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Technical Assistance for Southwest Solar Technologies Inc. Final Report

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Abstract

Southwest Solar Technologies Inc. is constructing a Solar-Fuel Hybrid Turbine energy system. This innovative energy system combines solar thermal energy with compressed air energy storage and natural gas fuel backup capability to provide firm, non-intermittent power. In addition, the energy system will have very little impact on the environment since, unlike other Concentrated Solar Power (CSP) technologies, it requires minimal water.

In 2008 Southwest Solar Technologies received a Solar America Showcase award from the Department of Energy for Technical Assistance from Sandia National Laboratories. This report details the work performed as part of the Solar America Showcase award for Southwest Solar Technologies. After many meetings and visits between Sandia National Labs and Southwest Solar Technologies, several tasks were identified as part of the Technical Assistance and the analysis and results for these are included here.

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CONTENTS

1. Introduction and Background	9
1.1. Addressing Intermittency.....	9
1.2. Reducing Water Consumption.....	9
1.3. How the System Works	10
1.3.1. The Dish Turbine Generator (DTG)	11
1.3.2 Compressed Air Energy Storage	11
1.4. History of the SolarCAT Solar Showcase Award.....	11
1.5. Project Scope and Objectives.....	12
1.6. Budget and Timeline	12
2. Cyber Analysis.....	15
2.1 Task Objectives.....	15
2.2 Technical Approach.....	16
2.3 Recommendations.....	16
3. Power Systems and Grid Impact Modeling	17
3.1 Systems Dynamics Model.....	17
3.1.1 Dish Turbine Generator Simulated Energy Flows.....	18
3.1.2 Home Page User Interface	19
3.1.3 User Inputs	19
3.1.4 Outputs.....	23
3.1.5 Master Table of Contents Interface.....	25
4. Compressed Air Energy Storage.....	29
4.1 Analysis: Internal Pressure Load (Steel Design)	29
4.1.1 Results.....	30
4.1.2 External Pressure Loading with Zero Internal Pressure (Concrete Design) ...	31
5. Solar Engineering.....	33
6. Conclusions.....	35
7. References.....	37
Distribution	38

FIGURES

Figure 1. Sample Power Production Curve of a Solar-Fuel Hybrid Turbine Energy System.	10
Figure 2. Dish Turbine Generator Conceptual Diagram.....	12
Figure 3. System Dynamics Model Simulated Energy Flows.	19
Figure 4. Home Page User Interface.....	20
Figure 5. User Inputs Interface.	21
Figure 6. Firm Demand Curve Interface for Jan-March.	22
Figure 7. Power Production Curves.....	24
Figure 8. Energy Production and Average Cost per kWh Produced.	24
Figure 9. Master Table of Contents	25

Figure 10. Conceptual Modular Design.....	29
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TABLES

Table 1. CSP Water Usage Comparison.....	10
Table 2. Deliverable Schedule	13
Table 3. Default Parameter Values.	20
Table 4. Master Table of Contents Interface – Hyperlink Description.....	26
Table 5. Summary of Cylinder Dimensions and Materials Required	32

1. INTRODUCTION AND BACKGROUND

Southwest Solar Technologies was founded in 2008 with the vision of designing and creating a firm-power Solar-Fuel Hybrid Turbine energy system that would address two difficult problems; intermittency and water consumption.

1.1. Addressing Intermittency

Photovoltaic (PV) technologies are an intermittent power source dependent wholly on the availability of the solar resource. There are several drawbacks to intermittent power including:

- Power production is not reliable or firm as the system can only provide power when the resource is available
- A system (PV or wind) cannot be a stand-alone system without the addition of some type of energy storage
 - Energy storage (e.g. batteries) can be very expensive, and may require difficult and time-consuming maintenance
- The intermittent nature of PV can cause stability issues in a system with high penetration levels.

The proposed system will address intermittency by giving the option of using natural gas (or other fuel) to provide cost effective and reliable power (See Figure 1). Using natural gas as backup will allow for power production when the time of day or weather prevents the system from meeting its objective power output levels (e.g. during the night or on a cloudy day). For utilities, fixed power is a more valuable resource than intermittent power because it may allow the utility to decrease their spinning reserve requirements, possibly resulting in cost savings. With an intermittent power source, utilities need to have spinning power reserve that will allow them to quickly generate any power that was not provided by the intermittent system. A fixed power source can also, in some cases, avoid the grid stability issues that may arise with intermittent power.

1.2 Reducing Water Consumption

Water and energy are both essential components of modern civilization. The demand for water and energy is proportional to population increase as well as increase in urbanization. Water scarcity is a growing problem in many parts of the world. Even in places where there is plenty of rainfall or freshwater, water scarcity can still be an issue due to the lack of infrastructure for fetching, treating, storing and distributing water [1]. Making the problem even more difficult is that energy and water are inevitably tied together; energy production requires large quantities of water and water extraction, processing and delivery also require large quantities of energy.

Traditional CSP technologies, such as parabolic trough's or power towers, typically use steam turbines that require large amounts of water to generate thermal and electric energy (See Table 1). The Solar Dish-Turbine is one of the few power generating options that requires very little water, making it an ideal choice in places where water is scarce or expensive to treat.

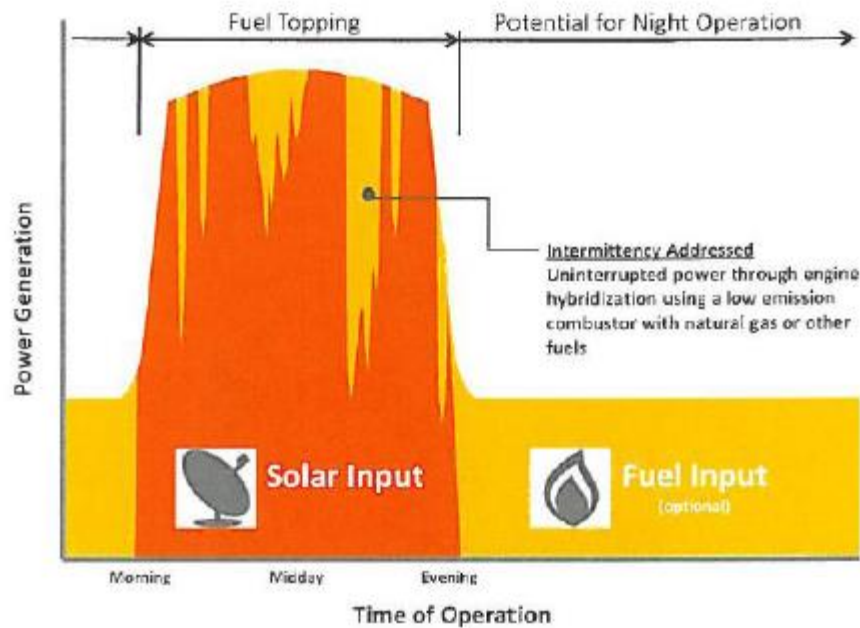


Figure 1. Sample Power Production Curve of a Solar-Fuel Hybrid Turbine Energy System.

Table 1. CSP Water Usage Comparison

Power Generation Technology	Gallons/MWh
Parabolic Trough or Power Tower	1000
Gas-Fired Steam	662
Nuclear	609
Coal-Fired Steam	541
Combined Cycle	360
Solar Dish-Turbine	< 1

1.3 How the System Works

The Solar-Fuel Hybrid Turbine energy system consists of one or several Dish-Turbine Generators (DTGs). Construction of a single DTG is underway at the Southwest Solar Research Park in Phoenix, Arizona. Southwest Solar Technologies (SWST) plans to construct arrays of DTGs that would provide firm power to customers in the southwest US and other desert regions

across the globe. The DTG is a 23 meter parabolic solar concentrating dish that directs sunlight into a heat exchanger to super heat the compressed air (See Figure 2). During times of insufficient solar input, firm power demand will be produced with augmentation from natural gas or other fuel of choice. The initial design configuration of the solar DTG integrates compressed air from ground-mounted air compression with Compressed Air Energy Storage (CAES) so that off-peak power, whether conventional or renewable (e.g. night-time wind, geothermal, etc.) may be used for compression. A second design configuration incorporates on-dish air compression in a more conventional Brayton turbine cycle, without the use of CAES, but still with the fuel hybrid capability for firm power during times of no-sun.

1.3.1. The Dish Turbine Generator (DTG)

The major components of the DTG are shown in Figure 2. The DTG will use energy released from solar-heated compressed air and augmented as necessary by a fossil fuel burner. In the solar receiver, thermal energy is transferred to the compressed air. The superheated compressed air is then directed to a turbine that drives an AC generator. The combined turbine and generator system is referred to as the dish turbine Power Conversion Unit (PCU). Air exiting from the PCU is routed through a recuperator for energy recovery where incoming compressed air is preheated before being introduced to the solar receiver. During periods of lower than required solar thermal input, natural gas or other fuels can be used in the combustor to augment or completely replace the solar input.

1.3.2 Compressed Air Energy Storage

Not illustrated in Figure 2 is the Compressed Air Energy Storage (CAES) system consisting of a compressor (or a chain of compressors hooked up in series) and a storage tank. The tank can be anything from a relatively small man-made tank that could cover power production for hours or a natural cavern that would provide compressed air for several days. A CAES system would allow charging during periods of low electricity (low pricing) and discharging during the peak demand (high market value of electricity generation). Without CAES, compression occurs on the engine during generation and becomes a parasitic load.

1.4 History of the SolarCAT Solar Showcase Award

In 2008, a Department of Energy (DOE) Solar America Showcase was awarded to SWST. In late 2009, DOE approved Sandia's recommendation to use the America Showcase award for cyber security, performance and efficiency modeling, and other technical support areas.

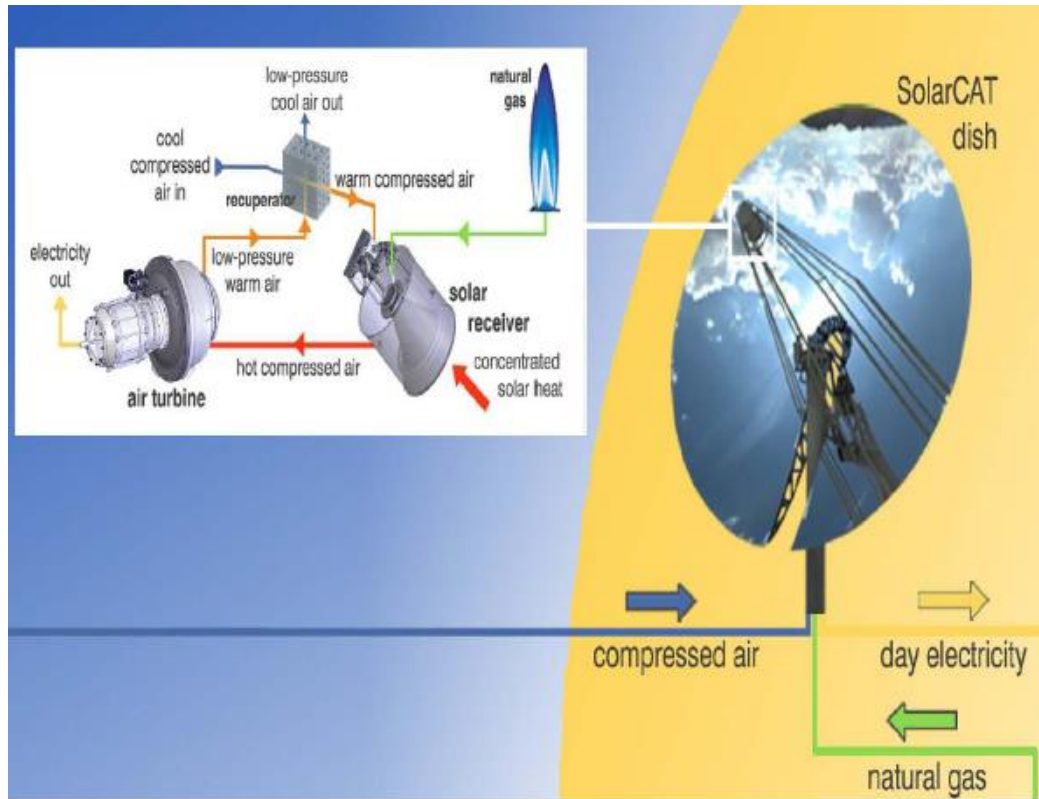


Figure 2. Dish Turbine Generator Conceptual Diagram.

1.5 Project Scope and Objectives

After visits, data gathering and several meetings, Sandia and the SWST team identified several tasks:

- Site Evaluation and Finalization of SOW
- Cyber Analysis
- Power Systems and Grid Impact Modeling
- Compressed Air Energy Storage
- Solar Engineering
- Project Management and Reporting

The Cyber analysis findings can be found in a separate report. This reports documents results and findings from the remainder of the tasks.

1.6 Budget and Timeline

The total cost to provide Technical Assistance to SWST for the tasks described above was \$252,000. Completion dates for all tasks are listed in Table 2.

Table 2. Deliverable Schedule

Task	Deliverable	Completion Date
1.0	Site Evaluation and Finalization of SOW	
2.0	Cyber Analysis	September 2010
2.1	Initial Review of Data	September 2010
2.2	Data Analysis and System Design Review	September 2010
3.0	Power Systems and Grid Impact Modeling	November 2011
4.0	Compressed Air Energy Storage	November 2011
5.0	Solar Engineering	November 2011
6.0	Project Management and Reporting	Ongoing until 60 days beyond the end of the project period

2. CYBER ANALYSIS

The full details of the Southwest Solar Architecture Cyber Analysis, including technical approach, findings, analysis and recommendations are given in a separate report titled, "Cyber Security Assessment of the SolarCAT/Southwest Solar Architecture, Tempe, AZ" and only a summary is given in this report.

The Solar-Fuel Hybrid Turbine energy system is unique in the renewable industry because it combines solar thermal energy with compressed air energy storage and natural gas fuel backup capability. To the best of the team's knowledge, there is no precedence for assessing the cyber security of this type of system. While this is a new architecture to assess, the foundational elements of cyber security energy systems apply to this analysis. The principles governing energy surety and continuity of operations and energy flow are followed in the assessment of this system.

In September, 2009 and January, 2010, Sandia staff visited both the Tempe and Research Park sites to determine the areas of support that could be accomplished by Sandia, and to gather data and perform an initial network architecture review. Sandia performed an assessment of the Solar-Fuel Hybrid Turbine energy system architecture, and supported ongoing interaction with the SWST IT and Engineering teams to ensure cyber security was built in to their life cycle plan. Initial discussions focused on SWST's architecture at the Tempe location. However, as SWST planned for the build-out at the Research Park site, Sandia was able to work with them to address the design and functionality of the new site's architecture in near real-time. It was determined that the greatest value to SWST would be to focus on the Research Park location and the remote connectivity to it and other distributed locations. Lessons learned from the upfront implementation of cyber security in the initial build-out of the Research Park site can be used in the development of other potential sites, such as the West Valley location.

Considering both the logical and physical design of the system, the team identified critical points of failure and areas of concern, including consideration of physical access and security at the site and pedestal. Research Park is a highly visible site and could potentially become a valuable target. Many interest groups will have some level of access to Research Park as well. These issues present challenges in securing the architecture, but the present state of development and design provide an opportunity to include security early on in the life-cycle.

2.1 Task Objectives

The cyber analysis focused on the Research Park site, and specifically addressed remote connectivity to the Research Park site, and connectivity with other distributed locations. Both the business and control system networks were considered in the analysis. Recommendations are applicable to future sites, such as the West Valley facility.

Several objectives were identified for the Cyber Analysis task. These include:

- Analyze the SWST business and control system architectures, and develop recommendations to implement an inherently secure architecture
- Provide analysis and assessment of the Solar-Fuel Hybrid Turbine energy system architecture, and support ongoing interaction with the SWST IT and Engineering teams, to ensure cyber security is built into the life cycle plan of existing, planned, and future installations
- Provide recommendations that can be used by other potential SWST projects, such as the West Valley facility, to ensure cyber security is built into the life cycle plan for all new installations
- Provide recommendations for secure remote access to SWST installations
- Provide recommendations for secure connectivity between all existing and planned SWST installations
- Make recommendations and provide mitigation strategies that have real world applicability, and that can be implemented with manageable cost and effort
- Provide information that will help SWST develop security policies that enable them to maintain and monitor their cyber security efforts

2.2 Technical Approach

Although the Solar-Fuel Hybrid Turbine energy system is unique because it combines solar thermal energy with compressed air storage and natural gas fuel backup capability, the standard process developed to address cyber security for renewable based energy systems is applicable. Cyber security analysis and assessment of energy systems includes:

1. Gathering data
2. Assessing the architecture
3. Identifying critical points of failure
4. Assessing risk in terms of threat, vulnerability, and consequence
5. Enumerating findings
6. Recommending mitigations

2.3 Recommendations

Based on findings and analysis of data gathered during site visits and ongoing collaboration with the SWST team, many detailed recommendations were made and are presented in the full report. Due to sensitivity issues, these recommendations have been omitted from this report.

3. POWER SYSTEMS AND GRID IMPACT MODELING

The DTG is a complex hybrid system where variable solar and fuel input may be combined with or without compressed air generation and/or storage in various design and operating scenarios. Simulation tools are needed to test configuration and dispatch options and calculate operation costs for economic and reliability analysis. The system dynamics model, the simulation tool described below, provides estimates of potential energy production and associated fuel costs based on user selected operation parameters.

The systems dynamics model is a time series model that allows investigation of fuel consumption and costs under different power generation and compression strategies. To accomplish this, the model simulates flows within the DTG based on user specified input. These flows include DTG power production from solar and fuel input, compressed air demand, and state of CAES given inputs from the user. The user has the option of excluding the CAES system in the model allowing for direct injection of compressed air from a compressor.

3.1 Systems Dynamics Model

The system dynamics model is built in Powersim Studio¹, a broadly used System Dynamics software package. The software has several benefits including:

- Model inputs can be easily altered by the use of sliders, radio buttons, etc. This is a great feature for projects with a lot of unknowns
- Simulations generally run rather quickly. This provides the capability to run numerous "what-if" scenarios quickly and efficiently
- Easy to understand outputs. This software platform has easy to use plotting functions that make it easy to understand what is going on in the model, find errors within the model and explain to others (possible stake-holders) how the model works

The model is designed to simulate energy flows in the DTG system. It is important to note that reheating of the air by the recuperator is not specifically included in the model, but its beneficial effects are included in the engine efficiency parameters. The user selects the net plant power production capacity, specifies a firm power curve and can either schedule compression for storage or specify net power generation to account for parasitic losses (e.g. power required for real time compression). The user specifies the firm power desired in blocks, where the power delivery goes from zero to a maximum power output in a series of steps. Other options for selecting a firm power curve are available to the user including:

¹ Additional information on Powersim Studio, including price information, can be obtained at the following website: <http://www.powersim.com>.

- Emulating a day of full DNI with no clouds
- Scaled-DNI curve converted to power
- Time cycle selection that repeats user specified interval of operation and power demand over a 24 hour period.

In any firm power selection routine, fuel energy is added to the system to make up the difference between power from solar input and that of the specified firm power curve.

Although currently in the US interest in funding large scale energy storage is low due to an excess of conventional power capacity with low natural gas prices, largely caused by the slowdown in electricity demand growth, the CAES component was left in the model as an option to the user.

3.1.1 Dish Turbine Generator Simulated Energy Flows

The system dynamics model simulates the predominant energy flows through the DTG system. These energy flows are depicted in Figure 3 and listed below:

- Thermal Energy for heating of compressed air is calculated using the Sky Harbor Typical Meteorological Year 3 (SH-TMY3) direct normal irradiance (DNI) data from the National Solar Radiation DataBase [2] and a conversion factor provided by SWST
- Solar input is augmented with fuel thermal energy for compressed air to support power production for firm power requirements during periods of wavering solar input and/or constant power output requirements
- Conversion of energy from expanding and heated compressed air to electrical energy is accomplished through a conversion factor provided by SWST
- Power used for compression is set by the user and is termed "Net Power Plant Production"
 - For the Compressed Air Energy Storage (CAES) case, the model only compresses during hours the user specifies through a Time of Use (TOU) table

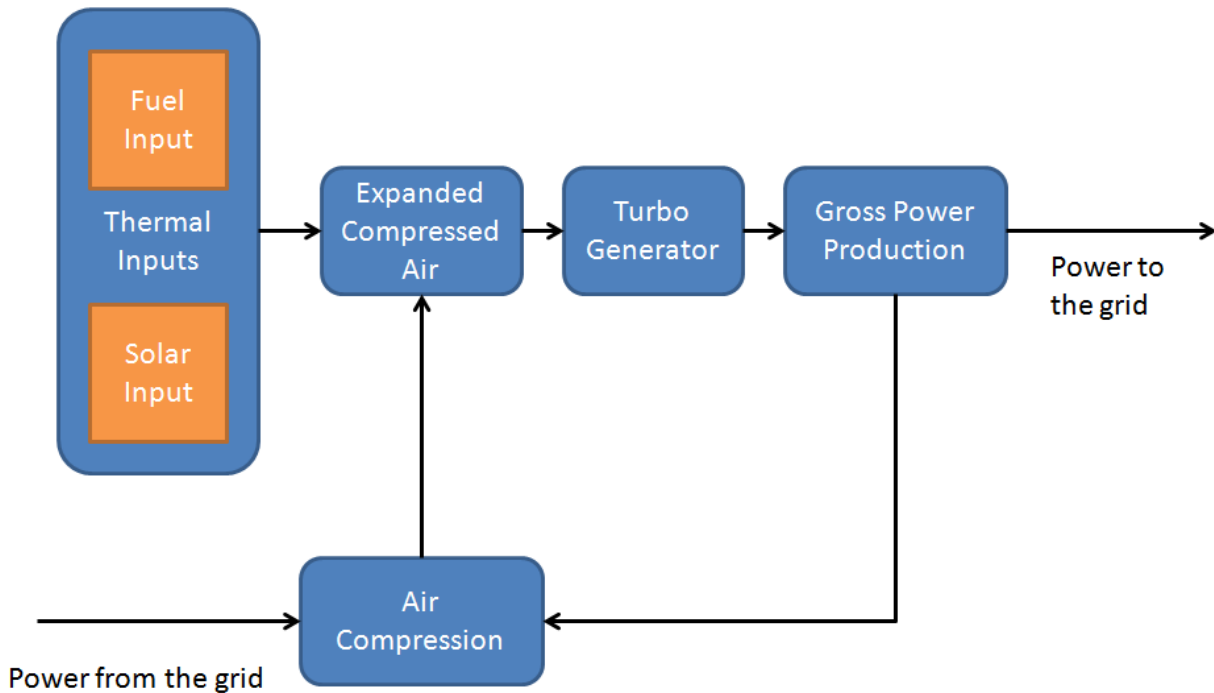


Figure 3. System Dynamics Model Simulated Energy Flows.

3.1.2 Home Page User Interface

The *Home Page* user interface, is the default interface that is displayed upon opening the model in Powersim Studio (Figure 4). This interface contains model input parameters, output plots and tables pertinent to exploring fuel consumption and costs associated with meeting a firm demand curve with real time air compression. The interface also contains hyperlinks, which provide a quick method for moving around within the model. Inputs and outputs selected for this interface were requested by SWST and in order to minimize interface clutter, all other inputs and outputs are not included.

3.1.3 User Inputs

Figure 5 shows the User Inputs interface. The following user inputs are available through the *Home Page* user interface:

- **Power Plant Net Capacity:** The total net capacity of the power plant
- **Dish Unit Net Power Production at 850 W/m² DNI:** The net power production from a single dish at 850 W/m² DNI
- **Minimum Burner Operation Threshold:** The minimum percentage that the burner can operate before it shuts off completely

- Burner Efficiency Factor: The efficiency of the burner (is used to account for air reheating)
- Energy Density (diesel and natural gas)
- Fuel Price (diesel and natural gas)

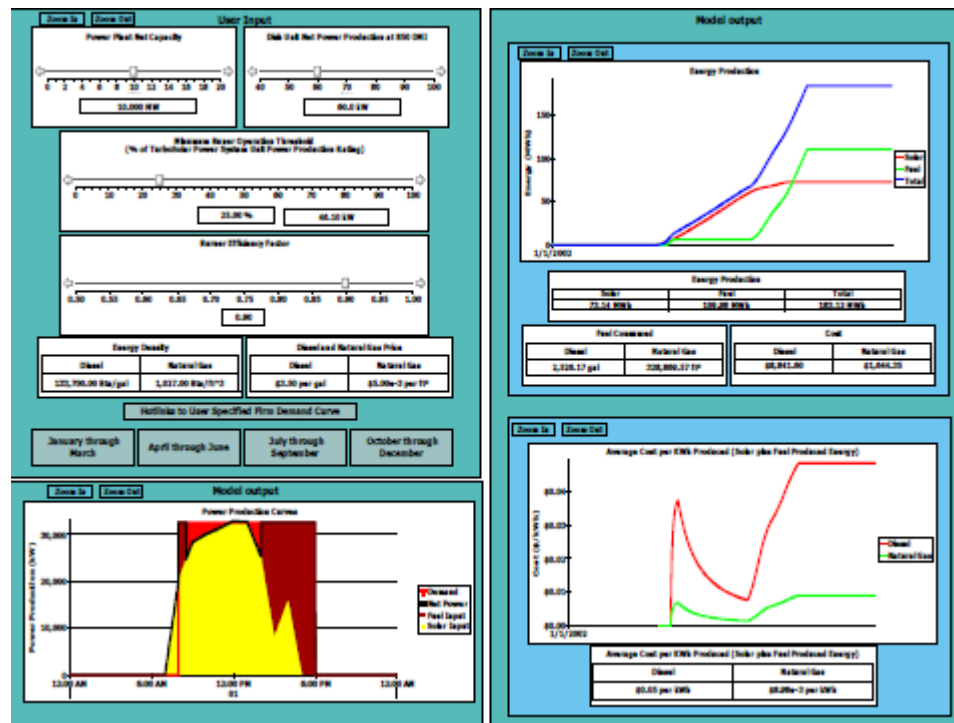


Figure 4. Home Page User Interface.

Default values for the user inputs above are given in Table 3 below.

Table 3. Default Parameter Values.

Parameter	Default Value
Power Plant Net Capacity	10 MW
Dish Unit Net Power Production at 850 W/m ²	60 kW
Minimum Burner Operation Threshold	25%
Burner Efficiency Factor	0.9
Energy Density – Diesel	133,700 Btu/gal
Energy Density – Natural Gas	1,027 Btu/ft ³
Fuel Price- Diesel	\$3.50/gal
Fuel Price – Natural Gas	\$0.005/ft ³

In addition to the inputs mentioned above, the user must also specify what the Firm Demand Curve should look like.

User Input

Net Power Plant Capacity
 Slider: 0 to 20
 Value: 10.000 MW

Dish Unit Net Capacity at 850 DNI
 Slider: 40 to 100
 Value: 60.0 kW

Minimum Burner Operation Threshold (% of TurboSolar Power System Unit Power Production Rating)
 Slider: 0 to 100
 Value: 25.00 %
 Value: 46.10 kW

Burner Efficiency Factor
 Slider: 0.50 to 1.00
 Value: 0.90

Energy Density	
Diesel	Natural Gas
133,700.00 Btu/gal	1,027.00 Btu/ft ³

Diesel and Natural Gas Price	
Diesel	Natural Gas
\$3.50 per gal	\$5.00e-3 per ft ³

Hotlinks to Firm Demand Curve Interface

January through March April through June July through September October through December

Figure 5. User Inputs Interface.

Firm Power Demand Curve Interface

The Firm Power Demand Curve (FPDC) Interface is accessed with the hot links as described earlier and it is presented in Figure 6 and briefly described next. The FPDC Interface is comprised of four identical interfaces, each containing consecutive three months of individual bar curves and associated tables of DNI values through which the user can adjust the firm power demand curve. Each bar corresponds to a full hour of the day, hence there are 24 bars. In its default setting, 14 of the bars have a zero value. A fourth plot at the bottom of the interface shows the users selection in kW given the default 184 kW/850 W/m² DTG rating. Note that this power production to DNI rating can be changed through the master interface discussed above.

Initially it may be confusing to the user that the DNI is the variable that the user is changing in order to specify the FPDC. The interface was built this way to accommodate a graphical comparison between the user selected FPDC and the maximum TMY3 DNI value for each hour for each month within the interface and to have an input that was independent of the default power to DNI rating. The maximum DNI is displayed as the green line in DNI the plots and is converted to power in the lower plot.

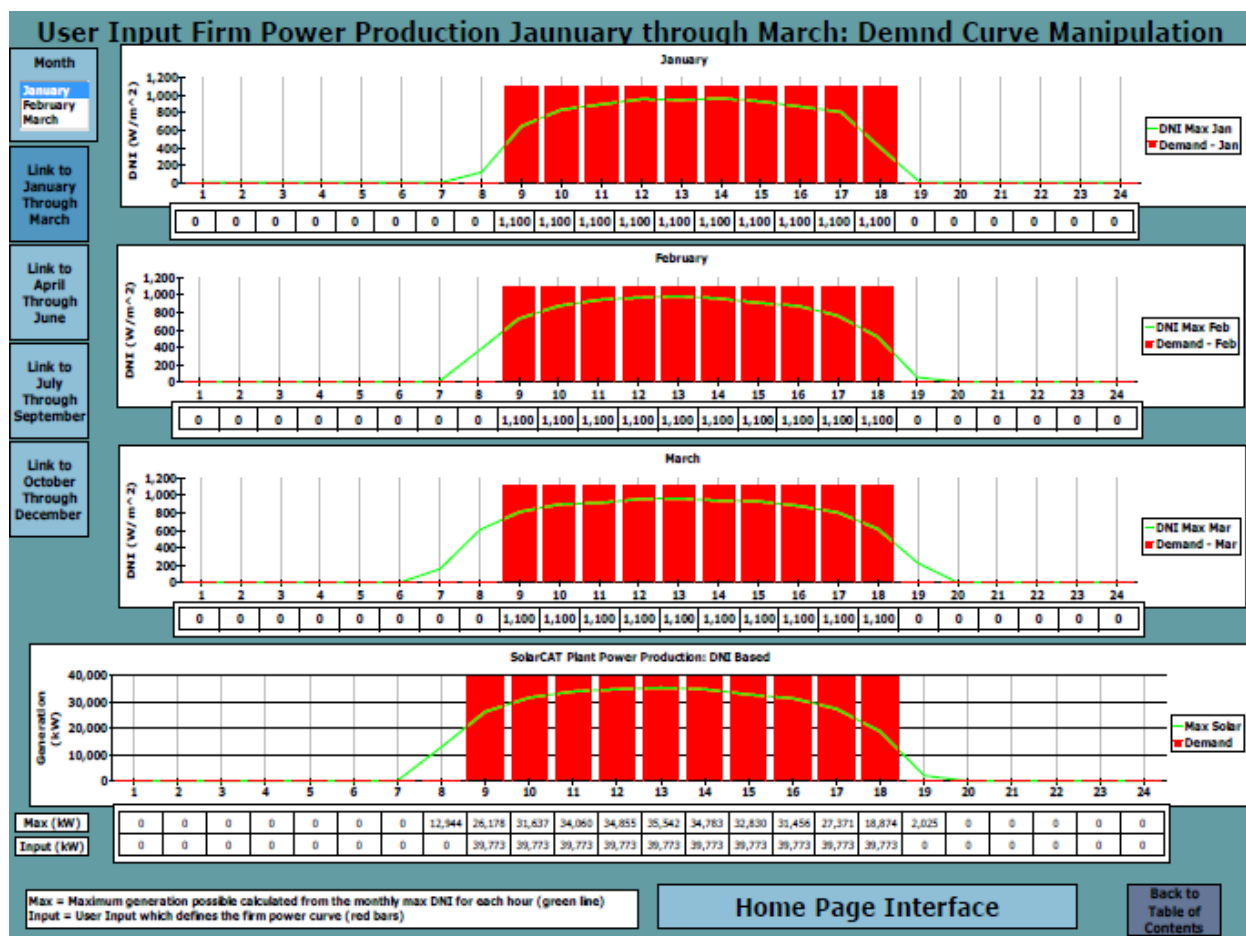


Figure 6. Firm Demand Curve Interface for Jan-March.

To use this interface, the user first picks the month in the list box in the upper left hand corner and adjusts the bars by clicking by dragging it up or down. The user can also enter the desired value in the associated table located immediately at the base of the plot. Note that as you change the DNI values, the kW value in of the associated hour in the bottom plot also changes.

Two tables are at the bottom of the kW plot, the upper of which gives the kW value for the green line (monthly hourly maximum) for that hour and the lower gives the kW value for the user selected DNI value.

The user can access the other two months on this interface by selecting the desired month in the list box at the upper left of the interface. Access to additional months can be obtained by clicking on the hyperlinks on the left side of the interface.

The default settings for the DNI bars are located in the Demand-User Input tab in the TMY3 Phoenix Sky harbor Intl AP.xlsx workbook.

3.1.4 Outputs

There are three main output plots displayed on the *Home Page*. These are listed below.

1. The "Power Production Curves" plot displays the following:
 - a. Desired Firm Demand Curve (FDC)
 - b. Power production using only solar input
 - c. Power production using solar and fuel input

Figure 7 shows a sample run. In the figure, the red curve is the FDC specified by the user. The yellow curve is the Power produced using solar input. It is important to note that the solar input allows for power production before the desired FDC commences. The area under the black bold line is the total power produced using both solar and fuel inputs. The total power production does not quite match the desired FDC. This is due to the burner limitations (25 % minimum threshold).

2. The "Energy Production" plot (Top plot in Figure 8) displays the number of MWh produced by solar, fuel and the addition of both since the start of the simulation. Values for "Fuel Consumed" and associated costs are also displayed.
3. The bottom plot in Figure 8 displays the average cost per kWh that has been produced since the start of the simulation. Both diesel and natural gas costs are plotted against each other for easy comparison. The total fuel costs are calculated from the accumulated Fuel Energy Production after converting to volumetric measures (given energy densities) and then to cost (given volumetric prices). The user has the option of changing the default energy densities and prices on the *Home Page* interface.

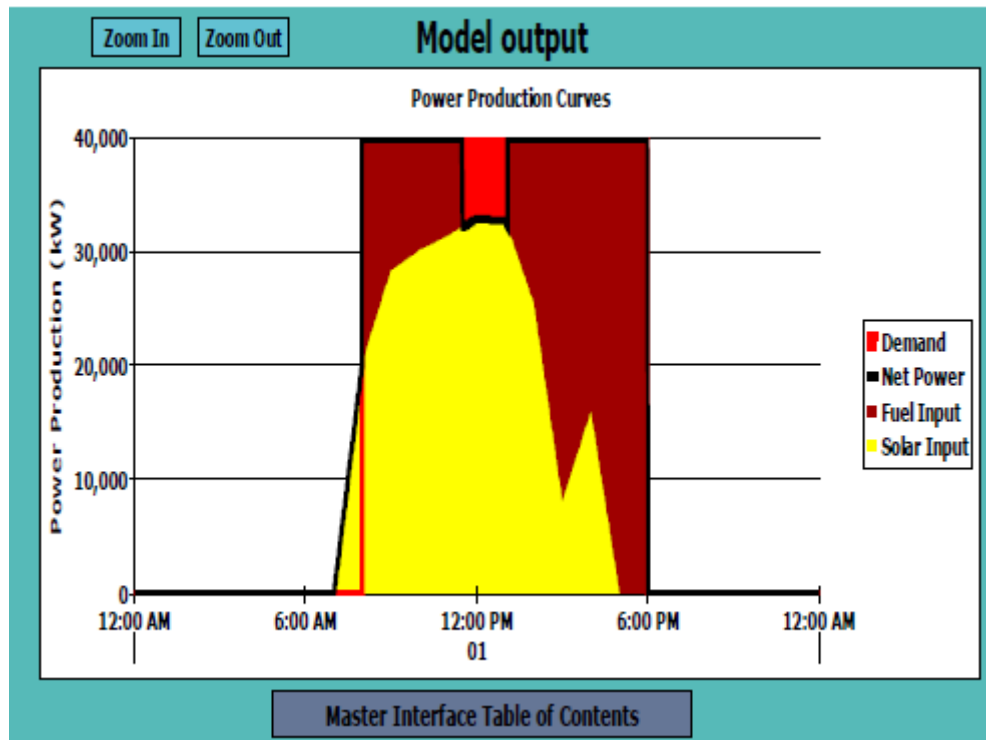


Figure 7. Power Production Curves.

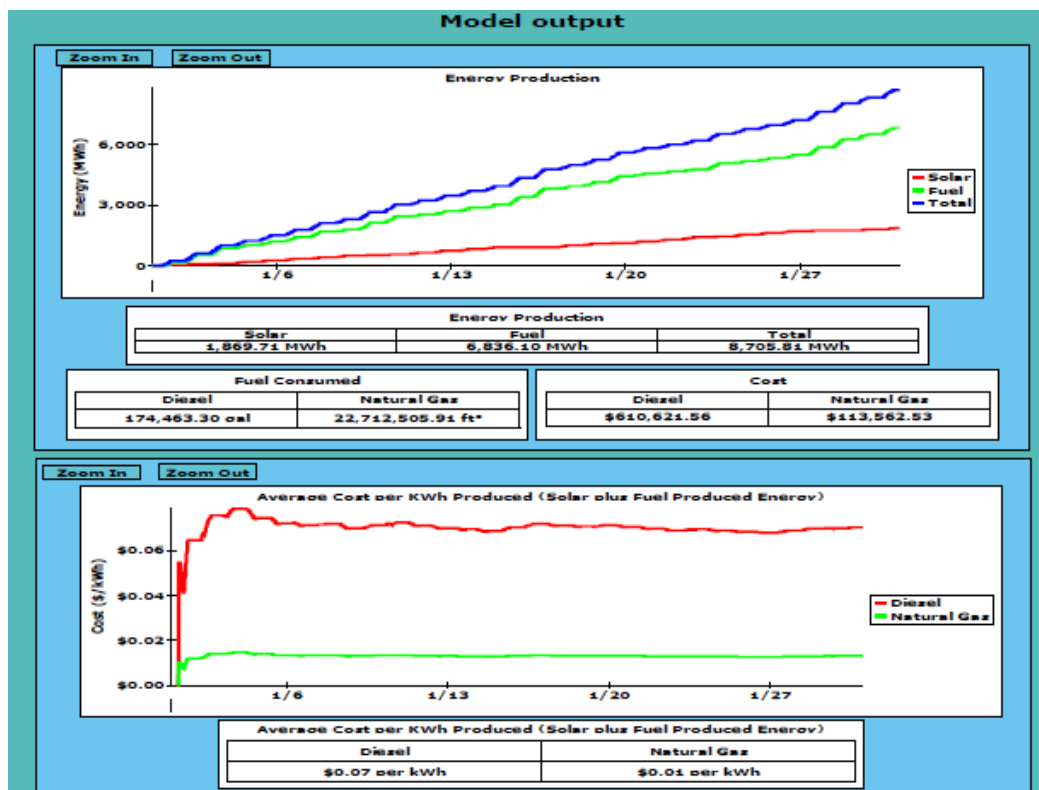


Figure 8. Energy Production and Average Cost per kWh Produced.

3.1.5 Master Table of Contents Interface

The Master Table of Contents (MTOC) (Figure 9) and its associated links can be accessed from the *Home Page* through the links at the bottom of the interface. This page includes a series of hotlinks used to move around the model. Additional user inputs and outputs, not on the *Home Page*, can also be accessed through the Master Table of Contents Interface. A list of all links and a brief summary of each is given in Table 4.

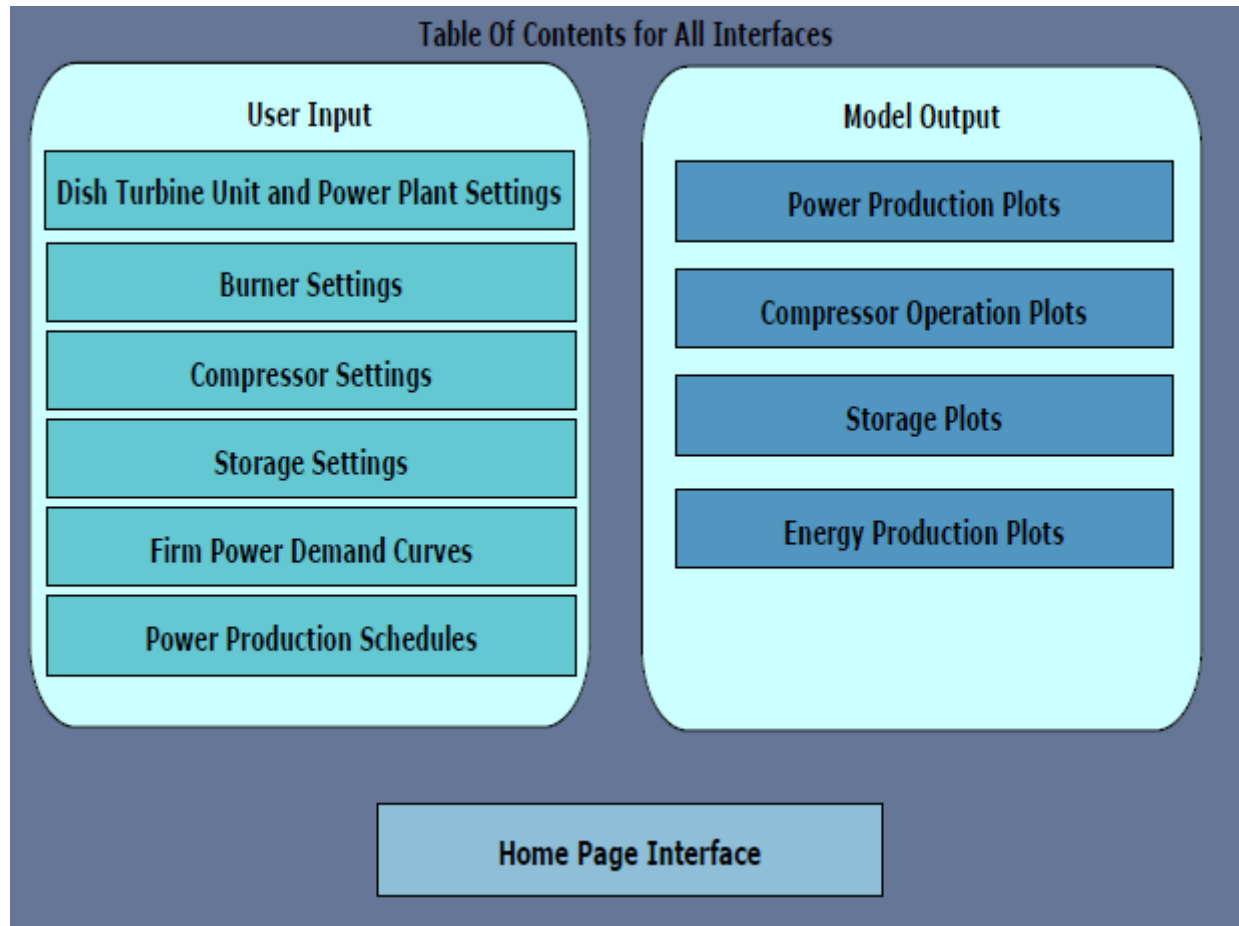


Figure 9. Master Table of Contents

Power Production and Compression Scheduling

In addition to selecting the DNI input data for the firm power curve, the user also has the option of scheduling the power production during specific times during the day. The model provides the option of using the selected DNI data as is, or sending it through a scheduling filter that sets power production to zero during specific times. Four options are available to the user. These are:

1. **No schedule:** This option results in using the SH-TMY3 DNI data as is.

2. **User Specified DNI Threshold:** The DNI threshold value is used to set the DNI to zero for values less than the threshold value the user chooses. This threshold can be used to keep power production from occurring during the early morning and late afternoon hours when solar input is significantly reduced or during the day when the solar input declines due to atmospheric conditions.
3. **User Specified Time of Power Production Rate Schedule:** This input provides the ability to produce power only during intervals of high power demand and associated peak pricing for wholesale power suppliers.
4. **User Specified Daily Time Cycle:** The time cycle option allows the user to specify a start time and duration for power production. The start time and duration is repeated daily.

Table 4. Master Table of Contents Interface – Hyperlink Description

Hyperlink	Description
Dish Turbine Unit and Power Plant Settings	Allows the user to modify the dish output power at 850 W/m ² and to modify the total Power Plant capacity
Burner Settings	Allows the user to modify the Minimum Burner Operation threshold and the Burner Efficiency Factor
Compressor Settings	Only used if running the storage model. User can modify Compressor Inflow, to Power Conversion factor. This value affects how much power is required for compression.
Storage Settings	Only used if running the storage model. Allows the user to vary the Volumetric Storage Capacity, Initial Storage Pressure and Storage Operation Temperature.
Firm Power Demand Curves	Provides access to the Firm Power Demand Curve interface described in section 3.1.3 above. Also provides access to the scaled DNI Demand Curve interface where the user chooses a scaling factor that is multiplied by the DNI to obtain a firm power curve.
Power Production Schedules	Provides access to the four Power Production Scheduling interfaces described briefly below.

A redundancy exists between this scheduling and the DNI selection when the User Selected DNI Curve option is selected. This DNI option does not require scheduling because the power production can be specified as zero over any time span covered by scheduling options 2, 3, and

4. However the user can, for example, input a constant DNI curve with a User Selected DNI Curve option and limit power production with one of the three scheduling options listed above.

Air compression also lends itself to strategizing operations. In the model compressors could be run while producing power, in which case compression becomes a parasitic loss on the system or it can occur during off-peak times allowing for all power production to be sold to the market. Compression scheduling is very similar to, and uses the same interfaces design as the power production scheduling.

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4. COMPRESSED AIR ENERGY STORAGE

As stated before, the US interest in funding large scale energy storage is low due to an excess of conventional power capacity with low natural gas prices, largely caused by the slowdown in electricity demand growth. However, both distributed generation and distributed storage are growing in popularity. With this in mind, SNL performed a preliminary analysis on the feasibility of designing manmade, underground storage vessels to store air at high pressures for CAES. The specific need for this type of container was presented in conjunction with certain solar technologies requiring smaller volumes of compressed air and lower storage pressures than more traditional CAES. Traditional CAES facilities require large underground storage (ca. 5 MMb) at greater pressures (1000-1500 psi).

4.1 Analysis: Internal Pressure Load (Steel Design)

The desired specifications for a pressure vessel suggested by SWST were:

- Maximum pressure: 350 psi
- Pressure vessel volume: $\sim 24000 \text{ m}^3$
- Depth to vessel top: $\sim 300 \text{ ft}$

These specifications of a pressure vessel would enable a Solar/CAES developer to modularize their units and locate storage adjacent to their solar generation. Figure 10 shows a conceptual diagram of the envisioned system.

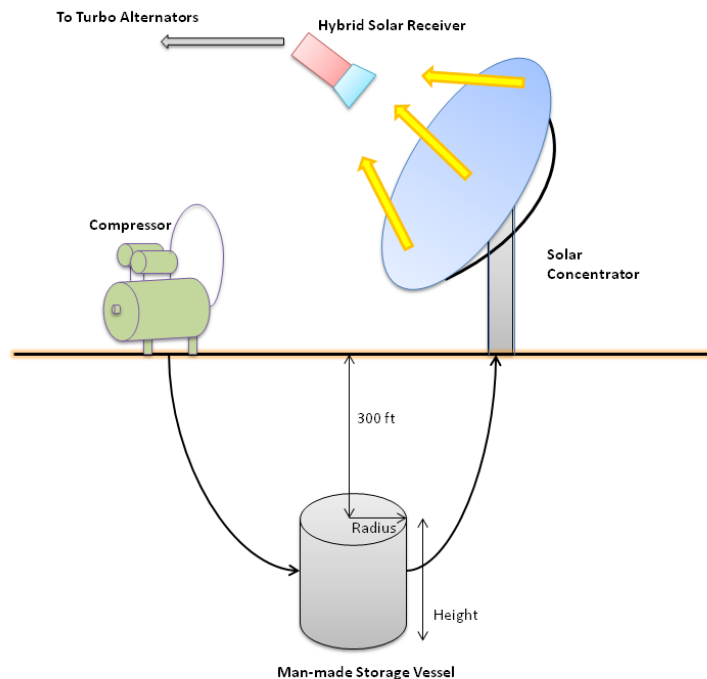


Figure 10. Conceptual Modular Design

It was assumed that the pressure vessel would be a right circular cylinder. This shape is not required for final design. The cylinders are assumed to be buried to a depth of 300 ft to the top of the cylinder. Excavating more than 300 ft would present additional challenges. This burial applies an external pressure to the cylinder, thus increasing the internal pressure capacity. The external pressure is a minimum at the vessel top (approximately 300 psi), and increases linearly with depth at 1 psi/ft.

Excavating to depths of interest, although challenging, is within the realm of possible engineering resources. Perhaps the simplest approach would be to bore such a hole. Secondly, there are pre-existent situations where one would not need to completely excavate, but instead achieve the depth by partial excavation and partial burial. In many near urban areas, pits have been dug to shallow depths to harvest, for example, road metal. This space could be used to site CAES containers by recovering the excavated space. Near some major cities mountains have been scarred by excavations to develop a gravel resource or raw material for construction or brick making; again this space could be reclaimed by CAES container construction followed by burial. Finally, there are many shallow mines in this country that have yet to be put to use. They lay waiting for such containers, and would only need to be backfilled after the containers are constructed.

There are multiple options available using standard structural design methods including:

- Reinforced concrete vessel
- Prestressed reinforced concrete vessel
- Steel vessel
- Reinforced concrete (with or without prestressing) with a steel liner

All of the options listed above can be used to withstand the desired loads.

All calculations were done assuming the use of standard deformed rebar with a minimum yield strength of 60 ksi. The radius (r) and height (h) are calculated to provide the required volume listed above. The required thickness of steel is an estimate based on the required pressure of the storage vessel, taking into account the benefit of the vessel being underground (~300ft) with a resulting compressive external pressure applied to the vessel. A safety factor of one was used coupled with a conservative set of material properties, chosen using engineering judgment, in this analysis.

4.1.1 Results

The options given in Table 5 below are estimates for the amount of steel required within a concrete vessel assuming that the steel provides the required capacity to prevent leakage. The thickness is also applicable as an estimate for a pure steel vessel, but because of functional requirements (corrosion and cost), it is recommended to focus on options utilizing concrete. The specific cases below were considered with a view towards minimizing the required thickness of steel and total weight of steel required (and thus cost).

Costs for steel and concrete are not included and left to the reader to calculate due to the large variability of the material cost that depends largely on supply and demand.

These thicknesses of steel can be obtained using standard reinforcing bars, or a combination of liner, reinforcing bar, and prestressing tendons.

Any more detailed design considerations and determination of type of reinforcing will require more detailed specifications (location of use, openings, transportability requirements, functionality specifications, depth ranges, thermal loading cycles, etc.). These calculations demonstrate that it is feasible to build such a vessel using steel and concrete to withstand the internal pressure loads desired.

4.1.2 External Pressure Loading with Zero Internal Pressure (Concrete Design)

In order to withstand the pressure loads applied to the vessel while underground and not filled with air, a thick concrete section is required (steel alone cannot withstand the load). To withstand the pressures at a depth of 300 ft, using standard concrete with a compressive strength of approximately 3000 psi, a thickness of at least 30 inches (of concrete) would be required. This calculation is merely to illustrate the need for a reinforced concrete design, and not to provide the final requirements for compressive strength and thickness.

Table 5. Summary of Cylinder Dimensions and Materials Required

Height-Radius Ratio (m)	Radius (m)	Height (m)	Concrete Volume (m³)	Thickness of Required Steel (in)	Min Steel Weight (lbs)
1.0	19.69	19.69	1,900	1.84	122,000
2.0	15.63	31.26	2,400	1.46	60,800
8.0	9.85	78.78	3,900	0.92	15,200
16.0	7.82	125.05	4,900	0.73	7,600
32.0	6.20	198.5	6,300	0.58	3,800

5. SOLAR ENGINEERING

The goal of this task was to have the Sandia team at the National Solar Thermal Test Facility (NSTTF) help Southwest Solar Technologies understand and solve engineering issues that might prevent their 300 m² dish-Brayton system from meeting its solar-collection performance goal. This work was scheduled to begin after the SW Solar team collected initial experimental data from an operating 300 m² dish and the Sandia team had time to review it. However, due to unforeseen delays, the SW Solar team was unable to provide the data required to perform the task. This led to the cancelation of the task per DOE guidance on August 2010.

6. CONCLUSIONS

This report described the various tasks performed by Sandia National Laboratories as part of the Technical Assistance grant for Southwest Solar Technologies Inc.

The system dynamics model was built to investigate fuel consumption and associated costs under different power generation and compression strategies. The model will be delivered to the SWST team so that they can run scenarios of interest and possibly share these with potential stakeholders. The capability to include a CAES system is present in the model and may be used in the future if desired. This model is a preliminary model but several improvements can be easily made if desired. For example, after the DTG is built, tested and data has been gathered, the model can be updated with real parameter values to improve the accuracy of the tool.

A preliminary analysis was performed to evaluate the feasibility of manmade underground storage vessels for CAES. The results from the preliminary analysis show that building these vessels is feasible (at desired specifications).

7. REFERENCES

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