SOUTHERN CALIFORNIA GAS COMPANY
Green H_2 Pipeline Study

Final Report

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. EXECUTIVE SUMMARY

A pre-feasibility study to develop possible solutions for Southern California Gas Company, delivering green hydrogen to potential customers in the LA Basin was undertaken by a team of SPEC Services (lead), Technip Energies, Strategen and other partners. This report presents the analysis performed on the production aspect of the work which was led by Technip Energies.

The objective of the overall study is to assess four potential green hydrogen production sites, with three cases of annual production: [redacted] of hydrogen per year. Each site is assessed independently to produce the target amount of green hydrogen.

For the first pass of the [redacted] case, a mix of photovoltaic (PV) and wind energy was assessed as a source of renewable energy. In addition, the production facility would consist of battery energy storage systems (BESS), electrolyzers, hydrogen low pressure storage (to de-couple the electrolyzers and compression) and compressors that discharge hydrogen into a pipeline.

Renewable energy time series (8760 profiles) for each site under consideration were provided by Strategen as an input to the production modeling. The analysis takes into account annual wind and solar power production profiles of each site and the design is optimized [redacted] the [redacted] while reaching at least 95% of the annual objective of production. [redacted]

Initially, the objective of [redacted] of hydrogen per year was considered as a constant required flowrate in outlet of the hydrogen pipeline. [redacted] To give some degree of freedom in the design, it is considered that the system at the outlet of the pipeline can accommodate fluctuations of flowrates, with a maximum of [redacted] From this point, the design with the minimum LCOH that allows reaching at least 95% of the annual objective of production is selected.

The value of [redacted] of maximum flowrate was determined by [redacted] This value could be optimized further with real product demand profiles at a later phase of engineering design.

The following table summarizes the obtained optimized designs for each site, for [redacted] with PV and Wind power generation:

Site	Whitewater	Blythe	Mojave	Five Points
PV array peak power	[redacted]			
Wind farm peak power				
Battery energy storage capacity				
Electrolyzer installed power				
Minimum electrolyzer power				
Volume of the LP storage				
Compressor maximum flowrate				
Year 1 potential energy production				
Year 1 energy consumption				
Year 1 percentage of curtailed energy				
Year 1 unsatisfied H_2 load				
Year 1 unsatisfied H_2 load percentage				
Total investment cost				
Levelized total cost over 20 years				
LCOH				

Table 1: [redacted]

Upon completion of the [redacted] case, a PV energy only scenario was performed. In addition to eliminating wind energy as an option [redacted]], the low end capacity was dropped to [redacted] and simulations with sensitivities and optimization around PV only, with large geological storage at downstream of the production sites were subsequently considered. [redacted]. Optimization was performed for Whitewater, and the other sites were prorated based on the PV potential. Production during the day was maximized and energy curtailment was minimized. Electrolyzers operated at minimum production capacity during night on stored energy from battery energy storage system.

[redacted]

The following table summarizes the obtained optimized designs for each site, for [redacted] with PV only power generation:

Site	**Whitewater**	**Blythe**	**Mojave**	**Five Points**
PV array peak power	[redacted]			
Wind farm peak power				
Battery energy storage capacity				
Electrolyzer installed power				
Minimum electrolyzer power				
Compressor maximum flowrate				
Year 1 potential energy production				
Year 1 energy consumption				
Year 1 percentage of curtailed energy				
Year 1 unsatisfied H_2 load				
Year 1 unsatisfied H_2 load percentage				
Total investment cost				
Levelized total cost over 20 years				
LCOH				

Table 2: [redacted]; PV only with unconstrained hydrogen storage

[redacted] Presented below is a breakdown of the CAPEX and OPEX costs for the [redacted] case for each of the sites (see Table 3).

[redacted] It was decided by the team that multiple sites with the potential to produce [redacted] each could be chosen along the pipeline corridor. [redacted]
PV energy potential of multiple sites were assessed and the production potential and cost was factored using Whitewater PV only results.

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)									
[redacted] ANNUAL PRODUCTION									
	Cost Basis	Five Points		Mojave		Whitewater		Blythe	
CAPEX		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]								
Battery Storage									
Electrolyzers									
Converters									
TOTAL CAPEX									
Project Low End (-50%)									
Project High End (+100%)									
	Cost Basis	Five Points		Mojave		Whitewater		Blythe	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]								
Battery Storage									
Electrolyzers									
Converters									
TOTAL OPEX									

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 3: [redacted] PV Only CAPEX and OPEX Costs

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)													
[redacted] ANNUAL PRODUCTION (DISTRIBUTED PRODUCTION)													
	Cost Basis	Five Points [redacted] Y		Mojave [redacted]		Whitewater - [redacted]		Blythe [redacted]		Delta - [redacted]		TOTAL - [redacted]	
CAPEX		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL CAPEX													
Project Low End (-50%)													
Project High End (+100%)													
	[redacted] Basis	Five Points		Mojave		Whitewater		Blythe		Delta		Delta	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL OPEX													

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 4: [redacted] PV Only CAPEX and OPEX Costs

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)													
[redacted] ANNUAL PRODUCTION (DISTRIBUTED PRODUCTION)													
	Cost Basis	Five Points [redacted]		Mojave - [redacted]		Whitewater [redacted]		Blythe - [redacted]		Delta - [redacted]		TOTAL [redacted] Y	
CAPEX		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL CAPEX													
Project Low End (-50%)													
Project High End (+100%)													
	Cost Basis	Five Points		Mojave		Whitewater		Blythe		Delta		Delta	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL OPEX													

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 5: [redacted] PV Only CAPEX and OPEX Costs

CONSIDERATIONS

Cost Reduction

In addition to further optimizing some of the design aspects mentioned in the report, consideration should be given to the benefits of economy of scale, federal tax credit programs for renewable energy production, power purchase agreements to sell curtailed power and monetization of oxygen. To demonstrate the benefit of these, analysis was conducted on the Whitewater. [redacted]

- [redacted]
- [redacted]

Cost Structure	Base Cost	Incentives and Commercial Strategies		
		10% Buy Down	10% RE Credit	3 cents/kWh PPA
Total Investment Cost	$ [redacted]			
Levelized O&M Cost	$			
Levelized Replacement Cost	$			
Levelized Total Cost	$			
LCOH	$			
LCOH Reduction				

Note: For PPA case, estimated cumulative credit is [redacted]

Table 6: Cost Reduction Potential ([redacted] case)

Wind Power

Wind power was utilized in the first run as originally indicated. [redacted] We believe, that it is beneficial to see this as a "base case" of the economics with the use of both green energy sources. There are two primary outcomes:

- [redacted]
- [redacted]

The LCOH provided in the previous revision of this report [redacted] we performed an additional analysis to determine the sensitivity of LCOH with [redacted]. [redacted]

Curtailment

For our initial analysis with both PV and wind energy considered, the amount of curtailed energy production is quite significant for all cases. This is an inherent characteristic of renewable energy sources and the design of the system for the lowest potential energy days vs. peak. [redacted] The LCOH calculated does not account for any benefit in the form of [redacted]. This could have made an appreciable effect on the economics, however it would not address [redacted].

The total curtailment can also be attenuated if we consider overload values for the electrolyzer. [redacted] echnip Energies has contact electrolyzer vendors to get a full understanding of overload capacities.

Gas Storage

We can reduce the curtailment by assuming a much higher production rate at peak power production (i.e. mid-day) vs. the original design [redacted]. However, this will require a very significant storage option of some form – LP, HP, liquefaction, etc. As noted in section 9.1.3, theoretically a vast LP storage could de-couple the compressors and electrolyzers and allow for more effective use of the energy available. [redacted] n evaluation with pipeline hydraulics if the storage is located away from the production site would be required. It is recommended to explore different storage options as part of a sensitivity analysis to determine the optimum solution.

Annual degradation of performance

The presented designs are optimized for year 1 but the H_2 production is decreased by the annual degradation of equipment performances. The worst annual production is found for [redacted] but the decrease is reasonable: [redacted]

Battery Storage Reduction

The optimization considered the requirement for battery storage sufficient to power the full production operations at a minimum of 5% electrolyzer capacity through the entire year, including auxiliaries and compression power requirements. [redacted] For the Whitewater case, the BESS represents approximately [redacted] of the production CAPEX, so a [redacted] reduction in the BESS would result in a [redacted] overall CAPEX reduction for the production costs in addition to lower lifetime OPEX.

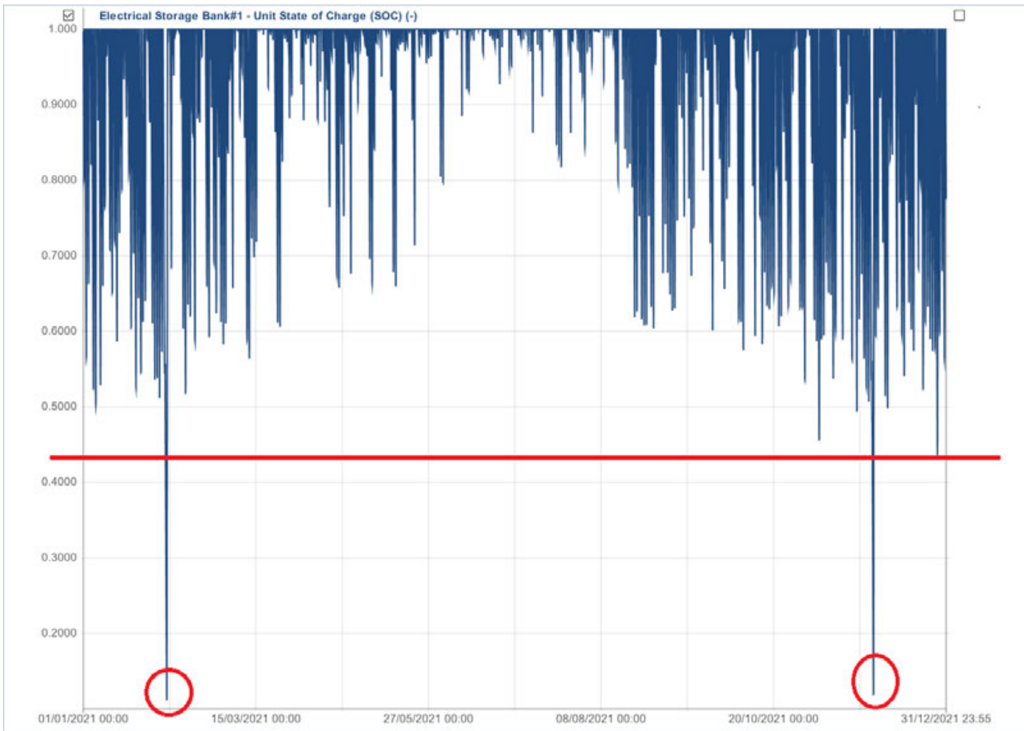


Figure 1: Battery Storage State of Charge for 1 year – Whitewater PV Only

Furthermore, there are other potential philosophies for the BESS sizing that could be considered. One option could be to eliminate battery storage altogether and instead include a grid power connection for purchasing energy when necessary. [redacted] For the Whitewater [redacted] base case, the batteries discharged a total of [redacted] MWh of energy over the first full year of production which would represent the total amount of energy that would need to be purchased. The complete economic evaluation is beyond the scope of this report but it should be considered and analyzed in detail at a later phase to determine the most economical solution.

Finally, in regards the BESS sizing criteria, the main driver is the requirement that the electrolyzers run at a minimum turndown rate [redacted]). Our analysis was based on PEM technology and assumes the minimum power consumption of 5% based on the total installed nameplate power for the electrolyzers. However, some electrolyzer manufacturers claim that their equipment can be run in a “Hot Stand-by” mode for up to 3 days at a time in which the production is effectively zero net hydrogen, but the electrolyzer stacks stay in a prepared state ready for a manual restart by local personnel. Assuming that this effectively reduces the stack power load to near zero at night, we ran the same simulation for the Whitewater [redacted] base case and the results indicated that the total energy discharged by the batteries was [redacted] over the first full year of production. [redacted]

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)									
[redacted] ANNUAL PRODUCTION - [redacted] REDUCED BATTERY CAPACITY									
	Cost Basis	Five Points		Mojave		Whitewater		Blythe	
CAPEX		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]								
Battery Storage									
Electrolyzers									
Converters									
TOTAL CAPEX									
Project Low End (-50%)									
Project High End (+100%)									
	Cost Basis	Five Points		Mojave		Whitewater		Blythe	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]								
Battery Storage									
Electrolyzers									
Converters									
TOTAL OPEX									

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 7: [redacted] PV Only CAPEX and OPEX Costs [redacted] Reduced Battery Storage

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)									
[redacted] ANNUAL PRODUCTION - [redacted] REDUCED BATTERY CAPACITY									
	Cost Basis	Five Points		Mojave		Whitewater		Blythe	
CAPEX	[redacted]								
PV Modules									
Battery Storage									
Electrolyzers									
Converters									
TOTAL CAPEX									
Project Low End (-50%)									
Project High End (+100%)									
	Cost Basis	Five Points		Mojave		Whitewater		Blythe	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]								
Battery Storage									
Electrolyzers									
Converters									
TOTAL OPEX									

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 8: [redacted] PV Only CAPEX and OPEX Costs [redacted] Reduced Battery Storage

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)													
[redacted] ANNUAL PRODUCTION (DISTRIBUTED PRODUCTION) - [redacted] REDUCED BESS													
	Cost Basis	Five Points - [redacted]		Mojave [redacted]		Whitewater - [redacted]		Blythe - [redacted]		Delta - [redacted]		TOTAL - [redacted]	
CAPEX		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL CAPEX													
Project Low End (-50%)													
Project High End (+100%)													
	[redacted] Basis	Five Points		Mojave		Whitewater		Blythe		Delta		Delta	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL OPEX													

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 9: [redacted] PV Only CAPEX and OPEX Costs [redacted] Reduced Battery Storage

HYDROGEN PRODUCTION COST SUMMARY (ALL COSTS IN MILLIONS OF DOLLARS)													
[redacted] PRODUCTION (DISTRIBUTED PRODUCTION) - [redacted] REDUCED BESS													
	Cost Basis	Five Points - [redacted]		Mojave - [redacted]		Whitewater [redacted]		Blythe - [redacted]		Delta - [redacted]		TOTAL - [redacted]	
CAPEX		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL CAPEX													
Project Low End (-50%)													
Project High End (+100%)													
	[redacted] Basis	Five Points		Mojave		Whitewater		Blythe		Delta		Delta	
OPEX[1]		*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM	*Installed kW*	USD $ MM
PV Modules	[redacted]												
Battery Storage													
Electrolyzers													
Converters													
TOTAL OPEX													

[1] OPEX is calculated for one year's operation and displayed in first year [2025] dollars.

Table 10: [redacted] PV Only CAPEX and OPEX Costs [redacted] Reduced Battery Storage

2. PHOTOVOLTAIC ONLY WITH UNCONSTRAINED LOW PRESSURE STORAGE

For similar Watt peak production, the land required by Wind Turbines is approximately 4 – 5 times the land required by photovoltaic production, but the photovoltaic production is more expensive than the wind energy production. This calls for sensitivity analysis.

Also, further into the report, production constraints due to limited low pressure [30 bar] buffer storage for compressors have been identified. The idea is to unconstrain / decouple the electrolyzer and compressor operations and not let the storage become a bottleneck for hydrogen generation.

[redacted]

To understand the sensitivities, Technip performed a simulation with PV only and unconstrained low pressure storage (i.e. effectively very large volume to de-bottleneck production). This sensitivity study was performed only on the Whitewater site to demonstrate the impact to levelized cost of hydrogen production. [redacted] We eliminated the wind generation and performed a PV only analysis with the unconstrained LP storage for comparison:

Site	Whitewater (PV+Wind, Constrained LP Storage)	Whitewater (PV+Wind, Unconstrained LP Storage)	Whitewater (PV only, Unconstrained LP Storage)
PV array peak power	[redacted]		
Wind farm peak power			
Battery energy storage capacity			
Electrolyzer installed power			
Minimum electrolyzer power			
Volume of the LP storage			
Compressor maximum flowrate			
Year 1 potential energy production			
Year 1 energy consumption			
Year 1 percentage of curtailed energy			
Year 1 unsatisfied H_2 load			
Year 1 unsatisfied H_2 load percentage			
Total investment cost			
Levelized total cost over 20 years			
LCOH			

Table 11: Whitewater comparison of PV only vs. PV+Wind for LP Storage Scenarios

By utilizing PV only the land use reduces from [redacted] acres to [redacted] acres, but the LCOH of hydrogen goes up from [redacted] USD/kg to [redacted] USD/kg. [redacted]

3. FOREWORD

This study and the results contained herein are the result of a collaborative effort between Technip Energies of Claremont, CA, USA and Technip SA Energy Transition Hub (ET Hub) of Paris, France. Any questions, clarifications, or further inquiries should be directed to Technip Energies, Claremont for further action.

Initial focus of the study was on the [redacted] case, as such the design basis, optimization, utility consumption, result discussion were conducted on that production capacity. Sections 4 to Section 11 and relevant appendices present data for the [redacted] case.

4. ELECTROLYZER TECHNOLOGIES

Currently, three types of electrolyzer technologies exist. They are classified as Alkaline, Proton Exchange Membrane (PEM) and Solid Oxide (SO) depending on their electrolyte and ions transportation. Alkaline and PEM technologies are currently available in the market, while the SO technology is still under research and development.
This write-up will focus on Alkaline and PEM electrolyzer technologies.

Alkaline Electrolyzers
In alkaline electrolyzers, the chemical reaction occurs in an aqueous solution composed of water and potassium hydroxide (25 – 30 % KOH) between two electrodes. These electrodes are located between a diaphragm, separating the generated gases from both electrodes and moving the hydroxide ions (OH-) from cathode to anode.

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Anode: $2OH^- \rightarrow ½ O_2 + H_2O + 2e^-$
Overall: $H_2O \rightarrow 2H_2 + O_2$

PEM Electrolyzers
PEM electrolyzers are composed of a solid polymer electrolyte that is in charge of transfer of protons from anode to cathode, the separation of the generated gas both at the anode and cathode, and the electrical insulation between both electrodes while acting as a reactant barrier against gas crossover.

Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
Cathode: $4H^+ + 4e^- \rightarrow 2H_2$
Overall: $2H_2O \rightarrow 2H_2 + O_2$

Comparison

	Alkaline	PEM
Advantages	Most mature technology	Ability to operate at part load and overload conditions (typical 5% – 120%)(1)
	Relatively low cost	Rapid system response
	Stacks in MW range (2021 basis)	High gas purity
	Longer lifetime (20 – 30 yrs)(1)	Compact design, lower footprint
		Faster cold start (< 20 mins)(1)
Disadvantages	Caustic (KOH) handling. Corrosive reactant.	High cost of components
	Lower partial load range (typical 20% – 40%)(1)	Lower lifetime (10 – 20 yrs) (1)
	Crossover gases (degree of purity)	Less mature
	Longer cold start (< 50 mins)(1)	Smaller stacks
	Slower dynamics (ramp-up & ramp-down)	

Table 12: Alkaline vs PEM

Notes
Technip has sought technical information from various electrolyzer manufacturers and awaits their response to verify some of the statements found on their brochures and websites.

Discussion
For the first pass of the study ([redacted]), Technip considered the PEM technology with a load range of [redacted] as it awaited confirmations from the electrolyzer vendors. Below are initial thoughts on choosing PEM for the first pass.

1. Caustic handling
   Since the production sites are mega hubs and in remote locations, make-up caustic transportation and handling could be a challenge. Use of alkaline electrolyzer also adds more process equipment to

the overall flow scheme increasing the footprint. Further investigation into sourcing, regulations (on storage) will have to be performed to explore this topic further.

2. Load range
   Since the electrolyzer design is based on renewable energy without back-up from grid, intermittency plays a significant role in the design of the system.
   As renewable power will not be available during parts of the day, it has to be supplemented by a battery energy storage system (BESS). BESS currently are an expensive alternate to store power, as a result it is necessary to minimize the capacity of BESS. [redacted]

3. Ramp rate
   PEM electrolyzers have a faster ramp rate, thus making it more suitable to operate in intermittent power supply.

4. Curtailed power
   To keep production rates fairly close to the target, during months when renewable energy is low, the design results in high amounts of curtailed power during the months of peak renewable power production. Technip has reached out to PEM electrolyzer vendors to confirm the maximum overload allowable and its effect on the cell stack degradation. By allowing a overload on the electrolyzers (>100%), it will be possible to optimize the number of stacks and hence lower the LCOH. Current alkaline electrolyzer technologies do not allow an operating overload.

After receiving confirmed vendor data Technip Energies will perform a thorough analysis of Alkaline vs PEM LCOH before recommending a technology for this large scale application. Alkaline electrolyzers do offer the advantage of lower cost and can be an attractive option if the cost of BESS can be offset.

5. GREEN HYDROGEN PRODUCTION FACILITY DESCRIPTION

The basic operation of a PEM electrolysis plant powered by renewable ("green") energy is presented below. A Block Flow Diagram (BFD) is also attached to follow along.

Energy Production and Storage

Energy is produced by either wind turbines or photovoltaic (PV) solar panels. Photovoltaic systems generate low voltage direct current (DC) power. Wind turbines produce low voltage alternating current (AC) power. There are multiple different configurations and methods for interconnecting renewable energy and battery energy storage systems (BESS), the technical details of which are beyond the scope of this report, but in general the following process occurs:

1. Individual photovoltaic panels ("modules") collect sunlight and produce a low voltage DC power output.
2. Multiple panels wired together in a combination of series and parallel (an "array") to achieve a nominal low voltage DC power.
3. A DC/DC boost converter [CV-101] increases the nominal voltage of the DC power output to that of a main DC bus.
4. The main DC bus is connected to both the BESS [B-101] and the downstream DC/AC inverter [IV-101]. A power control system splits the energy between the BESS and the downstream power inverter based on the real-time system requirements.
5. From the main DC bus, PV produced power must then be converted to AC power for transmission via DC/AC inverters. A power loss occurs, with a typical ratio of 1.4:1 for DC_{Wp}:$AC_{Wp.}$
6. This means that for every nominal 1,000 W AC power required you must generate 1,400 W DC power.
7. A step-up transformer will then convert the AC power output to the nominal medium voltage output, (typically between 4 ~ 34kV depending on the site specific requirements and power distribution) and distributed for use at the electrolysis plant.
8. Wind turbines produce a low voltage AC power output.
9. The AC power output must be converted to DC via a rectifier [RF-102] for storage in the BESS [B-101].
10. As with the PV produced power, a power control system directs the energy to either the BESS or the downstream power inverter [IV-102].
11. AC power voltage is increased via a step-up transformer [TF-102] to the nominal medium voltage AC bus output and distributed for use at the electrolysis plant.
12. During times of low or zero potential energy production, the power control system will discharge the BESS to the electrolysis plant. The BESS is comprised of numerous individual batteries interconnected to form the optimum energy storage and discharge bank for the requirements of the specific site.

There are numerous options and configurations available for each component, such as micro-inverters at the PV module, integrated rectifiers for battery storage, common step-up transformers, DC-coupled configuration, AC-coupled configuration etc. The details of the final architecture and configuration of the electrical power supply are dependent on the final technical parameters of the system and would be determined during a later phase of engineering planning and design. However, it is noted that the same general philosophy of power generation, storage and distribution is utilized for any Green Hydrogen production application and the representative schematic is applicable to all sites and results discussed in this report.

Electrolyzers

The technical details of electrolysis are presented in the earlier section of this report, but the general operation and key parameters of the electrolyzers are noted as follows:

Electrolyzers functionally require DC power at the stack level to facilitate the electro-chemical reaction and hydrogen generation. However, at the time of this study there still does not exist a viable commercial/utility scale solution for providing DC power directly from PV panels to the electrolyzers. All of the electrolyzer manufacturers solicited in the course of this study indicated that the power requirements at the electrolyzer battery limit are for medium voltage AC power. The final DC/AC rectifier providing the electrolysis power conversion is in the scope of the electrolyzer vendor and is non-negotiable in order to maintain manufacturer warranty and performance ratings. Thus, as noted above in the Energy Production section, there is a distinct and substantial penalty for the conversion of DC-to-AC power, and then AC-to-DC power for utilization. This penalty is manifest in the additional amount of installed energy production required for a given electrolyzer power consumption.

In addition, the electrolyzers must run at a minimum specified throughput at all times to prevent damage to the equipment. Frequent start and stop is not acceptable and therefore is not considered. Instead, the electrolyzers run at a minimum percentage of rated output, [redacted] minimum for PEM electrolyzers (typical), and [redacted] for Alkaline (typical). The requirement for continuous operation at a minimum rate means that there must be a continuous (i.e. uninterrupted) power supply available at all times, twenty-four hours per day, sufficient to maintain **all** of the installed electrolyzers at a minimum flow rate. For a power supply consisting solely of solar and wind power which has intermittent availability and periods of zero potential energy production, this makes the use of a BESS an absolute requirement.

The electrolyzers will produce gaseous hydrogen at a purity of 99.9% directly from electrolysis. The pressure at the output of the electrolyzers will be approximately 30 barA. Different electrolyzer manufacturers have various methodologies for achieving the 30 bar nominal output – "pressurized" water electrolysis, back-pressure control, product compression, etc. – however for the purpose of this study the specific method is inconsequential. Rather, the nominal output and associated energy requirements are considered in the overall analysis.

<u>Auxiliaries</u>
The electrolysis plant will require a small number of additional unit operations to facilitate the electrolyzers. Collectively, these units are referred to as the Balance of Plant (BOP). The BOP is comprised of the following:

1. <u>Feed Water Treatment / DMW Unit</u>

   The process of water electrolysis relies on the splitting of water to obtain product hydrogen and byproduct of oxygen. The water quality at the inlet of the electrolyzer must meet specific requirements for purity, conductivity, and specific mineral contents [see Design Basis for specific water requirements] so as not to poison the electrolyzer stack and damage the equipment. As such, it is assumed that some form of water treatment is always required upstream of the electrolyzer to ensure the inlet water meets the minimum standards. The type of water treatment and/or the extent to which the feed water must be treated are dependent on the supply water and would be determined during a later phase of engineering planning and design. There are many different solutions for water treatment, the extent of which is beyond the scope of this report. However, at a minimum it is assumed that there would be a form of water filtration and water demineralization or deionization required at site. Water treatment packages such as reverse osmosis and water deionization should be considered as a minimum for the electrolysis water supply.

2. <u>Waste Water Unit</u>

   The effluent of the Feed Water Treatment is typically a concentrated brine solution. The details of the waste water treatment are highly dependent on the feed water purity, site location and local jurisdiction. This may consist of a local water treatment, sewage collection, or local discharge. The details of this are beyond the scope of this report and would be determined during a later phase of engineering planning and design.

3. Utility Water Unit

   A utility water unit, typically a closed circuit chiller water unit providing cooling for the electrolyzer stacks.

4. Instrument Air Unit

   An instrument air compressor complete with dryer and surge tank for supply air necessary for control valves or purge requirements.

5. Nitrogen Unit

   A nitrogen generating unit, or bottle rack, sufficient for purging the electrolysis units during start-up, commissioning, or shut-down operations.

6. Flare System

   A flare system for emergency upset release and safety requirements. The flare may potentially be eliminated depending on site specific requirements and local jurisdiction.

7. Cooling Tower

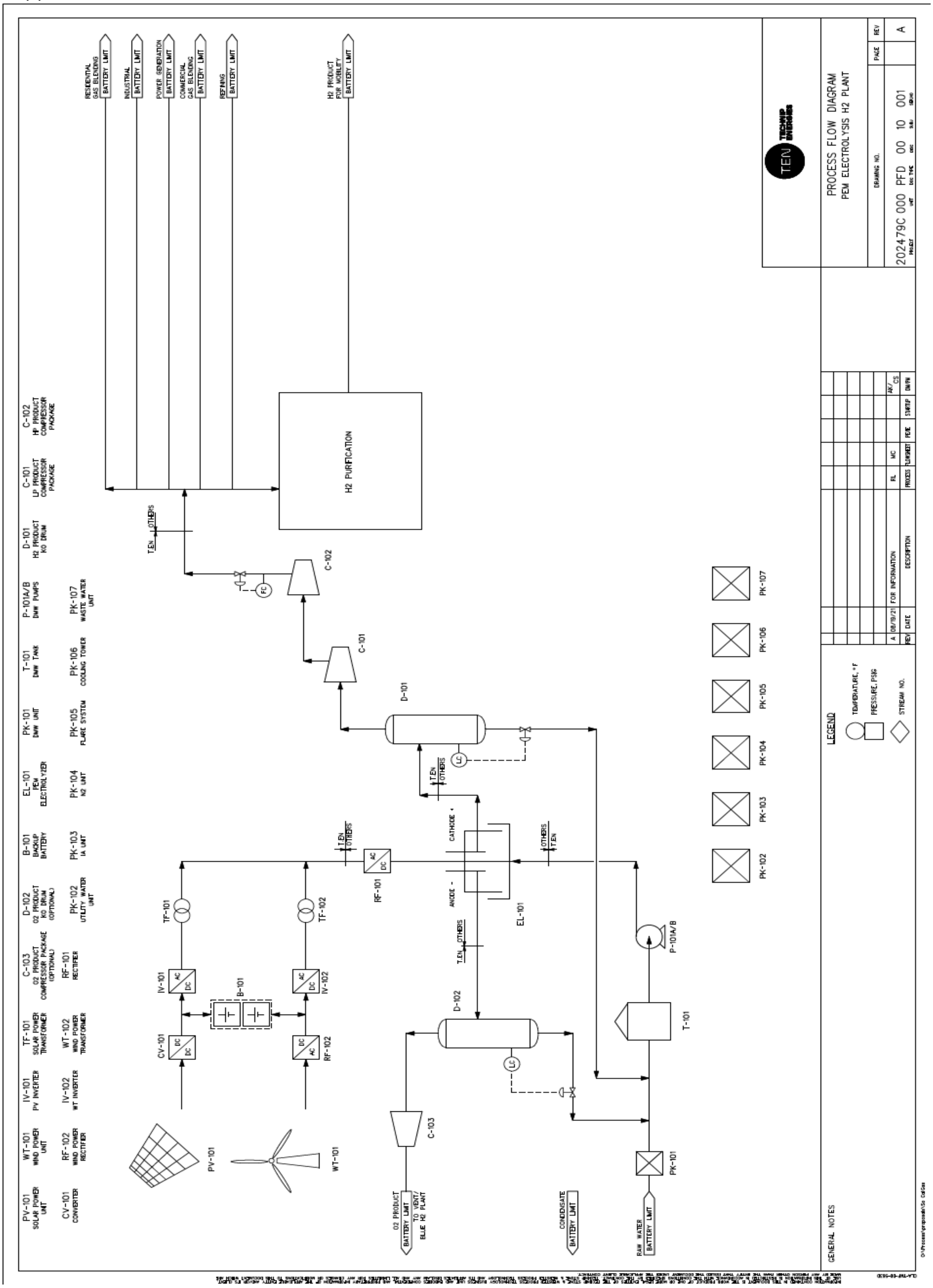
   A cooling tower would typically be required if product gas cooling is required.

General Operation

The design of the green hydrogen production facility aims to achieve the target hydrogen yearly production rate with the minimum amount of capital investment (CAPEX) and yearly recurring operating costs (OPEX). [redacted]

6. BLOCK FLOW DIAGRAM

Attached below is a block flow diagram for a PEM based green hydrogen production facility. For reference an Alkaline electrolyzer based green hydrogen facility block flow diagram is provided in the appendix



7. DESIGN BASIS

7.1 General

The purpose of this section is to specify the assumptions, underlying principles and parameters that will form the basis of the Green H2 Feasibility Study.

H2 Production

The hydrogen production requirement will form the foundation for the feasibility study. The volume of hydrogen required will determine the amount of electrolyzers for green hydrogen production. The quantity of electrolyzers will dictate the minimum energy requirements, which will be used to establish the minimum quantity of energy production at site.

Client has indicated that the production values shall range from [redacted] Within this range, three (3) discrete values of production will be investigated:

Low H_2 Production

The Low production range shall be defined as [redacted] Technip will evaluate the required design to accommodate the [redacted] production rate. Please refer to the H2 Demand Scenario Tables provided for a breakdown of the production rates.

Medium H_2 Production

The Medium production range shall be defined as [redacted]. Technip will evaluate the required design to accommodate the [redacted] production rate.

High H_2 Production

The High production range shall be defined as six to nine [redacted]. Technip will evaluate the required design to accommodate the [redacted] production rate.

The purpose of this study is to evaluate the potential for a green hydrogen future case. As such, the entirety of hydrogen production will be via the use of electrolysis. Electrolysis requires only water and electricity as feedstocks to produce hydrogen (and oxygen by-product) and therefore is extremely attractive for the zero-carbon initiative. However, it does not come without drawbacks as the electricity used in production is substantial. To maintain a zero-carbon footprint green energy must be utilized for the process.

Currently, electrolyzers for hydrogen production are limited to smaller capacities that can serve on-site hydrogen fueling stations or demonstrate concepts for green hydrogen to power, mobility or electrofuels. While feasibility studies and front-end design for larger installations are underway, single electrolyzer stacks can be limited in capacity, and require parallel units to meet industrial scale needs.

[redacted] Currently for this study, seven end user sectors have been identified. Commercial blending, residential blending, industrial use, refinery use, mobility and power generation. Of the seven sectors, only hydrogen for mobility needs ultra-pure hydrogen. As such [redacted]

Typically the purity of hydrogen from electrolyzers is 99.99% before purification with approximately 750 ppm of water vapor and 250 ppm of oxygen. As hydrogen is a highly flammable gas, consideration should be given to the presence of oxygen in the stream. In presence of pure oxygen the flammability limits of hydrogen are 4% - 94%, this puts the 99.99% pure hydrogen outside the flammability limits. Oxygen analyzers should be used in the product stream to monitor oxygen content and implement safety shut offs, if concentration exceeds certain thresholds.

The hydrogen production must maintain a minimum continuous production rate, i.e. the electrolyzers will not fully stop production at any point during the year. The minimum production rate will be the manufacturer's specified minimum turndown as a percentage of full throughput. This will be considered in the design of the plant when determining the amount of electrolyzers, the type and quantity of energy storage, footprint, cost, etc.

Hydrogen will be delivered at the battery limit at a nominal pressure of 30 BarG and 99.9% purity. Any additional purification (such as those for transportation use hydrogen) will be assumed outside of the production site, downstream at the users' takeoff.

Energy Production On-Site

In order to establish the scale of the hydrogen production facilities, both in physical footprint as well as economically, the energy production required for the electrolyzer stacks will be determined based on the production values mentioned above.

[redacted]

Site Data

Client has indicated four (4) possible production sites in the southern California region.

For the scale and scope of this study a representative time series solar and wind profile for the site will be utilized. Hourly resolution will be used (i.e. 8760 profiles).

Technip Energies will utilize the System Advisor Model (SAM) toolkit available via the National Renewable Energy Laboratory (NREL) website [sam.nrel.gov].

The sites considered will be the following:

Site	Latitude	Longitude
Whitewater, CA	[redacted]	
Blythe, CA		
Mojave, CA		
Five Points, CA		

Table 13: Latitude and longitude of sites

7.2 Technical

Product		
Name		HYDROGEN
Flowrate	MMT/yr	[redacted]
Temperature	°F	[redacted]
Pressure	barA	[redacted]
Purity	mol %	[redacted]
Impurities		[redacted]
O2	ppmv	[redacted]
H2O	ppmv	[redacted]
		[redacted]
Turndown		[redacted]
Capacity	%	[redacted]
		[redacted]
Feed Water (DM)		[redacted]
		[redacted]
Pressure	psig	[redacted]
Temperature	°F	[redacted]
Composition		[redacted]
Conductivity	µS/cm	[redacted]
SiO2	µg/kg	[redacted]
Fe	µg/kg	[redacted]
Cu	µg/kg	[redacted]
Al	µg/kg	[redacted]
Ca	µg/kg	[redacted]
K	µg/kg	[redacted]
Na	µg/kg	[redacted]
		[redacted]
		[redacted]
Export Oxygen		[redacted]
Pressure	psig	[redacted]
Temperature	°F	[redacted]
		[redacted]
Ambient Conditions		[redacted]
Max Ambient Temperature	°F	[redacted]
Design RH	%	[redacted]
Barometer	psia	[redacted]
		[redacted]
Photovoltaic Cells		[redacted]
Nominal Power Output	W	[redacted]
Nominal Size	m²	[redacted]
		[redacted]
Wind Turbines		[redacted]
Nominal Power Output	MW	[redacted]
Nominal Rotor Size	m	[redacted]
		[redacted]
		[redacted]
Battery Storage		[redacted]
Nominal Storage	kWh	[redacted]
Power Output	kW	[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]

NOTES:

1) Three different hydrogen production values of [redacted] and [redacted] will be considered.

Table 14: Technical basis

7.3 Cost

2025 projections were used to build the CAPEX and OPEX estimates.

1. Wind Farm

CAPEX	$/kW	[redacted]
Replacement Cost	$/kW	[redacted]
OPEX	$/kW/yr	[redacted]

2. PV Farm

CAPEX	$/kW	[redacted]
Replacement Cost	$/kW	[redacted]
OPEX	$/kW/yr	[redacted]

3. Battery Storage

CAPEX	$/kW	[redacted]
Replacement Cost	$/kW	[redacted]
OPEX	$/kW/yr	[redacted]

4. Electrolyzer

CAPEX	$/kW	[redacted]
Replacement Cost	$/kW	[redacted]
OPEX	$/kW/yr	[redacted]

5. Converter

CAPEX	$/kW	[redacted]
Replacement Cost	$/kW	[redacted]
OPEX	$/kW/yr	[redacted]

6. Discount Rate

Rate	%	[redacted]

Table 15: Cost basis

NOTE: For the final analyses with PV only, the cost of the LP storage and compressor were removed from the calculations. The LP storage is not considered for our final analysis as we assumed that the compressor throughput would exactly match the product hydrogen output from the electrolyzers. Physically, this requires some form of a gas storage system downstream of the production, which is beyond the scope of this hydrogen production report. The HP storage technical and economic considerations are discussed elsewhere in the report summary provided by SPEC Services.

Similarly, the cost of compression was removed from the production scope and is considered elsewhere in the report summary provided by SPEC Services.

The cost basis data from NREL is developed using a number of financial models with multiple assumptions and inputs to produce the CAPEX and OPEX costs. The parametric pricing therefore includes consideration for the following inputs:

- PV Module
- Inverter
- Structural BOS
- Electrical BOS
- Installation Labor & Equipment
- EPC Overhead
- Sales Tax
- Permitting Fee
- Interconnection Fee
- Transmission Line
- Developer Overhead
- Contingency
- EPC/Developer Profit

Since the majority of the cost of production is from the renewable energy production, the NREL model inputs are also provided for reference (Appendix 8). While the project specifics for each cost category will vary from project to project, the overall cost serves as a reasonable basis for developing the rough order of magnitude (ROM) estimate required of this study. These rates are based on a combination of existing similar, but much smaller scale projects. [redacted]

8. ANALYSIS METHODOLOGY

8.1 Simulations and optimization

A dynamic modeling tool with three main functions (below) was used to perform the analysis

1. Simulation for energy systems based on physical models implemented and used in the form of libraries. Thus, it provides information on the behavior of system components in response to an energy demand defined at each time step and subject to precise constraints (economic, technical and environmental). Each simulation can be evaluated from a technical point of view (e.g. operation of components), economics (e.g. operating costs), or even environmental (e.g. avoided CO_2 emissions).

2. Realization of optimizations on economic, technical and / or environmental criteria by choosing the parameters on which to act.

3. For each energy system, calculation of the influence of one or more parameters of the system on technical, economic and / or environmental indicators of interest.

8.2 Data and input to calculations

To perform the calculations on a specific case, the following steps are necessary:

1. Construction of the system architecture (choice of components, connections between components)

2. Configuration of the various components

3. Definition of the energy management strategy

   It is therefore necessary to carry out data collection work beforehand in order to be able to enter the various parameters. As such, the following information was input:

   - For the different components:
     - Sizing: indicates the size, the capacity of the component;
     - Performance model: model representing the functioning of the component at all times, making it possible, for example, to make the link between inputs and outputs. Time series characterizing the context in which the component operates may be necessary (temperature, illumination, wind speed, electricity consumption, renewable energy production, energy prices, etc.);
     - Degradation: aging mechanisms altering the performance model;
     - Replacement: indicates how often and on which criterion (s) the component must be replaced;
     - Component costs (investment, O&M and replacement): the costs to be charged to the investment, during the operation of the component and to each replacement.
   - For the energy management strategy:
     - A reflection on how the system should work;
     - A configuration of the various options and parameters.

9. SIMULATION SETUP

9.1 Overall Description

Four sites are studied:

- Whitewater
- Blythe
- Mojave
- Five Points

The following schematic presents the architecture for each of the 4 production sites:

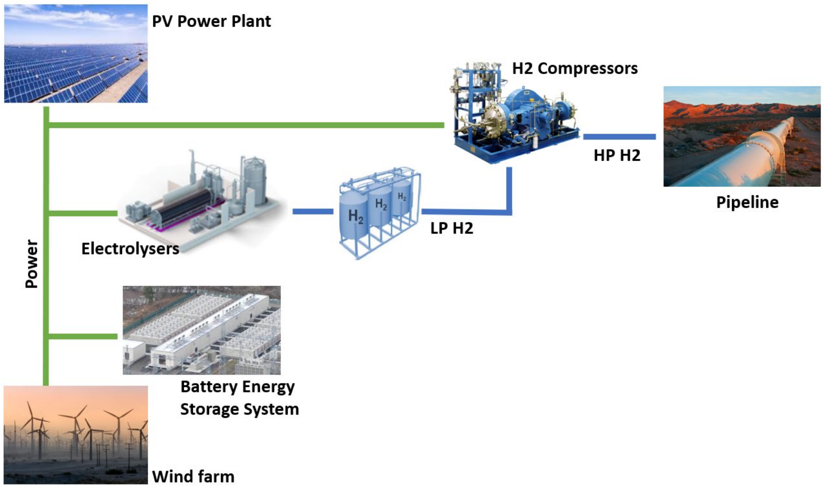


Figure 2: Architecture

Each site consists of:

- a photovoltaic plant,
- a wind farm,
- a battery energy storage system,
- electrolyzers,
- H_2 LP storages,
- H_2 compressors,
- A pipeline simulated as a H_2 HP storage.

A corresponding model was built in the simulation software as shown below:

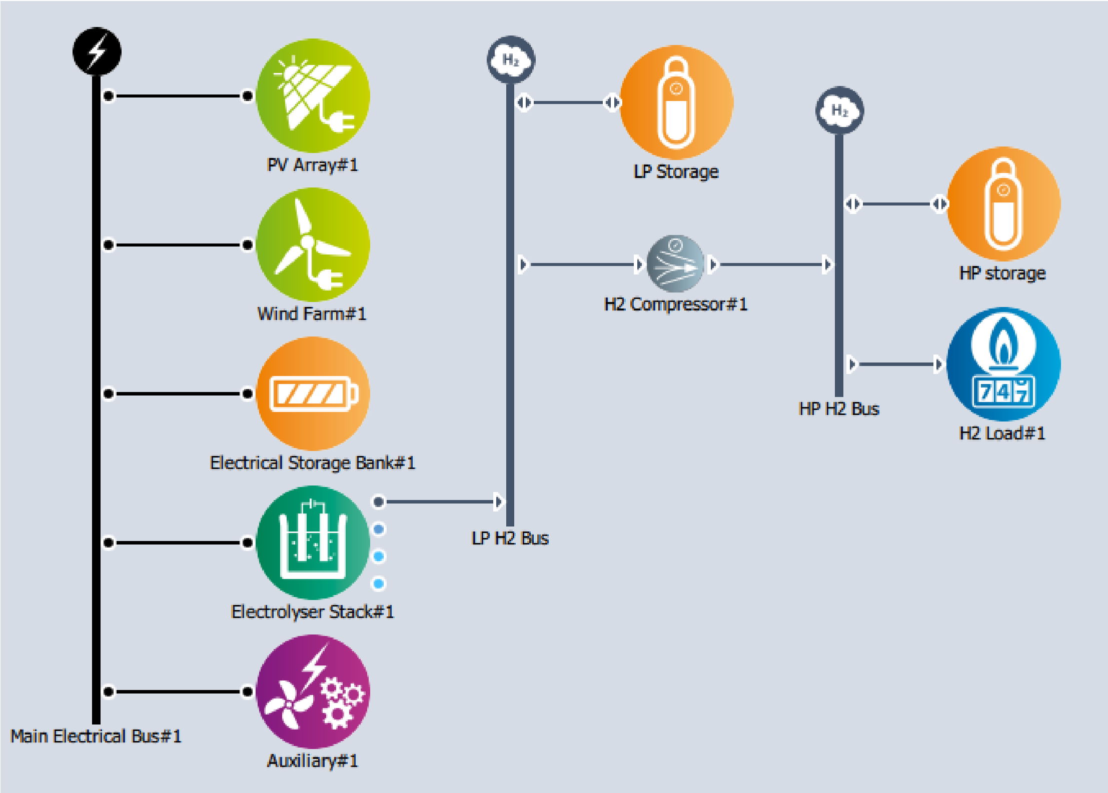


Figure 3: Model Overview

9.2 System Control Overview

The system is controlled using different algorithms that have been pre-defined for the purpose of the study, based on objective of the study.

For the study, the battery limits and algorithms are the followings:

1. Energy balance:
   a. Power sources by order of priority are:
      1. PV array & Wind farm
      2. BESS discharge
   b. Power consumers by order of priority are:
      1. the compressor auxiliary power
      2. BESS charge
      3. Electrolyzers
2. Electrolyzer control:
   a. When renewable sources are available, the electrolyzers produce H_2, consuming the maximum available renewable power.
   b. As a minimum, even if no renewable power is available, the electrolyzers consume their minimum power: BESS power is consumed.
3. Compressor control:

a. The compressors are started when all these conditions are reached:

[redacted]

9.3 Description of each component of the architecture

The following parts describes the inputs and assumptions taken for each component of the architecture:

9.3.1 General data

9.3.1.1 Design life

The architecture is designed for [redacted] years of operation.

9.3.1.2 General economic data

A discount rate of [redacted] is assumed.

9.3.2 PV Array

The PV array is a combination of modules with a nominal power of [redacted] [AC]) each.

The following table presents the PV Array data input to the model:

Parameter	Value	Reference
Number of Modules	Optimization parameter	
Footprint per module	[redacted]	
Power production	[redacted]	[redacted]
Annual Production Decrease Rate	[redacted]	
Total Investment Cost	[redacted]	Section 6.3
Annual O&M Cost	[redacted]	Section 6.3

Table 16: PV Array data

Notes:

- The replacement frequency is [redacted] years, longer than the architecture design life ([redacted]), thus the replacement cost ([redacted] USD per kWp) is not considered for the study.

The PV array is associated with a converter. The following table presents the converter data:

Parameter	Value	Reference
Efficiency	[redacted]	
Total Investment Cost	[redacted]	Section 6.3

Table 17: PV Array converter data

9.3.3 Wind farm

The wind farm is a combination of wind turbines with a nominal power of [redacted].

The following table presents the wind farm data:

Parameter	Value	Reference
Number of turbines	Optimization parameter	
Footprint per turbine	[redacted]	
Power production	[redacted]	[redacted]
Annual Production Decrease Rate	[redacted]	
Total Investment Cost	[redacted]	Section 6.3
Annual O&M Cost	[redacted]	Section 6.3

Table 18: Wind farm data

Notes:

- The replacement frequency is [redacted] years, equal to the architecture design life ([redacted] years), thus the replacement cost [redacted] per kWp) is not considered for the study.

9.3.4 Battery Energy Storage System (BESS)

The following table presents the BESS data:

Parameter	Value	Reference
Number of batteries	Optimization parameter	
Storage Capacity	[redacted]	
Minimum state of charge	[redacted]	
Initial state of charge	[redacted]	
Maximum charge/discharge rate	[redacted]	
Efficiency in charge/discharge	[redacted]	
Self-discharge	[redacted]	
Calendar degradation of storage capacity	[redacted]	
Investment Cost	[redacted]	Section 6.3
Replacement Frequency	[redacted]	
Replacement Cost	[redacted]	Section 6.3
Annual O&M Cost	[redacted]	Section 6.3

Table 19: BESS data

9.3.5 Electrolyzer Stack

The following table presents the Electrolyzer Stack data:

Parameter	Value	Reference
Number of stacks	Optimization parameter	
Stack Maximum Power	[redacted]	
Stack Minimum Power	[redacted]	
Efficiency	[redacted]	

Maximum ramp-up & ramp-down rate	[redacted]	
Efficiency Decrease	[redacted]	
Investment Cost	[redacted]	Section 6.3
Replacement Frequency	[redacted]	
Replacement Cost	[redacted]	Section 6.3
Replacement Cost Annual Decrease Rate	[redacted]	Assumed
Annual O&M Cost	[redacted]	Section 6.3

Table 20: Electrolyzer Stack data

Notes:

- The electrolyzer auxiliary power consumption is included in the electrolyzer efficiency.
- The produced hydrogen flowrate is obtained from the electrical power, the efficiency and the specific LHV of H_2 [redacted]) as follows:

$$Q_{H2} = \frac{\eta_{LHV} \times Power(t)}{LHV}$$

The following electrolyzer minimum powers are assessed, depending on the required flowrate:

Flowrate [MMTPY]	Electrolyzer minimum power [MW]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Table 21: Electrolyzer minimum power

9.3.6 H_2 LP storage

The following table presents the H_2 LP storage data:

Parameter	**Value**	**Reference**
Ambient temperature	[redacted]	
Minimum pressure	[redacted]	
Maximum pressure	[redacted]	
Initial pressure	[redacted]	
Volume	Optimization parameter	
Investment Cost	[redacted]	Section 6.3

Table 22: H_2 LP storage

9.3.7 H_2 Compressor

The following table presents the H_2 Compressor data:

Parameter	**Value**	**Reference**
Isentropic efficiency	[redacted]	
Electric motor efficiency	[redacted]	
Number of stages	[redacted]	
Discharge pressure	[redacted]	
Discharge maximum flowrate	Optimization parameter	
Investment Cost	[redacted]	Section 6.3
Annual O&M Cost	[redacted]	Section 6.3

Table 23: H_2 Compressor data

Note: the compressor power consumption is calculated and included in the power balance, using the following equation:

Compressor

Modeling approach:

Modeling of the compressor electrical power consumption

$$P_{comp} = \frac{Nb_{Stages} \times \dot{m}_{gaz} \times Cp_{gas} \times T_{in}}{\eta_{is} \times \eta_{el}} \times \left[\left(\frac{Pr_{out}}{Pr_{in}} \right)^{\frac{\gamma - 1}{Nb_{Stages} \times \gamma}} - 1 \right]$$

With:

P_{comp}	Compression electrical power (W)
Nb_{Stages}	Number of compression stages (-)
$\dot{m}_{gaz}$	Gas mass flow rate ($kg.s^{-1}$)
Cp_{gas}	Specific heat at constant pressure ($J.kg^{-1}.K^{-1}$)
T_{in}	Gas inlet temperature (K)
η_{is}	Compressor isentropic efficiency (-)
η_{el}	Electrical motor efficiency (-)
Pr_{out}	Gas inlet pressure (bar)
Pr_{in}	Gas outlet pressure (bar)
γ	Gas specific heat ratio (-)

Figure 4: Compressor model equation

With an inlet temperature of 80°F, an inlet pressure of 1 to 30 bara, a Cp of 14 389 J/(kg.K) at 80°F and 30 bara, an outlet pressure of 100 to 120 bara, a gas specific heat ratio of 1.408, the following minimum compression powers are assessed:

Flowrate [MMTPY]	Compression minimum power [MW]	Compression maximum power [MW]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 24: Compression minimum power

The investment & O&M costs were not considered part of the production economic scope and therefore were not included in the calculations. Compression power only was considered as part of the energy demand for the production plant.

9.3.8 H_2 pipeline

The pipeline is simulated as a HP storage tank. The following table presents the H_2 pipeline data:

Parameter	Value
Ambient temperature	[redacted]
Minimum pressure	
Maximum pressure	
Initial pressure	
Volume for [redacted]	
Volume for [redacted]	

Volume for [redacted]	[redacted]

Table 25: H_2 pipeline data

10. OPTIMIZATION METHODOLOGY

In the present analysis, the objective is to [redacted] by identifying the combinations of parameters allowing to [redacted] while complying as much as possible with the H_2 production objective of [redacted].

[redacted]

The design optimization is carried out considering only the first year of production, thus it does not take into account:

[redacted]

The economic calculation is carried out over [redacted] years and the LCOH considers all the economic data over [redacted] years.

The Typical Meteorological Year (TMY) time series for potential renewable power production at each site is obtained from the National Renewable Energies Laboratory (NREL) System Advisor Model (SAM). The TMY is an hourly potential energy profile created from a database of the hourly solar irradiance as measured at a given location over multiple years. It includes "typical" yearly weather phenomena, such as days with little or no potential solar production. [redacted] This was done initially to adequately model the LP storage volume effect, and retained on subsequent simulations after the LP constraint was removed. See Appendix 1 and 4 for details.

With a time step of [redacted] minutes, a simulation lasts from [redacted] minutes. Optimizations (run of multiple simulations) can last several hours.

The technical and economic characteristics of each component is input to the program (see Section 9.3 for details).

11. RESULTS

NOTE: The following results were initially obtained utilizing both PV array and wind energy and presented in Revision A of this report. We removed the wind farm from our final analysis and economic data presented in the Executive Summary, however the results and data below are retained for reference of the methodology.

11.1 Whitewater site – [redacted]

The following part describes the analysis carried out for Whitewater site, with a target H_2 production of [redacted].

11.1.1 Base case

It is to be noted that:

- The compressor flowrate shall exceed the target production of [redacted] kg/h).
- The electrolyzer maximum power shall allow producing more than [redacted] of H_2, which corresponds to a power of [redacted] GW.
- The sum of the PV array and wind farm peak powers shall exceed the sum of the compressor and electrolyzer consumed powers.

The following set of parameters is considered for a first simulation:

Parameter	Value
Number of PV modules	[redacted]
Number of Wind turbines	
Number of batteries	
Electrolyzer installed power	
Minimum electrolyzer power %	
Volume of the LP storage	
Compressor maximum flowrate	

Table 26: Whitewater – [redacted] - Base case parameters

With these inputs, the following main results are obtained:

Year 1 potential energy production	[redacted]
Year 1 energy production	
Year 1 percentage of curtailed energy	
Year 1 unsatisfied H_2 load	
Year 1 unsatisfied H_2 load percentage	

Table 27: Whitewater – [redacted] - Base case technical results

Total investment cost	[redacted]
Levelized O&M cost	
Levelized replacement cost	
Levelized total cost	
LCOH	

Table 28: Whitewater – [redacted] - Base case cost results

[redacted]

Detailed figures are presented in appendix 2.

11.1.2 Optimization of design

Optimization tool is run considering the following ranges for each parameter:

Parameter	Min value	Max value	Points
Number of PV modules	[redacted]	[redacted]	10
Number of Wind turbines	[redacted]	[redacted]	10
Number of batteries	[redacted]	[redacted]	10
Electrolyzer installed power	[redacted]	[redacted]	10
Minimum electrolyzer power %	[redacted]	[redacted]	5
Volume of the LP storage	[redacted]	[redacted]	5
Compressor maximum flowrate	[redacted]	[redacted]	8

Table 29: Whitewater – [redacted] - optimization parameters

An algorithm is used to simulate [redacted] cases over 2 000 000 combinations. After [redacted] generations, the best combinations allow reaching:

- [redacted] of unsatisfied load), but with a min LCOH of [redacted]
- [redacted] of unsatisfied load), but with a min LCOH of [redacted]

[redacted]

Figure 5: Whitewater – [redacted] - Optimization results

Case	[redacted] unsatisfied load	[redacted] unsatisfied load
Number of PV modules	[redacted]	[redacted]
Number of Wind turbines	[redacted]	[redacted]
Number of batteries	[redacted]	[redacted]
Electrolyzer installed power	[redacted]	[redacted]
Minimum electrolyzer power %	[redacted]	[redacted]
Volume of the LP storage	[redacted]	[redacted]
Compressor maximum flowrate	[redacted]	[redacted]
LCOH	[redacted]	[redacted]
Curtailed energy	[redacted]	[redacted]

Table 30: Whitewater – [redacted] - Optimization results

If the H_2 load at the outlet of the pipeline is allowed exceeding periodically [redacted], it is possible to improve the result, with the same design. A sensitivity is run with the second design, with a maximum H_2 load of [redacted] instead of [redacted]: the unsatisfied load is decreased to [redacted] (still comparing to the target of [redacted]) and the LCOH is decreased to [redacted].

A second optimization is done around the second design, with a maximum H_2 load of [redacted] MMTPY:

Parameter	Min value	Max value	Points
Number of PV modules	[redacted]	[redacted]	3
Number of Wind turbines	[redacted]	[redacted]	3
Number of batteries	[redacted]	[redacted]	3
Electrolyzer installed power	[redacted]	[redacted]	3
Minimum electrolyzer power %	[redacted]	[redacted]	2
Volume of the LP storage	[redacted]	[redacted]	2
Compressor maximum flowrate	[redacted]	[redacted]	7

Table 31: Whitewater – [redacted] - Optimization parameters - 2

The following design allows decreasing the unsatisfied load to less than [redacted], while keeping a LCOH of [redacted].

Case	Optimized design
Number of PV modules	[redacted]
Number of Wind turbines	[redacted]
Number of batteries	[redacted]
Electrolyzer installed power	[redacted]
Minimum electrolyzer power %	[redacted]
Volume of the LP storage	[redacted]
Compressor maximum flowrate	[redacted]

Table 32: Whitewater – [redacted] - Optimization results - 2

With this design, the following main results are obtained:

Year 1 potential energy production	[redacted]
Year 1 energy production	[redacted]
Year 1 percentage of curtailed energy	[redacted]
Year 1 unsatisfied H_2 load	[redacted]
Year 1 unsatisfied H_2 load percentage	[redacted]

Table 33: Whitewater – [redacted] - Optimization results - technical results - 2

Total investment cost	[redacted]
Levelized O&M cost	[redacted]
Levelized replacement cost	[redacted]
Levelized total cost	[redacted]
LCOH	[redacted]

Table 34: Whitewater – [redacted] - Optimization results - Cost results - 2

Detailed figures are presented in appendix 3.

<u>Discussion on LP storage volume</u>

It is observed that the selected LP storage volume ([redacted]) is small compared to the compressor flowrate ([redacted]): its buffer effect is very limited ([redacted] are sufficient to empty it) and the pipeline has also a limited volume. Thus, the LP storage and the pipeline are frequently full and the demand of [redacted] constrains the flowrate of the compressor and the flowrate of the electrolyzer to the same value.

In order to have a real buffer between the electrolyzer and the compressor, a LP storage of [redacted] of m^3 would be required, which has been disregarded as a first approach but could be feasible. A sensitivity has been carried out considering [redacted] of volume for the LP storage. In this case,

- [redacted]
- [redacted]
- [redacted]

11.1.3 Optimization of control parameters

This analysis is carried out for Whitewater site and the previous optimized case for the objective of [redacted] MMTPY only to assess the sensitivity of the design to the compressor control parameters.

Odyssey optimization tool is run considering the following ranges for each parameter:

Parameter	Initial value	Min value	Max value	Points
LP_tank_SOC_start	[redacted]			
HP_tank_SOC_start				
BESS_SOC_start				
LP_tank_SOC_stop				
HP_tank_SOC_stop				
BESS_SOC_stop				

Table 35: Whitewater – [redacted] - Optimization of control parameters

[redacted]

Figure 6: Whitewater – [redacted] - Optimization of control parameters

The following control parameter values allow slightly improving the design performances:

Parameter	Initial value	Optimized value
LP_tank_SOC_start	[redacted]	
HP_tank_SOC_start		
BESS_SOC_start		
LP_tank_SOC_stop		
HP_tank_SOC_stop		
BESS_SOC_stop		
LCOH		
Unsatisfied load		

Table 36: Whitewater – [redacted] - optimization of control parameters - results

[redacted]

11.1.4 Analysis of years 10, 15 and 20

[redacted]

The following results are obtained:

	Year 1	Year 10	Year 15	Year 20
Potential energy production	[redacted]			
Energy production				
Percentage of curtailed energy				
Satisfied H_2 load				
Unsatisfied H_2 load				
Unsatisfied H_2 load percentage				

Table 37: Whitewater – [redacted] – H_2 production versus time

As a result, the H_2 production is decreased by the annual degradation of equipment performances. The worst annual production is found for [redacted] but the decrease is reasonable: [redacted] compared to year 1.

11.1.5 Conclusions for Whitewater site & [redacted]

[redacted]

Another way to design the system would be to have a LP storage volume of [redacted]. It has been disregarded as a first approach but could be feasible.

11.2 Blythe site – [redacted]

The following part describes the analysis carried out for Blythe site, with a target H_2 production of [redacted]. In the same way as for Whitewater, it is considered that the H_2 load at the outlet of the pipeline is allowed reaching [redacted] as peak flowrate.

[redacted]

Odyssey optimization tool is run considering the following ranges for each parameter:

Parameter	Min value	Max value	Points
Number of PV modules	[redacted]	[redacted]	16
Number of Wind turbines	[redacted]	[redacted]	16
Number of batteries	[redacted]	[redacted]	7
Electrolyzer installed power	[redacted]	[redacted]	6
Minimum electrolyzer power %	[redacted]	[redacted]	5
Volume of the LP storage	[redacted]	[redacted]	4
Compressor maximum flowrate	[redacted]	[redacted]	10

Table 38: Blythe – [redacted] - optimization parameters

The genetic algorithm is used to simulate 400 cases over 2 150 400 combinations. The best combinations obtained after 10 generations are shown on the graph below:

[redacted]

Figure 7: Blythe – [redacted] - Optimization results

The best combination allowing reaching at least [redacted] of H_2 ([redacted] of unsatisfied load) has a LCOH of [redacted]:

Case	Optimized design
Number of PV modules	[redacted]
Number of Wind turbines	
Number of batteries	
Electrolyzer installed power	
Minimum electrolyzer power %	
Volume of the LP storage	
Compressor maximum flowrate	

Table 39: Blythe – [redacted] - Optimization results

With this design, the following main results are obtained:

Year 1 potential energy production	[redacted]
Year 1 energy production	
Year 1 percentage of curtailed energy	
Year 1 unsatisfied H_2 load	
Year 1 unsatisfied H_2 load percentage	

Table 40: Blythe – [redacted] - Optimization results - technical results

Total investment cost	[redacted]
Levelized O&M cost	
Levelized replacement cost	
Levelized total cost	
LCOH	

Table 41: Blythe – [redacted] - Optimization results - cost results

[redacted] more intermittent (see appendix 1), requiring more peak power capacity and/or more battery storage.

11.3 Mojave site – [redacted]

The following part describes the analysis carried out for Mojave site, with a target H_2 production of [redacted]. In the same way as for Whitewater, it is considered that the H_2 load at the outlet of the pipeline is allowed reaching [redacted] as peak flowrate.

[redacted]

Odyssey optimization tool is run considering the following ranges for each parameter:

Parameter	Min value	Max value	Points
Number of PV modules	[redacted]	[redacted]	5
Number of Wind turbines	[redacted]	[redacted]	5
Number of batteries	[redacted]	[redacted]	3
Electrolyzer installed power	[redacted]	[redacted]	3
Minimum electrolyzer power %	[redacted]	[redacted]	2
Volume of the LP storage	[redacted]	[redacted]	3
Compressor maximum flowrate	[redacted]	[redacted]	4

Table 42: Mojave – [redacted] - optimization parameters

The genetic algorithm is used to simulate 400 cases over 7 200 combinations. The best combinations obtained after 10 generations are shown on the graph below:

[redacted]

Figure 8: Mojave – [redacted] - Optimization results

The best combination allowing reaching at least [redacted] of H_2 ([redacted] of unsatisfied load) has a LCOH of [redacted]:

Case	Optimized design
Number of PV modules	[redacted]
Number of Wind turbines	
Number of batteries	
Electrolyzer installed power	
Minimum electrolyzer power %	
Volume of the LP storage	
Compressor maximum flowrate	

Table 43: Mojave – [redacted] - Optimization results

With this design, the following main results are obtained:

Year 1 potential energy production	[redacted]
Year 1 energy production	
Year 1 percentage of curtailed energy	
Year 1 unsatisfied H_2 load	
Year 1 unsatisfied H_2 load percentage	

Table 44: Mojave – [redacted] - Optimization results - technical results

Total investment cost	[redacted]
Levelized O&M cost	
Levelized replacement cost	
Levelized total cost	
LCOH	

Table 45: Mojave – [redacted] - Optimization results - cost results

[redacted]

11.4 Five Points site – [redacted]

The following part describes the analysis carried out for Five Points site, with a target H_2 production of [redacted]. In the same way as for Whitewater, it is considered that the H_2 load at the outlet of the pipeline is allowed reaching [redacted] as peak flowrate.

[redacted]

Odyssey optimization tool is run considering the following ranges for each parameter:

Parameter	Min value	Max value	Points
Number of PV modules	[redacted]	[redacted]	5
Number of Wind turbines	[redacted]	[redacted]	5
Number of batteries	[redacted]	[redacted]	7
Electrolyzer installed power	[redacted]	[redacted]	3
Minimum electrolyzer power %	[redacted]	[redacted]	2
Volume of the LP storage	[redacted]	[redacted]	3
Compressor maximum flowrate	[redacted]	[redacted]	4

Table 46: Five Points – [redacted] - optimization parameters

The genetic algorithm is used to simulate 400 cases over 3 763 200 combinations. The best combinations obtained after 10 generations are shown on the graph below:

[redacted]

Figure 9: Five Points – [redacted] - Optimization results

The best combination allowing reaching at least [redacted] of H_2 ([redacted] of unsatisfied load) has a LCOH of [redacted]:

Case	Optimized design
Number of PV modules	[redacted]
Number of Wind turbines	
Number of batteries	
Electrolyzer installed power	
Minimum electrolyzer power %	
Volume of the LP storage	
Compressor maximum flowrate	

Table 47: Five Points – [redacted] - Optimization results

With this design, the following main results are obtained:

Year 1 potential energy production	[redacted]
Year 1 energy production	
Year 1 percentage of curtailed energy	
Year 1 unsatisfied H_2 load	
Year 1 unsatisfied H_2 load percentage	

Table 48: Five Points – [redacted] - Optimization results - technical results

Total investment cost	[redacted]
Levelized O&M cost	
Levelized replacement cost	
Levelized total cost	
LCOH	

Table 49: Five Points – [redacted] - Optimization results - cost results

[redacted]

11.5 Required Land

Based on the results obtained in the previous sections for the number of PV Modules, batteries, and electrolyzers, the total land requirements are tabulated below for the [redacted]:

[redacted]

Table 50: Land usage summary

[redacted]

Table 51: Land usage summary (PV and Wind Original)

11.6 Required Water for Electrolyzers

The consumption of water is directly proportional to the amount of hydrogen produced. Working backward from the amount of water required for the water electrolysis reaction, we establish general requirements for the water consumption. In general, a volume of [redacted] of demineralized water is required for every kilogram of product hydrogen produced [for both PEM and Alkaline electrolysis]. This is the amount of water that will enter the electrolyzer stacks and will subsequently be separated into the constituent components, hydrogen and oxygen. This value is inherent to the water electrolysis process and is not affected by the selection of the electrolyzer technology. Electrolyzer manufacturers will provide their specific requirements for the water supply to the electrolyzer such as conductivity, purity, and specific threshold limits for minerals or other contaminants. For this report manufacturer's for both PEM and Alkaline electrolyzers provided their typical demineralized water requirements, provided below for reference.

DEMINERALIZED WATER REQUIREMENTS

[redacted]

Table 52: Typical Demineralized Water Requirements

In general, it should be noted that some form of water purification will be required at the production site to achieve the demineralized water quality required by the electrolyzers. The exact quality and composition of available water will determine the type and extent of water purification required. For water that meets typical potable water quality requirements, a minimum water treatment of reverse osmosis (RO) and water deionization will be necessary. The amount of power, equipment cost and footprint for the RO and water deionizer are thus included in the projected system costs and land estimate. A generic process diagram for the water treatment is provided for reference.

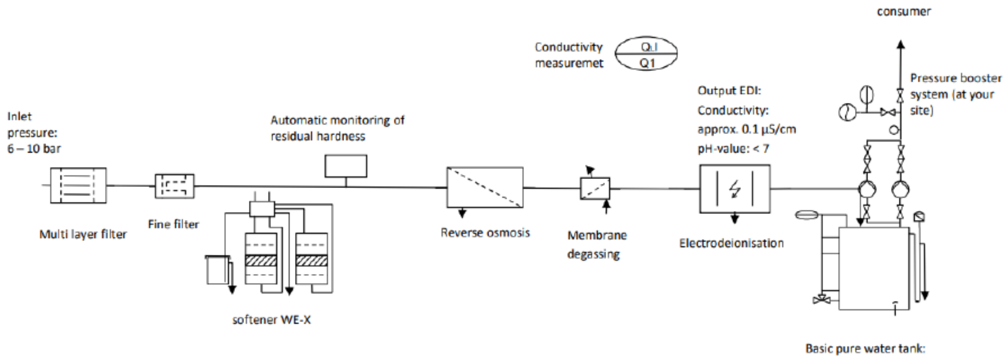


Figure 10: Water Treatment Process Diagram

Using the [redacted] demineralized water : 1 kg hydrogen ratio, we obtain the following minimum feed water requirements based on the projected hydrogen production quantities:

Water Consumption vs. Hydrogen Production
[redacted]
DEMINERALIZED WATER REQUIREMENT
[redacted]
POTABLE WATER REQUIREMENT (PEM ELECTROLYZER, typical)
[redacted]
POTABLE WATER REQUIREMENT (AE ELECTROLYZER, typical)
[redacted]

Conversions: $1\ USgallon = 3.78541\ Liters$
$1\ Acrefoot\ [AF] = 325{,}851\ US\ gallons$

Table 53: Water usage summary

The Demineralized Water Requirement value represents the amount of water into the electrolyzer for the electrolysis reaction. The Potable water requirements account for the anticipated loss for the RO and deionizer water treatment. This loss can increase the required value of feed water a minimum of [redacted] times or more, depending on the available water quality. For this report, the authors solicited information from multiple electrolyzer vendors for the water requirements. The PEM manufacturer specified that they require [redacted] L potable water per 1 kg hydrogen, while one of the Alkaline manufacturers specified that they require [redacted] i.e. [redacted] L potable water per 1 kg hydrogen. Table 44 above therefore reflects the expected water consumption values separately for the different types of electrolyzer technology. In general, the conservative estimate of [redacted] L potable water / 1 kg of hydrogen would therefore be adequate for either of the electrolyzer technologies, with the opportunity to reduce the overall water consumption at a later stage of engineering once the water quality is fully defined.

The amount of brine discharge from the water treatment (DMW unit) will be equal to the difference between the Potable Water requirements and the Demineralized Water requirement and is dependent on the incoming flow rate, incoming water quality/contaminants, and the final configuration of water treatment technology. In the Utility Summary we have assumed a Feed Water Flow Rate that is [redacted] the required demineralized water consumption. It should be noted that we have also provided the Instantaneous Maximum Feed Water Flowrate in addition to the Annual consumption. [redacted]

Additional water for cooling the electrolyzers and product gas cooling are required. However the electrolyzers consider a closed loop system for production heat transfer, typically a glycol and water mixture. [redacted]

12. BLUE HYDROGEN

12.1 Introduction

Blue hydrogen technologies entail either the use of Steam Methane Reforming (SMR) with carbon capture or Auto Thermal Reforming (ATR) based technology with carbon capture. The SMR technology reacts the feed and steam in the presence of catalyst to make syngas. This reaction is endothermic and is supported by burning natural gas and off gases. The ATR based technology uses oxygen to combust the feed in a pressurized vessel and then reforms the resulting product gases to generate Syngas. The endotherm for this reaction is supplied by the combustion of feed itself.

The production of green hydrogen results in oxygen as a by-product, which typically gets vented to the atmosphere if not monetized. While sale of oxygen is feasible, it requires transportation to the end user. Technip Energies (T.EN) conducted a high level assessment of complementing the green hydrogen production with blue hydrogen production for the [redacted] scenario. This assessment was based on using the by-product oxygen from the electrolyzer in a ATR based hydrogen plant.

[redacted]

The main process steps are listed below:

<u>Feed Treatment</u>

The mixture of natural gas feed and recycle hydrogen is heated against flue gas in Feed Preheat. This mixed stream is then introduced in the Feed Treater, where any organic sulfur in the feed gas is hydrogenated over the combo catalyst into H2S. The sulfur in the feed is absorbed by the combo catalyst in the following reaction:

$H_2S + ZnO \rightarrow ZnS + H_2O$

<u>Pre-Reforming</u>

After purification, desulfurized feed is mixed with process steam to achieve a target steam to carbon mole ratio. The mixed feed is then preheated in the Mixed Feed Preheat Coil in
the Fired Heater before being sent to the Pre-reformer. The Pre-reformer takes the feed, along with process steam, and converts the process gas into a mixture of methane, hydrogen, carbon monoxide, carbon dioxide and steam via the following reaction

Reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$ Endothermic

Shift: $CO + H_2O \rightarrow CO_2 + H_2$ Exothermic

Autothermal Reforming
The Pre-reformer effluent then enters the Reheat Coil in the Fired Heater to reheat before sending to ATR. The pre-reformed gas is reacted with oxygen from the electrolyzer. The chemical reactions taking places are a combination of combustion and steam reforming reaction. The combustion provides the heat for the endothermic steam reforming reaction.
The ATR is a licensor package unit. It consists a refractory lined pressure vessel with special burner design, a combustion chamber and a catalyst bed.

High Temperature Shift Conversion, Low Temperature Shift Conversion and Heat Recovery
Syngas at the exit of the ATR consists of a mixture of hydrogen, carbon oxides, unreacted methane and steam. The syngas is cooled down by generating steam in the Process Gas Boiler. In the Process Gas Boiler, the syngas flows on the tube side while the shell side is directly connected to the Steam Drum by multiple risers and downcomers. Additional process steam is added to Syngas downstream of the Process Gas Boiler before going to the High Temperature Shift reactor (HTS). In the HTS, carbon monoxide and steam react to produce hydrogen and carbon dioxide. The reaction is taking place in the following reaction:
$CO + H_2O \rightarrow CO_2 + H_2$ Exothermic
The syngas is then cooled through in a series of heat exchangers.
Before the Syngas is sent to the Low Temperature Shift reactor (LTS), Syngas is routed to Hot Process Condensate Separator, to remove any moisture that might exist during plant upsets and startup/shutdown. In the LTS, a further shift reaction of carbon monoxide and steam is reacted to produce additional hydrogen and carbon dioxide. The shift reaction is the same as the HTS.
Following LTS, the raw hydrogen gas is cooled through a series of exchangers.
The effluent from Air Cooler, is a two-phase stream consisting of syngas and process condensate. Process condensate is separated from syngas in the Cold Process Condensate Separator. Dry syngas is routed to CO_2 Removal Unit for CO_2 capture and Syngas separation. Condensate from Cold Process Condensate Separator is pumped by Process Condensate Pump to HP Stripper.

Syngas CO_2 Removal and Compression
Dry Syngas enters CO_2 Removal Unit. The CO_2 Removal Unit uses amine-based gas treatment technology to separate the CO_2 from the syngas. The treated gas from the CO_2 Removal Unit, which contains the majority of the Hydrogen, is sent to the PSA for further purification. Saturated acid off-gas, CO_2 rich, comes out from CO_2 Removal Unit.
CO_2 Removal Unit requires Reboiler to regenerate the Amine solution, the required heat source for the Reboiler is from the Syngas cooling train. CO_2 off gas from CO_2 Removal Unit is sent to CO_2 Product compressor for compression. CO_2 removal greater than 99% is possible using this scheme.

Hydrogen Purification and Compression
A pressure swing adsorption unit is typically employed to get up to 99.9% hydrogen purity. If lower hydrogen purity is acceptable, the methanation scheme can be employed. Typical hydrogen purity in a methanation scheme is between 95% to 97% with the remainder being CH_4. Product hydrogen is then compressed to the desired pressure.

Fired Heater Heat Recovery
Fired Heater is used to provide heat source for the process. Majority of the firing is provided by PSA purge gas if a PSA based scheme is employed. Alternately, hydrogen can be used to provide the heat, effectively reducing the carbon emissions. The Fired Heater typically provides heat to the mixed feed preheat coil, reheat coil and the feed preheat coil.

Steam Generation and Power Generation
A single Steam Drum acts as the sole collection vessel for all steam generated in the

plant. The elevation of the steam drum is set to permit natural circulation flow to and from the Process Gas Boiler, and Syngas Boiler. Steam from Steam Drum is superheated in Steam Superheater against Syngas. Part of the superheated steam is used as the process steam. The rest of the steam is routed to Steam Turbine Generator Unit for power generation. Steam condensate from Steam Turbine Generator is re-used as BFW for the plant.

<u>Oxygen Storage and compression</u>
Since the selected green hydrogen scheme is a PV only scheme, bulk of the hydrogen production (and hence the oxygen production) happens during the day time. Natural gas based hydrogen plants do not ramp up and ramp down at the same rate as an electrolyzer does and do not like cyclic operations. Hence it is assumed that the ATR based hydrogen plant will run at a constant capacity 24/7. This requires oxygen storage. For capacities at this scale it is best to liquefy and store oxygen in spherical tanks for consumption when electrolyzers will be at turndown.

12.3 Production Split

The amount of oxygen generated via electrolyzer based hydrogen production can support approximately twice the blue hydrogen production, hence the production split comes out to
Green hydrogen: [redacted]
Blue hydrogen: [redacted]
[redacted] for internal use as fuel)

12.4 Typical Utilities & Emissions for [redacted] Blue Hydrogen plant

Natural Gas Feed	MSCFH	[redacted]
Demin Water	GPM	[redacted]
Cooling Water	GPM	[redacted]
Power Generation	MW	[redacted]
CO_2 Produced	MMTPY	[redacted]

Table 54: Blue Hydrogen Utilities (does not include green hydrogen)

12.5 Plot Space

For a blue hydrogen plant this size [redacted] acres of land will be required in addition to the green hydrogen component which will require [redacted] [[redacted] square miles] for [redacted] MMTPY.

Total land required for a Green + blue solution: [redacted] acres

12.6 ROM [redacted]

[redacted]

Table 55: Blue + Green [redacted] estimate

Green hydrogen pro-rated from [redacted] *case*
Blue hydrogen costs are estimated by Technip Energies in-house data and high-level vendor quotes.
Compression costs (CO_2 and O_2) are not included in the above values.

13. MEDIUM ([redacted]) AND HIGH [redacted]) PRODUCTION CAPACITIES

The removal of wind energy consideration simplifies the comparison of different potential production sites as it becomes dependent on only one variable – the potential solar generation for the given location. The potential solar power profile, which can be expressed as either a capacity factor or in terms of the annual energy production, then can be used to scale the required amount of power generation and electrolysis for hydrogen production. For the ROM estimate required of this study it is sufficient to use the potential power production at a given site to linearly scale the quantity of PV panels, battery storage, electrolyzers and power converters and obtain a relative cost estimate. We established a baseline case and location, Whitewater [redacted] MMTPY, against which all other potential sites can be evaluated.

Using the same methodology as described in section 10 of this report, the annual PV energy generation per 1,000 kW AC installed PV array is obtained from NREL data. That value is then compared to the Whitewater to establish a linear ratio. [redacted]

The table below summarizes the relative solar generation potential of the original sites considered.

Location	State	Latitude	Longitude	Annual PV Energy per 1,000 kW AC [GWh]	Ratio to Whitewater	% Difference
Whitewater	CA	[redacted]				
29 Palms	CA					
Blythe	CA					
Mojave	CA					
5 Points	CA					

Table 56: Production Site Solar Potential

The same approach can thus be extended to any combination of sites to obtain the cost estimate and relative size of a distributed green hydrogen production system.

14. ABBREVIATIONS

T.EN	Technip Energies
BESS	Battery Energy Storage System
BOS	Balance of System
CAPEX	Capital Expenses
HP	High Pressure
LA	Los Angeles
LCOH	Levelized Cost Of Hydrogen
LHV	Lower Heating Value
LP	Low Pressure
MMTPY	Million (metric) tonnes per year
O&M	Operation and Maintenance
OPEX	Operating Expenses
PV	Photovoltaic
ROM	Rough Order of Magnitude
Wp	Watt peak AC Voltage (unless otherwise noted)

APPENDIX 1: PV & WIND FARM POWER PRODUCTION PROFILES

The power production profiles are obtained by using data from the National Renewable Energies Laboratory (NREL) website (https://sam.nrel.gov/) for a typical meteorological year (TMY). The input configuration for each of the time series is as follows:

PV Array power production:

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

APPENDIX 2: WHITEWATER – [redacted] – PV & WIND BASE CASE DETAILED RESULTS

Energy production over [redacted] years:

[redacted]

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Primary Production	80 207 615.6	79 806 577.5	79 407 544.6	79 226 974	78 615 454.4	78 222 377.1	77 831 265.2	77 654 279	77 054 898.3	76 669 623.8	76 286 275.7	76 112 802.8	75 525 320.1	75 147 693.5	74 771 955	74 601 925.7	74 026 104.8	73 655 974.3	73 287 694.4	73 121 040.2
TOTAL	**80 207 615.6**	**79 806 577.5**	**79 407 544.6**	**79 226 974**	**78 615 454.4**	**78 222 377.1**	**77 831 265.2**	**77 654 279**	**77 054 898.3**	**76 669 623.8**	**76 286 275.7**	**76 112 802.8**	**75 525 320.1**	**75 147 693.5**	**74 771 955**	**74 601 925.7**	**74 026 104.8**	**73 655 974.3**	**73 287 694.4**	**73 121 040.2**

[redacted]

Levelized expenses over [redacted] years:

[redacted]

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Investment	66 423 270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O&M	1 659 775	1 551 191.6	1 449 711.8	1 354 870.8	1 266 234.4	1 183 396.6	1 105 978.2	1 033 624.5	966 004.2	902 807.6	843 745.4	788 547.1	736 959.9	688 747.6	643 689.4	601 578.8	562 223.2	525 442.3	491 067.5	458 941.6
Replacement	0	0	0	0	0	0	0	0	0	0	2 086 265.5	0	0	0	0	390 409.5	0	0	0	0
TOTAL	**68 083 045**	**1 551 191.6**	**1 449 711.8**	**1 354 870.8**	**1 266 234.4**	**1 183 396.6**	**1 105 978.2**	**1 033 624.5**	**966 004.2**	**902 807.6**	**2 930 010.9**	**788 547.1**	**736 959.9**	**688 747.6**	**643 689.4**	**991 988.3**	**562 223.2**	**525 442.3**	**491 067.5**	**458 941.6**

[redacted]

Notes:

- Year 1 investment expenses:

[redacted]

- Year 11 replacement expenses: BESS [redacted]).
- Year 16 replacement expenses: Electrolyzer ([redacted]).
- Year 1 O&M expenses:

[redacted]

Cost structure by component:

[redacted]

Item	Value	Share
PV Array#1	[redacted]	
Wind Farm#1		
Electrical Storage Bank#1		
Electrolyser Stack#1		
Converter		
H2 Compressor#1		
LP Storage		
TOTAL		

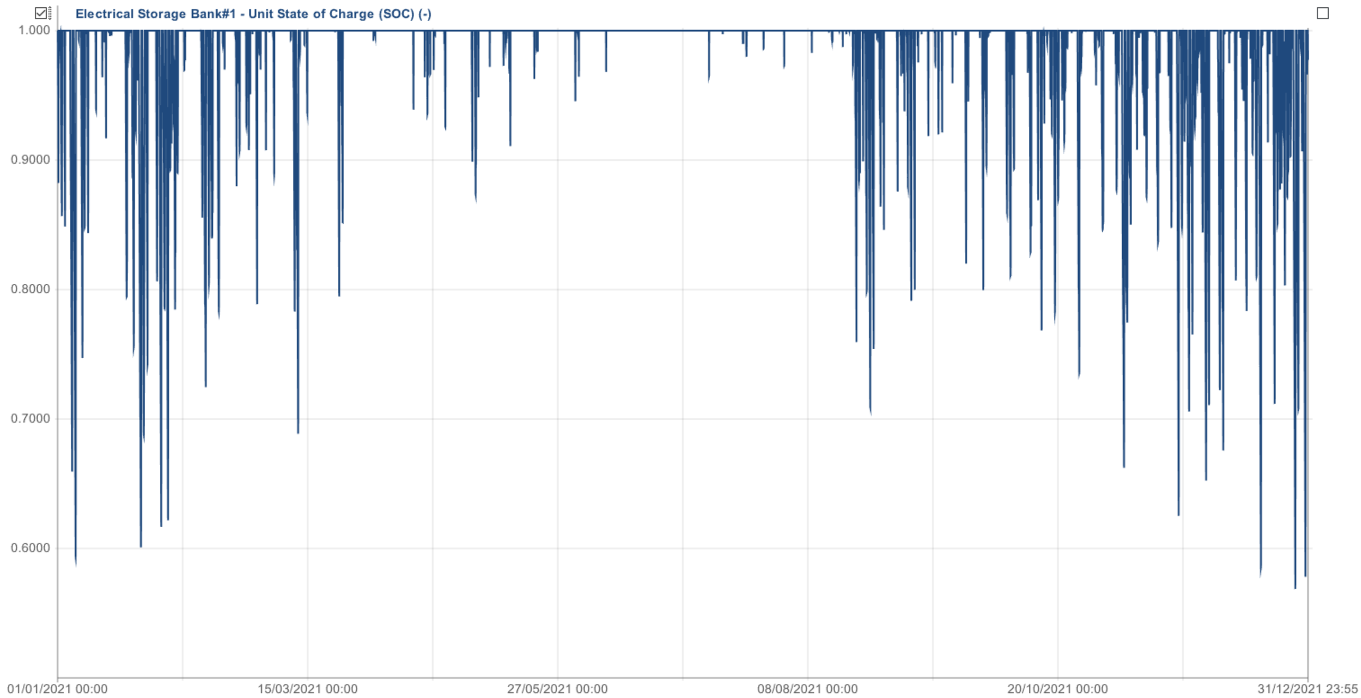
[redacted]

Primary production potential vs actual primary production (PV + wind farm power), over year 1 and over the first month:

[redacted]

36.1% of the available energy is not produced.

BESS state of charge over year 1:



The BESS is mainly used during winter and the state of charge does not go below 56%.

Electrolyzer produced mass flow over the first month:

[redacted]

LP storage state of charge over the first month:

[redacted]

H_2 pipeline state of charge over the first month:

[redacted]

APPENDIX 3: WHITEWATER – [redacted] – PV & WIND OPTIMIZED CASE DETAILED RESULTS

Energy production over [redacted] years:

[redacted]

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Primary Production	[redacted]																			
TOTAL																				
TOTAL Cumulative																				

Levelized expenses over [redacted] years:

[redacted]

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Investment	[redacted]																			
O&M																				
Replacement																				
TOTAL																				
TOTAL Cumulative																				

Cost structure by component:

[redacted]

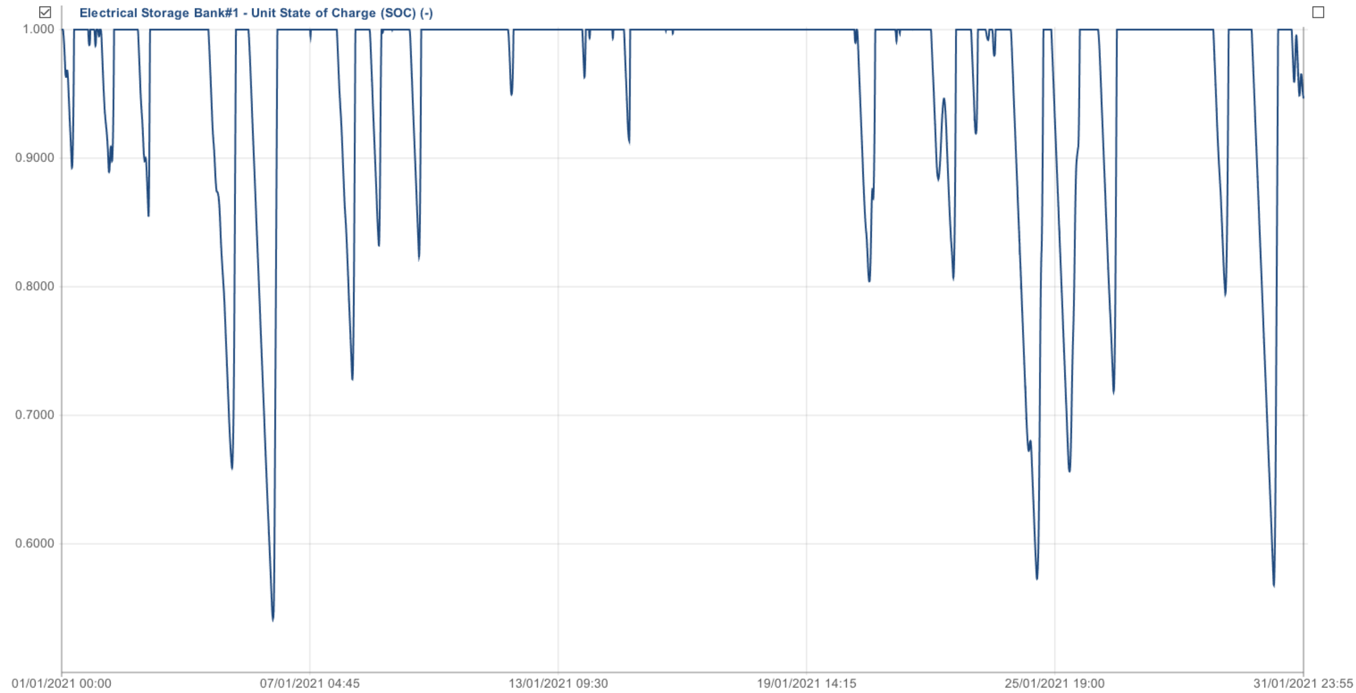
Item	Value	Share
Wind Farm#1	51 526 421.3	48.9%
PV Array#1	31 265 085.7	29.7%
Electrical Storage Bank#1	11 419 478.1	10.8%
Electrolyser Stack#1	9 237 573	8.8%
Converter	1 680 000	1.6%
H2 Compressor#1	215 985.9	0.2%
LP Storage	90 420	0.1%
TOTAL	**105 434 964**	**100%**

[redacted]

Primary production potential vs actual primary production (PV + wind farm power), over year 1 and over the first month:

[redacted]

BESS state of charge over year 1:



The BESS is mainly used during winter and the state of charge does not go below 54%.

Electrolyzer produced mass flow over the first month:

[redacted]

[redacted] corresponds to the maximum flowrate of the electrolyzer, that it can reach when renewable power is available and when the LP storage is not full.

The electrolyzer is limited to [redacted] when the LP storage is full and the compressor running at its maximum flowrate of [redacted].

The electrolyzer is limited to [redacted] when the LP storage is full and the compressor flowrate is limited to [redacted]) when the pipeline is full.

The electrolyzer is limited to [redacted] 5% of its maximum capacity, when not enough renewable energy is available and the battery is used.

LP storage state of charge over the first month:

[redacted]

Compressor flowrate over the first month:

[redacted]

Delivered H_2 flowrate at the outlet of the pipeline, over the first month:

[redacted]

APPENDIX 4: SENSITIVITY ON TIME STEP

The PV and wind farm power production profile were initially given with a time step of [redacted] which was directly used as simulation time step.

With this time step of [redacted]

Considering the pipeline of Whitewater, [redacted] min are sufficient to fully charge the pipeline from 100 to 120 bara at [redacted].

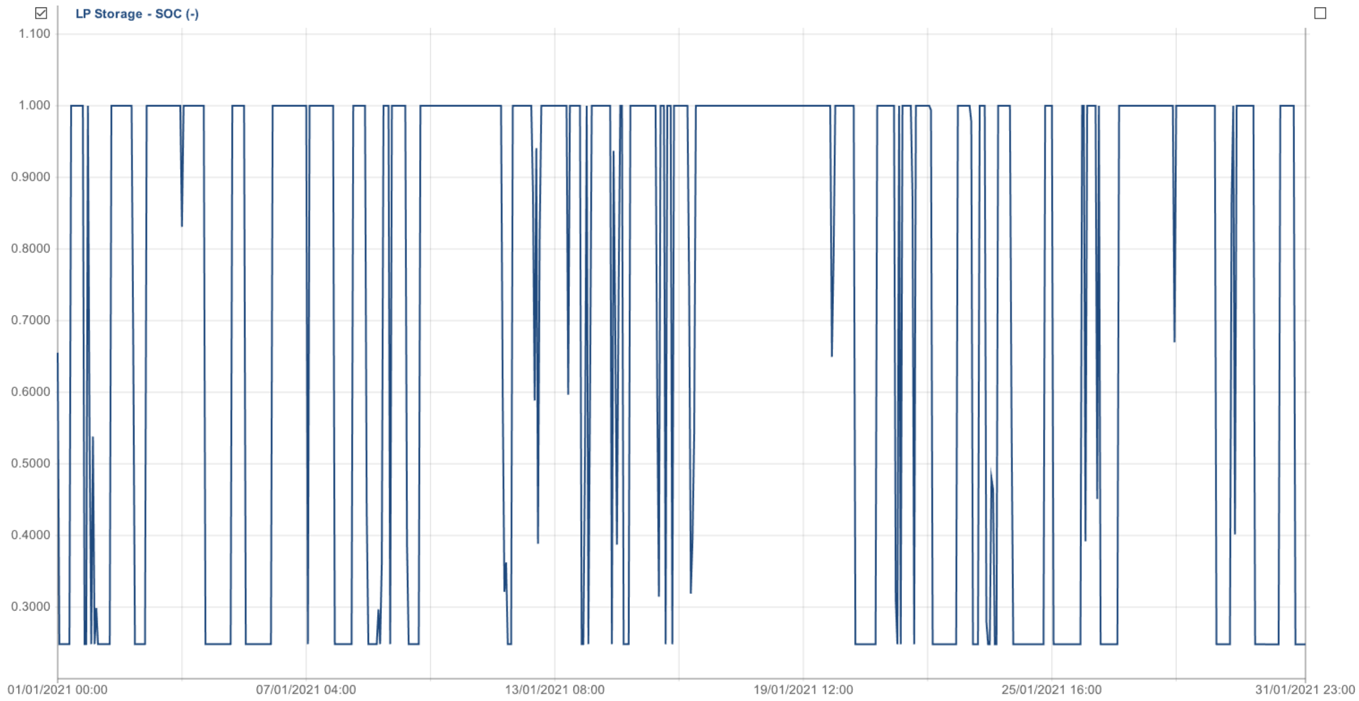
For a LP storage of [redacted] min are sufficient.

The following graphs are obtained with a time step of [redacted] for Whitewater optimized case. They shall be compared to the same case run with a time step of [redacted] min, presented in appendix 3. In the present simulation, it is observed that the state of charge of the H_2 pipeline remains equal to zero and that the flowrate seems limited to [redacted]

Electrolyzer produced mass flow over the first month:

[redacted]

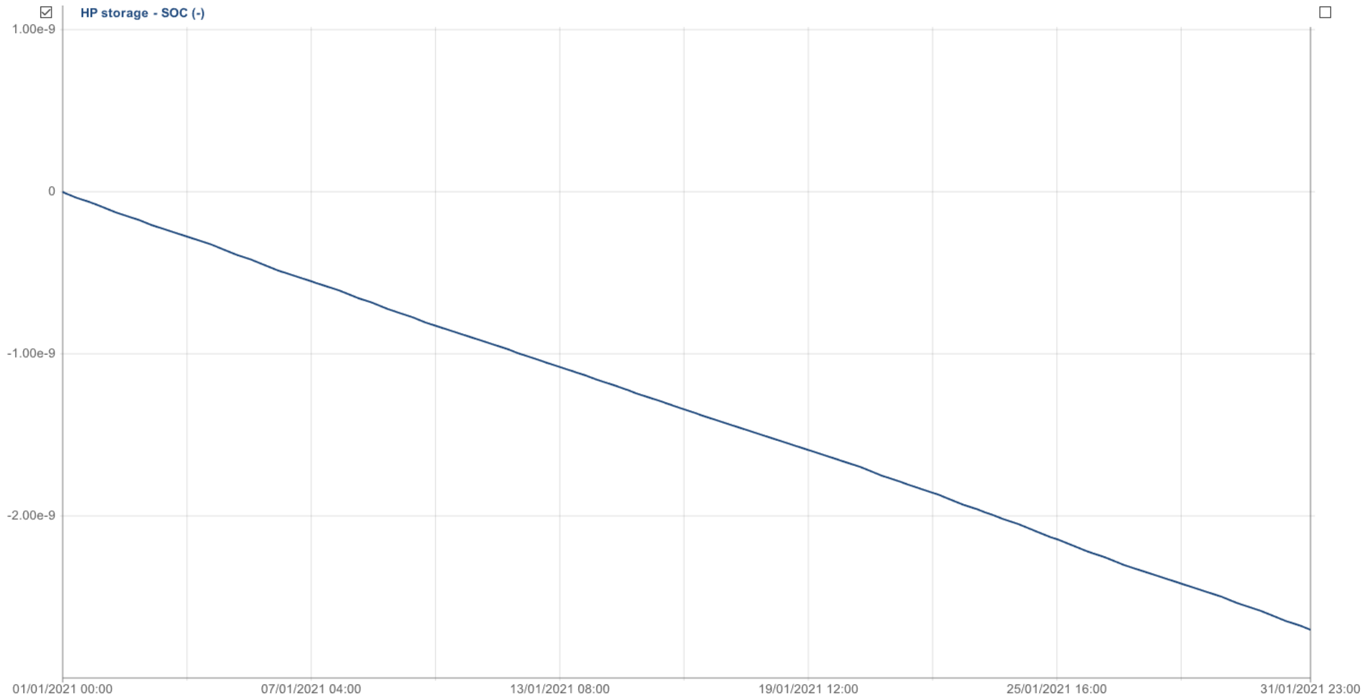
LP storage state of charge over the first month:



Compressor flowrate over the first month:

[redacted]

H_2 pipeline state of charge over the first month:



Delivered H_2 flowrate at the outlet of the pipeline, over the first month:

[redacted]

APPENDIX 5: ALKALINE ELECTROLYZER BLOCK FLOW DIAGRAM

[redacted]

APPENDIX 6: PRELIMINARY UTILITY SUMMARY

DOCUMENT NUMBER
202479C-000-NM-0001-0005 B [redacted]

CLIENT	UTILITY SUMMARY	Rev	Date	Description	
SCG		A	08/30/21	Issued for Information	[redacted]
LOCATION		B	09/30/21	Revised for Information	
California					
UNIT					
Hydrogen Plant					

PRODUCT

H_2 Product (Note 1)	Units	
Flow Rate	[redacted]	
Temperature		
Pressure		
O_2 Product		
Flowrate	TPY	[redacted]
Temperature	°F	
Pressure	Bara	

Utility (Note 2)

[redacted]

Electrolyzer Installed Power	GW	[redacted]
Instaneous Max Chilled Water for H_2 Product (Alkaline Option)	GPM	
Annual Chilled Water Circulation for H_2 Product (Alkaline Option)	MMGal / yr	
Instaneous Max Chilled Water for O_2 Product (Alkaline Option)	GPM	
Annual Chilled Water Circulation for O_2 Product	MMGal / yr	
Instaneous Max Demin Water Flowrate (Alkaline Option)	GPM	
Annual Demin Water Flowrate (Alkaline Option)	MMGal / yr	
Instaneous Max Demin Water Flowrate (PEM Option)	GPM	
Annual Demin Water Flowrate Requirement (PEM Option)	MMGal / yr	
Instaneous Max Feed Water Flowrate (Alkaline Option)Note 3	GPM	
Annual Feed Water Flowrate Requirement (Alkaline Option) - Note 3	MMGal / yr	
Instaneous Max Feed Water Flowrate (PEM Option) - Note 3	GPM	
Annual Feed Water Flowrate Requirement (PEM Option) -	MMGal / yr	
Instaneous Max IA	ft3/hr	
Annual Required IA	MMft3/yr	
N_2 (for Unit Purge)	MSCF	
Instaneous Max Brine Output - Note 3	ft3/hr	
Annual Total Brine Output - Note 3	MMft3/yr	

NOTES:

1. Net Hydrogen product.
2. All utility value to be confirmed during detailed engineering after vendor selection.
3. Feed water requirement to be confirmed when feed water quality is available at each site.

APPENDIX 7: WHITEWATER – [redacted] – PV ONLY OPTIMISED CASE DETAILED RESULTS

[redacted]

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Primary Production	[redacted]																			
TOTAL																				
TOTAL Cumulative																				

[redacted]

H2 Pipeline - Levelized Expenses (k$)

Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Investment	[redacted]																			
O&M																				
Replacement																				
TOTAL																				
TOTAL Cumulative																				

[redacted]

H2 Pipeline - Levelized Total Cost Structure by Component (k$)

Item	Value	Share
PV Array#1	[redacted]	
Electrical Storage Bank#1		
Electrolyser Stack#1		
Converter		
TOTAL		

[redacted]

Item	Value	Share
PV Array#1	39 965 640	[redacted]
Electrical Storage Bank#1	18 164 000	
Electrolyser Stack#1	11 223 000	
Converter	2 600 000	
TOTAL	**71 952 640**	

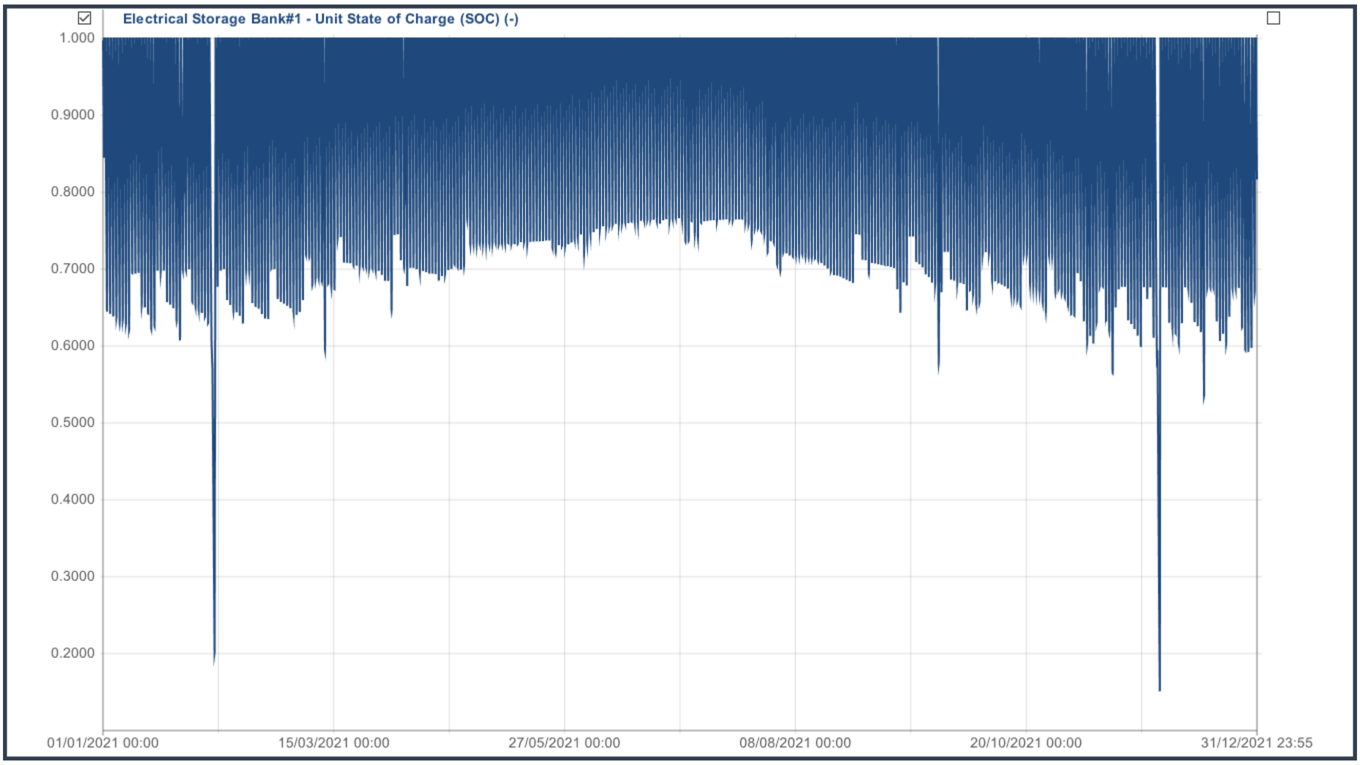
[redacted]

Item	Value	Share
[redacted]	8 420 306.9	[redacted]
Electrical Storage Bank#1	5 169 031.4	
Electrolyser Stack#1	3 780 421	
TOTAL	**17 369 759.3**	

Primary production potential vs actual primary production (PV + wind farm power), over year 1 and over the first month:

[redacted]

BESS state of charge over 1 year:



Note that two days are driving the size of the BESS. For the remainder of the year the BESS does not fall below 50% total charge.

Electrolyzer mass flow over the first month:

[redacted]

Whitewater - No Wind, [redacted] sq. mi.]

CAPEX		Qty.	Installed kW	CAPEX
[redacted]	PV	[redacted]		
	Wind			
	BESS			
	Electrolyzer			
	Converters			

[redacted]

Whitewater - No Wind, [redacted] sq. mi.]

OPEX		Qty.	Installed kW	OPEX
[redacted]	PV	[redacted]		
	Wind			
	BESS			
	Electrolyzer			
	Converters			

Whitewater - No Wind, [redacted] sq. mi.]

Freq. [yrs.]	REPLACEMENT		Qty.	Installed kW	REPLACEMENT
25	[redacted]	PV	[redacted]		
20		Wind			
10		BESS			
15		Electrolyzer			
N/A		Converters			

Whitewater - No Wind, [[redacted] sq. mi.]

[redacted] Discount Rate

0.00% Production Reduction at Year [redacted]

[redacted]	H2 Production	Levelized Production	Investment	O&M	Replacement	Sum
[redacted]						

$$LCOH = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ hydrogen\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

$I_t = Investment\ Costs\ in\ year\ t$

$M_t = Operations\ and\ Maintenance\ Costs\ in\ year\ t$

$F_t = Fuel\ Costs\ in\ year\ t\ (Not\ Applicable\ for\ Green\ H2)$

$H_t = Hydrogen\ Produced\ in\ year\ t\ [kg]$

$r = Discount\ Rate$

$n = Expected\ Lifetime\ of\ System$

APPENDIX 8: NREL COST BASIS MODEL INPUTS

The NREL cost basis data is based on financial models and cost assumptions for the underlying components of a PV system to produce the CAPEX and OPEX values used in this report. The data is provided at no cost, available to the public, by NREL at www.nrel.gov/publications. The assumptions table is provided here, as a quick reference. For further explanation on the costs estimate methodologies and the different technologies please refer to the original NREL report referenced below.

"U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020" Davide Feldman, Vinesh Ramasamy, Ran Fu, Ashwin Ramdas, Jal Desai, and Robert Margolis.

Technical Report NREL/TP-6A20-77324 January 2021

Table 7. Utility-Scale PV: Modeling Inputs and Assumptions

Category	Modeled Value	Description	Sources
System size	100 MW; range: 5 MW–100 MW	A large utility-scale system capacity	Model assumption
Module efficiency	19.5%	Average monocrystalline module efficiency	CA NEM 2020
Module price	$0.41/W_DC	Ex-factory gate (first buyer) price, Tier 1 monocrystalline modules	Wood Mackenzie and SEIA 2020; NREL 2020
Inverter price	$0.05/W_DC (fixed-tilt) $0.05/W_DC (one-axis tracker)	Ex-factory gate (first buyer) price, Tier 1 inverters DC-to-AC ratio = 1.37 for fixed-tilt and 1.34 for one-axis tracker	Wood Mackenzie and SEIA 2020; Bolinger, Seel, and Robson 2019
Structural components (racking)	$0.12/W_DC for a 100-MW system	Fixed-tilt racking or one-axis tracking system	MEPS 2019; model assumptions; NREL 2020
Electrical components	$0.07–$0.13/W_DC Varies by system size	Model was upgraded to a 1,500-V_DC system that includes conductors, conduit and fittings, transition boxes, switchgear, panel boards, onsite transmission, and other electrical connections	Model assumptions; NREL 2020; RSMeans 2017
EPC overhead (percentage of equipment costs)	8.67%–13% for equipment and material (except for transmission line costs); 23%–69% for labor costs; varies by system size and labor activity	Costs associated with EPC SG&A, warehousing, shipping, and logistics	NREL 2020
Sales tax	National average: 5%	Sales tax on equipment costs	RSMeans 2017
Direct installation labor	Electrician: $27.47 per hour Laborer: $18.17 per hour	Modeled labor rate assumes national average nonunionized labor	BLS 2019; NREL 2020
Burden rates (percentage of direct labor)	Total nationwide average: 18%	Workers compensation, federal and state unemployment insurance, FICA, builders' risk, public liability	RSMeans 2017
PII	$0.03–$0.07/W_DC Varies by system size	For construction permits fee, interconnection, testing, and commissioning	NREL 2020

Category	Modeled Value	Description	Sources
Transmission line (gen-tie line)	\$0.00–\$0.02/W_{DC} Varies by system size	System size < 10 MW uses 0 miles for gen-tie line System size > 200 MW uses five miles for gen-tie line System size = 10–200 MW uses linear interpolation	Model assumptions; NREL 2020
Developer overhead	2%–12% Varies by system size (100 MW uses 2%; 5 MW uses 12%)	Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions	Model assumptions; NREL 2020
Contingency	3%	Estimated as markup on EPC cost	NREL 2020
Profit	5%–8% Varies by system size (100 MW uses 5%; 5 MW uses 8%)	Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, and developer overhead	NREL 2020

APPENDIX 9: ELECTRICAL SINGLE LINE DIAGRAMS - CONCEPTUAL

Attached below are conceptual Single Line Diagrams (SLD) for a green hydrogen production facility. These documents provide a high-level view of the electrical architecture necessary to integrate the renewable energy generation and hydrogen production.

In addition to the SLD, the narrative below helps to describe the minimum requirements and characteristics of the plant energy control system.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

APPENDIX 10: ELECTRICAL EQUIPMENT LIST - CONCEPTUAL

[redacted]

APPENDIX 11: COST TABLES – BESS REDUCTION

The tables below depict the cost reduction for various scenarios of battery storage reduction.

Below is the economic data for Whitewater [redacted] with PV only considering a [redacted] reduction in the BESS versus the base design:

Whitewater - No Wind, [redacted] sq. mi.], [redacted] Reduced BESS

CAPEX		
[redacted]	PV	[redacted]
	Wind	
	BESS	
	Electrolyzer	
	Converters	

[redacted]

Whitewater - No Wind, [redacted] sq. mi.], [redacted] Reduced BESS

OPEX		
[redacted]	PV	[redacted]
	Wind	
	BESS	
	Electrolyzer	
	Converters	

Whitewater - No Wind, [[redacted] sq. mi.], [redacted] Reduced BESS

Freq. [yrs.]	REPLACEMENT		Qty.	Installed kW	REPLACEMENT
25	[redacted]	PV	[redacted]		
20		Wind			
10		BESS			
15		Electrolyzer			
N/A		Converters			

Whitewater - No Wind, [redacted] sq. mi.], [redacted] Reduced BESS

[redacted] Discount Rate 0.00% Production Reduction at Year [redacted]

[redacted]	H2 Production	Levelized Production	Investment	O&M	Replacement	Sum
[redacted]						

$$LCOH = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ hydrogen\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

$I_t = Investment\ Costs\ in\ year\ t$

$M_t = Operations\ and\ Maintenance\ Costs\ in\ year\ t$

$F_t = Fuel\ Costs\ in\ year\ t\ (Not\ Applicable\ for\ Green\ H2)$

$H_t = Hydrogen\ Produced\ in\ year\ t\ [kg]$

$r = Discount\ Rate$

$n = Expected\ Lifetime\ of\ System$

Below is the economic data for Whitewater [redacted] with PV only considering a [redacted] reduction in the BESS versus the base design:

CAPEX

[redacted]

Whitewater - No Wind, [redacted] sq. mi.], [redacted] Reduced BESS

	Qty.	Installed kW	CAPEX
PV	[redacted]		
Wind			
BESS			
Electrolyzer			
Converters			

[redacted]

OPEX

[redacted]

Whitewater - No Wind, [redacted] sq. mi.], [redacted] Reduced BESS

	Qty.	Installed kW	OPEX
PV	[redacted]		
Wind			
BESS			
Electrolyzer			
Converters			

Whitewater - No Wind, [redacted] sq. mi.], [redacted] Reduced BESS

Freq. [yrs.]	REPLACEMENT		Qty.	Installed kW	REPLACEMENT
25	[redacted]	PV	[redacted]		
20		Wind			
10		BESS			
15		Electrolyzer			
N/A		Converters			

Whitewater - No Wind, [[redacted] sq. mi.], [redacted] Reduced BESS

[redacted] Discount Rate 0.00% Production Reduction at Year [redacted]

[redacted]	H2 Production	Levelized Production	Investment	O&M	Replacement	Sum
[redacted]						

$$LCOH = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ hydrogen\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

$I_t = Investment\ Costs\ in\ year\ t$

$M_t = Operations\ and\ Maintenance\ Costs\ in\ year\ t$

$F_t = Fuel\ Costs\ in\ year\ t\ (Not\ Applicable\ for\ Green\ H2)$

$H_t = Hydrogen\ Produced\ in\ year\ t\ [kg]$

$r = Discount\ Rate$

$n = Expected\ Lifetime\ of\ System$