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An integrated energy storage scheme for a dispatchable solar and wind powered energy system[a)]

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This research analyzed an integrated energy system that includes a novel configuration of wind and solar coupled with two storage methods to make both wind and solar sources dispatchable during peak demand, thereby enabling their broader use. Named DSWiSS for Dispatchable Solar and Wind Storage System, the proposed system utilizes compressed air energy storage (CAES) that is driven from wind energy and thermal storage supplied by concentrating solar thermal power (CSP) in order to achieve firm power from intermittent, renewable sources. Although DSWiSS mimics the operation of a typical CAES facility, the replacement of energy derived from fossil fuels with energy generated from renewable resources makes this system unique. West Texas is a useful geographical testbed for this system because it has abundant co-located wind and solar resources; it has competitive electricity markets, which give producers an economic incentive to store night-time wind energy in order to be sold during peak price times; and it has a significant number of locations with geological formations suitable for CAES. Through a thermodynamic and a levelized lifetime cost analysis, the power system performance and the cost of energy are estimated for this integrated wind-solar-storage system. We calculate that the combination of these components yields an energy efficiency of 46% for the CAES main power block, and the overall system cost is only slightly more expensive per unit of electricity generated than the current technologies employed today. © *2011 American Institute of Physics*. [doi:10.1063/1.3599839]

I. INTRODUCTION

As concerns about global warming, carbon costs, and energy security converge, the power sector is seeking to implement carbon-free renewable energy systems that can be fueled by domestic resources.[1] Two promising energy sources are wind and solar. In 2009, these technologies accounted for 1.28% and 0.02% of electricity generation in the US, respectively.[2] However, both technologies have seen growth recently. For instance, the state of Texas has increased its installed wind capacity by more than a factor of seven during the past 5 yr with installations totaling over 9400 MW (Refs. 3 and 4). However, the growth of these two technologies is hindered by the inherent variability of the wind and solar resources, a key issue that this research attempts to address.

In their current form, both wind and solar energy are subject to diurnal (daily) variation, seasonal variation, and weather conditions, such that both require backup/reserve generation facilities as firming power in case of daily or seasonal outage. As seen in Figure 1, wind in West Texas is out of phase with demand in the load centers of Texas over a typical 1-day

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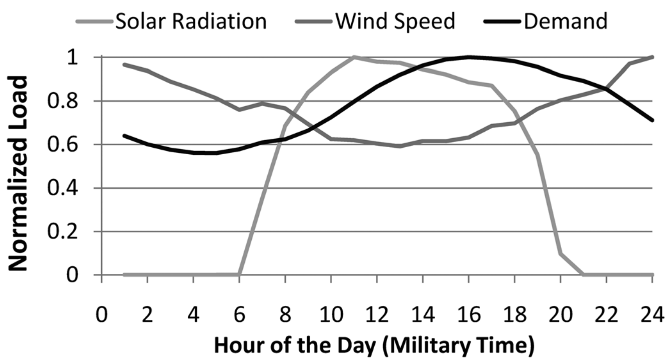

FIG. 1. The profiles of typical wind velocities, solar radiation, and ERCOT load in West Texas have important differences. Wind is out of phase with demand, while solar availability tracks demand more closely.

period in the summer. When demand is highest in the afternoon, wind is at its weakest and when demand is lowest at night wind energy reaches its peak.[5,6] Figure 1 also shows how solar radiation in West Texas increases along with demand in the afternoon, but as evening approaches it quickly drops off while demand is still high.[5,7,8]

One way to overcome the issues with the inherent variability of wind and solar resources and their mismatch with demand is to incorporate energy storage, so that they can then be used on a dispatchable, load-balancing basis much like natural gas plants.

II. COMPRESSED AIR ENERGY STORAGE AND THERMAL ENERGY STORAGE

As of today, there are only three practical and deployable industrial scale energy storage methods: compressed air energy storage (CAES), thermal storage, and pumped hydroelectric energy storage (PHS). Only PHS is currently in wide use today. However, major obstacles for PHS include the need for specific terrain requirements and water, which are not available in most regions of the USA where solar resources are more abundant, in particular, Texas. Consequently, the following discussion focuses on CAES and thermal storage.

A. Description of conventional CAES

Currently, there are two CAES facilities in the world, the first in Huntorf, Germany and the second in McIntosh, Alabama, that operate by using off-peak electricity to compress air that is stored in an underground cavern (see Fig. 2). Both CAES plants use natural gas-fired combustors to heat the compressed air before expansion, in order to generate electricity during times of peak demand. It is convenient to think of these facilities as similar to a conventional gas turbine power plant but with one important difference: the compressors are powered by cheap off-peak grid electricity so that all the power created by the turbines can be used to produce electricity in the generator.[9] In effect, this pre-compression step significantly increases the amount of produced electrical power per unit of heat required by the combustors (*Note*: By standard convention, no fuel use is associated with the consumed grid electricity, even though it is likely that fuels were used to generate that power).

In the case of a typical natural gas plant, the compression ratios are in the range of 15:1, which is much less than the 70:1 ratio of a CAES facility. With much more energy input from the compressors to reach such a high compression ratio, it could be anticipated that the CAES plant might not need to heat the air before entering the expansion turbine. However, because the heat removed from the air during compression in a series of intercoolers is not recovered, the air exits the storage cavern at a temperature of around 311 K. So, in order to increase the energy content and avoid freezing during the expansion process, the existing CAES facilities add heat by using a natural gas combustor.[10]

Even though CAES has only been built in two locations, it has been estimated that approximately 85% of the US would be able to access underground geological formations suitable for

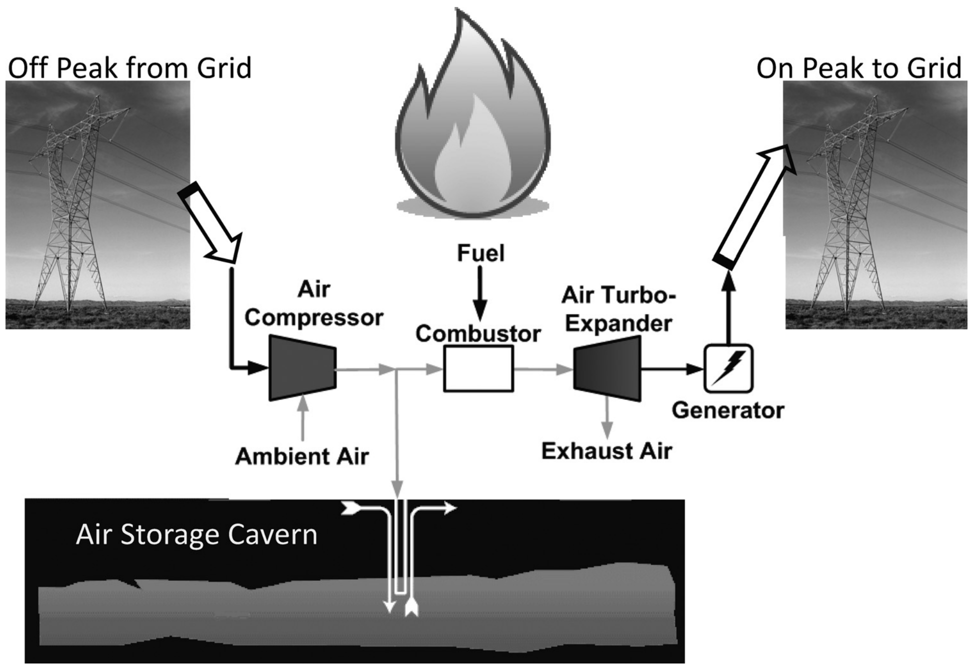

FIG. 2. CAES mimics a typical natural gas power cycle with the addition of an air storage cavern and the decoupling of the compressor and turbine.

compressed air storage and that most the West Texas areas of interest would actually have access to three different types of suitable formations.[11] A conventional CAES facility could provide a load leveling benefit to the electric grid which reduces the use of expensive and inefficient load following thermal generation units. Additionally, a CAES facility would also be able to compete in the ancillary services market as either spinning or non-spinning in order to gain extra revenue.

B. Description of thermal storage

There are a few types of thermal storage technologies currently used in the industrial market, including high pressure steam, molten salt, and hot oil. Thermal storage, though less mature than PHS, is already under development in industrial applications. NREL (National Renewable Energy Laboratory) demonstrated one of the first thermal storage systems in the Solar Two project in the mid 1990s. Solar Two was able to achieve a capacity factor (CF) of around 65%, which is remarkable when compared to the typical 25% capacity factor of solar technologies that do not incorporate thermal storage.[12]

The analysis detailed in this report does not include research or selection on the different types of thermal storage to be used, but rather just considers its total output. Later work will include this topic, as well as analysis necessary to design and size the particular solar thermal and thermal storage components.

III. DESCRIPTION OF THE INTEGRATED SYSTEM

The purpose of the proposed DSWiSS (Dispatchable Solar and Wind Storage System) system is to combine wind and solar energy with two storage techniques— compressed air and thermal storage—in a way that couples excess night-time wind capacity with peak solar output. In essence this design mimics the CAES plants previously described but replaces the natural gas combustor with concentrating solar power and thermal storage and will draw power to operate the compressors from excess off-peak wind energy instead of off-peak grid electricity. These key changes (1) eliminate all fossil fuel consumption of the CAES plant and (2) maintain the system's dispatchability. A detailed block diagram of the proposed energy system can be seen below in Figure 3.[13]

In this system, electricity from wind power drives the compression of air, which is then stored in underground caverns. Then, whenever the operator decides, the air is released from the cavern to be heated by the solar thermal system and expanded through the turbine-generator. Thermal storage is also incorporated here in order to ensure that the turbine-generator system can run into the early evening hours when the price for electricity is still high, or continue to run during off-peak hours as a form of firming power. Using this combination of technologies, the energy system should be able to operate on demand during afternoon and early evening hours. The duration of the system's operation in the evening is dependent on the size of the solar thermal and thermal storage system. These two components could be sized large enough to ensure 24 h operation. Additionally, the siting of this facility could take advantage of excess waste heat from already existing thermal generation units to reduce the heat demand of the CSP subsystem.

It is illustrated in this diagram that the compression and expansion processes will actually be accomplished by multistage units that utilize intercooling and reheat, respectively, all of which are modeled in the subsequent thermodynamic analysis. The compressor train modeled herein consists of four stages of compressors with three intercoolers and an aftercooler in order to minimize the required compression work. The turbine system consists of a two-stage turbine with a reheater supplied by the solar thermal system. By utilizing reheat, the second stage turbine will operate at conditions identical to that of a typical gas turbine. Also shown on the diagram is a recuperator that preheats the air exiting in the cavern by using the hot exhaust air from the turbine. This form of waste heat recovery will reduce the amount of heat the solar thermal system will need to provide. This turbomachinery system is identical to that located in the McIntosh CAES facility and was designed by Dresser Rand.[13]

The operation of such a combination of technologies will not be restricted to a single method. Based on real time variables like energy price and solar availability, the operator will

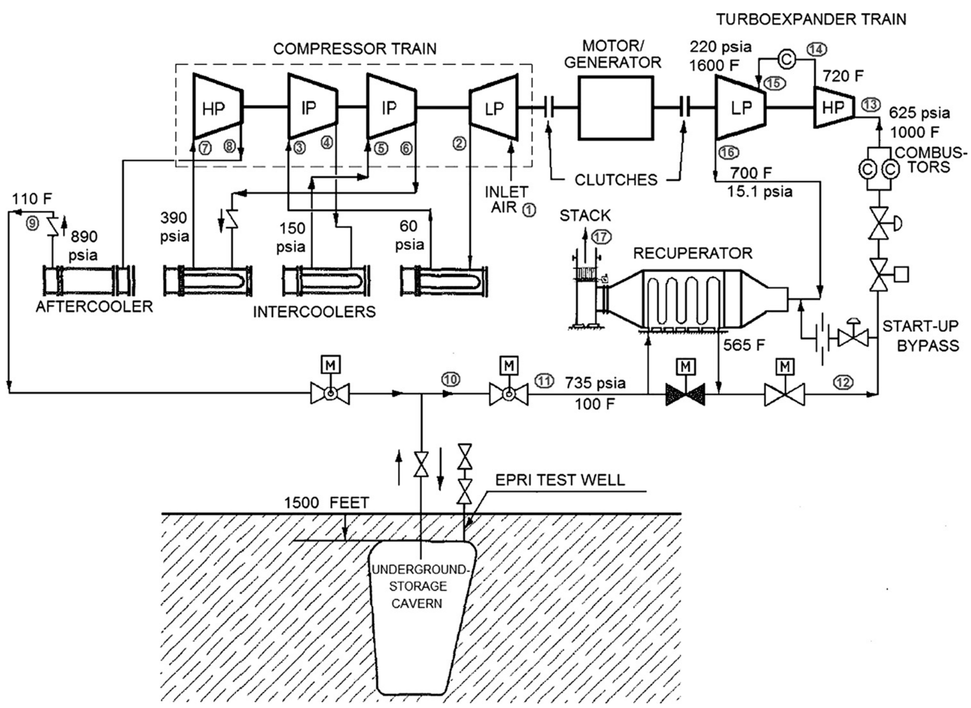

FIG. 3. A solar thermal and thermal storage system replaces the natural gas combustor © and electricity is supplied by wind turbines in order to turn the typical CAES plant into DSWiSS (LP = low pressure, IP = intermediate pressure, HP = high pressure). States 1 through 17 are indicated.[13]

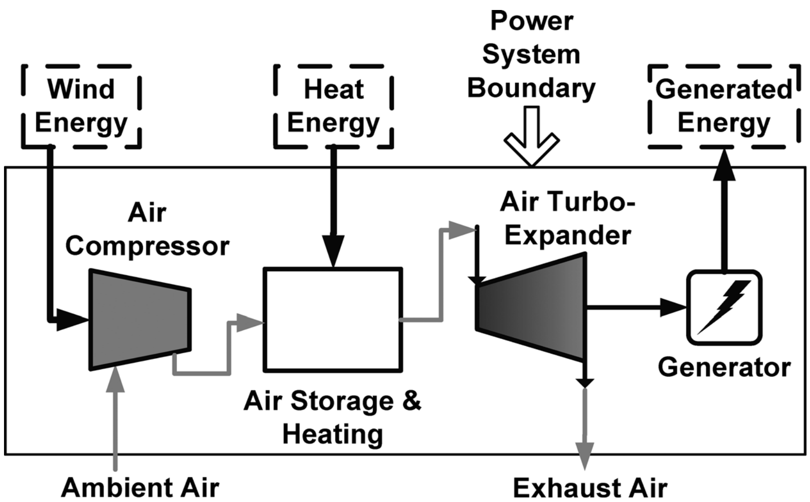

FIG. 4. The power system energy inflows and outflows (marked on this diagram) are needed to calculate the power generation efficiency.

be able to choose the mode of operation in order to maximize profits.[14] For instance, at any point in time, the operator may choose to sell the wind-generated electricity directly to the grid. This scenario might occur in the middle of the day when the price for electricity is highest. Once these types of decisions have been optimized, it is expected that the generation operation will be run only for a period of time when electricity price is high. Future research will include optimizing the operation of the system in an effort to increase efficiency and maximize profit. Additionally, this facility could instead contract with an already existing wind farm operator which would reduce risks of curtailment for the wind farm operator and provide the necessary electricity input to DSWiSS. This arrangement would also reduce the initial capitol expense of DSWiSS.

IV. THERMODYNAMIC ANALYSIS

A thermodynamic model was created for analyzing the performance of the DSWiSS power generation equipment. This detailed simulation uses first and second law concepts in order to estimate the required energy inputs per unit energy output. Figure 4 illustrates that the wind and solar components are not yet included in this model; rather, they are considered inputs. From this analysis the power system efficiency and required cooling loads will be calculated.

A. McIntosh CAES facility data and assumptions

Since the DSWiSS facility will operate similarly to a typical CAES facility, it was decided that the power generation equipment would be modeled after the turbomachinery at the McIntosh CAES plant. Table I lists the data used directly from the McIntosh plant as well as values that are calculated from McIntosh plant data.[13]

In addition to these data, some basic and detailed assumptions had to be made in order to complete the thermodynamic model. First, the four basic assumptions are: (1) kinetic and potential energy effects are negligible, (2) all components are well insulated (adiabatic), (3) air behaves as an ideal gas, and (4) inlet dry air molal composition is made up of oxygen, nitrogen, carbon dioxide, argon, and helium in mole fraction percentages of 20.95, 78.08, 0.03, 0.93, 0.01, respectively. In addition to these, Table II lists some specific assumptions that are made regarding particular components of the power generation equipment.

These parameters make up all the user specified data required to run a complete thermodynamic simulation of the power generation system.

TABLE I. These data, taken from the McIntosh CAES facility, are used for the thermodynamic simulation of DSWiSS (Ref. 13).

McIntosh parameter	Value	Unit
Inlet temperature to cavern	316	K
Inlet temperature to recuperator	311	K
Inlet temperature to turbine 1	811	K
Inlet temperature to turbine 2	1144	K
Installed generator capacity	100	MW
Air storage cavern maximum pressure	7.928	MPa
Air storage cavern minimum pressure	5.171	MPa
Calculated parameter		
Pressure ratio—compressor 1	4.16	—
Pressure ratio—compressor 2	2.55	—
Pressure ratio—compressor 3	2.65	—
Pressure ratio—compressor 4	2.33	—
Pressure ratio—turbine 1	2.48	—
Pressure ratio—turbine 2	14.57	—
Turbine 1 isentropic efficiency	89.1	%
Turbine 2 isentropic efficiency	87.39	%
Recuperator effectiveness	76.99	%
Recuperator pressure losses	2.65	%
Heat exchanger pressure losses	12.65	%

B. Creation of a thermodynamic property calculator

A thermodynamic property calculator was created for air. The calculator, for any specified temperature, pressure, and molal composition of oxygen, nitrogen, carbon dioxide, water vapor, argon, and helium, will determine the following properties: mixture molecular weight, mixture ideal gas constant, mass fraction of air mixture components, specific heats, mixture enthalpy, mixture internal energy, and mixture entropy.

At the heart of this property calculator is a seventh order polynomial function that calculates the specific heat at constant pressure (C_p) for each constituent based on temperature.[15] From the C_p values, the air enthalpy, internal energy, entropy, and all other values can be calculated by using appropriate reference values and the definition of each property.

TABLE II. These specific assumptions are necessary for the simulation of the power system and were not available from McIntosh data.

Parameter	Value	Unit
Ambient air temperature	295	K
Ambient air pressure	101.3	kPa
Compressor isentropic efficiencies	80	%
Cooler pressure losses	2	%
Cooler effectiveness	85	%
Heat exchanger effectiveness	85	%
Generator electrical efficiency	90	%
Motor electrical efficiency	90	%
Water coolant inlet temperature	295	K

C. Component details

The following sections describe in detail the multistage configuration that is modeled in the thermodynamic simulation. Note that all enthalpies expressed in the following sections are in units of kJ/kg.

1. Compression subsystem

This subsystem consists of a four-stage train of compressors that utilize intercooling and aftercooling between stages, as seen in Figure 3, in order to minimize the required compression work. Through this sequence, outside ambient air is compressed and cooled before being sent to an underground air storage cavern. States 1 through 9 are noted on the figure.

Using first law analysis and the previously listed data, the compression system can be analyzed. For each compressor, the exit enthalpy can be calculated based on the inlet enthalpy and compressor efficiency. For each cooler the air-side exit enthalpy can be determined from the air and coolant side inlet enthalpies and the cooler effectiveness, which is defined as the ratio of the actual amount of heat removed versus the maximum amount that could be removed.[16]

Using these calculations, in addition to the compression ratios and pressure losses through the coolers, the temperature and pressure at each state can be determined thereby setting all states 1 through 9. Once all temperatures and pressures have been found, the required energy per unit mass flow for each compressor can be found and the compressor train's total specific work can be calculated by simply summing the specific work of all four compressors. Additionally, the cooling load can be found by summing the cooling load of all four coolers.[16]

2. Turbine generator subsystem

This subsystem, seen in Figure 3, consists of a two-stage turbine, primary heater, reheater, recuperator, and generator. As air first exits the cavern it passes through a throttling valve and is heated first by the turbine exhaust in the recuperator and then by the primary heater. Next, after the first turbine stage a reheater increases the air temperature before the second stage turbine. Both the primary heater and reheater are supplied by the solar thermal system. For this model it is assumed that all necessary heat is available in order for the turbine inlet temperatures to be met.

The exit enthalpy of the air for each turbine can be calculated based on the inlet enthalpy and turbine isentropic efficiency. For the recuperator, the cold and hot side exit enthalpies can be calculated using the known inlet air temperature and the recuperator effectiveness. Based on these calculations as well as using the turbine pressure ratios and pressure losses through the recuperator, heater, and reheater, the temperature and pressure for each state can be determined, thereby setting the thermodynamic states 11 through 17. Next, the specific energy output for each turbine can be calculated and summed in order to calculate the total specific electrical power output from the generator. Additionally, the total required heat load for the solar thermal and thermal storage subsystem can be calculated from the combination of the heat loads of the heater and reheater. Knowing this heat load will help when determining the size of the solar thermal and thermal storage subsystems.[16]

3. Air storage cavern

The air storage cavern is inherently an unsteady device that requires a separate model to accurately determine thermodynamic conditions during the filling and emptying processes. However, the simple assumption that the earth acts as an infinite heat sink and an infinite heat source allows for the assumption that whether filling or emptying, the air in the cavern will be at a constant temperature equal to that of the ground temperature. Also of interest is the total volume required for the air storage cavern, which can be calculated using the ideal gas law at the charged and discharged states when the cavern pressure is at its maximum and minimum allowable limits. Determining the proper sizing will depend on the anticipated operation schedule, which for this analysis will be assumed constant. Future work will be done to optimize the operation in order to maximize profits while using variable wind and solar inputs.

4. Solar thermal and thermal storage subsystem

This analysis assumes that all the necessary heat input needed from the concentrating solar thermal power (CSP) and thermal storage system is adequately supplied. At this time, the analysis focuses on calculating the amount of heat required per unit air mass flow and estimating the sizes of the CSP and thermal storage units based on an assumed generation time window, which will be discussed more in Sec. IV E. It is expected that almost any CSP design could be used. More detail regarding the proper sizing of the solar collector and thermal storage subsystems is scheduled to be done in the near future.

5. Component summary and state table

Table III below gives a summary of the equipment in the power system and the thermodynamic states associated with the inlet and outlet of each piece of equipment. Additionally, the first law equation that governs each component is also shown.

D. Cycle analysis

By following the methodology and calculations detailed in Sec. IV C performance parameters that will be used to evaluate the DSWiSS concept, such as thermal efficiency, can be estimated. All calculations done to this point are on a per unit air mass flow basis, which is useful, but will be expanded upon in Sec. IV E. Every thermodynamic state of the power system in DSWiSS has been set based on the compression train and turbine train analyses already described. Now, using the calculated values for total specific compression work, total specific turbine work, and total specific heat input requirement of the heater and reheater, the thermodynamic efficiency, total specific energy input, and energy inputs per unit energy output of the DSWiSS power system can be calculated. Table IV lists the results.

Note that the power system efficiency is the efficiency of the power system only and does not include the efficiency of the wind turbines or solar thermal system.

In addition to these power and efficiency calculations, the power system process was sketched on *T-s* diagram, seen in Figure 5.

TABLE III. Summary of power system components inlet and outlet states and associated equations. (ω = specific work, q = specific heat transfer).

System component	State In	State Out	Equation
Compressor 1	1	2	$\omega_{C1} = h_2 - h_1$
Compressor 2	3	4	$\omega_{C2} = h_4 - h_3$
Compressor 3	5	6	$\omega_{C3} = h_6 - h_5$
Compressor 4	7	8	$\omega_{C4} = h_8 - h_7$
Intercooler 1	2	3	$q_{removed1} = h_2 - h_3$
Intercooler 2	4	5	$q_{removed2} = h_4 - h_5$
Intercooler 3	6	7	$q_{removed3} = h_6 - h_7$
Aftercooler	8	9	$q_{removed4} = h_8 - h_9$
Turbine 1	13	14	$\omega_{T1} = h_{13} - h_{14}$
Turbine 2	15	16	$\omega_{T2} = h_{15} - h_{16}$
Heater	12	13	$q_{added1} = h_{13} - h_{12}$
Reheater	14	15	$q_{added2} = h_{15} - h_{14}$
Recuperator (hot side)	11	12	$q_{exchange} = h_{12} - h_{11}$
Recuperator (cold side)	16	17	$q_{exchange} = h_{16} - h_{17}$

TABLE IV. The results show that DSWiSS must use both wind and solar resources.

Cycle analysis output parameters	
Turbine total specific work output (kJ/kg)	724.0
Generator specific work output (kJ/kg)	651.6
Heater total specific heat input req. (kJ/kg)	803.4
Compressor total specific work req. (kJ/kg)	545.0
Motor specific work req. (kJ/kg)	605.6
Coolers total specific heat removed (kJ/kg)	525.4
Energy input total (kJ/kg)	1409.0
Energy input fraction wind	0.43
Energy input fraction solar	0.57
Power system efficiency	0.46
Electricity input per unit energy output	0.93
Heat input per unit energy output	1.23

E. Assuming rated output capacity and generation time window

Ideally, determining how the DSWiSS plant will operate over a typical day is one of the goals. Therefore, calculating values such as the steady state air flow rate through the turbine or compressor trains, the steady state electrical energy and heat energy input required, the total daily air mass flow, and the air storage cavern size is useful. However, in order to calculate these values, two important assumptions must be made as follows:

- For this simulation, the rated capacity is assumed to be 100 MW, which is consistent with the McIntosh CAES facility.
- To calculate daily values, the time period when generation and compression takes place must be set. This simulation uses a generation time window of 4 h during the peak time period of the day when the electricity price is the highest. During the generation time period, since compression cannot be occurring, the electricity generated from the wind turbines could also be sold to the grid to increase profits.

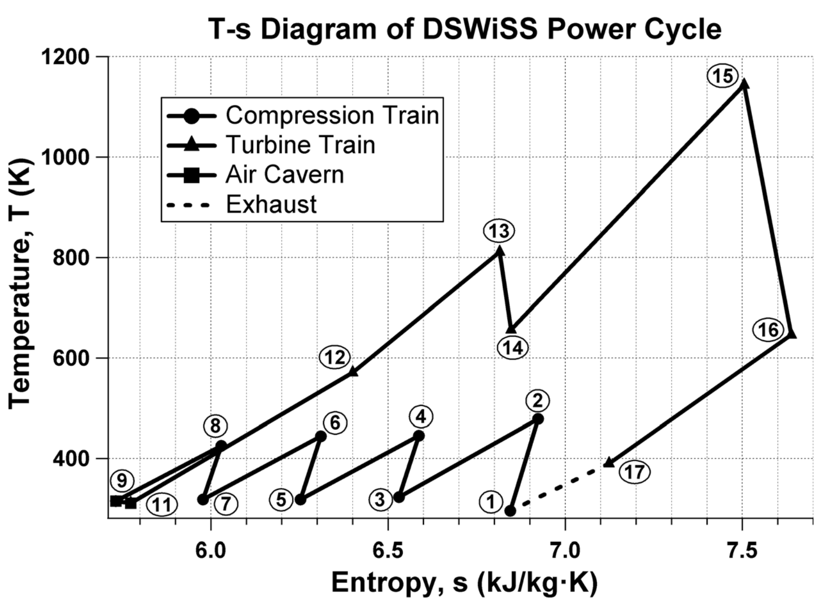

FIG. 5. Conceptual T-s (temperature-entropy) diagram of the DSWiSS cycle illustrates the complexity of the turbomachinery.

TABLE V. Steady state and daily output parameters.

Important output parameters	
Motor steady state work req. (MW)	18.6
Motor daily work req. (MW h)	371.7
Generator steady state work output (MW)	100.0
Heaters steady state heat input req (MW)	123.3
Heaters daily heat input req. (MW h)	493.2
Total daily air flow (kg)	2 210 000
Cavern volume (m^3)	500 000

Based on the specified rated power output and 4-h generation time window, a number of important parameters including the total daily air mass flow through the turbine and compressor train can be calculated. These results can be seen in Table V.

V. ECONOMIC ANALYSIS OF THE DSWISS POWER SYSTEM

In order to be utilized in today's electricity market, this renewable energy system will have to compete from an economic standpoint with coal, nuclear, and natural gas power plants. In order to make this economic comparison, a levelized lifetime cost approach was adopted. This method takes into account all capital, operation and maintenance, and fuel costs. For DSWiSS, the levelized cost of electricity (LCOE) must be estimated for each individual subsystem (wind, solar/thermal storage, and CAES), then combined to equal the total LCOE. In order to calculate the LCOE for each subsystem, all that is needed is an estimate of the capital expenditures (CAPEX) and the operational and maintenance expenditures (OPEX), along with appropriate values for the discount rate (d), technical lifetime (N), and plant capacity factor. With these values, both the CAPEX and OPEX can be calculated on a dollar per MW h generated basis.

In most references, the OPEX is already listed in dollar per MW h generated form. However, the CAPEX is nearly always given in the form dollar per kW, which is dollars per kW installed capacity. This value must then be annualized over the technical lifetime of the plant using the already specified discount rate, then converted from a per kW installed capacity value to a per MW h generated annually value by using two conversion factors (kW per MW and hour per year) and the plant's capacity factor. Table VI lists the CAPEX and OPEX values found in literature as well as the calculated LCOE.[11,17–19] All values are listed in 2008 dollars.

It must be pointed out that the LCOE values for the two solar technologies have been adjusted to incorporate the efficiency of a solar plant in converting the heat energy to electrical energy. Additionally, all solar costs have incorporated thermal energy storage and the CAES costs have incorporated any necessary equipment including all compressors, turbines, generators, recuperators, and storage caverns.

Each LCOE is given in dollars per MW h, but these do not refer to the same MW h. The wind system is in dollars per MW h of electricity supplied from the wind turbines. The solar thermal systems are in dollars per MW h of heat supplied to the air before entering the turbine. And the CAES system is in dollars per MW h of electricity sent to the grid from the DSWiSS facility.

TABLE VI. Selecting the CAPEX and OPEX costs allows for the calculation of the LCOE (Refs. 11, 17–19).

Subsystem	CAPEX ($/kW)	OPEX ($/MW h)	LCOE ($/MW h)
Wind	1604	10.5	55.0
Solar parabolic trough	4000	16.3	32.6
Solar power tower	4000	13.9	26.3
CAES	770	2.38	10.5

TABLE VII. Estimated LCOE for the DSWiSS using two different solar thermal technologies.

DSWiSS plant design	LCOE [$/MW h]
DSWiSS with power tower	94.1
DSWiSS with parabolic trough	101.8

The last step before calculating the entire system's LCOE is to incorporate the energy requirement ratios for the wind and solar subsystems. Shown previously in Table VI, incorporating these values allows the conversion of each subsystems cost to a basis of dollars per MW h of generator output; note that the LCOE for the CAES system is already in terms of dollars per MW h of generator output.

Seen in Table VII are two complete system LCOE values based on the different solar thermal technologies.

A. Comparison to other generation technologies

In the US, coal, natural gas, and nuclear plants are the majority providers of electricity. In 2007 these three combined to generate over 88% of all electricity consumed in the US.[2] Based on data from the Electric Power Research Institute (EPRI),[20] Figure 6 illustrates the relationship of the LCOE for all these types of facilities as well as a stand-alone wind farm[17] and solar thermal trough facility[18] to that of DSWiSS.

An important caveat is that currently the price of natural gas is lower than the 8–10 $/MMBTU used in the 2008 EPRI report.

VI. CONCLUSIONS

Through this analysis, the thermodynamic performance and cost of energy production from an integrated system consisting of wind and solar energy systems coupled to compressed air and thermal energy storage have been estimated. The combination of these components yielded a power system efficiency of over 46%. A better understanding of the size of the wind and solar components has been gained through the assumption of a rated generation capacity and generation time period. Additionally, the system has been shown to use both wind and solar resources fairly equally in order to generate dispatchable power.

The integrated system is also found to be slightly more expensive on a dollar per MW h generated basis than some of the current technologies employed around the world today but

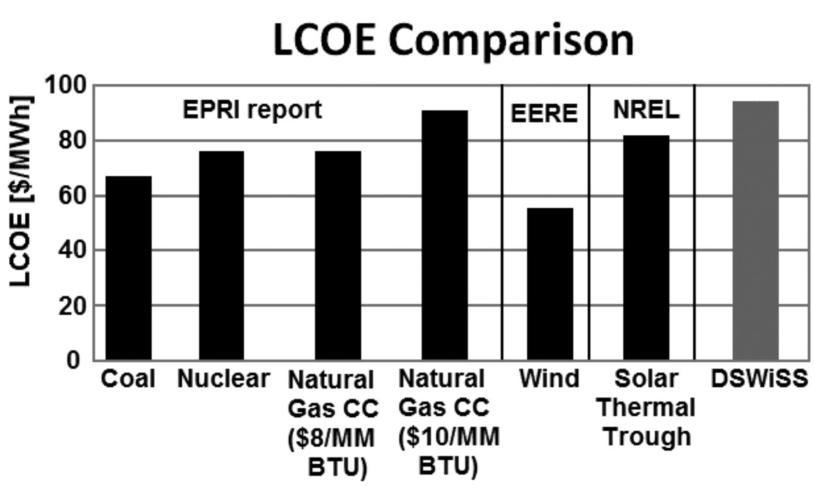

FIG. 6. LCOE for DSWiSS is competitive with that of current generation technologies.[17,18,20] However, this LCOE does not include any of the available tax credits or any carbon costs.

competitive with others, such as stand-alone solar facilities and natural gas facilities at a high fuel price. Even though the DSWiSS system was found to have higher expenses, there are many cost externalities that were not taken into account. These include rising fuel costs, fuel cost volatility, carbon costs, energy security costs, and the uncertainty over the future cost of emissions. Furthermore, the production tax credit (PTC), investment tax credit (ITC), and renewable energy credit (REC), all of which are available in the US, were not included in this economic analysis. Additionally, the DSWiSS facility will be dispatchable and able to quickly ramp up or down to provide valuable load-balancing power, a claim that only natural gas and hydroelectric power plants can currently make.

This analysis is the beginning of a much more detailed thermo-economic investigation of this energy system's performance and profitability. For future work, real time data will be incorporated including area specific wind velocity along with wind turbine power profiles, local solar radiation, real time electricity pricing, and local daily temperature variation. It is evident that system optimization will be needed in order to determine the operation scenario of maximum profit. Optimization parameters such as time interval of energy production, wind turbine energy split between compression versus direct selling, and time duration of thermal storage heating will all need to be considered in order to determine the most profitable design. Other studies have concluded that CAES might be a profitable method to provide load leveling capability to the electric grid by taking advantage of highs and lows in the electricity spot markets.[21] It is expected that future costs associated with carbon emissions, the continuing reduction in costs of wind and solar technologies, and the advancement of CAES systems through research will all help a system such as DSWiSS become an attractive and environmentally friendly addition to the electricity market.

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