ME 4315: Energy Systems
Section A — Fall 2025
Instructor: Dr. Simmons

Project 1:
Combined Cycle Analysis and Design

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Executive Summary

The Astoria plant and Plant two are two plants that are located in Georgia that are representative of a two Brayton and one Rankine combined cycle.

As per the provided excel manual by the instructor, during the previous year, the Astoria plant generated a total 2,546,292 MWh of energy. Plant two has generated 4,317,899 MWh of energy in the previous year.

In addition to the energy generation, the excel manual also provides fuel consumption data. In the previous year, the Astoria plant consumed 28,054,045 MMBtu of fuel. The excel manual does not provide any energy consumption data on Plant two.

Calibrated models were made to replicate the performance of the plant data provided by the excel manual.

Intensive modeling of the two plants revealed the many key findings.

In terms of thermodynamic efficiency, the Astoria calibrated plant displayed an efficiency of 73.13% and the Plant two calibrated plant displayed an efficiency of 71.85%.

In terms of total power output, the Astoria calibrated plant displayed a power output of 2,106,000 MWh while the Plant two calibrated plant displayed a power output of 4,103,000 MWh. This is the total power generated in a given year. The power generation calculated by the calibrated plants closely resemble that of the real power generation data.

In terms of economic performance of the plants, the Astoria calibrated plant displayed a LCOE of .039 $/kWh and the Plant two calibrated plant displayed a LCOE of .067 $/kWh.

These findings are adherent to the expected values of the real model, however; certain factors must be considered to the calibrated model. The calibrated model is purely an estimation to the performance of the real plant.

The model does not account for the lifespan of the cycle. It is expected that the plant's efficiency and workout output will slightly decrease over time, however; the calibrated model assumes a constant performance of the data of the lifespan of thirty years for both plants.

Additionally, the calibrated model is not able to account for seasonal changes. The calibrated model assumes an ambient condition of 300 K over the lifespan of the plant. Seasonally, it is expected that the ambient conditions will fluctuate over time. This can be noticed in the excel manual that displays varying fuel consumption and energy generation over different months.

As a result, the calibrated model is not a means of defining the real world performance of the plants, but rather a means of evaluating the relative performance of the plants and analyzing how certain parameters can affect the performance of the plants. This allows for means to evaluate methods to improve the work output of the plant or improvement to the total thermodynamic efficiency of the plant.

Motivation

In project one, two plants were introduced to the team: Astoria Plant and Plant Two. Both plants are systematically similar: a combined cycle with two Brayton cycles and one Rankine cycle. In adherence to the material taught from the course, the team was to analyze the performance of the two plants. This includes three important categories: engineering, techno-economic, emission.

For the purpose of the general study of the two specified plants, the Brayton cycles (Figure 1) and Rankine cycle (Figure 2) were initially individually modeled. Initial state points were provided by the project manual (Figure 3). A majority of the missing state points were obtained using the first law of thermodynamics (Figure 4). At the Rankine level, state points that existed within the vapor dome for the Rankine cycle, the relationships in Figure 5 were used to identify missing state points. At the Brayton level, the pressure ratio relationship was utilized to find missing state points at the compressor and turbine (Figure 6). The following EES code represents the full methodology to the Brayton and Rankine models.

For cycle incorporation, the HSRG is introduced. The HSRG allows for the subsystems to transfer heat in order to maximize system power output. The Brayton cycles feed to the stack. The Rankine cycle feeds to the cooling tower. The formula shown in Figure 7 displays the methodology to obtain the total integrated power. The following EES code represents the full methodology to the combined model.

The project manual provides data to the technical and economical performance of the specified plants (Figure 8). The formulas demarcated in Figure 9 represent the methods used to specify the plant's performance. The calculated performance was compared to the real performance provided by the project excel sheet. The following EES code represents the full methodology to the model comparison.

Exergy was additionally studied. Defined by the potential to do additional work, it was crucial to analyze the exergy at each state point for both the Rankine and Brayon cycle. This allows the team to understand the maximum amount of useful work that can be extracted from the system.

Parametric analysis was also additionally studied. This allows for certain identified features of the system to be made variable. As a result, the system can be analyzed over a range of values rather than a constant.

In both Exergy and Parametric analysis, the possible methods to the improvement of the system efficiency can be evaluated. By evaluating where improvement to the system efficiency can be performed, the team is able to determine how much more power can be generated given the current power generation of the plant.

Despite similar modeling to the performance of the Astoria Plant and Plant Two, it is important to identify key limitations. In the Brayton cycle analysis, the k value is assumed to be 1.4, however; the value of k does slightly reduce at higher operating temperatures. Additionally, seasonal changes are not considered in this analysis, which would greatly vary the ambient temperature of the year.

Major Results

After the modeling of the Brayton cycle subsystem, Figure 10 displays the key results of the model. As shown, the total work output of the individual Brayton cycle is deemed to be 806 Kj/kg. With the heat addition being 1232 kJ/kg, the Brayton cycle thermodynamic efficiency is 65.44%. This thermodynamic efficiency is expected to be higher than a cycle absent of the regenerator. This is because the regenerator allows the working fluid to be preheated from the wasted heat in order to conduct maximal work output at the turbine. Without the regenerator, a significantly lower efficiency can be expected.

The results of the Rankine cycle subsystem model are also shown in Figure 11. The net work of the rankine cycle remains the same with and without regeneration at 1252 kJ/kg. Additionally, the thermodynamic efficiency is 36.24% without the regenerator and 36.34% with the regenerator. The marginal change in the thermodynamic efficiency is due to the reduced pressure due of 10 kPa. The minimal pressure results in low temperature through the regenerator. As a result, the temperature difference of the regenerator is extremely low, thus there is minimal heat transfer occurring.

In consideration of the Brayton and Rankine subsystem, the HSRG is considered. Shown in Figure 12, it is noticed that the Brayton and Rankine cycle overlap in temperature. This would indicate that negative heat transfer is occurring between the Brayton and Rankine cycle in the system.

The negative heat transfer is thermodynamically impossible which is understood when observing the state points at the HSRG. At the Brayton inlet of the HSRG, a temperature of 782 Kelvin was specified by the manual. At the Rankine outlet of the HSRG, a temperature of 870 Kelvin is specified by the manual. This would break the integrity of the second law of thermodynamics as this would assume a higher transfer of heat than was available.

Possessing the subsystem design of the Rankine and Brayton cycle, the Astoria plant and Plant two were modeled.

From the model, it was noticed that the work of the Rankine cycle was significantly higher than the work of the Brayton cycle. The work of the Rankine cycle was 3096 kJ/kg and the work of the Brayton cycle was 503.3 kJ/kg (Figure 13 and 14).

Although initially surprising, the nature of the integrated cycle must be understood. The integrated cycle assumes no regeneration which reduces the amount of work that can be produced by the turbine from the Brayton cycle. Additionally, the HSRG from the integrated cycle allows for the heat of the air to be transferred to the Rankine cycle. This would increase the work output of the turbine on the Rankine cycle.

Shown in Figure 14, the Astoria plant produced a gross capacity of 595500 kW after the reduction from the parasitic loads. This converts to 2,106,000,000 kWh which is 2,106,000 MWh. The actual electricity generation of the plant was noted to be 2,546,292 MWh.

Shown in Figure 13, Plant two displays a calibrated power generation of 4,103,000,000 which is 4,103,000 MWh.The actual electricity generation of the plant was noted to be 4,317,899 MWh.

In both the Astoria plant and Plant two, there is a reduction in the electricity generation compared to the real model. A possible reason for the discrepancy is due to the lack of regenerator on the Brayton cycle for the calibrated models. As previously mentioned, the regenerator utilizes wasted heat to retrieve more work out of the turbine shaft. Thus, the absence of a regenerator would reduce the efficiency and ability to provide more power.

Along with the power generation, the Astoria plant is calibrated to have a thermodynamic efficiency of 73.13% (Figure 14). Plant two is calibrated to have a thermodynamic efficiency of 71.85% (Figure 13)

The thermodynamic efficiency of both plants is very reasonable. Both the Brayton and Rankine cycle as a subsystem does not reach thermal efficiencies beyond 70%. For the integrated plant, the HSRG serves to transfer the heat from the outlet of Brayton cycle to the Rankine cycle before the steam is received to the turbine. As a result, the more work can be extracted from the system and the thermodynamic efficiency would be expected to increase.

Despite similar state points, Plant two has a lower thermodynamic efficiency than Astoria plant due to the larger input of fuel than the Astoria plant.

In addition to the technical findings, the economic findings were also considered. For Plant two, the LCOE over the span of the 30 year life cycle of the plants was set to be .067 $/kWh (Figure 15). This is slightly larger than the current price of power in Georgia at .042 $/kWh. For the Astoria plant, the LCOE over the span of the 30 year life cycle of the plants was set to be at .039 $/kWh (Figure 16). This is very close to the current price of power in Georgia.

As previously mentioned, the LCOE of energy for both the Astoria plant and Plant two fall very close to the current cost of power in Georgia. This would indicate that the calibrated model accurately measures the cost of energy from the plants and the total fuel consumption of the plants are relatively accurate.

As a result of the higher name plate capacity, Plant two requires more CAPEX (Investment cost) and O&M (Operations and Management cost) than the Astoria plant. Thus, it is expected for Plant two to have higher LCOE than the Astoria plant despite identical project life, and discount rate.

In consideration to the real plant performance, it is important to understand that all parameters to the system are meticulously selected. Ideally, maximizing all the parameters such as turbine efficiency would allow for maximal performance, however; the technical performance of the system cannot be understood without the economical performance of the system integrated.

In many circumstances, the increase in a parameter performance cannot be justified by the larger cost in order to achieve that parameter value. As a result, the Astoria plant and Plant two are created with consideration on how to maximize energy output while minimizing the cost to produce that energy. If this was not considered, the LCOE of both plants would be significantly larger than competitor prices.

Conclusion

The real world performance of the Astoria plant and Plant two is closely replicated by the calibrated model created by the team. From the calibrated model, it has been estimated that the LCOE for the Astoria plant is .039 $/kWh and the estimated LCOE of Plant two is .067 $/kWh.

Despite relatively fair LCOE from both the Astoria plant and Plant two, measures can be taken to reduce the LCOE. Exergy analysis can be utilized to find where additional work can be extracted. Parametric analysis can be utilized to determine how variable parameters can affect the plant system performance.

Appendix

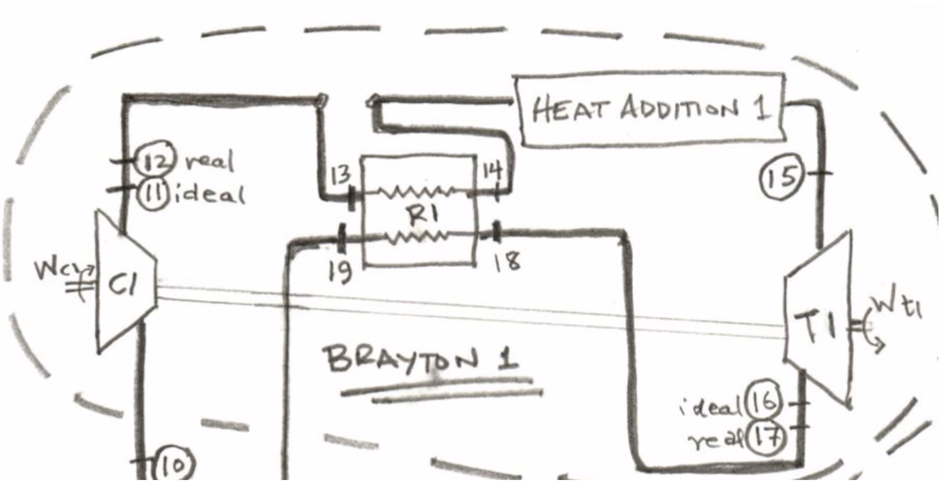

Figure 1: Brayton Cycle

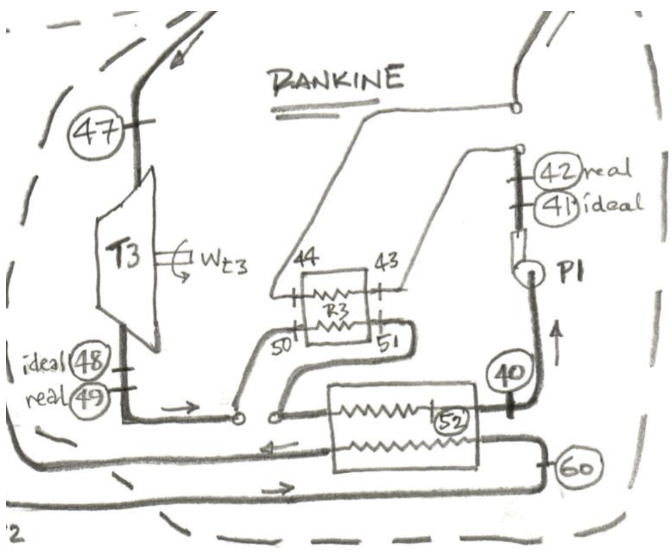

Figure 2: Rankine Cycle

Subsystem	State	Brief Description	T	P	Comment	Default Value/Range
			K	kPa		
Surroundings	0	Ambient Environment	300	101.4		
Brayton 1 (Gas Turb 1)	10	C1 Inlet	300	101.4		
	11	C1 Outlet, Ideal			PR=[5,25]	Initial: 10
	12	C1 Outlet, Real			η_{C1}=0.8	
	13	Regenerator 1 Inlet 1			Part 1A Only	
	14	Regenerator 1 Outlet 1			Part 1A Only	
	15	After Heat Addition	1600			
	16	T1 Outlet, Ideal	782-900	101.4		Single Cycle (782)
	17	T1 Outlet, Real			η_{T1}=0.9	
	18	Regenerator 1 Inlet 2			Part 1A Only	
	19	Regenerator 1 Outlet 2			Part 1A Only	
Brayton 2 (Gas Turb 2)	20	C2 Inlet	300	101.4		
	21	C2 Outlet, Ideal			PR=[5,25]	Initial: 10
	22	C2 Outlet, Real			η_{C2}=0.8	
	23	Regenerator 2 Inlet 1			Part 1A Only	
	24	Regenerator 2 Outlet 1			Part 1A Only	
	25	After Heat Addition	1600			
	26	T2 Outlet, Ideal	782-900	101.4		Single Cycle (782)
	27	T2 Outlet, Real			η_{T2}=0.9	
	28	Regenerator 2 Inlet 2			Part 1A Only	
	29	Regenerator 2 Outlet 2			Part 1A Only	
Combined Stream	30	Exit Air to HRSG/Rankine				Same as 16 and 26
HRSG- Hot Side	31	Air side, superheater				
	32	Air side, evaporator				
	33	Air side, economizer				
Stack	34	Exhaust gases in stack	500	101.4		
Rankine (Steam Turb)	40	Cold return water	315.5	10		
	41	Pump outlet, ideal		7140		Range 5K-10K
	42	Pump outlet, real		7140	η_P=0.8	Range 5K-10K
	43	Regenerator 3 Inlet 1			Optional, Part 1B Only	
	44	Regenerator 3 Outlet 1			Optional, Part 1B Only	
HRSG- Cold Side	45	Steam side, economizer				
	46	Steam side, evaporator				
	47	Steam side, superheater	840-900			Initial: 870K
Rankine (Steam Turb)	47	T3 Inlet		7140		Range 5K-10K
	48	T3 Outlet, Ideal		10		
	49	T3 Outlet, Real		10	η_{T3}=0.9	
	50	Regenerator 3 Inlet 2			Optional, Part 1B Only	
	51	Regenerator 3 Outlet 2			Optional, Part 1B Only	
	52	Steam Condenser, x=0	319	10	Sat. liquid, x=0	
	40	Steam side cold return	315.5	10	Sub-cooled T < sat liq.	
Cooling Water Loop	60	Cooling Water Inlet	299	101.4		
	61	Cooling Water Outlet	311	101.4		

Figure 3: Given State Points

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) \qquad (4.15)$$

Figure 4: First Law of Thermodynamics

$$\eta_t = \frac{(\dot{W}_t/\dot{m})}{(\dot{W}_t/\dot{m})_s} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

$$\eta_p = \frac{(\dot{W}_p/\dot{m})_s}{(\dot{W}_p/\dot{m})} = \frac{h_{4s} - h_3}{h_4 - h_3}$$

Figure 5: Rankine Real Cycle Analysis Equations

$$p_{r2} = p_{r1}\frac{p_2}{p_1} \qquad T_2 = T_1\left(\frac{p_2}{p_1}\right)^{(k-1)/k}$$

$$p_{r4} = p_{r3}\frac{p_4}{p_3} = p_{r3}\frac{p_1}{p_2} \qquad T_4 = T_3\left(\frac{p_4}{p_3}\right)^{(k-1)/k} = T_3\left(\frac{p_1}{p_2}\right)^{(k-1)/k}$$

Figure 6: Brayton Real Cycle Analysis Equations

$$0 = \dot{m}_g(h_4 - h_5) + \dot{m}_v(h_6 - h_7)$$

$$\dot{W}_{gas} = \dot{m}_g[(h_3 - h_4) - (h_2 - h_1)]$$

$$\dot{W}_{vap} = \dot{m}_v[(h_7 - h_8) - (h_6 - h_9)]$$

Figure 7: Combined Cycle Power Equations (Sum is total power)

Key Specs
575 MW combined power
2-on-1 design with the following rated gross capacities: 180MW/180MW/215MW
Assume electrical conversion efficiency $\eta_{gen+transformer} = 0.985$
Cooling water pump electrical power draw at 100% load: 3600 kW
Vacuum system electrical power draw at weighted annual average load: 750 kW
Other ancillary electrical power for controls, misc: 1000 kW

Key Specs
820 MW combined power
2-on-1 design with the following rated gross capacities: 273.5MW/273.5MW/273MW
Assume electrical conversion efficiency $\eta_{gen+transformer} = 0.985$
Cooling water pump electrical power draw at 100% load: 5000 kW
Vacuum system electrical power draw at weighted annual average load: 1000 kW
Other ancillary electrical power for controls, misc: 2000 kW

Cost Category Description	Plant	Cost	Basis of Cost
CAPEX	Astoria I	$690,000,000	CAPEX (one time)
	Plant #2	$984,000,000	CAPEX (one time)
OPEX $(O\&M)_t$	Astoria I	$8,625,000/yr	OPEX (annual)
	Plant #2	$12,300,000/yr	OPEX (annual)
ENERGY/FUEL (yr t)	Astoria I	TBD by student team	Fuel (annual)
	Plant #2	TBD by student team	Fuel (annual)

- Project life: 30 years
- Discount Rate: 9%
- Inflation: 0%

Figure 8: Technical and Economic Parameters of Plants Provided by Manual

$$\frac{\displaystyle\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\displaystyle\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t (including financing)

M_t = Operations and maintenance expenditures in year t

F_t = Fuel expenditures in year t

E_t = Electricity generation in year t

r = Discount rate

n = Life of the system

Figure 9: Equations to Solve LCOE

1..1	$W_{c,b1}$ [kJ/kg]	$W_{t,b1}$ [kJ/kg]	$W_{net,b1}$ [kJ/kg]	$q_{in,b1}$ [kJ/kg]	η_{b1}
Run 1	356.4	1162	806	1232	0.6544

Figure 10: Brayton Subsystem Analysis

Unit Settings: SI K kPa kJ mass deg

$\delta T_{available} = 2.804$	$\eta_p = 0.8$	$\eta_t = 0.9$	$\eta_{th,regen} = 0.3634$	$\eta_{th,simple} = 0.3624$
$h_{40} = 177.4$	$h_{41,ideal} = 184.5$	$h_{42} = 186.3$	$h_{47} = 3642$	$h_{48,ideal} = 2240$
$h_{49} = 2381$	$h_{R,post,reg} = 195.7$	$n_{reg} = 0.8$	$P_{40} = 10$	$P_{42} = 7140$
$P_{47} = 7140$	$P_{49} = 10$	$P_{high} = 7140$	$P_{low} = 10$	$q_{in,regen} = 3446$
$q_{in,simple} = 3456$	$s_{40} = 0.6037$	$s_{41,ideal} = 0.6037$	$s_{47} = 7.072$	$s_{48,ideal} = 7.072$
$T_{40} = 315.5$	$T_{42} = 316.2$	$T_{47} = 870$	$T_{49} = 319$	$T_{R,post,reg} = 318.4$
$T_{turbine,in} = 870$	$w_{net,regen} = 1252$	$w_{net,simple} = 1252$	$w_{p,regen} = 8.977$	$w_{p,simple} = 8.977$
$w_{t,regen} = 1261$	$w_{t,simple} = 1261$			

Figure 11: Rankine Subsystem Analysis

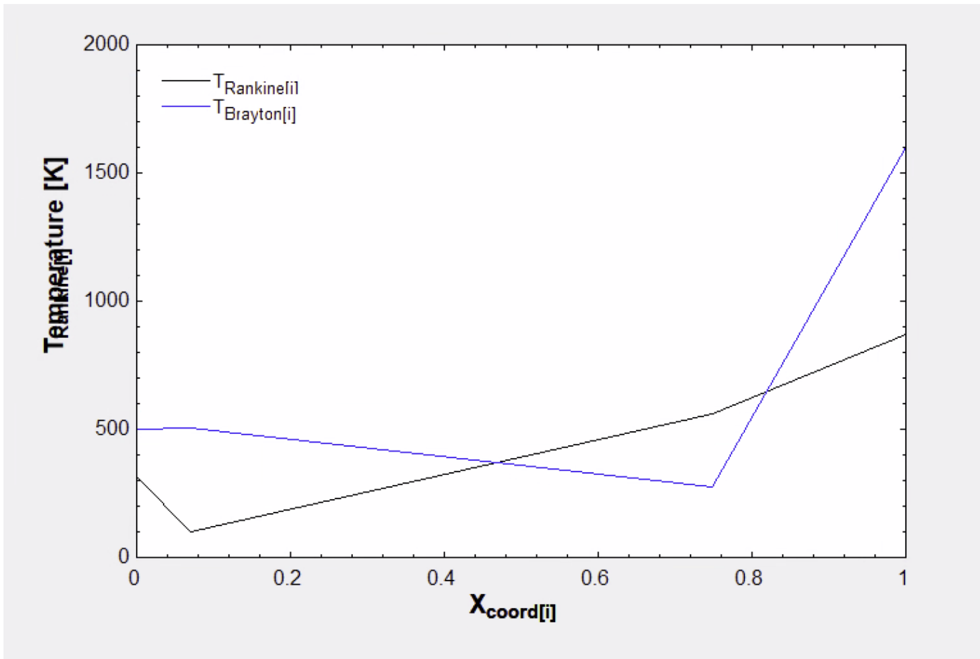

Figure 12: HSRG Plot

1..1	$work_g$	$work_v$	$Total_{Power}$	$Total_{Power,Year}$	n_{cycle}
Run 1	503.3	3096	530106	4.644E+09	0.7185

Figure 13: Plant 2 Combined Cycle Analysis

1..1	$work_g$	$work_v$	n_{cycle}	$Total_{Power}$
Run 1	503.3	3096	0.7313	595500

Figure 14: Astoria Plant Combined Cycle Analysis

Plant 2	Basis	Units	Value
Fixed Capital Investment (CAPEX)	Total	$	$ 984,000,000
Fixed Capital Investment Per Installed Unit Power (CAPEX/kW)	Cost Per Unit	$/kW	600
interest rate	Per Year	%	-0.09
Lifespan of plant (n)	Project Life	Years	30
Capital Recovery Factor (CRF)	Project Life	-	0.005648318
Annual Payment on Capital (CAPEX_t)	Yearly	$/yr	$ 5,557,944
Annual Operating and Maintenance Costs (O&M)	Yearly	$/yr	$ 12,300,000
Annual Fuel and Energy Costs	Yearly	$/yr	$ 451,500,000
Annual Fuel and Energy Costs Per Installed Unit Power	Yearly	$/kW/yr	$ 550.61
Total Annual Operating Expenses	Yearly	$/yr	$ 463,800,000
Nameplate Capacity of the Plant	Initial	MW	820
Capacity Factor	Annual Avg	-	0.97
Estimated Annual Generation (Gen_t)	Yearly	kWh/yr	7,002,901,680
Levelized Cost of Electricity (LCOE)	Project Life	$/kWh	$ 0.067

Figure 15: Technoeconomic Analysis Plant 2

Astoria Plant	Basis	Units	Value
Fixed Capital Investment (CAPEX)	Total	$	$ 690,000,000
Fixed Capital Investment Per Installed Unit Power (CAPEX/kW)	Cost Per Unit	$/kW	$ 1,200.00
interest rate	Project Life	%	-0.09
Lifespan of plant (n)	Project Life	Years	30
Capital Recovery Factor (CRF)	Project Life	-	0.005648318
Annual Payment on Capital (CAPEX_t)	Yearly	$/yr	$ 3,897,339.11
Annual Operating and Maintenance Costs (O&M)	Yearly	$/yr	$ 8,625,000
Annual Fuel and Energy Costs	Yearly	$/yr	$ 173,000,000
Annual Fuel and Energy Costs Per Installed Unit Power	Yearly	$/kW/yr	$ 300.87
Total Annual Operating Expenses	Yearly	$/yr	$ 181,625,000.00
Nameplate Capacity of the Plant (electrical output)	Initial	MW	575
Capacity Factor	Annual Avg	-	0.94
Estimated Annual Generation (Gen_t)	Yearly	kWh/yr	4,734,780,000
Levelized Cost of Electricity (LCOE)	Project Life	$/kWh	$ 0.039

Figure 16: Technoeconomic Analysis Astoria Plant