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Merit Study of Battery or Hydrogen Energy Storage for Large Scale, Combined Wind and Solar Electricity Generation

Ashley K. Moore
Wright State University

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MERIT STUDY OF BATTERY OR HYDROGEN ENERGY STORAGE FOR LARGE SCALE, COMBINED WIND AND SOLAR ELECTRICITY GENERATION

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Renewable Clean Energy Engineering

by

ASHLEY K. MOORE
B.S.M.E., Wright State University, 2008

2023
Wright State University
WRIGHT STATE UNIVERSITY
COLLEGE OF GRADUATE PROGRAMS AND HONORS STUDIES

November 17, 2023

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Ashley K. Moore ENTITLED Merit Study of Battery or Hydrogen Energy Storage for Large Scale, Combined Wind and Solar Electricity Generation BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Renewable and Clean Energy Engineering.

__________________________________________
James Menart, Ph.D.
Thesis Director

__________________________________________
Raghavan Srinivasan, Ph.D., P.E.
Chair, Mechanical and Materials Engineering Department

Committee on Final Examination:

__________________________________________
James Menart, Ph.D.

__________________________________________
Mitch Wolff, Ph.D.

__________________________________________
Hong Huang, Ph.D.

__________________________________________
Shu Schiller, Ph.D.
Interim Dean
College of Graduate Programs & Honor Studies
ABSTRACT

Moore, Ashely K. M.S.R.C.E., Department of Mechanical & Materials Engineering, Wright State University, 2023. Merit Study of Battery or Hydrogen Energy Storage for Large Scale, Combined Wind and Solar Electricity Generation.

In the past several years, the energy sector has experienced a rapid increase in renewable energy installations due to declining capital costs for wind turbines, solar panels, and batteries. Wind and solar electricity generation are intermittent in nature which must be considered in an economic analysis if a fair comparison is to be made between electricity supplied from renewables and electricity purchased from the grid. Energy storage reduces curtailment of wind and solar and minimizes electricity purchases from the grid by storing excess electricity and deploying the energy at times when demand exceeds the renewable energy supply.

The objective of this work is to study the generation of electric power with wind turbines and solar panels coupled to either battery energy storage or hydrogen energy storage. So that logical conclusions can be drawn on the economic effectiveness of battery and hydrogen energy storage, four scenarios are analyzed:

1) purchasing all required electricity from the grid,
2) generating electricity with a combined wind and solar farm without energy storage,
3) generating electricity with a combined wind and solar farm with battery energy storage, and
4) generating electricity with a combined wind and solar farm with hydrogen energy storage.

All four of these scenarios purchase electricity from the grid to meet demand that is not met by the renewable energy power plant. All scenarios are compared based on the lowest net present cost of supplying the specified electrical loads to serve 25,000 homes in Rio Vista, California over 25 years of operation.
The detailed economics and electric power production of both wind and solar combined with energy storage for any size of wind facility, solar facility, battery facility, and hydrogen facility are analyzed with a MATLAB computer program developed for this work. The program contains technical and economic models of each of these systems working in different combinations. Current equipment capital costs and operation and maintenance costs based on industry reports or general literature are utilized in the economic model. Electricity production and storage are modeled and compared to the specified load on an hour-by-hour basis. The program contains models of electricity production with solar panels given the amount of radiant energy incident on the panels in Rio Vista, California. Electricity production with wind turbines is modeled based on the local wind resource. The models of energy storage in lithium-ion batteries and chemical energy storage using hydrogen are included in the program. The hydrogen energy storage model includes hydrogen that is generated and consumed via reversible solid oxide electrolyzer/fuel cells and stored as compressed hydrogen in tanks buried in the ground.

The results from these models provide the least cost equipment configurations for each renewable energy power plant, given the local resources, local load demand, and equipment costs. The results from wind and solar with and without energy storage are compared to purchasing all load electrical power from the grid at prevailing prices. The economic results of wind and solar with both types of energy storage are calculated and compared to wind and solar alone to determine if energy storage is economically justified. In addition, the least cost equipment configurations show where adding energy storage justifies the installation of additional wind or solar capacity. While economic optimization is the primary focus of this work the performance of wind/solar/energy storage scenarios are also compared.

The net present cost results show that electricity generated by wind and solar without energy storage, wind and solar combined with battery energy storage, and wind and solar combined with hydrogen energy storage all result in significant cost savings versus purchasing all the electricity from the grid to serve the load. However, a strong economic case cannot be made to justify adding battery energy storage or hydrogen energy storage in combination with wind and solar versus wind and solar alone. The resulting optimum cost equipment configurations show that battery energy storage justifies more solar capacity than wind and solar alone, illustrating that battery energy storage is a good partner for solar in this location. At current equipment and electricity prices, the addition of a hydrogen energy storage system did not change the least cost
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Figure 4.54 The lowest net present cost regenerative cell size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California with 2.6 metric tons of compressed hydrogen storage. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating. .................................................................................................. 116

Figure 4.55: Electricity costs doubled comparison of percent load served by solar and wind generation, fuel cell and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell investigated (center), and least cost configuration without storage (right). The compressed hydrogen storage tanks hold 2.6 metric tons of hydrogen at 100 bar. The cost of electricity is $0.3506 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.52, Figure 4.53, and Figure 4.54. .................... 117

Figure 4.56: Electricity costs doubled comparison of percent energy sent directly to load, to electrolyzers, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind solar and fuel cell investigated (center) and least cost configuration without storage (right). The compressed hydrogen storage tanks hold 2.6 metric tons of hydrogen at 100 bar. The cost of electricity is $0.3506 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.52, Figure 4.53, and Figure 4.54. .................... 117

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Nomenclature

\( a \)  
Activity

\( A_{j_0} \)  
Pre-exponential factor

\( A_{\text{cell}} \)  
Regenerative cell area of one module

\( A_{\text{FR}} \)  
Surface area of the front row panels

\( A_i \)  
Anisotropy index

\( B \)  
Day fraction in year

\( B_{j_0} \)  
Pre-exponential factor

\( C_{\text{grid elec}} \)  
Cost of electricity purchased from the grid per unit

\( c_{H_2 \text{ catalyst}} \)  
Concentration of hydrogen at the catalyst surface

\( c_{H_2 \text{ ref}} \)  
Reference concentration of hydrogen

\( c_{H_2O \text{ catalyst}} \)  
Concentration of \( H_2O \) at the catalyst surface

\( c_{H_2O \text{ ref}} \)  
Reference concentration of \( H_2O \)

\( c_{O_2 \text{ catalyst}} \)  
Oxygen concentration at the oxygen electrode

\( c_{O_2 \text{ ref}} \)  
Reference oxygen concentration

\( c_{p,H_2} \)  
Specific heat of hydrogen

\( c_{p,H_2}^{0^+} \)  
Reference product concentration

\( c_{p,i} \)  
Reaction surface concentration of products

\( c_{p,i}^{0^+} \)  
Reference reactant concentration

\( c_{R,i} \)  
Reaction surface concentration of reactants

\( C_{\text{CB}} \)  
Capital cost per unit of battery name plate rating

\( C_{\text{CCell}} \)  
Capital cost per unit of electrolyzer name plate rating

\( C_{\text{CS}} \)  
Capital cost of the solar installation per unit of solar nameplate capacity

\( C_{\text{CTank}} \)  
Capital cost per cubic unit of tank volume

\( C_{\text{CW}} \)  
capital cost of the wind installation per unit of nameplate capacity

\( C_{\text{MB}} \)  
Fixed maintenance cost per unit of battery nameplate rating

\( C_{\text{MCell}} \)  
Fixed maintenance cost per unit of electrolyzer name plate rating

\( C_{\text{MS}} \)  
Fixed yearly maintenance cost per unit of solar nameplate capacity

\( C_{\text{MTank}} \)  
Fixed maintenance cost per unit of tank volume

\( C_{\text{MW}} \)  
Fixed yearly maintenance cost per unit of wind nameplate capacity

\( c_{\text{catalyst}} \)  
Concentration of the reactant at the catalyst layer

\( c_{R \text{ channel}} \)  
Concentration of the reactant in the channel

\( D_{\text{eff}} \)  
Effective diffusivity

\( E \)  
Equation of time

\( E^0 \)  
Standard-state reversible voltage
Battery energy in
Battery energy out
Hourly electrical energy produced by the back row panels
Hourly community electrical demand
Hourly deficit energy without energy storage
Hourly deficit energy including battery energy storage
Hourly deficit energy with hydrogen energy storage
Hourly excess energy including battery energy storage
Hourly excess energy with hydrogen energy storage
Hourly excess energy without energy storage
Hourly excess-deficit energy without energy storage
Hourly excess-deficit energy including battery energy storage
Hourly excess deficit energy with hydrogen energy storage
Hourly energy produced by the first row of panels
Total hourly electrical energy produced by all the panels
Hourly electricity produced by the wind turbines
Energy produced by the fuel cell over one hour after accounting for external power requirements
Battery energy in over one hour
Battery energy out over one hour
Energy provided to the electrolyzer including external power requirements over one hour
Battery maximum E-rate
Yearly deficit energy including battery energy storage
Yearly deficit energy with hydrogen energy storage
Total yearly electrical energy produced by all the panels, $E_{Y,S}$
Yearly wind power
Yearly wind power output
Activation energy for the reaction at the hydrogen electrode
Activation energy for the reaction at the oxygen electrode
Hypothetical ideal voltage calculated from the enthalpy of reaction
Battery maximum energy capacity
Reversible, thermodynamically predicted, fuel cell cell voltage
Faraday’s constant
Horizon brightening modification factor
Uniform series present worth factor
Extraterrestrial radiation
Solar constant
Hour of year
Enthalpy of water at the water source temperature
\( h_{H_2O,T} \)

Enthalpy of steam at the cell temperature and pressure

\( \text{heat}_{\text{air,preheat,per module}} \)

Heat consumed by preheating the air to the cell temperature

\( \text{heat}_{\text{fuel cell,per module}} \)

Heat generated by each fuel cell module

\( \text{heat}_{\text{H}_2\text{,preheat,per module}} \)

Heat consumed by preheating hydrogen from the tank temperature to the cell temperature

\( l \)

Total solar irradiation over one hour on the horizontal plane

\( i_{\text{available,charge}} \)

Current consumed when \( n_{\text{to full}} \) moles of hydrogen are produced by the electrolyzer in the hour

\( i_{\text{available,disch}} \)

Cell current if \( n_{\text{available}} \) moles of hydrogen are consumed in the hour

\( I_{b,n} \)

Solar beam energy irradiation over one hour normal to the direction of the beam

\( I_{b,t \text{ total}} \)

Total beam solar irradiation incident on tilted panel over one hour

\( I_{b,t \text{ totalBR}} \)

Total beam solar irradiation incident on tilted back row panel over one hour

\( I_{b,t} \)

Solar beam energy irradiation over one hour on a tilted panel

\( I_{d,CS} \)

Circumsolar diffuse radiation component

\( I_{d,HB} \)

Horizon brightening component

\( I_{d,iso} \)

Isotropic diffuse radiation component

\( I_{d,\text{total}} \)

Total diffuse solar irradiation incident on tilted panel over one hour

\( I_{g,BR} \)

Ground reflected solar irradiation incident on tilted back row panel over one hour

\( I_{o,n} \)

Extraterrestrial irradiation over one hour normal to the direction of the beam propagation

\( I_{b} \)

Solar beam energy irradiation over one hour on the horizontal plane

\( I_{\text{BR}} \)

Hourly solar irradiation on the back row panels

\( I_{d} \)

Diffuse radiation component on a horizontal surface

\( I_{FR} \)

Total solar irradiation incident on front row panel in over one hour

\( I_{g} \)

Ground reflected solar irradiation incident on tilted panel over one hour

\( I_{o} \)

Extraterrestrial irradiation over one hour on the horizontal plane

\( I_{t} \)

Total solar irradiation incident on tilted panel in over one hour

\( j \)

Current density

\( j_{L,x_{H_2 \text{ outlet}=0}} \)

Current density where the hydrogen mole fraction is zero at the channel outlet

\( j_{L,x_{H_2O \text{ outlet}=0}} \)

Current density where the \( H_2O \) mole fraction is zero at the channel outlet

\( j_{L,x_{O_2 \text{ outlet}=0}} \)

Current density where the oxygen mole fraction is zero at the channel outlet

\( J_{\text{air}} \)

Air flux at the channel inlet

\( J_{H_2O,\text{anode}} \)

Flux of water through the anode for a fuel cell
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{H_2O,\text{inlet}}$</td>
<td>$H_2O$ flux at the channel inlet</td>
</tr>
<tr>
<td>$J_{H_2O,\text{outlet}}$</td>
<td>$H_2O$ flux at the channel outlet</td>
</tr>
<tr>
<td>$J_{H_2,\text{anode}}$</td>
<td>Flux of hydrogen through the anode for a fuel cell</td>
</tr>
<tr>
<td>$J_{H_2,\text{inlet}}$</td>
<td>Hydrogen flux at the channel inlet</td>
</tr>
<tr>
<td>$J_{H_2,\text{outlet}}$</td>
<td>Hydrogen flux at the channel outlet</td>
</tr>
<tr>
<td>$J_{\text{max, fuel cell curve}}$</td>
<td>Current density upper limit for the fuel cell polarization curve</td>
</tr>
<tr>
<td>$J_{\text{min, electrolyzer cell curve}}$</td>
<td>Current density lower limit for the electrolyzer polarization curve</td>
</tr>
<tr>
<td>$J_{\text{nominal fuel cell}}$</td>
<td>Current density at the fuel cell nominal operating point</td>
</tr>
<tr>
<td>$J_{\text{nominal fuel cell}}$</td>
<td>Current density at the electrolyzer nominal operating point</td>
</tr>
<tr>
<td>$J_{O_2,\text{electrolyte}}$</td>
<td>Flux of oxygen ions through the electrolyte</td>
</tr>
<tr>
<td>$J_{O_2,\text{cathode}}$</td>
<td>Flux of oxygen through the cathode for a fuel cell</td>
</tr>
<tr>
<td>$J_{O_2,\text{inlet}}$</td>
<td>Oxygen flux at the channel inlet</td>
</tr>
<tr>
<td>$J_{O_2,\text{outlet}}$</td>
<td>Oxygen flux at the channel outlet</td>
</tr>
<tr>
<td>$j_0^0$</td>
<td>Exchange current density at the reference reactant and product concentrations</td>
</tr>
<tr>
<td>$j_0^{0,H_2\text{electrode}}$</td>
<td>Exchange current density at reference conditions for the hydrogen electrode</td>
</tr>
<tr>
<td>$j_0^{0,O_2\text{electrode}}$</td>
<td>Exchange current density at the oxygen electrode</td>
</tr>
<tr>
<td>$j_{\text{diff}}$</td>
<td>Diffusion flux of reactants toward the catalyst layer or the diffusion flux of products away from the catalyst layer</td>
</tr>
<tr>
<td>$L_{\text{loc}}$</td>
<td>Longitude of the location</td>
</tr>
<tr>
<td>$L_{st}$</td>
<td>Longitude of meridian on which the local standard time is based</td>
</tr>
<tr>
<td>$M_{H_2}$</td>
<td>Molar mass of hydrogen</td>
</tr>
<tr>
<td>$M_{H_2O}$</td>
<td>Molar mass of water</td>
</tr>
<tr>
<td>$m_{i0}$</td>
<td>Molar fraction exponent</td>
</tr>
<tr>
<td>$M_{\text{air}}$</td>
<td>$M_{\text{air}}$ molar mass of air</td>
</tr>
<tr>
<td>$n$</td>
<td>Day number</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of moles of electrons transferred per mol of reactant</td>
</tr>
<tr>
<td>$N_{\text{available modules}}$</td>
<td>Number of regenerative cell modules to discharge the tank to the minimum pressure during the time step</td>
</tr>
<tr>
<td>$n_{\text{end of time step}}$</td>
<td>Number of moles of hydrogen in the storage tank at the end of the timestep</td>
</tr>
<tr>
<td>$n_{H_2\text{elec}}$</td>
<td>Number of electrons transferred for the reaction at the hydrogen electrode</td>
</tr>
<tr>
<td>$n_{j_0}$</td>
<td>Molar fraction exponent</td>
</tr>
<tr>
<td>$N_{\text{modules max}}$</td>
<td>Maximum number of regenerative cell modules</td>
</tr>
<tr>
<td>$N_{\text{modules to charge}}$</td>
<td>Number of modules that needed to charge the tank to the maximum pressure during the hour</td>
</tr>
<tr>
<td>$N_{\text{modules to charge}}$</td>
<td>Number of electrolyzer modules available to operate</td>
</tr>
<tr>
<td>$N_{\text{modules, available}}$</td>
<td>Maximum number of modules available given the number of moles of hydrogen available in the tank</td>
</tr>
<tr>
<td>$N_{\text{modules, running}}$</td>
<td>Number of modules running</td>
</tr>
</tbody>
</table>
Number of electrons transferred for the reaction at the oxygen electrode

Number of moles of hydrogen to fill the tank to maximum pressure

Number of moles of hydrogen available in the tank above the number of moles of hydrogen at minimum pressure.

Number of moles of hydrogen consumed by fuel cells or produced by electrolyzers in the hour

Number of moles of hydrogen in the tank at the current time step

Minimum number of moles of hydrogen in the hydrogen storage tank

Number of wind turbines $N_w$

Net present cost of the wind solar farm project without energy storage

Net present cost of the wind and solar farm project combined with battery energy storage

Net present cost of the wind solar farm project combined with hydrogen energy storage

Wind power output over a 5-minute interval

Power consumed by the electrolyzer system when enough hydrogen is produced to fill the tank over the timestep of one hour, including external power requirements.

Battery power available during charging due to maximum SOC limits.

Battery power available during discharging due to minimum SOC limits

Battery external charging power

Battery external discharging power

Battery internal charging power

Battery internal discharging power

Power consumed to compress hydrogen gas to tank pressure for one electrolyzer module

Power consumed per electrolyzer module without external power requirements

Power that can be provided to the electrolyzer system is calculated as

Battery power limit due to E-rate

Power generated by one fuel cell module

Power produced by the fuel cell modules running

The maximum power that can be produced by the fuel cells after external losses

Heat removed by cooling hydrogen produced by one electrolyzer module from cell temperature to tank temperature
\( P_{H_2 \text{ electrode}} \) Pressure of gas at the hydrogen electrode
\( P_{\text{H}_2\text{O preheat module}} \) Power required to preheat water to cell temperature for one electrolyzer module
\( p_{j0} \) Molar fraction exponent
\( P_{\text{max cell}} \) Fuel cell maximum power produced per unit area
\( P_{\text{tank, max}} \) Maximum hydrogen storage tank pressure
\( P_{\text{tank, min}} \) Minimum hydrogen storage tank pressure
\( p_0 \) Standard-state pressure
\( P_{\text{Bint}} \) Battery internal power
\( P_{\text{electrolyzer}} \) Power consumed by the electrolyzer including external power requirements
\( P_H \) Heat production rate in W/m\(^2\) for the regenerative cell
\( p_i \) Partial pressure of gas for a species
\( P_{\text{in}} \) Community electricity demand less wind and solar power generated
\( P_{\text{max fuel cell ext}} \) Power produced by all modules after accounting for the balance of plant (BOP) power requirements.
\( P_{\text{min electrolyzer ext}} \) Power consumed by all electrolyzer modules after accounting for external power requirements
\( P_{\text{NPB}} \) Nameplate capacity of the battery energy storage system
\( P_{\text{NPCell}} \) Nameplate rating of the electrolyzer
\( P_{\text{NPS}} \) Nameplate rating of solar installation
\( P_{\text{NPW}} \) Nameplate rating of the wind installation
\( P_{\text{Tank}} \) Hydrogen storage tank pressure
\( R \) Universal ideal gas constant
\( R_{\text{Ni-BYSZ}} \) Ohmic resistance for H\(_2\) electrode
\( R_g \) Geometric factor
\( R_c \) Contact resistance
\( R_t \) Ohmic resistance for electrolyte
\( R_{\text{LSM}} \) Ohmic resistance for O\(_2\) electrode
\( R_{\text{ohm}} \) Ohmic resistance
\( \text{SOC}_{\text{end}} \) Battery state of charge at the end of the timestep
\( \text{SOC}_{\text{hourly}} \) Battery state of charge averaged over one hour
\( \text{SOC}_{\text{ini}} \) Battery state of charge at the beginning of the time step
\( \text{SOC}_{\text{max}} \) Battery maximum state of charge
\( T \) Regenerative cell temperature
\( T_{\text{avg air}} \) Air average temperature
\( T_0 \) Standard state temperature
\( t_{\text{sol}} \) Solar time
\( t_{\text{std}} \) Standard time
\( T_{\text{tank}} \) Temperature of the hydrogen storage tank
\( U \) Windspeed
\( V_{\text{cell}} \) Operating voltage of regenerative cell
\( V_{\text{nominal electrolyzer}} \) Voltage at the electrolyzer nominal operating point
Voltage at the fuel cell nominal operating point

Volume of the hydrogen storage tank

Stoichiometric coefficient

$H_2O$ mole fraction at the channel

$H_2O$ mole fraction at the channel outlet

Hydrogen mole fraction at the channel

Hydrogen mole fraction at the channel inlet

Hydrogen mole fraction at the channel outlet

Oxygen mole fraction at the channel

Oxygen mole fraction at the channel inlet

Oxygen mole fraction at the channel outlet

Mole fraction

Wind turbine hub height

Surface roughness length

Reference height

Charge transfer coefficient

Percentage of regenerative cell power consumed by balance of plant requirements

Charge transfer coefficient for the reaction at the hydrogen electrode

Charge transfer coefficient for the reaction at the oxygen electrode

Solar altitude angle

Slope of a panel

Surface azimuth angle

Solar azimuth angle

Declination angle, hourly

Declination angle, daily

Thickness of electrolyte

Thickness of $O_2$ electrode

Thickness of $H_2$ electrode

Enthalpy change for reaction

Entropy change for the reaction

Battery calculation time step

Battery columbic efficiency

Activation voltage

Activation and concentration voltage loss for the reaction at the hydrogen electrode

Activation and concentration voltage loss for the reaction at the oxygen electrode

Concentration voltage
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{ohmic}$</td>
<td>Ohmic voltage</td>
</tr>
<tr>
<td>$\eta_{pv}$</td>
<td>Efficiency of the photovoltaic panels</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of incidence</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>Zenith angle</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Stoichiometry factor</td>
</tr>
<tr>
<td>$\rho_{BYSZ}$</td>
<td>Conductivity for electrolyte</td>
</tr>
<tr>
<td>$\rho_{LSM}$</td>
<td>Conductivity for O$_2$ electrode</td>
</tr>
<tr>
<td>$\rho_{Ni-BYSZ}$</td>
<td>Conductivity for H$_2$ electrode</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Latitude of the location</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Hour angle</td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>Hour angle at the beginning of the interval</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>Hour angle at the end of the interval</td>
</tr>
<tr>
<td>$\omega_{SR}$</td>
<td>Sunrise hour angle</td>
</tr>
<tr>
<td>$\omega_{SS}$</td>
<td>Sunset hour angle</td>
</tr>
</tbody>
</table>
I am extremely grateful to my thesis advisor Dr. James Menart, the Director of the Renewable Clean Energy Master’s program at Wright State University for his guidance, patience, and invaluable feedback throughout my thesis. I appreciate his excellent teaching skills which helped me to make new connections with the material in the classroom. I would also like to thank Dr. Hong Huang and Dr. Mitch Wolff for being a part of my thesis defense committee.

Lastly, I’d like to thank my husband, Brian, for his constant support.
Chapter 1
Introduction

1.1. Objective of Work

The objective of this work is to study the generation of electric power by means of wind turbines and solar panels coupled to either battery energy storage or hydrogen energy storage so that curtailment of the combination solar and wind farm can be reduced. Ideally, it is desirable to meet all of the customer’s electricity demand with electricity directly from the wind and solar farm or indirectly through either battery energy storage or hydrogen energy storage. However, at the present time, a wind and solar renewable energy electric power plant that does not require some power from fossil fuel plants to meet its customer’s demands is not economically feasible. For this reason, the battery or hydrogen energy storage systems considered in this work are only sized to store some of the electricity produced by the wind and solar farm, and to only provide some of the electrical demand when the wind is not blowing and the sun is not shining. Electrical demand that cannot be met by a combined solar and wind farm coupled to either battery energy storage or hydrogen energy storage is purchased from the grid at prevailing prices.

More precisely, the objective of this work is to provide a techno-economic comparison of electricity generated by wind turbines and solar panels without energy storage, wind turbines and solar panels coupled to battery energy storage, and wind turbines and solar panels coupled to hydrogen energy storage to meet a specified load. These three renewable electric power plant scenarios are compared based on the lowest net present cost for 25 years of operation. Many combinations of sizes of the wind farm, solar farm, battery storage, and hydrogen storage are simulated, and many results are presented. The specified load for all results presented in this thesis is the electricity required to serve 25,000 homes in Rio Vista, California.

This work provides succinct, easy to understand, economic results to benchmark across energy storage technologies, while accounting for a great deal of technical inputs. Site specific
considerations like solar and wind resource availability and local energy prices, as well as a realistic hourly local energy demand are included in the analysis. Detailed technical inputs specific to solar photovoltaic panels, wind turbines, battery energy storage and regenerative solid oxide cells with compressed hydrogen storage are incorporated. Equipment capital costs and operation and maintenance costs based on industry reports or literature are utilized.

In the work of Rama [1], it was concluded that a mixture of wind and solar electricity generation can be more cost effective than wind or solar alone, depending on the local resources. In other works, techno-economic analysis is performed on photovoltaics in combination with energy storage [2], [3] or wind in combination with energy storage [4]. Performance models of combined wind, solar and battery energy storage, which did not consider equipment sizing or economics, have also been proposed [5]. Seasonal energy storage for existing large photovoltaic facilities has been analyzed, comparing lithium-ion battery energy storage to hydrogen energy storage using electrolyzers and hydrogen-fired gas turbines [6]. This work extends the ideas of the investigators cited above by analyzing the detailed economics and electric power production of both wind and solar combined with energy storage for any size of wind facility, solar facility, battery facility and hydrogen facility.

The results provide the optimum cost equipment configuration for an energy storage technology, given the local resources, local load demand and equipment costs. Furthermore, the entire range of results is provided in Chapter 4 of this thesis to allow the reader to see trends in how manipulating one or more equipment capacities impacts the net present cost of the project. An extension of the present work is that the characteristics of grid connected wind and solar combined with lithium-ion battery energy storage and wind and solar combined with reversible solid oxide cells with compressed hydrogen storage can now be compared. The economic results of wind and solar with both types of energy storage are compared to wind and solar alone to determine if energy storage is economically justified. Further, the results will illustrate whether energy storage helps to justify the installation of additional wind or solar capacity.

**1.2. Need for Renewable Energy**

The energy sector is experiencing change and clean energy installations are increasing at a rapid pace. It is projected that renewable energy will make increasing contributions to the energy sector both in terms of installed capacity and in terms of energy generated in the United States.
This is due to declining renewable capital costs for wind turbines, solar panels and batteries [7]. Renewable energy technologies such as solar photovoltaics and wind turbines increase energy security, support climate goals, and provide industrial opportunities [8].

The cost of generating electricity with wind and solar has declined significantly in the past several years. Certain configurations of unsubsidized wind and solar are already competitive with natural gas peaking or natural gas combined cycle units based on the levelized cost of energy. Technology improvements, declining capital costs and increased competition are cited as reasons for the cost decreases [9].

Predicted increases of installed capacity of renewable energy production equipment in all regions of the United States are also spurred on by expected increases in U.S. electric power demand through 2050, due to increased electrification and economic growth. Renewables are expected to meet an increasing share of the power demand in the future as natural gas, coal, and nuclear power generation portions of the energy mix decrease. Renewables such as wind and solar are the least cost option to meet demand once they are installed, because they have zero fuel costs [7]. Internationally, renewables are expected to be the primary source of new generation in the future [10].

Increases in solar and wind generation are already occurring the United States and globally. According to Electric Power Annual, published in 2022 by the U. S. Energy Information Administration [11], 161 TWh of electricity were generated by solar photovoltaics in the United States in 2021, which was a 26.6% increase from the previous year. These figures include both utility and small scale solar photovoltaic generation. In the year 2021, electricity generated with wind accounted for 378 TWh of generation, an increase of 11.9% over the previous year. According to the International Energy Agency Net Zero Roadmap [8], globally, solar photovoltaic installations have increased by 400% or almost 1 TW of additional capacity from the year 2015 to 2022. Stationary battery storage capacity has increased by 2,500% or nearly 45 GW over the same period. Global electrolyzer capacity has doubled in 2021 and 2022 and has reached nearly 700 MW. The recent history of global additions of solar photovoltaics and battery energy storage is illustrated in Figure 1.1.

While wind and solar have the advantage of no fuel costs, they are also intermittent in nature. Solar photovoltaics only produce electricity while the sun is shining, and wind turbines only produce electricity during favorable wind conditions. This leads to electricity generation which exceeds the load requirements at some times and a deficit of electricity generation versus the load during other times. Without storage, it is necessary to match the generation of electricity with the load requirement at every instant. Energy storage works with wind and solar to store excess electricity generation to be discharged during times of generation deficit. Energy storage supports a higher utilization of renewable energy and lowers curtailment.

1.4. Types of Energy Storage

Energy storage can be classified by technology type such as electrochemical, including batteries, mechanical, including compressed air or pumped hydro, thermal, including molten salts, and chemical, including hydrogen. There are many types of energy storage, but the focus of this work will be on battery energy storage and hydrogen energy storage. Energy storage can also be classified by duration of storage, which is the amount of time that the rated power can be provided until the storage is depleted. Lazard’s Levelized Cost of Energy report [9] defines long term energy storage as storage durations of longer than six to eight hours. Short term storage will be classified as any time less than six hours.

Figure 1.1: Global installations of solar photovoltaics and battery storage from 2010 to 2022 [8].
1.4.1. Battery Energy Storage

Battery energy storage can have different chemistries, uses and sizes. Examples of battery types include lithium-ion, lead-acid, flow, and liquid metal. Lithium-ion batteries are currently the most used technology for stationary battery energy storage on a large scale. Batteries can be used for utility, commercial, or residential applications. The current market trend for utility-scale lithium-ion battery energy storage is for it to be sized between one and four hours of nameplate power output [9].

When combined with solar and wind, battery energy storage better matches generation with system demand and reduces curtailment of renewable energy generation. Other stationary battery energy storage applications include energy arbitrage, grid support applications, ancillary service applications, such as frequency regulation and black start, behind-the-meter applications, such as peak-shaving and uninterruptable power supplies [12]. Stationary battery applications are already providing valuable support to the grid. For example, new load demand records in Texas were set 10 times in the summer of 2023 due to heat waves and new stationary battery energy storage installations helped to stabilize the grid in emergency situations [13].

The high round-trip efficiency of lithium battery energy storage, typically 85-90%, is an advantage for this technology [9]. Other advantages of lithium-ion batteries include fast response time, low self-discharge, modular construction that allows for incremental scaling of the installation [12]. Lithium-ion batteries are increasingly in demand for other applications such as electric vehicles, which could be a concern going forward if supply chains cannot support rapidly growing demand [8] [14].

1.4.2. Hydrogen Energy Storage

Hydrogen production has several current uses including oil refining, steel production, ammonia, and methanol production. There are many applications which can utilize green hydrogen to reduce CO₂ emissions in the future, such as transportation and power generation [15]. Hydrogen can be produced, stored, then blended with natural gas to be burned in a combustion turbine of a natural gas combined cycle unit. Hydrogen can also be used for stationary energy storage and converted back into electrical energy with a hydrogen fuel cell. Compressed hydrogen energy storage using a regenerative electrolyzer/fuel cell will be the focus of this work. In the future,
Lazard forecast that electric power generation will be an important new growth sector for clean hydrogen [9].

An advantage of hydrogen energy storage and other types of long-term energy storage is that it is not tied to the lithium-ion battery supply chain, which has demands outside of stationary energy storage. Large-scale hydrogen storage capable of storing energy to supply demand over days or seasons could play a role in encouraging more installation of intermittent renewable energy. A disadvantage of hydrogen energy storage and other types of long-duration energy storage is that the round-trip efficiency is less than the-round trip efficiency of lithium-ion battery energy storage [9].

1.4.2.1. Energy Conversion: Fuel Cells and Electrolyzers

Currently hydrogen is most often produced from fossil fuels using methane reforming and methane splitting processes [15]. However, so called green hydrogen can be produced via electrolysis which uses electricity generated from renewables and water. Alkaline and PEM type electrolyzers are the most developed currently. However, solid oxide electrolyzers have advantages for large stationary energy storage applications. Electrolysis with a solid oxide cell is carried out at high temperatures and a portion of the energy required to carry out electrolysis can be supplied as heat if waste heat sources are available. The balance of the energy required is supplied by electricity. Low temperature electrolysis is powered entirely by electricity [16]. Expensive catalysts are also not required for high temperature solid oxide electrolysis and fuel cells. Solid oxide cells can run in both fuel cell and electrolyzer mode. Solid oxide cells are suitable for utility-scale applications and can offer high efficiency in comparison to other fuel cell types [17].

1.4.2.2. Hydrogen Storage

Examples of hydrogen storage technologies include compressed gaseous hydrogen, liquid hydrogen, and reversible metal hydrides. Storing hydrogen as a compressed gas in tanks is a relatively simple technology. Storing pressures as high as 700 bars have been used, but high-pressure storage introduces safety concerns [18].

Papadias and Ahluwalia [19] provide an overview of the types and costs of compressed and liquid hydrogen storage. For small-scale compressed hydrogen storage, tanks can be used. For
medium scale storage, Papadias and Ahluwalia propose using spherical vessels or underground pipe facilities similar to existing installations for natural gas storage. For example, an existing seasonal natural gas storage facility in Germany has a capacity of up to 350,000 m$^3$ stored at a pressure of up to 90 bar. Geological storage in salt caverns or lined rock caverns is proposed for large-scale hydrogen storage. The authors conclude that for storage amounts of less than 20 metric tons of hydrogen, storage in buried pipes is more economical than storage in caverns and that the per unit cost of cavern storage decreases as the cavern size increases.

Underground geological storage in salt caverns has been used for natural gas storage and has been demonstrated for hydrogen storage. Capacities exceeding 1 million m$^3$ are feasible. However, this type of storage requires suitable underground salt formations which, in the United States, are mostly limited to the Gulf Cost. Papadias and Ahluwalia also explore the possibility of large-scale geological storage in lined rock caverns which have been demonstrated in a pilot project for natural gas storage.

Liquid hydrogen is currently used for large-scale hydrogen storage. NASA’s Kennedy Space Center has two 3200 m$^3$ capacity spheres. However, the process of cooling hydrogen to cryogenic temperatures, 22 K to condense hydrogen into a liquid, is energy intensive [20]. About 30% of the energy content of the hydrogen is required to liquify the hydrogen [18]. The liquid hydrogen can be stored at a low pressure and is generally stored in highly insulating Dewar flasks. The tanks cannot be perfectly insulated, so as hydrogen evaporates it is vented in order prevent the tank pressure rising too high [20].

Reversible metal hydrides are metals or alloys that adsorb and release hydrogen via the formation of hydrides. The metals are in the form of fine powder which is stored in a container. Temperature or pressure adjustments control the rates of adsorption and desorption [20]. Metal hydrides can store hydrogen at a higher volumetric energy density than liquid hydrogen storage, however the materials involved are expensive [18].

1.5. Organization of Thesis

This thesis presents a techno-economic analysis of a combined wind and solar farm in combination with battery or hydrogen energy storage. The electricity generation and storage equipment are sized to meet the load of 25,000 homes in Rio Vista California. The computer program for this work was developed in MATLAB and is an improvement upon the code used to
implement the techno-economic model of Rama [1], which optimized sizing of a wind and solar farm with fixed tilt photovoltaic panels, without energy storage. In the present work, the efficiency of the solar panels is 22% and the panels are modeled with single axis tracking, where the axis of rotation runs north-south, allowing the panels to follow the direction of the sun from east to west throughout the day. Each of the wind turbines have a nominal rating of 3 MW and an 84 m hub height. The batteries have a storage duration of two hours and have a 92% one-way efficiency for charging and discharging. Hydrogen energy storage is carried out with solid oxide cells that operate at atmospheric pressure at the thermoneutral point in electrolysis mode and at the maximum power point in fuel cell mode. The compressed hydrogen storage tanks have a maximum pressure of 100 bar.

Chapter 2 of this work summarizes literature covering works on optimization of wind or solar in combination with energy storage. Battery and hydrogen energy storage works are also reviewed. Finally, existing installations using electricity generated from wind and/or solar in combination with battery energy storage or hydrogen energy conversion are reviewed. Chapter 3 describes the mathematical models used in this work. The calculation of the solar energy radiating on a tilted photovoltaic panel, wind resource and turbine model, and battery energy storage model are included. The hydrogen energy storage model includes the reversible solid oxide fuel cell and electrolyzer cell models, which is a one-dimensional isothermal model. Compressing hydrogen into storage tanks is also modeled. The energy production and storage for each equipment configuration is simulated, and the costs of purchasing electricity from the grid for any unmet load are determined for every hour of the year. The costs for the project are converted into present day dollars using time value of money equations assuming a 10% discount rate. The last section of Chapter 3 describes the verification of the individual models used in this work. Chapter 4 covers the extensive volume of results generated for this work. Results from wind and solar without energy storage are first presented. The second set of results includes battery energy storage, and the third set of results incorporates hydrogen energy storage. The last section of Chapter 4 compares the results of the previous sections. Chapter 5 presents the highlights and conclusions of this work.
Chapter 2

Literature Survey

Literature topics examined in this chapter include articles that describe models of wind and/or solar in combination with energy storage, articles that describe actual physical installations of such systems, a review article that covers many aspects of lithium-ion battery energy storage analysis, and an article that covers a model of steam electrolysis. Since models of batteries and regenerative cells operating as both electrolysis cells and fuel cells are incorporated in this work, the battery analysis and steam electrolysis model articles are relevant to the present work. In this chapter, literature focused on modeling is covered in the first three sections, while built facilities are covered in the last section.

Works modeling renewable energy combined with energy storage include a simple performance model which is extended for optimization and economic analysis in the current work. There are differences between the works covered in the survey and the present work. Other works addressing renewable energy combined with energy storage address isolated loads that are not grid connected. A work covering an economic optimization of wind with hydrogen energy conversion models which interacts with the grid is reviewed. However, the cost of storage or delivery of hydrogen is not included in the optimization.

A review paper considering the many facets for techno-economic analysis and optimization of lithium-ion battery energy storage systems for stationary applications is summarized. This review highlights algorithms for battery energy storage optimization categorized by algorithm complexity, battery energy storage application and optimization goals. Equipment sizing is the optimization goal of the current work. Of the battery application types covered in the review, photovoltaics with a battery energy storage system (PV-BESS) is of most interest, as the current work aims to size wind, solar and battery equipment that is grid connected. Algorithms of varying
complexity are included in this review. The current work uses a simple but exhaustive brute force optimization method to minimize lifetime cost of the power produced.

A model appropriate for high temperature steam electrolysis using solid oxide cells is reviewed. The model is based on previous solid oxide fuel cell models. The two-dimensional model incorporates electrochemical and thermal aspects of the cell. The model in the present work is simplified to a one-dimensional isothermal model and extended to apply to hydrogen regenerative solid oxide cells operating in the fuel cell mode.

Examples of large stationary battery energy storage with renewable energy in the field are presented. The first example, Manatee Solar Energy Center and Manatee Energy Storage Center, is a large photovoltaic battery energy storage installation in Florida which was commissioned in 2021. The second example, Wheatridge Renewable Energy Project, is a combined wind turbine, solar photovoltaic, and battery energy storage facility in Oregon. The wind portion of this facility was commissioned in 2020 and commercial operation of the photovoltaic and battery energy portions of the project began in spring 2022.

Examples of large hydrogen production facilities powered by renewable energy in the field are also presented. The first example, Cavendish Nextgen Hydrogen Hub, in Florida utilizes electricity generated by photovoltaics to produce hydrogen. The hydrogen will be stored, then blended with natural gas to generate electricity in an existing combustion turbine coupled to an electric generator. The second example, Sulzgitter GrInHy2.0, in Germany uses solid oxide cell technology, which is the type of electrolysis cell that is modeled in the current work. The facility uses waste heat from the steel manufacturing process and electricity generated from renewable sources to produce hydrogen. The hydrogen produced is used in the steel manufacturing process. In a smaller proof of concept project at the same site, solid oxide cells were operated reversibly as electrolyzers and fuel cells.

2.1. Renewable Energy with Energy Storage

2.1.1. Validating Performance Models for Hybrid Power Plant Control Assessment

Peterson et al. developed a performance model of wind turbine generators, photovoltaics, and battery energy storage systems [5]. The aim of the work was to provide a simple yet accurate performance model to be used in future hybrid power plant studies based on information available
in public datasheets. The model was validated with field measurements of two Vestas wind turbines located in Denmark, as well as a 1-MW photovoltaic plant and 1-MW/1-MWh battery energy storage system located in Colorado.

The model subcomponents are described by equipment type. The wind turbine model utilized a power curve to obtain the turbine power output using an equivalent windspeed as an input. The wind turbine rotor inertia effect is included in the model. For the PV model, the plane-of-array irradiance and temperature measured at the solar facility site were used as inputs. A power temperature coefficient model was used to correct the predicted power using the temperature measurements acquired. The grid converter and controls were included in the model. The model of the battery energy storage system utilized the watt hour counting method to predict the state of charge. The power available to be charged or to be discharged from the battery energy storage system was predicted based on the power available from the solar array, the C-rate of the batteries and the current state of charge. The battery system and converter controls were tested in grid following and grid forming modes.

The model developed was verified against field measurements. The wind turbine and photovoltaic models correctly estimated the power generation given the variations in windspeed and solar irradiance measured. The battery energy storage system provided satisfactory results in estimating the state of charge. The work did not address economics, sizing or optimization of a grid connected wind, solar, battery system. It does present a simple performance model that could be extended for further analysis.

2.1.2. Sizing Optimization, Dynamic Modeling and Energy Management Strategies of a Stand-alone PV/Hydrogen/Battery-Based Hybrid System

In research done by Manuel Castañeda et al. [2], techno-economic sizing was performed for a combination of photovoltaic panels, lead-acid batteries, fuel cells, electrolyzers and compressed hydrogen storage to serve a specified load. Electricity from the grid was not used to serve the load. Sizing was also performed on a photovoltaic panel and battery only system, as well as a hydrogen system in combination with photovoltaic panels. The sizing was performed using the solve design optimize (SDO) function in MATLAB to perform optimization of the Simulink model.
Three control strategies were investigated to simulate the operation of the proposed combined battery and hydrogen energy storage system. All three strategies prioritized serving the load with electricity generated by photovoltaic panels. The strategies differed in how the different types of energy storage equipment were used. The first strategy aimed to maintain the battery state of charge to extend the battery life. The second strategy selected the battery or fuel cells to serve the load depending on the battery state of charge or the level in the compressed hydrogen storage tank. The third strategy incorporated the costs of cycling the battery, fuel cell and electrolyzers. The conclusion of this work was that the least expensive system was the battery and photovoltaic system. The hydrogen system with photovoltaic panels was the most expensive system.

2.1.3. All Year Power Supply with Off-grid Photovoltaic System and Clean Seasonal Power Storage

In research done by Matthis Brinkhause et al. [3], an all-year supply of energy was to be provided by photovoltaics, lead-acid batteries, and a hydrogen energy storage system which included a fuel cell, electrolyzer, and compressed hydrogen storage. The system was designed and analyzed. Batteries were used for short term energy storage and hydrogen energy storage was used for longer term energy storage. Grid purchased electricity was not used to serve the load. The load profile used was that of a typical European household. A summer scenario was tested during a day of high solar radiation availability. A winter simulation was obtained by turning off the photovoltaics to simulate a low solar radiation day, allowing the batteries and hydrogen system to supply the load.

Simulated hourly energy balances over one year were performed for the photovoltaic, hydrogen energy storage and battery energy storage system. The system was sized to serve the target load over the year. The fuel cell was only allowed to operate during the winter months, while the other components were allowed to operate year-round in the simulation. A simulation resulting in hourly energy balances from only photovoltaic panels and battery energy storage was also performed and compared. The analysis concluded that it was more favorable to supply short term electricity shortfalls from the photovoltaics, such as at night, with batteries. The batteries in the simulations were designed to serve the load over a maximum period of two days. Thus, the battery only system required more photovoltaic panels than the hydrogen and battery energy storage
system. It was concluded that hydrogen energy storage was required to guarantee energy supply for every day of the year, particularly seasonal shortfalls in the winter months.

2.1.4. Wind Electrolysis: Hydrogen Cost Optimization

A hydrogen production cost analysis performed by Saur and Ramsden [4] optimized the configuration of wind turbines to power low temperature electrolyzers sized to provide 50,000 kg of hydrogen per day. The cost optimizations allowed for the excess wind energy to be sold to the grid and deficit energy to be purchased from the grid. The cost of grid electricity was variable depending on the season and time of day. The cost optimization did not include hydrogen storage or delivery. Because electrolyzers are costly, they were sized to meet the demand by running at full capacity with minimal down time. The study notes that 50 or more electrolyzer units would be required to meet the demand and that the units would be sequenced on and off rather than running individual units at partial load.

The wind turbine power production model utilized NREL western wind datasets available at 10-minute intervals over the entire year from 136 selected sites in California. The dataset windspeeds were adjusted to the hub height windspeeds using the wind profile power law. The wind turbine power output was averaged over the hour for every hour of the year to perform the cost analysis. Four scenarios were modeled for each site. A cost balanced scenario sized the number of wind turbines to balance the cost of electricity purchased from the grid to supply the electrolyzers with the price of excess electricity generated by the wind turbines and sold to the grid over the year. A power balanced scenario simply balanced the projected excess and deficit power generated by the wind turbines after supplying power to the electrolyzers over the year. The third and fourth scenarios were like the first two scenarios, except no grid electricity was allowed to be purchased during the summer peak, which lead to electrolyzers operating at partial output at times, resulting in unmet hydrogen demand. The conclusion of this work was that high wind availability at a location will correlate to lower hydrogen costs, even in locations with lower windspeeds. Also, this work concluded that class 4, class 5, and class 6 wind sites are capable of producing hydrogen for approximately $4 per kg.
2.2. Battery Models

2.2.1. Lithium-Ion Battery Storage for the Grid - A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids

In the review performed by Holger Hess et al. [12], a summary of the optimization approaches and challenges for several stationary lithium-ion battery optimization goals such as system sizing, battery energy storage positioning and dispatch is provided. Publicly available modeling tools for techno-economic analysis are summarized. The gap that the authors aim to address is the lack of overview for stationary grid connected lithium-ion battery energy storage systems (BESS). The authors propose that the appropriate economic benchmark for the analysis of BESS is return on investment rather than levelized cost of electricity, and a formula incorporating the costs and economic benefits of a grid connected system is provided. The performance and degradation characteristics, design overview, and application categories of stationary BESS are reviewed.

A review of modeling tools and works covering system optimization is provided. Several computational approaches are categorized based on algorithmic complexity. The less complex algorithms include sensitivity studies and iterative methods. More complex optimization algorithms include gradient algorithms and deterministic optimization techniques such as linear programming, as well as stochastic and meta-heuristic methods which include fuzzy logic control, genetic algorithms, particle swarm optimization, inventory model, and model predictive control. The algorithms used in the open literature for stated applications of energy storage and the goals of the optimization are provided. Examples of applications of energy storage are PV-BESS, microgrids, peak shaving, and system control reserve. Examples of optimization goals are sizing of the BESS, placement of the system and dispatch of the system. All three categories of algorithmic approaches are matched with sizing a PV-BESS electrical power facility.

2.3. Hydrogen Models

2.3.1. Modelling of Solid Oxide Steam Electrolyzer: Impact of Operating Conditions on Hydrogen Production
In research done by J. Laurencin et al. [16], a two-dimensional model was developed for a solid oxide electrolyzer cell which incorporated thermal and electrochemical aspects of the cell. The voltage loss components, including the activation and concentration overvoltage of both electrodes, as well as the overvoltage due to ohmic losses for the electrolyzer, were analyzed. The model was based on previous models developed for solid oxide fuel cells.

The inlet gas conditions were defined at constant inlet flow rates and mole fractions. The gas inlet temperatures were taken as 800 °C. Both electrolyte supported cells and cathode supported cells were analyzed. The activation overpotential was calculated using the inverse hyperbolic sine approximation of the Butler-Volmer equation. The concentration overpotential was calculated using the Nernst equation with the species concentrations predicted at the electrode-electrolyte interface of each electrode. The ohmic loss calculation included the voltage losses from the anode, cathode, electrolyte and contact resistances.

The conclusion of the analysis was that the anode, which is the oxygen electrode, has an activation overpotential that is significant, as are the ohmic voltage losses. The cathode, which is the hydrogen and water electrode, has a concentration overpotential that is moderate for electrolyte supported cells and is more for cathode supported cells at high current densities. Including thermal effects impacted the ohmic losses the most. The results presented the ohmic losses for an isothermal condition and the ohmic losses when temperature changes are included in the model.

2.4. Wind and Solar Combined with Energy Storage in the Field

2.4.1. Manatee Solar Energy Center and Manatee Energy Storage Center

According to a Florida Power and Light factsheet [21], the Manatee Solar Energy Center located in Manatee County, Florida has a nameplate rating of 74.5 MW, and the co-located Manatee Energy Storage Center has a 409 MW/900 MWh rating. At the time of the energy storage center commissioning in 2021, the facility was the world's largest solar powered battery storage facility. The battery energy storage center was built by Irby Construction and consists of 53,144 battery modules in 132 containers.

The Manatee Solar Energy Center was commissioned in 2016. It is one of several 74.5 MW Florida Power and Light photovoltaic installations. Manatee consists of 341,880 photovoltaic panels and covers 751 acres. The panels have a fixed orientation [22].
2.4.2. Wheatridge Renewable Energy Project

According to a Portland General Electric factsheet [23] the Wheatridge Renewable Energy facility was the first major renewable energy project in North America to incorporate wind, solar and battery energy storage at the same location. The facility is in Morrow County, Oregon. The wind facility has a nameplate rating of 200 MW. There are 120 GE Turbines and most have a 90 m hub height. The wind facility was commissioned in 2020. The solar portion of the Wheatridge project has a 50 MW capacity. The battery storage facility is rated at 30 MW for four hours. The battery storage and solar portions of this facility were commissioned in spring 2022.

2.4.3. Cavendish Nextgen Hydrogen Hub

The Cavendish Nextgen Hydrogen Hub is a Florida Power and Light pilot project that will use electricity generated by solar photovoltaics to produce hydrogen via electrolysis [24]. The hydrogen will be stored in compressed hydrogen tanks. Hydrogen that is produced will be blended with natural gas to power the existing combustion turbine at the Okechobee Clean Energy Center, which is a 1,750 MW natural gas combined cycle facility. The electrolyzers will be installed by Cummins and will consist of 5 Cummins HyLYZER 1000 PEM units. The total nameplate capacity will be 25 MW and the facility will produce 10.8 tons of hydrogen per day. Cummins broke ground on the project in December 2022.

The Cavendish Solar Energy Center will supply power to the Cavendish Nextgen Hydrogen Hub. According to the Florida Power and Light 10 Year Power Plant Site Plan [22], the photovoltaic solar facility has a nameplate rating of 74.5 MW. The Cavendish Solar Energy Center was commissioned in January of 2023 and has panels that utilize tracking.

2.4.4. Sulzgitter GrInHy2.0 Solid Oxide Electrolyzer

The GrInHy project at Sulzgitter Flachstahl GmbH steelworks, located in Germany, uses a solid oxide electrolyzer supplied with waste heat from the steel manufacturing process and renewable electricity to generate green hydrogen for the steel annealing process. The electrolyzer has a nominal power input of 720 kW. Salzgitter announced in April of 2022 that the electrolyzers met the project technical objective of producing 200 Nm³ (normal cubic meters) or 18 kg of hydrogen per hour [25]. Sunfire produced the electrolyzer. The electrolyzer cells operate at 850 °C
and atmospheric pressure. The hydrogen processing unit dries the hydrogen and compresses the hydrogen to 10 bar [26].

Prior to the development of the GrInHy project, a reversible solid oxide cell system was developed and tested as proof of concept at Salzgitter iron and steel works [27]. In electrolysis mode, the system was specified to consume 142.9 kW of electricity and 45 kg/h of steam. The system was specified to produce 30 kW of electricity in fuel cell mode. The specified electrolyzer unit efficiency was 84% based on electricity input and lower heating value. In hydrogen fuel cell mode, the specified efficiency was 47% based on the lower heating value of hydrogen.
Chapter 3
Models

Models of four different energy systems are utilized in this work. These include a model of the electrical energy produced by solar panels due to the amount of radiant energy incident on the panels, a model of the electrical energy produced by wind turbines based on the wind resource present at a given location, a model of the storage of energy in batteries and a model of the storage of energy as hydrogen. The hydrogen energy storage model includes the electrolyzer, the fuel cells, and the pressurized storage of hydrogen in tanks. In addition to these models, an economic model of each of these systems working in different combinations is implemented in this work. Each of these models is described in its own section in this chapter. Also included is a section on the electric loads placed on the solar, wind, battery or hydrogen storage electrical power generating facility.

3.1. Solar Model

For this work a mathematical model that describes the amount of electricity that is produced by solar panels is required. The computer program for this work is an improvement upon the code used to implement the techno-economic model of Rama [1]. Model and code improvements implemented in this work are noted in the detailed description of the mathematical model given below. The solar model used here and by Rama [1] is based on the model described in Duffie and Beckman [28]; specifically, the HDKR model was used.

3.1.1. Solar Angles

3.1.1.1. Angles Related to the Orientation of the Sun

The angles of the sun are related to the time of day. The type of time used for all the sun-angle relationships is solar time. The solar time is not the same as the local clock time and is based on the apparent motion of the sun across the sky. In solar time, noon is the time at which the sun
The conversion of standard time, $t_{std}$, to solar time, $t_{sol}$, requires correction for the difference in longitude between the meridian on which the local standard time is based, $L_{st}$, and the longitude of the location of the panel, $L_{loc}$. It takes the sun 4 minutes to traverse one degree of longitude which is described by

$$t_{sol} - t_{std} = 4(L_{st} - L_{loc}) + E.$$  \hspace{1cm} (3.1)

where the difference in solar time and standard time is given in minutes. The solar time must also be corrected for the perturbations in the earth’s rate of rotation which is accounted for with the equation of time given by

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos(2B)$$

$$- 0.04089 \sin 2B), \hspace{1cm} (3.2)$$

where $E$ is in minutes and $B$ in the $n$th day of the year given by

$$B = (n - 1) \frac{360}{365}. \hspace{1cm} (3.3)$$

The solar time in hours is given by

$$t_{sol} = t_{std} + \frac{4(t_{std} - L_{loc}) + E}{60}. \hspace{1cm} (3.4)$$

The declination angle, $\delta$, is the north-south angular position of the sun, with respect to the plane of the equator. When the declination angle is calculated once per day, it is calculated at solar noon. The value of $\delta$ varies from $-23.45^\circ$ to $23.45^\circ$ and north is positive. The following equation is used to calculate the declination angle $\delta$ daily on the $n$th day of the year,

$$\delta_{daily} = 23.45 \sin \left(360 \frac{284+n}{365}\right). \hspace{1cm} (3.5)$$

Alternatively, the following equation is appropriate to calculate the declination hourly on the $h$th hour of the year

$$\delta = 23.45 \sin \left(360 \frac{284}{365} + \frac{h}{8760}\right). \hspace{1cm} (3.6)$$

The declination angle varies only slightly, about $0.4^\circ$ per day or less, throughout the day. However, the other angles calculated in this section are calculated on an hourly basis, so declination was calculated on an hourly basis as well.

The hour angle, $\omega$, describes the angular location of the sun east or west of the location of concern, due to the rotation of the earth. At solar noon, the hour angle is zero and the sun is directly overhead. Displacement east of the observer is negative, which occurs in the morning and
displacement west of the observer is positive, which occurs in the afternoon. For every hour, the
hour angle changes by 15° which gives

\[ \omega = 15(t_{sol} - 12). \] (3.7)

The sunset hour angle is given by

\[ \cos \omega_{ss} = -\tan \phi \tan \delta. \] (3.8)

where \( \phi \) is the latitude of the location of the observer. North of the equator is positive and south
of the equator is negative. The path of the sun across the sky is symmetric, therefore the sunrise
hour angle can be calculated by

\[ \omega_{sr} = -\omega_{ss}. \] (3.9)

It is common to calculate the values of the sun angles at the midpoint of the hour. For hours
that include sunrise and sunset, it is necessary to calculate the hour angle at the midpoint of the
shortened period between sunrise and the first hole daylight hour or the shortened period between
the last whole daylight hour and sunset.

The zenith angle, \( \theta_z \), is the angle between zenith, a vertical line over the panel, and the line
to the sun. The value of \( \theta_z \) is between 0° and 90° during the day. For values of \( \theta_z \) greater than 90°,
the sun is below the horizon. The zenith angle, \( \theta_z \), is given by

\[ \cos(\theta_z) = \cos(\phi) \cos(\delta) \cos(\omega) + \sin(\phi) \sin(\delta). \] (3.10)

The solar altitude angle, \( \alpha_s \), is the angle between the horizon and a line to the sun. The solar altitude
angle indicates how high the sun is in the sky and is the complement of the zenith angle, given by

\[ \alpha_s = 90° - \theta_z. \] (3.11)

The solar azimuth angle, \( \gamma_s \), is measured in the horizontal plane, like a compass direction
given in degrees. It is the angular displacement in the horizontal plane of the direction of the sun
from due south. Angular displacement east of south is negative and west of south is positive. The
values of \( \gamma_s \) can range from 180° to -180°. The solar azimuth angle can be related to the other solar
angles by

\[ \gamma_s = \text{sign}(\omega) \left| \cos^{-1} \left( \frac{\cos \theta_z \sin \phi - \sin \delta}{\sin \theta_z \cos \phi} \right) \right|. \] (3.12)

3.1.1.2. Angles Related to Location and Orientation of the Panels

The location of the panel on the globe is described by the latitude and longitude. The
latitude, \( \phi \), describes the north-south angular position from the equator, measured from the center
of the globe. The value of $\phi$ is $90^\circ$ at the north pole, $0^\circ$ at the equator, and $-90^\circ$ at the south pole. The longitudinal location, $L_{loc}$, is the angular location of panels west of the meridian at Greenwich, England. This angle is measured from the center of the globe and has values from $0^\circ$ to $360^\circ$.

The orientation of the panel is described by the surface azimuth angle and the slope of the panel, as shown in Figure 3.1. The surface azimuth angle, $\gamma$, measured in the horizontal plane, is like a compass direction in degrees. It is the angular displacement from south of a projection of the normal on the horizontal plane, east of south is negative and west of south is positive. The slope of a panel, $\beta$, is the angle between the panel and the horizontal, and has values from $0^\circ \leq \beta \leq 180^\circ$. When the value of $\beta$ is $0^\circ$ the panel is horizontal. When the value of $\beta$ is less than $90^\circ$ the panel has an upward facing orientation. When the value of $\beta$ is $90^\circ$, the panel is vertical. When the value of $\beta$ is greater than $90^\circ$, the panel has a downward facing orientation.

![Figure 3.1: Zenith angle, surface slope, surface azimuth angle, solar azimuth angle and plan view of the solar azimuth angle [28].](image)

### 3.1.1.3. Angle of Incidence

The angle of incidence, $\theta$, is the angle between the beam of radiation incident on the panel and the normal to the panel. The angle of incidence is related to the declination angle, latitude,
slope, surface azimuth angle and hour angle. The angle of incidence is dependent on the panel location, orientation, and the time of day. The angle of incidence equation tells us about the relationship between the solar beam radiation and the panel surface as a function of the angles given above. The cosine of the angle of incidence is

\[
\cos(\theta) = \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) + \\
\cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega) + \\
\cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega).
\]

(3.13)

The maximum amount of beam radiation is available when the panel is normal to the direction of the beam. This occurs when angle of incidence is equal to 0°. Stated another way, the maximum beam radiation is received when the panel is directly facing the sun. When the panel is not normal to the direction of the beam radiation, the amount of radiation incident on the panel is less. Thus, if the angle of incidence is small, more of the available radiant energy is incident on the panel. If the angle of incidence approaches 90°, less of the available radiant energy is incident on the panel. If the angle of incidence is greater than 90°, the beam is not incident on the front surface of the panel and the sun has set on the panel.

3.1.1.4. Single-Axis Tracking

The slope of a panel may be fixed or may move with the sun. One of the improvements to the solar model for this work was to update the model from a fixed slope panel to a panel with single-axis tracking where the rotation axis is horizontal and runs in the north-south direction. For a tracking system which allows the panel to rotate about a horizontal north-south axis, the panel will track the sun from east to west throughout the day. The tilt of the panel, \( \beta \), which will minimize the angle of incidence for a horizontal north-south axis tracker is given by

\[
\tan(\beta) = \tan(\theta_s) |\cos(\gamma - \gamma_s)|.
\]

(3.14)

For a north-south tracker, the surface azimuth angle \( \gamma \) of the panels will be -90° if the sun is located to the east, \( \gamma_s \leq 0° \), and the surface azimuth angle \( \gamma \) will be 90° if the sun is located to the west, \( \gamma_s > 0° \). The surface azimuth angle is given by

\[
\gamma = \begin{cases} 
90°, & \text{if } \gamma_s > 0° \\
-90°, & \text{if } \gamma_s \leq 0°.
\end{cases}
\]

(3.15)

In this work, the tilt of the panel is calculated hourly.
3.1.2. Anisotropic Sky Model: Predicting Radiation Incident on a Tilted Panel in Any Orientation

The radiation components incident on a tilted panel can be considered as three components, beam, diffuse and ground reflected. Beam radiation is the radiation received by the panel that has not been scattered by the atmosphere. The beam radiation comes from the direction of the sun. Beam radiation is sometimes referred to as direct solar radiation. Diffuse radiation is scattered by the atmosphere before striking the panel. In this work, the diffuse radiation is broken into two anisotropic components and one isotropic component. The two anisotropic diffuse components are circumsolar and horizon brightening, and the isotropic diffuse component is called isotropic. Each of the diffuse radiation components are described in more detail below.

3.1.2.1. HDKR Model

The model used in this work is known as the HDKR model. This model divides diffuse radiation into three components, isotropic diffuse radiation, circumsolar diffuse radiation, which is assumed to come from the direction of the solar disk, and horizon brightening diffuse radiation. Because the circumsolar diffuse radiation is assumed to travel along the same path as the beam radiation, it is lumped into the beam term of the equation. There are also beam radiation and ground reflected terms in the HDKR model equation to calculate the total radiation on a surface. All of these terms are presented below.

3.1.2.2. Beam and Circumsolar Radiation Components Incident on a Tilted Panel

Measurements or estimates of radiation on a horizontal surface are often available. To predict the energy production of panels in other orientations, it is necessary to know the relationship between the incident radiation on a tilted surface and the incident radiation on a horizontal surface. The solar beam irradiation over one hour on a tilted surface, \( I_b,T \), is related to the solar beam energy irradiation on a horizontal surface, \( I_b \), by the geometric factor \( R_b \) using the equation

\[
I_b,T = I_b R_b. \tag{3.16}
\]

where the geometric factor is given by

\[
R_b = \frac{I_{b,T}}{I_b} = \frac{\cos(\theta)}{\cos(\theta_2)}, \tag{3.17}
\]

which depends only on the angle of incidence and the solar zenith angle.
An important point to consider is that as the sun sets $\theta_z$ approaches $90^\circ$, and $\cos(\theta_z)$ approaches zero. This leads to $R_b$ going to infinity, which can predict $I_{b,T}$ values that are unrealistically large, if care is not taken to address this issue. One of the improvements made to the solar model for this work was to restate $R_b$ in terms of other known data to avoid unrealistically large $I_{b,T}$ values near sunrise and sunset. Fortunately, when data for the beam radiation on a surface normal to the beam, $I_{b,n}$, for each hour is available, $\cos(\theta_Z)$ can be eliminated from the denominator. The beam component incident on the tilted panel, $I_{b,T}$, is given by

$$I_{b,T} = I_{b,n}\cos\theta. \quad (3.18)$$

The circumsolar diffuse radiation is diffuse radiation that is more concentrated near the area of the sun. The equation describing the circumsolar diffuse term is

$$I_{d,CS} = I_d A_i R_b. \quad (3.19)$$

The anisotropy index, $A_i$, is used to divide the diffuse radiation into circumsolar and isotropic diffuse parts. The isotropic diffuse portion is incident on the panel equally from all directions. Under clear conditions, $A_i$ will be high, and more of the total diffuse radiation is circumsolar. When there is no beam radiation such as in hazy or cloudy conditions, $A_i$ will be zero, and the circumsolar diffuse radiation will be zero. The anisotropy index is given by

$$A_i = \frac{I_{b,n}}{I_{o,n}} = \frac{I_b}{I_o}. \quad (3.20)$$

To calculate the anisotropy index, the extraterrestrial irradiation over one hour on the horizontal plane, $I_o$, must be calculated. The details of this calculation are shown below. To calculate the extraterrestrial radiation on a horizontal surface over a defined period, such as one hour, the equation above can be integrated from the hour angles $\omega_2$ to $\omega_1$ to give the $I_o$ in watt-hours per square meter.

$$I_o = \frac{12}{\pi} G_{sc} \left[1 + 0.033 \cos \frac{360n}{365} \right] \left[\cos(\phi)\cos(\delta)(\sin(\omega_2) - \sin(\omega_1)) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin(\phi)\sin(\delta) \right] \quad (3.21)$$

where $G_{sc}$ is the solar constant, taken to be 1,353 watts per square meter, which is the energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the radiation just outside the earth’s atmosphere at the mean earth-sun distance. All the information needed to calculate the anisotropy index has now been fully described.
The circumsolar diffuse term was written in terms of \( R_b \), which we wish to eliminate for reasons described above. The circumsolar diffuse term can be rewritten in terms of the diffuse radiation on a horizontal surface, \( I_d \), as

\[
I_{d,CS} = I_d \frac{I_{b,n}}{I_o} \cos \theta.
\]  

(3.22)

This equation eliminates the \( R_b \) term. If the irradiation normal to the direction of the beam, \( I_{b,n} \), is known, the circumsolar diffuse term can be rewritten as

\[
I_{d,CS} = I_d \frac{I_{b,n}}{I_o} \cos \theta.
\]  

(3.23)

Because the circumsolar diffuse radiation comes from the direction of the sun, it is lumped together with the beam radiation to determine what is defined in this work as the total beam radiation. The total beam radiation on a tilted surface, \( I_{b,t\ total} \) is given by

\[
I_{b,t\ total} = I_{b,t} + I_{d,CS}.
\]  

(3.24)

### 3.1.2.3. Isotropic and Horizon Brightening Radiation Components Incident on a Tilted Panel

The isotropic diffuse term, \( I_{d,iso} \), accounts for the diffuse radiation from all parts of the sky. The isotropic diffuse term is given by

\[
I_{d,iso} = I_d \left( 1 - A_i \right) \frac{1 + \cos \beta}{2}. \]

(3.25)

The horizon brightening term, \( I_{d,HB} \), accounts for the diffuse radiation from a region of the sky near the horizon, which is more pronounced in clear conditions. The model for this work was enhanced from that used by Rama [1] by adding the horizon brightening term, given by

\[
I_{d,HB} = I_d \left( 1 - A_i \right) \frac{1 + \cos \beta}{2} \left( f \sin^3 \frac{\beta}{2} \right). \]

(3.26)

The modification factor \( f \) in horizon brightening is

\[
f = \sqrt{\frac{I_b}{I}}. \]

(3.27)

For the previous terms in the HDKR model the beam irradiation on a horizontal surface, \( I_b \), has been written in terms of other radiation components. This is also done for the modification factor \( f \) which is stated in terms if \( I \) and \( I_d \). We know for a horizontal surface the total solar irradiation over one hour, \( I \), is the sum of the horizontal beam and horizontal diffuse irradiation given as
\[ I = I_b + I_d. \]  
\[ (3.28) \]

So, \( f \) is
\[ f = \frac{\sqrt{1-I_d}}{1}. \]  
\[ (3.29) \]

Because the circumsolar diffuse was lumped together with the beam radiation, the isotropic diffuse and horizon brightening diffuse terms will make up what is called the total diffuse radiation in this work. The total diffuse radiation term is
\[ I_{d, total} = I_{d, iso} + I_{d, HB}. \]  
\[ (3.30) \]

### 3.1.2.4. Ground Reflected and Total Radiation Incident on a Tilted Panel

The ground reflected term, \( I_g \), accounts for the diffuse radiation reflected from a horizontal, diffusely reflecting ground and is given by
\[ I_g = I_{\rho g} \left( \frac{1 - \cos \beta}{2} \right). \]  
\[ (3.31) \]

At this point, all the terms of the HDKR model have been described in detail. The model includes the beam, circumsolar diffuse, isotropic diffuse, horizon brightening diffuse and ground reflected radiation components on a tilted panel. The complete equation describing the radiation on a tilted panel is
\[ I_t = I_{b, n} \cos \theta + I_d \frac{I_{b, n} \cos \theta}{I_b} + I_d (1 - A_i) \left( \frac{1 + \cos \beta}{2} \right) + I_d (1 - A_i) \left( \frac{1 + \cos \beta}{2} \right) \left( f \sin^3 \frac{\beta}{2} \right) + \]
\[ I_{\rho g} \left( \frac{1 - \cos \beta}{2} \right). \]  
\[ (3.32) \]

### 3.1.2.5. Electrical Energy Produced by Solar Panels

The solar panels are arranged in a rectangular array in rows and columns. The front row, closest to the sun, is unshaded by the other rows of panels. The solar irradiation on the front row of panels is the total solar irradiation incident on a tilted panel, which is simply the sum of the total beam, total diffuse, and ground reflected components on the tilted panel given by
\[ I_{FR} = I_{b, t \, total} + I_{d, total} + I_g. \]  
\[ (3.33) \]

The hourly electrical energy produced by the first row of panels, \( E_{H, FR} \), is simply the solar flux multiplied by the surface area of the front row panels, \( A_{FR} \), adjusted for the efficiency of the photovoltaic panels, \( \eta_{pv} \), as
The hourly solar irradiation and thus hourly electrical energy produced by the rows of panels behind the front row is impacted by shading. For this work, the effects of shading caused by neighboring panel rows is included. The shaded row panels will be referred to as back row panels. The shading model is unchanged from the model fully described in Rama [1]. Specifically, the total beam, $I_{b,t\text{total BR}}$, and ground reflected components, $I_{g, BR}$, of solar irradiation are impacted by shading of neighboring rows of panels. The diffuse component is unchanged for the back row panels. The dimensions that impact the fraction of shading are the length of the panels, $L$, taken to be 1 m and the spacing between the panel rows, $g$, taken to be 5 m. The hourly solar irradiation on the back row panels, $I_{BR}$, is 

$$I_{BR} = I_{b,t\text{total BR}} + I_{d\text{total}} + I_{g, BR},$$

where $I_{b,t\text{total BR}}$ is the total hourly beam irradiation on the back row panels, and $I_{g, BR}$ is the total ground reflected irradiation on the back row panels. The hourly electrical energy produced by the back row panels is

$$E_{H, BR} = I_{BR}A_{BR}\eta_{pv}.$$  

The total hourly electrical energy produced by all the panels, $E_{H, S}$, is

$$E_{H, S} = E_{H, FR} + E_{H, BR}. $$

The total yearly electrical energy produced by all the panels, $E_{Y, S}$, is the sum of the hourly total electrical energy produced by all the panels over the year given by

$$E_{Y, S} = \sum_{1}^{365} E_{H, S}. $$

### 3.2. Wind Model

The wind model was largely unchanged from Rama [1]; but will be fully described in this work so the reader understands how the wind electrical energy production was calculated. The improvement made to the wind calculation portion of Rama’s code was to store the wind power produced for each time interval for later use, rather than repeatedly interpolating the same information for each combination of wind and solar farm size. This improved the speed of the code but does not impact the results.

#### 3.2.1. Wind Resource

27
The wind resource must be quantified for the wind model to determine the hourly and yearly power produced by the wind farm. The wind speed data is taken from NREL Wind Prospector data sets [29], which are now retired. The data provides windspeeds at a height of 100 m from the ground for Rio Vista, California for every five-minute interval from the year 2012. The wind turbine is assumed to yaw into the wind, so wind direction data is not needed.

3.2.1.1. Adjusting Wind Speed to Hub Height

The mean windspeed profile increases with increasing height above the earth. The log law was used to predict the windspeed at the rotor hub height of 84 meters from the windspeed data at a height of 100 m above the ground as described in Rama [1].

3.2.2. Wind Power Production

The important input parameters for the wind model are as follows. The air density, \( \rho_{air} \), is the density of air at standard conditions which is 1.225 kg/m\(^3\). The input technical variables are taken from the Enercon E-82 E4 3.0 turbine. The cut in and cut out windspeeds for the rotor are 3 and 34 m/s, respectively, the rotor diameter is 82 m, and the hub height is 84 meters. The Enercon E-82 E4 3.0 turbine power curve is shown in Figure 3.2. The power produced by the wind turbine is determined by interpolating the power curve at the windspeed that was adjusted to the hub height for each 5-minute interval over the year. The hourly electricity produced by the wind turbines, \( E_{H,W} \), can be found by integrating the 5-minute wind power output, \( P_{5,w} \), over the hour multiplied by the number of wind turbines \( N_w \), given by

\[
E_{H,W} = N_w \frac{5}{60} \sum_{1}^{12} P_{5,w}. \tag{3.39}
\]

The yearly wind energy output, \( E_{Y,W} \), is the hourly wind energy output integrated over one year given by

\[
E_{Y,W} = \sum_{1}^{8760} E_{H,W}. \tag{3.40}
\]
3.3. Community Electricity Load

The hourly community electric demand, $E_{H,D}$, for this work is the electric demand for 25,000 homes in Rio Vista, California. The hourly electric usage by a home in Rio Vista is obtained from OpenEI datasets [30]. The hourly excess deficit energy, $E_{H,ex,def}$, can be found by subtracting the electric demand from the electric production of the wind turbines and solar panels. The hourly excess deficit energy, $E_{H,ex,def}$ is given by

$$E_{H,ex,def} = E_{H,S} + E_{H,W} - E_{H,D}. \quad (3.41)$$

Positive values for excess deficit energy indicate more power was produced than was used by the demand. Negative values for excess deficit energy indicate that less electricity was produced than was required by the load, and electricity must be purchased from the grid to meet the demand. Positive values of hourly excess deficit energy indicate an excess generated electricity in any given hour given as

$$E_{H,ex} = \max (E_{H,ex,def}, 0). \quad (3.42)$$

Negative values of excess deficit energy indicate a deficit of generated electricity in any given hour given by
\[ E_{H,\text{def}} = -\min (0, E_{H,\text{ex,def}}). \]  
(3.43)

The negative sign makes the negative excess deficit values a positive number. The hourly deficit energy is integrated over one year to get the yearly value, \( E_{Y,\text{def}} \), as

\[ E_{Y,\text{def}} = \sum_{1}^{8760} E_{H,\text{def}}. \]  
(3.44)

\( E_{Y,\text{def}} \) is the energy that must be purchased from the grid for the year.

### 3.4. Battery Energy Storage Model

#### 3.4.1. Battery Background

Battery packs are made up of smaller units called cells. Battery cells are the smallest electrochemical unit that can deliver voltage and are able to deliver electrical charge to power a load circuit. Battery cells may be classified as primary cells, which are single use, or secondary cells which are rechargeable. Lithium-ion cells include a negative electrode, a positive electrode, electrolyte, and separator (see Figure 3.3). Lithium-ion cells are insertion-electrode cells and do not use a redox reaction that chemically changes the reactants at the electrode surface. Lithium does not react with the electrode material but is inserted into empty spaces in the material structure, which is referred to as intercalation. This process can be reversed; deintercalation occurs when lithium is forced out from the electrode and into the electrolyte.

Electrodes must have open-crystal structures with empty “corridors” such as tunnels or layers for lithium to move through. Collectors may be a part of the electrodes or separate components. Thin metallic foil may be included on the electrodes to act as current collectors. Current collectors conduct current into and out of the cell.

Some lithium-ion cells include a separator which is sandwiched between the positive and negative electrodes. The separator is a membrane with pores that are large enough to pass lithium ions. The electrolyte-soaked separator serves to separate the positive and negative electrode and prevents an internal short circuit of the cell, while conducting lithium ions.

The electrolyte must be an ionic conductor and electronic insulator, which allows ionic charge to be transferred between electrodes. For lithium-ion cells with liquid electrolyte, a nonaqueous organic solvent and a lithium salt may be used [31]. In the case of gel-polymer batteries, the electrolyte will be a gel-polymer, where the salt and solvent are mixed or dissolved
in a polymer. Polymer electrolytes where salt is dissolved into a polymer and ceramic electrolytes are examples of solid electrolytes [32].

Figure 3.3: Schematic of the electrochemical process in a lithium-ion cell [32].

The quantity of charge in ampere-hours that a cell is rated to hold is the cell’s nominal charge capacity. The cell’s nominal energy capacity is the quantity of electrical energy in watt-hours that the cell can hold. The nominal energy of a battery or cell is the nominal voltage multiplied by its nominal charge capacity. The operating voltage of a battery or cell may vary above or below the nominal voltage [31].

C-rate relates the cell current to the cell charge capacity. It is the constant-current charge or discharge rate that the cell can sustain for 1 hour. For example, a 20-Ah cell should be able to deliver 20 A (a 1C rate) for 1 hour, 2 A (a C/10 rate) for about 10 hours, or 10 C for about 6 minutes [31]. In actual operation, cells discharged at high rates will deliver less than the nominal capacity and will operate for less time than noted. Also, cells operated at low discharge rates deliver more than the nominal capacity and will operate longer than predicted above. The E rate is analogous to the C rate and relates to the charge or discharge power of the battery [32]. A battery discharged at a 1 E rate will discharge in 1 hour.
3.4.2. Calculating the Battery Power Limits for Each Timestep

The power in or out of a battery used in this work must be calculated based on the load demand and the power available from the wind and solar farm. Other limits must be considered such as the rated power of the battery and the maximum and minimum state of charge of the battery. These limits are described below. The battery model in this work is largely based on the model in Petersen et al. [5]. The sign convention for the battery current is positive for discharging and negative for charging. The battery voltage is assumed to be a constant value.

The first of three power limits that will be described is the battery power limit, $P_{E-rate,max}$. The battery’s maximum continuous power is the rate at which energy can be charged or discharged from the battery, $E_{rate,max}$, and relates the maximum rate at which energy can be charged or discharged from the battery to the nominal energy capacity of the battery, $E_{max}$. The maximum E-rate limits the maximum power available given by

$$P_{E-rate,max} = \frac{E_{rate,max}}{1\text{hr}} E_{max}. \quad (3.45)$$

The second battery power limit relates to the state of charge (SOC) of the battery. The SOC cannot exceed the maximum SOC, $SOC_{max}$, when charging. The energy that is needed to charge the battery to the maximum SOC is divided by the length of the time step to obtain this power limit. The power required to fully charge the battery during any time step, $P_{ava, ch}$, is

$$P_{ava, ch} = \frac{(SOC_{ini} - SOC_{max})E_{max}}{\epsilon_{battery} \Delta t}. \quad (3.46)$$

where $\epsilon_{battery}$ is the battery columbic efficiency for charging alone and $SOC_{ini}$ is the state of charge at the beginning of the time step. The SOC also cannot fall below the minimum state of charge when the battery system is discharged. The energy that is obtained when the battery system is discharged to the minimum SOC, $SOC_{min}$, during one time step is divided by the length of the time step to obtain the discharge power limit. The available discharge power limit, $P_{ava, dch}$, is

$$P_{ava, dch} = \frac{(SOC_{ini} - SOC_{min})E_{max} \epsilon_{battery}}{\Delta t}. \quad (3.47)$$

The time step for battery calculations, $\Delta t$, is one minute or $1/60^{th}$ of an hour, and the battery columbic efficiency, $\epsilon_{battery}$, is assumed to be equal for charging and discharging.
The final limit that must be considered is the power which the community demands less the wind and solar power generated, $P_{in}$. $P_{in}$ is negative for charging and positive for discharging. It is the negative of the excess deficit power calculated on a minute-by-minute basis.

The discharging and charging power external to the battery are described by the equations below, Equation (3.48) and Equation (3.49). Note that the power into the battery, $P_{in}$, and $P_{ava, ch}$, will be negative. The power into the battery is calculated as

$$P_{BESS, ch} = \max[P_{in}, -P_{E-rate, max}, P_{ava, ch}].$$

(3.48)

This equation provides the smallest magnitude of the three numbers in the argument of the max function. The power discharged by the battery is calculated as

$$P_{BESS, dch} = \min[P_{in}, P_{E-rate, max}, P_{ava, dch}].$$

(3.49)

where $P_{in}$ will be positive for discharging. The energy into and out of the battery system is calculated from the power as

$$E_{battery, in} = P_{BESS, ch} \Delta t,$$

(3.50)

and

$$E_{battery, out} = P_{BESS, dch} \Delta t,$$

(3.51)

where charging values are negative and discharging values are positive.

### 3.4.3. Calculating State of Charge

The internal battery charging and discharging power, which is the power after accounting for battery efficiency losses, are used to calculate the SOC. The internal battery power, $P_{Bint}$, during charging and discharging is given by

$$P_{Bint, ch} = \varepsilon_{battery} P_{BESS, ch}$$

(3.52)

or

$$P_{Bint, dch} = \frac{P_{BESS, dch}}{\varepsilon_{battery}}$$

(3.53)

and

$$P_{Bint} = \begin{cases} P_{Bint, ch} & \text{if } P_{in} \leq 0 \\ P_{Bint, dch} & \text{if } P_{in} > 0 \end{cases}$$

(3.54)

The SOC is updated by watt hour counting, where the SOC increases if the battery is charging and decreases if the battery is discharging. The state of charge at the end of the time step, $SOC_{end}$, is given by

$$SOC_{end} = SOC_{ini} - \frac{P_{Bint} \Delta t}{E_{max}}.$$  

(3.55)

The values in the battery model were calculated on a minute-by-minute basis. The community load and solar irradiation data are available for every hour throughout the year. The
wind speed data is available every five minutes throughout the year. Average hourly SOC, battery energy input and battery energy output are calculated as

\[
SOC_{\text{hourly}} = \frac{\sum_{1}^{60} SOC_{\text{end}}}{60}, \tag{3.56}
\]

\[
E_{\text{Hourly,battery,in}} = \frac{\sum_{1}^{60} E_{\text{battery,in}}}{60}, \tag{3.57}
\]

and

\[
E_{\text{Hourly,battery,out}} = \frac{\sum_{1}^{60} E_{\text{battery,out}}}{60}. \tag{3.58}
\]

The hourly excess deficit with battery energy storage can now be calculated as

\[
E_{H,ex,\text{def, battery}} = E_{H,S} + E_{H,W} - E_{H,D} + E_{\text{Hourly,battery,in}} + E_{\text{Hourly,battery,out}}. \tag{3.59}
\]

Positive values of hourly excess-deficit energy indicate an excess energy generated and available from battery energy storage in any given hour given by

\[
E_{H,ex,\text{battery}} = \max (E_{H,ex,\text{def, battery}}, 0). \tag{3.60}
\]

Negative values of excess deficit energy indicate a deficit of energy generated and available from battery energy storage in any given hour, given by

\[
E_{H,\text{def, battery}} = -\min (0, E_{H,ex,\text{def, battery}}). \tag{3.61}
\]

The negative sign makes the negative excess deficit values a positive number. Because yearly deficit energy is of interest, the deficit energy is integrated over one year, \(E_{Y,\text{def,battery}}\), as

\[
E_{Y,\text{def, battery}} = \sum_{1}^{8760} E_{H,\text{def, battery}}. \tag{3.62}
\]

\(E_{Y,\text{def,battery}}\) is the energy that must be purchased from the grid for the year when battery energy storage is included.

3.5. Hydrogen Energy Storage Model

3.5.1. Regenerative SOFC SOEC Model

A fuel cell is an electrochemical cell that directly converts chemical energy that resides in a fuel into electrical power. For a \(H_2-O_2\) fuel cell, hydrogen and oxygen pass into the fuel cell and water and electricity are produced (see Figure 3.4). The solid oxide fuel cell (SOFC) reaction is
\[ H_2 + O^{2-} \rightarrow H_2O + 2e^- \]

\[ \frac{1}{2} O_2 + 2e^- \rightarrow O^{2-} . \]  

(3.63)

The two half reactions are spatially separated, and electrons must flow though the external circuit to complete the reaction. In an electrolysis cell the reaction is reversed. Energy and water are provided to the electrolysis cell and hydrogen and oxygen are produced by the reaction. The regenerative cells in this work are hydrogen oxygen fuel cells/electrolyzer cells.

### 3.5.1.1. One-Dimensional Solid Oxide Cell Model

In order to select the operating points of the regenerative cell when operating as a fuel cell or as an electrolyzer cell, the two-dimensional, nonisothermal electrolysis model presented in Laurencin et al. [16] was simplified to a one-dimensional isothermal model, with simplifications as used in the one-dimensional SOFC model in O'Hayre et al. [18]. The relevant equations are derived with the fuel cell reaction as the forward reaction.

![Solid oxide fuel cell diagram illustrating species flows](image)

**Figure 3.4: Solid oxide fuel cell diagram illustrating species flows [33].**

The SOFC one-dimensional model tracks fuel cell species moving through the fuel cell. The model tracks the \( H_2 \) and \( H_2O \) flowing into and out of the anode. For the cathode, \( O_2 \) flows
into and out of the cathode are tracked. Ions flowing across the electrolyte are also tracked. In a SOFC, \( O^{2-} \) ions flow from the cathode to the anode. The species’ fluxes are related to the current density, or charge flux. The current density is related to the fluxes of oxygen, hydrogen, and water by

\[
\frac{j}{2F} = J_{O^{2-},\text{electrolyte}} = J_{H_2,\text{anode}} = 2J_{O_2,\text{cathode}} = -J_{H_2O,\text{anode}}. \tag{3.64}
\]

The following assumptions are made for the one-dimensional fuel cell model, which are modified from those noted in O’Hayre et al. [18]:

1. The one-dimensional model considers transport in the cell along the z-axis only and convective transport within the cell is ignored, as convection occurs mostly in the y-direction.
2. Diffusion is ignored in the flow channels, but not in the electrodes.
3. The catalyst layers act as interfaces and are very thin. This means that conduction, convection, and diffusion can be neglected in the catalyst layer and only reaction kinetics are important. For most SOFCs, the catalyst layer and electrode are combined in a single body. The assumption is still justified because reactions are usually localized to a very thin region of the catalyst/electrode near the electrolyte.
4. Water exists only as water vapor. For SOFCs the typical operating temperatures justify this assumption.
5. The performance of the stack of cells scales with the performance of the cell and the cell area in the stack.
6. The cell is fed with a specified rate and mole fraction of reactants. The unused reactant is recycled.
7. Excess heat from the cell reaction and exiting products is used to preheat incoming reactants with 100% effectiveness.

### 3.5.1.2. Construction of the Polarization Curve

The operating voltage, \( V_{cell} \), of a fuel cell at current density \( j \) is calculated by

\[
V_{cell} = E_{thermo} - \eta_{ohmic} - \eta_{conc} - \eta_{act}, \tag{3.65}
\]

where \( E_{thermo} \) is the reversible, thermodynamical, fuel cell voltage at temperature \( T \) and constant pressure. The activation, ohmic and concentration voltages are subtracted from the thermodynamically predicted fuel cell voltage to obtain the operating voltage. For the fuel cell \( E_{thermo} \) can be calculated as

\[
E_{thermo} = E^0 + \frac{\Delta \delta}{nF}(T - T_0) - \frac{RT}{nF} \ln \left( \frac{\Pi a_{\text{products}}^\nu}{\Pi a_{\text{reactants}}^\nu} \right), \tag{3.66}
\]

where

\( E^0 \) is the standard-state reversible voltage (Volts),
\( \Delta \delta \) is the entropy change for the reaction (J/mol), 
\( n \) is the number of moles of electrons transferred per mol of reactant (mol/mol), 
\( F \) is Faraday’s constant (C/mol), 
\( T_0 \) is the standard state temperature (°K), 
\( R \) is the ideal gas constant (J/mol*°K), 
\( \alpha \) is the activity of the species, and 
\( v_i \) is the stoichiometric coefficient.

For ideal gases, activity is \( p_i/p_0 \) where \( p_i \) is the partial pressure of the gas species and \( p_0 \) is the standard-state pressure of 1 atm. The partial pressure of a gas in an ideal gas mixture is \( p_i = x_ip \) where \( p \) is the total pressure of the gas mixture. For solid oxide fuel cell operation Equation (3.66) for \( E_{thermo} \) can be written as

\[
E_{thermo} = E^0(T) - \frac{RT}{2F} \ln \left( \frac{1-x_{H_2,inlet}}{x_{H_2,inlet}x_{O_2,inlet}^{1/2}} \right),
\]

where \( E^0(T) \) is the reversible voltage at temperature \( T \), \( x_{H_2,inlet} \) is the hydrogen mole fraction at the channel inlet and \( x_{O_2,inlet} \) is the oxygen mole fraction at the channel inlet.

The voltage due to ohmic losses is

\[
\eta_{ohmic} = j \ast R_{ohm},
\]

where the ohmic losses in the electrolyte, as well as both electrodes, are accounted for as in Laurencin et al. [16] by,

\[
R_{ohm} = R_{LSM} + R_{Ni-YSZ} + R_e + R_c.
\]

The area specific resistances of the electrodes and electrolyte are

\[
R_{LSM} = \frac{\delta_{O_2 electrode}}{\rho_{LSM}},
\]

\[
R_{Ni-YSZ} = \frac{\delta_{H_2 electrode}}{\rho_{Ni-YSZ}},
\]

\[
R_e = \frac{\delta_{electrolyte}}{\rho_{YSZ}},
\]

where

\( \rho_{LSM} \) is \( O_2 \) electrode electrical conductivity (72 \( \Omega^{-1}\text{cm}^{-1} \)),
\( \rho_{Ni-YSZ} \) is electrode electrical conductivity (800 \( \Omega^{-1}\text{cm}^{-1} \)),
\( \rho_{YSZ} \) is the ionic conductivity of the electrolyte (\( \Omega^{-1}\text{cm}^{-1} \)),
\( \delta_{H_2 electrode} \) is \( H_2 \) electrode thickness (0.005 cm),
\( \delta_{O_2 electrode} \) is \( O_2 \) electrode thickness (0.005 cm),
\( \delta_{electrolyte} \) is electrolyte thickness (0.009 cm), and
\( R_c \) is the contact resistance (0.1 \( \Omega\text{cm}^2 \)).
Laurencin et al. [16] notes the electronic resistance of the electrodes is lower than the ionic resistance of the electrolyte, the electrode resistances are treated as if they are temperature independent. The ionic conductivity ($\Omega^{-1} \text{cm}^{-1}$), of the electrolyte is given by

$$\rho_{\text{YSZ}} = 466 \exp\left(-\frac{9934}{T}\right).$$

(3.73)

The voltage loss that occurs due to the change in concentration of products and reactants at the catalyst layer versus the bulk species concentrations is $\eta_{\text{conc}}$ (see Figure 3.5). The concentration differences are due to mass transport limitations through the electrodes. Reactants must diffuse through the electrodes from the bulk stream to the catalyst layer. Products must diffuse from the catalyst layer to the bulk stream. The diffusion equation relates the reactant flux to the concentration profile.

![Figure 3.5: Illustration of mass transport and concentration gradients in a fuel cell anode [18].](image)

During fuel cell operation, oxygen is the reactant that is diffused through the cathode to the catalyst and hydrogen is the reactant that is diffused through the electrode to the reaction sites on the anode side. In O’Hayre et al. [18], and in this work, Fick’s law of diffusion is used, given by

$$J_{\text{diff}} = -D^{\text{eff}} \frac{c_{\text{R}}^{\text{catalyst}} - c_{\text{R}}^{\text{channel}}}{\delta}.$$  

(3.74)

where $J_{\text{diff}}$ is the diffusion flux of reactants toward the catalyst layer or the diffusion flux of products away from the catalyst layer and $D^{\text{eff}}$ is the effective diffusivity. The relationship
between a reactant flux or product flux and current density is given in Equation (3.64) At steady state the fuel cell’s operating current density is related to the reactant or product diffusion flux by

\[ j = nFJ_{\text{diff}}, \]  

where \( n \) is the number of moles of electrons generated (+), or consumed (-), per mole of species. Thus, the current density is related to the concentration of reactant at the catalyst layer by

\[ c_{R}^{\text{catalyst}} = c_{R}^{\text{channel}} - \frac{jS}{nF \text{eff}}, \]  

In some models, the impact of reactant species consumption in the cell channel is neglected. However, in Laurencin et al. [16] this effect is included. The amount and ratios of gases fed into the cell are maintained at constant values in this work. The concentration of products and reactants at the outlet of the channel are a function of the current density and inlet conditions. The species’ outlet fluxes are the difference between the inlet flux and the flux due to the consumption of reactants or generation of products by the reaction, at the given current density. The oxygen flux at the outlet is calculated as follows for the oxygen electrode,

\[ J_{\text{O}_2,\text{outlet}} = J_{\text{O}_2,\text{inlet}} - \frac{j}{4F}, \]  

where \( J_i \) is the species flux in mol/(s-m²), at the noted location. When oxygen is fed to the cell in a gas mixture such as air, the air outlet flux is

\[ J_{\text{air, outlet}} = J_{\text{air}} - \frac{j}{4F}. \]  

In this work the molar flow rate of air at the inlet, \( J_{\text{air}} \), is 3.068 x 10⁻⁶ mol/(s-m²). Similarly, the hydrogen and steam flux for the hydrogen electrode is,

\[ J_{\text{H}_2,\text{outlet}} = J_{\text{H}_2,\text{inlet}} - \frac{j}{2F}, \]  

and

\[ J_{\text{H}_2\text{O, outlet}} = J_{\text{H}_2\text{O, inlet}} + \frac{j}{2F}. \]  

In this work the molar flow rate of hydrogen at the inlet, \( J_{\text{H}_2,\text{inlet}} \), is 6.90 x 10⁻⁶ mol/(s-m²) and the molar flow rate of steam at the inlet, \( J_{\text{H}_2\text{O, inlet}} \), is 6.90 x 10⁻⁶ mol/(s-m²). The outlet mole fractions are the ratio of the flux of the species to the total gas flux in the channel. For the oxygen electrode, the channel outlet mole fraction is

\[ x_{\text{O}_2\text{outlet}} = \frac{J_{\text{O}_2,\text{inlet}} - \frac{j}{4F}}{J_{\text{air}} - \frac{j}{4F}}. \]  

Similarly, for the H2 electrode the hydrogen and steam mole fractions are
\[ x_{H_2,\text{outlet}} = \frac{J_{H_2,\text{inlet}} - \frac{J}{2F}}{J_{H_2,\text{inlet}} + J_{H_2O,\text{inlet}}} \]  

and

\[ x_{H_2O,\text{outlet}} = \frac{J_{H_2O,\text{inlet}} + \frac{J}{2F}}{J_{H_2,\text{inlet}} + J_{H_2O,\text{inlet}}} \]  

In this work, a one-dimensional cell model is used. The average of inlet and outlet reactant and product mole fractions are used to determine the channel mole fractions used in subsequent calculations given by,

\[ x_{O_2,\text{channel}} = \frac{x_{O_2,\text{outlet}} + x_{O_2,\text{inlet}}}{2}, \]  

\[ x_{H_2,\text{channel}} = \frac{x_{H_2,\text{outlet}} + x_{H_2,\text{inlet}}}{2}, \]  

\[ x_{H_2O,\text{channel}} = \frac{x_{H_2O,\text{outlet}} + x_{H_2O,\text{inlet}}}{2}. \]  

The activation voltage is the voltage required to overcome the activation barrier associated with the chemical reaction. \( \eta_{\text{act}} \) accounts for the activation losses in volts. The activation losses can be calculated using the Butler-Volmer equation. The first term of the Butler-Volmer equation accounts for the changes in the activation barrier when the reaction proceeds in the forward direction. The second term of the equation accounts for the change in activation barrier for the reaction in the reverse direction. The extended Butler-Volmer equation as given in O’Hayre et al. [18] is

\[ j = j_0^0 \left( \prod \left( \frac{c^{0*}_{R,i}}{c_{R,i}} \right)^{\nu_i} e^{\alpha n F \eta / (RT)} - \prod \left( \frac{c^{0*}_{P,i}}{c_{P,i}} \right)^{\nu_i} e^{-(1-\alpha) n F \eta / (RT)} \right), \]  

where

- \( j_0^0 \) is the exchange current density at the reference reactant and product concentrations \( c_{R,i}^{0*} \) and \( c_{P,i}^{0*} \), respectively,
- \( c_{R,i}^{*} \) is the reaction surface concentration of reactants,
- \( c_{P,i}^{*} \) is the reaction surface concentration of products,
- \( \alpha \) is the charge transfer coefficient,
- \( n \) is the number of electrons transferred in the reaction,
- \( F \) is Faraday’s constant,
- \( \eta \) is voltage loss (volts),
- \( R \) is the ideal gas constant \((J/mol °K^{-1})\), and
- \( T \) is the temperature \((°K)\).

The Butler-Volmer equation is applied to each electrode. Because the hydrogen electrode is the anode in the fuel cell reaction and the cathode in the electrolysis reaction, referring to the anode and cathode reactions for the regenerative cell becomes confusing. The electrodes are
labeled with the species reacting at that location in this work. The extended Butler-Volmer equation can be applied to the hydrogen electrode, assuming that the electron activity terms can be neglected gives

\[ j = j_0 \left( \frac{c_{H_2, catalyst}}{c_{H_2, ref}} e^{\frac{a_{H_2, e} n_{H_2, electrolyte} F n_{H_2, electrolyte}}{RT}} - \frac{c_{H_2O, catalyst}}{c_{H_2O, ref}} e^{\frac{(1-a_{H_2, e}) n_{H_2, electrolyte} F n_{H_2, electrolyte}}{RT}} \right). \] (3.88)

The extended Butler-Volmer equation can be applied to the oxygen electrode as well, assuming the oxygen ion activity terms can be neglected gives,

\[ j = j_0 \left( \frac{c_{O_2, catalyst}}{c_{O_2, ref}} e^{\frac{a_{O_2, e} n_{O_2, electrolyte} F n_{O_2, electrolyte}}{RT}} - e^{\frac{(1-a_{O_2, e}) n_{O_2, electrolyte} F n_{O_2, electrolyte}}{RT}} \right), \] (3.89)

where the reference concentrations \( c_{H_2, ref}, c_{H_2O, ref}, \) and \( c_{O_2, ref} \) are taken to be the concentrations of the species at the inlet of the fuel cell channel. For ideal gases \( p_i = c_i R T \). The reference concentrations are equal to the concentration at the reaction surface when the current density is zero, which are taken to be the channel inlet concentrations for each species. The Butler-Volmer equation accounts for both the activation and concentration voltages. The voltage losses from solving the equations above for each electrode are summed to determine the combined activation and concentration losses for the cell.

The equations from Laurencin et al. [16] give the exchange current density as a function of mole fraction of products at the reaction surface, mole fraction of reactants at the reaction surface and temperature,

\[ j_0^{H_2, electrode} = A_{j_0} \left( x_{H_2}^{catalyst} (j = 0) \right)^{m_{j_0}} \left( x_{H_2O}^{catalyst} (i = 0) \right)^{n_{j_0}} \left( \frac{-E_{a_{H_2, electrode}}}{RT} \right) \] \( (3.90) \)

and

\[ j_0^{O_2, electrode} = B_{j_0} \left( x_{O_2}^{catalyst} (j = 0) \right)^{p_{j_0}} \left( \frac{-E_{a_{O_2, electrode}}}{RT} \right), \] \( (3.91) \)

where pre-exponential values \( A \) and \( B \) are scaled to match the \( j_0 \) values recommended in the literature and are shown in Table 3.1. When the current density is equal to zero, the species mole fractions at the catalyst surface are both taken to be equal to the species mole fractions at the channel inlet, \( x_{H_2, inlet}, x_{H_2O, inlet}, \) and \( x_{O_2, inlet}. \)
Table 3.1: Exchange current density parameters [16].

<table>
<thead>
<tr>
<th></th>
<th>Pre-exponential Factors (mA/cm²)</th>
<th>Molar Fraction Exponent</th>
<th>Activation Energy (KJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSM</td>
<td>$B_0=2.05 \times 10^8$</td>
<td>$p_0=1/4$</td>
<td>120</td>
</tr>
<tr>
<td>NI-8YSZ</td>
<td>$A_0=1.26 \times 10^{10}$</td>
<td>$m_0=n_0=1$</td>
<td>120</td>
</tr>
</tbody>
</table>

The voltage versus current density curve in Figure 3.6 can be calculated by tracking the concentration profiles inside the model cell. In the model, the current density, $j$, is the known quantity. The $O_2$ concentration in the oxygen electrode catalyst layer, as well as the $H_2$ and $H_2O$ concentration profiles in the hydrogen electrode catalyst layer, are inputs to the calculation of activation and concentration overvoltage. The program solves the overvoltage of each electrode’s extended Butler-Volmer equation, $\eta_{H2elec}$ and $n_{O2elec}$, for the input current density iteratively. Thus, the activation and concentration losses are determined in one step. The equation

$$V_{cell} = E_{thermo} - \eta_{ohmic} - \eta_{H2elec} - n_{O2elec}$$

(3.92)

is relevant for both positive current densities in fuel cell mode and negative current densities in electrolyzer cell mode.

Figure 3.6: Polarization curves of solid oxide regenerative cell.
To construct the polarization curve shown in Figure 3.6, an array of current density values is created to pass into the equations above. The largest and smallest current densities used to construct the regenerative cell curve must not allow the mole fraction of reactant species to fall below zero at the channel outlet given by

\[ j_{L,O_2,\text{outlet}} = 4FJ_{O_2,\text{inlet}} \]  
\[ j_{L,H_2,\text{outlet}} = 2FJ_{H_2,\text{inlet}} \]  
\[ j_{L,H_2O,\text{outlet}} = -2FJ_{H_2O,\text{inlet}} \]

The limiting current densities are positive for the fuel cell and negative for the electrolyzer cell. For the fuel cell mode portion of the polarization curve, the largest input current density will be chosen as the smallest of the limits for fuel cells as noted above and shown in the equation

\[ j_{max,fuel\ cell\ curve} = \min (j_{L,H_2,\text{outlet}} = 0, j_{L,O_2,\text{outlet}} = 0) \]  
For the electrolyzer cell mode portion of the polarization curve, the smallest input current density will be

\[ j_{min,electrolyzer\ cell\ curve} = j_{L,H_2O,\text{outlet}} = 0 \]  
A limiting current density occurs when the reactant concentration goes to zero at the reaction site, \( c_{R,\text{catalyst}} = 0 \). The relationship between concentration at the catalyst site and the current density is given by Equation (3.76). This condition does not occur for any of the reactants in fuel cell or electrolyzer mode in this model.

### 3.5.1.3. Fuel Cell and Electrolyzer Cell Nominal Operating Points

The nominal operating point of the regenerative cells in fuel cell mode is chosen as the maximum power point which is calculated as

\[ P_{max\ cell} = (V_{cell})_{max} \]  
The current density at the maximum power point will be the nominal current density of the fuel cell, \( j_{nominal\ fuel\ cell} \). The voltage at the maximum power point will be the nominal voltage of the fuel cell, \( V_{nominal\ fuel\ cell} \). Both \( V_{nominal\ fuel\ cell} \) and \( j_{nominal\ fuel\ cell} \) are taken from the power and polarization curves. The desirable operating point of the fuel cell is the maximum power point because increasing the current density beyond the maximum power point does not produce more power but uses more fuel.
The nominal operating point of the regenerative cells in electrolyzer cell mode is chosen as the thermoneutral voltage point, the theoretical voltage value for which heat does not have to be added or removed from the cell. The heat production rate in W/m² for the regenerative cell is calculated as

\[ P_H = (\lambda E_H - V_{cell})j, \]  

(3.99)

where \( \lambda \) is the stoichiometry factor and \( E_H \) is the hypothetical ideal voltage calculated from the enthalpy of reaction given by

\[ E_H = \frac{\Delta \hat{h}}{nF}, \]  

(3.100)

where \( \Delta \hat{h} \) is the enthalpy change for the reaction. The thermoneutral voltage is the cell voltage that results in \( P_H = 0 \). In this work, it assumed that any unused reactant is kept at the cell temperature and recycled, thus \( \lambda \) is taken as 1. Therefore, the heat production is zero when \( V_{cell} = E_H \). The current density corresponding to the thermoneutral voltage of the cell is taken from the polarization curve and set as the nominal current density of the electrolyzer, \( j_{nominal\,electrolyzer} \), and \( E_H \) is the nominal voltage of the electrolyzer, \( V_{nominal\,electrolyzer} \).

### 3.5.2. Compressed Hydrogen Storage Tank

In the model, hydrogen generated by the electrolyzer and used by the fuel cell is stored in pressurized tanks buried in the ground. The volume of storage available, maximum tank pressure, and minimum tank pressure are selected as model inputs. The tank temperature is selected to be the deep ground temperature which is equal to the average of the hourly air temperatures over a year in Rio Vista which is 16 °C.

#### 3.5.2.1. Calculation of Hydrogen Storage Tank Pressure

The model tracks the number of moles of hydrogen in the tank throughout the year. The tank pressure at any given time is calculated using the ideal gas law. The number of moles of hydrogen in storage at the selected minimum pressure, \( P_{tank,min} \), and maximum pressure, \( P_{tank,max} \), are calculated as
\[ n_{\text{max}} = \frac{P_{\text{tank, max}} V_{\text{tank}}}{RT_{\text{tank}}} \] (3.101)

and

\[ n_{\text{min}} = \frac{P_{\text{tank, min}} V_{\text{tank}}}{RT_{\text{tank}}} \] (3.102)

where \( T_{\text{tank}} \) is the tank temperature, \( V_{\text{tank}} \) is the tank volume, and \( R \) is the universal gas constant. The ideal gas assumption introduces an error in the predicted density of hydrogen of roughly 3\% at the maximum tank pressure of 100 bar as compared to the density listed in the fluid data listed by NIST [34] at the same conditions.

At the beginning of each timestep, the relevant limits to the regenerative cell system are calculated and used to determine the energy flowing into and out of the system, in a pattern that is like the battery model. For each hour of the year, several limits are checked to determine the regenerative cell operating point. If the solar and wind farm electricity generation falls short of the load demand for the hour, the regenerative cell will be in fuel cell mode and power will be generated to fill some of the deficit. The smallest of the power limits calculated will select the power generated. The power coming from the fuel cells is adjusted by turning a number of the cells on or off. A module of cells has a specified area, \( A_{\text{cell}} \). Thus, if the power to be generated by the fuel cells is known, the number of modules operating for the hour, \( N_{\text{modules running}} \), can be calculated.

The first limit that must be considered is the nominal power produced by all modules after accounting for the balance of plant (BOP) power requirements. Examples for items that utilize balance of plant power are the fuel delivery subsystem, power electronics, and heat management pumps. BOP power requirements are calculated as

\[ P_{\text{max fuel cell ext}} = P_{\text{fuel cell module}} (1 - \alpha_{\text{BOP percent}}) N_{\text{modules max}}, \] (3.103)

where \( N_{\text{modules max}} \) is the maximum number of modules and \( \alpha_{\text{BOP percent}} \) is the percentage of power required to run the balance of plant equipment. The power of one fuel cell module, \( P_{\text{fuel cell module}} \), operating at nominal voltage and nominal current density, with an area of \( A_{\text{cell}} \) is given by

\[ P_{\text{fuel cell module}} = A_{\text{cell}} V_{\text{nominal fuel cell}} j_{\text{nominal fuel cell}}. \] (3.104)

The second limit that must be considered is the power that can be produced by emptying the fuel in the tank over the timestep of one hour, after accounting for the BOP power requirements, given by
\[ P_{\text{ava fuel cell}} = P_{\text{fuel cell module}} (1 - \alpha_{\text{BOP\%}}) N_{\text{available modules}} \]  

where \(N_{\text{available modules}}\) is the number of modules that would need to operate during the hour to discharge the tank to the minimum pressure. This limit ensures that the tank pressure does not fall below the minimum pressure. This number is calculated for each hour of the year. The first step is to calculate the number of moles of hydrogen available in the tank at the beginning of the timestep, \(n_{\text{available}}\), given by

\[ n_{\text{available}} = n_{\text{current}} - n_{\text{min}}. \]  

If the tank were taken to minimum pressure over the hour, this would be associated with a fuel usage rate of \(n_{\text{available}}/3600\) and thus a current output from the fuel cell, \(i_{\text{available,disch}}\), given by

\[ i_{\text{available,disch}} = \frac{2F n_{\text{available}}}{3600}. \]  

The number of modules available is calculated by

\[ N_{\text{modules,available}} = \left\{ \begin{array}{ll} N_{\text{modules max}} & \text{if } i_{\text{available,disch}} \geq j_{\text{nominal fuel cell}} N_{\text{modules max}} A_{\text{cell}} \\ \frac{i_{\text{available,disch}}}{j_{\text{nominal fuel cell}} A_{\text{cell}}} & \text{if } i_{\text{available,disch}} < j_{\text{nominal fuel cell}} N_{\text{modules max}} A_{\text{cell}}. \end{array} \right. \]  

The final limit that must be considered is the power that is requested from the hydrogen system to supply the load, \(P_{\text{in}}\), which is the community electricity demand less wind and solar power generated. \(P_{\text{in}}\) is negative for charging and positive for discharging. It is the negative of the excess deficit calculated on an hourly basis for the hydrogen energy storage model. The power discharged by the fuel cell is calculated as

\[ P_{\text{fuel cell,ext}} = \min [P_{\text{in}}, P_{\text{max fuel cell ext}}, P_{\text{ava fuel cell}}]. \]  

Once the power that can be generated is known for each hour, the number of modules running can be determined by

\[ N_{\text{modules,running}} = \text{floor} \left( \frac{P_{\text{fuel cell,ext}}}{P_{\text{fuel cell module}} (1 - BOP\%)} \right). \]  

The number of moles of hydrogen used in the hour, \(n_{\text{consumed}}\), is given by
The power produced by the fuel cell modules running is given by

\[ P_{\text{fuel cell}} = \left[ P_{\text{fuel cell module}} (1 - \alpha_{\text{BOP percent}}) \right] N_{\text{modules, running}}. \]  

(3.112)

The heat generated by the fuel cell is more than would be required to heat hydrogen from the tank temperature to the temperature of the cell and air from the average air temperature to the temperature of the cell. The heat generated by each fuel cell module is given by

\[ \text{heat}_{\text{fuel cell, per module}} = A_{\text{cell}} \left( E_H - V_{\text{nominat fuel cell}} \right) J_{\text{nominat fuel cell}}. \]  

(3.113)

The heat consumed by heating the hydrogen from the tank temperature to the cell temperature is given by

\[ \text{heat}_{\text{H}_2 \text{preheat, per module}} = A_{\text{cell}} \frac{J_{\text{nominat fuel cell}}}{2F} M_{\text{H}_2} c_{p, \text{H}_2} (T_{\text{tank}} - T), \]  

(3.114)

where \( M_{\text{H}_2} \), is the molar mass of hydrogen and \( c_{p, \text{H}_2} \) is hydrogen’s specific heat. It is assumed that some of the waste heat from the fuel cell can be used to heat reactants. The heat that would be consumed by preheating the air to the cell temperature is

\[ \text{heat}_{\text{air, preheat, per module}} = A_{\text{cell}} J_{\text{air}} M_{\text{air}} c_{p, \text{air}} (T_{\text{avg air}} - T), \]  

(3.115)

where \( M_{\text{air}} \), is the molar mass and \( c_{p, \text{air}} \) is the specific heat for air and \( T_{\text{avg air}} \) is the average air temperature in Rio Vista, California.

The regenerative cell operating in electrolyzer mode has limits that are checked for each hour of the year. If the solar and wind farm generation exceeds the community electricity demand for the hour, the regenerative cell will be in electrolyzer cell mode and the excess power is used to generate and store hydrogen. The largest of the following values will select the power consumed by the electrolyzer system and thus, the number of modules operating for the hour.

The first limit that must be considered is the nominal power consumed by all modules after accounting for the external power requirements. This can be calculated as

\[ P_{\text{min electrolyzer ext}} = \left[ P_{\text{electrolyzer module}} \left( 1 + \alpha_{\text{BOP percent}} \right) + P_{\text{compressor module}} + P_{\text{H}_2 \text{O preheat module}} + P_{\text{H}_2 \text{ cooling module}} \right] N_{\text{modules max}}. \]  

(3.116)

The power of one electrolyzer module, \( P_{\text{electrolyzer module}} \), operating at nominal voltage and nominal current density, with an area of \( A_{\text{cell}} \) is given by
\[ P_{\text{electrolyzer module}} = A_{\text{cell}} V_{\text{nominal electrolyzer}} f_{\text{nominal electrolyzer}}. \]  

(3.117)

Isothermal compression is used to model the compressor power. The compressor power is approximated by compressing the hydrogen from the cell pressure of 1 atmosphere to the tank pressure at the beginning of the time step. The compressor power consumed per module, \( P_{\text{compressor module}} \), is given by

\[ P_{\text{compressor module}} = \frac{f_{\text{nominal electrolyzer}}}{2F} RT_{\text{tank}} \ln \left( \frac{p_{\text{tank}}}{p_{H_2 \text{electrode}}} \right) A_{\text{cell}}. \]  

(3.118)

In this model it is assumed that the heat required to preheat the steam provided to the electrolyzer will be supplied by electrical resistance heating from the wind and solar farm. The power consumed to preheat steam per module, \( P_{H_2O \text{ preheat module}} \), is given by

\[ P_{H_2O \text{ preheat module}} = \frac{-f_{\text{nominal electrolyzer}}}{2F} M_{H_2O} \left( h_{H_2O \text{source}} - h_{H_2O,T} \right) A_{\text{cell}}, \]  

(3.119)

where \( M_{H_2O} \) is the molar mass of water, \( h_{H_2O \text{source}} \) is the enthalpy of water at the water source temperature, assumed to be 289 K, and \( h_{H_2O,T} \) is the enthalpy of steam at the cell temperature and pressure. Power for steam preheating is negative for heat in. It is assumed that the cooling of hydrogen produced by the electrolyzer to the tank temperature can be used to partially preheat the steam provided to the electrolyzer. The power offset by cooling the hydrogen is given by

\[ P_{H_2 \text{ cooling module}} = \frac{-f_{\text{nominal electrolyzer}}}{2F} M_{H_2} c_{p,H_2} (T - T_{\text{tank}}) A_{\text{cell}}. \]  

(3.120)

The second limit that must be considered is the power that can be consumed by the electrolyzer system when enough hydrogen is produced to fill the tank over the timestep of one hour, after accounting for the BOP power requirements, compressor power requirements and power needed to heat the steam offset by the cooling of hydrogen from the electrolyzer temperature to the tank storage temperature, given by

\[ P_{\text{ave electrolyzer}} = \left[ P_{\text{electrolyzer module}} \left( 1 + \alpha_{\text{BOP percent}} \right) + P_{\text{compressor module}} + P_{H_2O \text{ preheat module}} + P_{H_2 \text{ cooling module}} \right] N_{\text{modules to charge}}. \]  

(3.121)

where \( N_{\text{modules to charge}} \) is the number of modules that would need to operate during the hour to charge the tank to the maximum pressure. This limit ensures that the tank pressure does not exceed the maximum pressure. This number is calculated for each hour of the year. The first step is to calculate the number of moles of hydrogen that are needed to fill the tank to maximum pressure, \( n_{\text{to full}} \), given by
\[ n_{\text{to full}} = n_{\text{max}} - n_{\text{current}}. \] (3.122)

If the tank were taken to maximum pressure over the hour, this would be associated with a fuel production rate of \( \frac{n_{\text{to full}}}{3600 \text{s}} \), and thus a current input to the electrolyzer, \( i_{\text{available,charge}} \), given by

\[ i_{\text{available,charge}} = \frac{-2Fn_{\text{to full}}}{3600}, \] (3.123)

where the current will be negative for charging. The number of modules available is calculated by

\[ N_{\text{modules to charge}} = \begin{cases} N_{\text{modules max}}, & \text{if } i_{\text{available,charge}} < i_{\text{nominal electrolyzer}}N_{\text{modules max}}A_{\text{cell}} \\ \frac{i_{\text{available,charge}}}{i_{\text{nominal electrolyzer}}A_{\text{cell}}}, & \text{if } i_{\text{available,charge}} \geq i_{\text{nominal electrolyzer}}N_{\text{modules max}}A_{\text{cell}}. \end{cases} \] (3.124)

The final limit that must be considered is the excess power that is available to produce hydrogen, \( P_{\text{in}} \), which is the community electricity demand less the wind and solar power generated. \( P_{\text{in}} \) is negative for charging and positive for discharging. It is the negative of the excess deficit calculated on an hourly basis for the hydrogen energy storage model. The power that can be provided to the electrolyzer system is calculated as

\[ P_{\text{electrolyzer,ext}} = \max [P_{\text{in}}, P_{\text{min electrolyzer ext}}, P_{\text{ava electrolyzer}}]. \] (3.125)

Once the power that can be used by the electrolyzer is known for each hour, the number of modules running can be determined by

\[ N_{\text{modules running}} = \text{floor} \left( \frac{P_{\text{electrolyzer,ext}}}{P_{\text{electrolyzer module}}(1+\alpha_{\text{BOP percent}})+P_{\text{compressor module}}+P_{\text{H2O preheat module}}+P_{\text{H2 cooling module}}} \right). \] (3.126)

The number of moles of hydrogen generated in the hour is the negative of \( n_{\text{consumed}} \), which is given by

\[ n_{\text{consumed}} = \frac{3600i_{\text{nominal electrolyzer}}}{2F}A_{\text{cell}}N_{\text{modules running}}. \] (3.127)

For hours where excess power is generated, the electrolyzer power consumed is
\[ P_{\text{electrolyzer}} = [P_{\text{electrolyzer module}} (1 + BOP_{\text{percent}}) + P_{\text{compressor module}} + P_{\text{H}_2 \text{O preheat module}} + P_{\text{H}_2 \text{ cooling module}}] N_{\text{modules, running}}. \] (3.128)

The equation for calculating the number of moles of hydrogen in the tank at the end of each timestep is given by

\[ n_{\text{end of timestep}} = n_{\text{current}} - n_{\text{consumed}}, \] (3.129)

which is valid for all hours whether the hydrogen system is in fuel cell mode or electrolyzer mode. The tank pressure at the beginning of the next time step is

\[ P_{\text{tank}} = \frac{n_{\text{end of timestep}} R T}{V_{\text{tank}}}. \] (3.130)

The energy provided by the fuel cell modules that are running when there is a deficit of energy from the wind and solar farm is

\[ E_{\text{Hourly fuel cell, out}} = P_{\text{fuel cell}} \frac{kW}{1000 W} 1 \text{hr}. \] (3.131)

The energy consumed by the electrolyzer modules that are running when there is an excess of energy from the wind and solar farm is

\[ E_{\text{Hourly electrolyzer, in}} = P_{\text{electrolyzer}} \frac{1 kW}{1000 W} 1 \text{hr}. \] (3.132)

### 3.5.3. Calculating the Excess and Deficit Energy

The wind and solar farm hourly excess deficit energy with hydrogen energy storage is calculated as

\[ E_{H, \text{ex, def hydrogen}} = E_{H, S} + E_{H, W} - E_{H, D} + E_{\text{Hourly electrolyzer, in}} + E_{\text{Hourly fuel cell, out}}. \] (3.133)

Positive values of hourly excess-deficit energy indicate an excess of generated electricity and electricity available from hydrogen energy storage in any given hour given by

\[ E_{H, \text{ex hydrogen}} = \max (E_{H, \text{ex, def hydrogen}}, 0). \] (3.134)

Negative values of excess deficit energy indicate a deficit of generated electricity and electricity available from hydrogen energy storage in any given hour, given by

\[ E_{H, \text{def hydrogen}} = -\min (0, E_{H, \text{ex, def hydrogen}}). \] (3.135)

The negative sign makes the negative excess deficit values a positive number. The deficit energy with battery energy storage integrated over one year, \( E_{Y, \text{def hydrogen}} \), is
\begin{equation}
E_{Y,\text{def hydrogen}} = \sum_{i}^{8760} E_{H,\text{def hydrogen}}. \tag{3.136}
\end{equation}

$E_{Y,\text{def hydrogen}}$ is the energy that must be purchased from the grid for the year when hydrogen energy storage is included.

### 3.6. Economic Model of Net Present Cost

The net present cost is the economic measure used to compare a range of wind and solar farm sizes coupled to either battery or hydrogen storage that supply electricity to 25,000 homes in Rio Vista, California. It is a requirement that all the loads must be served for every hour of the year. Therefore, grid electricity purchases will be required when sufficient electricity is not generated or available from storage. When electricity generated by wind and solar exceeds the load requirement and cannot be stored, the excess electricity is considered wasted. The goal of this work is to find the least net present cost equipment combination of wind and solar farm capacities without energy storage and in combination with battery or hydrogen energy storage.

#### 3.6.1. Wind and Solar without Energy Storage

The net present cost for the wind and solar farm will include the capital costs of the equipment, the yearly cost of operation and maintenance of the equipment, and the yearly cost of electricity that is purchased from the grid. The yearly costs of grid electricity purchases and equipment operation and maintenance must be adjusted to reflect the time value of the annual expenditures in future years. The adjustment is known as the uniform series present worth factor which is given by

\begin{equation}
F_{A \to P} = \frac{(1+i)^{n_y} - 1}{i(1+i)^{n_y}}, \tag{3.137}
\end{equation}

where $i$ is the interest rate and $n_y$ is the number of years of the project. For this work the interest rate was selected to be 10% and the duration of the project is 25 years, which gives $F_{A \to P} = 9.077$. The capital cost of the equipment occurs in the first year of the project and does not have to be adjusted in the net present cost calculation. The net present cost of the wind solar farm project is
\[ NPC = C_{CS} P_{NPS} + C_{MS} P_{NPS} F_{A \to P} + C_{CW} P_{NPW} + C_{MW} P_{NPW} F_{A \to P} + C_{grid \text{ elec}} E_{Y,def} F_{A \to P}, \]

(3.138)

where the terms on the right-hand side of Equation (3.138) are:

- \( C_{CS} P_{NPS} \) - the capital cost of the solar installation where \( C_{CS} \) is the capital cost of the solar installation per unit of nameplate capacity and \( P_{NPS} \) is the nameplate rating of solar installation,
- \( C_{MS} P_{NPS} \) - the operation and maintenance cost for the solar equipment where \( C_{MS} \) is the fixed yearly maintenance cost per unit of solar nameplate capacity,
- \( C_{CW} P_{NPW} \) - the capital cost of the wind installation where \( C_{CW} \) is the capital cost of the wind installation per unit of nameplate capacity and \( P_{NPW} \) is the nameplate rating of the wind installation,
- \( C_{MW} P_{NPW} \) - the operation and maintenance cost for the wind equipment where \( C_{MW} \) is the fixed yearly maintenance cost per unit of wind nameplate capacity, and
- \( C_{grid \text{ elec}} E_{Y,def} \) - the yearly cost of electricity purchased from the grid where \( C_{grid \text{ elec}} \) is the per unit cost of electricity and \( E_{Y,def} \) is the yearly amount of electricity purchased from the grid for a given size of wind and solar farm given by Equation (3.44).

The cost of supplying the load entirely with grid electricity for the duration of the project can be found by setting the wind and solar nameplate ratings to zero and \( E_{Y,def} \) to the entire demand in Equation (3.138).

### 3.6.2. Battery Energy Storage

The addition of battery energy storage impacts the net present cost of the project due to the capital cost of the battery system equipment, the operation and maintenance costs of the battery equipment, and the reduction in the amount of electricity purchased from the grid. The addition of battery energy storage allows excess electricity generated by the wind and solar farm to be stored for a time when the wind and solar farm cannot generate enough electricity to meet the demand. Thus, the yearly amount of electricity purchased from the grid is impacted by the size of battery energy storage. The net present cost of the wind and solar farm project combined with battery energy storage is

\[ NPC_{with \text{ battery ES}} = C_{CS} P_{NPS} + C_{MS} P_{NPS} F_{A \to P} + C_{CW} P_{NPW} + C_{MW} P_{NPW} F_{A \to P} + C_{CB} P_{NPB} + C_{MB} P_{NPB} F_{A \to P} + C_{grid \text{ elec}} E_{Y,def} F_{battery A \to P}. \]

(3.139)

Many of the terms in Equation (3.139) were described in conjunction with Equation (3.138). The additional terms related to battery energy storage on the right-hand side of Equation (3.139) are:
\( C_{CB}P_{NPB} \) - the capital cost of the battery installation where \( C_{CB} \) is the capital cost per unit of name plate rating and \( P_{NPB} \) is the nameplate capacity of the battery energy storage system,

\( C_{MB}P_{NPB} \) - the operation and maintenance cost of the battery system, where \( C_{MB} \) is the fixed maintenance cost per unit of nameplate rating, and

\( C_{\text{grid elec}}E_{Y,\text{def battery}} \) - the yearly cost of electricity purchased from the grid where \( C_{\text{grid elec}} \) is the per unit cost of electricity and \( E_{Y,\text{def battery}} \) is the yearly amount of electricity purchased from the grid for a given size of battery energy storage combined with a wind and solar farm.

3.6.3. Hydrogen Energy Storage

Like battery energy storage, the addition of hydrogen energy storage impacts the net present cost of the project due to the capital cost of the regenerative cells and storage tanks, the operation and maintenance cost of the regenerative cells and storage tanks and the reduction of the amount of electricity purchased from the grid. The net present cost of the wind and solar farm project combined with hydrogen energy storage is

\[
NPC_{\text{with hydrogen ES}} = C_{CS}P_{NPS} + C_{MS}P_{NPS}F_{A to P} + C_{CW}P_{NPW} + C_{MW}P_{NPW}F_{A to P} + C_{CCell}P_{NPCell} + C_{MCell}P_{NPCell}F_{A to P} + C_{CTank}V_{Tank} + C_{MTank}V_{Tank}F_{A to P} + C_{\text{grid elec}}E_{Y,\text{def hydrogen}}F_{A to P}. \tag{3.140}
\]

Many of the terms in Equation (3.140) were described below Equation (3.138). The additional terms on the right-hand side of Equation (3.140) are:

\( C_{CCell}P_{NPCell} \) - the capital cost of the regenerative cell installation where \( C_{CCell} \) is the capital cost per unit of electrolyzer name plate rating and \( P_{NPCell} \) is the nameplate rating of the electrolyzer,

\( C_{MCell}P_{NPCell} \) - the operation and maintenance cost of the regenerative cell installation where \( C_{MCell} \) is the fixed maintenance cost per unit of electrolyzer name plate rating,

\( C_{CTank}V_{Tank} \) - the capital cost of the compressed hydrogen storage installation, where \( C_{CTank} \) is the capital cost per unit of tank volume where \( V_{Tank} \) is the tank volume,

\( C_{MTank}V_{Tank} \) - the fixed operation and maintenance cost of the compressed hydrogen storage, where \( C_{MTank} \) is the fixed maintenance cost per unit of tank volume, and

\( C_{\text{grid elec}}E_{Y,\text{def hydrogen}} \) - the yearly cost of electricity purchased from the grid where \( C_{\text{grid elec}} \) is the per unit cost of electricity and \( E_{Y,\text{def hydrogen}} \) is the yearly amount of electricity purchased from the grid for a given configuration of
3.7. Model Verification

3.7.1. Solar

The amount of solar radiation incident on panels with a north-south, single axis tracking mechanism predicted with the model used in this work is compared to the output predicted from PVsyst software [35]. The solar data for Rio Vista, California and panel geometry used in this model was used as input for the PVsyst model. PVsyst predicts that the total radiation incident on the panels without shading is 2,817 kWh/m² and the solar model in this work predicts the total solar radiation incident on the panels is 2,836 kWh/m². The difference in predicted radiation incident on the panels by these two models is less than 1%. When shading is included the difference between the PVsyst model and the solar model for this work increases. For example, when the solar field includes 348 rows spaced 5 meters apart with 348 panels per row the solar model in this work predicts 2,785 kWh/m² of radiation incident on the panels after shading corrections. The PVsyst model predicts 2,672 kWh/m² of radiation incident on the panels after shading corrections in the same configuration. The difference in predicted radiation incident on the panels with shading corrections is 4.06%.

3.7.2. Wind

The wind portion of the model is compared to an algebraic solution of the wind power production if the windspeed is held constant over the entire year. According to the Enercon E-82 E4 3.0 turbine power curve, at a hub-height windspeed, \( U(z) \), of 13 m/s, 2,500 kW of electrical power is produced. The turbine hub height, \( z \), is 84 m, the reference height, \( z_r \), of the wind data is 100 m, and the surface roughness length, \( z_0 \), is taken for rough pasture at a value of 0.01 m. With this information the reference height windspeed, \( U(z_r) \), corresponding to a 13 m/s windspeed at 84 m can be calculated using the log law found in Manwell, McGowan and Rogers [36], which is
\[ U(z_r) = U(z) \frac{\ln(z_r)}{\ln(z_0)}. \] (3.141)

The resulting reference height windspeed is \( U(z_r) = 13.25 \) m/s. Therefore, when a constant windspeed of 13.25 m/s is used as the data set for every entry, the hourly turbine output power, \( E_{H,W} \), is 2,500 kWh and the yearly wind power is calculated from

\[ E_{Y,W} = \sum_1^{8760} E_{H,W}. \] (3.142)

The yearly energy predicted by wind turbine model used in this work equates exactly to a yearly wind power production of \( E_{Y,W} = \left( 8760 \frac{\text{hr}}{\text{yr}} \right) 2500 \frac{\text{kWh}}{\text{hr}} = 21.9 \times 10^6 \text{kWh} \).

### 3.7.3. Regenerative Cell

The regenerative cell polarization curve developed in this work is developed from the electrolyzer model presented in Laurencin et al. [16]. The model presented in Laurencin is a two-dimensional model which also incorporates a thermal model, and which uses the dusty gas model to predict reactant and product diffusion through the electrodes. The model in this work is a one-dimensional model at constant cell temperature which uses the simpler Fick’s law of diffusion to quantify the diffusion of reactants and products through the electrodes. The electrolyzer model of Laurencin et al. was extended to apply to the fuel cell for use in this work.

The model in this work is used to generate a polarization curve and voltage loss components using the inlet conditions examined in Laurencin et al. The voltage loss components calculated with this model are compared to the outputs of the Laurencin model in Figure 3.7 and Figure 3.8. The curves from the different models are very close and indicate the one-dimensional model used in this work is accurate.
Figure 3.7: Comparison of Laurencin model outputs [16] and this work’s one-dimensional model outputs for a solid oxide electrolyzer.

Figure 3.8: Comparison of Laurencin overvoltage components [16] and this work’s one-dimensional model outputs for a solid oxide electrolyzer.
Chapter 4
Results

4.1. Organization of Results

A large number of results are presented in this chapter. To aid the reader in understanding these results, the organization of these results is discussed first. All of Section 4.1 is dedicated to getting the reader familiar with how the numerous results from this work are present in this Chapter. First, the reader must realize that three types of energy storage are studied in this thesis. These are: 1) no energy storage, 2) battery energy storage and 3) hydrogen energy storage. For this reason, the major classification of results in this Chapter is by the type of energy storage. Results for wind and solar installations without energy storage are presented in Section 4.2, results for wind and solar installations with battery energy storage are presented in Section 4.3, and results for wind and solar installations with hydrogen energy storage are presented in Section 4.4. Finally, how the performance of these three types of energy storage compare is discussed in Section 4.5. The primary interest of these results is the economic performance of these three energy storage types; however, performance information is also provided.

To further help the reader understand all of these results, each section is divided into subsections. For the most part these subsections represent the conditions applied to each type of energy storage; however, subsections describing the inputs used and summarizing the results are also included. Results for wind and solar with no energy storage are given in Section 4.2 and are broken down into subsections with the names:

1. Technical and Cost Inputs,
2. Base Case, and
3. Double Electricity Cost.

The results for wind and solar with battery energy storage are given in Section 4.3 which is divided into sub-sections in the following manner:
The results for wind and solar with hydrogen energy storage are given in Section 4.4 which is divided into sub-sections with the names:

1. Technical and Cost Inputs,
2. Base Case,
3. Reduced Battery Costs by 50%,
4. Double Electricity Cost, and
5. Summary.

The first subsection in each section provides the inputs for the analysis. A table of input costs and technical information is included at the start of each energy storage type section. The costs included in the input tables are for the base case scenario. Some wind and solar technical inputs are included in Section 4.2, and are not repeated in Sections 4.3 and 4.4, as they are unchanged when energy storage is added to the system. After this, the base case results are reported. Base case results are reported using inputs that best represent the current situation and costs for wind, solar, battery storage, and hydrogen storage. At this point differences in the subsections between the three types of storage are utilized. The following subsections contain results for cases that change one input cost parameter. For example, all these energy storage cases look at the scenario where the cost of grid electricity may be doubled, and all other cost parameters are held constant. The battery storage case considers the scenario where the cost of the batteries is reduced by 50% while the hydrogen storage case considers the scenario where the fuel cells/electrolyzing cells are reduced by 50%. The hydrogen energy storage case also performs the what if scenarios of no cost hydrogen storage and no cost for the cells. For the cases with battery or hydrogen storage, the results for each scenario are summarized at the end of the section for easy comparison. For the base case and all additional cases considered, the information about net present cost is presented first. Most results are presented in the form of graphs and some comparison results are presented in tables. The minimum net present cost value, as well as the equipment sizes associated with the minimum cost, are indicated on the plots. Figures related to energy production and storage are the next set of results for the battery and hydrogen storage.
scenarios. The yearly energy produced and the yearly excess energy for the wind and solar installations are presented in Section 4.2 and are not repeated in sections considering battery or hydrogen energy storage, because these results do not change for all three storage situations.

For the subsections considering battery or hydrogen energy storage, we want to know: How much wind and solar generation was stored, then later used to supply the load? How much wind and solar energy was generated that was not utilized? How much wind and solar generation went directly to serving the load as opposed to going to energy storage? How much energy was supplied to the load from the grid (i.e., generation deficit)? This information is presented in the form of pie charts in Sections 4.3 and 4.4. In order to illustrate how frequently the energy storage is charged and discharged over the course of one year, state of charge plots are included in Section 4.3 and tank pressure plots are included in Section 4.4.

One important input for all studies is the hourly electrical load. The load used represents the electric demand for 25,000 homes in Rio Vista, California and varies from hour to hour and season to season. The load plot is not repeated for subsequent results, because the same load is used for all the results presented in this thesis.

A table summarizing the net present cost results for all cost variations is included in the battery energy storage section and a similar table is included in the hydrogen storage section. The results are compared to the net present cost of purchasing all energy required to meet the demand from the grid. The results including storage are also compared to the least net present cost case of supplying electricity with wind and solar installations without energy storage. These comparisons are meaningful in determining the efficacy adding battery or hydrogen storage to the wind and solar power generation facility.

Lastly, in this Chapter, Section 4.5 compares and summarizes all the results presented for each of the three storage cases. This is done verbally and in table form. This comparison emphasizes the benefits or disbenefits of using a particular type of configuration. Solar and wind without storage is compared to purchasing all required electricity directly from the grid. Comparisons are also made between using solar and wind with battery storage or solar and wind with hydrogen storage to solar and wind without energy storage and to buying all power from the grid.
4.2. Wind and Solar without Energy Storage

4.2.1. Technical and Cost Inputs

The technical and cost inputs for a wind and solar farm are included in Table 4.1. The cost of grid electricity is the commercial price of electricity, taken from the U.S. Energy Information Administration data [37]. Electricity that is required by the load and cannot be met by the electricity generated by wind or solar in any given hour must be purchased from the grid at the input electricity price. In all the simulations, energy is not sold back to the grid, as this would be using the grid as storage.

The capital costs and operation and maintenance costs for wind and solar are taken from Lazard’s 2021 [38] levelized cost of energy (LCOE) analysis. Solar costs are consistent with utility scale crystalline panels with single-axis tracking. Wind turbine costs are chosen to be consistent with the mid-range costs for onshore wind turbines. The input technical variables for the wind turbines are the same as the Enercon E-82 E4 3.0 turbine. The surface roughness and standard air density values used, are noted in reference [36].

The demand in MW for 25,000 homes in Rio Vista, California is plotted in Figure 4.1 for each hour in a typical year. The hourly electric usage by a home in Rio Vista is obtained from OpenEI datasets [30]. The total yearly demand for 25,000 homes in Rio Vista, California is 218,465 MWh and the mean load averaged over the year is 25 MW. The maximum load is 96 MW. Demand increases over the summer and in early fall, which is expected due to high cooling loads.

This plot indicates the seasons with vertical lines. Spring includes dates from March 1\textsuperscript{st} through May 31\textsuperscript{st} and goes from hour 1416 to hour 3624. Summer includes dates from June 1\textsuperscript{st} through August 31\textsuperscript{st} and is shown from hour 3624 to hour 5832. Fall is considered from September 1\textsuperscript{st} through November 30\textsuperscript{th} and is shown from hour 5832 to hour 8016. The winter season includes January 1\textsuperscript{st} through February 28\textsuperscript{th} and December 1\textsuperscript{st} through 31\textsuperscript{st} and is shown at the beginning and end of the plot from hour 0 to hour 1416 and from hour 8016 to hour 8760. There are 8760 hours in a non-leap year.
Table 4.1: Cost and technical inputs for wind and solar without energy storage base case.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric rate (commercial price of electricity)</td>
<td>$0.1753/kW-h</td>
</tr>
<tr>
<td>Capital cost of solar (utility scale crystalline with single-axis tracking)</td>
<td>$950/kW</td>
</tr>
<tr>
<td>Capital cost of wind, onshore (average of high and low costs)</td>
<td>$1187.5/kW</td>
</tr>
<tr>
<td>Operations and maintenance cost of solar (utility scale crystalline with single-axis tracking)</td>
<td>$13.0/kW-yr</td>
</tr>
<tr>
<td>Operations and maintenance cost of wind (onshore, average of high and low costs)</td>
<td>$29.25/kW-yr</td>
</tr>
<tr>
<td>Years of project</td>
<td>25</td>
</tr>
<tr>
<td>Interest rate</td>
<td>10%</td>
</tr>
<tr>
<td>Latitude</td>
<td>38.21 degrees north</td>
</tr>
<tr>
<td>Longitude</td>
<td>121.7 degrees west</td>
</tr>
<tr>
<td>Standard longitude</td>
<td>120 degrees west</td>
</tr>
<tr>
<td>Solar constant</td>
<td>1353 W/m²</td>
</tr>
<tr>
<td>Ground surface reflectance</td>
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</tr>
<tr>
<td>Panel length</td>
<td>1 m</td>
</tr>
<tr>
<td>Panel width</td>
<td>1.776 m</td>
</tr>
<tr>
<td>Row spacing</td>
<td>5 m</td>
</tr>
<tr>
<td>Efficiency of photovoltaic</td>
<td>22%</td>
</tr>
<tr>
<td>Type of panel tracking</td>
<td>one-axis tracking north-south axis</td>
</tr>
<tr>
<td>Wind turbine rated power</td>
<td>3 MW</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>13 m/s</td>
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<tr>
<td>Cut in wind speed</td>
<td>3 m/s</td>
</tr>
<tr>
<td>Cut out wind speed</td>
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</tr>
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<td>Reference hub height</td>
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</tr>
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<td>Hub height</td>
<td>84 m</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>82 m</td>
</tr>
<tr>
<td>Surface roughness length (rough pasture)</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Air density</td>
<td>1.225 kg/m³</td>
</tr>
</tbody>
</table>
4.2.2. Base case

Figure 4.2 shows the net present cost for a range of solar and wind capacity combinations. The lowest net present cost equipment combination without energy storage is 35.16 MW of solar panels and 36 MW of wind turbines. The net present cost of this equipment combination is $209 million dollars. The net present cost of purchasing electricity only from the grid over the project duration is $348 million dollars. Installation of the optimum sized wind solar farm results in savings of $139 million dollars over the duration of the project. This represents a 39.9% reduction in cost versus the cost of electricity supplied from the grid. This result shows that electricity generated with wind and solar is cost competitive with grid supplied electricity.

The net present costs for almost all of the solar and wind equipment size combinations shown in Figure 4.2 are less than the cost of grid supplied electricity. The results of wind generation alone can be read from Figure 4.2 on the y-axis. The results of solar generation alone can be read from Figure 4.2 by reading the costs from the blue line associated with 0 MW of installed wind. The cost of buying all the electrical power from the grid can be found by reading the point for 0 MW of installed wind power and 0 MW of installed solar power. Combining wind and solar generation at this site is effective in driving the net present cost of the project down. This
is because the hourly timing of the two types of generation in combination is a better match for the hourly load than either solar alone or wind alone.

Figure 4.2: The total net present cost for a range of wind and solar farm size combinations serving 25,000 homes in Rio Vista, California without energy storage. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, and the capital cost of wind turbines is $1187.5 per kW.

The yearly integrated power produced by a range of solar and wind farm sizes is shown in Figure 4.3. The solar farm utilizes panels with single-axis tracking. The rotating axis is oriented in the north-south direction, which allows the panels to track the sun in the east-west direction throughout the day. As expected, the total energy generated yearly varies linearly with the size of solar farm. While not as obvious on this plot, the energy generated also varies linearly with the size of the wind farm. This is indicated by the equal spacing between the lines in Figure 4.3 for equal increments in wind turbine capacity.

The yearly total excess energy in MWh is plotted in Figure 4.4 for a range of solar and wind farm size combinations serving the demand of 25,000 homes in Rio Vista California. If the excess energy is negative for a particular size combination of wind and solar farm, the load consumed more energy than was generated by the wind and solar farm, and an energy deficit occurred for the year. If the excess energy is positive for a given size combination wind and solar
farm, more energy was generated over the year than was consumed by the load. As expected, the excess energy generated increases linearly with the size of solar portion and size of the wind portion of this solar-wind farm.

Figure 4.3: Total energy produced over one year with a range of solar and wind farm size combinations in Rio Vista, California.

Figure 4.4: Yearly excess energy produced by a range of solar and wind farm size combinations serving 25,000 homes in Rio Vista, California.
4.2.3. Double Electricity Cost

Figure 4.5 shows the net present cost for a range of solar and wind farm equipment combinations when the cost of grid supplied electricity is doubled. With doubled grid electricity costs, the lowest net present cost equipment combination without energy storage is 44.1 MW of solar panels and 60 MW of wind turbines. The net present cost of this equipment combination is $303 million dollars. The net present cost of purchasing electricity only from the grid over the project duration is $695 million dollars. Installation of the optimum sized wind-solar farm results in savings of $393 million dollars over the duration of the project. This represents a 56.5% reduction in cost compared to the electricity supplied from the grid. These results demonstrate that doubling the cost of grid electricity makes larger solar and wind installations cost competitive. An additional 9 MW of solar capacity and an additional 24 MW of wind capacity were justified by doubling the cost of grid electricity. Again, installing wind and solar generation in combination is a better match for the hourly load and is more cost competitive than wind or solar alone. It should be noted that in this case all wind and solar capacity combinations included in the analysis have a lower net present cost than purchasing electricity from the grid at the doubled grid electricity price.

![Figure 4.5: The yearly net present cost for a range of wind and solar farm size combinations serving 25,000 homes in Rio Vista, California without energy storage. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, and the capital cost of wind turbines is $1187.50 per kW.](image-url)
4.3.Battery Energy Storage

4.3.1. Technical and Cost Inputs

The technical and cost inputs for coupling battery energy storage with a wind and solar farm are included in Table 4.2. The capital costs and operation and maintenance costs for batteries are taken from Lazard’s levelized cost of storage (LCOS) analysis [14]. The battery capital costs used are consistent with the mid-range cost of 100 MW/200 MWh wholesale stand-alone batteries. The cost of the 100 MW/200 MWh installation is estimated at $34 to $66 million dollars. The average of the high and low costs is $50 million dollars for 200 MWh of storage. Therefore, $250/kWh is the capital cost used for the batteries. This cost estimate includes modules, inverters, balance of system costs and engineering procurement and construction (EPC) costs. The operations and maintenance costs are noted as $1.5/kWh-$3.8/kWh for the 100 MW/200 MWh wholesale stand-alone battery case. This includes the general operation and maintenance costs as well as augmentation costs. The average of the high and low costs, which is $2.65/kWh of battery capacity, is used as the input value. The project duration is 25 years and the interest rate for the project is 10%.

The technical inputs are as follows. The input value for battery coulombic efficiency is 92%. The round-trip efficiency of the battery investigated in reference [5] was noted to be 85% or greater. Assuming charging and discharging coulombic efficiencies are the same, the one-way coulombic efficiency would be 92.2%. The battery efficiency assumed for Lazard’s LCOS analysis was 91%; and therefore, a coulombic efficiency of 92% was chosen as reasonable. Lazard’s LCOS analysis notes a 90% depth of discharge (DOD) was assumed. The input minimum state of charge (SOC) was chosen to be 10% and the maximum SOC was chosen to be 90%. The simulations start the year at the minimum SOC.
Table 4.2: Cost and technical inputs for battery base case.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Rate</td>
<td>$0.1753/kW-h</td>
</tr>
<tr>
<td>(commercial price of electricity)</td>
<td></td>
</tr>
<tr>
<td>Capital Cost of Solar</td>
<td>$950/kW</td>
</tr>
<tr>
<td>(utility scale crystalline with single-axis tracking)</td>
<td></td>
</tr>
<tr>
<td>Capital Cost of Wind</td>
<td>$1187.5/kW</td>
</tr>
<tr>
<td>(onshore, average of high and low costs)</td>
<td></td>
</tr>
<tr>
<td>Capital Cost of Batteries</td>
<td>$250/kW-h</td>
</tr>
<tr>
<td>(wholesale stand alone 100MW/200MW-h average of high and low costs)</td>
<td></td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Solar</td>
<td>$13.0/kW-yr</td>
</tr>
<tr>
<td>(utility scale crystalline with single-axis tracking)</td>
<td></td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Wind</td>
<td>$29.25/kW-yr</td>
</tr>
<tr>
<td>(onshore, average of high and low costs)</td>
<td></td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Batteries</td>
<td>$2.65/kW-h</td>
</tr>
<tr>
<td>(wholesale stand alone 100MW/200MW-h average of high and low costs)</td>
<td></td>
</tr>
<tr>
<td>Years of Project</td>
<td>25</td>
</tr>
<tr>
<td>Interest Rate</td>
<td>10%</td>
</tr>
<tr>
<td>Coulombic Efficiency</td>
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</tr>
<tr>
<td>C rate maximum</td>
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</tr>
<tr>
<td>SOC maximum</td>
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</tr>
<tr>
<td>SOC minimum</td>
<td>0.1</td>
</tr>
<tr>
<td>SOC initial</td>
<td>0.1</td>
</tr>
</tbody>
</table>

4.3.2. Base Case

Figure 4.6 shows the net present cost for a range of solar and wind farm equipment combinations with the least net present cost size of battery storage. The lowest net present cost equipment combination with battery energy storage is 38.03 MW of solar panels, 36 MW of wind turbines and 25 MW/50 MWh capacity batteries. Thus, the lowest net present cost battery capacity would be able to serve the mean load for roughly 2 hours.

The net present cost of this equipment combination is $206 million dollars. The net present cost of purchasing electricity from the grid over the project duration is $348 million dollars. Installation of the optimum sized wind solar farm with battery energy storage results in savings of $142 million dollars over the duration of the project. This represents a 40.8% reduction in cost compared to the electricity supplied from the grid.
It is the aim of this work to investigate the cost impact of energy storage paired with wind and solar compared to wind and solar alone. Installation of the optimum sized battery energy storage with wind and solar generation results in a savings of $2.99 million over the life of the project. This represents a 1.4% reduction in cost versus the least cost wind and solar installation without energy storage. Interestingly, the least cost sized solar installation increased from 35.16 MW without energy storage to 38.03 MW with battery energy storage. These results tell us that the installation of battery energy storage at base costs does not result in a meaningful amount of cost savings over the life of the project versus wind and solar without energy storage. The resulting cost reduction is quite small when the potential variability of input factors such as the variation in load, variation in solar and wind resources from year to year, and variations in costs can easily change this result. However, the resulting battery size did help to justify an additional 3 MW of solar capacity. Two hours of battery storage allows the sun’s energy to be collected during the day and used in the evening to power the load.

Figure 4.6: The yearly net present cost for a range of wind, solar, and battery size combinations serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kWh, and the capital costs for the batteries is $250 per kWh.

Inclusion of battery energy storage requires three-dimensional surface plots to visualize all the equipment sizes considered. This is because battery sizing is the third input variable, in addition
to wind capacity and solar capacity. Figure 4.7 and Figure 4.8 are two views of the same surface plot. These figures illustrate the same information and should be viewed together. Solar capacity is shown on the x-axis, wind capacity is shown on the y-axis and net present cost is shown on the z-axis in millions of dollars. Five battery capacities are illustrated, each indicated by the color of the surface. The least net present cost battery capacity is the color shown at the bottom of the set of surfaces. The sizes of solar, wind and battery storage from the least cost combination are marked on both Figure 4.7 and Figure 4.8.

Figure 4.7 illustrates a 3-dimensional view of all five surfaces. The net present cost axis minimum and maximum values are the same for all plots in the battery storage cases using base price grid electricity. When the distance between surfaces is small, the difference in net present cost between the battery sizes is small. Likewise, when the distance between the surfaces is large, a larger difference in net present cost between the battery capacities exists.

Figure 4.8 shows the same surfaces as Figure 4.7, viewed from the bottom. This view of the surfaces best illustrates the least cost battery capacity for a given combination of wind and solar capacities. The battery capacity color that is visible in Figure 4.8 is the least cost battery capacity. For example, the red surface illustrates the net present cost when the battery capacity is zero. Thus, when the red surface is the bottom surface for a given combination of wind and solar capacity, the least cost option is no battery energy storage. The least cost battery size with solar generation alone can be read from the plot by following the top horizontal axis of Figure 4.8. The least cost battery size with wind generation alone can read from the plot by following the left vertical axis of Figure 4.8.

When only solar capacity is considered, the least cost battery capacity increases quickly as the size of solar capacity increases. This makes sense because solar generation occurs only during daylight hours, but there is demand for electricity throughout the day and night. If the size of the solar farm is increased, an excess of energy beyond what is required to supply the load is generated and can be stored for later use instead of purchasing energy from the grid. Thus, a short duration of storage, on the order of hours, is useful on a daily basis throughout the year. These results tell us that battery energy storage is a good partner for solar generation. Also, when wind and solar are combined, Figure 4.8 indicates the least cost size of energy storage is generally smaller than with a large amount of solar alone.
Figure 4.7: The yearly net present cost for a range of wind, solar, and battery size combinations serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $250 per kWh.

Figure 4.8 The lowest net present cost battery size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $250 per kWh.
When only wind capacity is considered, the least cost battery size increases as the size of wind capacity increases, but slowly. Wind generation does not start and stop with the rising and setting of the sun, so there are not daily periods of over production and under production of electricity that can maximize the use of small capacity batteries to offset grid electricity purchases. Figure 4.8 indicates that battery storage is not as good a partner for wind generated electricity as solar generated electricity.

Figures illustrating energy production and storage of energy generated by wind and solar are the next set of information presented. The following side by side pie charts cover three scenarios: least cost configuration, largest sized wind, solar and energy storage rating investigated, and least cost configuration without energy storage. The first set of pie charts illustrates the percent of the yearly energy demand each energy source provides over the course of one year. Electricity demanded by 25,000 homes can be supplied by electricity generated by wind and solar directly, electricity from battery storage or electricity from the grid. The second set of pie charts illustrates where energy that is generated is used and there are three options: to serve the load, deliver to storage, or waste as excess energy.

The left pie graph in Figure 4.9 indicates that 29% of the demanded electricity is purchased from the grid, 5% of the demand is served by energy storage and 67% is served directly by electricity produced from wind and solar. In the least cost configuration without energy storage 34% of the demand electricity is purchased from the grid and 66% of demand is served by electricity produced from wind and solar. For this case, the batteries served 10.8 GWh of the load. It makes sense that a small amount of energy was stored in the least cost scenario because the capacity of the batteries is relatively small compared to the average load and compared to the name plate rating of the wind turbines and solar panels. The addition of batteries in the least cost configuration reduced the percentage of electricity that is purchased from the grid by 5%. 


Figure 4.9: Base case, comparison of percent load demand served by solar and wind generation, batteries and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind, solar and batteries investigated (center), and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.6, Figure 4.7, and Figure 4.8.

Figure 4.10: Base case comparison of percent energy sent directly to load, to batteries, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind, solar and batteries investigated (center) and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.6, Figure 4.7, and Figure 4.8.

The center pie graph in Figure 4.9 uses large solar, wind, and battery capacities. This graph demonstrates that increasing the wind, solar and battery capacities greatly increase the amount of load that is served directly by electricity generated from wind and solar. The load served from energy stored in the batteries is again relatively small. The largest battery size investigated is two times the size of the minimum cost battery. There is not as much of a load deficit for the battery to serve in a scenario where the wind and solar generation is oversized. This plot also shows that
increasing the capacity of wind and solar generation and including battery energy storage has driven the amount of grid supplied electricity down. This shows that choosing the configuration that results in less grid supplied electricity does not necessarily result in a lower net present cost for the project.

The left most pie graph in Figure 4.10 indicates that 6% of the energy generated by wind and solar goes to storage, while 70% of the electricity generated by wind and solar goes directly to the load and the balance of energy is wasted as excess. For this scenario, 12.7 GWh of electricity generated by wind and solar goes to storage. In the least cost configuration without energy storage, 72% of the energy generated by wind and solar goes directly to the load and the balance of energy is wasted as excess.

The center pie graph in Figure 4.10 shows results for the largest solar, wind, and battery capacities simulated. We see in this plot that increasing the wind, solar and battery capacities greatly increase the amount of energy generated above the load requirement. Thus, a great deal of electricity is wasted. The capacity of batteries in this configuration is small compared to the rating of the wind and solar generation.

Figure 4.9 and Figure 4.10 show the small impact that batteries have on the percentage of energy captured from wind and solar generation, and the percentage of energy used by the load in the least cost configuration of a wind and solar farm coupled to battery energy storage. This is because the capacity of the batteries is small compared to the average load and the solar and wind rated capacities in the least cost configuration. The center pie charts in Figure 4.9 and Figure 4.10 show that oversizing the wind and solar generation, results in a large amount of excess electricity, and a smaller percentage of the load is served from the grid. Finally, dividing the energy going out
of battery storage by the energy going into battery storage gives an average round trip efficiency of 84.6%.

Figure 4.11: Base case hourly battery state of charge for the least cost configuration of solar, wind and battery equipment sizes. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.6, Figure 4.7, and Figure 4.8.

The state of charge plot in Figure 4.11 shows that the batteries cycle frequently between the maximum and minimum state of charge throughout the year. The batteries do not always reach full state of charge during the winter months. This indicates that there is not enough excess generation in the winter months to charge the batteries during the day.

4.3.3. Reduced Battery Cost by 50%

Figure 4.12 shows the net present cost for a range of solar and wind farm capacities in combination with the least net present cost sized battery storage when the cost of batteries is reduced by 50%. The lowest net present cost equipment combination is 50.64 MW of solar panels, 24 MW of wind turbines and 75 MW/150 MWh batteries. This battery capacity is capable of serving the mean load for roughly 6 hours.

The net present cost of this equipment combination is $196 million dollars. In this case, installation of the optimum sized wind solar farm with battery energy storage results in savings of
$152 million dollars over the duration of the project. This represents a 43.7% reduction in cost versus the net present cost where all the electricity is supplied from the grid.

Figure 4.12: The yearly net present cost for a range of wind, solar, and battery size combinations serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $125 per kWh.

Compared to the net present cost of wind and solar alone, installation of the optimum sized battery energy storage results in a savings of $13.2 million over the life of the project. This represents a 6.3% reduction in cost versus the least cost wind and solar installation without energy storage. Interestingly, the least cost sized solar installation increased from 35.16 MW without energy storage to 50.64 MW with battery energy storage. However, the least cost wind capacity decreased from 36 MW without energy storage to 24 MW with battery energy storage. These results tell us that even a 50% reduction in battery cost does not result in an economically attractive amount of cost savings over the life of the project versus wind and solar without energy storage. The reduction of battery cost resulted in a least cost configuration with an increased battery size which did help to justify an additional 15 MW of solar. This is a 44% increase in capacity versus the least cost solar capacity without energy storage. The least cost wind capacity decreased by 12 MW, a 33% decrease versus the least cost wind capacity without energy storage. We can conclude
that increasing the battery size favors a larger capacity solar installation and decreases the favorability of wind capacity.

When the cost of batteries is reduced by 50%, it is no surprise that larger battery sizes are associated with the least net present cost configuration. We can see the impact of the larger size batteries in the surface plot by looking at the solar only portions of the surfaces in Figure 4.13. The distance between the surfaces indicates the net present cost difference between the battery sizes considered. There are larger gaps between the surfaces for this case as compared to the base case. The gaps between the wind only portions of the surface are not as large.

Again, in Figure 4.14 we see, when only solar capacity is considered, the least cost battery capacity increases quickly as the solar capacity increases. Also, when wind and solar are combined, the least cost size of energy storage is generally smaller than large amounts of solar alone. Like the base case results, when only wind capacity is considered, the least cost battery size increases when the wind capacity increases, but slowly.

As shown in the left pie chart of Figure 4.15, the least cost configuration for this scenario results in 24% of the demand being served by grid purchased electricity. This is a decrease from 29% of the demand being served by grid purchased energy in the least cost base case, which is a move in the right direction. The left pie chart of Figure 4.15 also indicates that 13% of the demand is served by energy storage and 63% is served directly by wind and solar electricity generation. The percentage of energy stored increased versus the least cost base case, due to the larger battery size.
Figure 4.13 The yearly net present cost for a range of wind, solar and battery size combinations serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $125 per kWh.

Figure 4.14: The lowest net present cost battery size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $125 per kWh.
Figure 4.15: Battery cost reduced by 50% comparison of percent load demand served by solar and wind generation, batteries and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind solar and batteries investigated (center), and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.12, Figure 4.13, and Figure 4.14.

Figure 4.16: Battery cost reduced by 50% comparison of percent energy sent directly to load, to batteries, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind solar and batteries investigated (center) and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.12, Figure 4.13, and Figure 4.14.

For the center pie graph of Figure 4.15, it is again demonstrated that applying the largest wind, solar and battery capacity investigated greatly increases the amount of load that is served directly by electricity generated from wind and solar. The load served from energy stored in the batteries is 10% of the total demand served. The amount of energy purchased from the grid is small, 5% of the total demand. However, this configuration is not optimal in terms of net present cost.
The left pie chart in Figure 4.16 indicates that 16% of the energy generated by wind and solar goes to storage, while 66% of the electricity generated by wind and solar goes directly to the load and 18% of the electricity generated by solar and wind is wasted as excess in the least cost configuration. The percentage of excess electricity for the least net present cost configuration in this scenario is less than in the base case least cost scenario. Figure 4.15 and Figure 4.16 show that reducing the cost of batteries by 50% results in a least cost configuration of wind, solar, and battery energy storage that provides a small improvement in the percentage of electricity generated from wind and solar that is delivered directly to the load.

![Battery cost reduced by 50% hourly battery state of charge for the least cost configuration solar, wind and battery equipment sizes. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.12, Figure 4.13, and Figure 4.14.](image)

Figure 4.17: Battery cost reduced by 50% hourly battery state of charge for the least cost configuration solar, wind and battery equipment sizes. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.12, Figure 4.13, and Figure 4.14.

The state of charge plot in Figure 4.17 shows that the batteries cycle frequently between the maximum and minimum state of charge throughout the year. The batteries do not always fully discharge in the late spring and summer months. The batteries seldom reach a full charge during the winter months in the lowest cost configuration. In the base case configuration, the batteries reached full charge in the winter months more frequently. This tells us that there is not enough electricity generated in the winter months to fill the larger batteries while delivering electricity directly to the load.
4.3.4. Double Electricity Cost

Figure 4.18 shows the net present cost for a range of solar and wind farm size combinations for the least net present cost sized battery storage when the cost of grid electricity is doubled. The lowest net present cost equipment combination is 61.3 MW of solar panels, 36 MW of wind turbines and 75 MW/150 MWh capacity batteries. The resulting battery capacity would be able to serve the mean load for roughly 6 hours.

The net present cost of this equipment combination is $282 million dollars. The net present cost of supplying grid electricity over the duration of the project is $695 million dollars. In this case, installation of the optimum sized wind solar farm with battery energy storage results in savings of $413 million dollars over the life of the project. This represents a 59.4% reduction in cost versus the cost of electricity supplied from the grid.

When the cost of grid electricity is doubled, the lowest net present cost wind and solar capacities without energy storage are 44.1 MW of solar panels and 60 MW of wind turbines. The net present cost of this configuration is $303 million. The resulting savings of $393 million represent a 56.5% reduction in cost versus the net present cost of supplying all electricity from the grid.

When compared to the net present cost of wind and solar generation alone when electricity costs are doubled, installation of the optimum sized battery energy storage with wind and solar generation results in a savings of $20.5 million dollars over the life of the project. This represents a 6.8% reduction in cost versus the least cost wind and solar installation without energy storage. The least cost sized solar installation increased from 44.1 MW without energy storage to 61.3 MW with battery energy storage. However, the least cost wind capacity decreased from 60 MW without energy storage to 36 MW for this case. These results tell us that when the cost of grid electricity is doubled, the least cost wind, solar, and battery storage configuration results in a small amount of cost savings over the life of the project versus wind and solar without energy storage. When the cost of grid electricity is doubled, the addition of battery energy storage shifted the solar wind generation mix in favor of solar. Solar capacity increased by 17.2 MW, a 39% increase in capacity versus the least cost solar capacity without energy storage. The least cost wind capacity decreased by 24 MW, a 40% decrease versus the least cost wind capacity without energy storage.

It is also interesting to compare the resulting least cost configuration when the price of grid electricity is doubled to the base case configuration with battery energy storage and base electricity
prices. The least cost solar capacity increased by 23.2 MW, a 61.1% increase in capacity versus the base case. However, the least cost wind capacity remained the same compared to the base case. The least cost battery capacity increased from 50 MWh to 150 MWh, a 200% increase. We can conclude that increasing the cost of grid electricity helps to justify more solar and battery capacity installation, but does not justify more wind capacity.

Figure 4.18: The yearly net present cost for a range of wind, solar and battery size combinations serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $250 per kWh.

In Figure 4.20 we once more see that when only solar capacity is considered, the least cost battery capacity increases quickly as the solar capacity increases. When wind and solar are combined to reach a total rated capacity, the least cost size of energy storage is generally smaller. Like the base case results, when only wind capacity is considered, the least cost battery size increases as the wind capacity increases, but slowly.
Figure 4.19: The yearly net present cost for a range of wind, solar and battery size combinations serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $250 per kWh.

Figure 4.20: The lowest net present cost battery size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.50 per kW and the capital costs for the batteries is $250 per kWh.
Figure 4.21: Electricity cost doubled comparison of percent load demand served by solar and wind generation, batteries and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind solar and batteries investigated (center), and least cost configuration without storage (right). The cost of electricity is $0.3506 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.18, Figure 4.19, and Figure 4.20.

The least cost configuration shown in the left pie chart of Figure 4.21 results in 18% of the demand being served by grid purchased energy when the cost of grid purchased electricity is doubled. This is an improvement from the least cost scenario with base grid electricity prices, where 29% of the demand was served by grid purchased electricity. Part of this 11% improvement...
is from tripling the battery capacity, and part of the improvement is from increasing the size of the solar installation. The least cost configuration without energy storage when the cost of electricity is doubled is shown on the right pie chart of Figure 4.21. This figure indicates 24% of the demand is served by grid purchased electricity. Thus, the least cost configuration with battery energy storage results in a 6% reduction in electricity purchased from the grid versus wind and solar alone.

The left chart in Figure 4.22 indicates that 11% of the energy generated by wind and solar goes to storage, while 56% of the wind and solar generation goes directly to the load and 32% of the electricity generated by solar and wind is wasted in the least cost scenario for double electricity prices. The percentage of excess electricity for the least net present cost configuration increased compared to the least cost scenario with base electricity prices, even though the batteries are larger for this case. This is because the capacity of the solar installation was increased versus the base case scenario.

Figure 4.23: Electricity cost doubled, hourly battery state of charge for the least cost configuration solar, wind and battery equipment sizes. The cost of electricity is $0.3506 per kWh. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.18, Figure 4.19 and Figure 4.20.

The state of charge plot in Figure 4.23 shows that the batteries cycle frequently between the maximum and minimum state of charge throughout the year. For the lowest cost configuration
when the electricity cost is doubled, the batteries seldom fully discharge in the late spring and summer months. The solar capacity increased and wind capacity did not change from the base case configuration with battery energy storage. The battery size increased versus the base case configuration. Batteries can serve the mean load for 6 hours for this case. The infrequency of full discharge in the summer demonstrates that there is often adequate generation in the summer months to supply the load in the lowest cost configuration.

4.3.5. Summary

Table 4.3 summarizes all the results when battery storage is coupled to a wind and solar farm. For comparison purposes, the results of Section 4.2 where wind and solar alone were investigated are also included in the table.

A strong economic case can be made for wind and solar installations alone or with battery energy storage when compared to the cost of purchasing all electricity from the grid. The least cost installations considered were associated with a costs savings of 40%, 41%, and 44% versus the cost of purchasing grid electricity at the base price for wind and solar alone, wind and solar with battery energy storage and wind and solar with battery energy storage with 50% reduced cost cells, respectively. If the cost of electricity is doubled, the economic case strengthens for wind and solar alone, and for wind and solar with battery energy storage. When the cost of electricity is doubled, the least cost configurations result in 56% and 59% cost savings versus the price of grid electricity for wind and solar alone and versus the price of grid electricity for wind and solar with battery energy storage, respectively.

However, a strong economic case cannot be made for the addition of battery energy storage versus wind and solar generation alone in Rio Vista, California. This is true even when the cost of batteries is reduced by 50%. When compared to the net present cost of wind and solar alone, the inclusion of battery energy storage results in net present cost savings of 1.4% and 6.3% for base cost cells and 50% reduced cost cells, respectively. When the cost of electricity was doubled the net present cost savings of batteries with wind and solar was 6.8% versus wind and solar alone. In the future, reductions in cell costs and/or increases in grid electricity prices beyond what were investigated in this work would be needed to make a strong economic case for the inclusion of battery energy storage with wind and solar installations versus wind and solar alone.
It is interesting to consider the impact of including battery energy storage on the least cost equipment configuration. Adding battery energy storage increased the amount of solar capacity but did not increase the amount of wind capacity for the minimum cost configuration. Reducing the battery cost by 50% justified larger battery capacity and more solar capacity but decreased the wind capacity versus the base case. Increasing grid electricity prices and including battery energy storage justified the installation of more solar and battery capacity, but not more wind capacity. The resulting least cost battery capacities for all cases considered were suitable for short term energy storage and could serve the mean load for 2 to 6 hours. It can be concluded that battery
energy storage is a good partner for solar in this location for the cases considered because larger solar installations result in an excess of energy beyond what is required to supply the load during the day. This energy can be stored in batteries during the day when the sun is shining for later use in the evening, offsetting some energy purchases from the grid. Thus, a short duration of storage, on the order of hours, is useful on a daily basis throughout the year when coupled with increased solar capacity.

4.4. Hydrogen Energy Storage

4.4.1. Technical and Cost Inputs

Unlike battery energy storage coupled to a solar and wind farm where there are three major capital costs, hydrogen energy storage coupled to a solar and wind farm has four major capital cost inputs. These are the cost of the solar panels, the cost of the wind turbines, the cost of the regenerative cells, and the cost of the hydrogen storage tanks. All these costs and the technical data for wind and solar coupled to hydrogen energy storage are given in Table 4.4. The capital costs and operation and maintenance costs for regenerative cells were derived from reference [39]. The capital costs and operation and maintenance costs for compressed hydrogen storage tanks are obtained from reference [19].

In the hydrogen energy storage configuration considered [19], it is concluded that the installation cost of compressed hydrogen storage using buried pipe is $560/kg of hydrogen and the operation and maintenance costs are $84/kg of hydrogen per year. These costs include the pipe coating, shipping, pipe installation and site preparation. Site preparation includes excavation and backfilling, land, project costs and the cost of above ground facilities, including compressors. In reference [19] 546,000 kg of hydrogen compressed to 100 bar are stored in 24,000 segments of buried 24” ID schedule 60 pipe which are 12 m long. From this information a density of stored hydrogen of 7.68 kg/m³, an installation cost of $4,303/m³ and operation and maintenance cost of $645/m³ is calculated.

It should be noted that storing compressed hydrogen in tanks is more economical for storage sizes less than 20 metric tons. For quantities of compressed hydrogen exceeding 20 metric tons, storage in lined rock caverns or salt caverns is more economical. Storing gas in underground salt caverns or other geological features limits the applicable sites for storage to locations where
these features are available. It is noted that pipe material costs are a major contributing factor to the cost of buried pipe storage and that capital and operating costs per kilogram of hydrogen stored do not decrease appreciably by increasing the amount of hydrogen stored. In reference [19], the capital costs of storage in salt caverns scales with the size of storage, ranging from roughly $95/kg of hydrogen stored for 100 metric tons of hydrogen to about $20/kg of hydrogen stored for 3,000 metric tons. The cost of storage in lined rock caverns also scales with the amount of hydrogen stored. The capital cost of storage for lined rock caverns is more than that for salt cavern storage of the same size. In Lazard’s 2023 levelized cost of energy plus report [9], a cost of hydrogen storage of $20/kg of hydrogen for storage sizes from 120 to 200 tons is stated. This is in line with the cost of storage in salt caverns.

The capital cost of regenerative cells and associated equipment is assumed to be the same as the cost of high temperature steam electrolyzers as noted in [39], which is $703/kW-dc electrolyzer stack power input for nth-of-a-kind (NOAK) technology. Fixed operation and maintenance costs are estimated to be $32.64/kW-dc-yr of electrolyzer stack rating. Many of the elements included in the variable operation and maintenance costs are already included in the analysis done for this work, such as the cost of electricity supplied, and the cost of heat supplied. Some variable operation and maintenance costs are small enough to ignore, such as the cost of treating process water. However, partial stack replacements need to be included in the operation and maintenance costs as the report notes that the average stack life is expected to be 4 years. The report predicts that 27.3% of the stacks will be replaced yearly at a cost of $78/kW-dc. Therefore $21.94/kW-dc was added to the fixed operation and maintenance costs. The total yearly operation and maintenance costs used in this work are $54.58/kW-dc.

The maximum tank pressure selected was 100 bar and the minimum tank pressure was selected to be 1 atm. The tank temperature is selected to be the ground temperature which is essentially equal to the average of the hourly air temperatures over the year. Yearly average air temperatures of 289 K were obtained from the National Solar Radiation Database [40] for Rio Vista, California. The percentage of energy used by balance of plant equipment was estimated to be 12%, as stated in reference [33]. The regenerative cell temperature is 1073 K as was used in the generation of the polarization curve. This temperature was used for solid oxide fuel cells and electrolyzers in [18] and [16].
The nominal operating point of the regenerative cells in fuel cell mode is chosen as the maximum power point. The desirable operating point of the fuel cell will be at the maximum power point or just to the left of the maximum power point. Increasing the current density beyond the maximum power point does not produce more power but uses more fuel.

Table 4.4: Cost and technical inputs for hydrogen energy storage base case.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Rate (commercial price of electricity)</td>
<td>$0.1753/kW-h</td>
</tr>
<tr>
<td>Capital Cost of Solar (utility scale crystalline with single-axis tracking)</td>
<td>$950/kW</td>
</tr>
<tr>
<td>Capital Cost of Wind (onshore, average of high and low costs)</td>
<td>$1187.5/kW</td>
</tr>
<tr>
<td>Capital Cost of Tank Storage</td>
<td>$4303/m³</td>
</tr>
<tr>
<td>Capital Cost of Regenerative Cell (based on electrolyzer cell rating)</td>
<td>$703/kW</td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Solar (utility scale crystalline with single-axis tracking)</td>
<td>$13.0/kW-yr</td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Wind (onshore, average of high and low costs)</td>
<td>$29.25/kW-yr</td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Tank Storage</td>
<td>$645/m³</td>
</tr>
<tr>
<td>Operations and Maintenance Cost of Regenerative Cell (based on electrolyzer cell rating)</td>
<td>$54.58/kW</td>
</tr>
<tr>
<td>Years of Project</td>
<td>25</td>
</tr>
<tr>
<td>Interest Rate</td>
<td>10%</td>
</tr>
<tr>
<td>Tank Minimum Pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>Tank Maximum Pressure</td>
<td>100 bar</td>
</tr>
<tr>
<td>Tank Initial Pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>Hydrogen Tank Temperature (average air temperature in Rio Vista, CA)</td>
<td>289 K</td>
</tr>
<tr>
<td>Percent Energy Used by Balance of Plant Equipment</td>
<td>12%</td>
</tr>
<tr>
<td>Cell Temperature</td>
<td>1073 K</td>
</tr>
<tr>
<td>Regenerative Cell Voltage in Electrolysis Mode</td>
<td>1.2930 Volts</td>
</tr>
<tr>
<td>Regenerative Cell Current Density in Electrolysis Mode</td>
<td>-6,667 A/m²</td>
</tr>
<tr>
<td>Regenerative Cell Voltage in Fuel Cell Mode</td>
<td>0.4279 Volts</td>
</tr>
<tr>
<td>Regenerative Cell Current Density in Fuel Cell Mode</td>
<td>10,000 A/m²</td>
</tr>
</tbody>
</table>
The nominal operating point of the regenerative cells in electrolyzer cell mode is chosen as the thermoneutral voltage point. The current density corresponding to the thermoneutral voltage of the cell is set as the current density of the electrolyzer. At this operating point, the current density of the electrolyzer is negative. At the thermoneutral current density, heat does not have to be added or removed from the electrolyzer cell.

4.4.2. Base Case

Before looking at the cost associated with the base case scenario, the net present cost of solar and wind farms coupled to regenerative cells as a function of hydrogen energy storage size is studied. The net present cost of each least cost configuration versus the size of compressed hydrogen storage is shown in Figure 4.24. For the base case scenario, none of the compressed hydrogen storage vessel sizes investigated resulted in a net present cost that was less than that of the least cost configuration of the solar and wind farm without energy storage. The curve in Figure 4.24 has its minimum when the tank size is 0 m$^3$. Without hydrogen storage there is no need for regenerative fuel cells. For this reason, the minimum cost study for the case of hydrogen storage shown below was done using 1 metric ton of compressed hydrogen storage. This allows the reader to see the effect of regenerative cells on system cost.

The net present costs for different wind and solar farm sizes when combined with the least cost sized regenerative cell system and compressed hydrogen storage are shown in Figure 4.25. The lowest net present cost equipment combination with hydrogen energy storage is 35.16 MW of solar panels, 36 MW of wind turbines and a regenerative cell system with a 0.75 MW fuel cell rating. The compressed hydrogen storage is taken to be 1 metric ton of hydrogen at 100 bar which is 125 m$^3$ of hydrogen energy storage. Since the least cost option was zero hydrogen storage, the next lowest cost option was chosen so that hydrogen storage effects could be included in the results.

The net present cost of this equipment combination is $210 million dollars. The net present cost of purchasing electricity from the grid over the project duration is $348 million dollars. Installation of the optimum sized wind and solar farm with a hydrogen energy storage system will result in a savings of $138 million dollars over the duration of the project. This represents a 39.6% reduction in cost versus the net present cost where all the electricity is supplied from the grid.
Figure 4.24: Total net present cost in millions of dollars for the least cost sized solar, wind and regenerative cell combination for a given compressed hydrogen storage volume. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$ and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.

It is important to compare the cost of wind and solar with hydrogen energy storage to the cost of wind and solar alone. The least net present cost option investigated with 1 metric ton of compressed hydrogen storage combined with wind and solar costs is $0.88 million dollars more than the least net present cost configuration of wind and solar alone. These results tell us that the installation of hydrogen energy storage at base costs is not economically attractive when compared to wind and solar alone. Additionally, the least cost regenerative cell size and 1 metric ton of hydrogen storage size did not help to justify any additional solar or wind capacity.

Figure 4.26 and Figure 4.27 show the net present cost surface plot of the combination of three of the four equipment size variables: solar equipment capacity, wind turbine capacity and regenerative cell size, indicated with the fuel cell capacity. The hydrogen storage size is fixed at 1 metric ton of hydrogen. Five fuel cell sizes are illustrated in these two figures, each indicated by the color of the surface. The minimum point of all the surfaces illustrates the lowest net present cost amount and associated equipment sizes. Figure 4.27 is a bottom-up view of the same information shown in Figure 4.26. Thus, the fuel cell size associated with the color shown for each solar and wind capacity combination is the lowest cost option for that wind and solar size combination.
Figure 4.25: The yearly net present cost for a range of wind and solar farm sizes using a least cost regenerative cell size of 0.75 MW on a fuel cell basis with 1 metric ton of compressed hydrogen storage serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.

The minimum cost fuel cell nameplate capacity is quite small compared to the minimum cost nameplate capacities of the wind turbines and solar panels. As a result, the addition of fuel cells in the least cost configuration does not make a significant impact on the minimum net present cost. One important point to note when considering the results in Figure 4.26 and Figure 4.27 is that cost of tank storage for 1 metric ton of compressed hydrogen is included. The least cost sized fuel cell capacity is so small that it can only serve a small fraction of the mean load in each hour. Because the least cost fuel cell size ratings are so small for the base case, economic input factors must be adjusted to give a clearer picture of how hydrogen storage could impact the least cost sized capacity of wind and solar. When only solar generation is considered the least cost size of the regenerative cells increases quickly as the solar capacity increases. When only wind generation is considered, the least cost sized fuel cell increases slowly as the wind capacity increases.
Figure 4.26: The yearly net present cost for a range of wind, solar and regenerative cell size combinations serving 25,000 homes in Rio Vista, California with 1 metric ton of compressed hydrogen storage. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.

Figure 4.27: The lowest net present cost regenerative cell size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California, with 1 metric ton of compressed hydrogen storage. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.
Figure 4.28: Base case comparison of percent load served by solar and wind generation, fuel cell and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell investigated (center), and least cost configuration without storage (right). The capacity of compressed hydrogen storage tanks is 1 metric ton of hydrogen at 100 bar. The cost of electricity is $0.1753 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.25, Figure 4.26, and Figure 4.27.

Figure 4.29: Base case comparison of percent energy sent directly to load, to electrolyzers, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind solar and fuel cell investigated (center) and least cost configuration without storage (right). The capacity of compressed hydrogen storage tanks is 1 metric ton of hydrogen at 100 bar. The cost of electricity is $0.1753 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.25, Figure 4.26, and Figure 4.27.

Figures illustrating energy production by wind, solar and storage of energy using hydrogen are presented in Figure 4.28. The left chart of Figure 4.28 illustrates that less than 1% of the load is served by fuel cells in the least cost configuration which represents 1.54 GWh of load. The fuel
cells meet little load in the least cost, base case scenario because the fuel cell size is small compared to the size ratings of the power generation equipment. The high cost of regenerative cells drove the least cost scenario to have a hydrogen storage system that provides no meaningful reduction in the amount of energy purchased from the grid.

Energy generated by the wind and solar equipment can be used directly by the load in the hour that it is generated, sent to the electrolyzer system to generate hydrogen, or wasted as excess. The left chart of Figure 4.29 indicates that 24% of the electricity generated by wind turbines and solar panels was wasted, 4% was sent to the electrolyzers and 72% of the electricity was used directly by the load in the least cost configuration. For this case, 7.18 GWh of electricity generated by wind and solar was sent to the electrolyzers. In the least cost configuration with wind and solar alone, 28% of the electricity generated by wind and solar was wasted as excess and 72% was used by the load. Electrolyzers take up relatively little energy because the cell rating is a small fraction of the size rating of the generation equipment. A round trip efficiency of 21.5% for the entire hydrogen storage system is given by dividing the electricity from the fuel cells by the electricity sent into the regenerative cell system for electrolysis, reactant heating and balance of plant uses.

![Figure 4.30 Base case, hourly tank pressure in the least cost configuration for solar, wind and regenerative cells with compressed hydrogen storage tanks that hold 1 metric ton of hydrogen at 100 bar. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.25, Figure 4.26, and Figure 4.27.](image-url)
An hourly plot of the tank pressure over the year resulting from the least net present cost equipment configuration with hydrogen energy storage is shown in Figure 4.30. This figure shows that the tank only cycles from full to empty occasionally throughout the year. The tank does not reach full pressure frequently until late spring. In the summer months the tank seldom discharges fully. In the early spring and winter the tank only partially fills before discharging again. The high cost for the least cost scenario using regenerative cells results in a regenerative cell capacity that is too small to fill and empty the hydrogen storage tanks frequently.

4.4.3. 50% Cell Costs

The least net present cost configuration when the capital cost of regenerative cells is reduced by 50% and base costs are used for hydrogen storage will now be investigated. Note that the cell replacement portion of the operating and maintenance costs was also reduced by 50%. Figure 4.31 shows the net present cost of each least cost configuration versus the size of the compressed hydrogen storage system. Compressed hydrogen storage with a capacity of 1 metric ton of hydrogen, or 125 m³, is the least net present cost size.

![Figure 4.31: Total net present cost in millions of dollars for the least cost sized solar, wind and regenerative cell combination for a given compressed hydrogen storage volume. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³ and the capital cost for the regenerative cells is $351.50 per kW of electrolyzer stack rating.](image-url)
The net present cost for each combination of wind and solar farm size when combined with the least cost sized hydrogen energy storage system are shown in Figure 4.32. This figure illustrates the case when the cost of regenerative cells is reduced by 50% along with base cost of compressed hydrogen storage. The lowest net present cost equipment combination with hydrogen energy storage is 35.16 MW of solar panels, 36 MW of wind turbines and a regenerative cell system with a 1.13 MW fuel cell rating and a compressed hydrogen storage sized to contain 1 metric ton of hydrogen at 100 bar which is 125 m³ of hydrogen energy storage.

The net present cost of this equipment combination is $209 million dollars. The net present cost of purchasing electricity from the grid over the project duration is $348 million dollars. Installation of the optimum sized wind and solar farms with hydrogen energy storage results in a savings of $139 million dollars over the duration of the project. This represents a 39.9% reduction in cost versus the net present cost where all the electricity is supplied from the grid.

Next, the cost of wind and solar with hydrogen energy storage is compared to the cost of wind and solar alone. The least net present cost option investigated with hydrogen energy storage and 50% reduced cost cells combined with wind and solar costs $0.16 million less than the least net present cost configuration of wind and solar alone. This is in contrast to the base case where no hydrogen storage was cost beneficial. Although, it is noted $0.16 million dollars is not a significant savings. These results tell us that the installation of hydrogen energy storage with 50% reduced cost regenerative cells and compressed hydrogen storage at base cost is not a significantly economically attractive option compared to wind and solar alone. Additionally, reducing the regenerative cell cost did not help justify any additional solar or wind capacity.

Figure 4.33 and Figure 4.34 show the net present cost surface plot for the combination of solar, wind and regenerative cells for the case where the regenerative cell costs are reduced by 50%. The least net present cost fuel cell nameplate capacity of 1.13 MW is quite small compared to the minimum cost nameplate capacities of wind and solar. As a result, the addition of least cost sized regenerative cells does not have a large impact on the minimum net present cost. In Figure 4.33 and Figure 4.34 the cost of a storage tank capable of storing 1 metric ton of hydrogen at 100 bar is included for all wind, solar and fuel cell combinations.

When only solar capacity is considered, the least cost fuel cell size increases quickly as the solar capacity increases. When both wind and solar are considered, the least cost sized regenerative cells do not justify additional solar or wind capacity. The least cost fuel cell size ratings are too
small for the case where the cost of cells is reduced by 50% to illustrate a clear picture of how hydrogen storage could impact the least cost sized capacity of wind and solar. Further cost reductions are still needed if one wishes to have an economically competitive wind and solar facility with hydrogen storage.

Figure 4.32: The yearly net present cost for a range of wind, solar and regenerative cell size combinations serving 25,000 homes in Rio Vista, California with 1 metric ton of compressed hydrogen storage. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$ and the capital cost for the regenerative cells is $351.50 per kW of electrolyzer stack rating.

Figure 4.35 illustrates less than 1% of the load is served by fuel cells and 33% of the load is served by grid purchased electricity for the least cost equipment configuration. In the least cost configuration with wind and solar alone, 34% of the load is served by grid purchased electricity. It can thus be seen that fuel cells serve little load in the least cost scenario where the cost of regenerative cells is reduced by 50%. This occurs because the fuel cell size is small compared to the size rating of the wind farm and solar farm. For the least cost scenario, the high cost of regenerative cells reduces the size of the hydrogen storage system so that no meaningful reduction in the amount of energy purchased from the grid is obtained.
Figure 4.33: The yearly net present cost for a range of wind, solar and regenerative cell size combinations serving 25,000 homes in Rio Vista, California with 1 metric ton hydrogen storage tanks. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$, and the capital cost for the regenerative cells is $351.50 per kW of electrolyzer stack rating.

Figure 4.34: The lowest net present cost regenerative cell size for a range of wind the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$ and solar capacities serving 25,000 homes in Rio Vista, California with 1 metric ton hydrogen storage tanks. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$, and the capital cost for the regenerative cells is $351.50 per kW of electrolyzer stack rating.
Figure 4.35: Cell costs reduced by 50% comparison of percent load served by solar and wind generation, fuel cell and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell investigated (center), and least cost configuration without storage (right). The compressed hydrogen storage tanks hold 1 metric ton of hydrogen at 100 bar. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.32, Figure 4.33, and Figure 4.34.

Figure 4.36: Cell costs reduced by 50% comparison of percent energy sent directly to load, to electrolyzers, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell investigated (center) and least cost configuration without storage (right). The compressed hydrogen storage tanks hold 1 metric ton of hydrogen at 100 bar. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.32, Figure 4.33, and Figure 4.34.

Figure 4.36 indicates that 23% of the electricity generated by wind and solar was wasted as excess, 5% was used by the electrolyzer system and 72% of the electricity was used directly by the load. In the least cost configuration with wind and solar alone, 28% of the electricity generated by wind and solar was wasted as excess and 72% was used by the load. The electrolyzer system takes up relatively little energy because the cell rating is small compared to the size rating of the generation equipment.
Figure 4.37: Cell costs reduced by 50%, hourly tank pressure for the least cost configuration for solar, wind and regenerative cells. The compressed hydrogen storage tanks hold 1 metric ton of hydrogen at 100 bar. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.32, Figure 4.33, and Figure 4.34.

An hourly plot of the tank pressure over the year resulting from the least net present cost equipment configuration with hydrogen energy storage when the regenerative cell cost is reduced by 50% is shown in Figure 4.37. This figure shows that the tank cycles from full to empty more frequently throughout the year than in the base case configuration, due to the larger regenerative cell size than the base case. The tank reaches full pressure more frequently in the late spring and summer months. In the late spring and summer months the tank seldom discharges fully, but it does so more frequently than in the base case due to the larger cells. In the spring, fall, and winter the tank often partially fills before discharging again.

4.4.4. Large, No Cost Storage

In the previous cases considered, the high cost of regenerative cells and compressed hydrogen storage forced the least cost scenario with hydrogen storage to have a small fuel cell size and small hydrogen storage capacity. This does not produce a clear picture of how hydrogen energy storage impacts the least cost configuration of wind and solar capacity if larger cells and hydrogen
storage were economically attractive. In this section, the least cost configuration assuming zero capital cost for hydrogen storage and base costs for regenerative cells is investigated. The operation and maintenance costs of compressed hydrogen storage are also taken to be zero for this scenario.

The net present costs for each combination of wind and solar farm size when combined with the least cost sized regenerative cells are shown in Figure 4.38. This figure illustrates the case where a large, zero cost hydrogen storage vessel is combined with base cost regenerative cells. To simulate infinite hydrogen storage, 6,354 metric tons of compressed hydrogen with a maximum operating pressure of 100 bar is utilized. The analysis determined the lowest net present cost equipment combination is 38.03 MW of solar panels, 48 MW of wind turbines and a regenerative cell system with a 4.5 MW fuel cell rating.

The net present cost of this equipment combination is $204 million dollars. Installation of the optimum sized wind solar farm with hydrogen energy storage results in savings of $144 million dollars over the duration of the project compared to the net present cost of purchasing all the electricity from the grid. This represents a 41.4% reduction in cost versus the electricity supplied from the grid. The least net present cost option investigated for wind and solar combined with regenerative cells and large, zero cost storage is $5.22 million less than the least net present cost configuration of wind and solar alone. This is a 2.5% savings over the least cost combination of wind and solar without energy storage. These results tell us that the installation of hydrogen energy storage does not result in meaningful savings versus the least cost configuration of wind and solar alone. Removing the capital cost of compressed hydrogen storage was not sufficient to make the hydrogen energy storage system economically attractive. The resulting least cost fuel cell rating was still small compared to the wind and solar capacity ratings and to the mean load. However, the addition of a large amount of hydrogen storage at zero cost did help to justify 12 MW of additional wind capacity. This is a 33% increase versus the wind capacity in the least cost configuration of wind and solar without energy storage. An additional 3 MW of solar capacity was also justified in this configuration.
Figure 4.38: The yearly net present cost for a range of wind and solar size combinations with a 4.5 MW fuel cell serving 25,000 homes in Rio Vista, California with large compressed hydrogen storage at zero cost. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.

Figure 4.39 and Figure 4.40 show the net present cost surface plot for the combination of solar equipment capacity, wind turbine capacity and regenerative cell size, indicated by the fuel cell capacity, for the case where large, zero cost hydrogen storage is combined with base cost regenerative cells. The minimum cost fuel cell capacity is 4.5 MW which is small compared to the minimum cost nameplate capacities of wind and solar. When solar is the only electricity generation equipment, the least cost regenerative cell size increases as the solar capacity increases. Similarly, if wind is the only electricity generation equipment, as the wind capacity increases the least cost regenerative cell size increases. When there is a deficit of electricity output from wind and solar available to serve the load, the fuel cell output can help to fulfill some of this deficit. The large storage vessel size can supply the fuel cell for a long duration when a deficit in solar or wind production occurs.
Figure 4.39: The yearly net present cost for a range of wind, solar and regenerative cell size combinations serving 25,000 homes in Rio Vista, California with large compressed hydrogen storage at zero cost. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.

Figure 4.40: The lowest net present cost regenerative cell size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California with large compressed hydrogen storage at zero cost. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, and the capital cost of the regenerative cells is $703 per kW of electrolyzer stack rating.
Figure 4.41: Large no cost storage comparison of percent load served by solar and wind generation, fuel cell and grid purchased power with large, no cost hydrogen storage large tanks for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell investigated (center), and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.38, Figure 4.39, Figure 4.40.

The left pie chart of Figure 4.41 illustrates that 5% of the load is served with fuel cells in the least net present cost configuration. The fuel cells meet a small percentage of the load in the least cost scenario for the case where large, zero cost hydrogen storage is combined with base cost.
regenerative cells. This occurs because the resulting fuel cell size is small compared to the size rating of the power generation equipment. The right chart in the figure indicates that 34% of the demand is served with electricity purchased from the grid in the least cost scenario with wind and solar alone, while 23% of the total demand electricity is purchased from the grid in the least cost scenario with hydrogen energy storage. Part of this 11% improvement is from the load served by the fuel cells and part of the improvement is from the 12 MW of additional wind capacity. The percentage of load served directly by wind and solar without energy storage in the least cost scenario is 66%. In the least cost scenario with hydrogen energy storage, 71% of the load was served directly with wind and solar.

Figure 4.42 indicates that 13% of the electricity generated by wind and solar was wasted as excess, 22% was sent to the electrolyzer system and 65% of the electricity was used directly by the load in the least cost configuration. In the least cost configuration with wind and solar alone, 28% of the electricity generated by wind and solar was wasted as excess and 72% was used by the load.

![Graph showing tank pressure over time](image_url)

*Figure 4.43: Large no cost storage, hourly tank pressure in the least cost configuration for solar, wind and regenerative cells. The compressed hydrogen storage tanks hold 6,354 metric tons of hydrogen at 100 bar.*
An hourly plot of the tank pressure over the year resulting from the least net present cost equipment configuration is shown in Figure 4.43. This hourly pressure plot looks different from the tank pressure plots for the other cases considered in this Chapter. This makes sense given the large size hydrogen storage. The tank never reaches full pressure but does increase in pressure slightly in the summer months before discharging to a minimum pressure in the winter months. This shows that in the least cost scenario with a large hydrogen storage capacity and base cost regenerative cells, all of hydrogen generated with excess energy from wind and solar was sent to the fuel cell system to produce electricity to offset grid electricity purchases.

4.4.5. No Cost Cells

To better evaluate the cost of hydrogen storage tanks on the optimum system costs, the least net present cost configurations are found where the cost of regenerative cells is taken to be zero and the base costs are used for compressed hydrogen storage vessels. The capital cost and operation and maintenance costs for the regenerative cells were set to zero for this scenario. The net present cost versus the size of compressed hydrogen storage for each least cost configuration is shown in Figure 4.44. Compressed hydrogen storage with a capacity of 5 metric tons (625 m$^3$ of volume) resulted in the least net present cost.

The net present costs for each size combination of wind and solar farm when combined with the least cost sized hydrogen storage system and zero cost regenerative cells are shown in Figure 4.45. In this case, the lowest net present cost equipment combination is 44.11 MW of solar panels, 36 MW of wind turbines, and a compressed hydrogen storage system sized to contain 5 metric tons of hydrogen at 100 bar which is 625 m$^3$ of hydrogen energy storage. The largest regenerative cell size tested was a 48 MW fuel cell rating. The 36 MW and 48 MW fuel cell planes were on top of the 24 MW fuel cell size plane. The 24 MW fuel cell size essentially mimics an infinite regenerative cell size because the 12 MW regenerative cell plane is just about on top of the 24 MW regenerative cell plane in Figure 4.46.

The net present cost of this equipment combination is $200 million dollars. This compares to the net present cost of purchasing all electricity from the grid over the project duration of $348 million dollars. This is a savings of $147 million dollars over the duration of the project which represents a 42.4% reduction in cost compared to supplying all the electricity from the grid.
Next, comparisons are made between the costs of wind and solar with hydrogen energy storage versus the cost of wind and solar alone assuming the capital cost of regenerative cells is zero. The least net present cost option investigated is $8.57 million dollars less than the least net present cost of wind and solar alone. This is a 4.1% reduction in costs, which is not significant. These results show that the installation of hydrogen energy storage with zero cost regenerative cells and compressed hydrogen storage vessels at base cost does not provide a meaningful amount of net present cost savings versus wind and solar alone. However, reducing the regenerative cell cost to zero does justify 9 MW more of solar capacity, but does not justify any additional wind capacity.

Figure 4.46 and Figure 4.47 show the net present cost surface plots of the combination of solar panel capacity, wind turbine capacity and regenerative cell size for the case where regenerative cell costs are reduced to zero. The large size fuel cell nameplate capacity of 24.1 MW is approximately equal to the average load capacity of 25 MW. Because the cost of additional regenerative cells is zero, increasing the cell capacity only impacts the net present cost by changing the amount of grid purchased electricity. There is no net present cost penalty for adding more
regenerative cells to the system; however, adding more cells will lower the net present cost only to a certain point. Figure 4.46 shows that there is almost no difference between 12 MW and 24 MW of cells. This means that 24.1 MW of regenerative cells on a fuel cell basis approximates an infinite cell size. Adding more cells does not continue to decrease the net present cost of the project. The surfaces do not cross in this case because adding zero cost regenerative cells always decreases the net present cost compared to the same combination of wind and solar without energy storage. In Figure 4.46 and Figure 4.47 the cost of storage capable of storing 5 metric tons of hydrogen is included for all wind, solar and fuel cell combinations. The least cost sized regenerative cells did help to justify an additional 9 MW of solar capacity but did not help to justify any additional wind capacity.

**Figure 4.45:** The yearly net present cost for a range of wind and solar capacities with 5 metric tons of compressed hydrogen storage and a large size of no cost regenerative cells serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, and the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$. 
Figure 4.46: The yearly net present cost for a range of wind, solar and regenerative cell size combinations with 5 metric tons of compressed hydrogen storage serving 25,000 homes in Rio Vista, California where the capital cost of the regenerative cells is taken to be zero. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, and the capital cost of compressed hydrogen storage tanks is $4303 per m³.

Figure 4.47: The lowest net present cost regenerative cell size for a range of wind and solar capacities with 5 metric tons of compressed hydrogen storage serving 25,000 homes in Rio Vista, California where the capital cost of the regenerative cells is taken to be zero. The cost of electricity is $0.1753 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, and the capital cost of compressed hydrogen storage tanks is $4303 per m³.
Figure 4.48: No cost cell comparison of percent load served by solar and wind generation, fuel cell and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind solar and fuel cell investigated (center), and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.45, Figure 4.46, Figure 4.47.

Figure 4.49: No cost cell comparison of percent energy sent directly to load, to electrolyzers, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell sizes investigated (center) and least cost configuration without storage (right). The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.45, Figure 4.46, Figure 4.47.

The left pie chart of Figure 4.48 illustrates the percentage of load served with fuel cells is 5%. The right pie chart indicates that 34% of the demand is served by grid purchased electricity with wind and solar alone. When hydrogen energy storage is included, 27% of the demand is served by grid purchased electricity, a 7% improvement.
The left pie chart of Figure 4.49 indicates that 12% of the electricity generated by wind and solar was wasted as excess, 22% was sent to the electrolyzer system and 66% of the electricity was used directly by the load. In the least cost configuration with wind and solar alone, 28% of the electricity generated by wind and solar was wasted as excess and 72% was used by the load. On a relative basis the electrolyzer system uses a larger portion of the excess energy than the base case (see Figure 4.28) because the regenerative cell size is much larger.

![Graph showing hourly tank pressure](image)

Figure 4.50: Zero cost regenerative cells, hourly tank pressure for the least cost configuration of solar, wind and regenerative cells. The compressed hydrogen storage tanks hold 5 metric tons of hydrogen at 100 bar. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.45, Figure 4.46, and Figure 4.47.

An hourly plot of the tank pressure over the year resulting from the least net present cost equipment configuration is shown in Figure 4.50. This figure shows that the tank cycles from full to empty more frequently than in the base case with hydrogen energy storage. The tank does not reach full pressure frequently until late spring. In the late spring and summer months the tank seldom discharges fully but it does so more frequently than in the base case due to the larger cells. In the early spring, fall, and winter the tank often partially fills before discharging again. In the base case the high cost of regenerative cells forced the least cost scenario to have a regenerative cell capacity that is too small to fill and empty the tank frequently. For this case, larger cell capacity
and an additional 9 MW of solar leads to the tank filling and emptying more frequently, even though the tank size increased from 1 metric ton in the base case to 5 metric tons in the current case.

4.4.6. Double Electricity Cost

This scenario illustrates the least net present cost configuration for hydrogen energy storage when the cost of electricity purchased from the grid is doubled. All other costs are the same as used in the base case. The size of the compressed hydrogen storage vessels versus the net present cost of each least cost configuration is shown in Figure 4.51. Compressed hydrogen storage with a capacity of 2.6 metric tons resulted in the least net present cost.

![Figure 4.51: Total net present cost in millions of dollars for the least cost sized solar, wind and regenerative cell combination for a given compressed hydrogen storage volume where the cost of electricity is doubled. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.](image)

The net present costs for each combination of wind and solar farm size when combined with the least cost sized hydrogen energy storage system are shown in Figure 4.52. For this case the lowest net present cost equipment is 44.1 MW of solar panels, 60 MW of wind turbines, a
regenerative cell system with a 3 MW fuel cell rating and compressed hydrogen storage sized for 2.6 metric tons of compressed hydrogen at 100 bar which is 312 m³ of hydrogen energy storage.

The net present cost of this equipment combination is $301 million dollars. The net present cost of purchasing electricity from the grid over the project duration is $695 million dollars. Installation of the optimum sized wind solar farm with hydrogen energy storage results in savings of $394 million dollars over the duration of the project. This represents a 56.7% reduction in cost versus the electricity supplied from the grid when the cost of grid purchased electricity is doubled.

The cost of wind and solar with hydrogen energy storage versus the cost of wind and solar alone will now be compared when the cost of grid purchased electricity is doubled for both cases. The least net present cost option investigated with hydrogen energy storage combined with wind and solar costs is $1.31 million dollars less than the least net present cost of wind and solar alone, an improvement of less than 1%. The least net present cost of wind and solar with hydrogen storage is essentially equal to the net present cost of wind and solar alone. These results tell us that the installation of a hydrogen storage system is still not a significantly economically attractive option versus wind and solar alone when the cost of grid purchased electricity is doubled. Additionally, doubling the cost of grid purchased electricity did not help to justify any additional solar or wind capacity versus wind and solar alone. However, doubling the grid electricity prices did result in the least cost configuration with a larger regenerative cell capacity, an increase in 1.57 MW of fuel cell rating versus the base case. The increased electricity prices also resulted in a least cost configuration with a larger compressed hydrogen storage vessel versus the base case.

Figure 4.53 and Figure 4.54 show the net present cost surface plot for the combination of solar equipment capacity, wind turbine capacity and regenerative cell size, indicated with the fuel cell capacity, for the case where grid purchased electricity is doubled. The minimum cost fuel cell nameplate capacity of 3 MW is small compared to the minimum cost nameplate capacities of wind and solar. As a result, the addition of fuel cells does not make a large impact on the minimum net present cost versus the least net present cost configuration using wind and solar alone. In Figure 4.53 and Figure 4.54 the cost of a storage tank capable of storing 2.6 metric tons of hydrogen is included for all wind, solar and fuel cell combinations. The least cost sized regenerative cells did not help to justify any additional solar or wind capacity versus the case where wind and solar alone are considered and the cost of grid electricity is doubled.
Figure 4.52: The yearly net present cost for a range of wind and solar farm sizes with 3 MW of regenerative cells fuel cell rating, and 2.6 metric tons of compressed hydrogen storage serving 25,000 homes in Rio Vista, California. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m$^3$, and the capital cost for the regenerative cells is $703$ per kW of electrolyzer stack rating.

The left pie chart of Figure 4.55 illustrates that 2% of the load is served with energy from regenerative cells. The fuel cells meet very little load in this configuration because the fuel cell size is small compared to the size rating of the power generation equipment. In the least cost configuration, 22% of the demand is served by grid purchased electricity. The right pie chart indicates that 24% of the demand was supplied by grid purchased electricity with wind and solar alone when the cost of grid electricity is doubled. Adding a hydrogen energy storage system only decreased the percentage of demand served by grid purchased electricity by 2% compared to wind and solar alone. The high cost of regenerative cells and compressed hydrogen storage tanks continue to drive the least cost scenario to have a hydrogen storage system that is too small to have a meaningful reduction in the amount of energy purchased from the grid, even when the cost of grid electricity is doubled.
Figure 4.53: The yearly net present cost for a range of wind, solar and regenerative cell size combinations serving 25,000 homes in Rio Vista, California with 2.6 metric tons of compressed hydrogen storage. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.

Figure 4.54: The lowest net present cost regenerative cell size for a range of wind and solar capacities serving 25,000 homes in Rio Vista, California with 2.6 metric tons of compressed hydrogen storage. The cost of electricity is $0.3506 per kWh, the capital cost of solar panels is $950 per kW, the capital cost of wind turbines is $1187.5 per kW, the capital cost of compressed hydrogen storage tanks is $4303 per m³, and the capital cost for the regenerative cells is $703 per kW of electrolyzer stack rating.
Figure 4.55: Electricity costs doubled comparison of percent load served by solar and wind generation, fuel cell and grid purchased power for the following scenarios: least cost configuration (left), largest sized wind, solar and fuel cell investigated (center), and least cost configuration without storage (right). The compressed hydrogen storage tanks hold 2.6 metric tons of hydrogen at 100 bar. The cost of electricity is $0.3506 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.52, Figure 4.53, and Figure 4.54.

Figure 4.56: Electricity costs doubled comparison of percent energy sent directly to load, to electrolyzers, and wasted as excess for the following scenarios: least cost configuration (left), largest sized wind solar and fuel cell investigated (center) and least cost configuration without storage (right). The compressed hydrogen storage tanks hold 2.6 metric tons of hydrogen at 100 bar. The cost of electricity is $0.3506 per kWh. The least cost configuration (left) provides the lowest cost of electricity as shown in Figure 4.52, Figure 4.53, and Figure 4.54.

Figure 4.56 indicates that 37% of the electricity generated by wind and solar was wasted as excess, 6% was sent to the electrolyzer system and 57% of the electricity was used directly by the load in the least cost configuration. In the least cost configuration with wind and solar alone,
43% of the electricity generated by wind and solar was wasted as excess and 57% was used by the load. The electrolyzer system reduces the amount of wasted energy by 6%.

![Graph showing electricity cost doubled, hourly tank pressure for the least cost configuration for solar, wind and regenerative cells. The compressed hydrogen storage tanks hold 2.6 metric tons of hydrogen at 100 bar. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.52, Figure 4.53, and Figure 4.54.]

Figure 4.57: Electricity cost doubled, hourly tank pressure for the least cost configuration for solar, wind and regenerative cells. The compressed hydrogen storage tanks hold 2.6 metric tons of hydrogen at 100 bar. This least cost configuration provides the lowest cost of electricity as shown in Figure 4.52, Figure 4.53, and Figure 4.54.

An hourly plot of the tank pressure over the year resulting from the least net present cost equipment configuration is shown in Figure 4.57. This figure shows that the tank only cycles from full to empty occasionally throughout the year. The tank reaches maximum pressure earlier in the year than in the base case described in Subsection 4.4.2. This is because there is more excess energy generated by the wind and solar equipment that have larger size ratings than in the base case. The sizes of the regenerative cells and tank have also increased versus the base case. In the late spring through early fall months, the tank seldom discharges fully. In the late fall, and winter the tank usually partially fills before discharging again. The high cost of regenerative cells forced the least cost scenario to have a regenerative cell capacity that is too small to fill and empty the tank frequently.
4.4.7. Summary

Table 4.5 summarizes the results of Section 4.4 where hydrogen energy storage is combined with wind and solar. For comparison purposes, the results of Section 4.2, where wind and solar alone were investigated, are also included in the table.

A strong economic case cannot be made for hydrogen energy storage with wind and solar compared to wind and solar alone for Rio Vista, California. This is true even when the cost of cells is reduced to zero or when the cost of compressed hydrogen storage is reduced to zero. The addition of hydrogen energy storage at base costs resulted in a least net present cost increase of 0.42% compared to the least net present cost of wind and solar alone. When compared to the least net present cost of wind and solar alone, the addition of hydrogen energy storage resulted in net present cost savings of 0.08%, 2.50% and 4.10% for reduced cost cells, base cost cells with zero cost compressed hydrogen storage, and zero cost cells with base cost hydrogen storage, respectively. When the cost of electricity was doubled, the net present cost of hydrogen energy storage combined with wind and solar was 0.43% less than wind and solar alone for the least net present cost configurations. In the future, reductions in cell costs and/or increases in grid electricity prices beyond those investigated in this work would be needed to make a strong economic case for the inclusion of hydrogen energy storage with wind and solar installations. Improvements in the efficiency of the hydrogen energy storage system would also have a positive impact.

The impact of including hydrogen energy storage on the least cost wind and solar equipment sizes is considered, as was done with batteries in Section 4.3.5. In most of the cases considered, the addition of a hydrogen energy storage system did not change the least cost sized capacities of wind and solar equipment compared to the least net present cost capacities of wind and solar alone. The first exception was the case with compressed hydrogen storage at zero cost with base cost cells. This case resulted in a least net present cost configuration that justified an additional 12 MW of wind capacity and an additional 3 MW of solar capacity compared to the least cost configuration of wind and solar alone. The second exception was the case with zero cost cells. This case resulted in a least net present cost configuration that justified an additional 9 MW of solar. The fuel cell sizes for all cases, except in the case with zero cost cells, were quite small compared to the mean load and the wind and solar nameplate capacities.
Table 4.5: Summary of results for hydrogen energy storage.

<table>
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<tr>
<th></th>
<th>Wind and Solar without Energy Storage</th>
<th>Full Cost Tanks and Cells</th>
<th>Cell Cost Decreased by 50%</th>
<th>Very Large $0 Tanks, Base Cost Cells</th>
<th>Cell Cost $0, Base Cost Tanks</th>
<th>Double Grid Price without Energy Storage</th>
<th>Double Grid Price, Full Cost Tanks, Cells</th>
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<td>Grid Electricity Purchase Price ($/kwh)</td>
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<td>Regenerative Cell Capital Cost ($/kW Electrolyzer Stack Capacity)</td>
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<td>Capital Cost of Tank Storage $/m³</td>
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<td>Wind Nameplate Capacity (MW)</td>
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<tr>
<td>Savings Compared to Wind and Solar without Energy Storage (Millions of Dollars)</td>
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<td>Savings Compared to 25 Years of Grid Purchased Electricity (Millions of Dollars)</td>
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<tr>
<td>Net Present Cost for 25 Years of Grid Purchased Electricity (Millions of Dollars)</td>
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4.5. Comparing Different Energy Storage Systems

Now that several cases of no energy storage, battery energy storage, and hydrogen energy storage have been investigated in combination with wind and solar, the results for these three types of energy storage can be compared. First, the relative capital and operation and maintenance costs of the three types of energy storage will be compared. Then, the results presented in the prior three sections of this chapter will be compared.

The capital costs and operation and maintenance costs are lower for batteries than for solid oxide regenerative cells. The capital cost of batteries is $500 per kW, and the capital cost of regenerative cells is $703 per kW of electrolyzer cell rating. The operation and maintenance cost of batteries is $5.30 per kW and the operation and maintenance cost of regenerative cells is $54.58 per kW of electrolyzer cell rating. Further, hydrogen systems require the additional capital and maintenance expense of compressed hydrogen tanks, while the battery system does not have separate storage costs beyond the cost of the batteries. However, hydrogen energy storage offers the flexibility to size the storage system and the energy conversion system separately. Of course, the cost of storage when there is no storage is zero dollars. The extra costs of the battery and hydrogen storage systems has to be made up relative to the no storage case by reducing the amount of electricity that is purchased from the grid by a large enough amount.

The round-trip efficiency of the modeled battery system is 84.6%. This is the energy sent to the load divided by the energy sent to the battery storage system from wind and solar generation systems. The modeled hydrogen energy storage system has a much lower efficiency of 21.5%. Major losses from the hydrogen energy storage system include heat generated by the fuel cell, fuel cell BOP losses, electrolyzer water heating from 289 K to 1073 K with electric resistance heating, electrolyzer BOP losses and power used to compress the hydrogen to tank pressure. It was assumed some of the electrolyzer water preheating was offset by cooling the hydrogen produced from the cell temperature to the storage temperature and the heat from the fuel cell could be used to preheat the fuel cell reactants. The BOP losses could be lowered if a convenient external heat source could be found to partially preheat the water sent to the electrolyzer, rather than using electricity from wind and solar facilities. However, the maximum theoretical efficiency of the fuel cell using hydrogen as a fuel operating at 1073 K is 66% relative to the higher heating value of the hydrogen [20]. Higher overall system efficiencies can be achieved by combining the fuel cells with a system
that uses the high temperature waste heat, such as a combined heat and power or a cogeneration system [20].

The base cases for wind and solar alone, wind and solar combined with battery energy storage and wind and solar combined with hydrogen energy storage all had similar least net present costs. However, the battery energy storage base case required the least amount of electricity to be purchased from the grid, compared to the least cost base configurations with hydrogen energy storage, or with wind and solar alone. The base case least cost sized fuel cell and hydrogen storage was so small, just 0.75 MW with a hydrogen tank sized to contain 1 metric ton of hydrogen at 100 bar, that less than 1% of the load was served by hydrogen energy storage. The least cost sized battery was larger, 25 MW/50MWh, so 5% of the load was served by the batteries in the base case. When the cost of batteries was reduced by 50%, the least net present cost sized batteries served 13% of the load. Least net present cost batteries served 12% of the load in the case where the cost of electricity was doubled.

In all cases considered with battery energy storage, more solar capacity was justified in the least net present cost equipment configuration compared to the least net present cost equipment configuration with wind and solar alone. The solar capacities were 6 to 17 MW larger than in the least cost wind and solar only cases. In all cases with battery energy storage, the least cost equipment configuration either had the same wind capacity or a reduced wind capacity versus the least cost equipment configuration with wind and solar alone. The resulting least cost battery capacities for all cases considered were suitable for short term energy storage and could serve the mean load for 2 to 6 hours.

The hydrogen energy storage base case did not increase the least cost wind or solar equipment sizes over the least net present cost equipment configuration with wind and solar alone. The only hydrogen energy storage cases that justified an increase in wind or solar equipment sizes were the most extreme cost cases investigated. The addition of hydrogen energy storage justified additional solar capacity in the case where the cost of the regenerative cells was zero, and compressed hydrogen storage was at base cost. For this case, an additional 9 MW of solar were justified versus the least cost equipment configuration of wind and solar alone. Increased wind and solar capacity were justified only in the case where compressed hydrogen storage had zero cost and regenerative cells were at base cost. For this case, an additional 12 MW of wind and 3 MW of solar were justified versus the least cost equipment configuration with wind and solar alone. For
the other cases considered, the least cost hydrogen storage systems were too small to have an impact on least cost equipment sizes. The resulting least cost equipment configurations served from less than 1% to 5% of the load with electricity from hydrogen energy storage.

In conclusion, a strong economic case cannot be made for battery or hydrogen energy storage in combination with wind and solar versus the least net present cost of wind and solar with no energy storage. However, for similar net present costs, the least cost combination with wind, solar and battery energy storage serves more load than hydrogen energy storage in combination with wind and solar, and more load than wind and solar without energy storage. Battery energy storage combined with wind and solar, hydrogen energy storage with wind and solar and wind and solar without energy storage all solidly outperform the net present cost of purchasing energy from the grid for Rio Vista, California. Battery energy storage capital and operation and maintenance costs were lower than solid oxide regenerative cells before considering the additional expense of separate compressed hydrogen storage. The overall roundtrip efficiency of battery energy storage is much higher, 84.6%, than that of the modeled solid oxide regenerative cells with compressed hydrogen storage, 21.5%.
Chapter 5

Conclusions

5.1. Conclusions of This Work

The objective of this work is to study the cost of generating electric power by means of wind turbines and solar panels coupled to either battery energy storage or hydrogen energy storage. This work shows electricity generated by wind and solar without energy storage, wind and solar combined with battery energy storage, and wind and solar combined with hydrogen energy storage all solidly outperform purchasing all the electricity demand from the local grid. For similar net present costs, the least cost combination with wind, solar and battery energy storage serves more load than wind and solar without energy storage. However, a strong economic case cannot be made to justify adding battery energy storage or hydrogen energy storage to a wind and solar farm versus the wind and solar farm alone.

The net present cost of electric power generation by means of wind turbines and solar panels coupled to either battery energy storage or hydrogen energy storage serving the electricity needs of 25,000 homes in Rio Vista, California for 25 years at an interest rate of 10% is calculated. The customer’s electricity demand must be met for every hour of the year, ideally with minimal electricity purchases from the grid. The base condition for each type of energy storage was studied, along with alternative cost conditions which changed one input cost from the base case scenario. For the case of electricity generated with wind and solar with no energy storage, a base case was studied and the case where grid purchased electricity prices are doubled were studied. Wind and solar in combination with battery energy storage included the base case, a case where battery costs were reduced by 50% and a case where the grid purchased electricity prices were doubled. Wind and solar in combination with hydrogen energy storage included the base case, a case where solid oxide cell costs were reduced by 50%, a case with large, compressed hydrogen storage at no cost,
a case with zero cost regenerative solid oxide cells, and a case where the grid purchased electricity prices were doubled.

Generating electricity with the optimum configuration of wind and solar with or without energy storage has favorable economic results compared to purchasing all the electrical needs from the local grid. The base cost of supplying electricity entirely from the grid for 25 years is $348 million dollars. The least cost for the base cases of wind and solar alone, wind and solar with battery energy storage, and wind and solar combined with hydrogen energy storage are associated with costs savings of 40%, 41%, and 39%, respectively, versus the cost of purchasing grid electricity at the going rate. If the cost of grid electricity is doubled, the cost of supplying electricity entirely from the grid for 25 years is $695 million dollars and the economic case strengthens. The least cost configurations for wind and solar alone, for wind and solar with battery energy storage, and wind and solar with hydrogen energy storage result in 56%, 59%, and 57% cost savings, respectively, versus the price of grid electricity when it is doubled.

For similar net present costs, the least cost combination with wind, solar and battery energy storage serves more load than wind and solar without energy storage and with hydrogen energy storage. For the base case least cost configuration with batteries, 5% of the load is served with electricity from battery energy storage over the year. When the cost of batteries is reduced by 50%, the least net present cost sized batteries serve 13% of the load. Least net present cost batteries serve 12% of the load in the case where the cost of electricity is doubled. In the least cost hydrogen energy storage configurations considered, less than 1% to 5% of the load is served with electricity from hydrogen energy storage.

A strong economic case cannot be made to justify adding battery energy storage or hydrogen energy storage to a wind and solar facility. When compared to the net present cost of wind and solar alone the savings due to the addition of battery energy storage are 1.4% and 6.3% for base cost cells and 50% reduced cost cells, respectively. When the cost of electricity is doubled the net present cost savings due to the addition of battery energy storage is 6.8% versus wind and solar alone. The addition of hydrogen energy storage at base costs caused the least net present cost to increase 0.42% compared to the least net present cost of wind and solar alone. The net present cost savings due to the addition of hydrogen energy storage is 0.08%, 2.50% and 4.10 % for reduced cost cells, base cost cells with zero cost compressed hydrogen storage, and zero cost cells with base cost hydrogen storage, respectively, when compared to wind and solar alone. When the
cost of electricity is doubled, the net present cost savings due to the addition of hydrogen energy storage is 0.43% compared to wind and solar alone. Reductions in energy storage costs and/or increases in grid electricity prices beyond what were investigated in this work would be needed to make a strong economic case for the inclusion of battery or hydrogen energy storage with wind and solar installations in Rio Vista, California.

The lower efficiency of the hydrogen energy storage system is a disadvantage when compared to battery energy storage. The modeled roundtrip efficiency of battery energy storage in this work is much higher, 84.6%, than that of the modeled solid oxide regenerative cells with compressed hydrogen storage, 21.4%. Furthermore, battery energy storage capital and operation and maintenance costs were lower than solid oxide regenerative cells, even before considering the additional expense of separate compressed hydrogen storage. However, an advantage of hydrogen energy storage is that the tank capacity can be sized separately.

This work presents least cost equipment configurations for each energy storage technology and for wind and solar alone. Battery energy storage helps to justify more solar capacity in all cases considered. The least cost equipment configurations with battery energy storage had solar capacities that were 6 to 17 MW larger than in the least cost wind and solar only cases. The wind capacities stay the same or are reduced versus the least cost equipment configuration with wind and solar alone. The optimum least cost battery capacities for all cases considered are suitable for short term energy storage and could serve the mean load for 2 to 6 hours. This work shows that battery energy storage is a good partner for solar in this location because energy can be stored in batteries during the day for later use in the evening, offsetting some energy purchases from the grid. Thus, a storage capacity that can serve several hours of load is useful daily throughout the year when coupled with increased solar capacity.

The addition of a hydrogen energy storage system does not change the least cost sized capacities of wind and solar equipment compared to the least net present cost capacities of wind and solar alone, except for the extreme cases where zero cost cells or zero cost compressed hydrogen storage are considered. The case with compressed hydrogen storage at zero cost with base cost cells results in a least net present cost configuration that justified an additional 12 MW of wind capacity and an additional 3 MW of solar capacity compared to the least cost configuration of wind and solar alone. The case with zero cost cells results in a least net present cost configuration that justifies an additional 9 MW of solar.
5.2. Recommendations for Future Research

For the current work, the cost of electricity supplied by the grid is assumed to be constant. A better understanding of the economic implications of energy storage could be gained by studying electricity generated with wind and/or solar combined with battery or hydrogen energy storage with variable electricity prices. Depending on the rate structure of the local utility, the time of use of the electricity impacts the price. For example, during times of peak energy use or low electricity supply, usually midday to early evening, the price is higher. During times of low electricity demand or excess electricity supply, the price is lower. Electricity demand and prices also vary seasonally. Further energy storage research could be conducted considering the impacts of energy arbitrage. That is, charging the energy storage system using low value electricity from the grid to be sold at times where the cost of power is higher. Commercial customers are at times subject to demand charges, which are fees assessed to the customer based on the highest peak demand during the billing cycle, averaged over a short period such as 15 minutes. Demand charge management is not addressed in the present work and would be an interesting factor to include.

In the present work the solar, wind, battery energy storage, and hydrogen energy storage models were applied in one location, Rio Vista, California, which has good wind and solar resources. To better understand the implications of this work, further study could be carried out for locations with excellent solar resources and poor wind resources in combination with battery energy storage. The model could also be extended to cover multiple locations. For example, the model could be applied to multiple potential sites to find the least net present cost equipment combinations and locations of solar, wind, and energy storage for a larger geographic area, such as a state.

The lower round-trip efficiency of hydrogen energy storage is noted as a disadvantage of this technology. The round-trip efficiency for reversible solid oxide cells could be improved if a source of waste heat provided some of the energy needed for electrolysis, such as in a combined heat and power or cogeneration system, rather than supplying heat with electrical resistance heating powered by the wind and solar farm as is done in this work. However, the requirement for waste heat would require the solid oxide cells to be co-located with the heat source. Further research is needed to determine if these efficiency improvements would yield an economically
attractive configuration that produces hydrogen utilizing electricity generated from renewable energy sources.
References


