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Light Water Reactor Sustainability Program

Comparison of Energy Storage and Arbitrage Options for Nuclear Power

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EXECUTIVE SUMMARY

Nuclear power is the most reliable source of clean energy and plays a crucial role in decarbonization efforts and national energy security. Achievement of Net-Zero targets depends on the deployment of new Nuclear Power Plants (NPPs) – both advanced reactors and large-scale Light-Water Reactors (LWRs) – as well as continued operations at existing LWR plants. The Light-Water Reactor Sustainability (LWRS) Program seeks to extend the lifetime of existing LWR NPPs and improve their economic performance through research into plant modernization, Flexible Plant Operation and Generation (FPOG) (including techno-economic evaluations of hybrid generation options such as energy storage, coupling with industry, etc), risk-informed systems analysis, materials research, and physical security.

The FPOG pathway investigates the techno-economics of hybrid generation options such as energy storage and arbitrage and innovative coupling of LWR heat and electricity with industry applications to create alternative revenue streams and profitability paradigm shifts for LWRs. The topic of this current analysis is energy arbitrage, which is the storing of energy when electricity prices are driven low by diurnal cycles influenced by demand and periodic oversupply of renewable energy and the subsequent release of this energy at an opportune time when energy demand, and therefore the wholesale price of electricity, is higher as electricity onto the grid or to make value-added products. The energy can be stored chemically, electrically, or thermally, and used to regenerate electricity at a later time. The purpose of this report is to compare and rank energy storage technologies that can store energy from an LWR for a wide spectrum of storage durations. For the purposes of this report 500 MWe-AC of discharge capacity was chosen as the capacity upon which all of the energy storage options are compared. The options herein evaluated include:

- Utility-Scale Lithium-ion Batteries
  - Lithium iron phosphate (LFP) and
  - Nickel molybdenum cobalt (NMC)
- Power to Hydrogen to Power:
  - High Temperature Steam Electrolysis (HTSE) + H_2 Combustion Turbine
  - Reversible Solid Oxide Cells (rSOC)
  - HTSE + Solid Oxide Fuel Cells
- Thermal Energy Storage
  - Electro-Thermal Energy Storage (ETES)
  - Liquid Based Sensible Heat Thermal Energy Storage (SH-TES).

Figure ES 1 displays the Levelized Cost of Storage (LCOS) for two lithium-ion battery chemistries (Section 2), three hydrogen systems (Section 3), and two TES systems (Section 0) for durations up to one week, with an inset axis providing more detail for daily storage. As a general trend, the LCOS decreases as the storage duration increases, to a point, where it provides better utilization of the capital investment. Hydrogen and thermal systems tend to stay relatively affordable as the storage duration increases, as the cost of additional storage tanks is small compared to the overall system, though the maximum possible throughput stays constant. Conversely, the LCOS increases for long-duration storage lithium-ion batteries, as it requires purchasing more storage blocks which means a significant increase to the cost of the project.

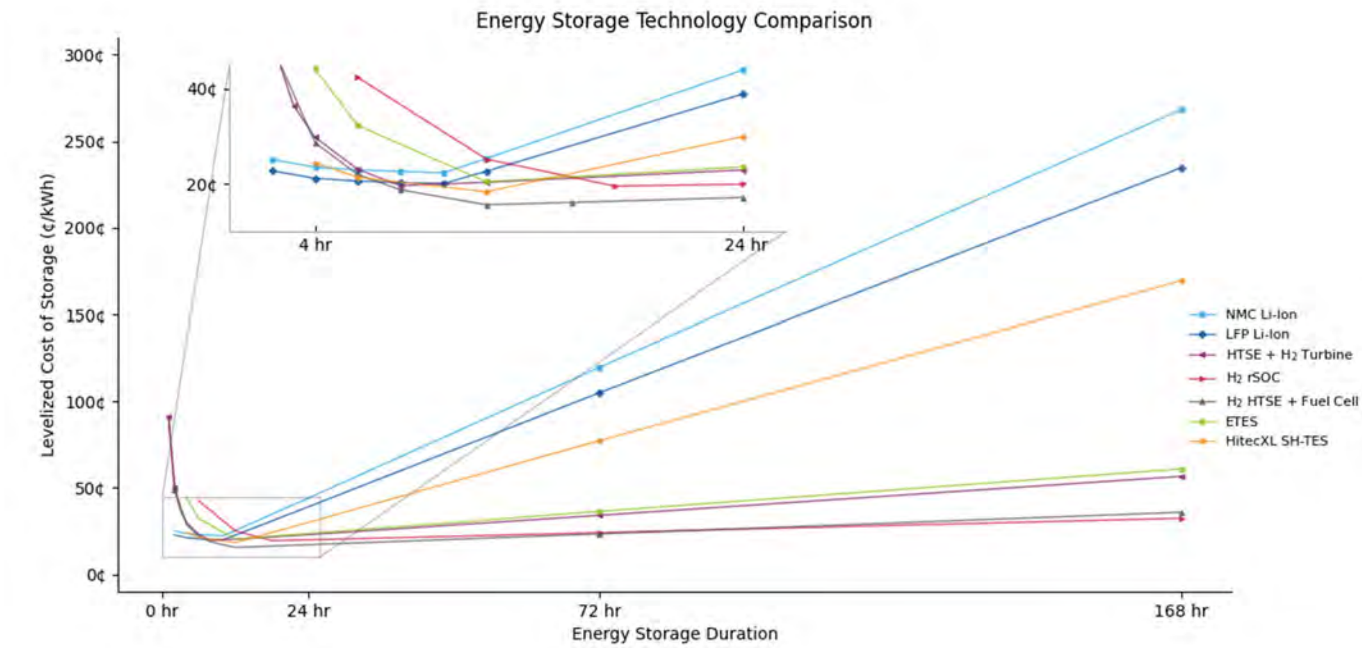

Figure ES 1.: Comparison of LCOS for different energy storage technologies.

The following is a summary of the high-level conclusions of this analysis and energy storage technology comparison.

- NMC & LFP Li-ion batteries have the lowest LCOS from 0 to 6 hours of energy storage duration., after which the hydrogen systems such as the HTSE + fuel cell system begin to be competitive.
- The HTSE + H_2 Fuel Cell system has the lowest LCOS for long-term energy storage duration starting at greater than 7 hours.
- SH-TES performs better than all other technologies except for the HTSE + H_2 fuel cell system from about 9 to 15 hours of energy storage durations. The H_2 rSOC has the lowest LCOS from 16 hours upward except for the HTSE + H_2 Fuel cell system.
- For any storage duration longer than the optimal value for a given technology, the power equipment *(e.g.* rectifiers/inverters and transformers, fuel cells, turbines, and other equipment whose price can be defined in $/kW-e) utilization plateaus, as the number of possible charge/discharge cycles reduces proportionally to the length of the cycle.
- Longer-duration storage requires more storage equipment, including individual battery cells, storage tanks, sensible heat storage media, and hydrogen tube trailers, whose price is defined in $/kWh-e. This raises the total capital investment required for the project and therefore the LCOS, as the same total amount of energy can be discharged.
- Lithium-ion battery storage systems, which offer the most cost-effective form of grid-scale energy storage for durations shorter than 6 hours, require more batteries to be purchased to facilitate long-duration storage. This results in the technology scaling poorly for durations longer than 10-12 hours.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

AC	Alternating-Current
APEA	Aspen Process Economic Analyzer
CAPEX	Capital Expenditures
CEPCI	Chemical Engineering Plant Cost Index
DC	Direct-Current
DoD	Depth-of-Discharge
EDR	Exchanger Design and Rating
ESS	Energy Storage System
ETES	Electro-Thermal Energy Storage
FC	Fuel Cell
FPOG	Flexible Plant Operation and Generation
HTSE	High Temperature Steam Electrolysis
INL	Idaho National Laboratory
LCOH	Levelized Cost of Hydrogen
LCOS	Levelized Cost of Storage
LFP	Lithium Iron Phosphate
LHV	Lower Heating Value
LTE	Low-Temperature Electrolysis
LWR	Light-Water Reactor
LWRS	Light-Water Reactor Sustainability
NMC	Nickel Molybdenum Cobalt
NPP	Nuclear Power Plant
O&M	Operation and Maintenance
PNNL	Pacific Northwest National Laboratory
rSOC	Reversible Solid Oxide Cell
RTE	Round Trip Efficiency
SH	Sensible Heat
SOC	Solid Oxide Cell
TES	Thermal Energy Storage
WACC	Weighted Average Cost of Capital

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Comparison of Energy Storage and Arbitrage Options for Nuclear Power

1 INTRODUCTION

Nuclear Power Plants (NPPs) primarily supply baseload power. With increasing grid penetration from intermittent energy sources (namely solar and wind), interest among NPP owners has increased in energy storage and arbitrage options. When a mismatch between electricity demand and generation from renewable sources creates a market with very low wholesale electricity prices, baseload providers can lose money by putting power on the grid; unplanned market-driven shutdowns are even more costly. The purpose of this report is to investigate the relative economics of various utility-scale energy storage technologies that could be coupled with nuclear power to allow NPP operators to take advantage of inexpensive electricity prices to transfer electrical energy into storage for energy arbitrage. Later, when electricity exceeds the sum of baseload and renewable generation capability, the stored energy can be converted back to electricity which can be sold at peak rates. Such systems can also increase the total guaranteed power delivery capability of the NPP, which could be sold at a premium in the carbon-free commercial and industrial energy markets. An investment in a cost-effective energy storage technology could allow an NPP to increase profits in an evolving energy sector. For the purposes of this report, all of the energy storage technologies analyzed are set to a capacity of 500 MWe discharge capacity unless otherwise specified.

Previously, INL has studied energy arbitrage to compare different energy storage charging and discharging options [1]. The current research in this report extends the previous research by updating assumptions and costs as well as including new energy storage technologies for evaluation. The following is a list of notable updates::

- Utility-scale lithium-ion batteries. This report leverages a recent study by interpolating results to provide a cost estimate for 500 MWe systems of varying storage durations;
- Hydrogen is produced by High Temperature Steam Electrolysis (HTSE). Electricity is regenerated by:
    - Recuperated simple cycle hydrogen combustion turbine— A new process model was developed in Aspen HYSYS, and ground-up LCOS calculations were performed;
    - Reversible solid oxide cell— A previous process model was modified to improve the hydrogen recycle system. Capital investment was assumed to be mostly taken up by the HTSE system, with a small cost adder considered to make the balance-of-plant reversible;
    - Hydrogen fuel cells— Coupled with HTSE hydrogen producing system, hydrogen SOC fuel cells were evaluated.
- Thermal Energy Storage (TES) including Electro-Thermal Energy Storage (ETES) and Liquid-based Sensible Heat Thermal Energy Storage (SH-TES)
    - The installed costs for ETES and SH-TES are updated from $2018 to $2022 for accurate comparison with the other technologies;
    - The unit costs for the four different storage media (Hitec, Hitec XL, Therminol-66, and Dowtherm A) of SH-TES are updated with the most recent research data;
    - Simplified LCOS estimation is performed to compare the results with the other energy storage options.

Two key figures of merit are used for comparison of the energy storage technologies: Round-trip Efficiency (RTE), which quantifies the percentage of stored electricity that can be regenerated by the specific energy storage technology and LCOS, which is the average price (in ¢/kWh) that regenerated electricity must be sold at for the project to break even. For hydrogen systems, the Levelized Cost of

Hydrogen (LCOH) is used as an intermediate calculation that has a strong impact on the variable Operation and Maintenance (O&M) contribution to the LCOS.

When discussing levelized costs in the context of this report, a simplified levelized cost estimation approach was used. To illustrate this, the mathematical derivation of simplified LCOS is shown in Equation (1).

$$LCOS_i = \sum_t^T \frac{(CapEx_{i,t} + VarO\&M_{i,t} + FixO\&M_{i,t})DF_t}{Qty_{i,t}DF_t} \qquad \text{Equation (1)}$$

where:

- i represents a given storage technology,
- t represents a given year,
- $LCOS_i$ represents the levelized cost of storage in \$/kWh-e,
- $CapEx_i$ represents total capital costs in dollars, including upfront power equipment and storage equipment and replacement of consumable equipment. The CAPEX for each storage technology is described in Sections 2, 3, and 0.
- $VarO\&M_i$ represents variable operating and maintenance (O&M) in dollars,
- $FixO\&M_i$ represents fixed operating and maintenance (O&M) in dollars,
- Qty_i represents the maximum quantity of stored electrical power available for discharge in kWh-e,
- DF_t represents the discount factor, which was held constant across technologies.

DF_t is calculated as shown in Equation (2).

$$DF_t = \frac{1}{(1 + WACC)^t} \qquad \text{Equation (2)}$$

where:

- t represents a given year,
- DF_t represents the discount factor,
- $WACC$ represents the weighted average cost of capital, which was held constant across technologies, resulting in DF_t also being constant across technologies.

In this instance, the LCOS calculated in Equation (1) is referred to as simplified because it does not account for additional costs such as taxes associated with income and impacts to taxable income from additional factors like interest from debt and depreciation of capital assets. A more in-depth LCOS could be calculated by generating complete discounted cashflow models that factor in projected sales price, depreciation, taxes, interest, etc. However, for the purposes of this analysis, a levelized comparison metric that could be used equally to compare each of the energy storage technologies against one another was deemed sufficient.

2 UTILITY SCALE BATTERIES

Batteries are arguably the simplest means of grid-scale energy storage. Electricity is converted to chemical potential through an electrochemical reaction that is reversed when the battery is discharged. In Figure 1 Alternating-Current (AC) electricity from the power plant may be rectified to DC power and stored in the battery during periods of low demand. Later, when the demand for electricity increases, the batteries release Direct-Current (DC) electricity which is inverted to AC power and put on the grid. There are of course some losses associated with the rectification and inversion conversion of the electrical power, as well as the step-up/step-down transformers. Each stage was assumed to have a 99% efficiency, resulting in a 4% loss on top of the ~86% DC-DC RTE of the battery itself.

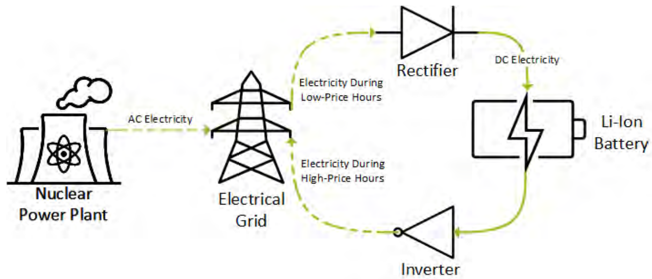

Figure 1. Lithium-ion battery energy storage schematic.

Pacific Northwest National Laboratory (PNNL) conducted a technology cost study in 2022 on several energy storage technologies, including two different lithium-ion battery chemistries, Nickel Molybdenum Cobalt (NMC) and Lithium Iron Phosphate (LFP) [2]. The dataset was published with discharge rates of 1, 10, 100, and 1000 MW-e and storage durations of 2, 4, 6, 8, 10, 24, and 100 hours, providing costs for storage block, balance of system, and construction in $/kWh, and power equipment, grid integration, and fixed O&M in $/kW [3]. These figures were scaled and interpolated to obtain cost estimates for 500 MWe systems, presented in Table 1.

Table 1. 500 MWe Lithium-Ion Battery Grid Storage System Cost Breakdown.

Battery Chemistry	Lithium Iron Phosphate (LFP)					Nickel Molybdenum Cobalt (NMC)				
Storage Duration (hr)	4	8	24	72	168	4	8	24	72	168
Storage Block ($/kWh)	$160	$158	$154	$151	$148	$188	$185	$181	$177	$174
Installed Equipment ($/kWh)	$369	$348	$330	$318	$312	$415	$395	$375	$362	$355
Fixed O&M ($/kW)	$4.06	$7.31	$20.08	$55.32	$119	$4.53	$8.24	$22.77	$63.15	$136
LCOS (¢/kWh)	21.1¢	20.2¢	38.9¢	$1.04	$2.34	23.5¢	22.6¢	44.0¢	$1.19	$2.68

The PNNL report demonstrates that LFP batteries are more cost-effective than NMC, while also being effective for more charge-discharge cycles [2]. Both chemistries produce an AC-to-AC RTE (which aggregates the Coulomb efficiency of the battery with the energy losses in the transformers, rectifier, and inverter) of 83%. The LCOS reported in Table 1 for LFP and NMC utility battery installations was calculated in the following section.

2.1 Levelized Cost of Storage

The data in Table 1 was used along with the following project schedule and assumptions to calculate the LCOS for lithium-ion batteries:

- 25-year project lifetime defined by the PNNL study [2];
  - Full investment in year 0;
  - 30% availability in year 1, 100% availability in years 2-20, 50% availability in years 21-24;
  - 80% Depth-of-Discharge (DoD) in years 1-6, 60% in years 7-24;
  - Half of the cells replaced in years 7, 12, and 16; and
  - Decommissioning in year 25;

- Charging price of 3¢/kWh, which is consistent with previous work [1]; and
- Equivalent maximum of 100% DoD per day as required by the battery warranty [2], with charge/discharge/rest cycle being considered for longer duration storage;
- WACC of 12%, which was selected in consultation with an economist familiar with utility investments.

Figure 2 displays the LCOS for LFP lithium-ion battery systems from 1 to 12GWh-e (2 to 24 hours at 500 MW-e), broken down to illustrate the contribution to the LCOS from initial capital investment, replacement of battery cells, and fixed and variable O&M. The LCOS is driven by capital expenditure, both as an initial investment and augmentation. As expected, capacity utilization is a large contributor to storage system profitability. The LCOS is therefore minimized when utilization is maximized, where the batteries store 8 to 10 hours of full power discharge. For storage durations shorter than optimal, the LCOS is higher than the minimum value. This is because of the warranty, which only allows the equivalent of one full DoD cycle per day; the batteries are not utilized fully. More total throughput is possible during the optimal storage duration. The LCOS increases after this point as more batteries need to be purchased, but the maximum amount of time when power is discharged remains the same at ~50% during the life of the project.

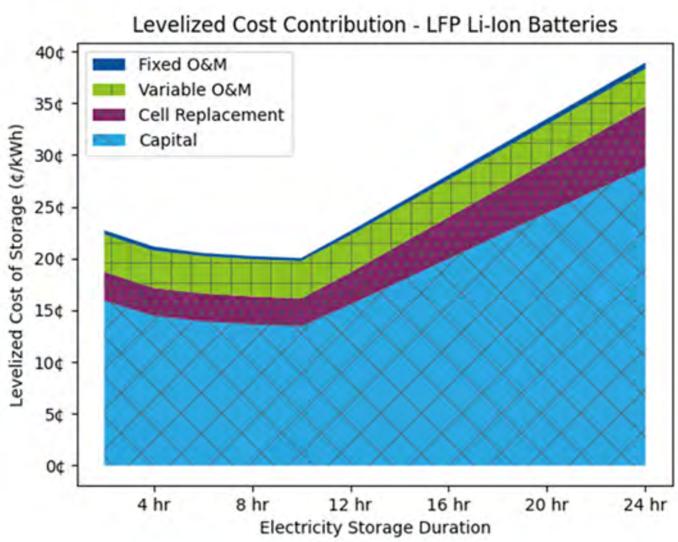

Figure 2. LCOS breakdown for 500 MW-e Grid Storage LFP lithium-ion batteries from 1 to 12 GWe-hr (1 to 24 hr of storage).

2.2 Sensitivity Analysis

Cost drivers were identified and varied to illustrate the effect that changes to technological and market parameters have on the LCOS for 500 MW-e of lithium-ion battery storage. For this analysis, a 500 MWe discharge LFP system with 8 hours of discharge capacity was used as the baseline. The findings of this sensitivity analysis are portrayed in a tornado chart (Figure 3). The blue and green bars depict the impact of adjusting sensitivity parameters, with key metrics that have the most significant effect being plotted at the top of the chart. Considering that the LCOS is heavily driven by capital investment and utilization of depreciable assets, it is expected that capital investment and capacity factor are among the leading cost drivers. The capacity factor is the percentage of total possible operation that the system is operated. The charging price is the cost of electricity at the time of storage. The project lifetime is the amount of time from construction to decommissioning. The storage capacity is the discharge rate (power at which stored energy can be put onto the grid) times the storage duration. The depth-of-discharge (DoD) is the percentage of total storage capacity discharged per cycle.

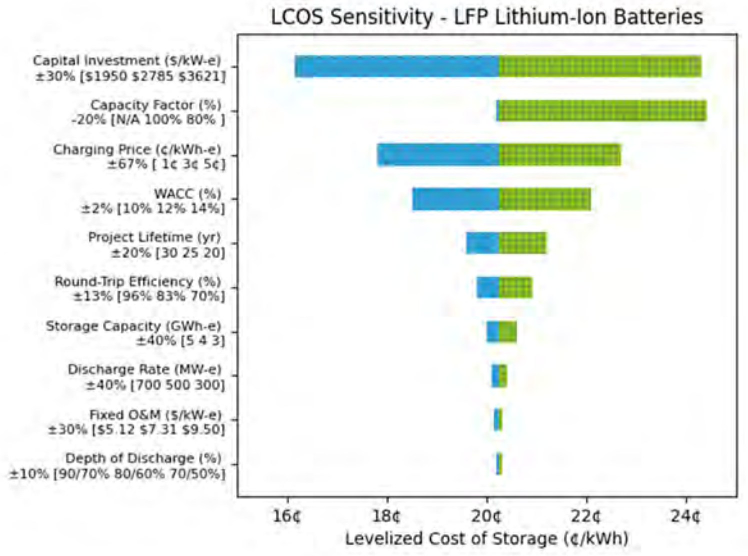

Figure 3. Tornado chart displaying sensitivity of LCOS to cost drivers for LFP lithium-ion batteries.

Per Figure 3, the following adjustments were made to cost drivers to complete the sensitivity analysis:

- 30% increase/decrease in capital investment to account for variability and potential inaccuracies in the cost analysis performed by the PNNL study [3]. ±30% was selected to cover an uncertainty range of approximately 100% centered on the cost estimates provided in the literature;
- 20% decrease in capacity factor to consider that demand patterns may not permit full utilization of ESS (Energy Storage System) equipment and was assumed with the goal of providing a benchmark that may be extrapolated upon in future studies;
- 2¢/kWh increase/decrease in electricity charging price;
- 2% increase/decrease in WACC to investigate the effect of different market futures and risk tolerance;
- 5-year extension/abridgment to the project lifetime with corresponding changes to the cell replacement schedule. This is roughly equivalent to one additional (or one less) battery cell replacement. The project lifetime will most likely be determined by the expected lifespan of the specific electrical substation equipment purchased, which is typically in the range of 20 to 30 years;
- 13% increase to the RTE to assume a maximum of 100% Coulombic efficiency (only considering inefficiency from transformers and converters), and a corresponding decrease;
- 1 Gwe-hr increase/decrease in total storage capacity to study the impact of increasing/decreasing the storage duration by 2 hours. This is a design parameter that can be adjusted to optimize the system size;
- 200 MWe increase/decrease in output capability. Future studies may optimize the percentage of the NPP's power output that can be stored by analyzing grid electrical price patterns. A range from approximately 30% to 70% of the output provides a wide range that can inform more detailed analysis;
- 30% increase/decrease in fixed O&M costs, account for variability and potential inaccuracies in the cost analysis performed by the PNNL study [3];

- 10% increase/decrease in-DoD. This is primarily a manufacturer specification, although grid patterns may intermittently drive actual operation towards shorter DoD.

3 HYDROGEN FOR ENERGY STORAGE

As an alternative to battery storage, three hydrogen energy storage technologies coupled with nuclear power were investigated. When the price of energy is low, electricity and heat from the NPP can be diverted to produce hydrogen via high temperature steam electrolysis (HTSE) (Section 3.1) which is compressed and stored in gaseous tube trailers (Section 3.2). Later, when the price of energy rebounds, the stored hydrogen could be consumed in a combustion turbine (Section 3.3), fuel cell (Section 3.5), or reversible solid oxide cell (Section 3.4) to produce electricity to put back on the grid.

3.1 High Temperature Steam Electrolysis Hydrogen Production

HTSE is a technology for producing hydrogen from water. Compared to low-temperature electrolysis (LTE), HTSE has the advantages of higher efficiency and zero catalyst requirements due to the higher operating temperatures. Nuclear power can provide a large portion of the thermal energy required to heat and vaporize the water for the reaction as well as provide the electricity for the electrolysis. Other reports have extensively reported on the cost analysis and benefits of HTSE integrated with nuclear power [1, 4, 5]. Equation (3) is the overall reaction. Energy (ΔH_r) must be added to drive the forward reaction, and because water has very low chemical potential, free electrons are needed to reduce the hydrogen into diatomic gas. Hydrogen is an attractive candidate for energy storage due to the reversibility of this reaction.

$$2H_2O_{(g)} + \Delta H_r \overset{4e^-}{\longleftrightarrow} 2H_{2(g)} + O_{2(g)} \qquad \text{Equation (3)}$$

3.1.1 Electrolysis Cell

Figure 4 depicts how superheated steam at 790°C and 1 atm is electrolyzed to produce oxygen and hydrogen gas. Free electrons reduce the water molecule to diatomic hydrogen at the cathode, producing oxygen anions, which are transported across a solid oxide electrolyte by the voltage between the cathode and anode. The anions re-combine to form diatomic oxygen, liberating the free electrons at a lower electric potential. Solid oxide electrolysis stacks (not including the necessary balance-of-plant – BOP) were estimated to cost $89.90/kW-e DC by escalating the unit price listed in a literature source [5] according to the Chemical Engineering Plant Cost Index (CEPCI) [6].

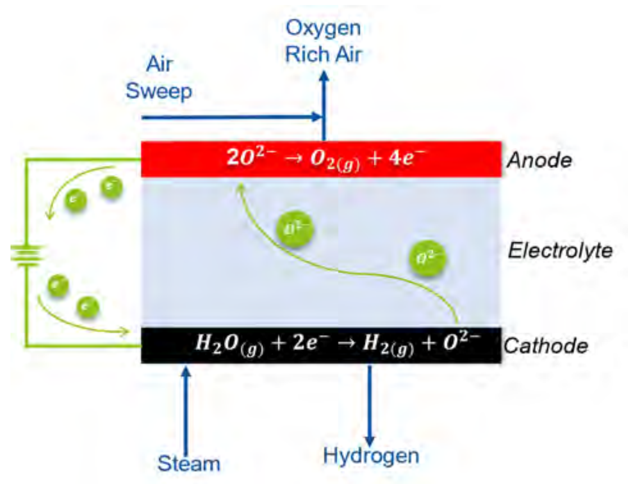

Figure 4. Hydrogen by HTSE Schematic.

3.1.2 Balance-of-Plant

Vaporizing and superheating steam to such high temperatures is energy-intensive. In previous work, a model was developed in Aspen HYSYS [5, 1, 4] to optimize recuperation and utilization of nuclear process heat and minimize the electrical trim heating duty. The model was modified to fit the parameters of this project. A screenshot of the modified model is included in Figure 5.

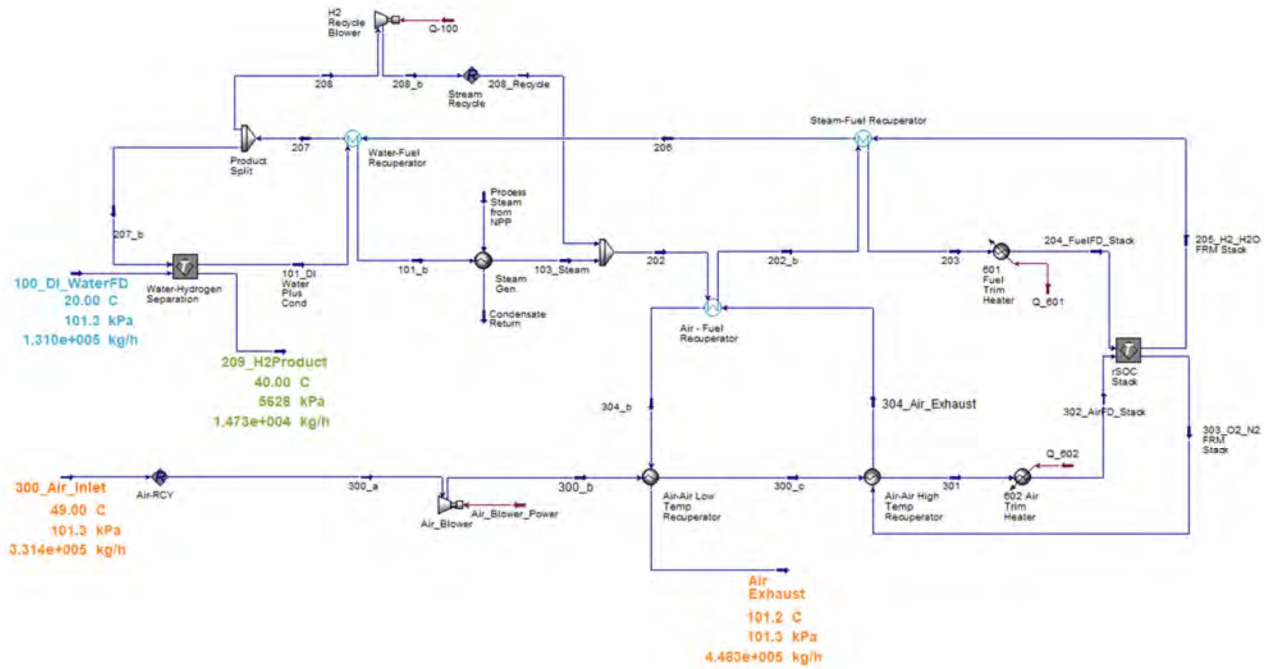

Figure 5. HTSE Balance-of-Plant HYSYS Model.

The Water-Hydrogen Separation flowsheet shown on the left side of the flowsheet contains within it three knockout vessels and two 2-stage compressors with each stage having a compression ratio of 2.8, producing a 56.28 bar, 20°C hydrogen product with 0.05 mol% moisture content (99.95% purity H_2). The appendices contains complete stream tables and process flow diagrams of the sub-flowsheets. A subset of these stream flows are highlighted in Table 2.

Table 2. Selected HTSE stream flows

Stream	Component	Flow (kgmole/hr)
Balance-of-Plant		
100_DI_WaterFD		7274
300_Air_Inlet		11,488
	Nitrogen	*9075*
	Oxygen	*2412*
209_H2Product		7309
	Hydrogen	*7305*
	Water	*4*
AirExhaust		15,138
	Nitrogen	*9075*
	Oxygen	*6063*

Stream	Component	Flow (kgmole/hr)
Electrolysis Stack		
204_FuelFD_Stack		9535
	Hydrogen	945
	Water	8590
302_AirFD_Stack		11,488
	Nitrogen	*9075*
	Oxygen	*2412*
204_FuelFD_Stack		9535
	Hydrogen	8247
	Water	1288
303_O2_N2		15138
	Nitrogen	*9075*
	Oxygen	6063

The model was used with Aspen Exchanger Design and Rating (EDR) to size the equipment and Aspen Process Economic Analyzer (APEA) to price out the balance-of-plant equipment and to calculate the utility consumption listed in Table 4.

Table 3. Uninstalled Equipment Costs for HTSE Balance-of-Plant.

Equipment	Cost Estimate ($MM)	Notes
Air-Air Low Temp Recuperator	17.03	0.1 Mass Flow Rate Ratio
Air-Air High Temp Recuperator	61.11	0.1 Mass Flow Rate Ratio
Air-Fuel Recuperator	34.14	0.1 Mass Flow Rate Ratio
Steam-Fuel Recuperator	20.02	0.1 Mass Flow Rate Ratio
Water-Fuel Recuperator	0.738	
Preheater 1	0.063	
Preheater 2	0.113	
Preheater 3	0.342	
Steam Generator	0.816	
Cooler 1	0.667	Air Cooler
Compressor 1 Intercooler	0.154	Air Cooler
Compressor 1 Aftercooler	0.121	Air Cooler
Compressor 2 Intercooler	0.093	Air Cooler
Compressor 2 Aftercooler	0.121	Air Cooler
H_2 Recycle Blower	0.064	Vaneaxial fan
Compressor 1 Stage 1	49.13	Centrifugal Gas Compressor
Compressor 1 Stage 2	22.25	Centrifugal Gas Compressor
Compressor 2 Stage 1	8.41	Centrifugal Gas Compressor
Compressor 2 Stage 1	3.65	Centrifugal Gas Compressor
Inlet Water Pump	0.026	Centrifugal Pump

Equipment	Cost Estimate ($MM)	Notes
Water Drain Pump	0.027	Centrifugal Pump
Air Blower	0.064	Vaneaxial Fan

Table 4. HTSE Utility Requirements.

	Utility Demand	Utility Price	Cost ($/kg-H2)
AC Electricity	607,806 kW	3¢/kWh-e	$1.238
DC to Electrolyzer	500,000 kW	-	-
AC to Rectifier	559,189 kW	-	-
Trim Heating	10,237 kW	-	-
Compression	38,381 kW	-	-
Steam from NPP	84,540 kW	1¢/kWh-th	5.7¢
Cooling Water	8,280 ton/hr	0.52¢/ton	0.3¢
Process Water	130,956 kg/hr	53¢/ton	0.4¢
Hydrogen Product	14,729 kg/hr	-	$1.303

3.1.3 Levelized Cost of Hydrogen

The model was used with Aspen Exchanger Design and Rating (EDR) to size the equipment and Aspen Process Economic Analyzer (APEA) to price out the balance-of-plant equipment and to calculate the utility consumption listed in Table 4.

Table 2. Selected HTSE stream flows

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	Oxygen	6063

The model was used with Aspen Exchanger Design and Rating (EDR) to size the equipment and Aspen Process Economic Analyzer (APEA) to price out the balance-of-plant equipment and to calculate the utility consumption listed in Table 4.

Table 3and Table 4 were used along with the following project schedule and assumptions to calculate the LCOH for a 500 MW-e DC system:

- 25-year project lifetime;
  - Full investment in year 0;
  - 30% availability in year 1, 100% availability beginning in year 2;
  - Stack lifetime of 4 active years;
  - 25% of stacks replaced per year when required;
  - Stack removal instead of replacement if lifespan ends in years 23-24; and
  - Decommissioning in year 25;
- WACC of 12%;
- Fixed O&M of $37.58/kW-e DC [5]; and
- Utility prices as follows [5];
  - Electricity price of 3¢/kWh;
  - Nuclear process heat price of 1¢/kWh;
  - Cooling water price of 0.53¢/ton;
  - Process water price of 53¢/ton.

Figure 6 displays the LCOH for a 500 MW-e DC HTSE system that is operated from 2 to 24 hours per day, broken down to illustrate the contribution to the LCOH from initial capital investment, replacement of electrolysis stacks, and fixed and variable O&M. The LCOH is minimized by maximizing utilization of the initial investment (i.e. producing hydrogen for as long as possible) and fixed O&M; although increased utilization requires more frequent stack replacement, this makes up a small contribution to the LCOH even at high utilization. Variable O&M contributes $1.30/kg to the LCOH for all case studies.

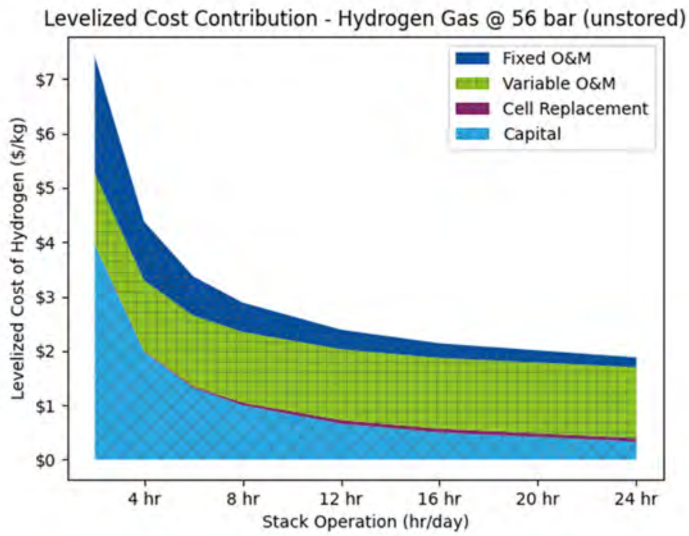

Figure 6. LCOH breakdown for 500 MWe HTSE producing un-stored H_2 gas at 56.28 bar and 20°C.

It is worth noting that, unlike an HTSE plant designed to produce H_2 as a product for industry, an energy arbitrage HTSE system is not intended to operate constantly. This can lead to an economic disadvantage due to the low-capacity factor and hence low capital utilization in some operating schemes. The maximum feasible capacity factor depends heavily on the method used to regenerate electricity from hydrogen. Reversible Solid Oxide Cell (rSOC) systems (discussed in Section 3.4) have faster kinetics in electrolysis mode than in fuel cell mode, so it takes 3-4 times as long to burn through a stock of hydrogen than it took to generate. Conversely, a turbo-mechanical power cycle such as a combustion turbine (discussed in Section 3.3) can only convert ⅓ to ½ of the thermal energy released by combustion into usable work. As such, an rSOC system can only produce hydrogen for up to the equivalent of 5-6 hours per day, before considering the electricity market patterns that drive arbitrage decisions. Alternatively, an HTSE plant can operate for 12 hours if additional fuel cells are also purchased such that the generation and consumption rate are equivalent, and as much as 16-18 hours per day if it is coupled to a combustion turbine.

3.1.4 Sensitivity Analysis

Cost drivers were identified and varied to illustrate the effect that changes to technological and market parameters have on the LCOH for a 500 MWe HTSE system. The findings of this sensitivity analysis are portrayed in a tornado chart (Figure 7). When the capital equipment is properly utilized (e.g., more than 8 hours of operation per day), the variable O&M is the most significant contributor. As such, it is natural to observe that the electricity price is the largest cost driver. The cell life is the number of equivalent years of operation before the electrolysis stacks must be replaced.

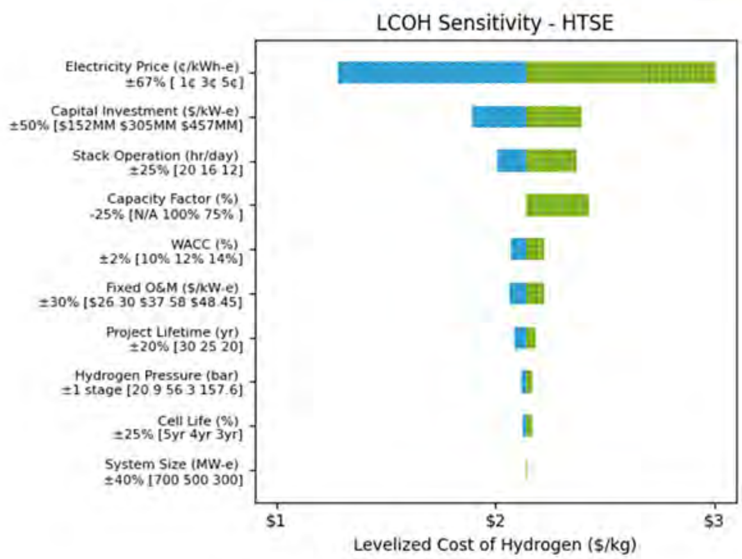

Figure 7. Tornado chart displaying sensitivity of LCOH to cost drivers for a 16 hour 500 MWe HTSE system.

The following adjustments were made to cost drivers to complete the sensitivity analysis:

- 2¢/kWh increase/decrease in electricity price;
- 30% increase/decrease in capital investment to account for variability and potential inaccuracies in the cost analysis performed by the 2022 INL study [5] and Aspen tools;
- 2 GWh-e (4 hours at 500 MW-e) increase/decrease in total storage capacity;
- 25% decrease in capacity factor to consider that demand patterns may not permit full utilization of ESS equipment;
- 2% increase/decrease in WACC to investigate the effect of different market futures.
- 30% increase/decrease in fixed O&M costs; to account for variability and potential inaccuracies in the cost analysis performed by the 2022 INL study [5] and Aspen tools;
- 5-year extension/abridgment to the project lifetime with corresponding changes to the cell replacement schedule;
- 2.8-fold increase/decrease in hydrogen storage pressure, corresponding to the addition/subtraction of 1 compressor stage;
- 1 year increase/decrease in electrolysis stack operational lifetime;
- 200 MW-e increase/decrease in output capability;

-

- ;

3.2 Hydrogen Storage

The LCOH reported in Section 3.1 considers the equipment and utilities to supply hydrogen to a pipeline, but not H_2 storage. Reddi et al. [7] investigated the cost of different tube trailer configurations. These costs were escalated from 2018 to 2023 using CEPCI [6] for this study. The HTSE model was modified to include additional compressors and coolers to increase the stored pressure. EDR and APEA were used to generate cost estimates for the additional equipment, and the utility costs in Table 4 were used to calculate the additional variable O&M costs. Figure 8 depicts a diminishing return but no optimal condition, on the normalized cost with increasing pressure. The capital cost of the tube trailers dominates the levelized cost contribution, meaning that the additional power and equipment to pressurize the hydrogen is worth-while.

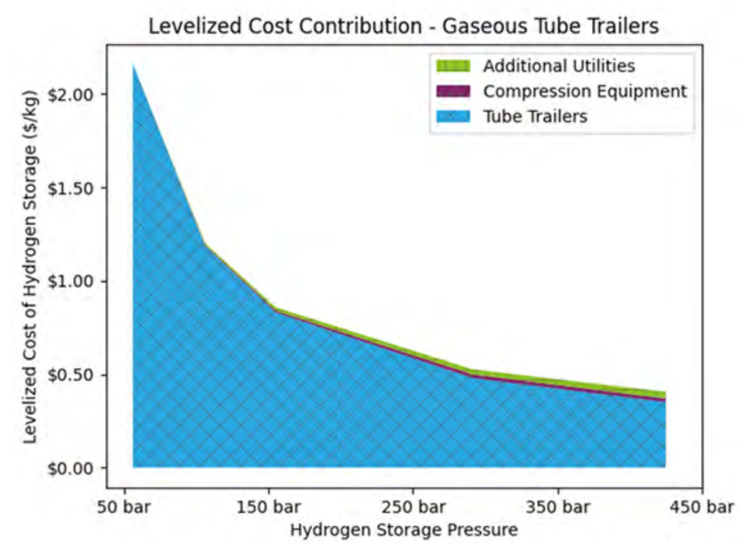

Figure 8. LCOH breakdown for gaseous storage in hydrogen tube trailers at 20°C.

Two compressors with a pressure ratio of 2.8 yields a final pressure of around 425 bar, which is near the maximum allowable pressure for tube trailers, so it was selected as the storage pressure for this analysis. A tank array capable of storing 8 GWh (16 hr of 500 MWe capacity) would require 260 trailers totaling $216MM and covering approximately 6 acres. It requires compression work totaling to 3.44% of the lower heating value (LHV) of H_2. Each compression stage costs around $5MM, and the additional heat exchangers cost $1MM.

Figure 9 is identical to Figure 6, except stack replacement and the costs of hydrogen storage are included in the capital expenditure. This analysis shows that at 16 hours of HTSE operation per day, as would be used for a 4 GWh-e (8 hours at 500MW-e) combustion turbine storage system, the LCOH falls in the range of $2.51/kg.

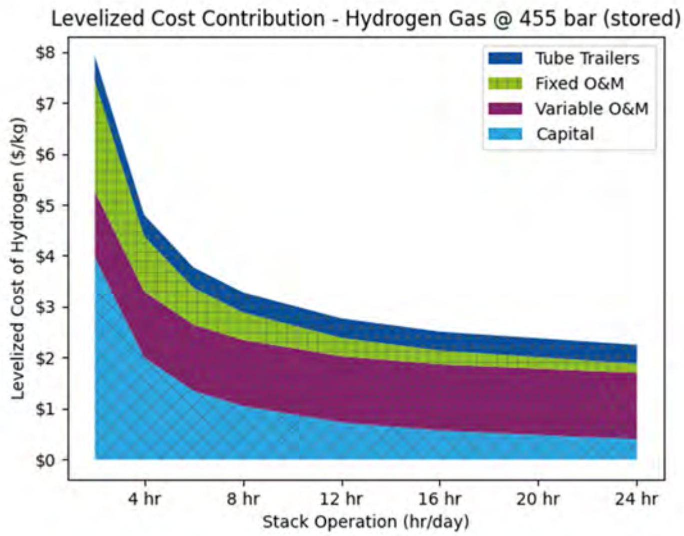

Figure 9. LCOH breakdown for 500 MW-e HTSE storing H_2 gas in tube trailers at 426 bar and 20°C.

The minimal cost of storing hydrogen occurs at different storage durations for hydrogen-to-power systems. If the HTSE system is operated for long enough each day that the hydrogen-to-power system cannot consume it all within the remaining daytime, additional tube trailers must be purchased, while the total number of possible cycles is reduced. This leads to an increased contribution of physical storage to the stored LCOH.

3.3 Hydrogen to Power: HTSE & Hydrogen Combustion Turbine System

As with natural gas, hydrogen can be combusted to drive a power cycle. For an energy arbitrage application, it was determined that a recuperated simple cycle combustion turbine is preferred, in support of demand-response and load-following applications. Figure 10 depicts how hydrogen can be used for energy arbitrage using a hydrogen combustion turbine to generate electricity in a more valuable time window.

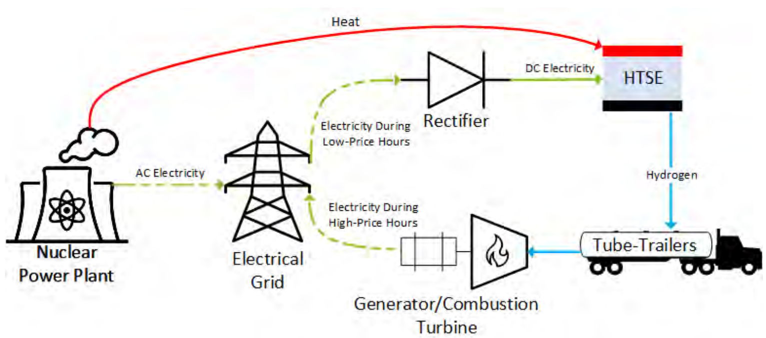

Figure 10. HTSE with combustion turbine schematic.

3.3.1 Hydrogen Combustion Turbine Modeling Approach

A process model (Figure 11) for a hydrogen combustion turbine was developed in Aspen HYSYS with the Peng-Robinson equation of state to study the fuel efficiency and assist with cost estimates. It is common to operate combustion turbines at a high pressure ratio (10-15:1), and to use the bottoming heat to drive a Rankine cycle to improve the overall thermal efficiency of the power plant. The bottoming cycle, which operates in the two-phase regime, provides significant inertia to the power controller, therefore, combined cycle power plants are preferred for baseload power. For energy arbitrage, a more dynamic plant with quicker black-start capability is desired to allow the system to respond more rapidly to a call for power. With this in mind, a recuperated simple cycle with a lower pressure ratio was designed with the parameters listed in Table 5. The model results in a fuel efficiency of 18.6 kWh-e/kg-H_2 (56% thermal efficiency on an LHV basis). A report containing stream conditions and compositions was generated by Aspen HYSYS and included in Appendix B.

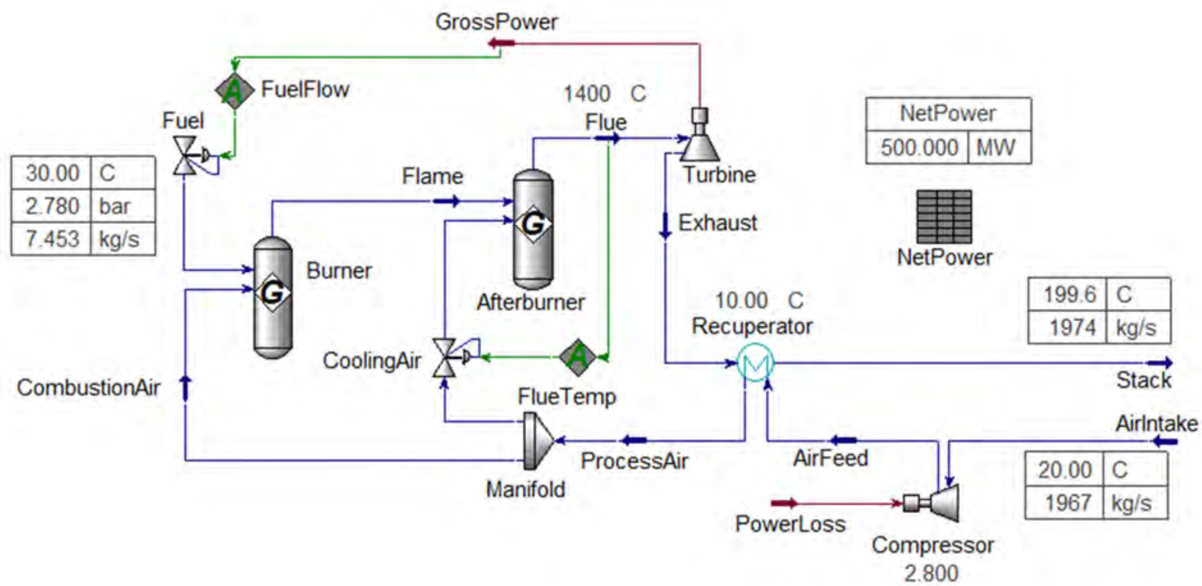

Figure 11. Combustion Turbine Model.

The combustion chamber is broken down into two separate Gibbs reactors (reactors within the AspenTech suite which are pre-programmed to determine products from reactants based on the theoretical provision of the minimization of Gibbs free energy) with identical combustion reaction packages attached. The purpose for this setup is to preserve the peak flame temperature to give a more accurate estimate of minor equilibrium reactions (nitrogen oxides, hydrogen peroxide, and ammonia). The reaction package is listed below:

$$2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(g)} \quad \text{Equation (4)}$$

$$N_2 + 3H_2 \leftrightarrow 2NH_3 \quad \text{Equation (5)}$$

$$N_2 + O_2 \leftrightarrow 2NO \quad \text{Equation (6)}$$

$$2N_2 + O_2 \leftrightarrow 2N_2O \quad \text{Equation (7)}$$

$$N_2 + 2O_2 \leftrightarrow 2NO_2 \quad \text{Equation (8)}$$

$$H_2 + O_2 \leftrightarrow H_2O_2 \quad \text{Equation (9)}$$

Table 5. Combustion Turbine Model Parameters.

Equipment	Parameter	Value	Unit
Compressor	Compression Ratio	2.8	-
	Isentropic Efficiency	75	%

Equipment	Parameter	Value	Unit
Turbine	Net Power	500	MW
	Isentropic Efficiency	90	%
Recuperator	Allowable Pressure Drop (shell/tube)	2	%
	Minimum Approach	10	°C
	Effectiveness	98.9	%
Combustion Chamber	Excess Air (Burner)	20	%
	Adiabatic Flame Temperature (Afterburner)	1400	°C
Inlet Air	Temperature	20	°C
	Relative Humidity	50	%

3.3.2 Levelized Cost of Storage

According to a 2019 study, large simple cycle combustion turbines cost $713/kW to build [8], which was escalated using CEPCI, and the installed cost of the recuperator ($52.6MM, obtained using Aspen EDR) was added to find a total CAPEX of $531.4MM. The report also states that black-start costs $25k per black-start, fixed O&M amounts to $9.4/kWyr, and variable O&M (other than fuel) accounts for 80.6¢/MWh [8]. This information, along with the LCOH displayed in Figure 9 and the following project schedule was used to calculate the LCOS for the hydrogen combustion turbine.

- 25-year project lifetime;
  - Full investment in year 0;
  - 30% availability in year 1, 100% availability in years 2-24;
  - The combustion turbine is operated for half the duration of HTSE, once per day;
  - Decommissioning in year 25;
- Fuel price is dependent on storage duration; and
- WACC of 12%.

Figure 12 displays the LCOS for a combustion turbine with energy storage from 0.5 to 12 GWh-e (1 to 24 hr of storage at 500 MWe discharge), broken down to illustrate the contribution to the LCOS from initial capital investment and fixed and variable O&M. The LCOS is driven by the cost of hydrogen (variable O&M), with significant contribution from capital expenditure for short term storage/low utilization. The LCOS is therefore minimized when the hydrogen price is minimized, where the HTSE is fully utilized. Because the combustion turbine has a fuel efficiency of 18.63 kWh-e/kg-H_2 and the HTSE consumes the equivalent of 42.98 kWe-hr/kg-H_2, this ESS has an RTE of 43.4%, and the HTSE needs to operate for approximately twice as long as the turbine to produce enough hydrogen. As such, the LCOS is minimized at 4 GWh-e (8 hours at 500 MW-e) of storage. Beyond 8 hours, the cost of additional tube trailers increases the LCOH of the HTSE and compressed hydrogen storage system, and therefore the variable O&M of the hydrogen turbine.

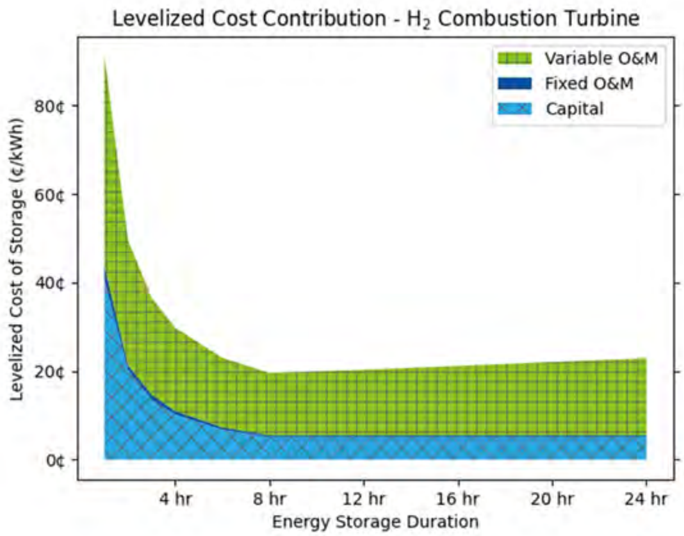

Figure 12. LCOS breakdown for 500 MWe Hydrogen combustion turbine from 0.5 to 12 GWh-e.

3.3.3 Sensitivity Analysis

Cost drivers were identified and varied to illustrate the effect that changes to technological and market parameters have on the LCOS for a 500 MWe hydrogen combustion turbine system. The findings of this sensitivity analysis are portrayed in a tornado chart (Figure 13). The cost of hydrogen production is taken from the LCOH calculated for the specific project parameters. The thermal efficiency is the electrical power produced divided by the LHV of the hydrogen.

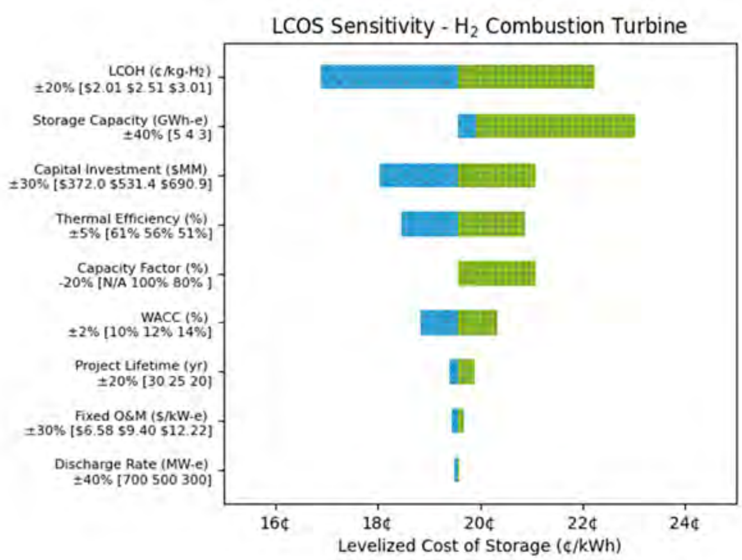

Figure 13. Tornado chart displaying sensitivity of LCOS to cost drivers for an 8-hour 500 MWe hydrogen combustion turbine.

The following adjustments were made to cost drivers to complete the sensitivity analysis:

- 50¢/kg increase/decrease in LCOH;
- 1 GWh-e (2 hours at 500MW-e) increase/decrease in total storage capacity;

- 30% increase/decrease in capital investment to account for variability and potential inaccuracies in the cost analysis performed by the 2019 Sargent & Lundy study [8] and Aspen tools;
- 5% increase/decrease in cycle thermal efficiency;
- 20% decrease in capacity factor to consider that demand patterns may not permit full utilization of ESS equipment;
- 2% increase/decrease in WACC to investigate the effect of different market futures;
- 5-year extension/abridgment to the project lifetime with corresponding changes to the cell replacement schedule;
- 30% increase/decrease in fixed O&M costs;
- 200 MWe increase/decrease in output capability;
-

3.4 Hydrogen to Power: Reversible Solid Oxide Cells (rSOCs)

The stacks used for HTSE can typically be reversed to operate as a fuel cell, if designed ahead of time for such purpose. In this case the stack system is often referred to as a reversible solid oxide (rSOC) system. Figure 14 depicts that the polarity is reversed, and oxygen anions transport across the solid oxide electrolyte and react with hydrogen to form water. This reaction increases the electric potential of the free electrons, directly converting the chemical potential of hydrogen into electrical power.

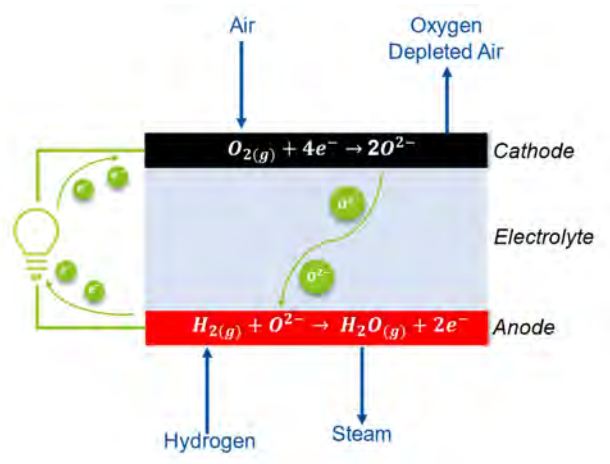

Figure 14. rSOC Fuel Cell Mode Schematic.

Figure 15 depicts how the rSOC cell can be used in energy arbitrage. In a given rSOC, the fuel cell reaction has slower kinetics than the electrolysis, so a lower flow rate of hydrogen must be used. This poses a number of challenges when using rSOCs for energy arbitrage as it restricts the amount of time that the rSOC system can be operated in HTSE mode. Figure 9 depicts a very large increase in LCOH with decreasing utilization. As a consequence, the fuel cost for rSOC systems are expected to be larger than in the combustion turbine system studied in Section 3.3. Further, a very large upfront investment is required for an rSOC system capable of discharging 500 MW-e AC. This requires that the system entire system, including SOC stacks, balance-of-plant, compressed hydrogen storage, and electrical substation, be sized on the scale of 2 GW-e, so rSOC systems of this scale are only viable at NPPs with multiple gigawatt scale LWR units.

For this analysis, a hydrogen flow rate of about one-third of the HTSE mode flow rate is used for fuel cell mode, producing about 20% of the total power consumed in HTSE mode. Incorporating process heat in both HTSE and fuel cell mode, corresponds to an RTE of 51.7%.

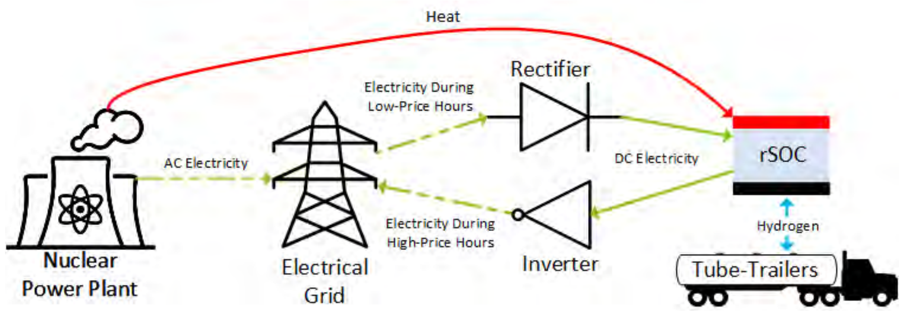

Figure 15. rSOC Schematic.

The hydrogen electrode cannot be run “dry” at the inlet; an inlet composition of 10 mol% steam is required to protect the anode material. Process heat from the NPP is required to vaporize the feedwater. Similarly, all of the hydrogen cannot be consumed in a single pass, and to recycle the unconsumed hydrogen, a portion of the effluent must be cooled enough to condense out the water product. Table 6 lists the utility requirements and costs for the rSOC in fuel cell mode.

Table 6. rSOC Fuel Cell Mode Utility Requirements.

	Utility Demand	Utility Price	Cost (¢/kg-H_2)
Steam from NPP	3,693 kW	1¢/kWh-th	0.8¢
Cooling Water	6,502 ton/hr	0.52¢/ton	0.7¢
Hydrogen Fuel (22.23 kWh/kg)	4,671 kg/hr	Variable	-
Net Electricity Generated	105,063 kW	-	*1.5¢

*Combined hot/cold utility cost per kg of hydrogen *consumed* to generate electricity

3.4.1 Levelized Cost of Storage

Because an rSOC system reuses the depreciable capital from HTSE, CAPEX has a relatively small contribution to the LCOS. However, the contribution of Variable O&M to the LCOH is larger because of the lower hydrogen production time and rate means that the LCOH must come from the left side of Figure 9. The utility costs in Table 6 and the project schedule below was used to calculate the LCOS for Hydrogen rSOC.

- 25-year project lifetime;
  - Full investment in year 0;
  - 30% availability in year 1, 100% availability beginning in year 2;
  - Stack lifetime of 4 active years;
  - 25% of stacks replaced per year when required, in addition to the stack replacements already considered in the LCOH calculation;
  - Stack removal instead of replacement if lifespan ends in years 23-24; and
  - Decommissioning in year 25;
- WACC of 12%;
- Fixed O&M of $18.79/kW-e DC [5], based on the assumption that operating the system reversibly requires an additional 50% in Fixed O&M; and

- Capital investment of $30.49MM, based on the assumption that the additional piping, valving, and instrumentation needed to run the balance of the plant reversibly requires a 10% adder to the HTSE CAPEX;

Figure 16 displays the LCOS for an rSOC system with energy storage from 3 to 12 GWh-e (6 to 24 hours at 500 MW-e) broken down to illustrate the contribution to the LCOS from additional capital investment, additional stack replacement, and fixed and variable O&M. Due to the re-use of capital equipment from the HTSE system, the LCOS is driven almost entirely by the cost of hydrogen (variable O&M). The LCOS is therefore minimized when the LCOH is minimized, where the rSOC system is fully utilized. Up to 18 hours, longer energy storage durations correspond to greater utilization of the HTSE balance-of-plant and an LCOH from further right on Figure 9. With fuel costs making up the majority of variable O&M, this results in a significantly lower contribution from variable O&M for rSOC systems designed for storage durations over 12 hours.

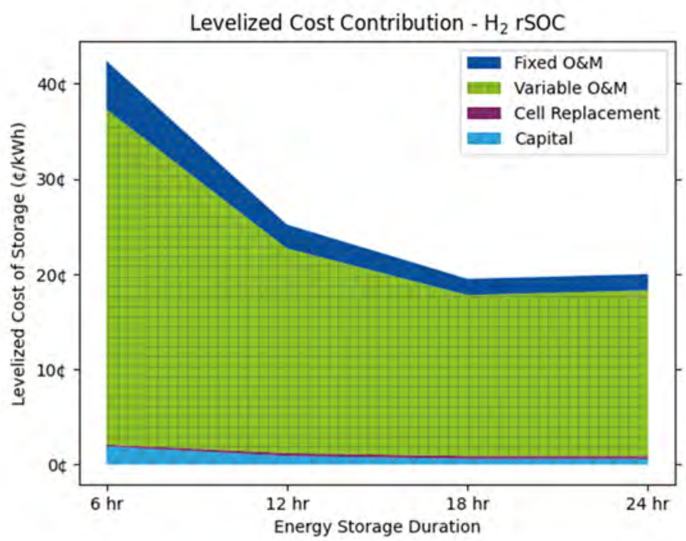

Figure 16. LCOS breakdown for 100 MW-e Hydrogen rSOC in fuel cell mode from 3 to 12 GWh-e.

Given that the hydrogen flowrate in fuel cell mode is ⅓ that of HTSE mode, the minimum LCOH used in this analysis is \$3.77/kg-H_2 (corresponding to 6 hours per day of electrolysis). This yields an LCOS of 19.5¢/kWe-hr for a discharge duration of 18 hours. Beyond 18 hours, the cost of additional tube trailers increases the LCOH in HTSE mode, and therefore the variable O&M in fuel cell (FC) mode.

3.4.2 Sensitivity Analysis

Cost drivers were identified and varied to illustrate the effect that changes to technological and market parameters have on the LCOS for a 500 MW-e hydrogen combustion turbine system. The findings of this sensitivity analysis are portrayed in a tornado chart (Figure 17).The following adjustments were made to cost drivers to complete the sensitivity analysis:

- 50¢/kg increase/decrease in LCOH;
- 3 GWh-e (6-hours at 500 MW-e) increase/decrease in total storage capacity;
- 5% increase/decrease in thermal efficiency;
- 30% increase/decrease in fixed O&M costs to account for variability and potential inaccuracies in the cost analysis performed by the 2019 Sargent & Lundy study [8] and Aspen tools;

- 20% decrease in capacity factor to consider that demand patterns may not permit full utilization of ESS equipment;
- 2% increase/decrease in WACC to investigate the effect of different market futures;
- 30% increase/decrease in capital investment to account for variability and potential inaccuracies in the cost analysis performed by the 2019 Sargent & Lundy study [8] and Aspen tools;
- 5-year extension/abridgment to the project lifetime with corresponding changes to the cell replacement schedule;
- 200 MW-e increase/decrease in output capability;
-
-

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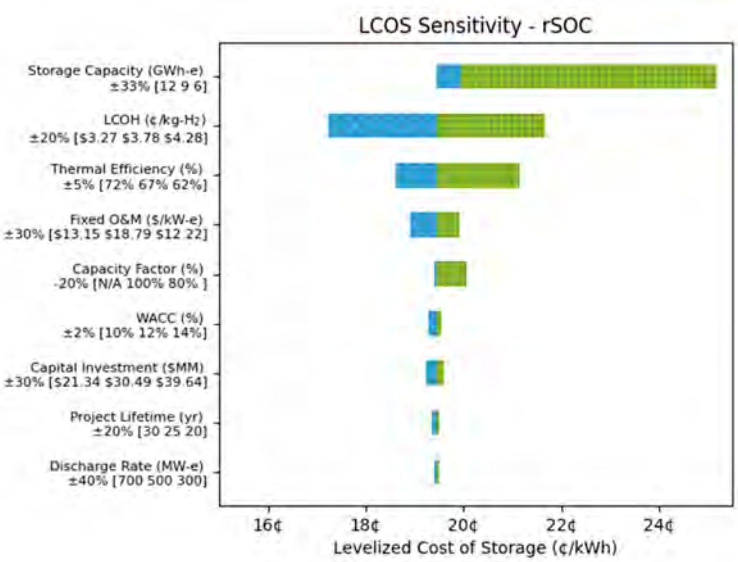

Figure 17. Tornado chart displaying sensitivity of LCOS to cost drivers for an 18-hour 500 MW-e rSOC.

3.5 Hydrogen to Power: HTSE & Fuel Cell System

For an additional capital investment of SOC (Solid Oxide Cell) stacks, more power is generated, and the hydrogen consumption rate matches the production rate from the HTSE system. Returning to the estimate of $89.90/kW-e DC for SOC stacks in the electrolysis mode, it requires an additional investment of $181MM to be able to consume 22,094 kg/hr of hydrogen, producing 500 MW-e, on top of the $457MM investment for a 750 MW-e DC HTSE plant (With a thermal efficiency of 67% on a LHV basis). It is assumed that the HTSE balance-of-plant can be refactored and used during FC operation. The high temperature SOC was selected over low-temperature proton exchange membrane fuel cells due to the availability of the HTSE balance-of-plant, which is capable of recuperating the high temperatures required for this specific type of FC. As was discussed in Section 3.4, SOCs in FC mode require lower flow rates than in electrolysis mode. Instead of re-using the electrolysis stacks in FC mode and accepting the lower flow rate, three times as many dedicated fuel cells were modeled to maximize the capacity of the balance-of-plant. Figure 18 is a schematic drawing of the HTSE+FC system which includes 320,000 HTSE stacks and 960,000 FC stacks.

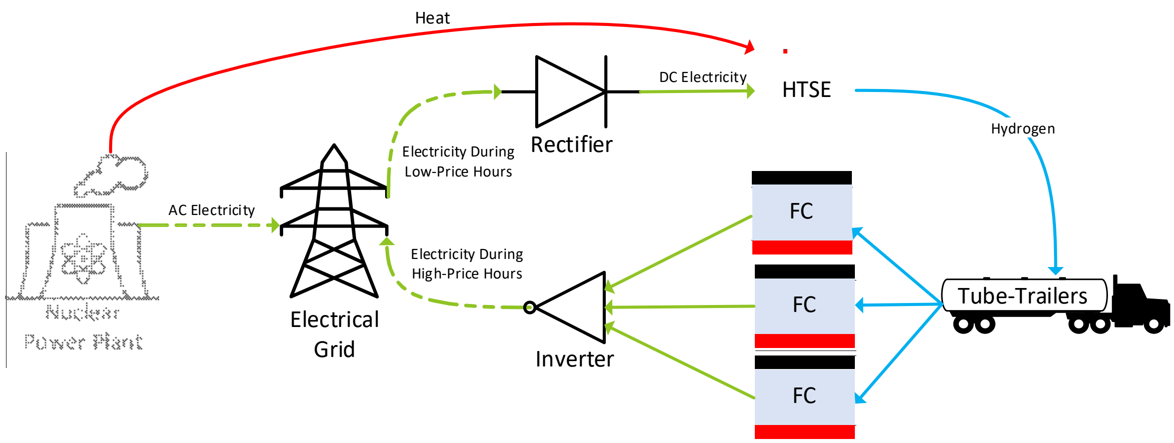

Figure 18: HTSE + FC Schematic

3.5.1 Levelized Cost of Storage

The LCOS for fuel cells was calculated using the financial and project parameters listed in Section 3.4 with the addition of the $202MM for the fuel cells and adjusting the LCOH used to align with the balanced charging/discharging flow rates.

Figure 19 displays the LCOS for a fuel cell system with energy storage from 1 to 12 GWh-e (2 to 24 h at 500 MWe discharge) , broken down to illustrate the contribution to the LCOS from capital investment, stack replacement, and fixed and variable O&M. As the storage duration approaches 12 hours, the balance-of-plant for the combined system is assumed to be utilized around the clock (12 hours in FC mode, 12 hours in HTSE mode); this is not possible for any of the other hydrogen system energy storage technologies investigated in this report. This, combined with the relatively small additional investment of the standalone FC stacks leads to the result of this being the most cost-effective hydrogen ESS. Due to the re-use of capital equipment from the rSOC HTSE system, the LCOS is driven primarily by the cost of hydrogen (variable O&M).

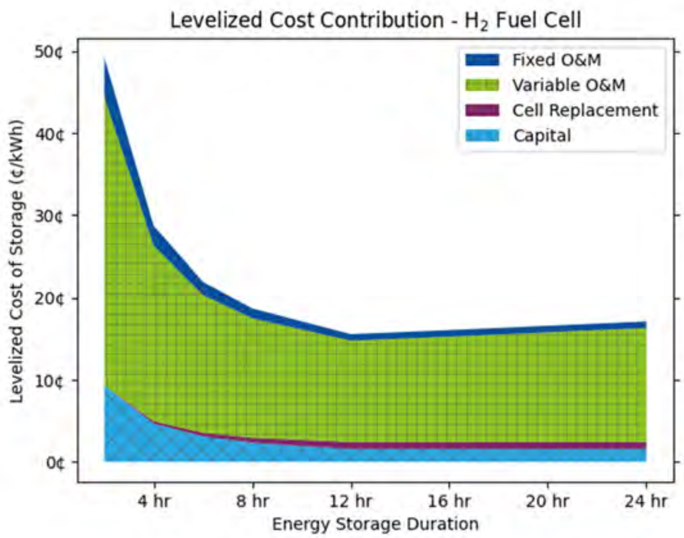

Figure 19. LCOS breakdown for 500 MW-e Hydrogen Fuel Cell from 1 to 12 GWh-e.

The LCOS is therefore minimized when the LCOH is minimized, where the combined HTSE/fuel cell system is fully utilized. This yields an LCOS of 15.7¢/kWh-e for a discharge duration of 12 hours. Beyond

12 hours, the cost of additional tube trailers increases the LCOH of the HTSE system, and therefore the variable O&M for the standalone fuel cells.

3.5.2 Sensitivity Analysis

Cost drivers were identified and varied to illustrate the effect that changes to technological and market parameters have on the LCOS for a 330 MW-e hydrogen combustion turbine system. The findings of this sensitivity analysis are portrayed in a tornado chart (Figure 20).

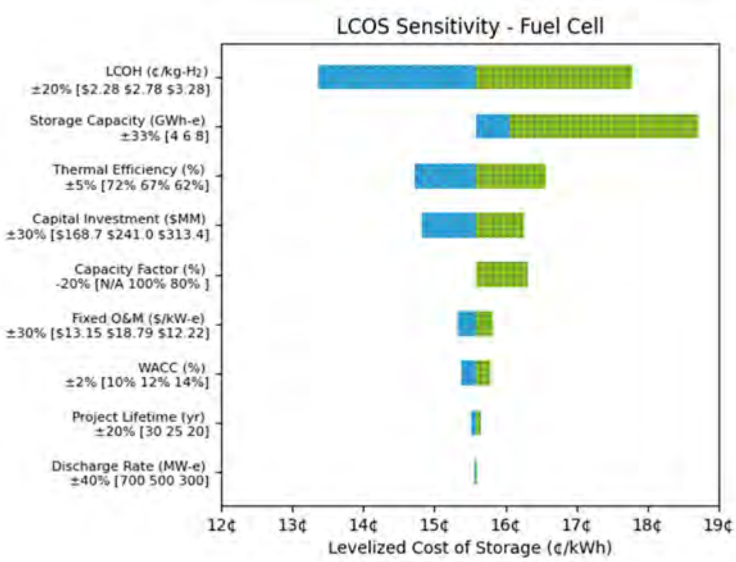

Figure 20. Tornado chart displaying sensitivity of LCOS to cost drivers for a 12 hour 500 MW-e fuel cell.

The following adjustments were made to cost drivers to complete the sensitivity analysis:

- 50¢/kg increase/decrease in LCOH;
- 2 GWh-e (4-hours at 500 MW-e) increase/decrease in total storage capacity;
- 5% increase/decrease in thermal efficiency;
- 30% increase/decrease in capital investment to account for variability and potential inaccuracies in the cost analysis performed by the 2019 Sargent & Lundy study [8] and Aspen tools;
- 20% decrease in capacity factor to consider that demand patterns may not permit full utilization of ESS equipment;
- 30% increase/decrease in fixed O&M costs;
- 2% increase/decrease in WACC to investigate the effect of different market futures;
- 5-year extension/abridgment to the project lifetime with corresponding changes to the cell replacement schedule;
- 200 MWe increase/decrease in output capability;

Adjustments

- Adjustments to study the impact of different project parameters
-

THERMAL ENERGY STORAGE

This study investigates two types of TES technologies: (a) ETES and (b) liquid-based SH-TES. Process configurations and critical inputs for estimating LCOS are demonstrated for ETES (Section 3.6) and SH-TES (Section 3.7). The LCOS for both ETES and SH-TES are compared in Section 3.8. These systems were previously evaluated [1] and this work updates those analyses to be applicable and current to the other analyses presented in this report. ETES and is essentially a heat pump using a supercritical CO_2 cycle that takes electricity as an input and stores it in the form of thermal energy to be later released and used to regenerate electricity. SH-TES is sensible heat thermal energy storage where thermal energy is taken as an input and stored in a heat storage medium such as sand or solar salt. Later the heat is released from the medium and used in a power cycle to generate electricity. Note that ETES requires conversion of heat to electricity to heat and back to electricity, whereas SH-TES requires only heat to electricity as part of the processes.

3.6 Electro-Thermal Energy Storage.

ETES can use electricity from an NPP to run a supercritical carbon dioxide heat pump during the charge cycle. During the discharge cycle, 500 MWe of electricity is generated by a supercritical carbon dioxide Brayton cycle drive between the cold storage vessels and hot particle containments using high and low-pressure turbines. The sand is used as the working fluid for the heat exchanges between the hot particle containments [9] while 10% propylene glycol (PG) aqueous solution is used for the heat exchanges between the cold storage vessels. The charge and discharge cycles are shown in Figure 21 and Figure 22, respectively.

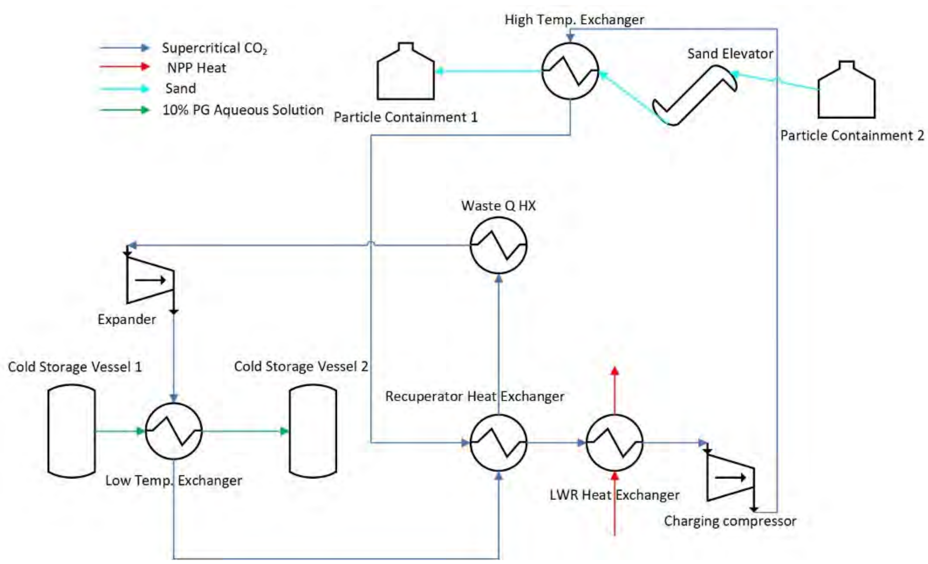

Figure 21. Charge cycle for LWR-integrated ETES configuration.

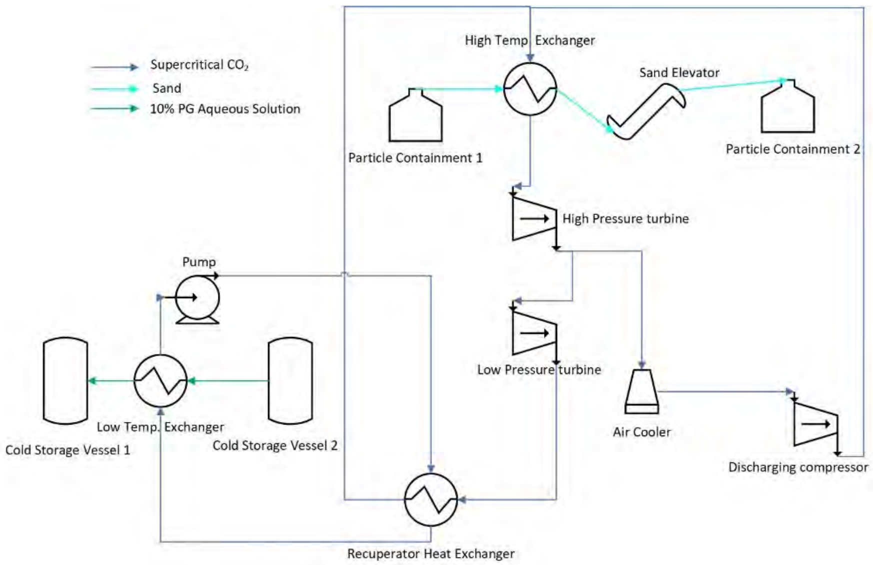

Figure 22. Discharge cycle for LWR-integrated ETES process configuration.

To estimate the LCOS, the installed costs for each component are calculated by adjusting the costs reported in the previous INL study [1] from 2018 to 2022 using CEPCI [6] as shown in Table 7.

Table 7. Installed costs for ETES ($2022).

Cycles	Equipment	Installed Costs
Discharge	Pump	$36,438,033
Charge	Expander	$100,049,671
Discharge	High- and Low-Pressure Turbine/Discharging Compressor	$92,233,301
Charge/Discharge	Low-Temperature Exchanger	$41,099,255
Charge/Discharge	Recuperator Heat Exchanger	$377,857,387
Charge/Discharge	High-Temperature Exchanger	$411,490,040
Charge/Discharge	Sand Elevator	$31,807,276
Charge	Waste Q HX	$20,385,310
Charge	Charging Compressor	$10,105,898
Discharge	Air Cooler	$69,368,373

The charging/discharging equipment and installation costs in Table 7 are not affected by storage duration. However, the costs associated with storage components and materials increase when the storage duration increases. The costs per kWh-e for each material for ETES are reported in Table 8.

Table 8. Cost rates of the storage components and materials for ETES [1].

Storage components for ETES	Storage costs ($/kWh-e)
Sand	$1.88
10% PG aqueous solution	$3.51
Particle containment 1 and 2	$39.36
Cold storage vessels 1 and 2	$10.53

3.7 Liquid-based Sensible Heat Thermal Energy Storage

SH-TES utilizes molten salt or synthetic oils as the storage media to exchange heat between the heat exchanger and the reservoir (i.e., hot and cold tank). Molten salts absorb heat directly from the heat exchanger and store the energy in the reservoir during the charging cycle; this heat is later released through the exchanger during the discharging cycle to generate 500 MW-e of electricity as shown in Figure 23.

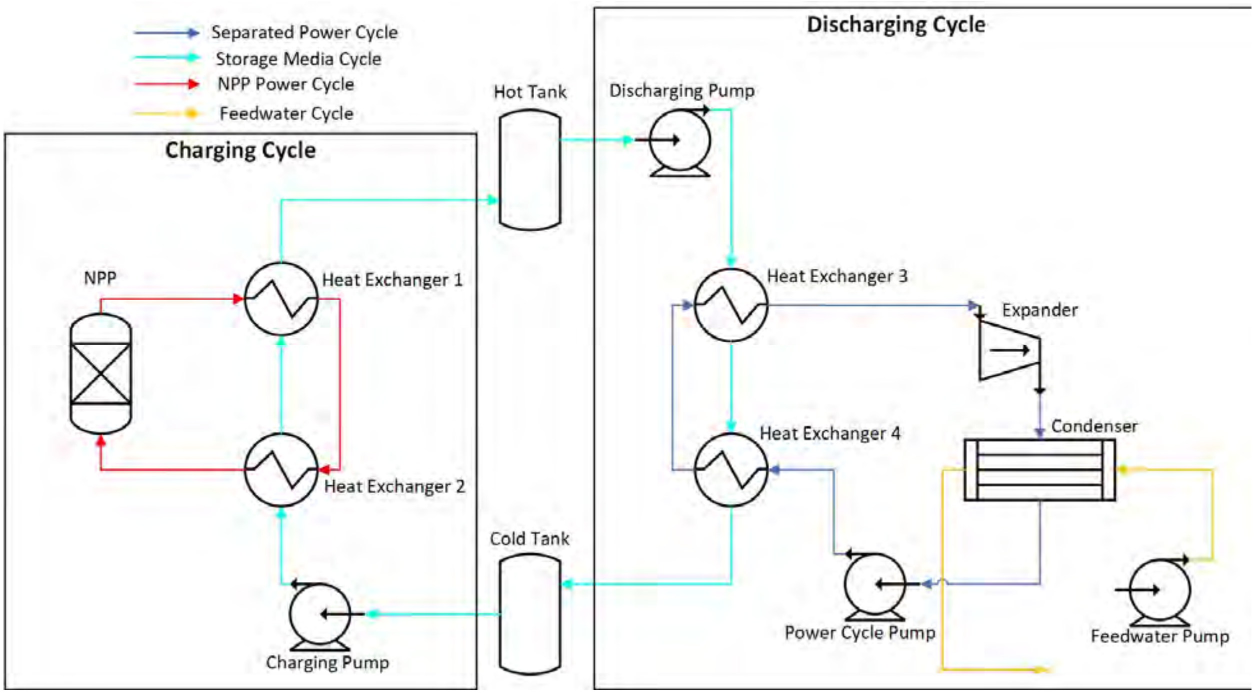

Figure 23. Charge and discharge cycles for LWR-integrated liquid-based Sensible Heat Thermal Energy Storage (SH-TES) process configuration.

The installed costs for two different molten salts (Hitec and Hitec XL) and two synthetic oils (Therminol-66 and Dowtherm A) are calculated by adjusting the costs reported in a previous INL study [1] from 2018 to 2022 using CEPCI [6] as shown in Table 9.

Table 9. Installed Cost for Hitec, Hitec XL, Therminol-66, and Dowtherm A based SH-TES systems ($2022).

	Hitec	Hitec XL	Therminol-66	Dowtherm A
HX1	$65,751,679	$67,600,779	$59,313,545	$45,326,453
HX2	$11,503,276	$17,342,088	$8,816,237	$9,030,506
Charging Pump	$18,399,626	$16,781,823	$44,008,186	$48,472,950
HX3	$10,834,808	$29,326,594	$14,408,844	$14,106,991
HX4	$34,999,643	$8,337,449	$2,820,988	$28,553,480
Condenser	$36,542,485	$37,510,293	$36,542,485	$37,517,734
Discharging Pump	$6,217,683	$4,917,102	$9,751,749	$12,272,713
Power Cycle Pump	$964,573	$973,908	$961,867	$962,543
Feedwater Pump	$8,779,272	$8,819,863	$8,765,742	$8,779,272

	Hitec	Hitec XL	Therminol-66	Dowtherm A
Expander	$115,820,992	$115,820,992	$115,820,992	$115,820,992

The cost rates for the storage media of SH-TES are shown in Table 10. The cost of hot and cold storage tanks per kW-e is adopted from the previous study [1]. The cost for each storage media ($/kg) is obtained from different studies with the commonly used costs from the literature. The storage media cost ($/kWh) is calculated based on the storage media cost ($/kg) and the mass flow rate for a 500 MW-e system.

Table 10. Component and material cost rates for SH-TES with various storage media including Hitec, Hitec XL, Therminol-66, and Dowtherm A.

	Hitec	Hitec XL	Therminol-66	Dowtherm A
Hot Storage Tank ($/kW-e) [1]	$22	$22	$22	$22
Cold Storage Tank ($/kW-e) [1]	$22	$22	$22	$22
Storage Media ($/kg)	$1.80 [10]	$1.66 [11]	$3.17 [12]	$3.96 [13]
Mass Flow Rate (ktonne/hr)	49.38	45.17	30.87	35.13
Storage Media ($/kWh)	$178	$150	$196	$278

3.8 Levelized Cost of Storage for ETES and SH-TES

In addition to the installation costs and cost rates for the storage components and material, Table 11 shows the design and financial parameters adopted from the previous INL study [1] for estimating LCOS. The RTE is assumed to be the same as the maximum conversion efficiency, which is calculated as the ratio of the net power out to the heat into the cycle [1]. The RTE for ETES includes the conversion from electricity produced in an NPP to electricity outputs from the ETES while the RTE for SH-TES with different storage media such as Hitec, Hitec XL, Therminol-66, and Dowtherm A includes the conversion from thermal heat from an NPP to electricity outputs from SH-TES. To use the same unit of the charging costs for comparison purpose, the energy inputs to calculate RTE for SH-TES is translated to the electrical equivalent from the thermal energy. The underlying assumption of this translation is that the thermal to electricity efficiency from an NPP is 33%. Due to the 33% of thermal efficiency, the charging costs of 3¢/kWh-e is equivalent to 1¢/kWh-t. It is assumed that there is no debt and depreciation considered in the LCOS estimations. No inflation is considered in the cost estimations.

Table 11. Design and financial parameters used to estimate LCOS [1].

	ETES	Hitec	Hitec XL	Therminol-66	Dowtherm A
Interval between start of discharge cycles (day)	1	1	1	1	1
Depth-of-Discharge	100%	100%	100%	100%	100%
Round-trip efficiency	55.2%	82.2%	82.2%	82.2%	82.2%
Charging Costs	3¢/kWh-e	3¢/kWh-e	3¢/kWh-e	3¢/kWh-e	3¢/kWh-e
Nominal WACC	12%	12%	12%	12%	12%

	ETES	Hitec	Hitec XL	Therminol-66	Dowtherm A
Combined Tax Rate	26%	26%	26%	26%	26%
Contract Term / Project Life	25	25	25	25	25

The LCOS for ETES and SH-TES are calculated based on the cost contributions reported in Table 7, Table 8, Table 9, Table 10, and Table 11 as shown in Table 12.

Table 12. LCOS for ETES and SH-TES with different storage media including Hitec, Hitec XL, Therminol-66, and Dowtherm A (¢2022/kWh) for 12-hour storage.

TES method	Charging Costs (¢/kWh-e)						
	0¢	1¢	2¢	3¢	4¢	5¢	6¢
ETES	15.7	17.6	19.4	21.2	23.0	24.8	26.6
SH-TES: Hitec	17.2	18.4	19.6	20.8	22.0	23.3	24.5
SH-TES: Hitec XL	14.6	15.9	17.1	18.3	19.5	20.7	21.9
SH-TES: Therminol -66	17.3	18.5	19.8	21.0	22.2	23.4	24.6
SH-TES: Dowtherm A	22.5	23.7	24.9	26.1	27.3	28.5	29.8

Based on Table 12, higher charging costs per kWh-e results in a higher LCOS. In this case study, Hitec XL has the lowest LCOS compared to other TES options at 12 hours. In contrast, Dowtherm A has the highest LCOS compared to the other SH-TES options and ETES, which are different from the results reported in the previous INL study [1]. The main reason is that the most updated unit costs for Hitec and Hitec XL increases 93% and 51%, respectively while the unit costs for Therminol-66 reduces 52%. While the unit costs for Dowtherm A does not change, the LCOS for SH-TES with Dowtherm A increases 67% due to the escalation of dollar value from 2018 to 2022 and the simplified treatment for the LCOS estimation. However, the reader should not focus on the absolute value of LCOS but the relationships among the LCOS of different options.

The LCOS of ETES and SH-TES with the capacity of 500 MW-e are broken down into capital costs, variable O&M, and fixed O&M as shown in Figure 24. The capital cost is the main contributor to the LCOS of thermal storage, meaning that reducing the overall capital costs including equipment installed costs, storage media costs, and storage tank costs has the largest impact on LCOS. Figure 24 show that the LCOS reduces when the energy storage duration increases before reaching 12 hours. If more than 12 hours are stored, the LCOS increases significantly. Comparing the minimum LCOS at 12 hours of energy storage, Figure 24 shows that Dowtherm A has the highest LCOS while Hitec XL has the lowest LCOS, which is consistent with the observation in Table 12.

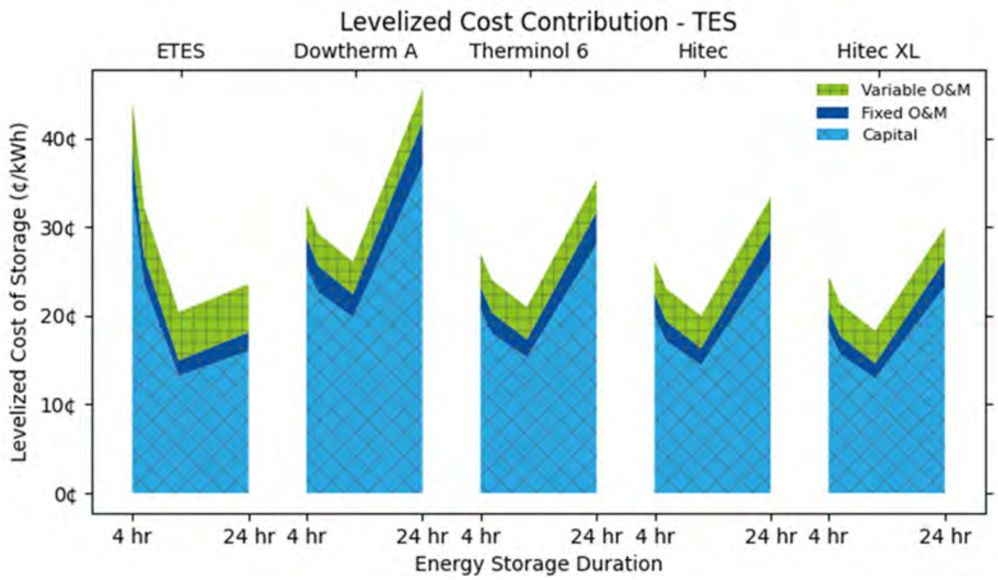

Figure 24. LCOS breakdown for 500 MW-e liquid-based SH-TES and ETES from 2.0 to 12.0 GWh-e.

3.9 Sensitivity Analysis for ETES and SH-TES

A total of nine cost drivers including capital investment, charging price, storage capacity, capacity factor, WACC, project lifetime, fixed O&M, RTE, and discharge rates are selected for sensitivity studies. The following adjustments were made to cost drivers by increasing or decreasing the specified percentage with respect to the nominal value to perform the sensitivity analysis as shown in Figure 25 and Figure 26 for ETES and SH-TES (Hitec XL), respectively:

- 67% increase/decrease charging prices;
- 20% increase/decrease in CAPEX;
- 20% decrease in capacity factor to consider that demand patterns may not permit full utilization of ESS equipment;
- 33% increase/decrease storage duration;
- 17% increase/decrease in WACC (equivalent to 2% change in actual value) to investigate the effect of different market futures;
- 5-year extension/abridgment to the project lifetime with corresponding changes to the cell replacement schedule;
- 30% increase/decrease in fixed O&M costs;
- 9% increase/decrease in RTE (equivalent to 5% change in the actual value);
- 40% increase/decrease in discharge rate;

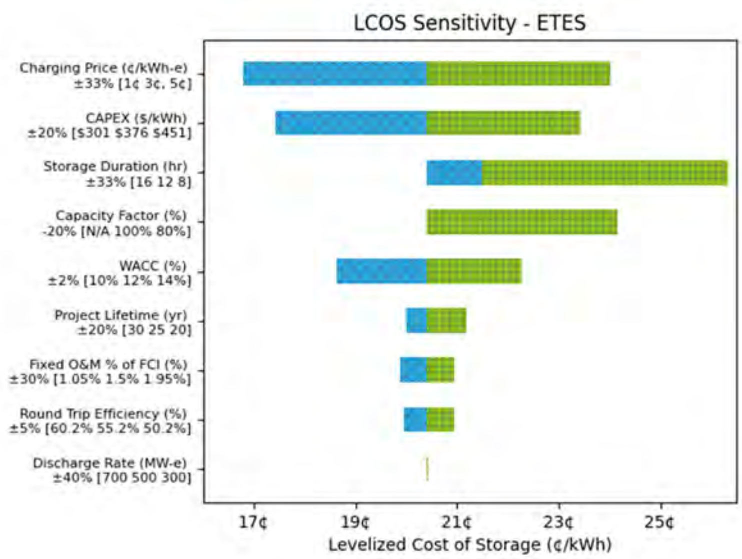

Figure 25. Tornado chart displaying sensitivity of LCOS to cost drivers for a 12-hour 500 MW-e ETES system.

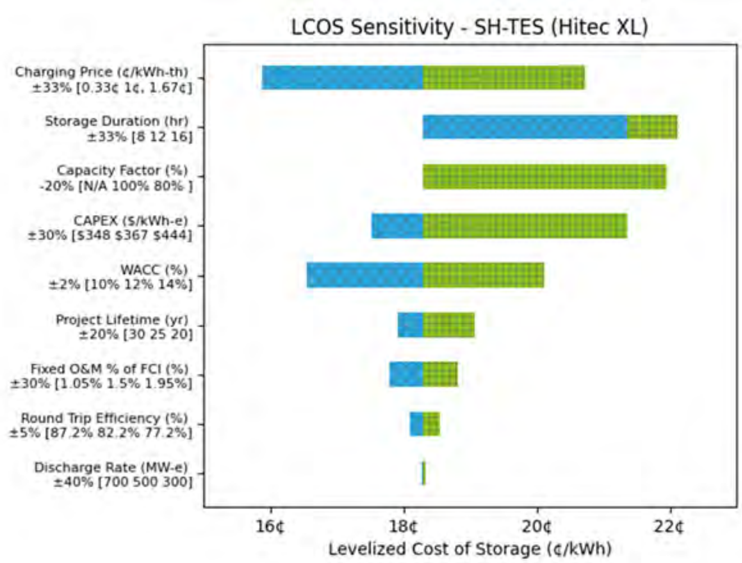

Figure 26. Tornado chart displaying sensitivity of LCOS to cost drivers for a 12-hour 500 MW-e SH-TES system with Hitec XL.

From Figure 25 and Figure 26, charging price is the most sensitive parameters for estimating LCOS of ETES and SH-TES (Hitec XL). The discharge rate has negligible impacts of LCOS of ETES and SH-TES (Hitec XL). Therefore, reducing the costs associated with capital investment and the charging price has more effect on reducing the LCOS than changing the discharge rate.

4 TECHNOLOGY COMPARISON

4.1 Levelized Cost of Storage

The analyses conducted in Sections 2-0 were conducted in a manner allowing them to be directly compared in Figure 27 and Figure 28. The same data is displayed on each plot; the gray box drawn in the lower left corner of Figure 27 is the zoomed-in area that is plotted in more detail in Figure 28, and Figure 29 is a further narrowed scope.

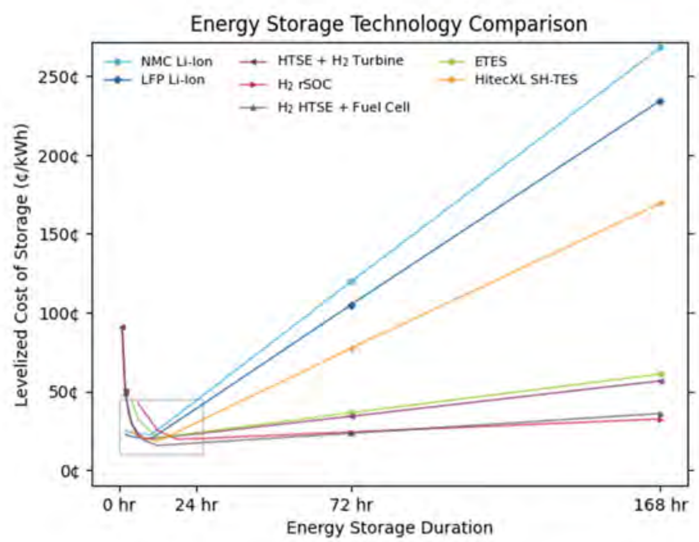

Figure 27. Comparison of LCOS for 7 energy storage technologies – long-duration storage.

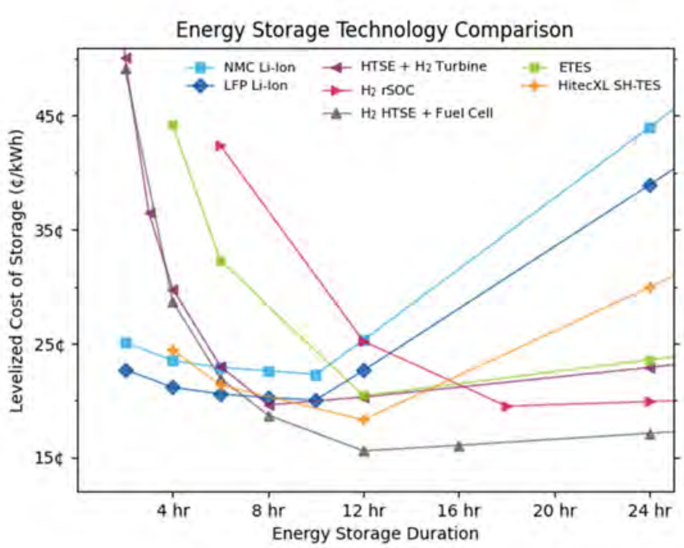

Figure 28. Comparison of LCOS for 7 energy storage technologies – short duration storage.

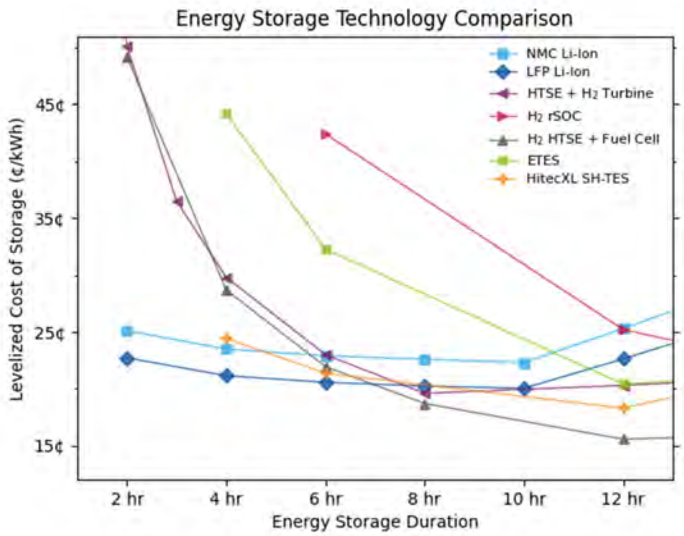

Figure 29: Comparison of LCOS for 7 energy storage technologies – 0 to 12 hours

From Figure 28, it is notable that the minimum LCOS occurs at different energy storage durations in different energy storage technologies. This is primarily due to the differing charging/discharging patterns of each technology. The LCOS for lithium-ion batteries is minimized between 10 and 12 hours per day as it charges and discharges at the same rate (500 MW-e), with an 83% RTE. The approximately 50% thermal efficiency of the hydrogen turbine means that generating 500 MW-e for 8 hours per day requires around 16 hours of hydrogen production. An individual rSOC stack consumes hydrogen at about 1/3 the rate in fuel cell mode than it produces in the electrolysis mode. This makes it optimal for rSOC to charge (produce H_2 in electrolysis mode and store it) for 6 hours and discharge (consume H_2 in fuel cell mode) for 18 hours per day; factoring in the combined RTE of the total system, just 100 MW-e can be produced during these 18 hours. The standalone fuel cell system was designed to consume hydrogen at the same rate that the HTSE system produces it, regenerating 330 MW-e at 12 hours of storage. The minimum LCOS occurs at the 12 hours of energy storage for ETES and liquid-based SH-TES with Hitec XL as the storage media. This is because the same amount of time is used for charging and discharging durations for both ETES and liquid-based SH-TES. The LCOS for ETES and liquid-based SH-TES are higher before reaching 12 hours since additional waiting time is required. Therefore, additional profits lost or increased LCOS are necessary for charging durations less than 12 hours. The slope of the lines for storage durations longer than the optimal storage (minimum LCOS) is dominated by the cost of storage equipment. For any storage duration longer than the optimal value for a given technology, the power equipment (*e.g.* rectifiers/inverters and transformers, fuel cells, turbines, and other equipment whose price can be defined in \$/kW-e) utilization plateaus, as the number of possible charge/discharge cycles reduces proportionally to the length of the cycle. In contrast, longer-duration storage requires more storage equipment, including individual battery cells, storage tanks, sensible heat storage media, and hydrogen tube trailers, whose price is defined in \$/kWh-e. This raises the total capital investment required for the project and therefore the LCOS, as the same total amount of energy can be discharged.

Lithium-ion battery storage systems, which offer the most cost-effective form of grid-scale energy storage for durations shorter than 6 hours, require more batteries to be purchased to facilitate long-duration storage. This results in the technology scaling poorly for durations longer than 10-12 hours. TES and hydrogen systems on the other hand simply require more tanks/thermal storage media, and tube trailers, respectively. The thermal oils and molten salts used in SH-TES are quite expensive compared to the sand and propylene glycol used in ETES, leading to a steeper slope for SH-TES. The storage system required for hydrogen is relatively inexpensive even for proportionally lower throughput, which allows for a palatable LCOS even for suboptimal operation.

The slope of the lines in Figure 28 to the left of the minimum values is primarily defined by the cost of power (charge/discharge) equipment, while the slope of the lines in Figure 27 to the right of the minima is defined by the cost of storage equipment. Two of the most cost-effective ESSs, HTSE + H_2 combustion turbine and HTSE + FC illustrate this behavior quite nicely; For very short duration storage the two systems coincidentally have approximately the same LCOS. Compared to the FC system, the combustion turbine requires a larger capital investment but enjoys lower fuel costs due to the H_2 production/consumption mismatch driven by the cycle's thermal efficiency. These lower fuel costs are also driven by utilization of depreciable capital, so the two ESSs follow roughly the same LCOS path as the storage duration increases. Due to the mismatched flow rates, the combustion turbine reaches its minimum LCOS earlier than the FC, at around 4 GWh-e AC (8 hours at 500 MW-e). The FC system by design has equal production/consumption rates, leaving its optimal storage duration at 12 hours. For storage durations longer than their respective minima, the combustion turbine's LCOS line has a steeper slope due to its slightly lower thermal efficiency; generating 500MW-e for longer than the optimal time period requires more tube trailers (which have suboptimal thruput) compared to the more efficient FCs.

It is important to note that the long-duration LCOS calculation is a low estimate, as it is unlikely for grid patterns to adequately support the notion of consistently storing and regenerating energy week by week. The results do however indicate that, of the technologies considered in this report, HTSE with gaseous tube-trailer storage at ~425 bar and a fuel cell system that makes use of the HTSE balance-of-plant to pre-heat and recuperate the feed streams into dedicated FCs is likely to be the most cost-effective way to stockpile energy for emergency backup power. Such a system falls outside of the realm of energy arbitrage but can provide separate value in the form of energy security.

4.2 Round Trip Efficiency

RTE is a secondary figure of merit to compare ESS technologies. It is inherently included in LCOS calculations, as factors such as charging costs and optimal storage duration depend on it. Still, it is possible that a less efficient overall process that is much cheaper to operate yields a lower LCOS. Of the ESSs considered in this report, only lithium-ion batteries use only electrical power. To make thermal and electrical power utilization directly comparable, an NPP thermal efficiency of 33.33% was assumed; i.e. 300 MW-th is treated as the equivalent of 100MW-e for the purposes of the calculations presented in Table 13.

Table 13: Comparison of RTE by ESS technology

	Charging Cycle			Discharging Cycle			RTE (%)
	Thermal (MW-th)	Electrical (MW-e AC)	Duration (hr/day)	Thermal (MW-th)	Electrical (MW-e AC)	Duration (hr/day)	
Li-Ion Batteries	0	500	13	0	500	11	83%
HTSE+Turbine	84.5	608	16	0	500	8	39%
rSOC	253	1824	6	-15.5	500	18	52%
HTSE+FC	127	912	12	-15.5	500	12	52%
ETES	2	905	12	0	500	12	55%
SH-TES	1825	715 kW	12	0	500	12	82%

The RTE for grid-scale lithium-ion batteries was obtained from the PNNL study, which aggregates rectification, inversion, and coulombic losses [2]. The power equipment (transformers, rectifiers, and inverters) are sized for 500 MW-e AC, which is the same as the discharge rating, the charging cycle must be longer than the discharge cycle to account for these losses.

The HTSE system, including the electrolysis cell and balance-of-plant consumes 41.27 kWh-e AC, and the equivalent of 1.91 kWh-e in thermal power to produce 1 kg of H_2. On an LHV (33.33kWh-kg) basis, HTSE is a 77.19% overall efficient charging cycle. This figure must be aggregated with a discharge efficiency, e.g. 51% for the combustion turbine, to obtain the RTE for hydrogen ESSs. In particular, FC based ESSs (rSOC and HTSE+FC) require thermal power input on the discharge cycle. This heat could have been used to generate electricity in the primary NPP power cycle, so the electrical equivalent has been subtracted from the discharge rate for the purposes of RTE calculation.

The two types of TES have very different charging cycles. In ETES, very little heat is taken from the NPP. Instead, electricity is used to run a heat pump compressor. This attains a higher temperature which drives a high thermal efficiency CO_2 cycle Brayton cycle. Only stored heat (e.g. no additional heat from the NPP) is converted to work in the discharge cycle. SH-TES instead stores thermal power, avoiding the losses of initial conversion from the NPP power cycle. This makes the charging cycle much more efficient, but, the lower temperature of the storage media leads to a discharge Rankine cycle with a lower thermal efficiency. The upfront efficiency still results in SH-TES having one of the highest RTEs, on the same level as lithium-ion batteries.

5 FINAL REMARKS

5.1 Conclusions

The conclusions of this study are summarized in the points below:

Utility scale batteries:

- LFP and NMC Li-ion batteries have the lowest LCOS for short-term storage of 6 hours or less.
- NMC Li-ion batteries are more expensive than LFP.
- Capital investment is the most significant contribution to LCOS and is the primary cause of the high increase in LCOS at higher storage durations. Capital investment is the most sensitive cost driver for the LCOS.
- Following capital investment and in order of LCOS most impact, variable capacity factor, charging price, and WACC are the next most sensitive cost drivers.

Hydrogen for energy storage:

- The primary cost driver of LCOH for HTSE is capital investment for lower stack operation (0 to 6 hours per day). After 6 hours/day, variable O& M is the primary cost driver. Capital equipment is properly utilized after more than 8 hours of operation per day.
- Electricity price is the most significant cost driver for LCOH sensitivity with capital investment with a much lower impact as the second cost driver.
- With respect to hydrogen storage in tube trailers, the impact of tube trailers on the LCOH storage is halved as the pressure increases from 50 bar to 150 bar. The LCOHS continues to decrease at a lower rate at higher pressures (LCOHS is halved as pressure increases from 150 bar to 425 bar). The tube trailer costs dominate compression equipment and additional utility costs, therefore high compression (425 bar) is cost-effective.
- Capital costs dominate the LCOH for the short term (0 to 6 hours). Variable O&M costs dominate over the long-term (6 to 24 hours) for pressurized hydrogen (425 bar).

- A hydrogen storage compression facility costs just over \$2MM and will cover 6 acres.
- For the hydrogen combustion turbine, for short-term energy storage, the capital investment dominates, for long-term energy storage, the fixed O&M dominates due to the cost of the hydrogen storage containers.
- LCOH and storage capacity are the cost drivers that have the biggest impact on the LCOS sensitivity.
- The hydrogen turbine has a thermal efficiency of 56%.

Thermal energy storage:

- rSOC has a round trip efficiency of 51.7% and the variable O&M dominates the LCOS.
- The cost of hydrogen significantly drives (>75%) the LCOS for rSOC.
- Storage Capacity followed by LCOH are the most significant cost drivers of the sensitivity of LCOS for rSOC.
- For the hydrogen fuel cell, variable O&M costs dominate the LCOS due to primarily the cost of hydrogen.
- LCOH followed by storage capacity are the most significant cost drivers of the sensitivity of LCOS for the hydrogen fuel cell.
- Capital Investment dominates the LCOS breakdown for both ETES and SH-TES systems.
- The most sensitive cost driver for ETES is capital investment, followed by charging price, and storage capacity.
- Charging price is the most sensitive cost driver for SH-TES with Hitec XL, followed by discharge rate, and capital investment.

Technology comparison:

- NMC & LFP Li-ion batteries have the lowest LCOS from 0 to 6 hours of energy storage duration. The battery systems dominate the LCOS even up to 10 hours except for the H_2 Fuel cell.
- The H_2 Fuel Cell has the lowest LCOS storage for long-term energy storage duration from about 7 hours up.
- SH-TES performs better than all other technologies except the H_2 fuel cell from about 9 to 15 hours of energy storage durations. The H_2 rSOC has the lowest LCOS from 16 hours upward except for the H_2 Fuel cell.
- For any storage duration longer than the optimal value for a given technology, the power equipment *(e.g.* rectifiers/inverters and transformers, fuel cells, turbines, and other equipment whose price can be defined in \$/kW-e) utilization plateaus, as the number of possible charge/discharge cycles reduces proportionally to the length of the cycle.
- Longer-duration storage requires more storage equipment, including individual battery cells, storage tanks, sensible heat storage media, and hydrogen tube trailers, whose price is defined in \$/kWh-e. This raises the total capital investment required for the project and therefore the LCOS, as the same total amount of energy can be discharged.
- Lithium-ion battery storage systems, which offer the most cost-effective form of grid-scale energy storage for durations shorter than 6 hours, require more batteries to be purchased to facilitate long-duration storage. This results in the technology scaling poorly for durations longer than 10-12 hours.

5.2 Future Work

The following points summarize possible future work:

- Refinement of methodology
  - Extend the simplified LCOS calculations performed in this report to include depreciation, financing, investment/production tax credits, etc.
  - Incorporate historical electrical price data (either actual or synthetic) for regulated and unregulated markets to add net-present-value as an additional figure of merit.
- Improvements to process modeling for hydrogen systems
  - Modeling of hybrid systems in which an FC is operated at slightly elevated pressure (2-5 bar), and the effluent is expanded through an air turbine. Previous and ongoing work at the National Energy Technology Laboratory demonstrated that such a system can produce more electricity per unit of natural gas than either a combustion turbine or FC alone [14]. Preliminary work at INL shows promising results for a similar system based on stored hydrogen.
  - The pressure-volume work used during a charging cycle to store hydrogen gas at high pressure is a sunk cost necessary to make the energy density of a hydrogen-based ESS practical. By replacing throttle valves with heat integration and turbo-expansion, it may be feasible to recover this work when regulating the inlet of the discharge cycle in what may be thought of as a time-delayed Brayton cycle.

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Appendix A

HTSE Report Generated by HYSYS

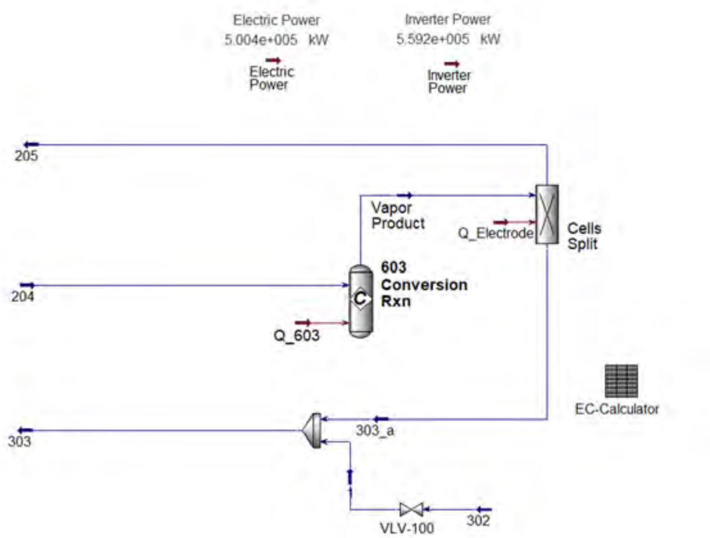

Figure A 1. HTSE sub-flowsheet rSOC.

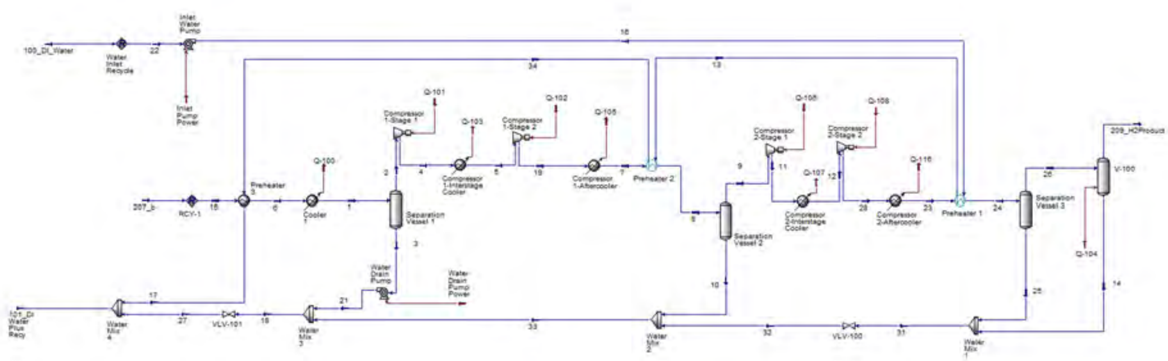

Figure A 2. HTSE sub-flowsheet H_2/H_2O Separation

HTSE-Report.pdf

aspentech	BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	500MW_HTSE_Demo_Reversible_EC_85_recuperation_CLEAN_V5i.hs
		Unit Set:	EC Mode
		Date/Time:	Tue Sep 12 11:53:49 2023

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		202_b	203	207	205_H2_H2O FRM St	204_FuelFD_Stack
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	1.0000
Temperature	(C)	322.6	699.4	58.72	790.0	790.0
Pressure	(kPa)	114.4	112.1	103.4	107.6 *	109.8
Molar Flow	(kgmole/h)	9535	9535	9535	9535	9535
Mass Flow	(kg/h)	1.567e+005	1.567e+005	3.984e+004	3.984e+004	1.567e+005
Liquid Volume Flow	(USGPM)	802.8	802.8	1150	1150	802.8
Heat Flow	(kW)	-5.501e+005	-5.123e+005	-8.395e+004	-2.458e+004	-5.026e+005

Name		302_AirFD_Stack	303_O2_N2 FRM Stac	300_b	301	304_Air_Exhaust
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	1.0000
Temperature	(C)	790.0	790.0	66.56	785.0 *	332.6
Pressure	(kPa)	109.8	107.6	116.7	112.1	105.5
Molar Flow	(kgmole/h)	1.149e+004	1.514e+004	1.149e+004	1.149e+004	1.514e+004
Mass Flow	(kg/h)	3.314e+005	4.482e+005	3.314e+005	3.314e+005	4.482e+005
Liquid Volume Flow	(USGPM)	1687	2139	1687	1687	2139
Heat Flow	(kW)	7.660e+004	1.018e+005	3860	7.607e+004	3.911e+004

Name		208_Recycle	209_H2Product	202	103_Steam	300_a
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	1.0000
Temperature	(C)	74.24 *	20.00	102.7	106.0 *	49.00 *
Pressure	(kPa)	116.7 *	5628	116.7	116.7	101.3 *
Molar Flow	(kgmole/h)	1093 *	7309	9535	8442	1.149e+004 *
Mass Flow	(kg/h)	4567	1.480e+004	1.567e+005	1.521e+005	3.314e+005
Liquid Volume Flow	(USGPM)	131.9	928.5	802.8	671.0	1687
Heat Flow	(kW)	-9487	-555.0	-5.703e+005	-5.608e+005	2216

Name		100_DI_WaterFD	101_DI Water Plus Co	101_b	206	Air Exhaust
Vapour Fraction		0.0000	0.0000	0.1179	1.0000	1.0000
Temperature	(C)	20.00 *	48.72	104.5	332.6	101.2
Pressure	(kPa)	101.3 *	121.5	119.1	105.5	101.3
Molar Flow	(kgmole/h)	7274	8442	8442	9535	1.514e+004
Mass Flow	(kg/h)	1.310e+005	1.521e+005	1.521e+005	3.984e+004	4.482e+005
Liquid Volume Flow	(USGPM)	578.1	671.0	671.0	1150	2139
Heat Flow	(kW)	-5.791e+005	-6.669e+005	-6.453e+005	-6.241e+004	9407

Name		300_c	304_b	300_Air_Inlet	208	207_b
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	1.0000
Temperature	(C)	166.3 *	176.3	49.00 *	58.72	58.72
Pressure	(kPa)	114.4	103.4	101.3 *	103.4	103.4
Molar Flow	(kgmole/h)	1.149e+004	1.514e+004	1.149e+004	1093	8442
Mass Flow	(kg/h)	3.314e+005	4.482e+005	3.314e+005	4567	3.527e+004
Liquid Volume Flow	(USGPM)	1687	2139	1687	131.9	1018
Heat Flow	(kW)	1.333e+004	1.888e+004	2216	-9625	-7.433e+004

Name		208_b	Process Steam from N	Condensate Return	CoolingWater	
Vapour Fraction		1.0000	1.0000 *	0.0000 *	0.0000	
Temperature	(C)	74.24	184.4	183.5	15.00 *	
Pressure	(kPa)	116.7	1103 *	1081	101.3 *	
Molar Flow	(kgmole/h)	1093	8326	8326	8904	
Mass Flow	(kg/h)	4567	1.500e+005	1.500e+005	1.604e+005 *	
Liquid Volume Flow	(USGPM)	131.9	661.7	661.7	707.6	
Heat Flow	(kW)	-9487	-5.480e+005	-6.325e+005	-7.098e+005	

Workbook: Case (Main) (continued)

Compositions

Fluid Pkg: Basis-1

Name	202_b	203	207	205_H2_H2O FRM St	204_FuelFD_Stack
Comp Mole Frac (H2O)	0.9008	0.9008	0.1351	0.1351	0.9008
Comp Mole Frac (Hydrogen)	0.0992	0.0992	0.8649	0.8649	0.0992
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	302_AirFD_Stack	303_O2_N2 FRM Stac	300_b	301	304_Air_Exhaust
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000 *	0.0000
Comp Mole Frac (Hydrogen)	0.0000	0.0000	0.0000	0.0000 *	0.0000
Comp Mole Frac (Nitrogen)	0.7900	0.5995	0.7900	0.7900 *	0.5995
Comp Mole Frac (Oxygen)	0.2100	0.4005	0.2100	0.2100 *	0.4005
Name	208_Recycle	209_H2Product	202	103_Steam	300_a
Comp Mole Frac (H2O)	0.1351 *	0.0005	0.9008	1.0000	0.0000 *
Comp Mole Frac (Hydrogen)	0.8649 *	0.9995	0.0992	0.0000	0.0000 *
Comp Mole Frac (Nitrogen)	0.0000 *	0.0000	0.0000	0.0000	0.7900 *
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.2100 *
Name	100_DI_WaterFD	101_DI Water Plus Co	101_b	206	Air Exhaust
Comp Mole Frac (H2O)	1.0000 *	1.0000	1.0000	0.1351	0.0000
Comp Mole Frac (Hydrogen)	0.0000 *	0.0000	0.0000	0.8649	0.0000
Comp Mole Frac (Nitrogen)	0.0000 *	0.0000	0.0000	0.0000	0.5995
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.4005
Name	300_c	304_b	300_Air_Inlet	208	207_b
Comp Mole Frac (H2O)	-0.0000	0.0000	0.0000 *	0.1351	0.1351
Comp Mole Frac (Hydrogen)	-0.0000	0.0000	0.0000 *	0.8649	0.8649
Comp Mole Frac (Nitrogen)	0.7900	0.5995	0.7900 *	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.2100	0.4005	0.2100 *	0.0000	0.0000
Name	208_b	Process Steam from N	Condensate Return	CoolingWater	
Comp Mole Frac (H2O)	0.1351	1.0000 *	1.0000	1.0000 *	
Comp Mole Frac (Hydrogen)	0.8649	0.0000 *	0.0000	0.0000 *	
Comp Mole Frac (Nitrogen)	0.0000	0.0000 *	0.0000	0.0000 *	
Comp Mole Frac (Oxygen)	0.0000	0.0000 *	0.0000	0.0000 *	

Energy Streams

Fluid Pkg: All

Name	Q_601	Q_602	Air_Blower_Power	Q-100	
Heat Flow (kW)	9700	531.9	1644	137.7	

Workbook: rSOC Stack (rSOC)

Material Streams

Fluid Pkg: All

Name	Vapor Product @rSO(	Liq @rSOC	303_a @rSOC	205 @rSOC	204 @rSOC
Vapour Fraction	1.0000	0.0000	1.0000	1.0000	1.0000
Temperature (C)	790.0 *	790.0	790.0	790.0	790.0
Pressure (kPa)	107.6	107.6	107.6	107.6	109.8
Molar Flow (kgmole/h)	1.319e+004	0.0000	3650	9535	9535
Mass Flow (kg/h)	1.567e+005	0.0000	1.168e+005	3.984e+004	1.567e+005
Liquid Volume Flow (USGPM)	1602	0.0000	452.1	1150	802.8
Heat Flow (kW)	667.6	0.0000	2.525e+004	-2.458e+004	-5.026e+005

Workbook: rSOC Stack (rSOC) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		303 @rSOC	302 @rSOC	1 @rSOC		
Vapour Fraction		1.0000	1.0000	1.0000		
Temperature	(C)	790.0	790.0	790.0		
Pressure	(kPa)	107.6	109.8	107.6		
Molar Flow	(kgmole/h)	1.514e+004	1.149e+004	1.149e+004		
Mass Flow	(kg/h)	4.482e+005	3.314e+005	3.314e+005		
Liquid Volume Flow	(USGPM)	2139	1687	1687		
Heat Flow	(kW)	1.018e+005	7.660e+004	7.660e+004		

Compositions

Fluid Pkg: All

Name	Vapor Product @rSOC	Liq @rSOC	303_a @rSOC	205 @rSOC	204 @rSOC
Comp Mole Frac (H2O)	0.0977	0.0977	0.0000	0.1351	0.9008
Comp Mole Frac (Hydrogen)	0.6254	0.6254	0.0000	0.8649	0.0992
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.2768	0.2768	1.0000	0.0000	0.0000
Name	303 @rSOC	302 @rSOC	1 @rSOC		
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000		
Comp Mole Frac (Hydrogen)	0.0000	0.0000	0.0000		
Comp Mole Frac (Nitrogen)	0.5995	0.7900	0.7900		
Comp Mole Frac (Oxygen)	0.4005	0.2100	0.2100		

Energy Streams

Fluid Pkg: All

Name		Q_603 @rSOC	Q_Electrode @rSOC	Electric Power @rSOC	Inverter Power @rSOC	
Heat Flow	(kW)	5.032e+005	0.0000 *	5.004e+005	5.592e+005	

Workbook: Water-Hydrogen Separation (H2/H2O)

Material Streams

Fluid Pkg: All

Name		100_DI_Water @H2/H	207_b @H2/H2O	2 @H2/H2O	3 @H2/H2O	4 @H2/H2O
Vapour Fraction		0.0000	1.0000	1.0000	0.0000	1.0000
Temperature	(C)	20.00	58.72	40.00	40.00	183.2 *
Pressure	(kPa)	101.3	103.4	99.27	99.27	278.0
Molar Flow	(kgmole/h)	7274	8442	7888	559.2	7888
Mass Flow	(kg/h)	1.310e+005	3.527e+004	2.522e+004	1.007e+004	2.522e+004
Liquid Volume Flow	(USGPM)	578.1	1018	974.5	44.45	974.5
Heat Flow	(kW)	-5.791e+005	-7.433e+004	-3.816e+004	-4.428e+004	-2.905e+004
Name		5 @H2/H2O	7 @H2/H2O	8 @H2/H2O	9 @H2/H2O	10 @H2/H2O
Vapour Fraction		1.0000 *	0.9523	0.9356	1.0000	0.0000
Temperature	(C)	60.50	60.50	40.00 *	40.00	40.00
Pressure	(kPa)	278.0	762.7	747.5	747.5	747.5
Molar Flow	(kgmole/h)	7888	7888	7888	7380	507.8
Mass Flow	(kg/h)	2.522e+004	2.522e+004	2.522e+004	1.607e+004	9149
Liquid Volume Flow	(USGPM)	974.5	974.5	974.5	934.1	40.36
Heat Flow	(kW)	-3.687e+004	-4.135e+004	-4.433e+004	-4122	-4.021e+004

Workbook: Water-Hydrogen Separation (H2/H2O) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		11 @H2/H2O	12 @H2/H2O	23 @H2/H2O	24 @H2/H2O	25 @H2/H2O
Vapour Fraction		1.0000	1.0000 *	0.9941	0.9915	0.0000
Temperature	(C)	185.4 *	59.68	59.68	40.00 *	40.00
Pressure	(kPa)	2093	2093	5743	5628	5628
Molar Flow	(kgmole/h)	7380	7380	7380	7380	62.44
Mass Flow	(kg/h)	1.607e+004	1.607e+004	1.607e+004	1.607e+004	1125
Liquid Volume Flow	(USGPM)	934.1	934.1	934.1	934.1	4.963
Heat Flow	(kW)	4457	-2971	-3475	-4869	-4942
Name		26 @H2/H2O	209_H2Product @H2/I	14 @H2/H2O	15 @H2/H2O	16 @H2/H2O
Vapour Fraction		1.0000	1.0000	0.0000	1.0000	0.0000
Temperature	(C)	40.00	20.00 *	20.00	58.66 *	20.00
Pressure	(kPa)	5628	5628	5628	103.4 *	126.5
Molar Flow	(kgmole/h)	7317	7309	8.026	8447 *	7305
Mass Flow	(kg/h)	1.494e+004	1.480e+004	144.6	3.529e+004	1.316e+005
Liquid Volume Flow	(USGPM)	929.2	928.5	0.6379	1019	580.6
Heat Flow	(kW)	73.39	-555.0	-638.8	-7.438e+004	-5.815e+005
Name		17 @H2/H2O	18 @H2/H2O	19 @H2/H2O	21 @H2/H2O	22 @H2/H2O
Vapour Fraction		0.0000	0.0000	1.0000	0.0000	0.0000
Temperature	(C)	50.07	39.95	212.7 *	40.06	20.00 *
Pressure	(kPa)	121.5	747.5	778.3	747.5	101.3 *
Molar Flow	(kgmole/h)	7305	1138	7888	559.2	7305 *
Mass Flow	(kg/h)	1.316e+005	2.049e+004	2.522e+004	1.007e+004	1.316e+005
Liquid Volume Flow	(USGPM)	580.6	90.41	974.5	44.45	580.6
Heat Flow	(kW)	-5.768e+005	-9.007e+004	-2.716e+004	-4.428e+004	-5.815e+005
Name		28 @H2/H2O	31 @H2/H2O	32 @H2/H2O	33 @H2/H2O	101_DI Water Plus Re
Vapour Fraction		1.0000	0.0000	0.0001	0.0000	0.0000
Temperature	(C)	214.2 *	37.72	38.80	39.85	48.72
Pressure	(kPa)	5860	5628	747.5	747.5	121.5 *
Molar Flow	(kgmole/h)	7380	70.47	70.47	578.3	8442
Mass Flow	(kg/h)	1.607e+004	1269	1269	1.042e+004	1.521e+005
Liquid Volume Flow	(USGPM)	934.1	5.601	5.601	45.96	671.0
Heat Flow	(kW)	6214	-5581	-5581	-4.579e+004	-6.669e+005
Name		13 @H2/H2O	34 @H2/H2O	27 @H2/H2O	6 @H2/H2O	1 @H2/H2O
Vapour Fraction		0.0000	0.0000	0.0000	1.0000	0.9338
Temperature	(C)	28.84	47.74	40.09	53.29	40.00 *
Pressure	(kPa)	126.5	124.0	121.5	101.3	99.27
Molar Flow	(kgmole/h)	7305	7305	1138	8447	8447
Mass Flow	(kg/h)	1.316e+005	1.316e+005	2.049e+004	3.529e+004	3.529e+004
Liquid Volume Flow	(USGPM)	580.6	580.6	90.41	1019	1019
Heat Flow	(kW)	-5.802e+005	-5.772e+005	-9.007e+004	-7.474e+004	-8.244e+004
Name		pipeline @H2/H2O	boosted1 @H2/H2O	stored1 @H2/H2O	boosted2 @H2/H2O	stored2 @H2/H2O
Vapour Fraction		1.0000	1.0000	0.9998	1.0000	0.9997
Temperature	(C)	20.00 *	157.9	20.00 *	159.4	20.00 *
Pressure	(kPa)	5628 *	1.576e+004	1.544e+004 *	4.325e+004	4.238e+004 *
Molar Flow	(kgmole/h)	7309 *	7309	7309	7309	7309
Mass Flow	(kg/h)	1.480e+004	1.480e+004	1.480e+004	1.480e+004	1.480e+004
Liquid Volume Flow	(USGPM)	928.5	928.5	928.5	928.5	928.5
Heat Flow	(kW)	-555.0	7661	-531.8	8238	-194.1

Workbook: Water-Hydrogen Separation (H2/H2O) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		in @H2/H2O	out @H2/H2O	cwin @H2/H2O	cwout @H2/H2O	
Vapour Fraction		1.0000	0.9997	0.0000	0.0000	
Temperature	(C)	159.4 *	20.00 *	15.00 *	40.00 *	
Pressure	(kPa)	4.325e+004 *	4.238e+004 *	120.0	100.0 *	
Molar Flow	(kgmole/h)	7309 *	7309 *	1.563e+004	1.563e+004	
Mass Flow	(kg/h)	1.480e+004	1.480e+004	2.815e+005	2.815e+005	
Liquid Volume Flow	(USGPM)	928.5	928.5	1242	1242	
Heat Flow	(kW)	8238	-194.1	-1.246e+006	-1.237e+006	

Compositions

Fluid Pkg: All

Name	100_DI_Water @H2/H	207_b @H2/H2O	2 @H2/H2O	3 @H2/H2O	4 @H2/H2O
Comp Mole Frac (H2O)	1.0000	0.1351	0.0738	1.0000	0.0738
Comp Mole Frac (Hydrogen)	0.0000	0.8649	0.9262	0.0000	0.9262
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	5 @H2/H2O	7 @H2/H2O	8 @H2/H2O	9 @H2/H2O	10 @H2/H2O
Comp Mole Frac (H2O)	0.0738	0.0738	0.0738	0.0101	1.0000
Comp Mole Frac (Hydrogen)	0.9262	0.9262	0.9262	0.9899	0.0000
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	11 @H2/H2O	12 @H2/H2O	23 @H2/H2O	24 @H2/H2O	25 @H2/H2O
Comp Mole Frac (H2O)	0.0101	0.0101	0.0101	0.0101	0.9999
Comp Mole Frac (Hydrogen)	0.9899	0.9899	0.9899	0.9899	0.0001
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	26 @H2/H2O	209_H2Product @H2/	14 @H2/H2O	15 @H2/H2O	16 @H2/H2O
Comp Mole Frac (H2O)	0.0016	0.0005	0.9999	0.1351 *	1.0000 *
Comp Mole Frac (Hydrogen)	0.9984	0.9995	0.0001	0.8649 *	0.0000 *
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000 *	0.0000 *
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000 *	0.0000 *
Name	17 @H2/H2O	18 @H2/H2O	19 @H2/H2O	21 @H2/H2O	22 @H2/H2O
Comp Mole Frac (H2O)	1.0000	1.0000	0.0738	1.0000	1.0000 *
Comp Mole Frac (Hydrogen)	0.0000	0.0000	0.9262	0.0000	0.0000 *
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000 *
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000 *
Name	28 @H2/H2O	31 @H2/H2O	32 @H2/H2O	33 @H2/H2O	101_DI Water Plus Re
Comp Mole Frac (H2O)	0.0101	0.9999	0.9999	1.0000	1.0000
Comp Mole Frac (Hydrogen)	0.9899	0.0001	0.0001	0.0000	0.0000
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	13 @H2/H2O	34 @H2/H2O	27 @H2/H2O	6 @H2/H2O	1 @H2/H2O
Comp Mole Frac (H2O)	1.0000	1.0000	1.0000	0.1351	0.1351
Comp Mole Frac (Hydrogen)	0.0000	0.0000	0.0000	0.8649	0.8649
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	pipeline @H2/H2O	boosted1 @H2/H2O	stored1 @H2/H2O	boosted2 @H2/H2O	stored2 @H2/H2O
Comp Mole Frac (H2O)	0.0005 *	0.0005	0.0005	0.0005	0.0005
Comp Mole Frac (Hydrogen)	0.9995 *	0.9995	0.9995	0.9995	0.9995
Comp Mole Frac (Nitrogen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000

aspentech	BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	500MW_HTSE_Demo_Reversible_EC_85_recuperation_CLEAN_V5i.hs
		Unit Set:	EC Mode
		Date/Time:	Tue Sep 12 11:53:49 2023

Workbook: Water-Hydrogen Separation (H2/H2O) (continued)

Compositions (continued)

Fluid Pkg: All

Name	in @H2/H2O	out @H2/H2O	cwin @H2/H2O	cwout @H2/H2O	
Comp Mole Frac (H2O)	0.0005 *	0.0005 *	1.0000 *	1.0000	
Comp Mole Frac (Hydrogen)	0.9995 *	0.9995 *	0.0000 *	0.0000	
Comp Mole Frac (Nitrogen)	0.0000 *	0.0000 *	0.0000 *	0.0000	
Comp Mole Frac (Oxygen)	0.0000 *	0.0000 *	0.0000 *	0.0000	

Energy Streams

Fluid Pkg: All

Name	Q-101 @H2/H2O	Q-102 @H2/H2O	Q-103 @H2/H2O	Q-105 @H2/H2O	Q-106 @H2/H2O
Heat Flow (kW)	9116	9715	7826	1.419e+004	8579
Name	Q-107 @H2/H2O	Q-108 @H2/H2O	Q-116 @H2/H2O	Q-104 @H2/H2O	Water Drain Pump Po
Heat Flow (kW)	7427	9184	9688	-1267	2.429
Name	Inlet Pump Power @H	Q-100 @H2/H2O	boost1 @H2/H2O	boost2 @H2/H2O	chill1 @H2/H2O
Heat Flow (kW)	1.215	7700	8216	8770	8193
Name	chill2 @H2/H2O				
Heat Flow (kW)	8432				

 * Specified by user.

Appendix B

Combustion Turbine Report Generated by HYSYS

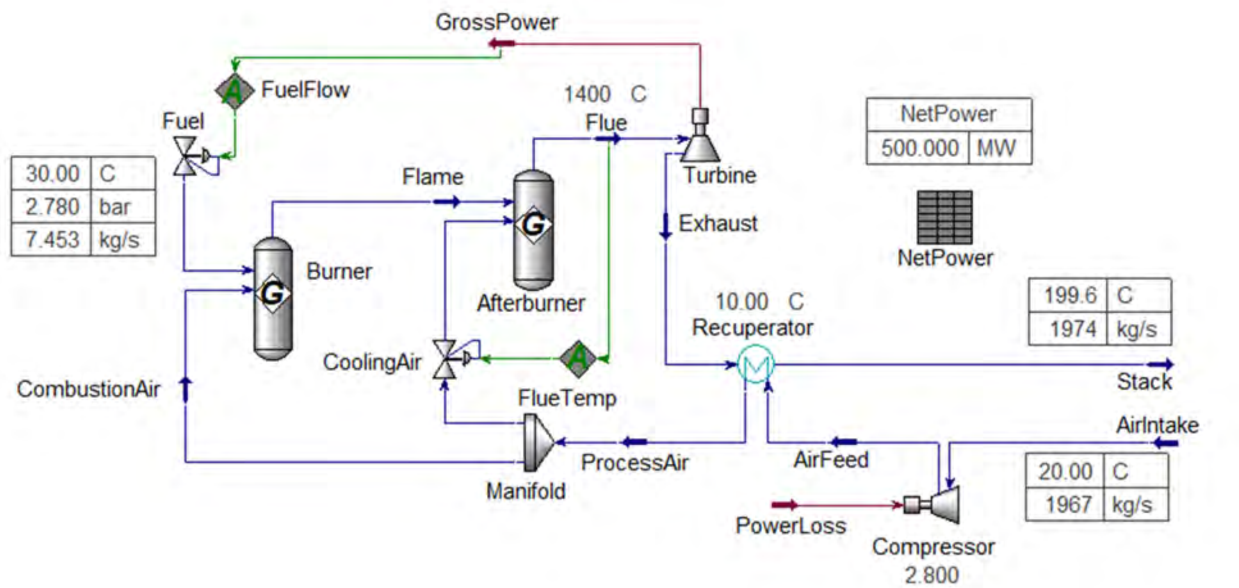

Figure B 1: Combustion Turbine Model. This figure is identical to Figure 11.

H2CT-Report.pdf

aspentech	BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	500MWe_HydrogenTurbine_recuperated.hsc
		Unit Set:	AmeyS2e
		Date/Time:	Wed Sep 27 09:15:46 2023

Material Stream: Fuel

Fluid Package: CombustionTurbineProce

Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	30.00 *	30.00			
Pressure:	(bar)	2.780	2.780			
Molar Flow	(kgmole/h)	1.331e+004	1.331e+004			
Mass Flow	(kg/s)	7.453 *	7.453			
Std Ideal Liq Vol Flow	(m3/h)	384.1	384.1			
Molar Enthalpy	(kJ/kgmole)	142.0	142.0			
Molar Entropy	(kJ/kgmole-C)	115.1	115.1			
Heat Flow	(MW)	0.5248	0.5248			
Liq Vol Flow @Std Cond	(m3/h)	3.148e+005 *	3.148e+005			

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydrogen	13308.4696	1.0000	26829.8751	1.0000	384.0570	1.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	13308.4696	1.0000	26829.8751	1.0000	384.0570	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydrogen	13308.4696	1.0000	26829.8751	1.0000	384.0570	1.0000
Nitrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	13308.4696	1.0000	26829.8751	1.0000	384.0570	1.0000

Aspen Technology Inc. Aspen HYSYS Version 11 Page 1 of 16

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* Specified by user.

aspentech	BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	500MWe_HydrogenTurbine_recuperated.hsc
		Unit Set:	AmeyS2e
		Date/Time:	Wed Sep 27 09:15:46 2023

Material Stream: AirIntake

Fluid Package: CombustionTurbineProce

Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	20.00 *	20.00			
Pressure:	(bar)	1.013 *	1.013			
Molar Flow	(kgmole/h)	2.465e+005	2.465e+005			
Mass Flow	(kg/s)	1967	1967			
Std Ideal Liq Vol Flow	(m3/h)	8178	8178			
Molar Enthalpy	(kJ/kgmole)	-2958	-2958			
Molar Entropy	(kJ/kgmole-C)	152.0	152.0			
Heat Flow	(MW)	-202.5	-202.5			
Liq Vol Flow @Std Cond	(m3/h)	5.824e+006 *	5.824e+006			

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2857.0521 *	0.0116 *	51470.0804 *	0.0073 *	51.5739 *	0.0063 *
Hydrogen	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
Nitrogen	192493.4427 *	0.7808 *	5.392318905e+06 *	0.7615 *	6687.1188 *	0.8177 *
Oxygen	51169.1430 *	0.2076 *	1.637412576e+06 *	0.2312 *	1439.2558 *	0.1760 *
Methane	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
Ethane	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
CO2	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
N2O	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
NO2	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
NO	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
SO2	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
H2S	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
CO	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
H2O2	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
Ammonia	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *	0.0000 *
Total	246519.6378	1.0000	7.081201561e+06	1.0000	8177.9485	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2857.0521	0.0116	51470.0804	0.0073	51.5739	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	192493.4427	0.7808	5.392318905e+06	0.7615	6687.1188	0.8177
Oxygen	51169.1430	0.2076	1.637412576e+06	0.2312	1439.2558	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	246519.6378	1.0000	7.081201561e+06	1.0000	8177.9485	1.0000

* Specified by user.

Material Stream: BurnerCondensate

Fluid Package: CombustionTurbineProce

Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase
Vapour / Phase Fraction		0.0000	0.0000	0.5000	0.5000
Temperature:	(C)	2387	2387	2387	2387
Pressure:	(bar)	2.730	2.730	2.730	2.730
Molar Flow	(kgmole/h)	0.0000	0.0000	0.0000	0.0000
Mass Flow	(kg/s)	0.0000	0.0000	0.0000	0.0000
Std Ideal Liq Vol Flow	(m3/h)	0.0000	0.0000	0.0000	0.0000
Molar Enthalpy	(kJ/kgmole)	2.651e+004	2.651e+004	2.651e+004	2.651e+004
Molar Entropy	(kJ/kgmole-C)	233.6	233.6	233.6	233.6
Heat Flow	(MW)	0.0000	0.0000	0.0000	0.0000
Liq Vol Flow @Std Cond	(m3/h)	0.0000 *	0.0000	0.0000	0.0000

COMPOSITION

Overall Phase

Vapour Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.2861	0.0000	0.2072	0.0000	0.1519
Hydrogen	0.0000	0.0162	0.0000	0.0013	0.0000	0.0138
Nitrogen	0.0000	0.6547	0.0000	0.7371	0.0000	0.6691
Oxygen	0.0000	0.0318	0.0000	0.0408	0.0000	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0112	0.0000	0.0135	0.0000	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Vapour Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.2861	0.0000	0.2072	0.0000	0.1519
Hydrogen	0.0000	0.0162	0.0000	0.0013	0.0000	0.0138
Nitrogen	0.0000	0.6547	0.0000	0.7371	0.0000	0.6691
Oxygen	0.0000	0.0318	0.0000	0.0408	0.0000	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0112	0.0000	0.0135	0.0000	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

* Specified by user.

Material Stream: BurnerCondensate (continue

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

COMPOSITION

Liquid Phase

Phase Fraction 0.5000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.2861	0.0000	0.2072	0.0000	0.1519
Hydrogen	0.0000	0.0162	0.0000	0.0013	0.0000	0.0138
Nitrogen	0.0000	0.6547	0.0000	0.7371	0.0000	0.6691
Oxygen	0.0000	0.0318	0.0000	0.0408	0.0000	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0112	0.0000	0.0135	0.0000	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Aqueous Phase

Phase Fraction 0.5000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.2861	0.0000	0.2072	0.0000	0.1519
Hydrogen	0.0000	0.0162	0.0000	0.0013	0.0000	0.0138
Nitrogen	0.0000	0.6547	0.0000	0.7371	0.0000	0.6691
Oxygen	0.0000	0.0318	0.0000	0.0408	0.0000	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0112	0.0000	0.0135	0.0000	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Material Stream: Flue

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase
Vapour / Phase Fraction		1.0000	1.0000	0.0000	0.0000
Temperature:	(C)	1400	1400	1400	1400
Pressure:	(bar)	2.730	2.730	2.730	2.730
Molar Flow	(kgmole/h)	2.532e+005	2.532e+005	0.0000	0.0000
Mass Flow	(kg/s)	1974	1974	0.0000	0.0000
Std Ideal Liq Vol Flow	(m3/h)	8478	8478	0.0000	0.0000
Molar Enthalpy	(kJ/kgmole)	3.049e+004	3.049e+004	3.049e+004	3.049e+004
Molar Entropy	(kJ/kgmole-C)	202.5	202.5	202.5	202.5

Material Stream: Flue (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase	
Heat Flow	(MW)	2144	2144	0.0000	0.0000	
Liq Vol Flow @Std Cond	(m3/h)	5.977e+006 *	5.977e+006	0.0000	0.0000	

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	16165.1670	0.0639	291217.1082	0.0410	291.8048	0.0344
Hydrogen	0.3486	0.0000	0.7027	0.0000	0.0101	0.0000
Nitrogen	192174.0963	0.7591	5.383373054e+06	0.7574	6676.0249	0.7874
Oxygen	44194.2520	0.1746	1.414216065e+06	0.1990	1243.0701	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0486	0.0000	2.1409	0.0000	0.0026	0.0000
NO2	3.0108	0.0000	138.5141	0.0000	0.0942	0.0000
NO	635.5847	0.0025	19071.3557	0.0027	267.3953	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0060	0.0000	0.2053	0.0000	0.0001	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	253172.5141	1.0000	7.108019145e+06	1.0000	8478.4022	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	16165.1670	0.0639	291217.1082	0.0410	291.8048	0.0344
Hydrogen	0.3486	0.0000	0.7027	0.0000	0.0101	0.0000
Nitrogen	192174.0963	0.7591	5.383373054e+06	0.7574	6676.0249	0.7874
Oxygen	44194.2520	0.1746	1.414216065e+06	0.1990	1243.0701	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0486	0.0000	2.1409	0.0000	0.0026	0.0000
NO2	3.0108	0.0000	138.5141	0.0000	0.0942	0.0000
NO	635.5847	0.0025	19071.3557	0.0027	267.3953	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0060	0.0000	0.2053	0.0000	0.0001	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	253172.5141	1.0000	7.108019145e+06	1.0000	8478.4022	1.0000

Liquid Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0639	0.0000	0.0410	0.0000	0.0344
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.7591	0.0000	0.7574	0.0000	0.7874
Oxygen	0.0000	0.1746	0.0000	0.1990	0.0000	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

* Specified by user.

Material Stream: Flue (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

COMPOSITION

Liquid Phase (continued)

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0025	0.0000	0.0027	0.0000	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Aqueous Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0639	0.0000	0.0410	0.0000	0.0344
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.7591	0.0000	0.7574	0.0000	0.7874
Oxygen	0.0000	0.1746	0.0000	0.1990	0.0000	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0025	0.0000	0.0027	0.0000	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Material Stream: Exhaust

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase
Vapour / Phase Fraction		1.0000	1.0000
Temperature:	(C)	1095	1095
Pressure:	(bar)	1.033	1.033
Molar Flow	(kgmole/h)	2.532e+005	2.532e+005
Mass Flow	(kg/s)	1974	1974
Std Ideal Liq Vol Flow	(m3/h)	8478	8478
Molar Enthalpy	(kJ/kgmole)	1.960e+004	1.960e+004
Molar Entropy	(kJ/kgmole-C)	203.4	203.4
Heat Flow	(MW)	1378	1378
Liq Vol Flow @Std Cond	(m3/h)	5.977e+006 *	5.977e+006

* Specified by user.

Material Stream: Exhaust (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	16165.1670	0.0639	291217.1082	0.0410	291.8048	0.0344
Hydrogen	0.3486	0.0000	0.7027	0.0000	0.0101	0.0000
Nitrogen	192174.0963	0.7591	5.383373054e+06	0.7574	6676.0249	0.7874
Oxygen	44194.2520	0.1746	1.414216065e+06	0.1990	1243.0701	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0486	0.0000	2.1409	0.0000	0.0026	0.0000
NO2	3.0108	0.0000	138.5141	0.0000	0.0942	0.0000
NO	635.5847	0.0025	19071.3557	0.0027	267.3953	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0060	0.0000	0.2053	0.0000	0.0001	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	253172.5141	1.0000	7.108019145e+06	1.0000	8478.4022	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	16165.1670	0.0639	291217.1082	0.0410	291.8048	0.0344
Hydrogen	0.3486	0.0000	0.7027	0.0000	0.0101	0.0000
Nitrogen	192174.0963	0.7591	5.383373054e+06	0.7574	6676.0249	0.7874
Oxygen	44194.2520	0.1746	1.414216065e+06	0.1990	1243.0701	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0486	0.0000	2.1409	0.0000	0.0026	0.0000
NO2	3.0108	0.0000	138.5141	0.0000	0.0942	0.0000
NO	635.5847	0.0025	19071.3557	0.0027	267.3953	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0060	0.0000	0.2053	0.0000	0.0001	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	253172.5141	1.0000	7.108019145e+06	1.0000	8478.4022	1.0000

Material Stream: AirFeed

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	151.4	151.4			
Pressure:	(bar)	2.836	2.836			
Molar Flow	(kgmole/h)	2.465e+005	2.465e+005			
Mass Flow	(kg/s)	1967	1967			
Std Ideal Liq Vol Flow	(m3/h)	8178	8178			
Molar Enthalpy	(kJ/kgmole)	926.1	926.1			
Molar Entropy	(kJ/kgmole-C)	154.4	154.4			

* Specified by user.

Material Stream: AirFeed (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Heat Flow	(MW)	63.42	63.42			
Liq Vol Flow @Std Cond	(m3/h)	5.824e+006 *	5.824e+006			

COMPOSITION

Overall Phase Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2857.0521	0.0116	51470.0804	0.0073	51.5739	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	192493.4427	0.7808	5.392318905e+06	0.7615	6687.1188	0.8177
Oxygen	51169.1430	0.2076	1.637412576e+06	0.2312	1439.2558	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	246519.6378	1.0000	7.081201561e+06	1.0000	8177.9485	1.0000

Vapour Phase Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2857.0521	0.0116	51470.0804	0.0073	51.5739	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	192493.4427	0.7808	5.392318905e+06	0.7615	6687.1188	0.8177
Oxygen	51169.1430	0.2076	1.637412576e+06	0.2312	1439.2558	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	246519.6378	1.0000	7.081201561e+06	1.0000	8177.9485	1.0000

Material Stream: CombustionAir

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	1085	1085			
Pressure:	(bar)	2.780	2.780			

* Specified by user.

Material Stream: CombustionAir (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Molar Flow	(kgmole/h)	3.847e+004	3.847e+004			
Mass Flow	(kg/s)	307.0	307.0			
Std Ideal Liq Vol Flow	(m3/h)	1276	1276			
Molar Enthalpy	(kJ/kgmole)	3.130e+004	3.130e+004			
Molar Entropy	(kJ/kgmole-C)	191.8	191.8			
Heat Flow	(MW)	334.5	334.5			
Liq Vol Flow @Std Cond	(m3/h)	9.088e+005 *	9.088e+005			

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	445.8506	0.0116	8032.0438	0.0073	8.0483	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	30039.1170	0.7808	841485.7992	0.7615	1043.5428	0.8177
Oxygen	7985.0817	0.2076	255522.6155	0.2312	224.5997	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	38470.0494	1.0000	1.105040459e+06	1.0000	1276.1908	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	445.8506	0.0116	8032.0438	0.0073	8.0483	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	30039.1170	0.7808	841485.7992	0.7615	1043.5428	0.8177
Oxygen	7985.0817	0.2076	255522.6155	0.2312	224.5997	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	38470.0494	1.0000	1.105040459e+06	1.0000	1276.1908	1.0000

* Specified by user.

aspentech	BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	500MWe_HydrogenTurbine_recuperated.hsc
		Unit Set:	AmeyS2e
		Date/Time:	Wed Sep 27 09:15:46 2023

Material Stream: CoolingAir

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	1085	1085			
Pressure:	(bar)	2.780	2.780			
Molar Flow	(kgmole/h)	2.080e+005	2.080e+005			
Mass Flow	(kg/s)	1660 *	1660			
Std Ideal Liq Vol Flow	(m3/h)	6902	6902			
Molar Enthalpy	(kJ/kgmole)	3.130e+004	3.130e+004			
Molar Entropy	(kJ/kgmole-C)	191.8	191.8			
Heat Flow	(MW)	1809	1809			
Liq Vol Flow @Std Cond	(m3/h)	4.915e+006 *	4.915e+006			

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2411.2015	0.0116	43438.0365	0.0073	43.5257	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	162454.3257	0.7808	4.550833105e+06	0.7615	5643.5760	0.8177
Oxygen	43184.0613	0.2076	1.381889960e+06	0.2312	1214.6561	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	208049.5884	1.0000	5.976161102e+06	1.0000	6901.7578	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2411.2015	0.0116	43438.0365	0.0073	43.5257	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	162454.3257	0.7808	4.550833105e+06	0.7615	5643.5760	0.8177
Oxygen	43184.0613	0.2076	1.381889960e+06	0.2312	1214.6561	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	208049.5884	1.0000	5.976161102e+06	1.0000	6901.7578	1.0000

* Specified by user.

aspentech

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	500MWe_HydrogenTurbine_recuperated.hsc
Unit Set:	AmeyS2e
Date/Time:	Wed Sep 27 09:15:46 2023

Material Stream: Flame

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase
Vapour / Phase Fraction		1.0000	1.0000	0.0000	0.0000
Temperature:	(C)	2387	2387	2387	2387
Pressure:	(bar)	2.730	2.730	2.730	2.730
Molar Flow	(kgmole/h)	4.549e+004	4.549e+004	0.0000	0.0000
Mass Flow	(kg/s)	314.4	314.4	0.0000	0.0000
Std Ideal Liq Vol Flow	(m3/h)	1546	1546	0.0000	0.0000
Molar Enthalpy	(kJ/kgmole)	2.651e+004	2.651e+004	2.651e+004	2.651e+004
Molar Entropy	(kJ/kgmole-C)	233.6	233.6	233.6	233.6
Heat Flow	(MW)	335.0	335.0	0.0000	0.0000
Liq Vol Flow @Std Cond	(m3/h)	1.071e+006 *	1.071e+006	0.0000	0.0000

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	13015.3926	0.2861	234473.6060	0.2072	234.9468	0.1519
Hydrogen	738.8685	0.0162	1489.5590	0.0013	21.3223	0.0138
Nitrogen	29783.6983	0.6547	834330.7540	0.7371	1034.6697	0.6691
Oxygen	1444.7455	0.0318	46231.8545	0.0408	40.6370	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0287	0.0000	1.2632	0.0000	0.0015	0.0000
NO2	0.2089	0.0000	9.6125	0.0000	0.0065	0.0000
NO	510.5698	0.0112	15320.1586	0.0135	214.8006	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0571	0.0000	1.9413	0.0000	0.0013	0.0000
Ammonia	0.0013	0.0000	0.0221	0.0000	0.0000	0.0000
Total	45493.5707	1.0000	1.131858771e+06	1.0000	1546.3858	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	13015.3926	0.2861	234473.6060	0.2072	234.9468	0.1519
Hydrogen	738.8685	0.0162	1489.5590	0.0013	21.3223	0.0138
Nitrogen	29783.6983	0.6547	834330.7540	0.7371	1034.6697	0.6691
Oxygen	1444.7455	0.0318	46231.8545	0.0408	40.6370	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0287	0.0000	1.2632	0.0000	0.0015	0.0000
NO2	0.2089	0.0000	9.6125	0.0000	0.0065	0.0000
NO	510.5698	0.0112	15320.1586	0.0135	214.8006	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0571	0.0000	1.9413	0.0000	0.0013	0.0000
Ammonia	0.0013	0.0000	0.0221	0.0000	0.0000	0.0000
Total	45493.5707	1.0000	1.131858771e+06	1.0000	1546.3858	1.0000

* Specified by user.

Material Stream: Flame (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

COMPOSITION

Liquid Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.2861	0.0000	0.2072	0.0000	0.1519
Hydrogen	0.0000	0.0162	0.0000	0.0013	0.0000	0.0138
Nitrogen	0.0000	0.6547	0.0000	0.7371	0.0000	0.6691
Oxygen	0.0000	0.0318	0.0000	0.0408	0.0000	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0112	0.0000	0.0135	0.0000	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Aqueous Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.2861	0.0000	0.2072	0.0000	0.1519
Hydrogen	0.0000	0.0162	0.0000	0.0013	0.0000	0.0138
Nitrogen	0.0000	0.6547	0.0000	0.7371	0.0000	0.6691
Oxygen	0.0000	0.0318	0.0000	0.0408	0.0000	0.0263
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0112	0.0000	0.0135	0.0000	0.1389
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Material Stream: ProcessAir

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	1085 *	1085			
Pressure:	(bar)	2.780	2.780			
Molar Flow	(kgmole/h)	2.465e+005	2.465e+005			
Mass Flow	(kg/s)	1967	1967			
Std Ideal Liq Vol Flow	(m3/h)	8178	8178			
Molar Enthalpy	(kJ/kgmole)	3.130e+004	3.130e+004			
Molar Entropy	(kJ/kgmole-C)	191.8	191.8			

* Specified by user.

Material Stream: ProcessAir (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Heat Flow	(MW)	2143	2143			
Liq Vol Flow @Std Cond	(m3/h)	5.824e+006 *	5.824e+006			

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2857.0521	0.0116	51470.0804	0.0073	51.5739	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	192493.4427	0.7808	5.392318905e+06	0.7615	6687.1188	0.8177
Oxygen	51169.1430	0.2076	1.637412576e+06	0.2312	1439.2558	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	246519.6378	1.0000	7.081201561e+06	1.0000	8177.9485	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	2857.0521	0.0116	51470.0804	0.0073	51.5739	0.0063
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	192493.4427	0.7808	5.392318905e+06	0.7615	6687.1188	0.8177
Oxygen	51169.1430	0.2076	1.637412576e+06	0.2312	1439.2558	0.1760
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	246519.6378	1.0000	7.081201561e+06	1.0000	8177.9485	1.0000

Material Stream: Stack

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase			
Vapour / Phase Fraction		1.0000	1.0000			
Temperature:	(C)	199.6	199.6			
Pressure:	(bar)	1.013 *	1.013			

Material Stream: Stack (continued)

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase
Molar Flow	(kgmole/h)	2.532e+005	2.532e+005
Mass Flow	(kg/s)	1974	1974
Std Ideal Liq Vol Flow	(m3/h)	8478	8478
Molar Enthalpy	(kJ/kgmole)	-9982	-9982
Molar Entropy	(kJ/kgmole-C)	168.9	168.9
Heat Flow	(MW)	-702.0	-702.0
Liq Vol Flow @Std Cond	(m3/h)	5.977e+006 *	5.977e+006

COMPOSITION

Overall Phase

Vapour Fraction 1.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	16165.1670	0.0639	291217.1082	0.0410	291.8048	0.0344
Hydrogen	0.3486	0.0000	0.7027	0.0000	0.0101	0.0000
Nitrogen	192174.0963	0.7591	5.383373054e+06	0.7574	6676.0249	0.7874
Oxygen	44194.2520	0.1746	1.414216065e+06	0.1990	1243.0701	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0486	0.0000	2.1409	0.0000	0.0026	0.0000
NO2	3.0108	0.0000	138.5141	0.0000	0.0942	0.0000
NO	635.5847	0.0025	19071.3557	0.0027	267.3953	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0060	0.0000	0.2053	0.0000	0.0001	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	253172.5141	1.0000	7.108019145e+06	1.0000	8478.4022	1.0000

Vapour Phase

Phase Fraction 1.000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	16165.1670	0.0639	291217.1082	0.0410	291.8048	0.0344
Hydrogen	0.3486	0.0000	0.7027	0.0000	0.0101	0.0000
Nitrogen	192174.0963	0.7591	5.383373054e+06	0.7574	6676.0249	0.7874
Oxygen	44194.2520	0.1746	1.414216065e+06	0.1990	1243.0701	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0486	0.0000	2.1409	0.0000	0.0026	0.0000
NO2	3.0108	0.0000	138.5141	0.0000	0.0942	0.0000
NO	635.5847	0.0025	19071.3557	0.0027	267.3953	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0060	0.0000	0.2053	0.0000	0.0001	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	253172.5141	1.0000	7.108019145e+06	1.0000	8478.4022	1.0000

* Specified by user.

aspentech

BATTELLE ENERGY ALLIANCE
Bedford, MA
USA

Case Name:	500MWe_HydrogenTurbine_recuperated.hsc
Unit Set:	AmeyS2e
Date/Time:	Wed Sep 27 09:15:46 2023

Material Stream: AfterburnerCondensate

Fluid Package: CombustionTurbineProce
Property Package: Peng-Robinson

CONDITIONS

		Overall	Vapour Phase	Liquid Phase	Aqueous Phase	
Vapour / Phase Fraction		0.0000	0.0000	0.5000	0.5000	
Temperature:	(C)	1400	1400	1400	1400	
Pressure:	(bar)	2.730	2.730	2.730	2.730	
Molar Flow	(kgmole/h)	0.0000	0.0000	0.0000	0.0000	
Mass Flow	(kg/s)	0.0000	0.0000	0.0000	0.0000	
Std Ideal Liq Vol Flow	(m3/h)	0.0000	0.0000	0.0000	0.0000	
Molar Enthalpy	(kJ/kgmole)	3.049e+004	3.049e+004	3.049e+004	3.049e+004	
Molar Entropy	(kJ/kgmole-C)	202.5	202.5	202.5	202.5	
Heat Flow	(MW)	0.0000	0.0000	0.0000	0.0000	
Liq Vol Flow @Std Cond	(m3/h)	0.0000 *	0.0000	0.0000	0.0000	

COMPOSITION

Overall Phase

Vapour Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0639	0.0000	0.0410	0.0000	0.0344
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.7591	0.0000	0.7574	0.0000	0.7874
Oxygen	0.0000	0.1746	0.0000	0.1990	0.0000	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0025	0.0000	0.0027	0.0000	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Vapour Phase

Phase Fraction 0.0000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0639	0.0000	0.0410	0.0000	0.0344
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.7591	0.0000	0.7574	0.0000	0.7874
Oxygen	0.0000	0.1746	0.0000	0.1990	0.0000	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0025	0.0000	0.0027	0.0000	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

* Specified by user.

aspentech	BATTELLE ENERGY ALLIANCE Bedford, MA USA	Case Name:	500MWe_HydrogenTurbine_recuperated.hsc
		Unit Set:	AmeyS2e
		Date/Time:	Wed Sep 27 09:15:46 2023

Material Stream: AfterburnerCondensate (con

Fluid Package: CombustionTurbineProce

Property Package: Peng-Robinson

COMPOSITION

Liquid Phase

Phase Fraction 0.5000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0639	0.0000	0.0410	0.0000	0.0344
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.7591	0.0000	0.7574	0.0000	0.7874
Oxygen	0.0000	0.1746	0.0000	0.1990	0.0000	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0025	0.0000	0.0027	0.0000	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Aqueous Phase

Phase Fraction 0.5000

COMPONENTS	MOLAR FLOW (kgmole/h)	MOLE FRACTION	MASS FLOW (kg/h)	MASS FRACTION	LIQUID VOLUME FLOW (m3/h)	LIQUID VOLUME FRACTION
H2O	0.0000	0.0639	0.0000	0.0410	0.0000	0.0344
Hydrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.7591	0.0000	0.7574	0.0000	0.7874
Oxygen	0.0000	0.1746	0.0000	0.1990	0.0000	0.1466
Methane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NO	0.0000	0.0025	0.0000	0.0027	0.0000	0.0315
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonia	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000

Energy Stream: GrossPower

Fluid Package: CombustionTurbineProce

Property Package: Peng-Robinson

CONDITIONS

Duty Type:	Direct Q	Duty Calculation Operation:	Turbine		
Duty SP:	766.0 MW	Minimum Available Duty:	0.0000 MW	Maximum Available Duty:	---

Energy Stream: PowerLoss

Fluid Package: CombustionTurbineProce

Property Package: Peng-Robinson

CONDITIONS

Duty Type:	Direct Q	Duty Calculation Operation:	Compressor		
Duty SP:	266.0 MW	Minimum Available Duty:	0.0000 MW	Maximum Available Duty:	---

* Specified by user.