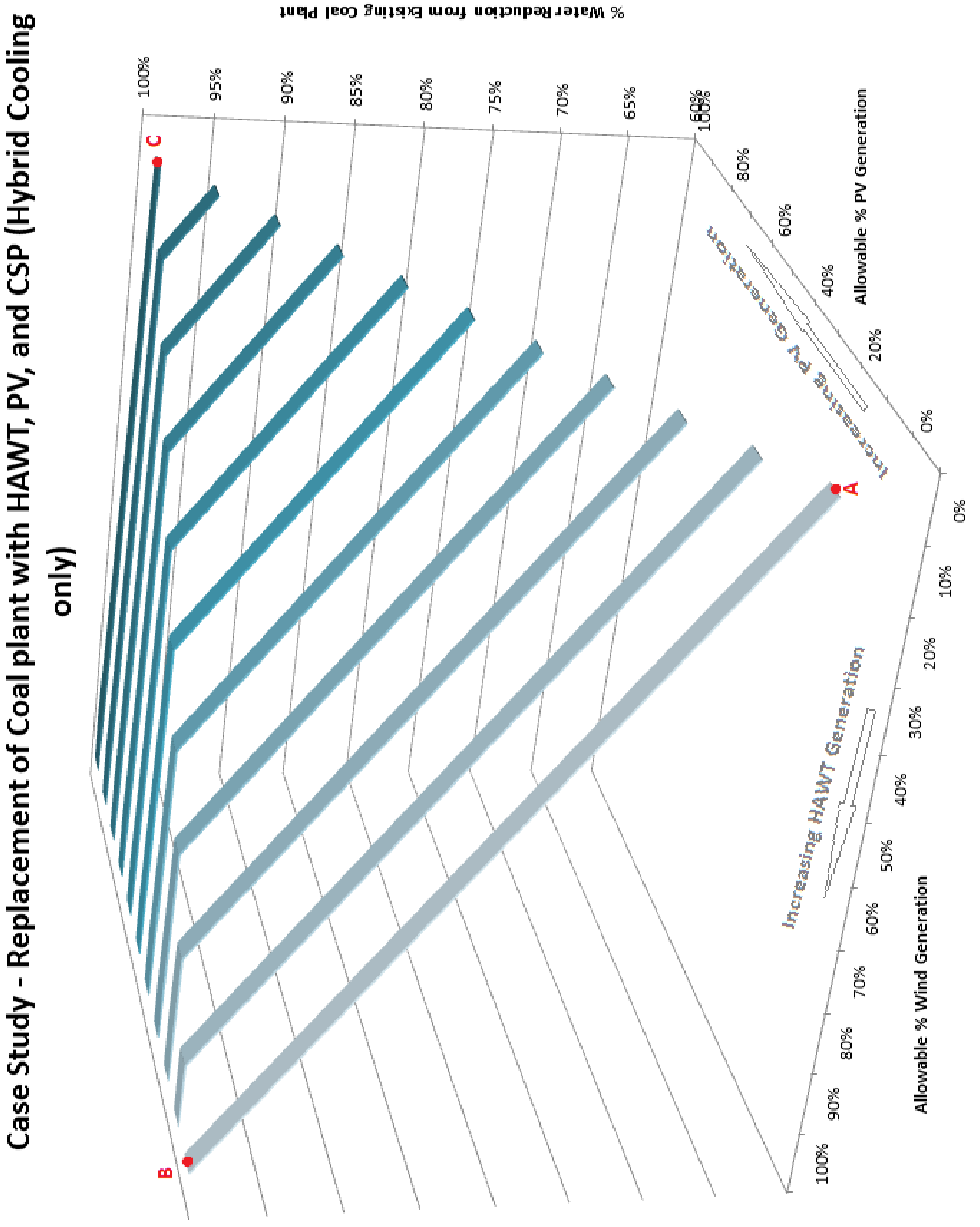


Figure 8: Case Study - Replacement of coal plant with HAWT, PV, and CSP hybrid cooling

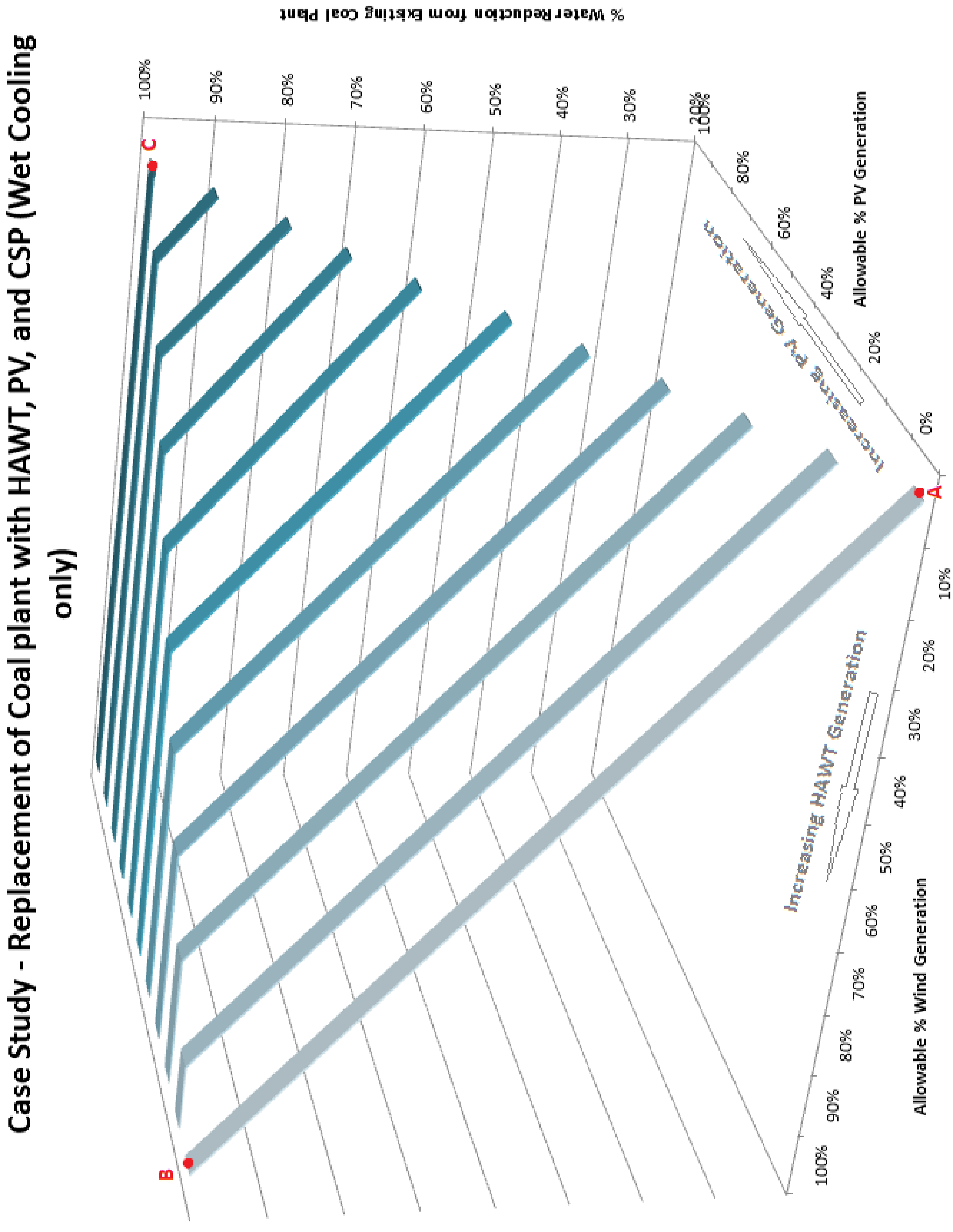


Figure 9: Case Study - Replacement of coal plant with HAWT, PV, and CSP wet cooling

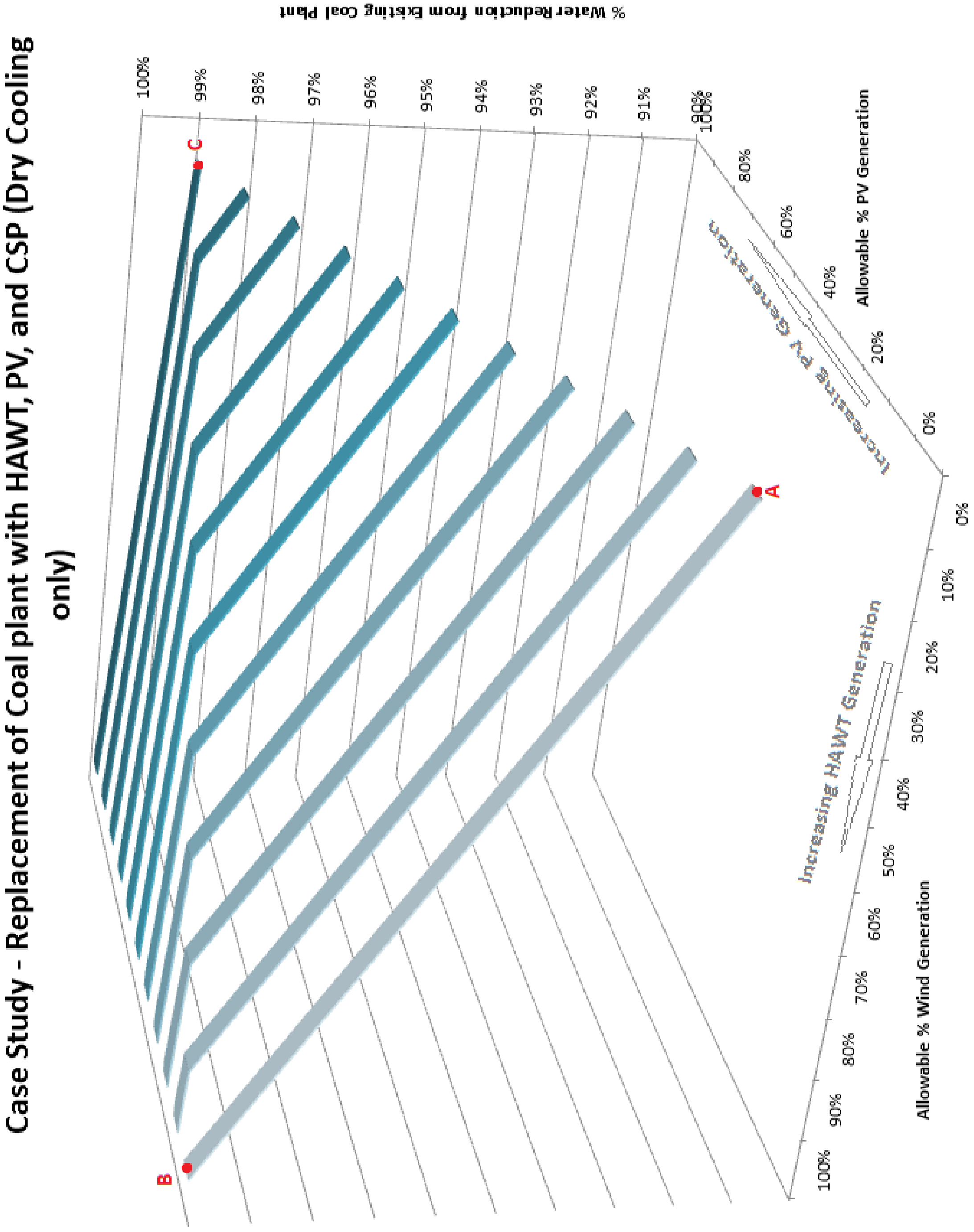


Figure 10: Case Study - Replacement of coal plant with HAWT, PV, and CSP dry cooling

4.3 Case Study II – Retiring coal plant with finite land availability

The model was employed to replace the nameplate generation from the J.T. Deely Station with renewable technologies installed in 16 unique locations with finite land availability. The locations were selected from undeveloped land in Texas available for sale at the time of the model setup. These locations of varying size, and are indicated in Figure 11 and Table 4.

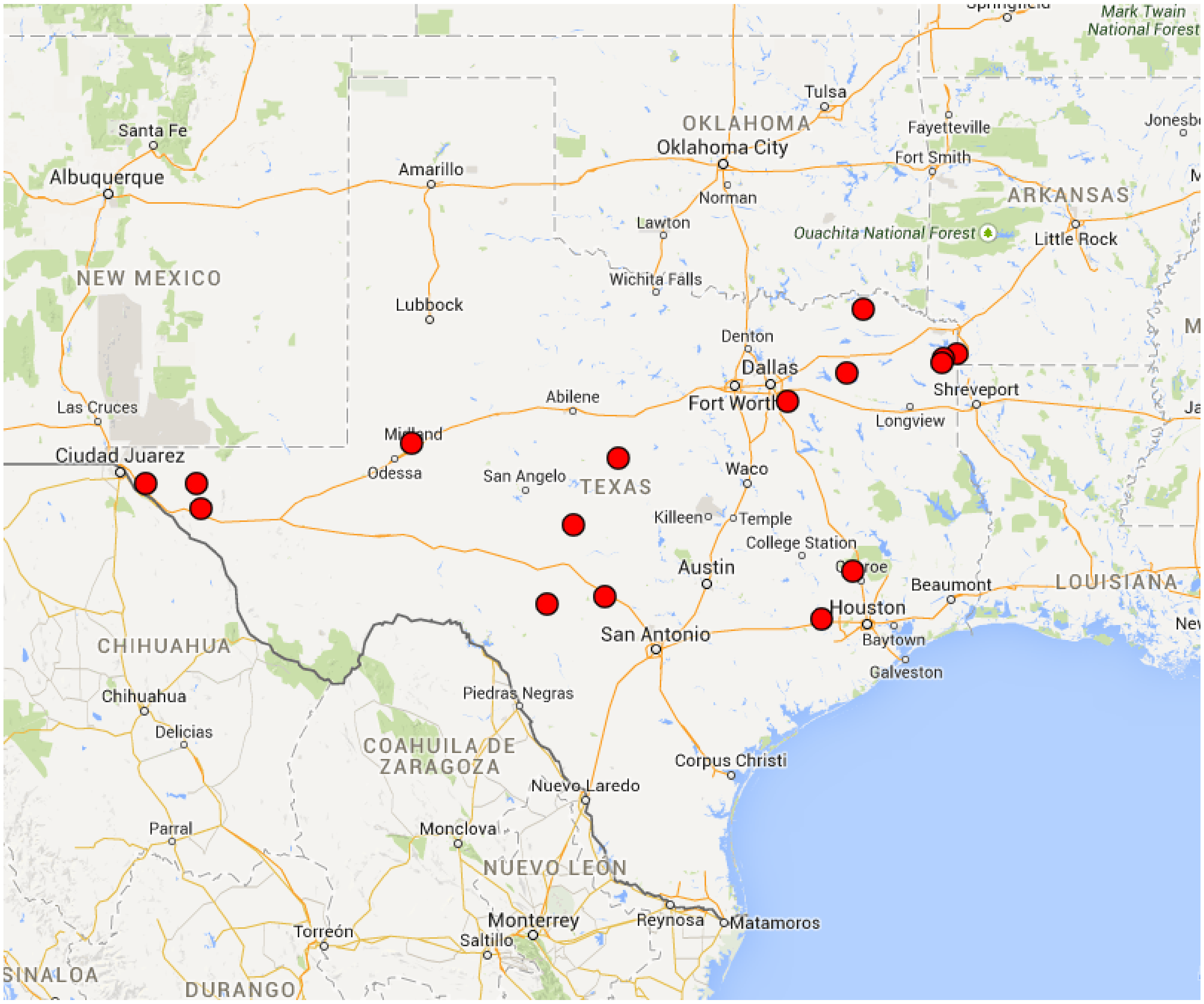


Figure 11: Available installation locations used within the case study

Table 4: Available installation locations and land area used within the case study

Location #	Area (sq. meters)	Latitude	Longitude
1	242812	31.505	-106.154
2	2300235	33.6625	-95.5477
3	447987	29.7742	-96.1575
4	47632	32.5353	-96.6669
5	80937	31.1819	-105.341
6	129500	33.0081	-94.3644
7	257987	33.07	-94.35
8	86198	30.3894	-95.6981
9	1378765	31.81896	-99.1563
10	2055805	32.01202	-102.223
11	85632	30.97957	-99.8133
12	475506	30.06903	-99.3603
13	323749	31.51145	-105.392
14	1618744	32.87163	-95.7752
15	323749	33.12177	-94.1615
16	900831	29.96709	-100.211

As shown below in Figures 12 and 13, the water requirements per MW for each technology included in the current model does not correlate to capacity based land requirements. In locations where water is plentiful, a more water intensive but less land intensive technology such as CSP could be considered more desirable than the land intensive PV. In this case study, the trade-off between water savings and land use can be explored due to the land availability restrictions.

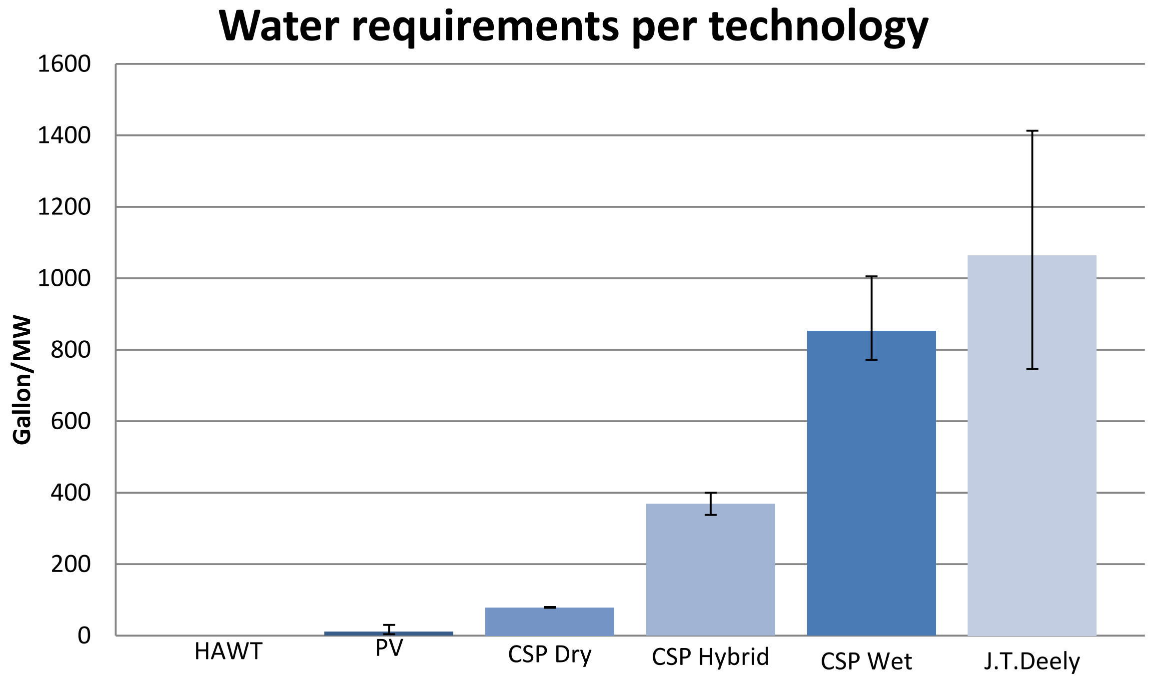


Figure 12: Water requirements per technology

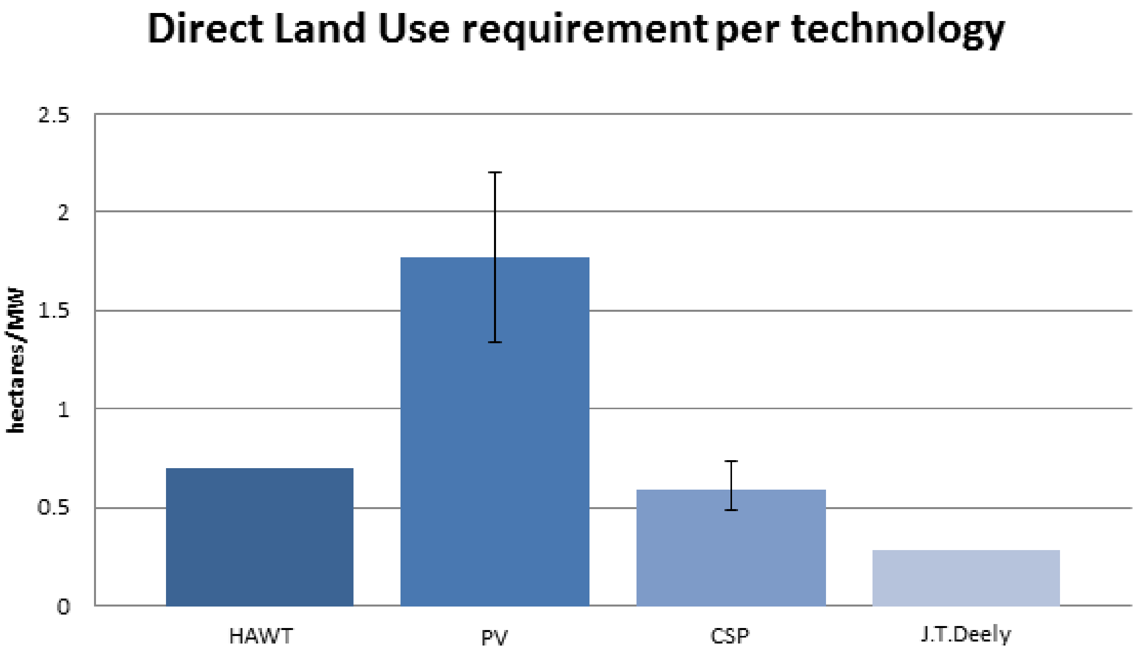


Figure 13: Capacity weighted direct land use requirement per technology

As with the infinite land case study, the results of this case study were evaluated while varying the percentage of allowable generation from HAWT from 0% to 100%. Our model was utilized to examine three examples of the case study, excluding different CSP cooling technologies for each instance. Example 1 allowed the selection of any technology, and the resultant selections are shown in Figure 14. As expected, in each scenario the model utilized all available HAWT generation allowed. When 50-100% HAWT generation was allowed, the model satisfied the remaining generation requirement by utilizing PV generation, the second least water intensive technology. When allowable HAWT generation was 40% or less, however, the land area restrictions do not permit all remaining generation from PV; the model begins to incorporate CSP with dry cooling. This trend continues until, at 0% allowable HAWT generation, the land area available was not sufficient to satisfy all generation requirements with only CSP with dry cooling. In this scenario, our model incorporates CSP with hybrid cooling, as hybrid cooling increases the overall efficiency of the CSP.

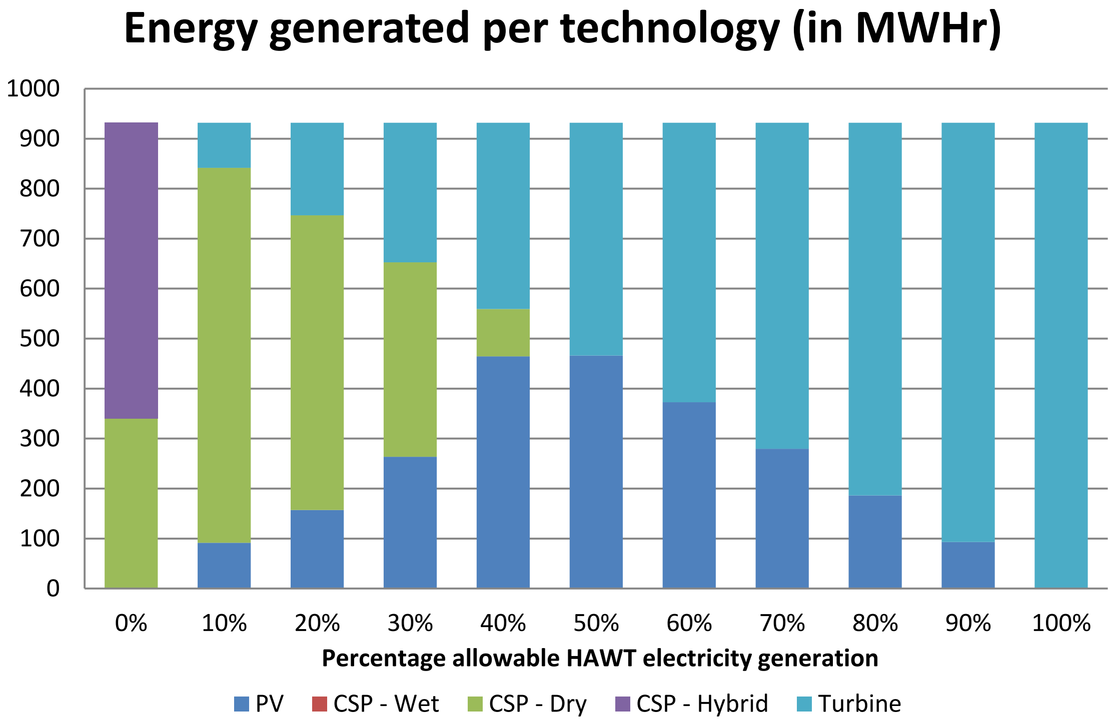


Figure 14: Replacement of generation from coal plant with any modeled technology

In Example 2, shown in Figure 15, with CSP with dry cooling excluded from the model, the analysis resulted in a technology portfolio similar to Example 1. However, in all instances where CSP with dry cooling was selected previously, CSP with hybrid cooling is substituted. CSP with hybrid cooling was efficient enough to generate nearly the entire electricity requirement when the allowable HAWT generation is set to 0%, with some land allocated for PV.

Similarly in Example 3, both CSP with dry cooling and hybrid cooling were excluded from the model, and scenarios are examined with varying percentages of allowable HAWT generation. In the resultant technology portfolios, all allowable HAWT generation was utilized in each scenario, as shown in Figure 16. As with both previous examples, at 40% allowable HAWT generation and below, the electricity requirement can no longer be satisfied exclusively with HAWT and PV, and CSP with wet cooling is incorporated.

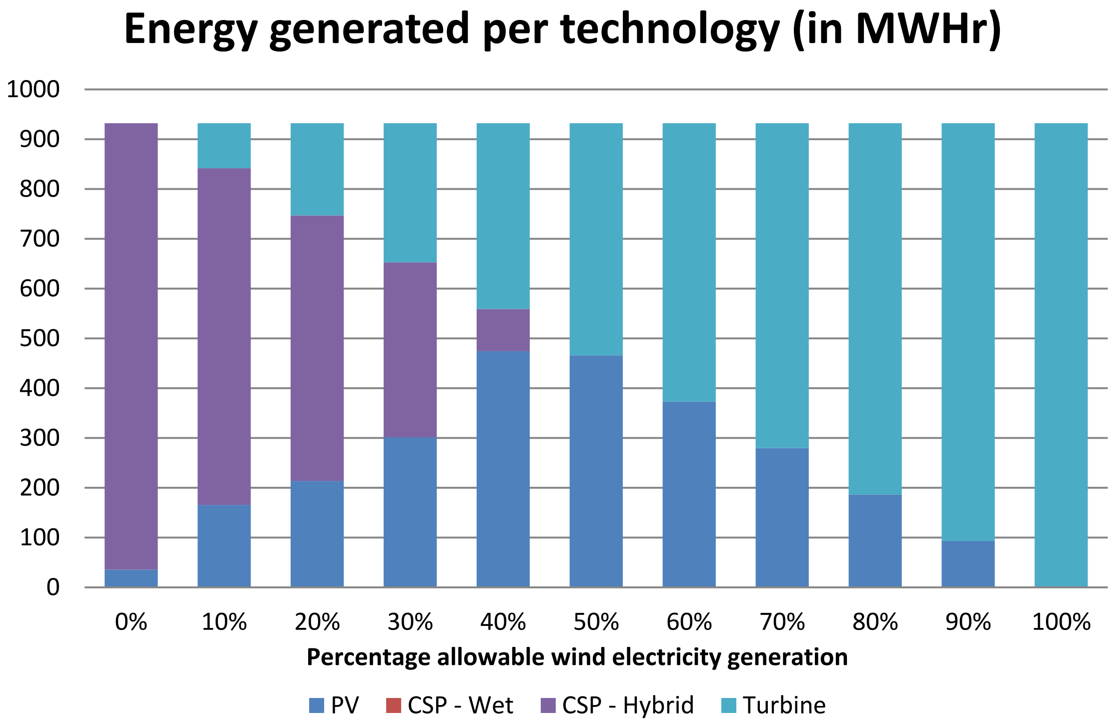


Figure 15: Replacement of generation from coal plant with any modeled technology, excluding CSP with dry cooling

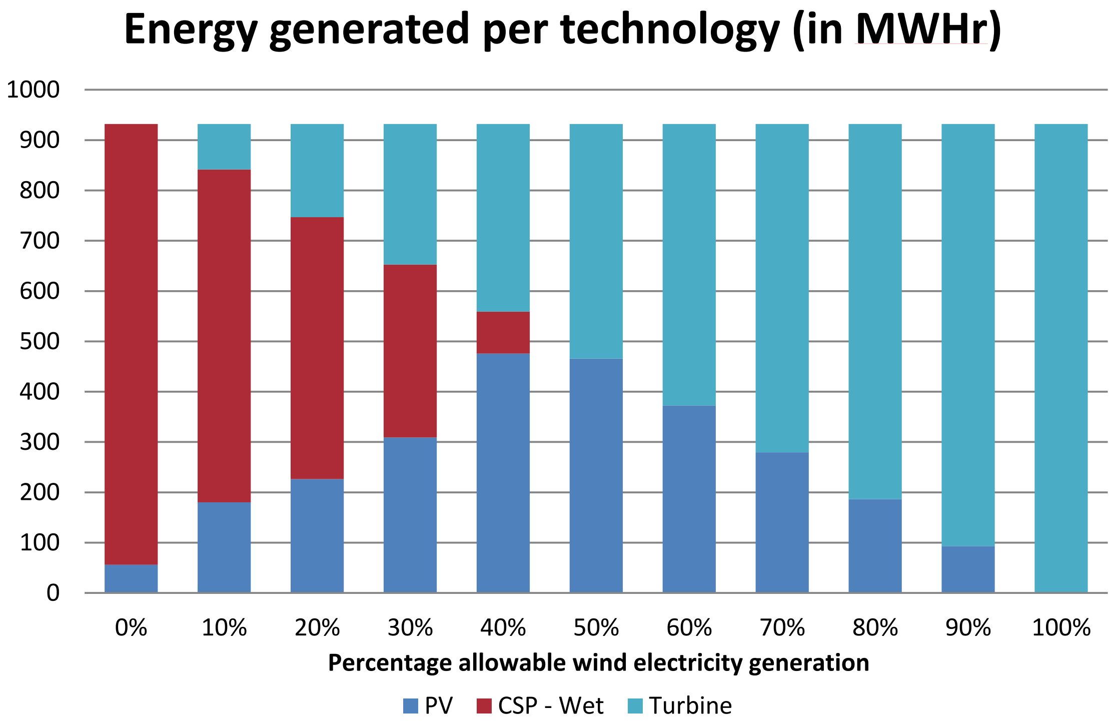


Figure 16: Replacement of generation from coal plant with any modeled technology, excluding CSP with dry and hybrid cooling

In all examples, scenarios allowing 50% or more of the generation from HAWT satisfied all generation requirements with HAWT and PV only. This resulted in reducing the water requirement of the new system by 99-100% of the water previously required by the J.T. Deely plant. In the scenarios allowing 40% or less of the generation from HAWT, the three examples begin to diverge. As Example 1 begins to incorporate CSP with dry cooling, the water savings decreased from 99% at 40% HAWT, to 94% at 10% HAWT generation. A steeper decrease occurred at 0% allowable HAWT in Example 1, as CSP with dry cooling is incorporated due to land area constraints. This new portfolio reduces the water savings to 75%.

Similarly in Examples 2 and 3, the water savings decreased more rapidly when 40% or less of the generation is allowed from HAWT. Water savings in Example 2 is decreased to 67% when no generation is allowed from HAWT, and savings in Example 3 decreased to 25% in the same scenario.

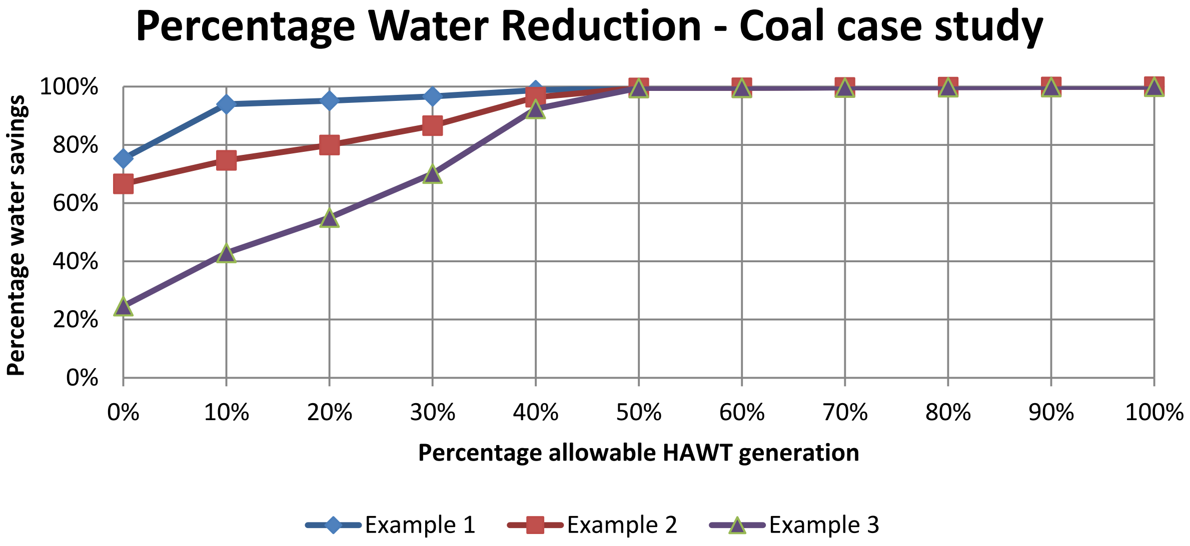


Figure 17: Percentage water reduction from coal plant

4.4 Case Study III – Equivalently sized gas plant with finite land availability

The replacement of the J.T. Deely Station was further analyzed by comparing the replacement of an equivalently sized gas-fired plant. An average gas-fired plant will use approximately 560 gallons water/MWhr, a significant reduction from the average estimated requirements at the J.T. Deely Station of 1065 gallons/MWhr.

In all examples, scenarios allowing 50% or more of the generation from HAWT satisfied all generation requirements with HAWT and PV only. This resulted in a reduction of the water requirements by 99-100% of the water required by an average 932 MW gas plant. As before, in the scenarios allowing 40% or less of the generation from HAWT, the three examples began to diverge. As Example 1 began to incorporate CSP with dry cooling, the water savings decreased from 99% at 40% HAWT, to 89% at 0% HAWT generation. A steeper decrease occurred at 0% allowable HAWT in Example 1, as CSP with hybrid cooling was incorporated due to land area constraints, bringing the water savings to 56%.

In Examples 2, the water savings began a steeper decrease when 40% or less of the generation is allowed from HAWT, similar to the previous case study. Water savings in Example 2 is decreased to 41% when no generation is allowed from HAWT.

Example 3, however, gives the first scenarios with increased water requirements with the replacement technology portfolio. At 10% allowable HAWT generation in Example 3, the water requirement increased 1% over the base case, and at 0% allowable HAWT generation the water requirement increased by 34%.

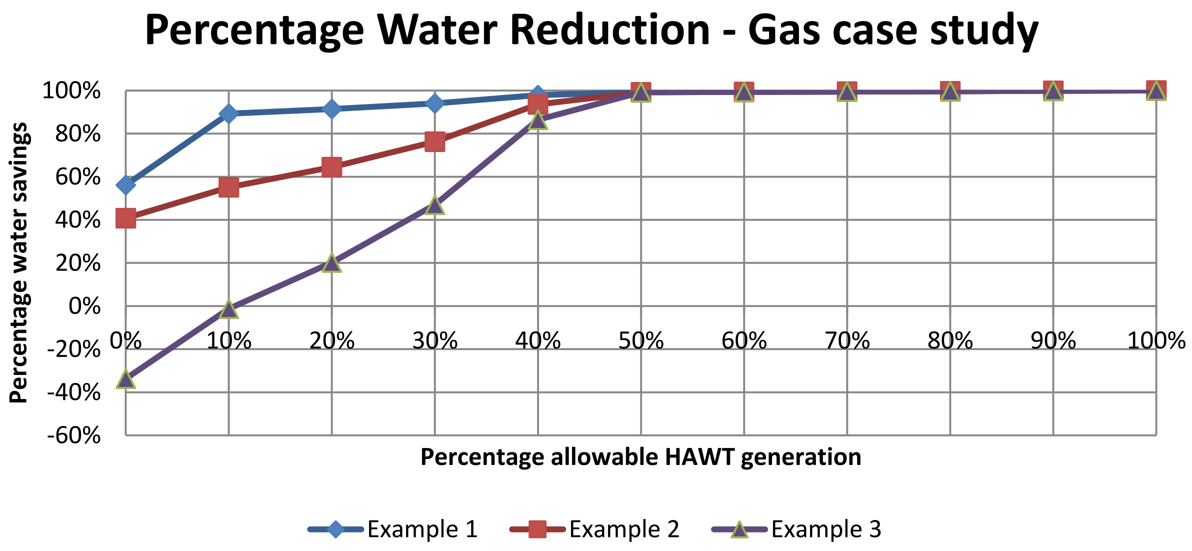


Figure 18: Percentage water reduction from gas plant

5. Comparison to results from existing models and data

Our model focused on calculated water use for electricity generation using renewable resources. Other models of alternative power generation have focused on other aspects, such as land use and monetary costs. None have focused strictly on water requirements. Since there is no direct comparison available for the resultant water use for electricity generation, we looked at other aspects of our model to compare to existing model results in the literature. These aspects include the land requirements, the estimated hourly output of proposed technology distribution, and size and capacity of each proposed installation.

We compared our model's output of the land use requirements per unit of electricity produced to land use results of published models and calculations.

We also calculated the minimum and maximum proposed plant sizes for each technology to existing utility scale installations and the hourly electricity output that our model provided for a suggested technology distribution. These values were compared to the reported sizes of existing installations.

Lastly, we estimated hourly output electricity of the proposed technology distribution, and compared it to the known hourly electricity demands of the region.

5.1 Electricity production per unit land area

While there is no generally accepted metric for the land-use impacts of electricity generation technologies, there are several methods in use. They can be separated into three distinct categories: 1) the total land area impacted, 2) the duration of impact, and 3) the quality of impact [61, 62]. The results of our water-energy optimization model are evaluated based solely on the land area impacted, since quality and duration of impact can only be evaluated on a case-by-case basis for each installation [62].

The area of impact can be computed using two different metrics: total and direct land-use. The total area comprises all land enclosed by the site boundaries, whereas the direct area includes only land area occupied by the installed technology, i.e. solar panels and arrays, wind turbines, and other infrastructure. The land area requirements calculated in our model are direct impact land-use.

The required land area was compared to results obtained from two different models: results from an analysis by NREL evaluating land requirements of existing and proposed plants, and the results of the System Advisor Model (SAM), created as “a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry” [63].

5.1.1 Land-use: Solar PV

Land-use requirements for PV systems can be defined in two different ways: total land-use, highlighted in yellow in Figure 19, and direct land-use, highlighted in orange. The direct area is land that is no longer available for alternative uses, and is occupied by the solar panels, required access roads, or other infrastructure. The total land use area is the direct area as well as all land enclosed by the site boundaries [64]. Land area requirements per unit of electricity generated is calculated by dividing either the total or direct land-use by the average electricity generation of the array.

The direct area of land required for each PV installation in the model is dependent upon the dimensions of the solar panel, the angle of installation, and the average solar altitude and solar azimuth, as described in Equations (1) - (3) and the design of the facility with respect to supporting structures and access. The total land use is less well defined, as there is not always a uniform perimeter or boundary around each installation.

Figure 19: NREL mesa top PV system - example of direct and total land use [64]

5.1.2 Land-use: Solar CSP

For solar CSP, the land area requirement per unit of electricity generated is calculated by dividing the total or direct land-use by the average electricity generation of the plant. The calculation becomes more involved due to the effect of storage and the solar multiple (SM) [65]. The solar multiple is a design parameter used to normalize the size of the solar field with respect to the capacity of the power block [66]. A system with an SM of 1 has a solar field aperture area large enough to produce exactly the energy for the power block under specific reference conditions. The example shown in Figure 20 demonstrates the power produced by a solar field of a 600 MW CSP plant with SM of 2. Any electrical energy that exceeds the power block capacity can be stored and delivered to the power block when less solar insolation is available

[66]. Due to the effect of the SM, it is more significant to evaluate the land-use compared to total plant generation, as opposed to per unit of capacity of the power block [65].

The direct use land area calculated within the model for CSP installations includes a fixed value, a_c, to account for the land area required for power block and thermal storage, with the addition of a field area to generate the required power output of the solar plant.

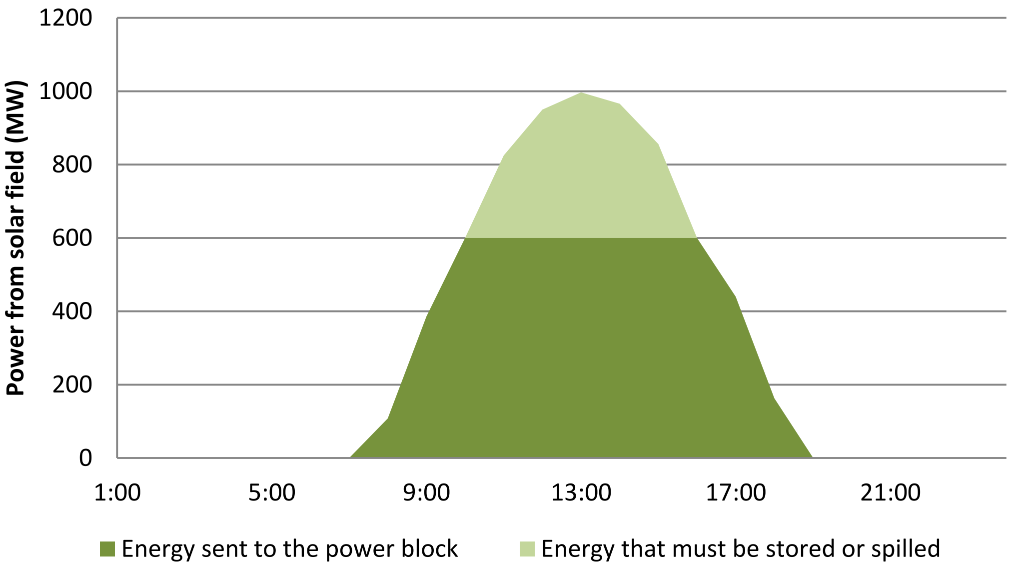


Figure 20: Example solar field power output - SM of 2

5.1.3 Land-use: HAWT

HAWT's are typically distributed over a large area depending on the wind, topography and land use around the turbine. This arrangement can result in a significant difference between total area and direct use area for wind turbines. An example of the differing area measurements for a wind power plant is shown in Figure 21. The total land area impacted can be difficult to calculate given irregular strings of HAWT installations and uneven terrain.

Since all turbines used within the model are of equivalent size, the direct land-use area calculated within the model is a fixed value of 0.25 acres per turbine, to account for the expected permanent service roads and turbine pad required for each turbine.

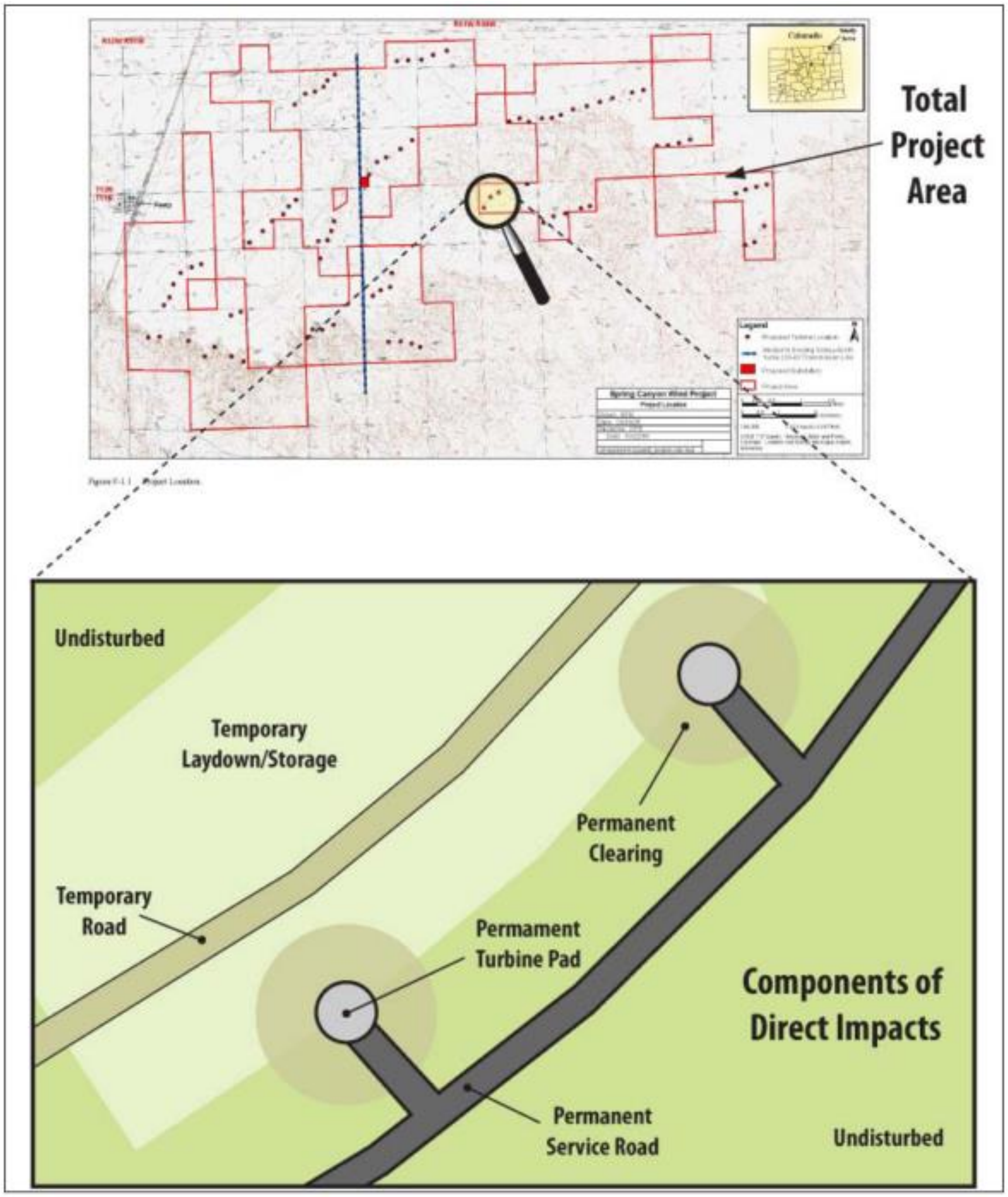


Figure 21: Example of total and direct land-use for a wind power plant [62]

5.2 Direct land comparison: NREL

Comparisons were made between the land area requirement per unit of electricity generation of our water-energy model output and published data. The first comparison was made to reports by NREL which compile data and analyze the land use of wind and solar technologies, and summarize the land use per MWHr of these technologies [62, 64]. Land requirements of existing, proposed and planned PV, CSP and wind turbine plants are compiled and are compared to reported or estimated power generation of these plants.

5.2.1 NREL data availability

Any analysis is only as good as the data on which it is based [67], thus a comparison between models must also be accompanied by a comparison between datasets. For each technology the NREL reports use reported data from existing, proposed and planned sites throughout the US, all of which span a wide range of installation years and geographical locations.

For PV installations, panel efficiencies range across a wide spectrum based on the year the photovoltaic cell was developed, and the technology used. As shown in Figure 22, the date of development and the technology used in a photovoltaic cell can have a drastic effect on overall plant efficiency. The range of installation ages of the 192 sites included in the NREL report was not explicitly stated. It is known that the calculations include projects completed as early as 2008 to projects only in the proposal stage. The reported efficiencies of the technologies used in these installations range from 10% to 31%, and locations range from Texas to Illinois, and California to Vermont.

The smaller data set available of CSP provides both an advantage and disadvantage for our comparison. The range of installation years is rather limited for CSP installations, and as such there are a more limited number of CSP installations in the United States. So while the efficiencies of the installed technologies are comparable across the range of 24 CSP installations included in the NREL report, we are limited by a small dataset.

The data for 172 existing or proposed wind projects collected in the NREL report was collected from plants constructed after 2000, with a capacity of 20 MW or greater. While this a wide range of installation years, this range offers less of a limitation for the model results due to the nature of HAWT technologies. Older wind turbines tend to be smaller, and generate correspondingly less electricity; as such the age of the plant has little effect on the analysis of land use per unit of electricity generation.

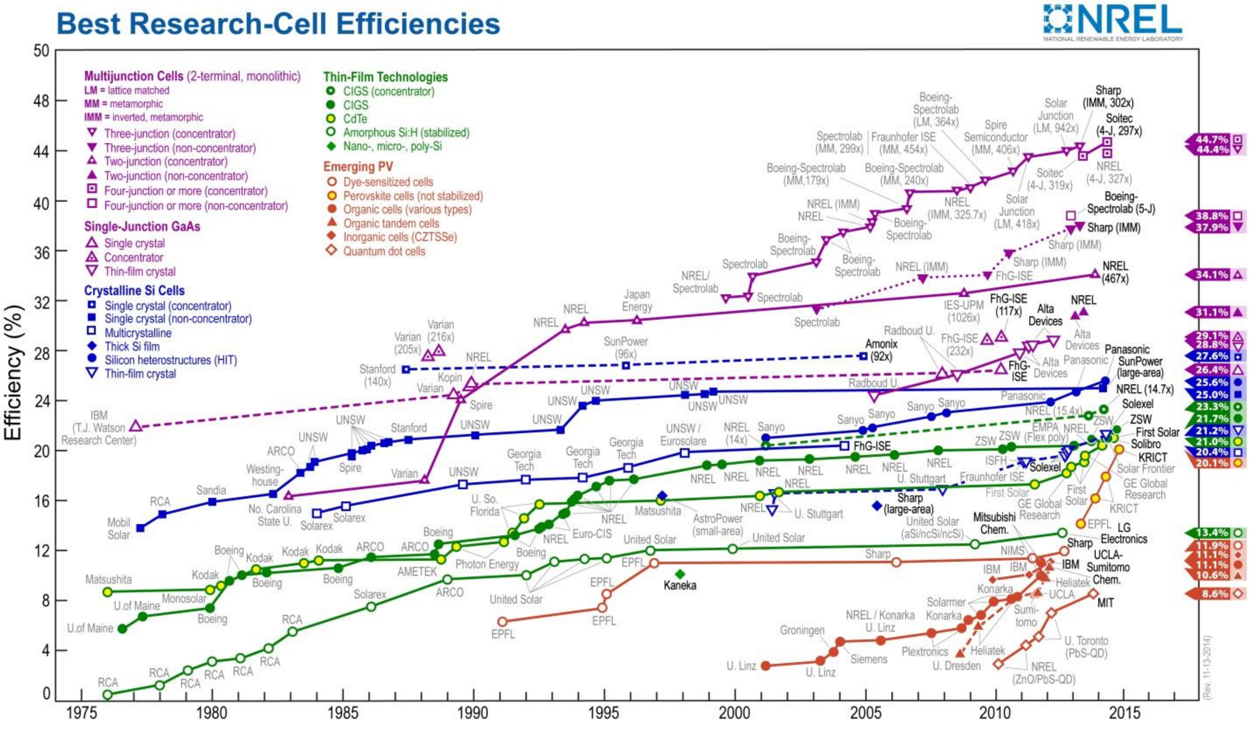


Figure 22: NREL report on record PV cell efficiencies [68]

5.2.2 NREL land comparison: Solar PV

The PV installations in the technology distribution proposed by the model estimate an average land area requirement of 1.66 hectares/MW. As an initial baseline comparison, the NREL report on land-use requirements for solar power plants found the average direct land area requirements to be approximately 2.2 hectares/MW for fixed axis PV, marking a 75% difference from our model results. The difference between the NREL values and our values could be caused by one or more of the following reasons: evolution of solar technologies, small sample sizes, and the quality of reported data [64].

The data evaluated in the report captured a limited sample size, with installations of varying age. All PV and CSP installations included in the analysis are shown in Figure 23. Older installations, using older technologies or outdated panels, would likely require more land per MW produced than newer installations, and therefore this reported value reflects past performance of fixed PV [64]. Additionally, as shown in Figure 23, the evaluated sites are spread over a wide geographical area. The reduced performance of plants installed in areas with less solar average insolation would be reflected in the overall average land-use value.

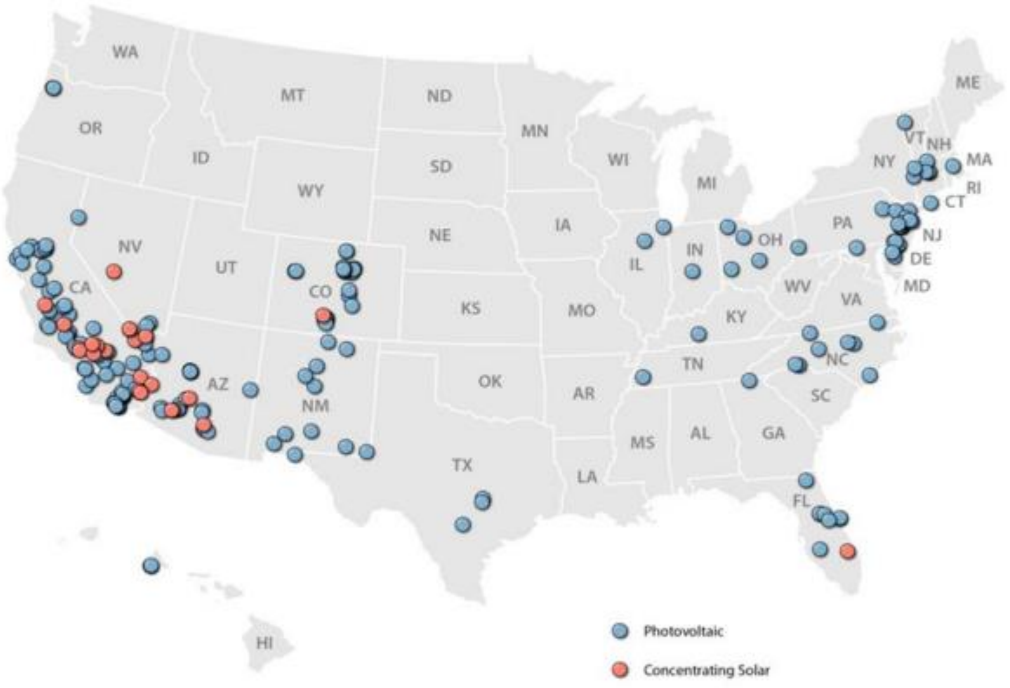


Figure 23: Map of PV and CSP installations evaluated in NREL technical report [62]

5.2.3 NREL land comparison: Solar CSP

The average value for CSP parabolic through direct land use in the NREL report on land-use requirements for solar power plants was approximately 2.51 hectare/MW [64], which marks a 188% difference from the average land requirements calculated with our model, at 0.87 hectare/MW.

In addition to the limitations discussed for available data for PV installations, the analysis of CSP installations is limited by an ever smaller sample size, as shown in Figure 23. The land requirement per unit of electricity generated can also be affected by the presence of thermal storage. Storage allows for increased generation of the plant, without affecting the capacity of the power block or size of the field land area, thus reducing the land-use per unit of electricity produced.

As there is no widely accepted value for the conversion efficiency from solar insolation to aperture area, the baseline area per MW of the CSP plants calculated in the model was based on the performance of a series of CSP parabolic trough plants operating in California, shown in Table 5. The values included in the model were capacity weighted, with an average of approximately 0.63 hectares/MW, while the generation weighted average approaches those of the NREL report, around 2.99 hectares/MW.

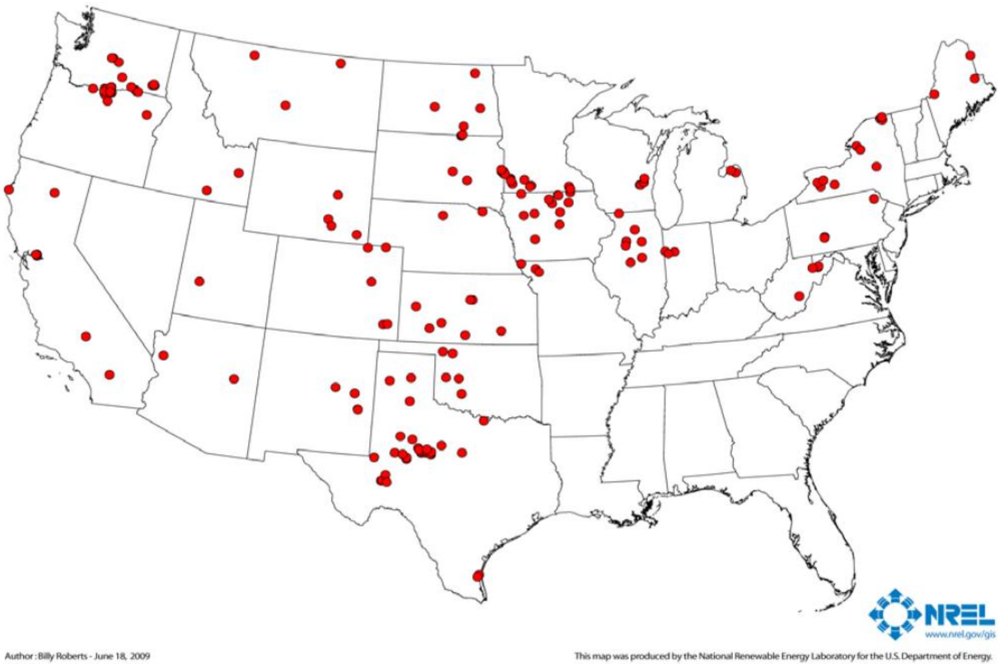
Table 5: Evaluated land requirements per MW of generation for SEGS CSP plants

SEGS #	Field Area	Generation	Capacity weighted		Generation weighted	
	hectare	MWh	MW	hectare/MW	MW	hectare/MW
I	8.30	16,500	44	0.56	9.24	2.69
II	16.54	32,500				
III	23.03	68,555	150	0.73	31.50	3.47
IV	23.03	68,278				
V	25.05	72,879				
VI	18.80	67,758				
VII	19.43	65,048				
VIII	46.43	137,900	160	0.59	33.60	2.82
IX	48.40	125,036				
			Average	0.63	**Average**	2.99
				Hectare/MW		Hectare/MW

5.2.4 NREL land comparison: HAWT

The NREL report of land-use requirements of modern wind power plants report compiled data on approximately 80% of the installed wind capacity of the US, and the average direct impact area calculated was 0.7 hectares/MW [62]. This value is very close to the average land requirements of 0.92 hectares/MW for HAWT installations calculated in our water-energy model, showing only a 23% difference in land-use.

The analysis of land area for wind power plants has advantages over the analysis of solar technologies. As reflected in equation (6), the power produced by a HAWT is proportional to the size of the turbine, and as turbines increase in size the required land area per turbine increases as well. Older wind turbines tend to be smaller and generate commeasurably less power. Thus the age of the plant is expressed almost explicitly in the land use formulation. This creates a more linear comparison between old and new or small and large installations that isn't possible with solar technologies. With the inclusion of 172 individual projects, shown in Figure 24, the report shows rather uniform land requirements for HAWT, as approximately 80% of the evaluated projects show direct land use below 0.4 hectares/MW.



Author : Billy Roberts - June 18, 2009

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

Figure 24: Locations of wind power plants evaluated in NREL report of land-use requirements [62]

5.3 Total land use comparison: SAM

The U.S. Department of Energy and National Renewable Energy Laboratory's System Advisor Model (SAM) is a program intended to allow users to model the capabilities of various renewable energy installations. SAM produces performance predictions, cost analyses, and detailed hourly information from either the utility or consumer side of the model. SAM automatically populates a set of default variables and parameters based on the users modeling choices, and allow the user to input information such as project location, equipment details, and costs. The user can also modify the default values of given parameters. The simulation results include average and hourly generation data, and cost analyses for the system [31].

To evaluate the results of our model, we compared the estimated land-use requirements of the proposed solutions in the model to those produced by SAM. For each proposed installation in the model, an equivalent simulation was run in SAM. All default values were used in SAM, except where specified. Additionally, in the case of both solar and wind technologies, the data for the closest location in SAM to those used in the model were selected for the simulation.

5.3.1 SAM data availability

The results of any model can vary widely depending upon the input data. To compare results, the distances between measurement sites and the difference in average measured values for the solar and wind data used in each model were compared.

In the case of available solar insolation data, the closest measurement location in SAM was geographically very close to the data available in the model. Shown below in Table 6, the linear distance in degrees between reported locations of solar data collection varies between 0.01 and 0.29 degrees latitude and longitude, with one outlier at 9.46 degrees latitude and longitude. This outlying value indicated the location used in the model for which data was unavailable in SAM. Overall, the average solar insolation values for the sites available in SAM are comparable to those used in our water-energy optimization model, allowing a more direct comparison between the results of both models.

Table 6: Solar data availability comparison between the model and SAM

Station Name	Linear distance (degrees)
Montgomory Co	0.29
Longview Gregg County	0.12
Kerrville Municipal	0.09
Brenham	0.06
Cox Fld	0.01
Greenville/Major	0.08
Dallas/Redbird Airport	0.12
Pine Springs	9.46
Midland International	0.11
Brownwood Municipal	0.10
El Paso International	0.03
Junction Kimball County	0.03

Wind speed data records are far less available than solar insolation reports. For the six wind data locations used within our water-energy model, SAM contained two measurement locations, and all locations were a significant distance from the model locations. These linear distances, shown in Table 7, vary between 1.03 and 5.47 degrees latitude and longitude, with an average distance of 3.24 degrees latitude and longitude.

Table 7: Wind data availability comparison between the model and SAM

Station Name		Linear Distance
Water-energy model	SAM	(degrees)
ABILENE-1	Jefferson	2.30
ABILENE-2	Jefferson	2.36
BIG SPRINGS	Lynn	1.03
BRYAN	Jefferson	4.09
COLLEGE STA	Jefferson	4.18
COTULLA	Lynn	5.47

This geographical distance between wind speed measurement locations is significant, as wind speeds can vary greatly by location. Furthermore, as demonstrated by equation 6, the power output of a HAWT increases exponentially with wind speed. By comparing the wind data from our model to that available within SAM, we see a wide variety in recorded averages, as shown in Table 8. The difference in the wind speeds available within SAM vary from 53% to 141% higher speeds as compared to average wind speeds in our model. The difference in wind speed averages can have a drastic effect on final estimated generation, which could make a comparison between the two models ambiguous.

Table 8: Average wind speed comparison between the model and SAM

Station Name		Linear Distance (degrees)	Mean Wind Speed (m/s)	% increase
Water-energy model	Closest SAM station			
ABILENE	Jefferson	2.29	5.2	53%
ABILENE	Jefferson	2.35	3.9	104%
BIG SPRINGS	Lynn	1.03	6.2	39%
BRYAN	Jefferson	4.08	3.3	141%
COLLEGE STA	Jefferson	4.18	4.1	94%
COTULLA	Lynn	5.47	4.2	106%

Jefferson Country, OK	7.93	(m/s)
Lynn	8.63	(m/s)

5.3.2 SAM land comparison: Solar PV

Land-use per unit of electricity generation was calculated for PV installations using both our water-energy optimization model and SAM. The difference between our model and SAM remained consistent, and values were comparatively close. SAM consistently predicted approximately 80% of the required land area for the same generation capacity the model predicted. The final average area/MW value from SAM was 1.34 hectare/MW, as compared to 1.66 hectares/MW from our model. This variation could be due to slightly different packing factors for the solar fields or slightly different panel efficiencies, and is considered to be within a reasonable range of error.

The data presented Table 9 shows a direct comparison between the land required with each model. Each row represents a location in our water-energy optimization model for which PV was used in at least one scenario. For each location, SAM was used to generate the same magnitude of electricity generation proposed in our model. The resultant land requirement for SAM and our model for this generation is shown in column one and two, respectively.

Table 9: PV land comparison between SAM and the model

SAM land area (meters^2)	Model land area (meters^2)	Multiplier
198,423	242,812	0.82
1,877,472	2,300,235	0.82
376,003	447,987	0.84
37,512	47,632	0.79
61,618	80,937	0.76
101,609	129,500	0.78
209,155	257,987	0.81
70,262	86,198	0.82
1,141,902	1,378,765	0.83
67,457	85,632	0.79
387,224	475,506	0.81
1,328,944	1,618,744	0.82
264,217	323,749	0.82
749,135	900,831	0.83

5.3.3 SAM land comparison: Solar CSP

We compared the results from our water-energy optimization model with those obtained from SAM for 16 different CSP installations, using default settings within SAM, including a SM of 1. The relationship between SAM and the CSP land estimates in the model was quite consistent; however the correlation exhibits a significant difference in magnitude. On average the land requirement established by SAM for CSP parabolic trough plants was 2.7 times larger than the estimates produced by the model. The average area per MW in the SAM model for CSP is 3.28 hectare/MW and the average from the model was 1.15 hectare/MW.

Table 10 presents a direct comparison between the land required with our model and SAM. Each row represents a location in our water-energy optimization model for which CSP was used in at least one scenario. SAM was used to generate the same magnitude of electricity generation for each location as proposed in our model. The resultant land requirement for SAM and our model for this generation is shown in column one and two, respectively.

The consistent difference between the two land area requirements suggests that the cause lies within the calculations used in each model, rather than any discrepancy within the location specific data. This leads to the efficiency of field area to electricity generation. In our model, this efficiency was calculated using generation data and field area from existing plants. It is likely that a differing SM, storage potential, and natural gas generation backup (up to 10% of plant generation) used within these plants have the effect of decreasing the land required per unit electricity generation in our water-energy model.

Table 10: CSP land comparison between SAM and the model

SAM land area (meters^2)	Model land area (meters^2)	Multiplier
696,060	242,812	2.87
6,321,195	2,300,235	2.75
1,311,183	447,987	2.93
109,265	47,632	2.29
206,390	80,937	2.55
348,030	129,500	2.69
728,435	257,987	2.82
238,765	86,198	2.77
3,998,298	1,378,765	2.90
5,973,165	2,055,805	2.91
238,765	85,632	2.79
1,359,745	475,506	2.86
902,450	323,749	2.79
4,471,780	1,618,744	2.76
914,590	323,749	2.83
2,622,365	900,831	2.91

5.3.4 SAM land comparison: HAWT

Land-use estimated from SAM for HAWT generation uses total land area where as our water-energy optimization model uses direct land area. As discussed in Section 5.1.3 Land-use: HAWT, this introduces significant variability. This variability is what we observed during a direct comparison.

The estimated land requirements in SAM varied from approximately half of those estimated in the model, to just over 70 times the land requirements, shown in Table 11, with an average area per MW of 15.8 hectares/MW. The average value from NREL reports was 0.7 hectares/MW, and the average from our model was 0.92 hectares/MW. This significant variation is due to both the variation in average wind speeds, as discussed in section 5.3.1 SAM data availability, as well as the differences stemming from the use of direct vs total land area requirements.

The data in Table 11 presents a direct comparison between the land required with our model and SAM. Each row represents a location in our water-energy optimization model for which HAWT was used in at least one scenario. SAM was used to size the generation capacity for each location as proposed in our model.

Table 11: HAWT land comparison between SAM and the model

SAM land area (meters^2)	Model land area (meters^2)	Multiplier
12,250,000	242,812	50.45
18,000,000	2,300,235	7.83
5,000,000	447,987	11.16
2,560,000	80,937	31.63
960,000	129,500	7.41
49,000,000	1,378,765	35.54
144,000,000	2,055,805	70.05
245,000	475,506	0.52
16,000,000	323,749	49.42
5,000,000	781,277	6.40
490,000	900,831	0.54

5.4 Proposed plant size

To evaluate the feasibility of the new renewable technology installations proposed by the model solution, the maximum and minimum installation capacities as listed in Table 12 were compared to existing plants. In the case of PV and HAWT, the proposed plants fall well within the range of existing installation capacities. For CSP, while the maximum proposed plant size falls within the range of existing plant capacities, the minimum proposed installation is significantly smaller than any existing or panned CSP parabolic trough plant. This may point to the need for the inclusion of a minimum size constraint for CSP plants in our model.

Table 12: Maximum and minimum installation size comparison

Water-energy model plant size (hectare)

	CSP	PV	HAWT
Maximum	193.36	281.71	464.85
Minimum	6.74	4.61	5.46

NREL report plant size (hectare)

Maximum	280	700	901
Minimum	75	0.2	15

5.5 Estimated hourly generation

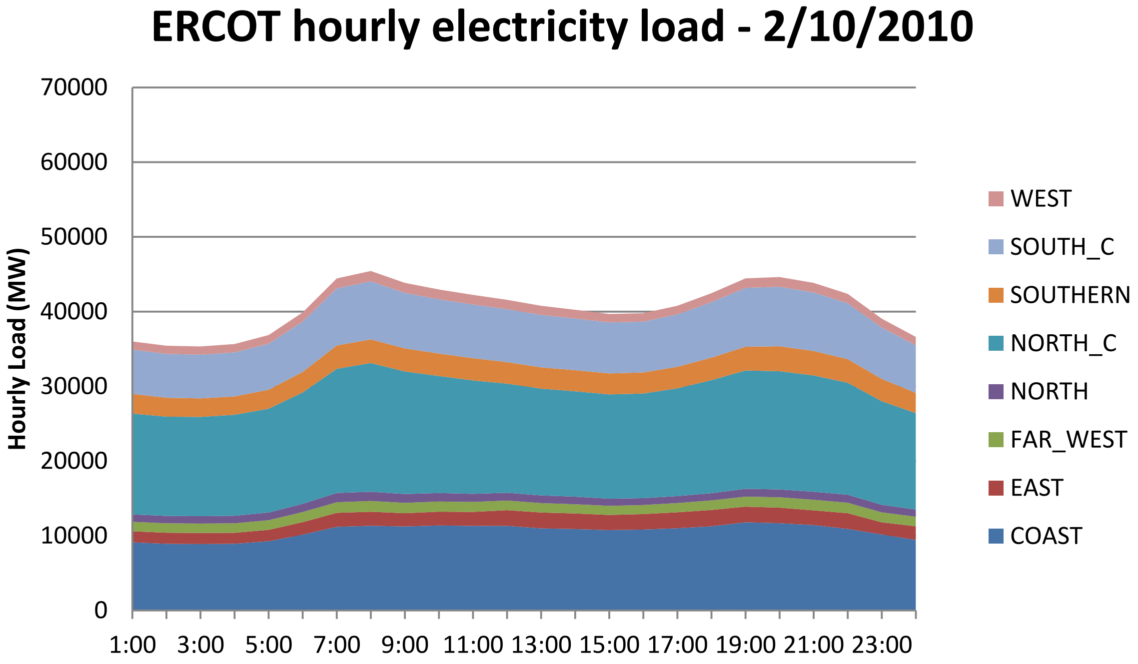
Estimated hourly generation for two 24 hour periods were evaluated using data from 2010. The days chosen for analysis were February 10th and August 10th. The latter was selected for having statistically some of the highest temperatures of the year for Texas, and the former as a 6 month counterpoint to that date.

Figure 25 presents the hourly electricity load for the chosen dates as reported by the eight regions in the Electric Reliability Council of Texas (ERCOT). In cooler months, as represented by the data from the February date, electricity demand peaks at approximately 7:00 and 20:00. The electricity load on days in warmers months like August has a much higher and more distributed peak, highest at approximately 17:00. Electricity generation that can easily conform to those peak demand times is the most desirable to integrate into the grid.

Figure 25 and Figure 26 present the estimated hourly generation from our water-energy model results on February 10th, 2010 and August 10th, 2010 respectively. These results are displayed as if all electricity deployed as it is generated, with no regard for demand. For the scenarios limiting HAWT generation to 20% and 40%, solar electricity generation is the majority, and the generation capacity peaks just past mid-day, as expected. For higher percentages of HAWT, the peaks move to 3 – 5 am and 8 pm in colder months, and a relatively flatter profile in warm weather.

This generation does not always coincide with demand. To allow for a more even distribution of the generated electricity, thermal storage was incorporated in all proposed CSP installations, results of which are shown in Figure 27 and Figure 28. A solar multiple of approximately 2 was set for the CSP installations, and the average stored energy was deployed during the hours in which the power block was not at capacity. This storage has the effect of flattening the midday peak for scenarios with 20% HAWT generation, with slightly less effect for 40% HAWT generation. In addition to the consistent deployment of energy stored in CSP, this storage could instead be deployed during peak demand, to better match the grid load.

This comparison brings to light an interesting trade off not often used in the analysis of renewable energy portfolios: water requirements vs grid integration. CSP is the highest water user, but incorporates storage which can be used to more closely match dispatch with demand. A balance between water saving and ease of grid integration could be included in renewable energy portfolio designs to incorporate this tradeoff.



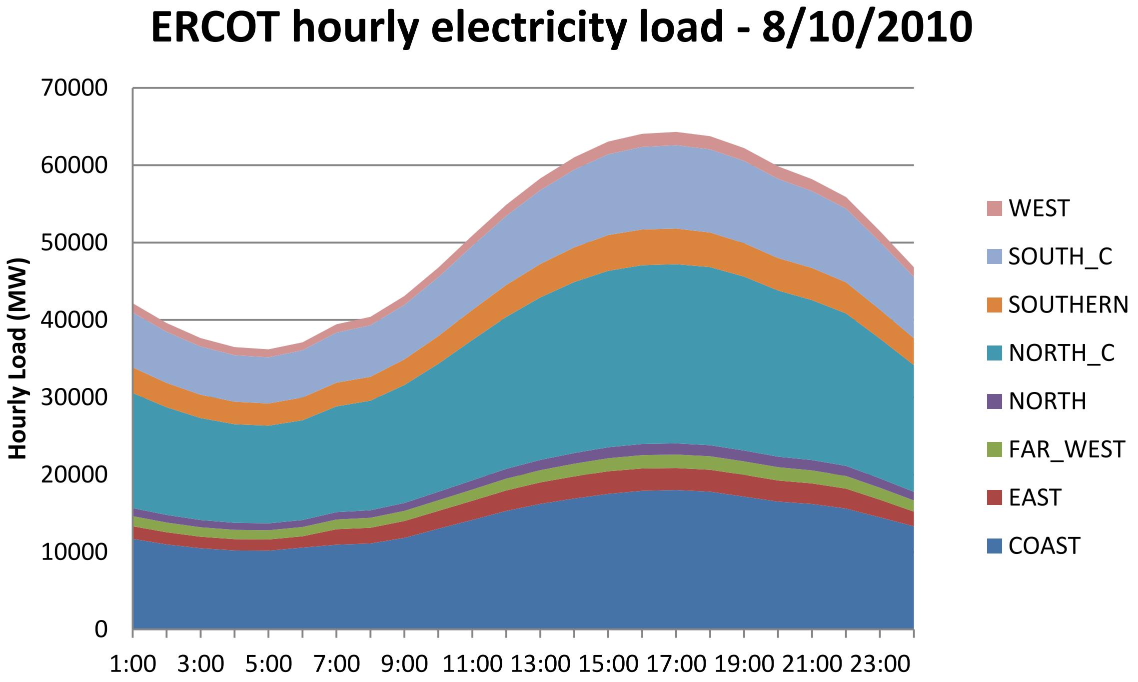


Figure 25: ERCOT hourly electricity load - 2/10/2010 and 8/10/2010 [69]

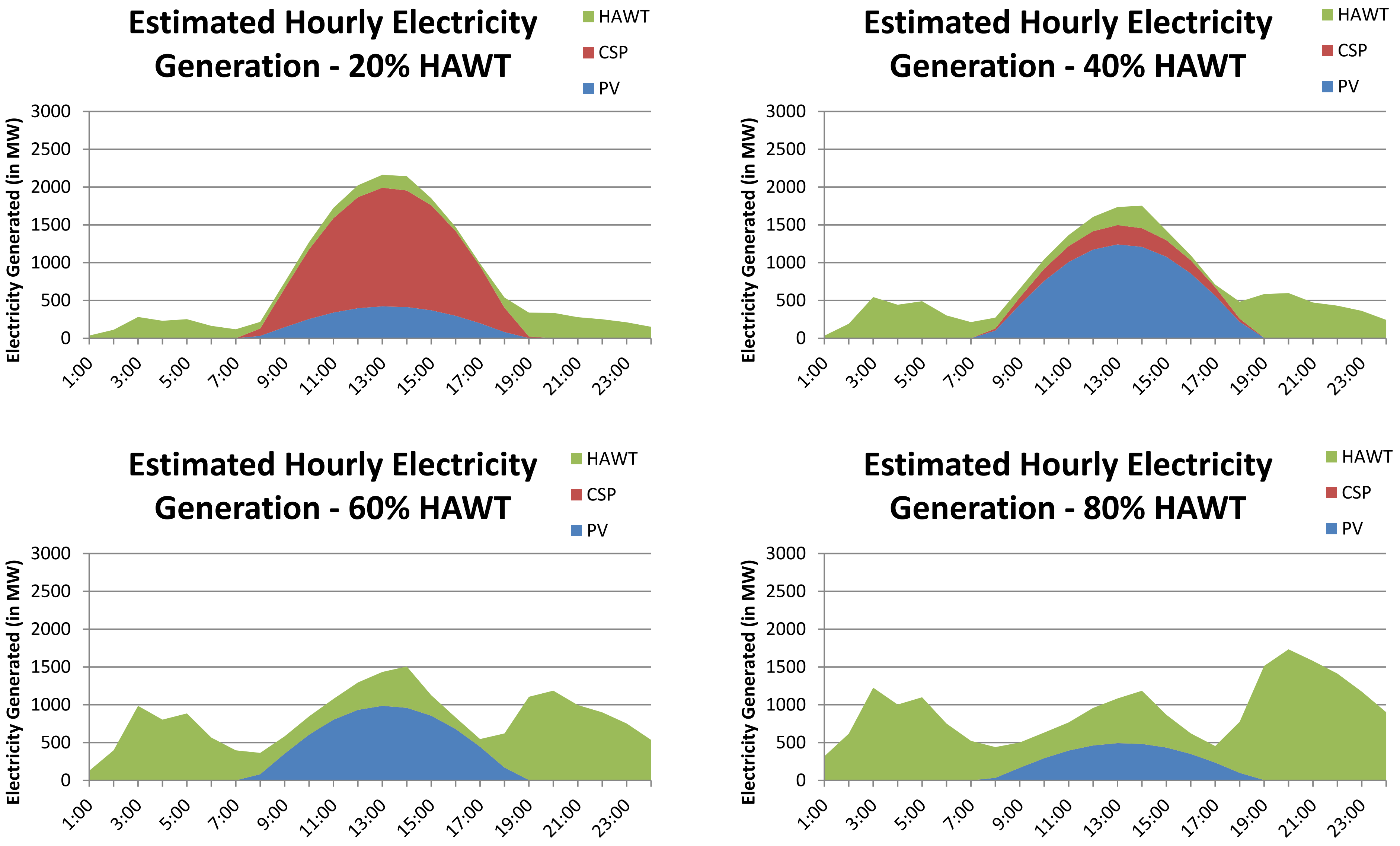


Figure 26: Estimated hour generation by proposed technology portfolio based on data recorded on 2/10/2010

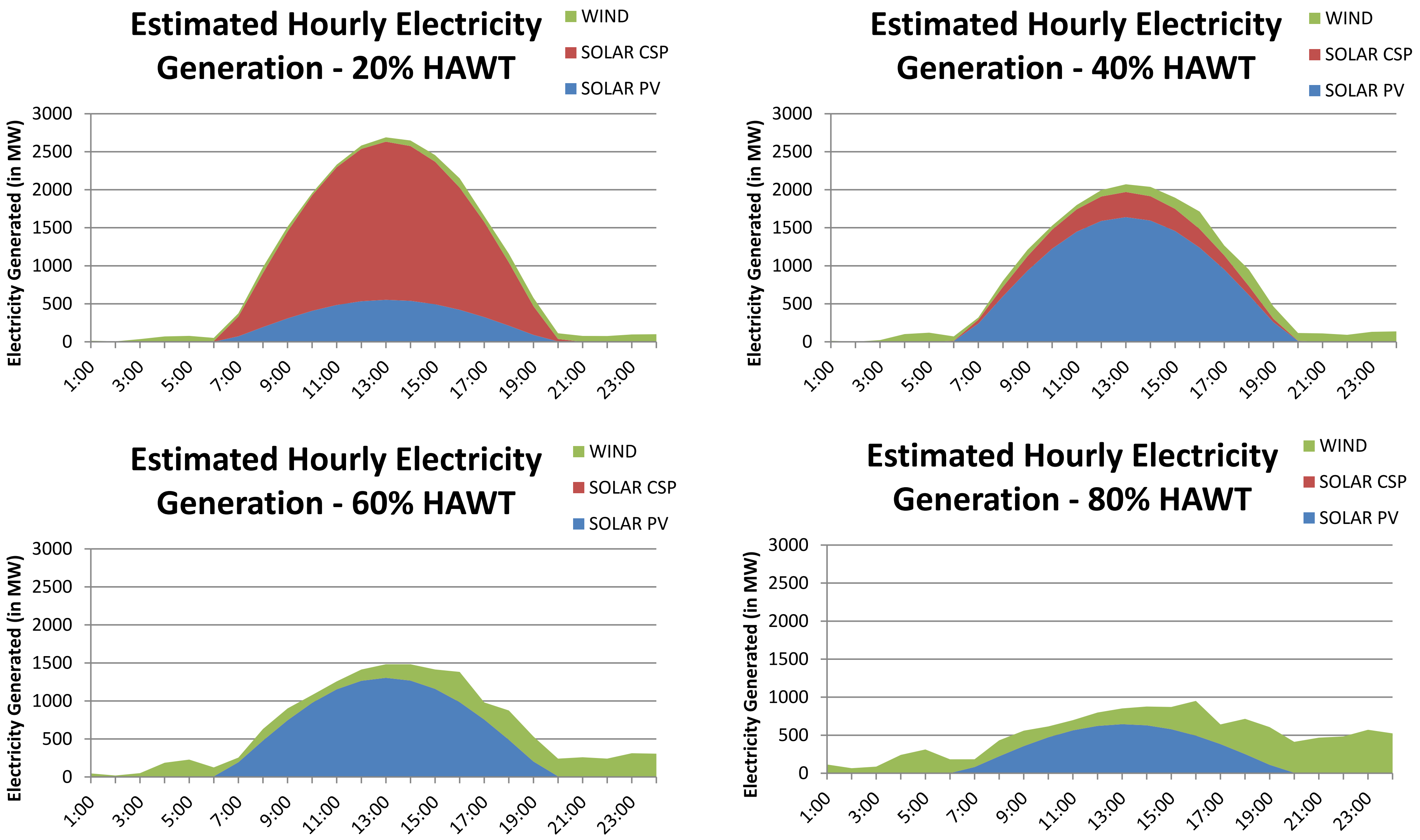


Figure 27: Estimated hour generation by proposed technology portfolio based on data recorded on 8/10/2010

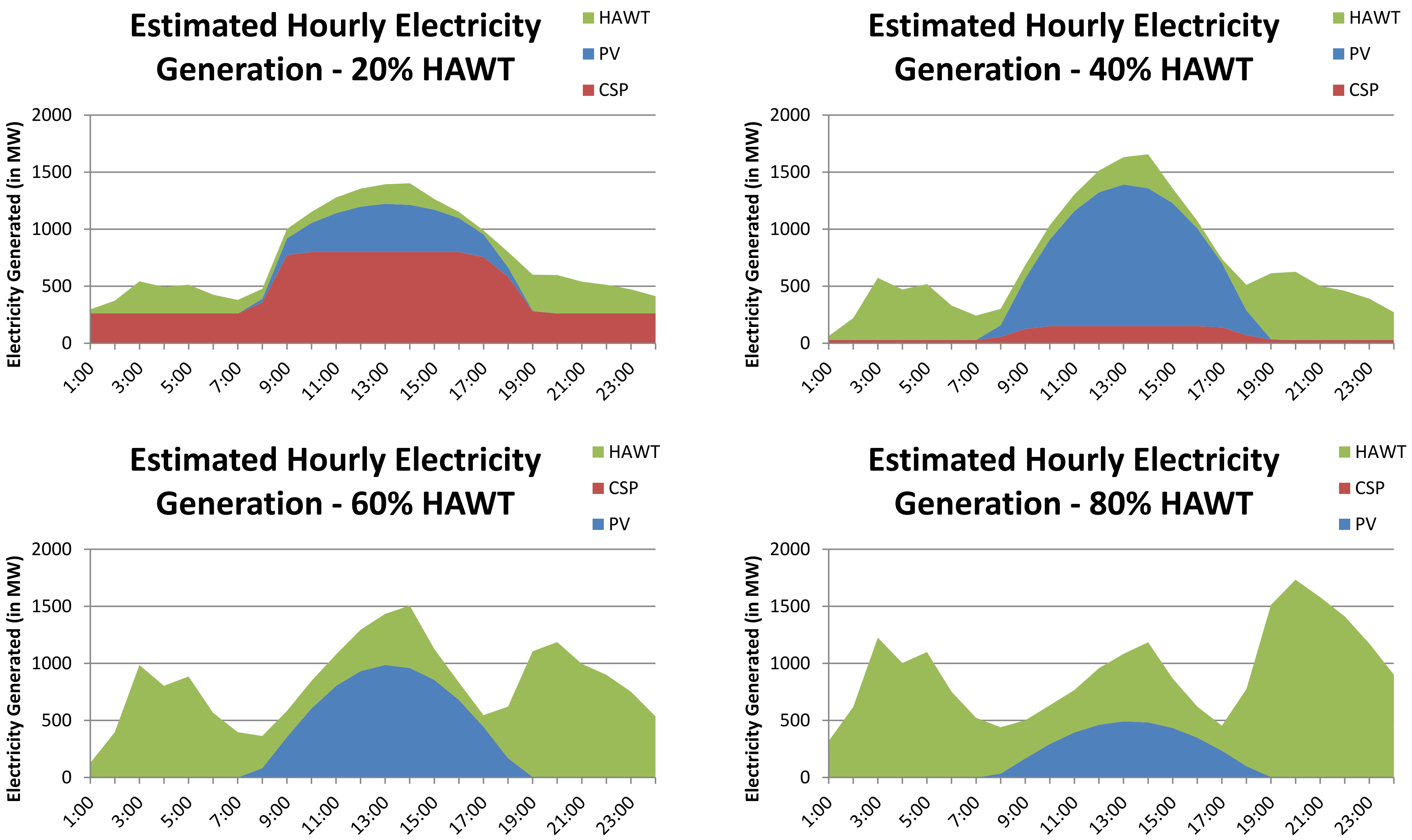


Figure 28: Estimated hour generation by proposed technology portfolio with CSP thermal storage based on data recorded on 2/10/2010

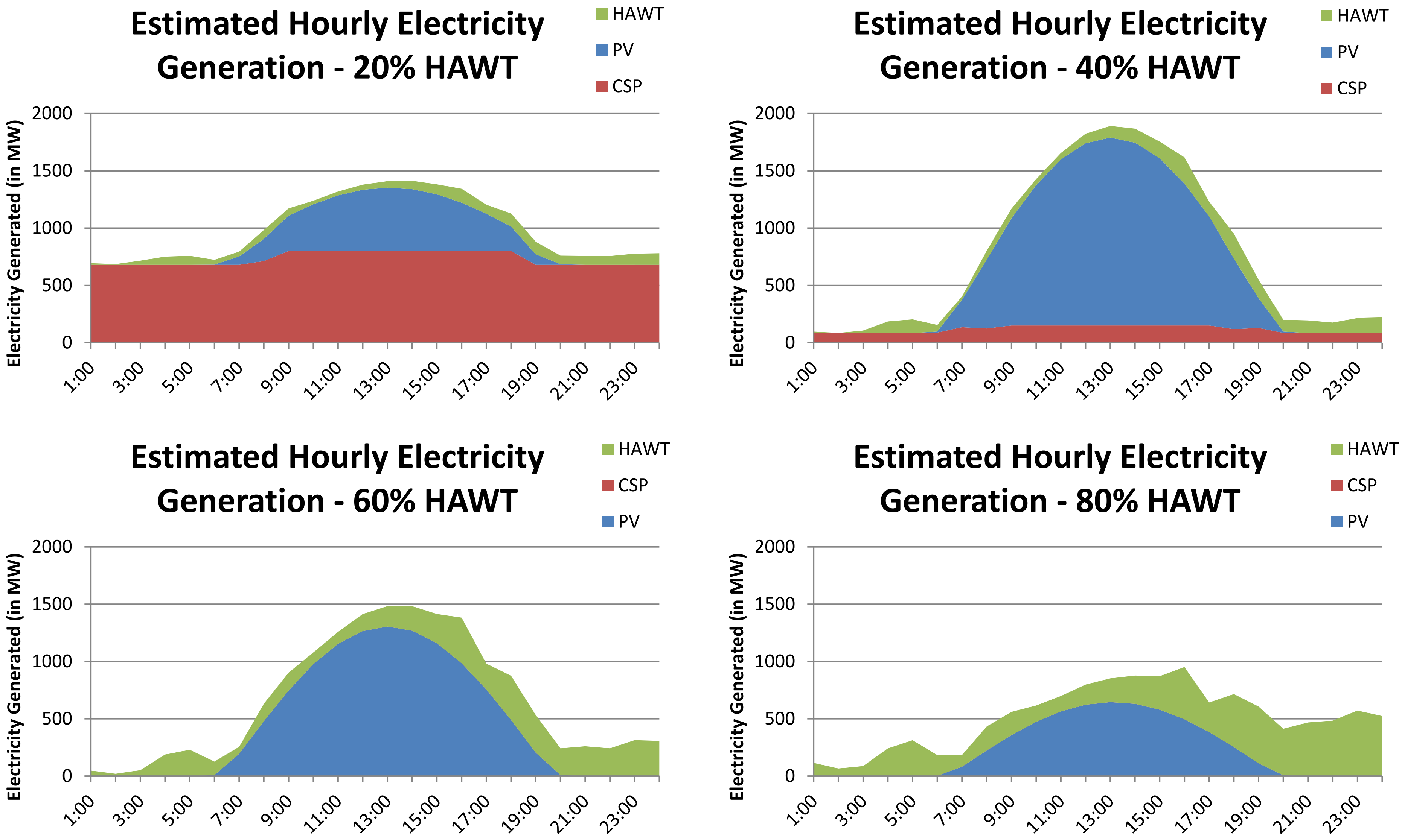


Figure 29: Estimated hourly generation by proposed technologies portfolios with CSP thermal storage using solar and wind data from 8/10/2010

6. Conclusions

- This work focuses on water demand for power generation with renewable energy technologies. This aspect is usually ignored in analyses of renewable energy use.
- We show that the explicit consideration of water demands for power generation using renewable energy technologies will affect the technology portfolio under consideration.
- We developed a water-energy optimization model that utilizes mixed integer linear program to minimize water requirements for electricity generation by changing the selected technology distribution.
- The model is generally applicable at different granularities for any locations and technologies with the appropriate input data.
- With our model, we replace the generation capacity of an existing coal-fired power plant in Texas with three potential alternative technologies: solar photovoltaic (PV) panels, concentrated solar power (CSP), and horizontal axis wind turbines (HAWT). This is done for 3 case studies:
    - Without constraints on land use
    - Limited by actual available land (near the retiring coal power plant)
    - In comparison to an equivalent size gas powered plant
- Our results indicate that water savings over the existing needs of the retiring plant were possible in all but three scenarios.
    - Without land constraints, water savings were a minimum of 93% with CSP restricted to dry cooling only, 65% savings with hybrid CSP cooling only, and 20% with wet CSP cooling.
    - With finite land availability, water savings calculated were a minimum of 73% with CSP restricted to dry cooling only, 67% savings with hybrid CSP cooling only, and 25% with wet CSP cooling.

  - Given a comparison to a gas fired plant of equivalent size, water savings for cases limited to dry CSP cooling and hybrid CSP cooling were a minimum of 56% and 41% respectively. Portfolios restricted to wet CSP cooling require a minimum of 20% HAWT generation to maintain water savings. Showing that renewable portfolios could use more water than existing gas technologies.
- The scenarios assessed in this research concentrated on one particular question regarding technological options for electricity generation: the sensitivity of water requirements in regards to renewable electricity generation technology distribution.
  - Problems such as meeting hourly demand-side changes or satisfying base load vs. peak load generation were not considered as quantified scenarios.
  - While background research has supported that the scenarios considered here are feasible, we do not explicitly address the feasibility of each technology distribution or limit the possible scenario solutions proposed within the model.
  - Future work could include a more robust demand constraint within the model, to examine daily or hourly electricity demand.
- Comparison of calculated land use with the model with data calculated for existing models show good agreement with anticipated land requirements per MW of generated electricity.
- The results of this work show power generation and water use should be considered together when considering technology alternatives for next generation power production.

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Appendix A: Solar data macro

```
Sub SolarData()

Locations = Worksheets("Optimization Model").Cells(1, 2)

iRow = Locations + 3
Sheets("Optimization Model").Activate
bestyet = 10000000000#

For i = 4 To iRow

    For j = 4 To 92

    xnaught = Worksheets("Optimization Model").Cells(i, 2)
    ynaught = Worksheets("Optimization Model").Cells(i, 3)
    xone = Worksheets("Solar Data").Cells(j, 3)
    yone = Worksheets("Solar Data").Cells(j, 4)

    distance = ((xnaught - xone) ^ 2 + (ynaught - yone) ^ 2) ^ (1 / 2)
    If distance < bestyet Then bestyet = distance
    If distance = bestyet Then bestrow = j

    Next

bestyet = 10000000000#

Worksheets("Optimization Model").Cells(i, 4) = Worksheets("Solar Data").Cells(bestrow, 5)

Worksheets("Optimization Model").Cells(i, 25) = bestrow

Next

MsgBox "Solar Data for " & Locations & " Locations Updated"

End Sub
```

Appendix B: Wind data macro

```
Sub WindData()

Locations = Worksheets("Optimization Model").Cells(1, 2)

iRow = Locations + 3
Sheets("Optimization Model").Activate
bestyet = 10000000000#

For i = 4 To iRow

    For j = 4 To 43

    xnaught = Worksheets("Optimization Model").Cells(i, 2)
    ynaught = Worksheets("Optimization Model").Cells(i, 3)
    xone = Worksheets("Wind Data").Cells(j, 5)
    yone = Worksheets("Wind Data").Cells(j, 6)

    distance = ((xnaught - xone) ^ 2 + (ynaught - yone) ^ 2) ^ (1 / 2)
    If distance < bestyet Then bestyet = distance
    If distance = bestyet Then bestrow = j

    Next

bestyet = 10000000000#

Worksheets("Optimization Model").Cells(i, 5) = Worksheets("Wind Data").Cells(bestrow, 13)

Worksheets("Optimization Model").Cells(i, 26) = bestrow

Next

MsgBox "Wind Data for " & Locations & " Locations Updated"

End Sub
```

Appendix C: Solar data

					Daily Average	
#	Name	Lat	Long	ETR (Wh/m^2)	ETRN (Wh/m^2)	Glo Mod (Wh/m^2)
690190	Abilene Dyess AFB	32.433	-99.85	359.2160959	688.9765982	210.1660959
722410	Port Arthur Jefferson County	29.95	-94.017	367.664992	688.9705412	193.5529801
722416	New Braunfels	29.717	-98.05	368.3335616	688.8592466	196.7208904
722420	Galveston/Scholes	29.3	-94.8	369.6730594	688.7901826	197.8681507
722427	Houston/Clover Fld	29.517	-95.233	368.981621	688.8546804	192.8449772
722429	Houston/D.W. Hooks	30.067	-95.55	367.1992009	688.8396119	190.8622146
722430	Houston Bush Intercontinental	30	-95.367	367.4182648	688.8681507	190.2017123
722435	Houston William P Hobby AP	29.65	-95.283	368.5513699	688.8391553	192.3513699
722436	Houston Ellington AFB [Clear Lake - UT]	29.57	-95.09	368.8086758	688.8219178	193.8199772
722444	Montgomery Co	30.35	-95.417	366.2745434	688.8730594	192.5015982
722445	College Station Easterwood Fl	30.583	-96.367	365.5021689	688.8563927	194.9372146
722446	Lufkin Angelina Co	31.233	-94.75	363.3273973	688.9099315	196.3652968
722447	Longview Gregg County AP	32.383	-94.717	359.3885845	689.0054795	195.4947489
722448	Tyler/Pounds Fld	32.35	-95.4	359.5055936	688.981621	197.4641553
722469	Corsicana	32.033	-96.4	360.5990868	688.9747717	197.9563927
722470	Longview Gregg County AP [Overton - UT]	32.29	-94.98	359.7125571	688.9772831	197.7384703
722479	Arlington	32.667	-97.1	358.3980594	689.0170091	198.3287671
722489	Terrell	32.717	-96.267	358.2242009	688.9878995	193.6160959
722499	Nacogdoches (AWOS)	31.583	-94.717	362.1449772	688.9559361	195.635274
722500	Brownsville S Padre Isl Intl	25.9	-97.433	379.9687215	688.5884703	201.761758
722505	Harlingen Rio Grande Valley I	26.233	-97.65	379.0155251	688.6334475	201.825
722506	McAllen Miller Intl AP [Edinburg - UT]	26.31	-98.17	378.7914384	688.6291096	207.0173516
722508	Port Isabel/Cameron	26.15	-97.213	379.2539954	688.6151826	207.7357306

				Daily Average		
#	Name	Lat	Long	ETR (Wh/m^2)	ETRN (Wh/m^2)	Glo Mod (Wh/m^2)
722510	Corpus Christi Intl Arpt [UT]	27.88	-97.63	374.1076484	688.6859589	201.6610731
722515	Corpus Christi NAS	27.683	-97.283	374.7130137	688.7214612	207.353653
722516	Kingsville	27.5	-97.817	375.2660959	688.6848174	200.0600457
722517	Alice Intl AP	27.733	-98.033	374.5621005	688.7059361	200.0504566
722520	Laredo Intl AP [UT]	27.57	-99.49	375.0547945	688.6940639	215.2697489
722523	San Antonio/Stinson	29.333	-98.467	369.5746575	688.8146119	199.6853881
722524	Rockport/Aransas Co	28.083	-97.05	373.4865297	688.721347	205.0902968
722526	Cotulla FAA AP	28.45	-99.217	372.352968	688.7550228	208.5777397
722527	Angleton/Lake Jacks	29.117	-95.467	370.2561644	688.8019406	190.6215753
722530	San Antonio Intl AP	29.533	-98.467	368.9280822	688.8229452	197.5938356
722533	Hondo Municipal AP	29.367	-99.167	369.4607306	688.7739726	199.6930365
722535	San Antonio Kelly Field AFB	29.383	-98.583	369.4128995	688.7937215	199.3324201
722536	Randolph AFB	29.533	-98.283	368.9311644	688.8027397	199.3405251
722537	Kerrville Municipal	29.983	-99.083	367.4702055	688.8111872	200.4073059
722539	San Marcos Muni	29.883	-97.867	367.7976027	688.8539954	198.6317352
722540	Austin Mueller Municipal AP [UT]	30.29	-97.74	366.4703196	688.8747717	198.3850457
722544	Camp Mabry	30.317	-97.767	366.3796804	688.866895	196.3863014
722545	Bergstrom AFB/Austi	30.2	-97.683	366.7623288	688.8369863	196.3958904
722546	San Marcos Gary AFB	29.883	-97.867	367.7976027	688.8539954	198.6317352
722547	Georgetown (AWOS)	30.683	-97.683	365.1689498	688.8737443	198.5546804
722550	Victoria Regional AP	28.867	-96.933	371.0522831	688.7490868	192.6325342
722552	Gainesville	33.65	-97.2	354.9070776	689.0684932	196.4229452
722553	Brenham	30.217	-96.367	366.70879	688.8321918	194.3673516
722554	Lagrange	29.9	-96.95	367.7454338	688.8571918	195.5543379
722555	Palacios Municipal AP	28.717	-96.25	371.5178082	688.7649543	198.3304795
722560	Waco Regional AP	31.617	-97.233	362.0239726	688.9252283	201.5691781
722563	McGregor (AWOS)	31.483	-97.317	362.4850457	688.9513699	200.7328767

					Daily Average	
#	Name	Lat	Long	ETR (Wh/m^2)	ETRN (Wh/m^2)	Glo Mod (Wh/m^2)
722570	Fort Hood	31.133	-97.717	363.6652968	688.9110731	201.3850457
722575	Killeen Muni (AWOS)	31.083	-97.683	363.8323059	688.8711187	199.7770548
722576	Robert Gray AAF	31.067	-97.833	363.8848174	688.9186073	199.1452055
722577	Draughon Miller Cen	31.15	-97.4	363.6030822	688.9013699	199.052968
722583	Dallas Love Field	32.85	-96.85	357.752968	689.0284247	195.8257991
722585	Dallas Hensley Field NAS	32.733	-96.967	358.1695205	689.0197489	196.8271689
722587	Cox Fld	33.633	-95.45	354.9688356	689.0762557	192.2438356
722588	Greenville/Majors	33.067	-96.067	356.990411	689.033105	193.8406393
722589	Denton (ASOS)	33.2	-97.183	356.5155251	689.0380137	196.948516
722590	Dallas-Fort Worth Intl AP	32.9	-97.017	357.5800228	688.9998858	196.1834475
722593	Dfw NEXRAD	32.567	-97.3	358.7461187	688.9899543	200.5557078
722594	Fort Worth Alliance	32.983	-97.317	357.2877854	689.0178082	198.2694064
722595	Fort Worth NAS	32.767	-97.45	358.0444064	688.9950913	199.9134703
722596	Fort Worth Meacham	32.817	-97.367	357.8742009	689.0303653	198.5692922
722597	Mineral Wells Municipal AP	32.783	-98.067	357.989726	689.0077626	201.7070776
722598	Dallas/Addison Arpt	32.967	-96.833	357.3401826	689.0207763	196.5914384
722599	Dallas/Redbird Arpt	32.683	-96.867	358.3421233	689.036758	195.5734018
722600	Stephenville Clark Field	32.217	-98.183	359.9603881	688.96621	204.3544521
722610	Del Rio [UT]	29.38	-100.91	369.415411	688.7783105	210.426484
722615	Del Rio Laughlin AFB	29.367	-100.783	369.461758	688.7742009	207.2389269
722618	Fort Stockton Pecos	30.917	-102.9	364.3877854	688.9378995	235.9577626
722620	Pine Springs Guadalupe Mounta	31.833	-104.817	361.290411	688.9605023	240.2021689
722630	San Angelo Mathis Field	31.35	-100.5	362.9373288	688.9323059	212.1738584
722636	Dalhart Municipal AP	36.017	-102.55	346.1699772	689.2687215	218.8888128
722640	Marfa AP	30.367	-104.017	366.2140411	688.8691781	239.8218037

#	Name	Lat	Long	Daily Average ETR (Wh/m^2)	ETRN (Wh/m^2)	Glo Mod (Wh/m^2)
722648	Odessa-Schlemeyer F	31.917	-102.383	360.9995434	688.9589041	223.5608447
722650	Midland International AP	31.95	-102.183	360.8841324	688.9631279	220.2923516
722656	Wink Winkler County AP	31.783	-103.2	361.4589041	688.9363014	230.6278539
722660	Abilene Regional AP [UT]	32.47	-99.71	359.0850457	689.0085616	211.7907534
722666	Brownwood Municipal	31.8	-98.95	361.4007991	688.9336758	207.3665525
722670	Lubbock International AP	33.667	-101.817	354.8474886	689.0872146	216.2143836
722673	Sherman-Denison	33.717	-96.667	354.671347	689.0599315	194.2438356
722675	Reese AFB	33.6	-102.05	355.091895	689.0731735	216.311758
722700	El Paso International AP [UT]	31.77	-106.5	361.5026256	688.9307078	241.8437215
723510	Wichita Falls Municipal Arpt	33.983	-98.5	353.7107306	689.1037671	202.871347
723604	Childress Municipal AP	34.433	-100.283	352.071347	689.1490868	208.3085616
723630	Amarillo International AP [Canyon - UT]	34.99	-101.9	350.0207763	689.1802511	214.7108447
723635	Borger/Hutchinson	35.7	-101.4	347.3738584	689.2765982	212.6623288
747400	Junction Kimble County AP	30.517	-99.767	365.7194064	688.8818493	209.3490868

Appendix D: Wind data

				Mean Wind Speed (m/s) and Wind Power Density (Watt/m2)									
				Annual		Winter		Spring		Summer		Autumn	
Station Name	Lat	Long	Elevation	Speed	Power	Speed	Power	Speed	Power	Speed	Power	Speed	Power
ABILENE	32.3	-99.41	537	5.8	209	6.1	253	6.6	284	5.5	148	5.2	158
ABILENE	32.3	-99.41	537	5.7	195	5.8	229	6.5	259	5.4	136	5.3	156
ABILENE	32.3	-99.41	537	5	148	5.2	162	5.6	191	4.5	99	4.6	122
ABILENE	32.3	-99.41	537	5.2	134	5.2	146	5.9	183	4.9	100	4.7	108
ABILENE/DYESS	32.3	-99.51	542	3.6	66	3.7	70#	4.5	111#	3.3	41#	3.2	46#
ABILENE/DYESS	32.3	-99.51	542	3.9	80	3.8	89#	4.5	116#	3.7	59#	3.4	59#
ALICE	27.4	-98.02	55	4.9	146	4.6	126	5.7	200	5.3	176	4	87
AMARILLO	35.1	-101.4	1099	6	210	6	235	6.7	283	5.6	150	5.6	177
AMARILLO	35.1	-101.4	1099	5.5	156	5.6	173	6	209	4.9	98	5.3	136
AMARILLO	35.1	-101.4	1099	6.2	216	6.1	221	7	298	6	168	5.9	179
AUSTIN	30.2	-97.42	183	4.4	100	4.5	118	4.8	123	4.2	73	4	86
AUSTIN	30.2	-97.42	183	4.2	83	4.2	90	4.8	114	4	61	3.7	64
AUSTIN	30.2	-97.42	183	4.1	80	4.4	109	4.6	100	3.7	49	3.7	65
AUSTIN/BERGS.	30.1	-97.4	155	5.1	175	5.7	237	5.4	203	4.8	134	4.4	136
AUSTIN/BERGS.	30.1	-97.4	155	3.5	70	3.6	82	4.1	98	3.2	46#	3	55
AUSTIN/BERGS.	30.1	-97.4	155	3.3	65	3.4	77#	4	87#	3.3	51#	2.8	46#
BEEVILLE	28.2	-97.4	62	4	84	4.1	93	4.5	110	3.9	74	3.6	63
BEEVILLE	28.2	-97.4	62	3.4	65	3.4	67	4.3	98	3.2	52	2.8	41
BEEVILLE	28.2	-97.4	62	3.5	63	3.7	77	4.1	88	3.1	45	3	42
BIG SPRINGS	32.1	-101.3	784	5.3	157	5.1	151	6	213	5.4	139	4.8	118
BIG SPRINGS	32.1	-101.3	784	4.7	116	4.4	112#	5.5	167#	4.6	94#	4.2	92#
BIG SPRINGS	32.1	-101.3	773	5.4	166	5.4	182	6.2	248	5.2	131	4.8	127
BIG SPRINGS	32.1	-101.3	773	6.2	230	6	231	7.1	322	6.2	197	5.6	167
BROWNSVILLE	25.5	-97.26	10	5.4	178	5.4	184	6.3	253	5.3	160	4.6	120
BROWNSVILLE	25.5	-97.26	10	5.5	177	5.4	170	6.5	250	5.5	164	4.8	121

				Mean Wind Speed (m/s) and Wind Power Density (Watt/m2)									
				Annual		Winter		Spring		Summer		Autumn	
Station Name	Lat	Long	Elevation	Speed	Power	Speed	Power	Speed	Power	Speed	Power	Speed	Power
BROWNSVILLE	25.5	-97.26	10	5	144	5	146	5.9	208	4.8	123	4.2	100
BRYAN	30.4	-96.28	81	3.6	67	3.8	83	4.2	95	3.3	41	3.2	55
BRYAN	30.4	-96.33	84	3.3	56	3.6	75	3.6	71	3	35	2.8	39
CHILDRESS	34.3	-100.2	596	4.5	114	4.5	110	5.5	196	4.2	73	4	81
CHILDRESS	34.3	-100.2	596	5.2	161	5.2	169	6	249	5	122	4.7	115
CLARENDON	34.6	-100.6	874	6.1	237	6.2	258	6.7	315	5.3	124	5.9	234
COLLEGE STA.	30.4	-96.22	97	4.1	93	4.7	146	4.3	102	3.8	62	3.6	68
CORPUS CHRISTI	27.5	-97.24	14	5.5	191	5.8	221	6.4	260	5.4	166	4.6	123
CORPUS CHRISTI	27.5	-97.24	14	5	138	4.8	133	5.6	179	4.9	124	4.5	112
CORPUS CHRISTI	27.5	-97.3	17	5.4	167	5.5	178	6.3	230	5	131	4.8	129
CORPUS CHRISTI	27.4	-97.17	6	6.4	250	6.1	239	7.2	328	6.5	235	5.7	191
CORPUS CHRISTI	27.4	-97.17	6	4.9	130	4.8	133	5.6	162	4.9	116	4.5	112
CORPUS CHRISTI	27.4	-97.17	6	4.7	117	4.5	124	5.4	153	4.5	94	4.3	98
CORPUS CHRISTI	27.4	-97.27	14	6.4	282	6.4	298	7.2	374	6.3	255	5.6	197
COTULLA	28.3	-99.13	141	4.2	94	3.6	72	4.9	132	4.9	117	3.5	60