ERCOT Solar Generation Patterns

Project Summary Report

March 8, 2013

URS

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Project Overview

In order to better understand the potential implications of widespread installation of solar electricity generation capacity across Texas and assist in long-range planning efforts, ERCOT requires detailed estimates related to the magnitude and timing of electricity production from potential solar installations of different sizes, technologies, and geographical locations. Using 20 years of historical meteorological and solar radiation data (1991-2010), URS utilized specialized modeling software to generate 20 years of estimated hour-by-hour electricity output for four solar technologies in each of the 254 counties in Texas. The resulting database provides a robust tool by which ERCOT can incorporate different solar deployment scenarios into its existing models.

The project was divided into five Tasks:

- **Task 1: Data Collection**
  - Collection of historical meteorological and solar radiation data for Texas
  - Conversion of data into format compatible with modeling software
- **Task 2: Model Development**
  - Configuration of individual models for four solar technologies: fixed tilt crystalline (1 MW), single-axis tracker (1MW), concentrating solar power (50MW), and rooftop residential (5 kW).
  - Group each of the 254 Texas counties with a Class I or Class II weather station based on proximity, solar radiation profile, elevation, and other factors.
- **Task 3: Run model simulations**
  - Feed raw meteorological and solar radiation data through the configured models to produce hour-by-hour DC and AC production estimates for the years 1991-2010, plus a single "typical meteorological year (TMY)" for each raw dataset.
  - With 34 weather stations included in the analysis and each weather station having 20 years of data plus a TMY year, the result of Task 3 is 2,856 (43 * 21 * 4) individual data files each representing a full year of hourly electricity production estimates based on the configuration of the associated technology.
- **Task 4: Sensitivity and Uncertainty Analysis**
  - QA/QC of the produced data
  - Variance analysis through comparison of results using nearby weather station data
  - Statistical variability calculations for a sampling of sites
- **Task 5: Prepare Final Report and Presentation**

This report describes the processes and methodologies used in collecting and generating the data and summarizes the results of the final production model data output. It is organized into four sections:

- 1: Solar Radiation & Meteorological Data
- 2: Extrapolation of Weather Station Data
- 3: Solar Production Modeling
- 4: Statistical Analysis

1: Solar Radiation & Meteorological Data

URS collected both historic and typical weather and solar radiation data for weather stations across Texas to use as inputs to the solar models. The historical weather data was obtained in the National Climatic Data Center (NCDC) format and the typical year data was obtained in the TMY3 format. Both of these sets of weather data are part of the 1991-2010 National Solar Radiation Database (NSRDB) and were downloaded from the US Department of Energy National Renewable Energy Laboratory (NREL) website. The NSRDB 1991-2010 update contains 20 years of historical weather data for a total of 89 weather stations across Texas. URS downloaded all available historical data for Texas and data from four additional stations in adjacent states. TMY3 data developed as part of the NSRDB 1991-2010 update was available for 61 of the weather stations in Texas and all four of the stations in neighboring states. URS created a directory for each of the historical NSRDB weather stations following the naming convention, “Station_Name-USAFStationIdentifer” within the directories “NSRDB Historical Weather Files” and “NSRDB Historical Weather Files-notInTX”. Similarly, URS created directories for each of the typical year weather stations, which are a subset of the NSRDB stations, following the naming convention, “Station_Name-USAFStationIdentifer-StationQualityClassification” within the “TMY3 Files” and the “TMY3 Files-notInTX” directories.

The collected weather data contains records of the ambient conditions for each hour of the year. The solar radiation data and ambient conditions data are the primary drivers of the energy production models. The energy production models are most sensitive to the selection of parameters within the weather data files that are presented in Table 1. The highlighted rows distinguish weather data input values with particular influence on energy production models of photovoltaic (PV) and concentrating solar power (CSP) electricity generating systems. Some psychrometric parameters not included as raw data in the weather input files are calculated by the energy production model from the available parameters when necessary.

Table 1: Typical Required Weather Data for Solar Simulations

Entry	Units
Dry-bulb temperature	°C
Dew-point temperature	°C
Relative humidity	%
Wind speed	m/s
Wind direction	deg
Atmospheric pressure	mbar
Global horizontal radiation	W/m²
Direct normal radiation	W/m²
Direct horizontal radiation	W/m²

Source: System Advisory Model (SAM) Weather Data Documentation- 12/7/2011

National Solar Radiation Database (NSRDB)

The 1991-2010 National Solar Radiation Database is a collection of measured and modeled solar radiation data with accompanying meteorological fields for a period of 20 years for weather stations across the United States. The current NSRDB data set is an update to a dataset for 1991-2005, which was released in 2007. The most current dataset (1991-2010) was released in 2012.

The NSRDB data is almost entirely composed of data generated by the NREL Meteorological-Statistical Model (METSTAT). NREL used ground-based measurements of weather data from the weather stations included in the NSRDB dataset as inputs to the METSTAT model to produce values for the ground-level solar radiation. NREL used actual measured ground radiation, available for a limited number of sites, to validate the METSTAT model. When available, the measured data is included in the NSRDB data files in addition to the modeled ground level radiation data. No additional measured solar data beyond 2005 were included in the 1991-2010 update.

NREL's objective was to produce the 1991-2010 NSRDB as a serially complete dataset for the entire period of record. To accomplish this goal NREL employed four levels of data-filling methods. These are short-term interpolation, up to 5 hour gaps and gaps at night; medium-term filling, gaps up to 24 hours; long-term filling, gaps up to 1 year; last-ditch filling, gaps greater than a year. NREL used the quantity of data filling required to produce a serially complete dataset as a contributing factor when determining the uncertainty of the NSRDB dataset. The results of the uncertainty analysis contribute to the classification of a weather station as Class I, Class II, or Class III.[1]

The NCDC provided all of the meteorological data used to input the NSRDB dataset. The University of Texas Solar Energy Laboratory, University of Oregon Solar Radiation Monitoring laboratory network, and other similar radiation monitoring networks provided the ground-level solar radiation measurements.

The 1991-2010 NSRDB dataset is available in multiple formats from different sources. URS has downloaded data in the (NCDC) format from the NREL website.[2]

For a complete list of the fields in the NCDC formatted 1991-2010 NSRDB dataset and an in depth description of data sources and the data production methodology please refer to the *National Solar Radiation Database 1991-2010 Update: User's Manual*.[3]

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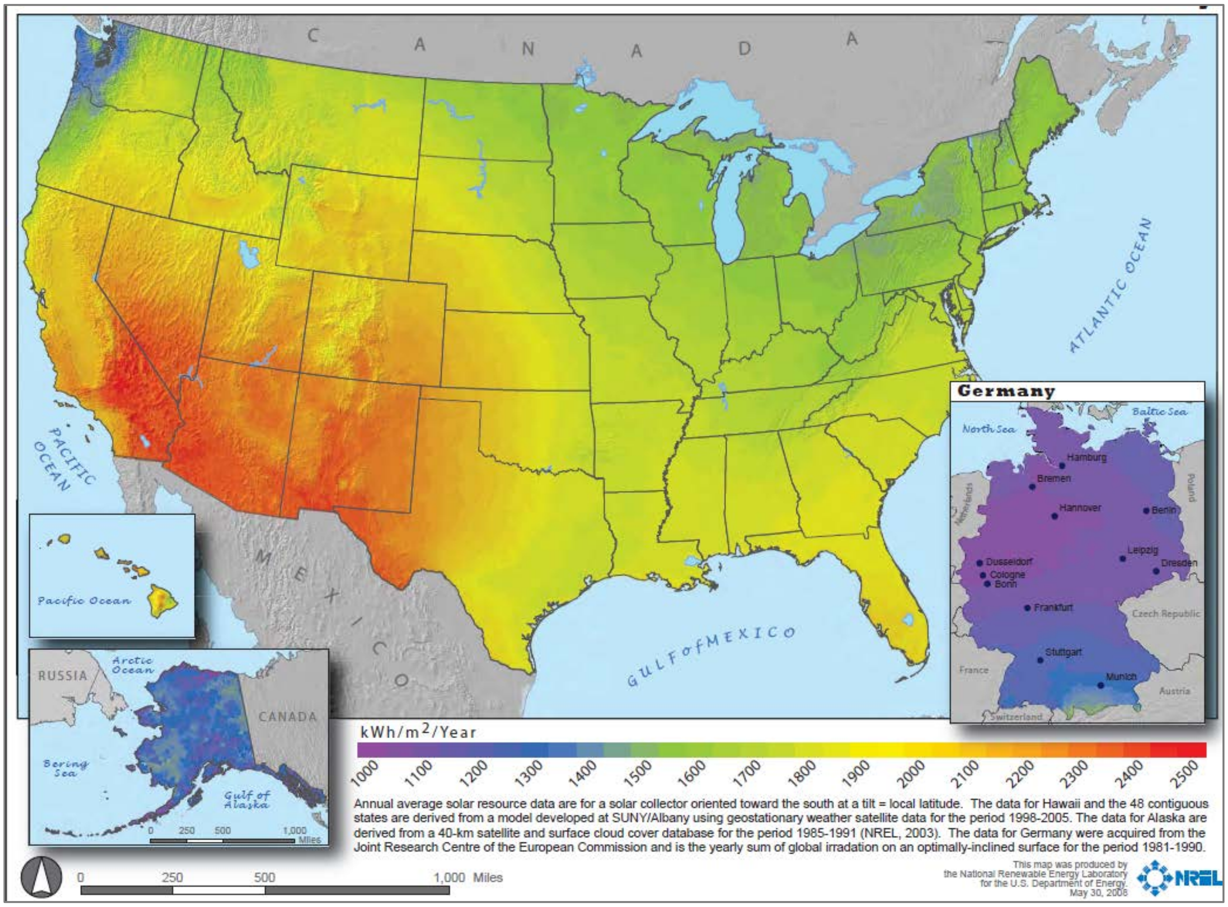
[1] National Solar Radiation Database 1991-2010 Update: User's Manual, Stephen Wilcox, 2010, p. 50-51. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/#doc

[2] "Distribution of the NSRDB is authorized through the National Climatic Data Center (NCDC), which has experienced some ingest and cataloging delays for the updated NSRDB. To expedite release of this data set to users, NREL has received temporary authorization for distribution of all NSRDB products." http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/

[3] National Solar Radiation Database 1991-2010 Update: User's Manual, Stephen Wilcox, 2010, http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/#doc

Figure 1: Photovoltaic Solar Resource in US and Germany



Source: US DOE, National Renewable Energy Laboratory

Typical Meteorological Year (TMY)

A typical meteorological year (TMY) dataset provides hourly values of solar and weather data for a year, which typify the conditions of a particular geographic location for a significant period of time. The TMY3 data that URS downloaded and used as inputs for the solar energy production models is based on data produced by the 1961-1990 NSRDB, Version 1.1 and the 1991-2005 NSRDB update.[4]

The TMY3 datasets are created using a modified procedure first developed by Sandia National Laboratories. The procedure to create the TMY3 dataset compares months based on 10 daily indices. These indices are the Max Dry Bulb Temperature, Min Dry Bulb Temperature, Mean Dry Bulb Temperature, Max Dew Point Temperature, Min Dew Point Temperature, Mean Dew Point Temperature, Max Wind Velocity, Mean Wind Velocity, Global Radiation, and Direct Radiation. The TMY3 process selects the historical month with values for these indices most closely matching the

[4] User's Manual for TMY3 Data Sets, S. Wilcox and W. Marion, May 2008, p.1, http://www.nrel.gov/docs/fy08osti/43156.pdf.

typical values of the entire time period with available data. Where discontinuities are created between months due to this process, they are smoothed for 6 hours on each side.[5]

The resulting TMY dataset contains time-series meteorological measurements and modeled solar values representing typical years for each hour of the year. Building designers are the most frequent users of these TMY files. The TMY format provides a useful input to models of building physics that can assist in sizing building mechanical systems for typical weather. As an input to solar energy production models, TMY files produce an estimate for the solar energy produced in a typical year. However, energy production models produced with TMY input files do not account for year-to-year fluctuations in the solar resource caused by volcanic eruptions, El Niño and La Niña cycles, and sun spot cycles.[6]

Data Format Conversion

URS used the NREL System Advisor Model (SAM) to model the four solar technologies and generate annual estimates of their energy production. SAM reads weather data files that are in the TMY2, TMY3 or the EPW format. The NCDC-formatted NSRDB data was converted to the TMY3 format for use as an input to SAM. The conversion process was automated using Bash shell scripts and Unix programming languages, including AWK and SED.

URS developed a script to automate the process of converting each of the 1,860 (20 years for each of the 93 weather stations) annual weather data files from the NCDC NSRDB format to the TMY3 format. Each of the NSRDB formatted historical weather files is named with the convention "NSRDB_StationData_*yyyymmdd_yyyymmdd_USAFStationIdentifier*.csv", where the first date is the first day of record and the second date is the last day of record. The *USAFStationNumber* is the United States Air Force Station Identifier. The weather file format conversion script produces a file with the same name, but the file extension ".tm3". *Please note that although the extension assigned to the converted NSRDB historical weather files is the same as the TMY3 files, the converted file* <u>*is not a typical year file*</u>. The ".tm3" file extension is used to denote that the converted weather file is in the same format as the typical year file.

The conversion process reformats the date and time stamp to the TMY3 format and reorders the fields (columns) in the NCDC formatted NSRDB data to match the TMY3 fields. The conversion process includes measured solar radiation data in the converted file when available. The TMY3 file format contains 68 fields while the NCDC NSRDB data format contains only 49 fields. Fields present in the TMY3 file for which no data was available in the NSRDB data where filled with a value of "-9900" indicating a missing value. A table of the conversion process which shows the field labels for both file formats is included in Appendix I. Due to the differences in the conventions used for fields indicating the source of the data, many of these fields are filled with the TMY3 flags for missing data. Similarly, some of the uncertainty fields are filled with the TMY3 flag for undefinable uncertainty. Where available uncertainties provided as percentages were carried through the conversion process. In part to maintain a record of these flags the conversion process generates a report file for each weather file converted. The report file contains 6 header rows above the weather data in the TMY3 format, but with the original NSRDB source and uncertainty flags. The header rows provide a summary 'map' to the conversion process. The report files follow the naming convention,

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[5] User's Manual for TMY3 Data Sets, S. Wilcox and W. Marion, May 2008, http://www.nrel.gov/docs/fy08osti/43156.pdf.

[6] P50/P90 Analysis for Solar Energy Systems Using the System Advisor Model, A. Dobos, P. Gilman, M. Kasberg, June 2010.

"NSRDB_StationData_*yyyymmdd_yyyymmdd_USAFStationIdentifier*-convReport.rep". Please note that all files with the ".tm3" and the ".rep" are comma-separated value files.

The weather data was further processed prior to use as inputs to the SAM energy production models because SAM only simulates 8,760 hours per year. This limitation prevents SAM from correctly processing leap years. SAM uses the data for February 29th if it is present within a weather input file, but will fail to process the data for December 31st. To maintain consistency between simulations URS archived the leap year weather files and generated a copy of the annual weather file without the data for February 29th. The archived leap year weather files were appended with the ".leap" extension, but remain in the comma-separated value format.

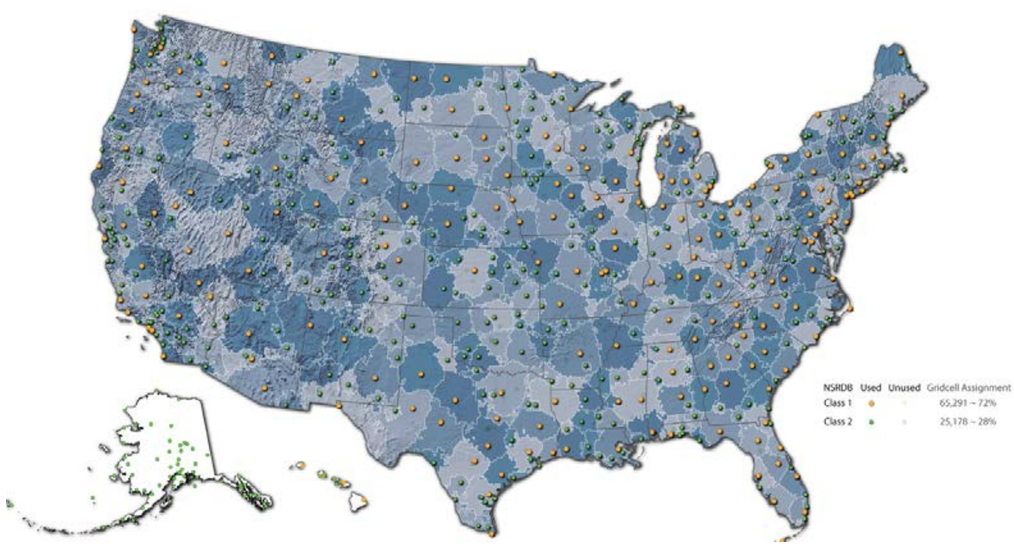
2: Extrapolation of Weather Station Data

ERCOT requested meteorological and solar production data spanning at least 15 years for each county in Texas. The meteorological data originates from NSRDB weather stations which are classified according to the quality of the historical dataset associated with that station. Class I Stations have a complete period of record (all hours 1991–2010) for solar and key meteorological fields and have the highest quality solar modeled data (16 sites in Texas). Class II Stations have a complete period of record but significant periods of interpolated, filled, or otherwise lower-quality input data for the solar models (37 in Texas). Class III Stations have some gaps in the period of record but have at least 3 years of data that might be useful for some applications (36 in Texas). Since at least 15 years of high-quality data was required for this analysis, only Class I and Class II weather station data was used. With 53 Class I and II weather stations in Texas and 254 counties, an extrapolation process was developed by URS to create groups of counties around each weather station. This section of the report describes the methodology used to develop the weather station-county groupings and provides a summary of the results.

Grouping Methodology

In 2011 NREL generated a map of the United States that delineates "areas of influence" around each NSRDB Class I and II weather station in the country. The purpose of this delineation is to provide an indication of which solar radiation and meteorological dataset is most appropriate for modeling a given solar installation's location. The zones around each weather station were defined by NREL to a granularity of 10km^2 using solar radiation profile, elevation and proximity as the main variables in an algorithm used to group each 10km^2 grid to the Class I or II weather station that represents the best match for that grid (see Figure 2).

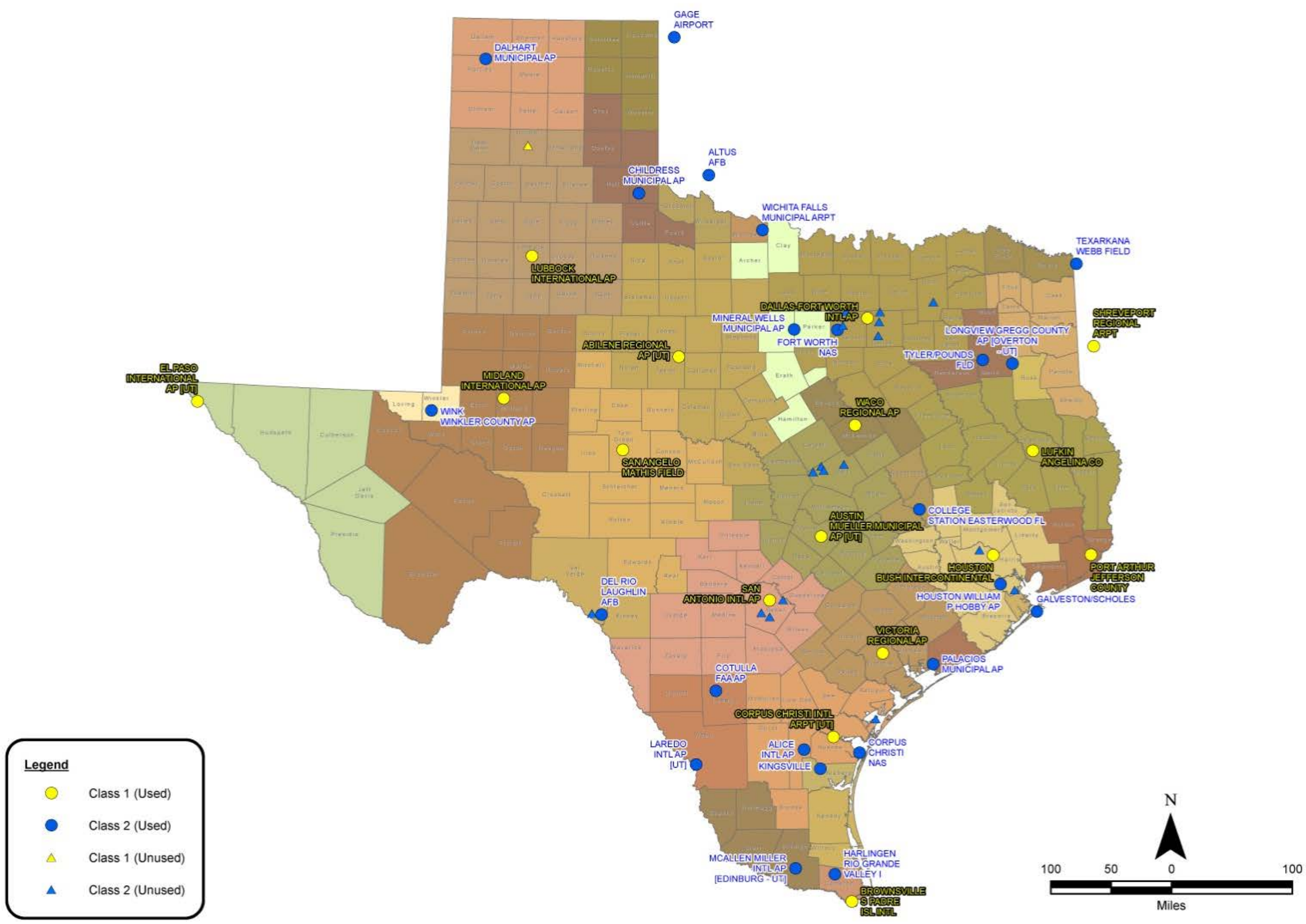
Figure 2: NREL NSRDB Weather Station "Areas of Influence" Map



Source: US DOE, National Renewable Energy Laboratory

Because of overlapping "areas of influence" caused by the close proximity of several weather stations in Texas, 19 of the 53 Class I and II weather stations in Texas were excluded due to redundancy from the NREL map. URS used the information contained in the NREL map as the basis for grouping each county to the most representative of the 34 Class I or II NSRDB weather stations. This was done by calculating the percentage of geographical coverage of each county by different "areas of influence" and assigning a county to the one weather station that represented the highest percentage of its total coverage. For example, if a county contained 45% of Zone A, 30% of Zone B, and 25% of Zone C, the county was assigned to Weather Station A. Four weather stations from outside of Texas were identified as the best fits for some border counties. Figure 3 below shows the location of both the used and unused Class I and II weather stations in Texas along with the corresponding counties that have been grouped with the 34 "used" weather stations. See Appendix II for a complete listing of the weather stations used in this analysis and the counties grouped to each.

Figure 3: Weather Station-County Groupings



Source: URS GIS Dept.

3: Solar Production Modeling

URS utilized the NREL System Advisor Model (SAM) to produce energy production estimates for four different solar system configurations for geographic locations across Texas. This section of the report describes the assumptions and inputs used to model a 1MWe-AC fixed tilt photovoltaic (PV) solar system (PVFT), a 1-MWe-AC single-axis tracking PV system (PVSAT), a 5kWe-AC residential PV system (RES), and a 50MWe-AC parabolic trough concentrating solar power system (CSP).

National Renewable Energy Laboratory (NREL) System Advisor Model (SAM)

SAM was fist jointly developed in 2005 as an internal systems-based solar analysis tool by NREL and Sandia National Laboratories. The first commercial version of SAM was released in 2007. URS downloaded and utilized the most recent version of SAM, SAM 2013.1.15, for all solar energy production modeling for this project.[7] URS selected SAM from among the other modeling software options like PVSyst because of its integration with historic weather data, modeling functionality, and the alignment of its model results with the intended analytical use by ERCOT.

SAM includes a variety of physical models of different solar technologies which can be customized through user input selections. Additional control and automation of SAM simulations is provided through the built-in SamUL scripting language. SAM includes a variety of financial models in addition to the physical models of solar technologies. The simulations URS performed did not utilize any of the financial modeling capabilities of SAM.

URS utilized the “Flat Plate PV” model to simulate the performance of the PVFT, PVSAT, and the RES systems and the “CSP Physical Trough” model to simulate the CSP system. The PVFT, PVSAT, and RES models are distinguished by the equipment and tracking parameters specified for each model. The assumptions and inputs for each of these models are described in the remainder of this section.

Solar Technologies Overview

Fixed Tilt Crystalline Silicon

The majority of fixed tilt PV arrays utilize modules composed of individual crystalline silicon (C-Si) cells. Crystalline silicon (C-Si) is the most common type of solar cell and consequently has the lowest initial cost per installed watt of all solar PV technologies. C-Si cells can be further differentiated into either monocrystalline or polycrystalline silicon. Monocrystalline silicon cells are cut from cylindrical ingots of single-crystal silicon. Polycrystalline silicon cells are cut from large blocks of silicon containing many individual crystals and are typically less efficient and less expensive than monocrystalline silicon cells. The module conversion efficiency, or percentage of the sun’s energy that is converted into electricity, of commercially available C-Si modules is between 13-16% for polycrystalline modules and 14-20% for monocrystalline modules.

Fixed tilt systems utilize driven piles, ballast, or concrete footers as a foundation for a metallic racking structure which holds the PV modules at a fixed orientation. The ideal orientation to maximize annual

[7] NREL System Advisor Model (SAM) 2013.1.15 Help

energy output from a fixed tilt solar array is with an azimuth pointed due south and a slope (or tilt) of the modules equal to the latitude of the solar array installation location. [8] The ideal orientation for maximum energy production maintains the plane of the solar module normal to the sun through the day and year. Fixed tilt systems produce less energy than single-axis or dual-axis tracking systems due to their below optimal orientation but require less capital expense and maintenance costs compared to tracking systems which would be required to maintain an optimal orientation.

The solar modules are electrically connected serially in 'strings'. The number of modules which can be connected in series is dependent on the maximum input voltage of the inverter and the ambient temperatures of the site. The voltage of the solar module is inversely related to the operating temperature of the solar cells. The output of paralleled groups of strings are brought together and combined at an inverter, which converts the DC power produced by the solar modules to AC power for consumption or distribution to the electric grid.

The nameplate rating of solar modules is determined based on testing performed at Standard Test Conditions (STC). For PV testing, these are an irradiance of 1000 W/m^2, a solar spectrum of AM 1.5, and a temperature of 25°C.

Single-Axis Tracking (SAT)

Single-axis tracking (SAT) systems increase the energy produced by a solar array by tracking the sun from east to west diurnally. The tilt of SAT systems are usually kept flat, normal to the zenith, and have a total east-west tracking range of 90°. A control algorithm keeps the solar modules tilted toward the sun throughout the course of the day.

A range of configurations exist for SAT, but the most common is north-south rows of piles supporting a single torque tube to which individual modules are mounted. The tracking motion of groups of rows is provided through a mechanical linkage and a common drive motor.

SAT systems are designed to maximize land use without causing self-shading. The balance of system (BOS) components of a SAT system are similar to those of a fixed-tilt system.

Residential Rooftop Solar

Residential solar utilizes the same components of a fixed-tilt system, but is constrained to the orientation of the building roof. Also, the physical size and electrical capacity of residential components are less than those of a utility scale SAT or fixed-tilt system.

Residential solar arrays typically range from 2kW to 16kW. The BOS may be minimal for a residential system; strings of solar modules may be electrically connected directly to the solar inverter, which is in turn connected to the electrical distribution panel of the residence.

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[8] "The slope is the angle between the plane of the surface in question and the horizontal…The surface azimuth angle is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian." The - Duffie, J.A. & Beckman, W. A. (2006). *Solar engineering of thermal processes* (3rd ed.). Hoboken: John Wiley & Sons.

CSP

Concentrating solar power (CSP) plants utilize concentrated solar radiation to generate thermal energy, which is used to power a conventional electricity producing steam turbine generator. There are two primary types of power concentrating solar power plants: parabolic troughs and power towers. Parabolic troughs utilize long parabolic mirrors to concentrate solar radiation on a tubular absorber which is held in the focal point of the mirror. The parabolic troughs track the sun along a single north-south axis from east to west throughout the day. Power towers use arrays of mirrors (heliostats) which track the sun over two axes and focus the radiation on a single fixed absorber which is elevated above the field of heliostats. URS elected to model a parabolic trough type CSP plant due to the historical data available from plants of this type constructed in the US (see Appendix III).

CSP plants often utilize thermal energy storage (TES) to increase the plant capacity and smooth short-term transients in the available solar radiation. TES systems for current CSP plants utilize a two-tank indirect molten salt storage system.[9]

Production Modeling Methodology Overview

The following sections detail the value URS selected for the significant user inputs for each solar model.

PV Fixed Tilt Model (PVFT)

PV Module Selection

URS performed a parametric study of four solar modules to select a module for use in the PVFT model. The candidate modules are all typical 72-cell solar modules produced by large manufacturers which supply modules to utility scale solar development projects.

Table 2: Parametric Study of Four Solar Modules

	Mod/ String	Parallel Strings	Inverters	kW-DC	kW-AC	DC/AC	Nominal DC Energy (kWH-DC)	Net DC Output (kWh-DC)	% DC Losses	Net AC Output (kWh-AC)
Yingli- YL285P-35b	12	358	2	1223.11	1000	1.22311	2,244,300	1,974,950	-13.64%	1,897,690
MEMC-P285AMC-24	12	358	2	1225.73	1000	1.22573	2,249,090	1,952,760	-15.17%	1,876,720
Suntech STP285-24-Vd	12	358	2	1222.68	1000	1.22268	2,243,510	1,982,600	-13.16%	1,904,120
Trina TSM-285PA14A	12	358	2	1224.23	1000	1.22423	2,246,350	2,003,450	-12.12%	1,923,440

SunEdison, a subsidiary company to MEMC, is a solar developer that has developed several projects within Texas using MEMC modules. Additionally, Yingli was the largest module supplier in 2012.[10] This parametric simulation held constant all values except the module parameters. The average DC losses, which are only affected by the module parameters, is -13.52%. This average value most closely matches

[9] Thermal Storage Commercial Plan Design Study for a 2-Tank Indirect Molten Salt System, B. Kelly and D. Kearney, NREL.

[10] Top 10 PV module suppliers in 2012, PVTECH, January 28th, 2013, http://www.pv-tech.org/guest_blog/top_10_pv_module_suppliers_in_2012

the loss by the Yingli module. URS selected the Yingli-YL285P-35b module for use in the PVFT simulation due to the prevalence of Yingli modules and the degree to which they provide typical performance for a range of modules commonly used in utility scale PV plants.

Inverter Selection

URS selected the SMA 500HE-US 200V inverter equipment model for use in the PVFT model. SMA is among the industry leading manufacturers of utility-scale central inverters. The use of (2) 500kW-AC inverters in the model provides an even 1MW-AC capacity, which allows the output data to be easily scaled to provide approximate energy production for a range of plant capacities 1MW-AC or greater.

The SMA 500HE-US inverter has a maximum input voltage (DC) of 600V. It is increasingly common to design utility-scale PV plants around central inverters with a 1000V DC input voltage. However, the inverter equipment models available do not include a 1000V inverter with a rated output power of 500 kW-AC. URS deemed the departure from the most likely equipment configuration for future plants acceptable to provide energy production results for 1MW-AC system. Possible differences between a simulation with a 1000V inverter and a 600V inverter of the same capacity include changes in DC wire losses and inverter efficiencies. URS did not quantify these potential differences in efficiency.

Array Sizing

The number of modules in each string was selected based on statistical weather data compiled by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). The lowest temperature used to calculate the string voltage is 11°F (-11.67°C), which is the 97.5% design dry-bulb temperature for the Amarillo AP. This is the lowest temperature expected for 97.5% of winter hours. This is the lowest winter design-dry bulb temperature for the locations in Texas listed in the source.[11] The ASHRAE statistical temperature data is referenced by the National Fire Protection Agencies 2011 National Electric Code Handbook, section 690.7.

The number of parallel strings was determined by calculating the DC power necessary for the ratio of DC power to AC power to be 1.2. This is a common ratio in the industry, which reduces time the inverter is underpowered due to ambient conditions differing from the standard test conditions.

Array Orientation

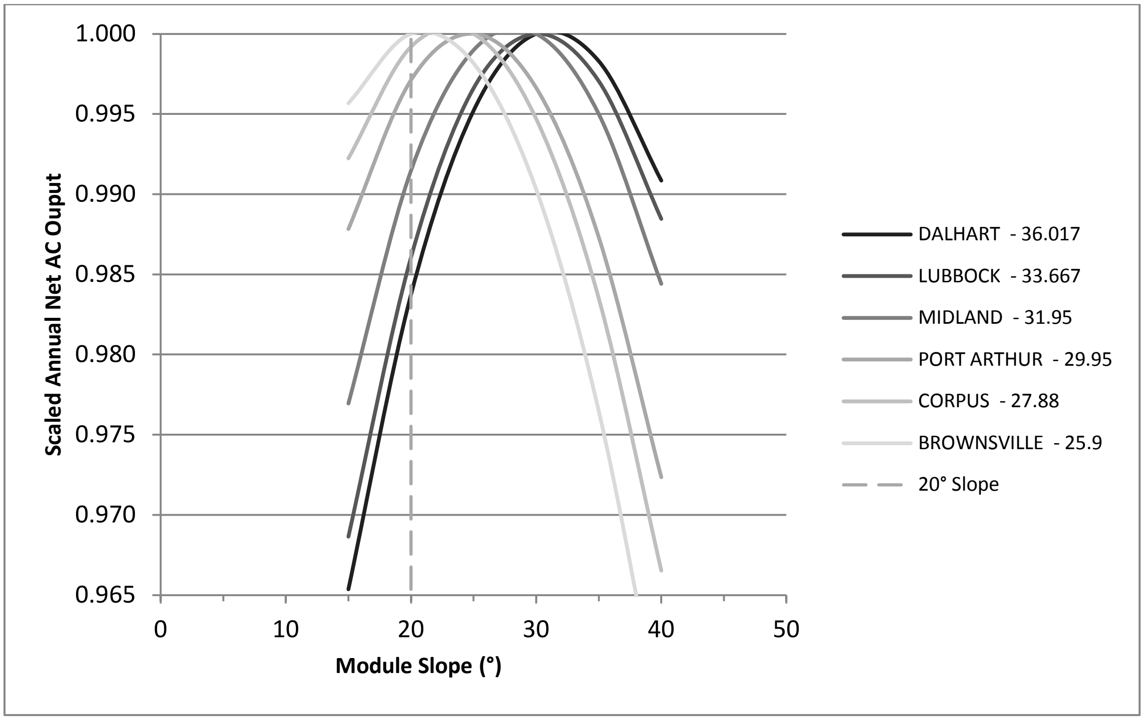
URS performed parametric simulations to inform the selection of a module slope for the PVFT model. The parametric simulations held all input values constant, except for the weather input file (location). URS set the slope for the parametric simulations to 25°. The results of the parametric simulation express the relationship between slope and power input. The results are also influenced by the site specific weather conditions, but the correlation between annual energy generation, slope, and latitude is readily apparent despite the effects of localized weather conditions. The results of the parametric simulation are shown in the figure below.

URS selected a slope of 20° for the PVFT model. This is below optimal for the weather stations in the northern part of Texas. However, as shown in Figure 4, the reduction in power output for a system with modules oriented with a 20° slope is less than 2% from the optimum production. Additionally, the lower module slope allows reduced north-south row-to-row spacing within the solar array. For solar arrays with a limited land area, the reduced row-to-row spacing generally allows for a greater total system

[11] Mechanical and Electrical Equipment for Buildings. Benjamin Stein, John S. Reynolds, Walter T. Grondzik, and Alison G. Kwok. 10th Ed. 2006, Hoboken, NJ: John Wiley & Sons, Inc.

capacity (kW-DC). This greater capacity generally results in energy production, which exceeds the losses from a non-optimal slope. URS used a system azimuth as due south for the PVFT model.

Figure 4: Parametric Simulations of Module Slope



System Losses

URS specified system losses which are typical for design values of utility-scale solar systems as model input parameters. These include AC and DC wiring losses of 0.5% and 1.5%, respectively. A 0.3% loss is included for one day of system unavailability per year. This loss is added to the -0.67% annual light induced degradation to determine the 99.03% value for the percent of annual system output adjustment.

Summary of Input Parameters

Table 3: PV Fixed Tilt – Module Input Parameters

Module: Yingli Energy (China) YL285P-35b							
Module Characteristics at Reference Conditions							
Efficiency	14.60	%	Temperature Coefficients				
Maximum Power (Pmp)	284.71	Wdc	-4.700e-001	%/C	-1.338e+000	W/C
Max Power Voltage (Vmp)	35.5	Vdc				
Max Power Current (Imp)	8.02	Adc				
Open Circuit Voltage (Voc)	45	Vdc	-3.430e-001	%/C	-1.543e-001	V/C
Short Circuit Current (Isc)	8.5	Adc	4.320e-002	%/C	3.672e-003	A/C
Physical Characteristics							
Material	Multi-c-Si						
Module Area	1.95	m2					
Number of Cells	72						

Table 4: PV Fixed Tilt – Inverter Input Parameters

Inverter: SMA America: SC 500HE-US 200V [CEC 2010]					
Inverter Characteristics					
AC Voltage	200	V	C0	-4.02894e-008	1/W
Power ACo	500,000	Wac	C1	3.10557e-005	1/V
Power DCo	511,510	Wdc	C2	0.00565754	1/V
PowerSo	1,879.21	W	C3	0.000739241	1/V
PowerNTare	101	W	MPPT_low	330	V
Vdcmax	600	V	Vdco	370.784	V
Idcmax	1600	A	MPPT_hi	600	V

Table 5: PV Fixed Tilt – Array Sizing and Losses

Modules per String	12				
Strings in Parallel	352				
Number of Inverters	2				
Actual Layout					
Modules			**Inverters**		
Nameplate Capacity	1202.62	kWdc	Total Capacity	1000	kWa
Number of Modules	4224		Number of Inverters	2	
Modules per String	12		Vdcmax (dc-inverter)	600	V
Strings in Parallel	352		MPPT_low	330	V
Total Module Area	8236.8	m2	MPPT_hi	600	V
Voc (String)	540	V			
Vmp (String	426	V			
Interconnection Derates					
AC wiring losses	0.995	(0..1)			
Step-up transformer losses	0.9936	(0..1)			
Total interconnection derate	0.988632	(0..1)			
Tracking and Orientation					
Tracking/Fixed	Fixed				
Tilt (deg)	20				
Azimuth (deg)	180				
Shading and Soiling					
Annual average soiling (0..1)	0.99				
Pre-inverter Derates					
Mismatch (0..1)	0.99				
Diodes and connections (0..1)	1				
DC wiring loss (0..1)	0.985				
Tracking error (0..1)	1				
Nameplate (0..1)	1				
Estimated DC power derate (0..1)	0.97515				

Table 6: PV Fixed Tilt – Degradation

System Output Adjustments		
Percent of annual output	99.03 %	

PV Single-Axis Tracking (SAT)

URS used the same inverter, module, and array size for the PVSAT input parameters as those used in the PVFT model.

Array Orientation

URS used a due south input for the PVSAT array orientation azimuth. URS determined the range of the tracker motion based on a review of current SAT manufacturer specifications (Table 6).

Table 7: PV Single-Axis Tracker – Range of Tracker Motion

	Tilt	Tracking Range of Motion	Tracking Accuracy
ATI DuraTrackHZ	0	+/-45°	+/-2°
PVHardware Axone	0	+/-45°	UA
SPG SunSeeker	0	+/-45°	UA

URS selected a tracking range of +/- 45° due to the prevalence of this range in currently manufactured SAT equipment. URS also specified the use of backtracking and a row width of 1.97m and row-to-row-spacing of 5m. The row width is a typical value for the width of 72 cell solar modules. The row-to-row spacing provides a ground-cover-ratio (GCR) of 40%. This is a common design parameter for utility-scale solar systems, which maximizes the use of the available ground area without causing self-shading.

Table 8: PV Single-Axis Tracker – Array Sizing and Losses

String Configuration	
Strings in array	352
Subarray 1	
Strings allocated to subarray	352
Tracking and Orientation	
Tracking/Orientation	1-Axis
Tilt (deg)	0
Azimuth (deg)	180
Tracker rotation limit (deg)	45
Row width	1.97
Space between edges of adjacent rows (m)	5
Shading and Soiling	
Annual average soiling (0..1)	0.99
Pre-inverter Derates	
Mismatch (0..1)	0.99
Diodes and connections (0..1)	1
DC wiring loss (0..1)	0.985
Tracking error (0..1)	0.98
Nameplate (0..1)	1
Estimated DC power derate (0..1)	0.955647

Residential PV Model (RES)

URS configured the residential model to use Solarworld SW250 Polysilicon modules. These are 62 cell modules, which are a common physical size and power capacity for residential systems. Similarly, URS used the SMA Sunny Boy SB5000US-11 240V inverter due to the quality of products of SMA and its nameplate power rating.

URS specified the same modules per string (12) for the residential model as the PVFT and PVSAT models. The same DC/AC ratio was kept constant across models as well and resulted in 2 strings for a nameplate DC capacity of 6.023 kW.

URS specified the slope of the modules for the RES model as 22.6°, which is equivalent to the common 5/12 roof pitch.

The "percent of annual output" parameter was set to 99.3%, which assumes -0.67% light induced degradation per year for 25 years. This rate of degradation matches the warranty specified by the module manufacturer.

Table 9: PV Residential – Module Input Parameters

Module: SolarWorld SW250 Poly						
Module Characteristics at Reference Conditions						
Efficiency	15.67	%	Temperature Coefficients			
Maximum Power (Pmp)	250.096	Wdc	-4.500e-001	%/C	-1.125e+000	W/C
Max Power Voltage (Vmp)	30.8	Vdc				
Max Power Current (Imp)	8.12	Adc				
Open Circuit Voltage (Voc)	37.6	Vdc	-3.890e-001	%/C	-1.463e-001	V/C
Short Circuit Current (Isc)	8.64	Adc	8.300e-002	%/C	7.171e-003	A/C
Physical Characteristics						
Material	Multi-c-Si					
Module Area	1.596	m2				
Number of Cells	60					

Table 10: PV Residential – Inverter Input Parameters

SMA America: SB50000US-11 240V [CEC 2007]					
Inverter Characteristics					
AC Voltage	240	V	C0	-5.02814e-006	1/W
Power ACo	5000	Wac	C1	6.26654e-005	1/V
Power DCo	5204.6	Wdc	C2	0.00232889	1/V
PowerSo	51.4071	W	C3	0.000450495	1/V
PowerNTare	0.72	W	MPPT_low	250	V
Vdcmax	0	V	Vdco	309.883	V
Idcmax	0	A	MPPT_hi	480	V

Table 11: PV Residential – Array Sizing and Losses

Specify System Size					
Desired Array Size	4	kWdc			
Modules per String	12				
Strings in Parallel	2				
Number of Inverters	1				
Actual Layout					
Modules			**Inverters**		
Nameplate Capacity	6.0023	kWdc	Total Capacity	5	kWa
Number of Modules	24		Number of Inverters	1	
Modules per String	12		Vdcmax (dc-inverter)	0	V
Strings in Parallel	2		MPPT_low	250	V
Total Module Area	38.304	m2	MPPT_hi	480	V
Voc (String)	451.2	V			
Vmp (String)	369.6	V			
Interconnection Derates (AC)					
AC wiring losses	0.99	(0..1)			
Step-up transformer losses	1	(0..1)			
Total interconnection derate	0.99	(0..1)			
Tracking and Orientation					
Fixed/Tracking	Fixed				
Tilt (deg)	22.6				
Azimuth (deg)	180				
Shading and Soiling					
Annual average soiling (0..1)	0.95				
Pre-inverter Derates					
Mismatch (0..1)	0.99				
Diodes and connections (0..1)	1				
DC wiring loss (0..1)	0.99				
Tracking error (0..1)	1				
Nameplate (0..1)	0.99				
Estimated DC power derate (0..1)	0.970299				

Table 12: PV Residential – Degradation

System Output Adjustments		
Percent of annual output	99.3	%

Concentrating Solar Power (CSP)

Where possible, URS used CSP model input parameters consistent with the design of the SEGSI through SEGSIX and the Nevada Solar One plants, which are all parabolic trough systems built in the United States. Appendix III and Appendix IV provide more detailed information about the parameters of these 10 plants.

Solar Field

To develop an input parameter for the field aperture of the parabolic trough collectors URS utilized ratios of design values for the Nevada Solar One (NSO) plant, which is of a similar size and has the same thermal storage capacity, 0.5 hrs, as the URS SAM model.

URS assumed a design irradiation for the Nevada Solar One parabolic trough plant of 950 W/m^2.

From available data URS calculated the ratio of aperture area to the plant gross MWe for NSO to be 4,762.66 m^2/MWe. URS selected a design gross capacity for the CSP model of 55MWe, which provides an expected net capacity of 50MWe. The 50MWe value was originally specified as the capacity for concentrating solar power by ERCOT.

URS determined the product of the gross plant capacity for the URS model and the aperture area to plant gross capacity ratio for the NSO plant to be 261,946m^2. URS used this field aperture as in initial input to the SAM model.

With the design irradiation parameter specified as 950W/m^2 SAM calculates an actual solar multiple of 1.23002.

URS based some of the inputs for the CSP plant on the assumption that the plant would be located in the El Paso area. This assumption is justified by the increased productivity of CSP plants in areas with strong direct normal irradiation (DNI). The El Paso region has the strongest DNI of the NSRDB weather stations in Texas. The Nevada Solar One plant is near Las Vegas, which has higher DNI for more hours of the year than El Paso. Due to this difference in the solar resource, a CSP plant in El Paso would need a greater ratio of collector area to gross plant capacity. URS accounted for this difference through an analysis of available typical year weather data for Las Vegas and El Paso. In Las Vegas 8% of the hours with measurable DNI have DNI which is equal to or greater than 950W/m^2. Using a guess and check methodology the DNI at which 8% of the hours with measurable DNI is equal to or greater than a given value provides a DNI of 927 W/m^2 in El Paso.

Changing the design irradiation parameter in the SAM model to 927 W/m^2 reduces the actual solar multiple to 1.19891. A guess and check process using the SAM field aperture parameter to bring the actual solar multiple back to 1.23317 (as close as SAM would calculate to 1.23002) results in a final field aperture of 269,100m^2.

Collectors (SCAs) & Receivers (HCEs)
For representative simulation purposes, URS specified the Solargenix SGX-1 as the collector and the Solel UVAC 3 as the receiver. Similar equipment was used for the SEGS and NSO systems.

Power Cycle
URS selected a rated cycle conversion efficiency of 37.6%, which matches the rated efficiency for SEGS VIII and IX. These plants are similar in capacity and design as the modeled plant.

Plant Capacity
URS selected a design gross capacity for the CSP model of 55MWe, which provides an expected net capacity of 50MWe. The 50MWe value was originally specified as the capacity for concentrating solar power by ERCOT. This system size is reasonable for the range of plant sizes that have been designed and constructed in the US, including SEGSI through SEGSIX and Nevada Solar One (75MWe gross).

URS selected a boiler operating pressure of 100 bar, which is consistent with the SEGS plants.

URS selected an evaporative condenser for the CSP model. This selection matches the type of heat rejection used for the NSO plant. Plants with evaporative heat rejection are more efficient due to the lower condensing temperatures obtainable with evaporative cooling. URS used SAM to generate psychrometric values based on the TMY3 weather file for El Paso. A SAM run was used to create a file containing the hourly DNI and wet bulb temperatures for El Paso. URS used the data in this file to calculate average wet bulb temperatures for hours with DNI equal to or greater than 800 W/m^2 and 950 W/m^2. The average of the wet bulb temperatures for these hours were 10.668°C and 7.246°C for the hours with DNI greater than 800W/m^2 and 950W/m^2, respectively.

URS selected a design wet bulb temperature for the cooling system of 10.668 due to greater hours of operation, 32% of hours with measurable DNI rather than 5% for the 7.246°C temperature.

Storage system
URS specified 0.5 hours of TES. This value matches the TES capacity of the NSO plant and provides enough storage for transient conditions. SAM calculates the necessary storage volume based on the user input of storage capacity.

SAM calculates the tank diameter, but allows the user to input a value for the tank height. An ideal height to diameter ratio for TES is 1:3. This provides for stratification with in the storage tank, but does not sacrifice increase the surface area to volume ratio dramatically. Using this ratio URS calculated a tank height of 23.2m. The SAM calculated tank diameter with this rank height was 7.72977m.

SAM calculates thermal losses from a storage tank based on a tank loss coefficient, the tank volume, and the tank temperature. The tank volume is calculated by SAM and the tank temperature is calculated for each time-step as the simulation runs. URS specified a tank loss coefficient of 1.49 W/m^2-K. This value is based on a correlation developed for large storage tank between the tank volume and an optimal insulation thickness.

$$y = 21.404x^{0.3669}$$

This correlation provides the insulation thickness (y,mm) for a given storage volume (x, m^3).[12] Using the tank volume of 1088.71m^3 the correlation produces an insulation thickness of 278.444mm. Typical insulation for this type of storage tank is calcium silicate block, which has a thermal conductivity of 0.0633 W/mK. URS calculated the tank loss coefficient using this thermal conductivity, the assumption that the storage tank has 7mm thick steel walls, and is exposed to an ambient air temperature of 22°C.

Performance Adjustment

URS estimated the plant would be out of operation for 7 days out of the year. This lack of availability is expressed in the CSP model as a 98.1% system output adjustment.

Table 13: Concentrating Solar Power – Solar Field

Solar Field Parameters		
Field aperture	269100	m2
Row spacing	15	m
Stow angle	170	deg
Deploy angle	10	deg
Irradiation at design	927	W/m2
Heat Transfer Fluid		
Field HTF fluid	Therminol VP-1	
Design loop inlet temp	293	‘C
Design loop outlet temp	391	‘C
Design Point		
Single loop aperture	3762.4	m2
Loop optical efficiency	0.751213	
Total loop conversion efficiency	0.718323	
Total required aperture, SM=1	219672	m2
Required number of loops, SM=1	58.3862	
Actual number of loops	72	
Total aperture reflective area	270893	m2
Actual solar multiple	1.23317	
Field thermal output	180.384	MWt

Table 14: Concentrating Solar Power – Collectors and Receivers

Collectors (SCAs)	Solargenix SGX-1
Receivers (HCEs)	Solel UVAC 3

[12] A Solar Thermal System With Seasonal Storage for a Net-Zero Energy School, Master’s Thesis, Ben Taylor, RPI, 2012.

Table 15: Concentrating Solar Power – Power Cycle

Plant Capacity		
Design gross output	55	MWe
Estimated gross to net conversion factor	0.9	
Estimated net output at design (nameplate)	50	MWe
Power Block Design Point		
Rated cycle conversion efficiency	0.376	
Design inlet temperature	391	'C
Design outlet temperature	293	'C
Boiler operating pressure	100	bar
Steam cycle blowdown fraction	0.02	
Fossil backup boiler LHV efficiency	0.9	
Aux heater outlet set temp	391	'C
Fossil dispatch mode	Minimum backup level	
Cooling System		
Condenser type	Evaporative	
Ambient temp at design	10.668	'C
Ref. Condenser Water dT	10	'C
Approach temperature	5	'C
Cooling system part load levels	2	

Table 16: Concentrating Solar Power – Thermal Storage

Storage System		
Full load hours of TES	0.5	hr
Storage volume	1088.71	m3
TES Thermal capacity	73.1383	MWt
Parallel tank pairs	1	
Tank height	23.2	m
Tank fluid minimum height	1	m
Tank diameter	7.72977	m
Min fluid volume	46.927	m3
Tank loss coefficient	1.49	W/m2-K
Estimated heat loss	0.292815	MWt
Cold tank heater set point	250	'C
Hot tank heater set point	365	'C

Simulation Management and Results Processing

The SamUL scripting language was used to automate the process of running each of the four solar models for the 20 historical year data files for each of the 93 weather stations and the 65 TMY files. Additional post-processing was completed using a Unix Bash shell script and the AWK programming language to prepend the date and time from the input weather file to each output file and to add a column containing the exported energy (kWH-AC), which did not contain negative values (energy consumption by the plant) per ERCOT's request.

See Appendix V for summary graphs showing the 20 years of historical annual electricity production estimates for six representative sites across Texas. To facilitate comparison between the different solar models URS linearly scaled the results of the PVSAT, PVFT, and RES models shown in Appendix V to the equivalent output of a 50MW-AC solar plant.

4: Statistical Analysis of Data

P50/P90 Exceedance Probabilities

The likelihood that a solar array will generate a certain amount of electricity in any given year over the facility's expected life can be determined using statistical analysis of solar radiation and meteorological data. Interannual solar resource variability can be quantified by calculating the exceedance probabilities representing the amount of energy expected to be produced by a solar generation facility. An exceedance probability is the probability that a certain value will be exceeded. For example, a P50 value of 100,000 kWh for the annual output of a solar array means that there is a 50% likelihood that the system's annual output will be greater than 100,000 kWh. A P90 value of 100,000 kWh indicates that there is a 90% likelihood that the system's annual output will be greater than 100,000 kWh.

URS calculated the exceedance probabilities for six of the 34 weather stations included in this analysis. The six weather stations selected represent different areas of the state to highlight regional differences in magnitude and variability of annual electricity production. URS calculated the P50 and P90 values for each of the six stations (see Figure 5) by generating cumulative distribution functions (CDF) from both the normal distribution of the dataset using the mean and standard deviation of the values and from the empirical data (see Figure 6). URS then determined the P50 and P90 exceedance probabilities either directly from the normal CDF equation or by linearly interpolating the empirical CDF table.

The CDF graphs in Figure 6 demonstrate the differences in magnitude and variability of the annual electricity output for a 1MW fixed tilt PV system located in the area of influence of the respective station.

Figure 5: Min, P90, P50, and Max of Annual Output, PV Fixed Tilt

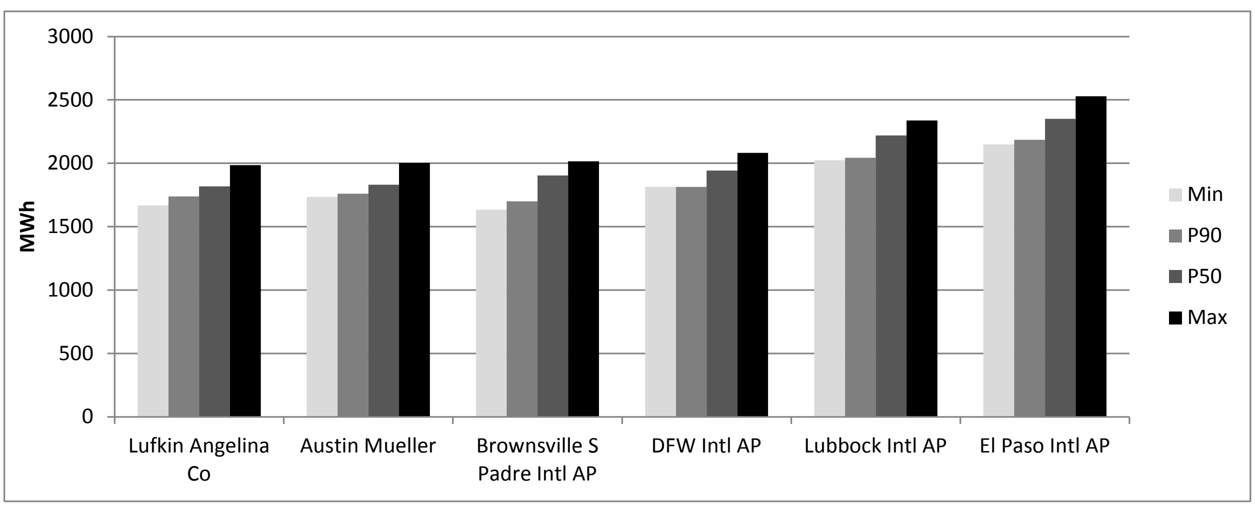
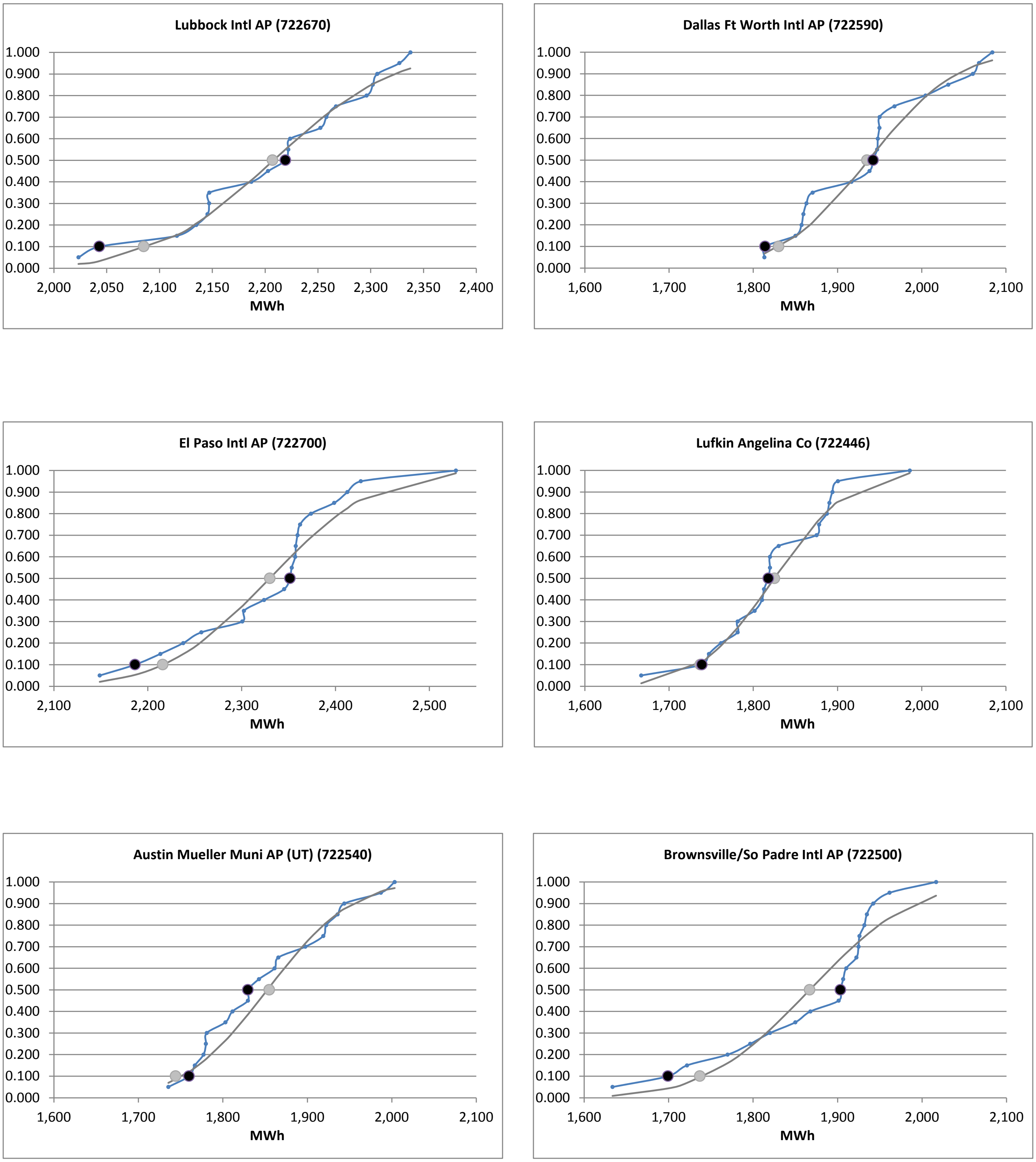


Figure 6: Cumulative Distribution Functions of Annual AC Output, PV Fixed Tilt

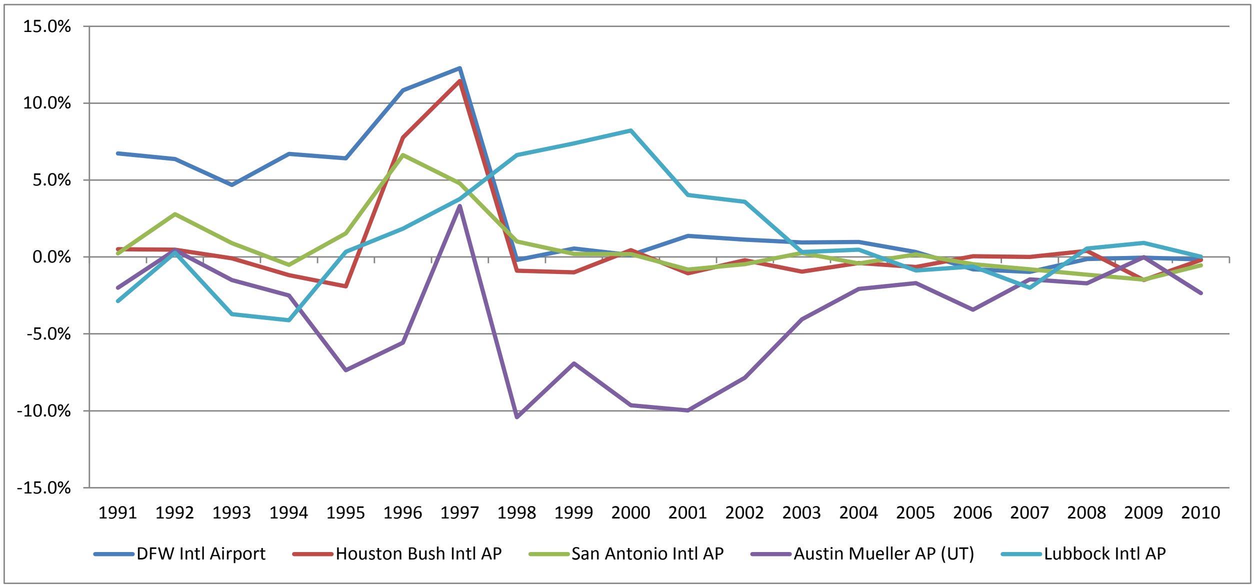


	Empirical CDF
	Normal Dist. CDF
●	Empirical P50/P90
○	Normal Dist. P50/P90

Variance Analysis of Nearby Weather Stations

URS conducted a comparison of the production model results generated from the Class I weather stations used in this analysis with nearby weather stations that were not used due to redundancy in geographic coverage. This comparison uses five Class I weather stations located at airports in major metropolitan areas (Dallas/Ft. Worth, Houston, Austin, San Antonio, and Lubbock) and compares the 20-year annual production values with the same model results from nearby weather stations (see Figure 7). The objective of this analysis is to understand the magnitude and trends of potential variances in the data across different regions of the state.

Figure 7: Weather Station Variance Analysis Results



The Y axis in Figure 7 is the percent variance between the annual production model results for the selected Class I weather station and a nearby weather station that was not used in the analysis (see Figure 8 for the names/locations of comparison stations). The decreasing variability between stations after 1998 is most likely due to the introduction of satellite imagery data in the model used to produce the NSRDB data. Satellite imagery data was not available for the time period of 1991-1997. Many Class II weather stations relied upon inferior statistically derived cloud cover data prior to 1998. As described in the NSRDB User's Manual, the algorithm used to distinguish between Class I and Class II weather stations measures the uncertainty for each hourly modeled value in the global field. If less than 25% of the data for the period of record exceeds an uncertainty of 11%, the station receives a Class I designation. Otherwise, it receives a Class II designation. Uncertainty calculations performed by NREL validate that the 11% uncertainty threshold discriminates between the data modeled with good human-observed or satellite-derived cloud cover and the filled or statistically derived cloud cover.

Figure 8: Weather Station Variance Analysis Data

Weather Station	DFW Intl Airport	Dallas Addison Arpt	
ID #	722590	722598	
Class	1	2	% Variance
1991	1,814,041	1,692,024	6.7%
1992	1,813,117	1,697,642	6.4%
1993	1,870,325	1,782,809	4.7%
1994	1,857,171	1,732,614	6.7%
1995	1,947,855	1,823,023	6.4%
1996	2,067,839	1,843,747	10.8%
1997	1,863,155	1,634,368	12.3%
1998	1,949,608	1,953,371	-0.2%
1999	2,060,615	2,049,399	0.5%
2000	1,949,967	1,947,559	0.1%
2001	1,937,965	1,911,484	1.4%
2002	1,942,135	1,920,289	1.1%
2003	1,947,011	1,928,683	0.9%
2004	1,850,065	1,831,981	1.0%
2005	2,004,435	1,998,134	0.3%
2006	2,083,696	2,100,418	-0.8%
2007	1,859,378	1,877,354	-1.0%
2008	2,031,400	2,034,222	-0.1%
2009	1,916,381	1,917,358	-0.1%
2010	1,967,426	1,970,800	-0.2%

Weather Station	Houston Bush Intl AP	Houston DW Hooks	
ID #	722430	722429	
Class	1	2	% Variance
1991	1,616,428	1,608,179	0.5%
1992	1,692,978	1,684,981	0.5%
1993	1,743,682	1,745,297	-0.1%
1994	1,688,447	1,708,408	-1.2%
1995	1,794,178	1,828,535	-1.9%
1996	1,744,967	1,609,550	7.8%
1997	1,594,154	1,411,823	11.4%
1998	1,806,399	1,822,671	-0.9%
1999	1,919,035	1,938,089	-1.0%
2000	1,871,106	1,862,687	0.4%
2001	1,794,828	1,813,760	-1.1%
2002	1,795,887	1,799,642	-0.2%
2003	1,769,443	1,786,360	-1.0%
2004	1,739,574	1,746,477	-0.4%
2005	1,903,182	1,915,520	-0.6%
2006	1,843,595	1,842,822	0.0%
2007	1,770,694	1,770,721	0.0%
2008	1,861,349	1,854,082	0.4%
2009	1,772,273	1,798,931	-1.5%
2010	1,836,895	1,840,486	-0.2%

Weather Station	San Antonio Intl AP	San Antonio Kelly AFB	
ID #	722530	722535	
Class	1	2	% Variance
1991	1711322.754	1707389.88	0.2%
1992	1772861.634	1723579.829	2.8%
1993	1788471.714	1772462.838	0.9%
1994	1753031.83	1762159.562	-0.5%
1995	1910030.913	1880595.483	1.5%
1996	2018121.524	1884467.198	6.6%
1997	1836137.072	1748391.946	4.8%
1998	1928321.968	1908962.325	1.0%
1999	1993075.774	1989228.01	0.2%
2000	1897997.874	1894378.418	0.2%
2001	1878452.186	1893904.456	-0.8%
2002	1893135.026	1901879.898	-0.5%
2003	1838930.552	1834214.885	0.3%
2004	1769725.839	1777110.418	-0.4%
2005	1917752.419	1914479.178	0.2%
2006	1942125.533	1951110.874	-0.5%
2007	1787732.497	1802080.599	-0.8%
2008	1937849.395	1960296.928	-1.2%
2009	1906998.203	1934914.536	-1.5%
2010	1933926.518	1944369.765	-0.5%

Weather Station	Austin Mueller AP (UT)	Ft Hood	
ID #	722540	722570	
Class	1	2	% Variance
1991	1759842.455	1795106.947	-2.0%
1992	1842753.696	1834657.574	0.4%
1993	1865556.422	1893647.359	-1.5%
1994	1811309.154	1856785.598	-2.5%
1995	1803045.311	1935709.392	-7.4%
1996	1829658.037	1931513.358	-5.6%
1997	1897570.124	1834816.105	3.3%
1998	1766848.618	1950836.122	-10.4%
1999	1918808.856	2051756.653	-6.9%
2000	1779958.509	1951681.229	-9.6%
2001	1735448.253	1908686.03	-10.0%
2002	1780864.463	1920551.569	-7.8%
2003	1861122.595	1936426.404	-4.0%
2004	1777056.936	1813875.902	-2.1%
2005	1943621.992	1976559.893	-1.7%
2006	2003338.778	2072177.263	-3.4%
2007	1829567.57	1856255.451	-1.5%
2008	1986941.188	2020863.831	-1.7%
2009	1922315.339	1922485.899	0.0%
2010	1935697.131	1981361.939	-2.4%

Weather Station	Lubbock Intl AP	Amarillo Intl AP	
ID #	722670	723630	
Class	1	1	% Variance
1991	2023217.81	2081342.722	-2.9%
1992	2043075.822	2037539.705	0.3%
1993	2116353.447	2195072.466	-3.7%
1994	2145446.741	2233611.783	-4.1%
1995	2147152.555	2139805.708	0.3%
1996	2337498.497	2294628.607	1.8%
1997	2134710.534	2054303.875	3.8%
1998	2306136.21	2153213.463	6.6%
1999	2296080.349	2126558.941	7.4%
2000	2252224.616	2067266.726	8.2%
2001	2221911.509	2132464.231	4.0%
2002	2223634.314	2143930.092	3.6%
2003	2301951.149	2294477.369	0.3%
2004	2146929.172	2136655.829	0.5%
2005	2219259.971	2238616.024	-0.9%
2006	2267023.482	2280984.14	-0.6%
2007	2186870.031	2230798.281	-2.0%
2008	2327046.304	2314365.552	0.5%
2009	2258052.729	2237281.387	0.9%
2010	2202765.681	2202541.856	0.0%

Appendix I: NSRDB to TMY3 Data Conversion Field Label Summary

NSRDB FIELD NAME	YYYY-MM-DD	HH:MM (LST)	ETR (Wh/m^2)	ETRN (Wh/m^2)	Glo Mod (Wh/m^2) OR Meas Glo (Wh/m^2)	Glo Mod Source	Glo Mod Unc (%) OR FILLED
TMY3 FIELD NAME	Date (MM/DD/YYYY)	Time (HH:MM)	ETR (W/m^2)	ETRN (W/m^2)	GHI (W/m^2)	GHI source	GHI uncert (%)
NSRDB FIELD NAME	Dir Mod (Wh/m^2) OR Meas Dir (Wh/m^2)	Dir Mod Source	Dir Mod Unc (%) OR FILLE	Dif Mod (Wh/m^2)	Dif Mod Source	Dif Mod Unc (%) OR FILLED	ABSENT
TMY3 FIELD NAME	DNI (W/m^2)	DNI source	DNI uncert (%)	DHI (W/m^2)	DHI source	DHI uncert (%)	GH illum (lx)
NSRDB FIELD NAME	ABSENT	ABSENT	ABSENT	ABSENT	ABSENT	ABSENT	
TMY3 FIELD NAME	GH illum source	Global illum uncert (%)	DN illum (lx)	DN illum source	DN illum uncert (%)	DH illum (lx)	
NSRDB FIELD NAME	ABSENT	ABSENT	ABSENT	ABSENT	ABSENT	TotCC (10ths)	
TMY3 FIELD NAME	DH illum source	DH illum uncert (%)	Zenith lum (cd/m^2)	Zenith lum source	Zenith lum uncert (%)	TotCld (tenths)	
NSRDB FIELD NAME	TotCC Flg	ABSENT	OpqCC (10ths)	OpqCC Flg	ABSENT	Dry Bulb (C)	
TMY3 FIELD NAME	TotCld source	TotCld uncert (code)	OpqCld (tenths)	OpqCld source	OpqCld uncert (code)	Dry-bulb (C)	
NSRDB FIELD NAME	Dry Bulb Flg	ABSENT	Dew Pnt (C)	Dew Pnt Flg	ABSENT	Rel Hum (%)	
TMY3 FIELD NAME	Dry-bulb source	Dry-bulb uncert (code)	Dew-point (C)	Dew-point source	Dew-point uncert (code)	RHum (%)	
NSRDB FIELD NAME	Rel Hum Flg	ABSENT	Baro Press (mbar)	Baro Press Flg	ABSENT	Wind Dir (deg)	
TMY3 FIELD NAME	RHum source	RHum uncert (code)	Pressure (mbar)	Pressure source	Pressure uncert (code)	Wdir (degrees)	
NSRDB FIELD NAME	Wind Dir Flg	ABSENT	Wind Speed (m/s)	Wind Speed Flg	ABSENT	Hor Vis (m)	
TMY3 FIELD NAME	Wdir source	Wdir uncert (code)	Wspd (m/s)	Wspd source	Wspd uncert (code)	Hvis (m)	
NSRDB FIELD NAME	Hor Vis Flg	ABSENT	Ceil Hgt (m)	Ceil Hgt Flg	ABSENT	Precip Wat (cm)	
TMY3 FIELD NAME	Hvis source	Hvis uncert (code)	CeilHgt (m)	CeilHgt source	CeilHgt uncert (code)	Pwat (cm)	
NSRDB FIELD NAME	Precip Wat Flg	ABSENT	AOD (unitless)	AOD Flg	ABSENT	ABSENT	
TMY3 FIELD NAME	Pwat source	Pwat uncert (code)	AOD (unitless)	AOD source	AOD uncert (code)	Alb (unitless)	
NSRDB FIELD NAME	ABSENT	ABSENT	Liq Precip Depth (mm)	Liq Precip Quantity (h	Liq Precip Depth Flg	ABSENT	
TMY3 FIELD NAME	Alb source	Alb uncert (code)	Lprecip depth (mm)	Lprecip quantity (hr)	Lprecip source	Lprecip uncert (code)	

Appendix II: Weather Station-County Groupings

Weather Station #	722410	722420	722430	722445	722446	722448	722470
Weather Station Name	PORT ARTHUR JEFFERSON COUNTY	GALVESTON/ SCHOLES	HOUSTON BUSH INTERCONTINENTAL	COLLEGE STATION EASTERWOOD FL	LUFKIN ANGELINA CO	TYLER/ POUNDS FLD	LONGVIEW GREGG COUNTY AP [OVERTON - UT]
Class	1	2	1	2	1	2	2
TX County Name(s)	Chambers	Galveston	Austin	Brazos	Anderson	Henderson	Rusk
	Hardin		Brazoria	Burleson	Angelina	Smith	
	Jefferson		Fort Bend	Robertson	Cherokee	Wood	
	Orange		Grimes		Freestone		
			Harris		Houston		
			Liberty		Jasper		
			Montgomery		Leon		
			San Jacinto		Madison		
			Waller		Nacogdoches		
			Washington		Newton		
					Polk		
					Sabine		
					San Augustine		
					Trinity		
					Tyler		
					Walker		

Weather Station #	722480	722500	722505	722506	722510	722516	722526
Weather Station Name	SHREVEPORT REGIONAL ARPT	BROWNSVILLE S PADRE ISL INTL	HARLINGEN RIO GRANDE VALLEY I	MCALLEN MILLER INTL AP [EDINBURG - UT]	CORPUS CHRISTI INTL ARPT [UT]	KINGSVILLE	COTULLA FAA AP
Class	1	1	2	2	1	2	2
TX County Name(s)	Camp	Cameron	Kenedy	Hidalgo	Aransas	Kleberg	Dimmit
	Cass		Willacy	Jim Hogg	Bee		LaSalle
	Franklin			Starr	Brooks		Webb
	Gregg			Zapata	Duval		
	Harrison				Jim Wells		
	Marion				Live Oak		
	Morris				McMullen		
	Panola				Nueces		
	Shelby				Refugio		
	Titus				San Patricio		
	Upshur						

Weather Station #	722530	722540	722550	722555	722560	722590	722597
Weather Station Name	SAN ANTONIO INTL AP	AUSTIN MUELLER MUNICIPAL AP [UT]	VICTORIA REGIONAL AP	PALACIOS MUNICIPAL AP	WACO REGIONAL AP	DALLAS-FORT WORTH INTL AP	MINERAL WELLS MUNICIPAL AP
Class	1	1	1	2	1	1	2
TX County Name(s)	Atascosa	Bastrop	Calhoun	Matagorda	Bosque	Collin	Archer
	Bandera	Bell	Colorado		Limestone	Cooke	Clay
	Bexar	Blanco	Dewitt		McLennan	Dallas	Erath
	Comal	Burnet	Goliad			Delta	Hamilton
	Frio	Caldwell	Gonzales			Denton	Palo Pinto
	Gillespie	Coryell	Jackson			Ellis	Parker
	Guadalupe	Falls	Karnes			Fannin	Somervell
	Kendall	Fayette	Lavaca			Grayson	
	Kerr	Hays	Victoria			Hill	
	Maverick	Lampasas	Wharton			Hood	
	Medina	Lee				Hopkins	
	Uvalde	Llano				Hunt	
	Wilson	Milam				Jack	
	Zavala	Travis				Johnson	
		Williamson				Kaufman	
						Lamar	
						Montague	
						Navarro	
						Rains	
						Rockwall	
						Tarrant	
						Van Zandt	
						Wise	

Weather Station #	722615	722630	722636	722650	722656	722660	722670
Weather Station Name	DEL RIO LAUGHLIN AFB	SAN ANGELO MATHIS FIELD	DALHART MUNICIPAL AP	MIDLAND INTERNATIONAL AP	WINK WINKLER COUNTY AP	ABILENE REGIONAL AP [UT]	LUBBOCK INTERNATIONAL AP
Class	2	1	2	1	2	1	1
TX County Name(s)	Kinney	Coke	Carson	Andrews	Loving	Baylor	Armstrong
	Val Verde	Concho	Dallam	Borden	Winkler	Brown	Bailey
		Crockett	Hansford	Brewster		Callahan	Briscoe
		Edwards	Hartley	Crane		Coleman	Castro
		Irion	Hutchinson	Dawson		Comanche	Cochran
		Kimble	Moore	Ector		Eastland	Crosby
		Mason	Oldham	Gaines		Fisher	Deaf Smith
		McCulloch	Potter	Glasscock		Haskell	Dickens
		Menard	Sherman	Howard		Jones	Floyd
		Mitchell		Martin		King	Garza
		Real		Midland		Knox	Hale
		Runnels		Pecos		Mills	Hockley
		Schleicher		Reagan		Nolan	Kent
		Sterling		Reeves		San Saba	Lamb
		Sutton		Terrell		Scurry	Lubbock
		Tom Green		Upton		Shackelford	Lynn
				Ward		Stephens	Motley
						Stonewall	Parmer
						Taylor	Randall
						Throckmorton	Swisher
						Young	Terry
							Yoakum

Weather Station #	722700	723418	723510	723520	723527	723604
Weather Station Name	EL PASO INTERNATIONAL AP [UT]	TEXARKANA WEBB FIELD	WICHITA FALLS MUNICIPAL ARPT	ALTUS AFB	GAGE AIRPORT	CHILDRESS MUNICIPAL AP
Class	1	2	2	2	2	2
TX County Name(s)	Culberson	Bowie	Wichita	Hardeman	Hemphill	Childress
	El Paso	Red River		Wilbarger	Lipscomb	Collingsworth
	Hudspeth				Ochiltree	Cottle
	Jeff Davis				Roberts	Donley
	Presidio				Wheeler	Foard
						Gray
						Hall

Appendix III: Installation Details of Existing Parabolic Trough CSP Plants in US

Plant Name	SEGS I	SEGS II	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII	SEGS VIII	SEGS IX	NSO
Location	Daggett, CA	Daggett, CA	Kramer Junction, CA	Kramer Junction, CA	Kramer Junction, CA	Kramer Junction, CA	Kramer Junction, CA	Harper Lake, CA	Harper Lake, CA	
Start Year	1985	1986	1987	1987	1988	1989	1989	1990	1991	2007
Participants										
Developer(s):	Luz	Luz	Luz	Luz	Luz	Luz	Luz	Luz	Luz	Acciona Solar Power
Owner(s) (%):	Cogentrix (100%)	Cogentrix (100%)	NextEra (50%)	NextEra (38%)	NextEra (46%)	NextEra (41%)	NextEra (50%)	NextEra (50%)	NextEra (50%)	Acciona Energía (100%)
Operator(s):	Cogentrix	Cogentrix	NextEra	NextEra	NextEra	NextEra	NextEra	NextEra	NextEra	Acciona Solar Power
Generation Offtaker(s):	Southern California Edison	Southern California Edison	Southern California Edison	Southern California Edison	Southern California Edison	Southern California Edison	Southern California Edison	Southern California Edison	Southern California Edison	NV Energy
Plant Configuration										
Solar Field										
Solar-Field Aperture Area:	82,960 m²	190,338 m²	230,300 m²	230,300 m²	250,500 m²	188,000 m²	194,280 m²	464,340 m²	483,960 m²	357,200 m²
SCA Manufacturer (Model):	Luz (LS-1)	Luz (LS-1)	Luz (LS-2)	Luz (LS-2)	Luz (LS-2)	Luz (LS-2)	Luz (LS-2)	Luz (LS-3)	Luz (LS-3)	Acciona Solar Power (SGX-2)
SCA Description:	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	Parabolic trough SCA	
Solar-Field Outlet Temp:	307°C	316°C	349°C	349°C	349°C	390°C	390°C	390°C	390°C	393°C
Power Block										
Turbine Capacity (Gross):	13.8 MW	30.0 MW	30.0 MW	30.0 MW	30.0 MW	30.0 MW	30.0 MW	89.0 MW	89.0 MW	75.0 MW
Turbine Capacity (Net):	13.8 MW	30.0 MW	30.0 MW	30.0 MW	30.0 MW	30.0 MW	30.0 MW	80.0 MW	80.0 MW	72.0 MW
Output Type:	MHI regenerative steam turbine	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	MHI regenerative steam turbine, solar preheat and steam generation, natural-gas-fired superheater	
Power Cycle Pressure:	40.0 bar	40.0 bar	40.0 bar	40.0 bar	40.0 bar	100.0 bar	100.0 bar	100.0 bar	40.0 bar	
Turbine Efficiency:	31.5% @ full load	29.4% @ full load	30.6% @ full load	30.6% @ full load	30.6% @ full load	37.5% @ full load	37.5% @ full load	37.6% @ full load	37.6% @ full load	
Fossil Backup Type:	None	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	
Thermal Storage										
Storage Type:	2-tank direct									
Storage Capacity:	3 hour(s)									0.5 hour(s)
Thermal Storage Description:	Storage system was damaged by fire in 1999 and was not replaced									0.5 hours full-load storage
HCE Manufacturer (Model):			Solel Solar Systems (Solel UVAC)	Solel Solar Systems (Solel UVAC)	Solel Solar Systems (Solel UVAC)	Solel Solar Systems (Solel UVAC)	Solel Solar Systems (Solel UVAC)	Solel Solar Systems (Solel UVAC)	Solel Solar Systems (Solel UVAC)	Schott/Solel
HCE Type (Length):			Evacuated (4 m)	Evacuated (4 m)	Evacuated (4 m)	Evacuated (4 m)	Evacuated (4 m)	Evacuated (4 m)	Evacuated (4 m)	
Heat-Transfer Fluid Type:			Therminol	Therminol	Therminol	Therminol	Therminol	Therminol	Therminol	DOWTHERM A
									HTF Company:	Dow Chemical
									# of Solar Collector Assemblies (SCAs):	760
									# of SCAs per Loop:	8
									SCA Aperture Area:	470 m²
									SCA Length:	100 m
									Mirror Manufacturer:	Flabeg
									# of Heat Collector Elements (HCEs):	18240
									Solar-Field Inlet Temp:	318°C
									Solar-Field Temp Difference:	75°C
									Cooling Method:	Wet cooling
									EPC Contractor:	Lauren Engineering
Land Area:										400 acres
Solar Resource:								2,725 kWh/m2/yr	2,725 kWh/m2/yr	2,606 kWh/m2/yr
Source of Solar Resource:								National Solar Resource Data Base	National Solar Resource Data Base	Las Vegas TMY2 Data
Electricity Generation:										134,000 MWh/yr (Expected/Planned)

Data compiled from http://www.nrel.gov/csp/solarpaces/by_project.cfm

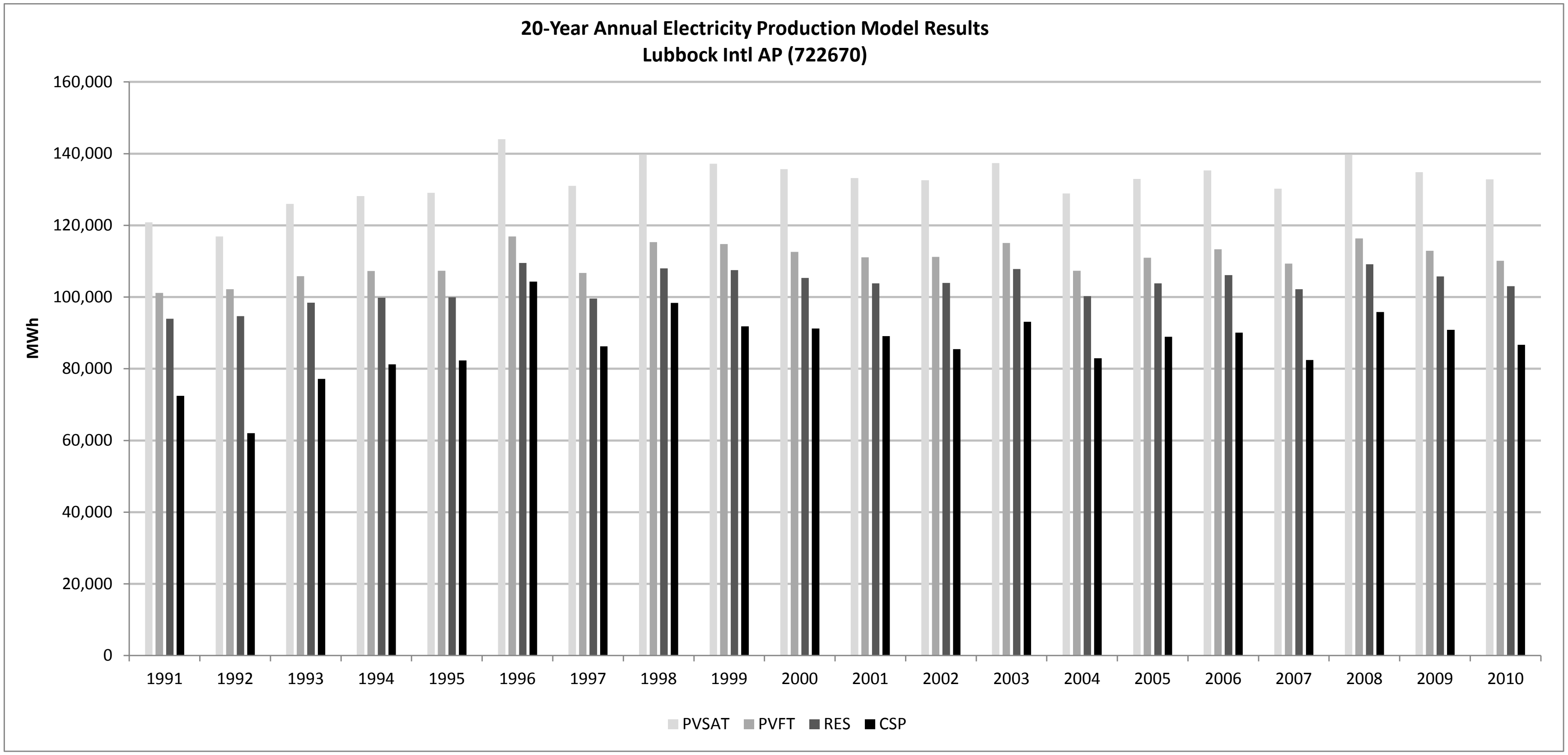
Appendix IV: Summary of Existing Parabolic Trough CSP Plants in US

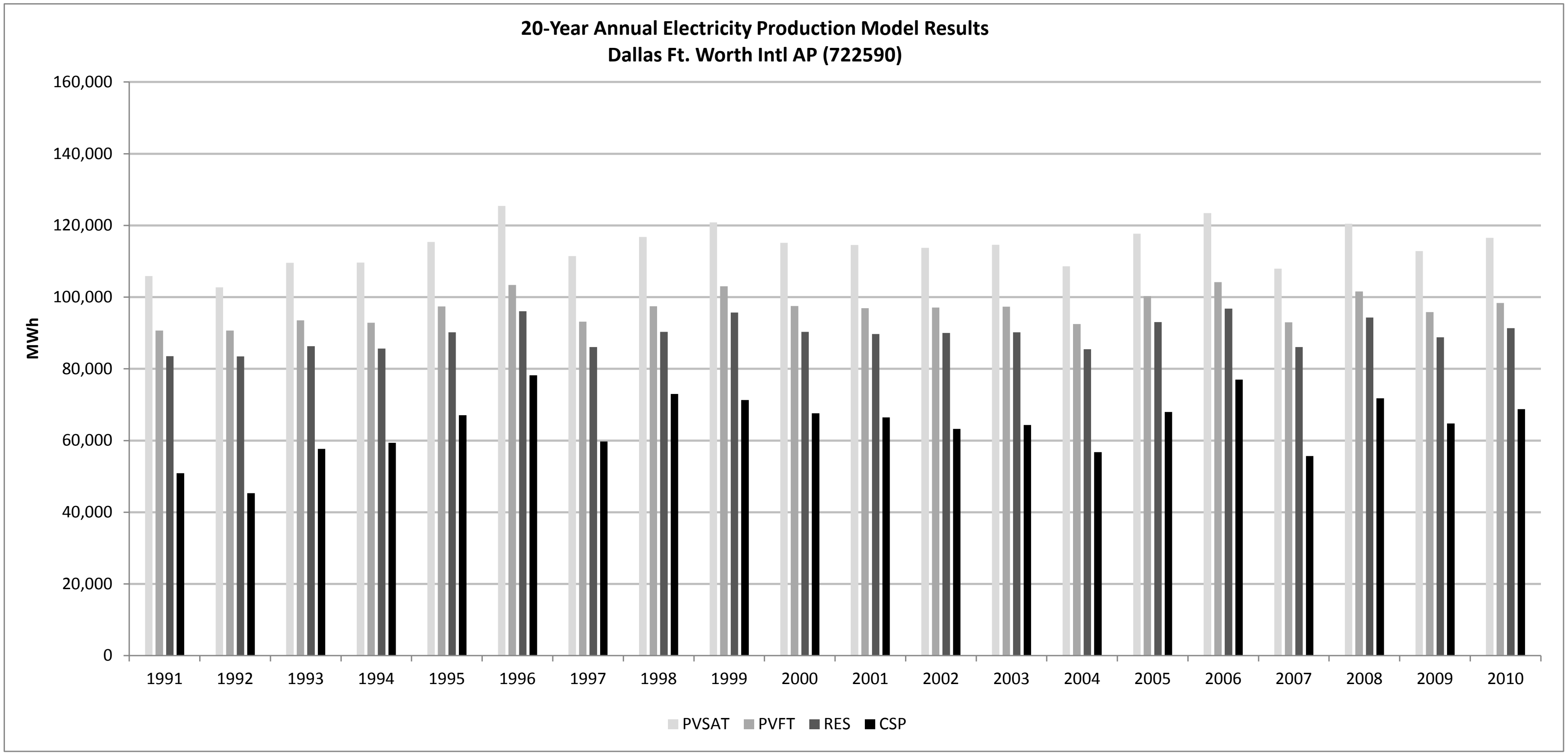
Plant Name	Location	First year of Operation	Net Output (MWe)	Solar Field Outlet (°C)	Solar Field Area (m2)	Solar Turbine Effic. (%)	Power Cycle	Dispatchability Provided By
Nevada Solar One	Boulder City, NV	2007	72*	390	357200	37.6	100 bar, reheat	None
APS Saguaro	Tucson, AZ	2006	1	300	10340	20.7	ORC	None
SEGS IX	Harper Lake, CA	1991	80	390	483960	37.6	100 bar, reheat	HTF heater
SEGS VIII	Harper Lake, CA	1990	80	390	464340	37.6	100 bar, reheat	HTF heater
SEGS VI	Kramer Junction, CA	1989	30	390	188000	37.5	100 bar, reheat	Gas boiler
SEGS VII	Kramer Junction, CA	1989	30	390	194280	37.5	100 bar, reheat	Gas boiler
SEGS V	Kramer Junction, CA	1988	30	349	250500	30.6	40 bar, steam	Gas boiler
SEGS III	Kramer Junction, CA	1987	30	349	230300	30.6	40 bar, steam	Gas boiler
SEGS IV	Kramer Junction, CA	1987	30	349	230300	30.6	40 bar, steam	Gas boiler
SEGS II	Daggett, CA	1986	30	316	190338	29.4	40 bar, steam	Gas boiler
SEGS I	Daggett, CA	1985	13.8	307	82960	31.5	40 bar, steam	3-hrs TES

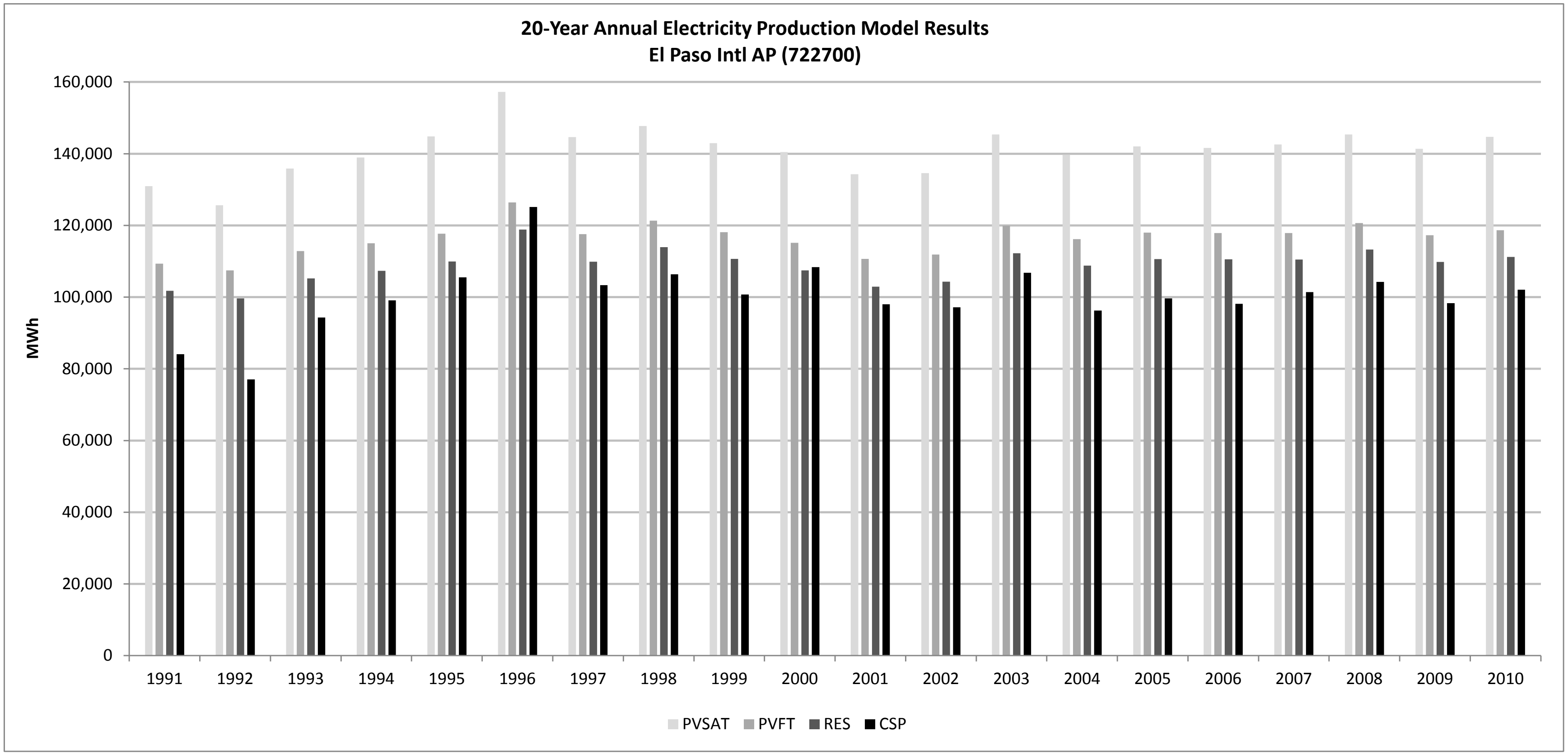
http://www.nrel.gov/csp/troughnet/power_plant_data.html
*Net output updated based on data from: http://www.nrel.gov/csp/solarpaces/by_project.cfm

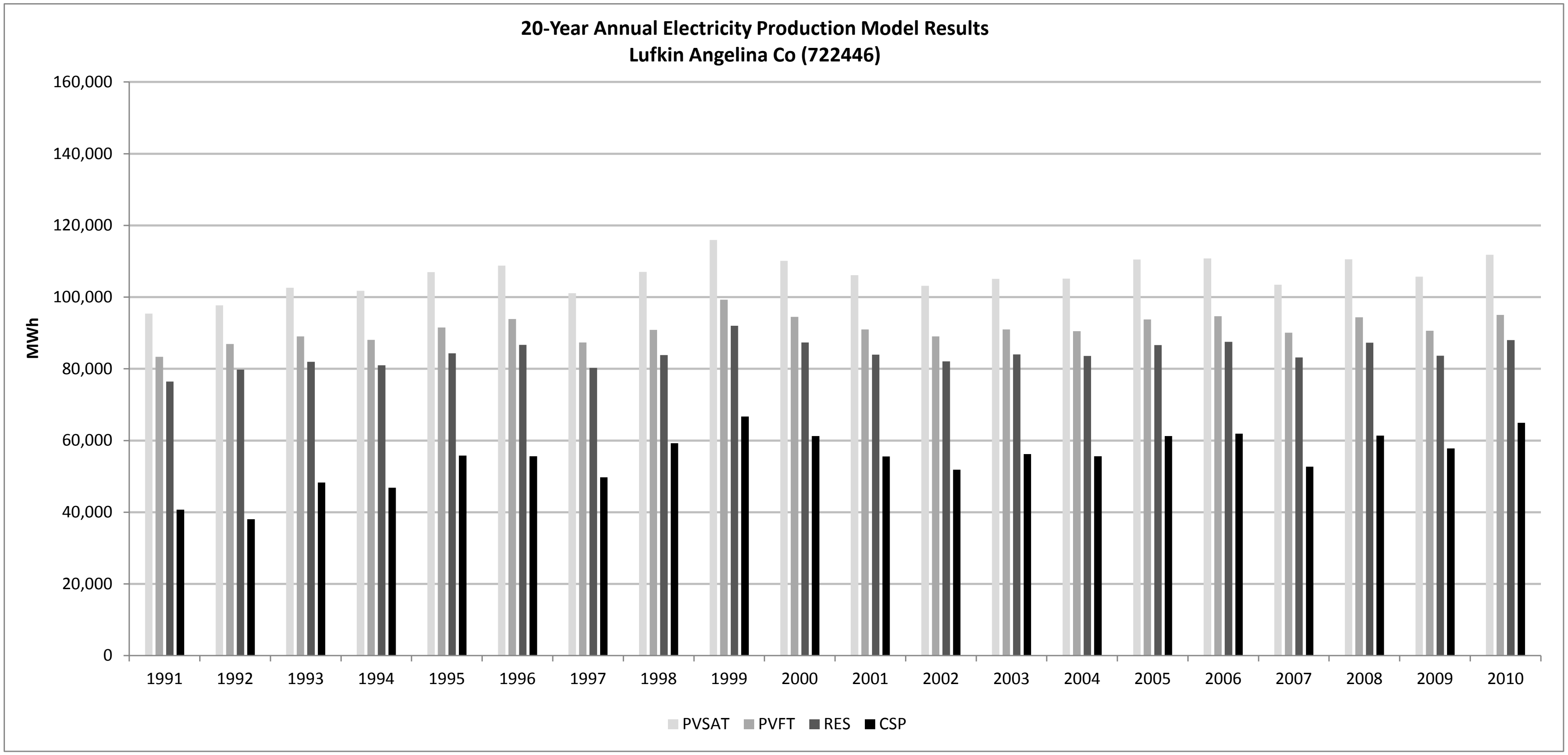
Appendix V: 20-Year Solar Production Estimates

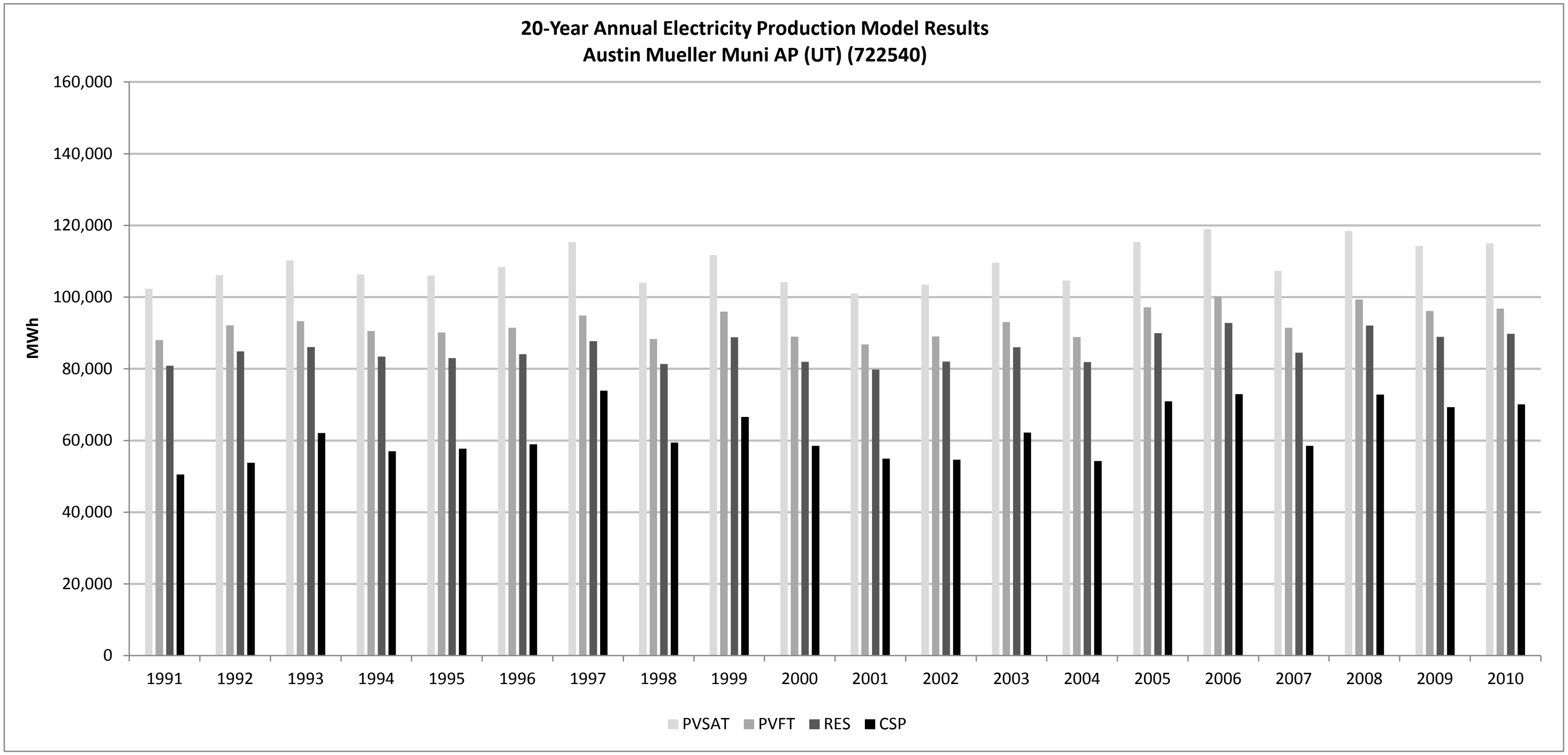
(Production values normalized to 50-MW equivalent)

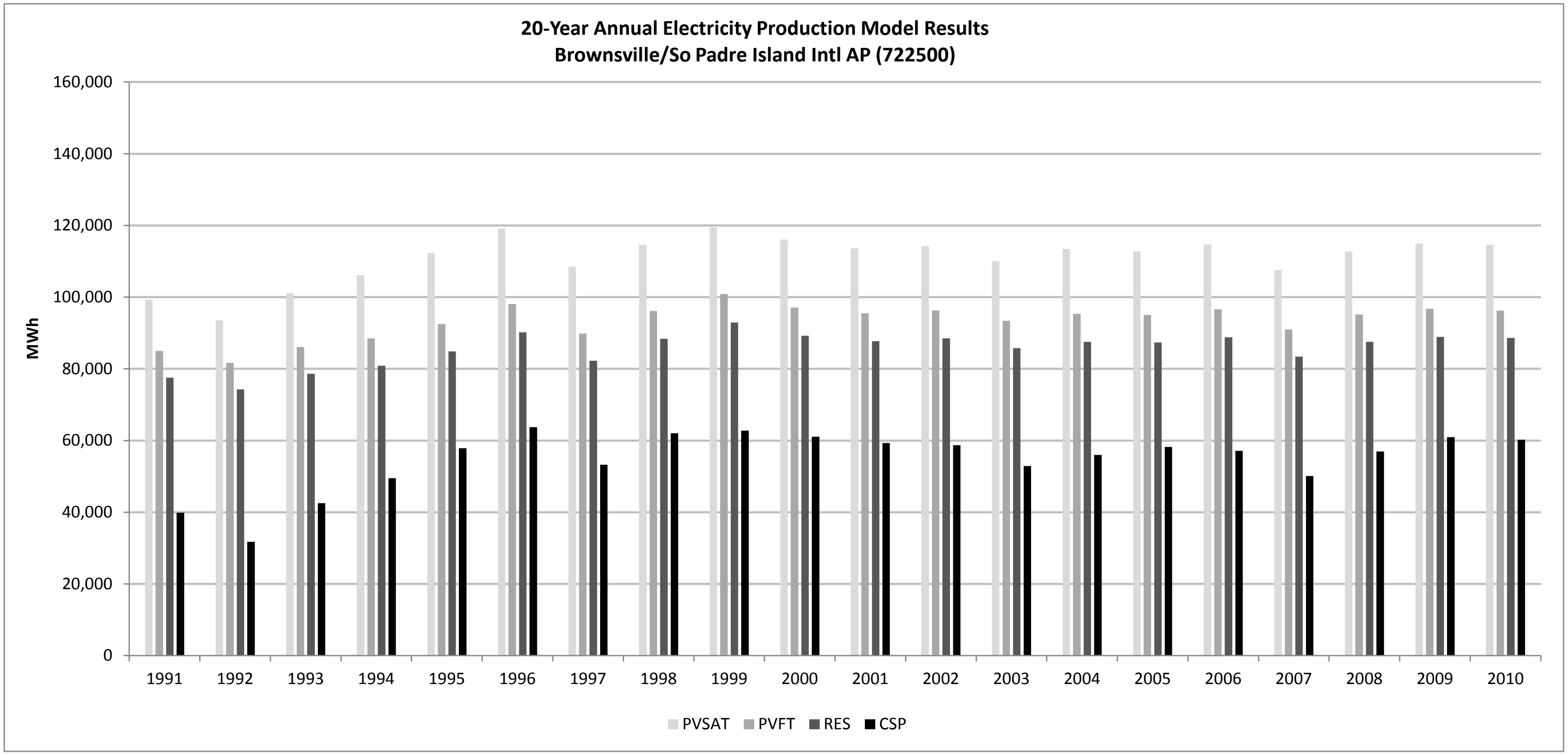



20-Year Annual Electricity Production Model Results
Dallas Ft. Worth Intl AP (722590)
MWh
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
PVSAT
PVFT
RES
CSP


20-Year Annual Electricity Production Model Results
El Paso Intl AP (722700)
MWh
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
PVSAT PVFT RES CSP


20-Year Annual Electricity Production Model Results
Lufkin Angelina Co (722446)
MWh
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
PVSAT
PVFT
RES
CSP


20-Year Annual Electricity Production Model Results
Austin Mueller Muni AP (UT) (722540)
MWh
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
PVSAT
PVFT
RES
CSP


20-Year Annual Electricity Production Model Results
Brownsville/So Padre Island Intl AP (722500)
MWh
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
PVSAT
PVFT
RES
CSP