EXECUTIVE SUMMARY

LOW-CARBON ENERGY SUPPLY TECHNOLOGY COST AND PERFORMANCE STUDY

The Electric Power Research Institute (EPRI) has contracted Wood PLC to perform a study to develop representative performance and cost estimates for various low-carbon energy supply technologies, including hydrogen production technologies, ammonia synthesis, and power generation technologies.

The purpose of this study is to establish a baseline of cost and performance data sets that will be used to inform system modeling and other related techno-economic analysis as part of the Low-Carbon Resources Initiative (LCRI). The LCRI is a joint collaborative effort between EPRI and GTI Energy to address the need to accelerate development and demonstration of low- and zero-carbon energy technologies (www.LowCarbonLCRI.com).

The focus of the activities is to develop and update the design performance, capital cost, and economics of various state-of-the-art hydrogen production technologies, including: electrolysis, natural gas reforming, and gasification of various feedstocks (coal, biomass, and waste); moreover, ammonia synthesis technology (with capture of carbon dioxide) and power generation technologies were also assessed, the latter including: solid oxide fuel cells, advanced combustion turbines, and reciprocating engines using hydrogen, ammonia, or a combination of both as fuel. CO_2 storage costs are not included in this analysis

The study provides data to enable the development of scalable and customizable cost and performance estimates based on technology type, locational attributes, and project size.

For part of the key technologies involved in the study, technology suppliers have been contacted to gather information required to meet study objectives. Non-binding and budgetary offers, along with a sufficient level of technical information, were used to complete the preliminary design and cost estimating activities of specific cases. In this regard, Wood, EPRI, and GTI warmly acknowledge ABSL, Nexterra, and MAN Energy Solutions for their participation in the study effort.

The market survey tried to involve a larger number of licensors, technology suppliers, or original equipment manufacturers. We understand that significant work is ongoing on the topic objective of this study, and still some development is needed; moreover, many of the respondents were not able to disclose information that are deemed confidential. Therefore, in case of some lack of information for the modeling purposes of this study, Wood, EPRI, and GTI Energy jointly worked to take the most reasonable assumptions, to then allow Wood to complete the techno-economic assessments of each technology case.

The primary results of this study are shown in the following sections of this Executive Summary, while detailed results of each specific case are given in the full report.

Process Alternatives

The study investigates a wide range of low-carbon energy supply technologies gathered into three main groups:

- Hydrogen Production
- Ammonia Synthesis
- Power Generation

Table 1 displays the list of technologies included in each group.

Table 1. List of technologies by group

Hydrogen Production Technologies
Electrolysis
Alkaline water electrolysis
Polymer electrolyte membrane (PEM) water electrolysis
High temperature solid oxide water electrolysis (SOEC)
Natural Gas Reformation
Steam methane reformation (SMR) with 90% CO_2 capture
Gasification Technologies
Hydrogen production from coal gasification with 90% CO_2 capture
Hydrogen production from biomass gasification with 90% CO_2 capture
Hydrogen production from waste gasification with 90% CO_2 capture
Ammonia Synthesis
Ammonia production via Haber Bosch with 90% CO_2 capture
Power Generation Technologies
New aeroderivative hydrogen combustion turbine (CT)
New advanced class hydrogen 1x1 combustion turbine combined-cycle (CTCC)
New advanced class ammonia/H_2 blend CT
New ammonia reciprocating engine
New hydrogen solid oxide fuel cell

The list of cases for each technology is provided in their dedicated sections hereinafter.

Hydrogen Production Technologies

The report investigates 7 different typologies of hydrogen production technologies (see Table 1) and different hydrogen production rates, resulting overall in 15 study cases.

ELECTROLYSIS

For each electrolysis type (polymer electrolyte membrane [PEM], Alkaline, solid oxide electrolysis cells [SOEC]), two cases were assessed, corresponding to two different target hydrogen production capacities: 1,500 kg/day and 50,000 kg/day. The technological assessment and commentary for electrolysis systems were based upon information provided by different electrolysis suppliers who engaged with Wood's request for information (REI) process. This included suppliers such as NEL, Green Hydrogen, Siemens, Hydrogen Pro, and Haldor Topsoe. Information received from suppliers has been aggregated (with literary sources and in-house data where appropriate) and anonymized to provide an overall response for the cases.

STEAM METHANE REFORMATION (SMR)

Two different technology plant configurations were assessed:

- "Standard Configuration," as benchmarked in public domain study reports and mainly based on the post-combustion capture of the carbon dioxide from the flue gases of the SMR.
- "Advanced Configuration," under development by Wood, introducing technology innovation and improvements of the SMR-based plant configuration. These cases show some limited information only, due to the confidentiality of the plant scheme.

For each alternative, two cases were developed, corresponding to two different target hydrogen production capacities: 50,000 kg/day and 300,000 kg/day.

COAL GASIFICATION

Two cases were developed for this process alternative, corresponding to two different target hydrogen production capacities: 50,000 kg/day and 300,000 kg/day.

A technology neutral scheme has been derived upon information collected during the preparation of former EPRI studies. The technical data estimated for these cases are a reliable representation of a dry-feed, entrained-flow, and quench gasifier, though not being representative of any specific licensed technology.

BIOMASS GASIFICATION

Two different biomass gasification cases were modeled, based upon two licensor-specific gasification technologies: 1) fluidized bed gasifier followed by a plasma converter, and 2) fixed bed updraft gasifier followed by a catalytic cracker.

The target hydrogen production capacity is 50,000 kg/day for both cases.

WASTE GASIFICATION

A single case was developed for mixed plastics waste gasification, based on fluidized bed gasification technology.

The target hydrogen production capacity is 50,000 kg/day for both cases. For all of the SMR and gasification-based cases, a target CO_2 capture of 90% was considered.

Table 2 summarizes the 15 hydrogen-production technology cases objective of the assessment.

Table 2. List of hydrogen-production cases

Case	Technology	Design Point	CO_2 Capture
1	Alkaline water electrolysis	1,500 kg/day	Not Applicable (N/A)
2	Alkaline water electrolysis	50,000 kg/day	(N/A)
3	Polymer electrolyte membrane (PEM) water electrolysis	1,500 kg/day	(N/A)
4	Polymer electrolyte membrane (PEM) water electrolysis	50,000 kg/day	(N/A)
5	High temperature solid oxide water electrolysis (SOEC)	1,500 kg/day	(N/A)
6	High temperature solid oxide water electrolysis SOEC)	50,000 kg/day	(N/A)
7	SMR "Advanced Technology"	50,000 kg/day	Yes (90%)
8	SMR "Advanced Technology"	300,000 kg/day	Yes (90%)
9	SMR "Traditional Technology"	50,000 kg/day	Yes (90%)
10	SMR "Traditional Technology"	300,000 kg/day	Yes (90%)
11	Coal gasification	50,000 kg/day	Yes (90%)
12	Coal gasification	300,000 kg/day	Yes (90%)
13	Biomass gasification (fluidized)	50,000 kg/day	Yes (90%)
14	Biomass gasification (fixed)	50,000 kg/day	Yes (90%)
15	Waste gasification (fluidized)	50,000 kg/day	Yes (90%)

SMR = steam methane reformation.

Ammonia Synthesis

Two study cases have been modeled for ammonia synthesis. They differ for target ammonia-production capacity: 1,000 tonnes/day and 2,500 tonnes/day. Both cases are based on the Haber Bosch process and they are technology neutral, based on average performances of commercially available technologies. For both cases, 90% CO_2 capture was considered.

Table 3. List of ammonia-synthesis cases

Case	Technology	Design Point	CO_2 Capture
1	Ammonia production via Haber Bosch	1,000 tonnes/day	Yes (90%)
2	Ammonia production via Haber Bosch	2,500 tonnes/day	Yes (90%)

Power Generation Technologies

The study investigates the four alternatives of power generation technologies as listed in Table 1, resulting in four different study cases. Due to the novelty of the technology and general lack of information from Technology Suppliers, only a literature review was carried out for new hydrogen solid oxide fuel cells. For all the cases, a NOx abatement system is included to meet the required environmental limit of 10 ppmv (dry, 15% O_2) at the stack outlet. Table 4 summarizes each case in terms of type, target power production, fuel, and NOx abatement system.

The 10 ppmv (dry, 15% O_2 corrected) NOx limit is assumed based on common permits with natural gas fuels. However, permitted NOx limits are likely to vary on a ppmv basis depending on fuel type[1, 2]. The implications for this study is an over or under-aggressive SCR, but the main cost takeaways of this study are relatively insensitive to this effect. There are ongoing research efforts within EPRI and the LCRI to better understand low-carbon fueled turbine and engine outlet conditions which would enable environmental control equipment design optimization.

Table 4. Power generation cases

Case	Technology	Fuel	Design Point	NOx Abatement System
1	New aeroderivative hydrogen CT	H_2	40 MWe	Water Injection
2	New advanced class hydrogen 1x1 CTCC	H_2	550 MWe	SCR
3	New advanced class ammonia/H_2 blend CT	NH_3-H_2 50-50% vol.	400 MWe	SCR
4	New Ammonia Reciprocating Engine	NH_3 + diesel	50 MWe	SCR

CT = combustion turbine; CTCC = combustion turbine combined-cycle; SCR = selective catalytic reduction.

Note: SOFC technology overview and performance data are included in the full report but cost estimating was not performed under this study.

Project Design Basis

The site location assumed for modeling purposes is Kenosha, Wisconsin, a site typical for power generation facilities, located in the upper midwestern United States with access to water and rail transportation.

Feedstock considered for the different process alternatives include:

- Natural gas (CH_4 93.9% vol., pressure at battery limit: 34.5 barg)
- Montana Rosebud Powder River Basin sub-bituminous coal (25.7% wt. moisture [AR] and 0.73% wt. sulfur)
- Torrefied southern pine biomass (5.72% wt. moisture [AR])
- Mixed waste plastics (> 40% wt. PET, dry)

For the hydrogen-production technology cases, the plant capacity is fixed to match the target hydrogen of the case. For the ammonia-synthesis cases, the plant capacity is fixed to match the target ammonia production of the case. For the power generation cases, the plant capacity is fixed to match the target power generation of the case. The environmental limits considered for the modeling are summarized in Table 5. The 10 ppmv (dry, 15% O_2 corrected) NOx limit is assumed based on common permits with natural gas fuels. However, permitted NOx limits are likely to vary on a ppmv basis depending on fuel type [1, 2]. The implications for this study is an over or under-aggressive SCR, but the main cost takeaways of this study are relatively insensitive to this effect.

[1] Douglas, C. E. (2022). Nitrogen Oxide Corrections, Emissions Reporting, and Performance Considerations for Hydrogen-Hydrocarbon Fuels in Gas Turbines. ASME Turbo Expo.

[2] Douglas, C. E. (2022). White Paper: NOx Emissions from Hydrogen-Methane Fuel Blends. Georgia Institute of Technology.

Table 5. Guarantee emissions level chart

Pollutant	Unit of Measurement	Data
NOx (1)	ppmv, dry	10
SOx	ppmv, wet	2.0
PM (filterable – front half of sampling train)	lb/hr/GT	18
Total PM (including condensables – back half of sampling train)	lb/hr/GT	37
CO	ppmv, dry	25
CO_2 (if applicable)	lb/gross MWh	1,100
Unburned hydro carbons (UHC) as CH_4	ppmv, wet	7
Volatile organic compound (VOC) (1)	ppmv, wet	1.4
Mercury (Hg)	-	No more than 10% of mercury in coal as air emission
Slip ammonia (1)	ppmv, dry	5.0

(1) Referenced to 15% O_2 for combustion turbine or 6% O_2 for conventional boilers.

For the cases including CO_2 capture, carbon dioxide characteristics at plant battery limits are the following:

Status:	Supercritical
Pressure:	152 barg (2,200 psig)
Purity:	> 95% vol.
H_2S content:	0.01% vol.
CO content:	35 ppmv
Moisture:	500 ppmv

For the hydrogen-production cases, hydrogen characteristics at plant battery limits are the following:

Pressure:	103.5 barg (1,500 psig)
Purity:	> 98% vol.

The plant has access to raw water, mainly used as makeup water for the cooling water system, which is based on mechanical draft multi-cell, evaporative cooling towers.

Performance Results

Hydrogen Production Technologies

The main performance data of the modeled hydrogen-production cases are summarized in Table 6 and Table 7.

The primary conclusions that can be drawn for the six electrolysis cases are the following:

- Alkaline and SOEC cases (Cases 1, 2, 5, and 6) show the highest electric power demand for hydrogen compression. This is mainly due to the hydrogen product pressure at the outlet of the electrolyzer typically being lower than that of the PEM cases (30 barg).
- Alkaline and PEM technologies represent the low temperature electrolysis systems, which is illustrated by the typical cell operating temperature being in the region of 60–90°C. The difference within this temperature range could be easily as much of a difference in supplier operation as it is a difference in the technologies. SOEC technology is a high temperature electrolysis system, exhibiting cell temperatures in the region of 800°C, but again this can depend on how it is operating or even the supplier being used.
- Concerning system size, PEM will require the largest electrolyzer capacity to meet the hydrogen-production requirement, while SOEC will be the smallest. The reason for this larger system size is based on efficiency. The current lower efficiency at stack level of the PEM technology option means that a larger electrolyzer size (in terms of MW) is required.
- SOEC cases (Cases 5 and 6) show the highest cumulative degradation rate based on annual loss in efficiency, which is mainly due to a higher percentage loss of production rate (hydrogen power output) at a constant efficiency than that of alkaline and PEM cases. The primary reasons for this larger degradation of SOEC will likely be a combination of the novelty, or lack of maturity, of the SOEC technology and the much higher temperature at which the system operates at. As SOEC technology becomes more mature, it is anticipated that the degradation rate will decrease.

Table 6. Hydrogen production technology—performance summary (electrolysis)

CLIENT:	EPRI				REVISION	0	
PROJECT NAME:	Low Carbon Energy Supply Technology				DATE	Nov 21	
PROJECT NO:	1BD1212A				MADE BY	VN	
LOCATION:	Kenosha, Wisconsin				APPROVED BY	LM	
Performance Summary – Hydrogen Production Technologies							
Overall Performances							
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Technology	–	Alkaline Electrolysis	Alkaline Electrolysis	PEM Electrolysis	PEM Electrolysis	SOEC Electrolysis	SOEC Electrolysis
Hydrogen Production Rate	kg/day	1,500	50,000	1,500	50,000	1,500	50,000
Potable Water Flow Rate	t/h	1	35	1	35	1	35
Rejected Water Flow Rate	t/h	0.5	16	0.5	16	0.5	16
Deionized Water Flow Rate	t/h	0.6	19	0.6	19	0.6	19
Electric Power Consumption of Hydrogen Compression	MWe	0.2	4.95	0.04	1.34	0.15	4.95
Total Electric Power Consumption	MWe	3	112	4	120	3	104
Total Cooling Water Consumption	t/h	76	2,293	93	3,069	25	552
Electrolyzer Efficiency	kWh/kg	50	50	55	55	38	38
Pressure of Hydrogen Out of Electrolyzer	barg	atm	atm	30	30	atm	atm
Cell Temperature	°C	80	80	60	60	800	800
Electrolyzer Capacity	MW	3.13	104.17	3.44	114.58	2.4	80
Degradation (Annual Loss in Efficiency)	%	1–1.5%	1–1.5%	1.5%	1.5%	15%	20%

The primary conclusions that can be drawn from the SMR- and gasification-based cases are the following:

- Comparing the cases with the same target hydrogen-production rate, the feedstock feed rate differs from technology to technology, depending on both the process efficiency and the amount of H_2 of the feedstock itself.
- SMR traditional cases (Cases 9 and 10) show the highest thermal energy demand of feedstock, due to the lower efficiency conversion, compared to the same technology in the advanced configuration as proposed by Wood (Cases 7 and 8); in fact, the advanced configuration allows avoiding use of fuel gas, while reducing need for steam generation.
- Concerning the coal cases, the amount of coal required for Case 12 is proportionally higher than that of Case 11, since part of the syngas produced in Case 12 is not routed to the pressure swing adsorption (PSA), but used in the power generation unit as additional fuel for power generation, thus avoiding the import of a significant amount of electricity from the external grid. For the lower hydrogen production case (Case 11), instead, it is assumed that a low amount of electricity is taken from the grid. This ultimately affects the conversion efficiency of the various cases.

- Biomass and plastic gasification cases (Cases 13 to 15) show higher electric internal consumption, compared to coal (Case 11). This is mainly to be addressed by the need for syngas compression upstream of the shift section. In fact, biomass and plastic gasification processes are carried out at nearly atmospheric pressure, thus introducing the need for a syngas compression stage to properly operate the downstream syngas conditioning units.
- Also, biomass and plastic cases (Cases 13 to 15) show a lower gross power production than coal, compared to the same hydrogen target production (Case 11). This is mainly due to the water requirement of the shift reaction, which leads to the addition of medium pressure steam to the syngas from the biomass and plastic gasification, which in turn results in a lower power production; this is not needed for the coal case, due to the operating pressure and technology type of the gasification.

Table 7. Hydrogen production technology—performance summary (SMR and gasification)

CLIENT:	EPRI							REVISION	0	wood.
PROJECT NAME:	Low Carbon Energy Supply Technology							DATE	Nov 21	
PROJECT NO:	1BD1212A							MADE BY	VN	
LOCATION:	Kenosha, Wisconsin							APPROVED BY	LM	
Performance Summary – Hydrogen Production Technologies										
Overall Performances										
		Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15
Technology	–	SMR "Advanced Technology"	SMR "Advanced Technology"	SMR "Traditional Technology"	SMR "Traditional Technology"	Coal Gasification	Coal Gasification	Biomass Gasification (ABSL)	Biomass Gasification (Nexterra)	Plastic Gasification
Hydrogen Production Rate	kg/day	50,000	300,000	50,000	300,000	50,000	300,000	50,000	50,000	50,000
Type of Feedstock	–	NG	NG	NG	NG	PRB Coal	PRB Coal	Torrefied Biomass	Torrefied Biomass	Mixed Plastics Waste
Feedstock (As Received)	t/h	7	40	6	35	21	157	21	17.5	13 (2)
Feedstock LHV (As Received)	kJ/kg	47,840	47,840	47,840	47,840	19,190	19,190	21,410	21,410	31,470 (2)
Fuel (Natural Gas)	t/h	–	–	2	12	–	–	–	–	–
Thermal Energy of Feedstock (A)	MWth (LHV)	90	537	104 (1)	622 (1)	111	838	126	104	111 (2)
Hydrogen Thermal Power (LHV) (B)	MWth (LHV)	70	400	70	400	70	400	70	70	70
Gross Electric Output	MWe	–	–	–	–	7	92	3	2	4
Total Electric Power Consumption	MWe	3	17	5	33	14	92	27	23	22
Net Electric Power Requirement (C)	MWe	3	17	5	33	7	–	24	21	18
Feedstock/H_2 Conversion Efficiency (Thermal: B/A)	% (LHV)	73	73	63	63	62	49	55	66	62
Feedstock/H_2 Conversion Efficiency—Thermal + Electric: B/(A+C)	% (LHV)	71	71	60	60	58	–	46	55	53.5
CO_2 Capture Rate	%	90	90	90	90	90	90	90	90	90

1. Including fuel thermal power.
2. Dry basis.

AMMONIA SYNTHESIS

The main performance data of the modeled alternatives are summarized in Table 8. No remarkable differences can be identified between the two cases assessed, the main difference being related to the size of the plant and its ammonia-production capacity.

Table 8. Ammonia-synthesis performance summary

CLIENT:	EPRI		REVISION	2	wood.
PROJECT NAME:	Low Carbon Energy Supply Technology		DATE	Jan 22	
PROJECT NO:	1BD1212A		MADE BY	VN	
LOCATION:	Kenosha, Wisconsin		APPROVED BY	LM	

Performance Summary – Ammonia Synthesis			
Overall Performances			
		Case 1	Case 2
Technology	–	Ammonia synthesis via Haber Bosch	
Type of Feedstock	–	NG	NG
Feedstock (as received)	Nm^3/h	25,104	62,760
Fuel (Natural Gas)	Nm^3/h	9,862	24,655
Feedstock LHV (as received)	$MJ/Nm^3/h$	37	37
Thermal Energy of Natural Gas (A)	MWth (LHV)	359	897
Ammonia Production Rate (C)	t/h	42	104
	t/day	1,000	2,500
Ammonia Thermal Energy (LHV)	MWth	214	535
Electric Power Consumption of NH_3 Production Complex	Mwe	13	32
Thermal Energy of Electric Power (assuming 1 Mwe = 2.5 MWth) (B)	MWth	31.8	79.4
Overall Efficiency per Ton of Product ((A+B)/C)	MWth/t	9.4	9.4
CO_2 Capture Rate	%	90	90

POWER GENERATION TECHNOLOGIES

The main performance data of the modeled power generation technology alternatives are summarized in Table 9.

The primary conclusions that can be drawn for the four cases are the following:

- Case 2 only, among the assessed cases, is a combined-cycle power plant. This is evident in its overall plant efficiency, which is nearly 20 percentage points higher than the other cases.
- The amount of fuel required by Case 3 combustion turbine (114 t/h) is considerably higher than Case 2 (26 t/h), despite a power output difference from the machine of 30 MWe. The reason shall be addressed as the difference in the heating value (and ultimately in fuel type): Case 3 involves an equimolar ammonia-hydrogen blend, whose LHV is 4 times lower than the one of hydrogen, which is the fuel for Case 2.
- For Case 3, additional fuel is required to handle the steam demand of the plant, mainly required for ammonia vaporization, being ammonia is stored on site in refrigerated tanks. Therefore, there is an equivalent loss of power production from the plant.
- The net power production reflects the trend of the gross power production, as the electric power demand of each case changes marginally from 2 to 3.6% of the gross power production.

Table 9. Power generation technologies' performance summary

CLIENT:	EPRI		REVISION	1	wood.
PROJECT NAME:	Low Carbon Energy Supply Technology		DATE	18/02/2022	
PROJECT NO.:	1BD1212A		MADE BY	VN	
LOCATION:	Kenosha, Wisconsin		APPROVED BY	LM	
Performance Summary – Power Generation Technologies					
Overall Performances					
		Case 1	**Case 2**	**Case 3**	**Case 4**
Technology	–	**Aeroderivative H_2 Combustion Turbine**	**H_2 Combustion Turbine Combined-Cycle**	**New Advanced Class NH_3/H_2 Blend Combustion Turbine**	**NH_3 Reciprocating Internal Combustion Engine**
Type of Feedstock	–	Hydrogen	Hydrogen	Ammonia/Hydrogen	Ammonia/Diesel
Hydrogen	t/h	3	26	12	–
Ammonia	t/h	–	–	102	22
Diesel	t/h	–	–	–	1
Feedstock LHV	kJ/kg	120,034	120,034	29,393	19,675
Feedstock Thermal Energy (LHV)	MWth (LHV)	101	871	930	123
Additional Fuel	t/h	–	–	2	–
Additional Fuel (LHV)	kJ/kg	–	–	120,034	–
Total Thermal Energy Input (A)	MWth (LHV)	101	871	981	123
Gas Turbine/Engine Power Output	Mwe	40	370	400	57
Steam Turbine Power Output	Mwe	–	276	–	–
Gross Electric Power Output (B)	Mwe	40	546	400	57
Electric Power Consumption	Mwe	1	11	7	2
Net Electric Power Output (C)	MWe	39	535	393	55
Gross Plant Electrical Efficiency (B/A)	% (LHV)	40	63	41	46
Net Plant Electrical Efficiency (C/A)	% (LHV)	39	61	40	45
Fuel Consumption Per Net Power Production (LHV Based)	MWth/MWe	2.59	1.63	2.51	2.25

COST ESTIMATE RESULTS

For each case of the study, the Total Plant Cost (TPC) is broken down into the main process units and, for each unit, split into the following items:

- Direct materials
- Construction
- Other costs
- Engineering, procurement, and construction services
- Contingency

Besides the TPC, the Total Capital Requirement (TCR) is defined as the sum of the TPC, owner's costs, and interests during construction (IDC). Owner's costs include:

- Prepaid royalties, startup costs
- Inventory capital
- Initial cost for catalyst and chemicals
- Land

For most of the study cases, the TPC estimate was based on up-to-date information from Wood's in-house database, through the development of conceptual estimating models, based on the specific characteristics, materials, and design conditions of each item of the plant.

A project contingency of 15% of each unit of the plant is assumed in this study, for consistency with previous EPRI studies. Different process contingencies are applied in order to quantify the uncertainty in the technical performance and cost of commercial-scale equipment, according to the novelty of the technology and the state of development. Process contingencies assumed in this study are summarized in Table 10.

Table 10. Assumed process contingencies

Technology	Percentage of Total Installed Cost
Biomass Gasification Island	10%
Plastic Gasification Island	20%
Syngas Conditioning (Plastic Gasification)	10%
Electrolysis (PEM)	10%
Aeroderivative H_2 CT	20%
H_2 Fired CT	20% (1)
Advanced Class NH_3/H_2 blend CT	30%
NH_3 Reciprocating Internal Combustion Engine	30%

1. Resulting in 10% process contingency applied on overall CTCC TIC.

The other components of the TCR have been mainly estimated as percentages of the other cost estimates in the plant. The plant capital costs are reported in 2Q-2021 U.S. dollars. The expected accuracy of the estimate is -30%/+30%. The expected accuracy is defined in the AACE Standard and referred to as an estimate type Class 4.

TOTAL PLANT COST

Hydrogen Production Technologies

Table 11 and Table 12 show a summary of the TPC and TCR of the different study cases for the hydrogen-production technologies, together with their specific investment costs (TPC/H_2 production capacity, kg/day).

The TPC, thus the TCR, for SOEC technology (Cases 5 and 6) does not appear to be practical at this time; due to the technology maturity level, Wood cannot confidently provide an aggregated or generic technology cost estimation.

Figure 1 and Figure 2 present a breakdown of the specific investment cost of each case, showing the relative weight of each plant unit. The main differences between the assessed cases are highlighted in the following:

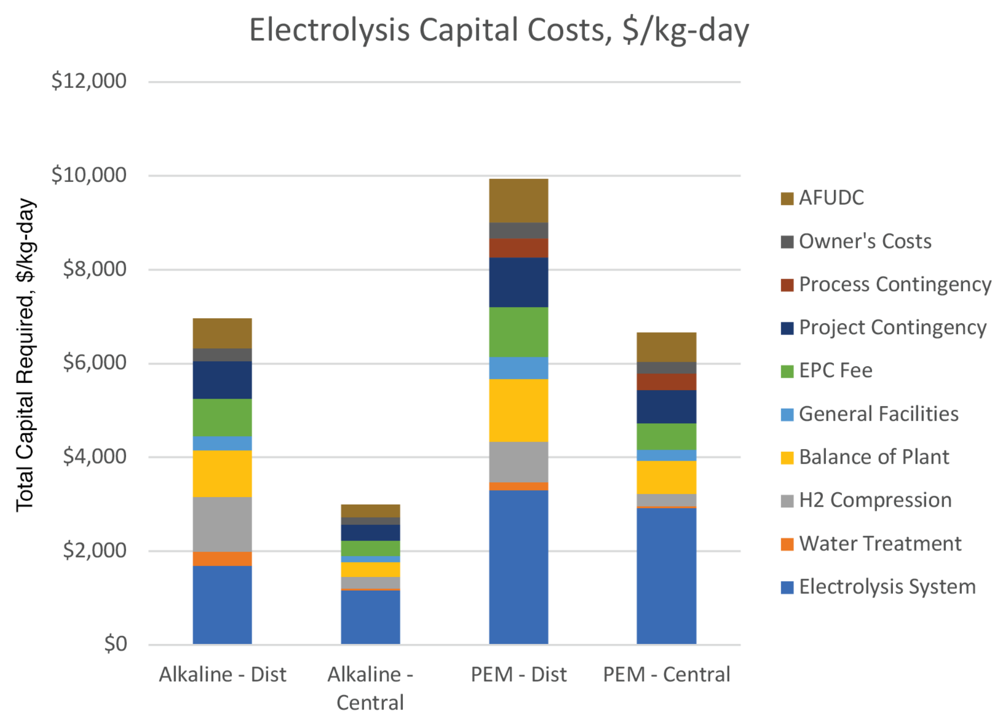
- With regard to electrolysis, PEMs are generally more capital intensive than alkaline (about 40%), which is still mainly due to the lower maturity of the PEM technology.
- Concerning the hydrogen compression cost (gray band in Figure 1; yellow in the Figure 2), alkaline plants (Cases 1 and 2) have the highest values, as a result of the typical lower hydrogen generation pressure of the alkaline electrolyzer.
- For Cases 1 and 2, no remarkable differences can be identified. The main difference is related to the economy of scale, and the same consideration can be done for Cases 3 and 4.
- The difference between Case 2 and Case 4 in terms of cost is related to the size of the cell and the development of the technology.
- The SMR advanced cases as proposed by Wood (Cases 7 and 8) have a simple unit configuration and are more efficient. This results in a lower TPC, when compared to the cases with a traditional post-combustion capture (Cases 9 and 10); in fact, the overall plant cost savings is about 35%.
- For the SMR cases, the economy of scale for the respective plants with higher hydrogen production is evident. By increasing 6 times the overall hydrogen-production rate, the equivalent specific cost savings of the project is about 45%. The same concept is almost valid for the coal gasification cases (Figure 3), though in these cases there are some differences in the design principles of the plants (as previously discussed), which make the cost differences more difficult to interpret.
- CO_2 capture for coal gasification cases (Cases 11 and 12) also includes the Sulfur Recovery Unit and Tail Gas Treatment unit (SRU and TGT), which are not required for biomass and plastic cases (Cases 13, 14, and 15). This suggests a higher unit of TPC for Case 11 (refer to the first light orange band in Figure 3), compared to that of Cases 13, 14, and 15, targeting the same hydrogen-production capacity.
- With reference to the biomass cases (Cases 13 and 14), there are significant technological differences in the gasification island, but the overall specific cost variation is relatively small, being in the range of about 12%. See also Figure 4.
- Despite the significant difference between the feedstock types (coal, biomass, and plastics) and the technology type of gasification, all of the cases producing the same amount of hydrogen (Cases 11, 13, 14, 15) show a low specific cost variation, the major difference again being 12%.

Table 11. Hydrogen-production technologies—TPC summary (electrolysis)

Case	Description	Total Plant Cost (TPC) US$	Total Capital Requirement (TCR) US$	Specific Cost (TPC/H_2 production, kg/day)	Specific Cost (TCR/H_2 production, kg/day)
1	Alkaline water electrolysis (1,500 kg/day)	9,070,000	10,455,000	6,050	6,970
2	Alkaline water electrolysis (50,000 kg/day)	128,060,000	149,693,900	2,560	2,990
3	Polymer electrolyte membrane (PEM) water electrolysis (1,500 kg/day)	12,950,000	14,864,000	8,630	9,910
4	Polymer electrolyte membrane (PEM) water electrolysis (50,000 kg/day)	289,290,000	333,841,200	5,790	6,660
5	High temperature solid oxide water electrolysis (SOEC) (1,500 kg/day)	Not Available	Not Available	Not Available	Not Available
6	High temperature solid oxide water electrolysis (SOEC) (50,000 kg/day)	Not Available	Not Available	Not Available	Not Available

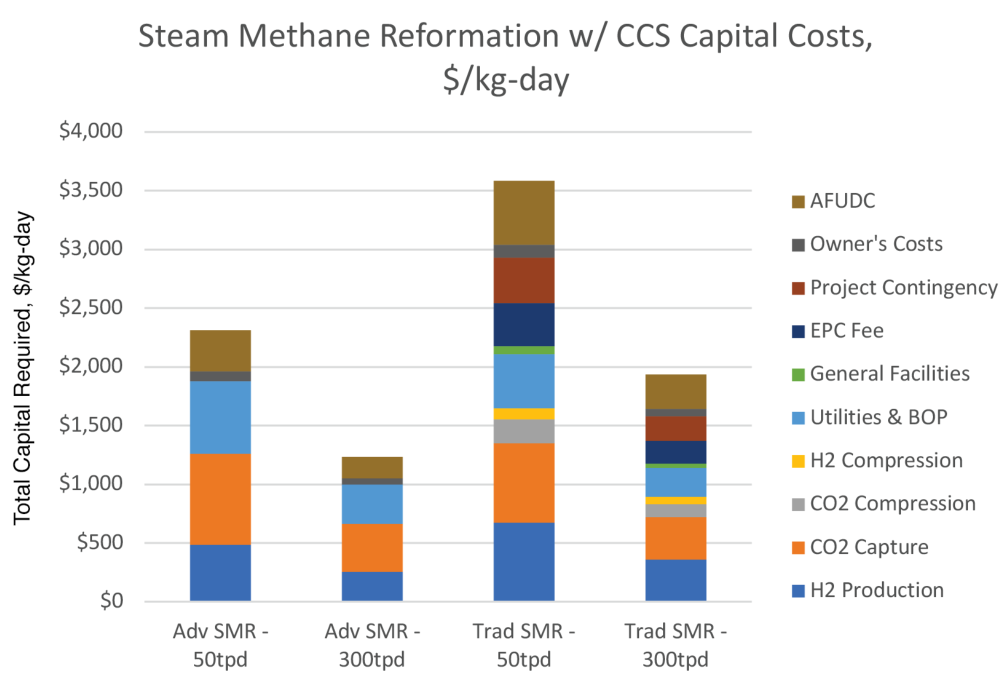
Table 12. Hydrogen-production technologies—TPC summary (SMR and gasification)

Case	Description	Total Plant Cost (TPC) US$	Total Capital Requirement (TCR) US$	Specific Cost (TPC/H_2 production, kg/day)	Specific Cost (TCR/H_2 production, kg/day)
7	SMR "Advanced Technology" (50,000 kg/day)	94,000,000	115,587,800	1,880	2,310
8	SMR "Advanced Technology" (300,000 kg/day)	300,000,000	370,084,300	1,000	1,230
9	SMR "Traditional Technology" (50,000 kg/day)	146,400,000	178,322,700	2,930	3,590
10	SMR "Traditional Technology" (300,000 kg/day)	473,000,000	580,677,600	1,580	1,940
11	Coal gasification (50,000 kg/day)	413,600,000	505,953,000	8,270	10,120
12	Coal gasification (300,000 kg/day)	1,503,000,000	1,846,044,100	5,010	6,150
13	Biomass Gasification (Fluidized Bed) (50,000 kg/day)	425,750,000	521,242,100	8,520	10,420
14	Biomass Gasification (Fixed Bed) (50,000 kg/day)	374,650,000	458,831,000	7,490	9,180
15	Waste Gasification (Fluidized Bed) (50,000 kg/day)	414,320,000	509,643,700	8,290	10,190



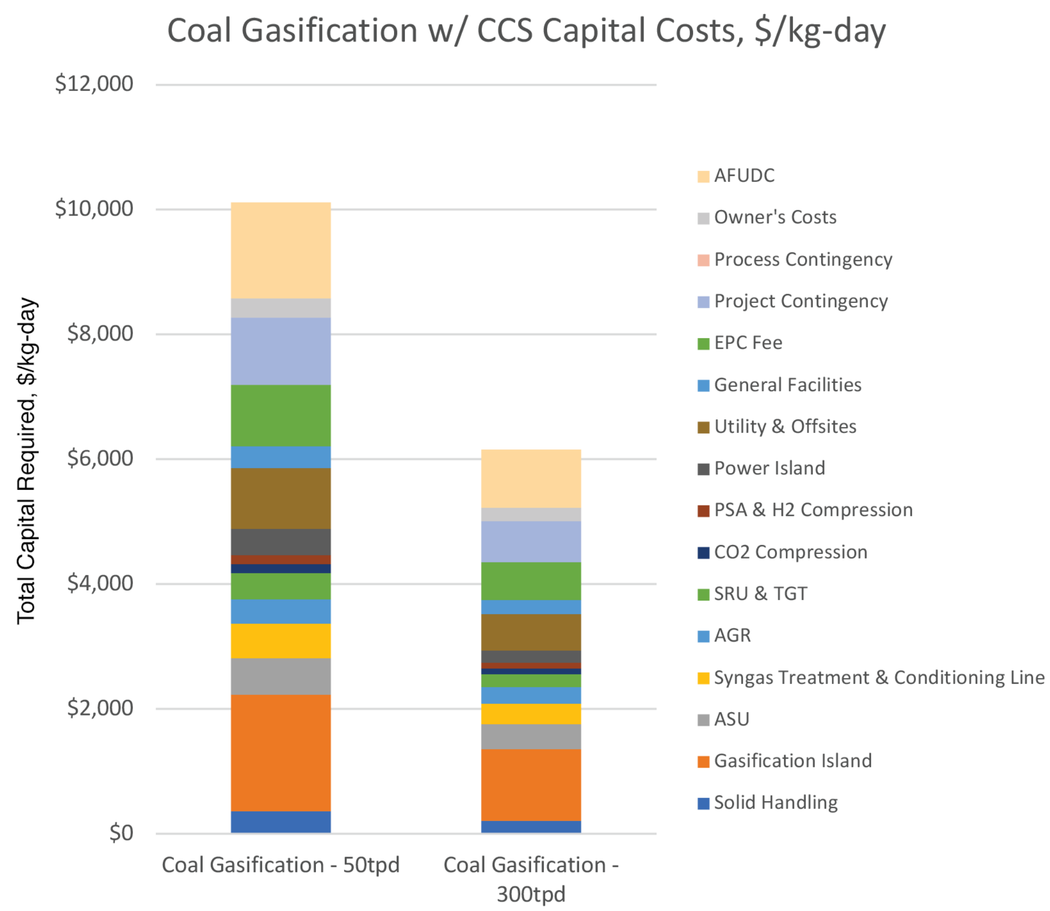
Notes:
Dist: Distributed, 1,500 kg/day
Central: 50,000 kg/day
AFUDC = Allowance for funds used during construction

Figure 1. Hydrogen production technologies—specific TCR costs breakdown (electrolysis)



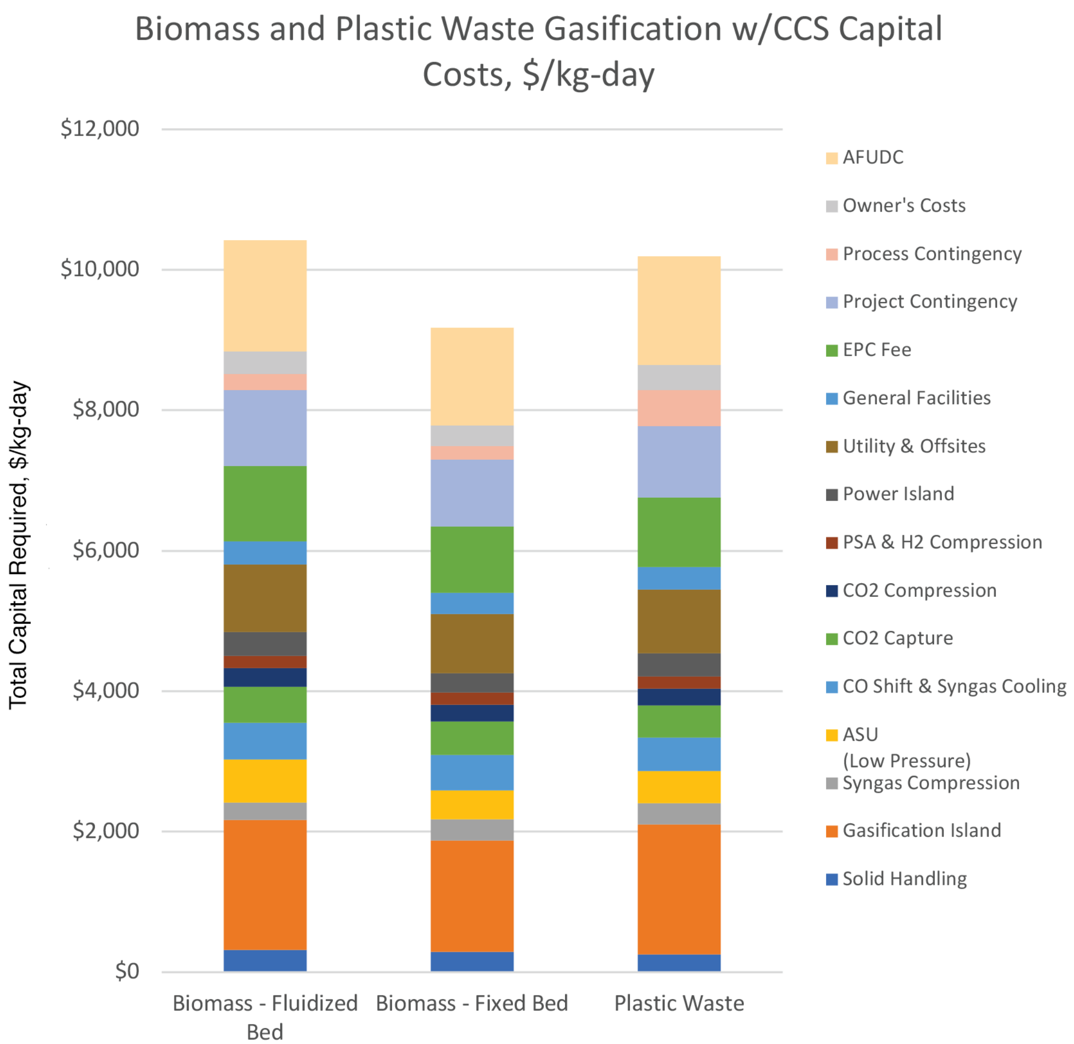
AFUDC = Allowance for funds used during construction

Figure 2. Hydrogen production technologies—specific TCR costs breakdown (SMR)



AFUDC = Allowance for funds used during construction

Figure 3. Hydrogen production technologies—specific TCR costs breakdown (coal gasification)



AFUDC = Allowance for funds used during construction

Figure 4. Hydrogen production technologies—specific TCR costs breakdown (biomass and plastic gasification)

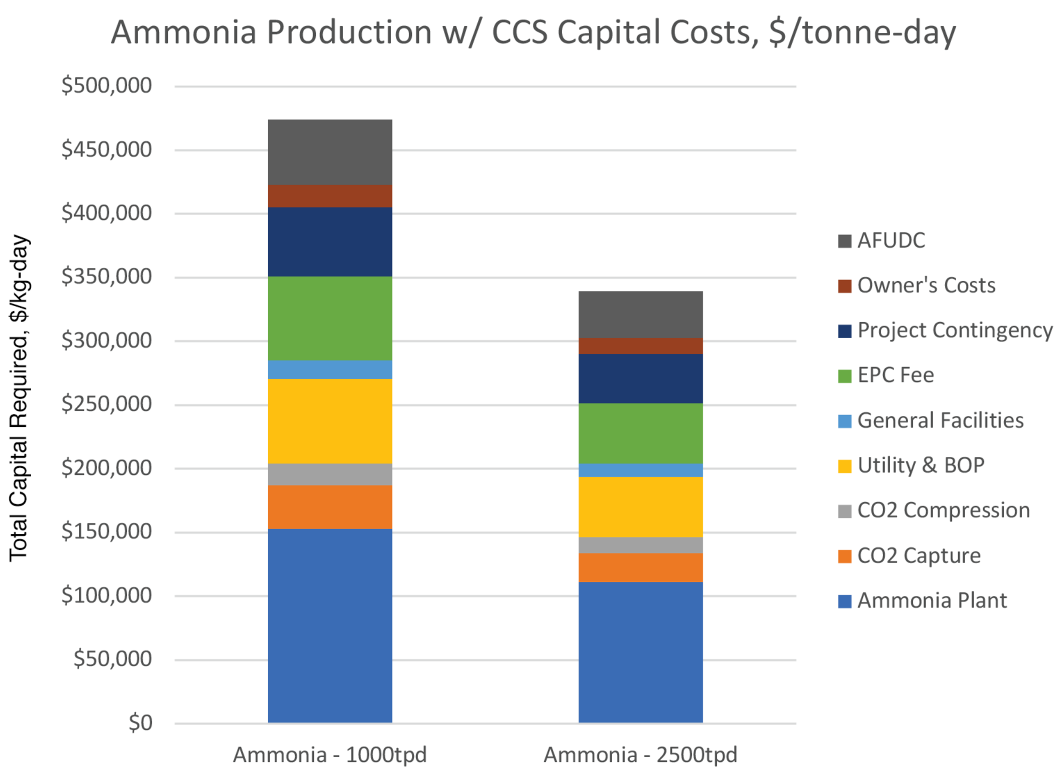
Ammonia Synthesis

Table 13 shows a summary of the TPC of the different study cases for ammonia synthesis, together with their specific investment costs (TPC/NH_3 production capacity, tonne/day), while Figure 5 presents a breakdown of the specific investment cost of each case, showing the relative cost of the ammonia production facility, major process components, and project-related costs.

The main difference between the two cases assessed is related to the plant capacity. By increasing 2.5 times the overall ammonia production rate, the equivalent specific cost savings of the project is about 30%.

Table 13. Ammonia synthesis—TPC summary

Case	Description	Total Plant Cost (TPC) US$	Total Capital Requirement (TCR) US$	Specific Cost (TPC/NH_3 production, kg/day)	Specific Cost (TCR/NH_3 production, kg/day)
1	Ammonia production via Haber Bosch (1,000 tonnes/day)	405,082,680	474,248,080	410	470
2	Ammonia production via Haber Bosch (2,500 tonnes/day)	725,048,080	848,925,980	290	340



AFUDC = Allowance for funds used during construction

Figure 5. Ammonia synthesis—specific TCR costs breakdown

Power Generation Technologies

Table 14 shows a summary of the TPC of the different study cases for the power generation technologies, together with their specific investment costs (TPC/gross power output, kWe).

Figure 6 presents a breakdown of the specific investment cost of each case, showing the relative cost of the power generation unit and of the balance of plant (BOP) and utilities.

For each case, the significant difference in the technology type (combustion turbine, reciprocating engine), the feedstock type (hydrogen, ammonia, or a mixture of the two), and the plant configuration (combined cycle, open cycle) and its power generation size (from 40 to 550 MWe) do not allow a straight comparison of the cost results. In fact, the study objectives were to perform techno-economic assessments of innovative solutions, part of which still require further development that are expected to come from the various suppliers in the near future.

Table 14. Power generation technologies—TPC summary

Case	Description	Total Plant Cost (TPC) US$	Total Capital Requirement (TCR) US$	Specific Cost (TPC/net power output, kWe)	Specific Cost (TCR/net power output, kWe)
1	New Aeroderivative Hydrogen CT (40 MWe)	58,398,000	71,035,300	1,490	1,810
2	New Advanced Class Hydrogen 1x1 CTCC (550 MWe)	470,699,520	576,738,120	880	1,080
3	New Advanced Class Ammonia/H_2 blend Combustion Turbine (400 MWe)	251,901,150	368,364,650	640	940
4	New Ammonia Reciprocating Engine (50 Mwe) (1)	77,696,480	106,780,380	1,420	1,940

1. Involving three gas engines to match the target gross power output.

OPERATING AND MAINTENANCE COSTS

Operating and maintenance (O&M) costs are estimated for one year of normal operation and presented in 2Q-2021 U.S. dollars. O&M costs are generally allocated as fixed and variable costs.

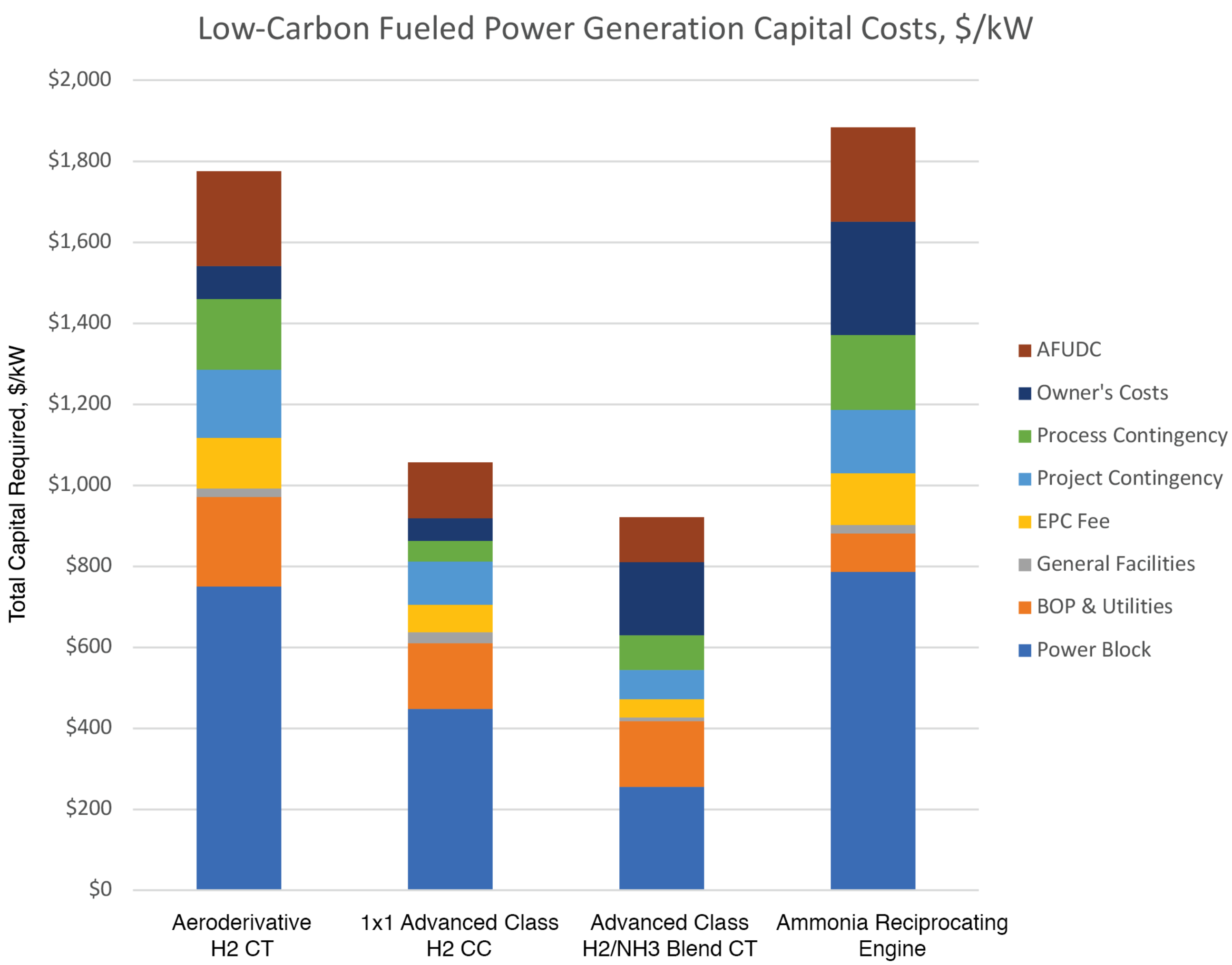
Fixed operating costs are composed of the following sources:

- Operating labor
- Overhead charges
- Total maintenance costs

Variable O&M include:

- Feedstock
- Raw water
- Chemicals
- Catalyst
- Waste disposal

The consumption of the various items and the corresponding costs are yearly, based on the expected equivalent availability of the plant of 90% capacity factor.



AFUDC = Allowance for funds used during construction

Figure 6. Power generation technologies—specific TCR costs breakdown

Hydrogen Production Technologies

Table 15 and Table 16 provide a summary of the O&M costs for the 15 hydrogen-production technology study cases.

The main differences between the assessed cases are highlighted in the following:

- Comparing electrolysis-based plants with the same hydrogen-production capacity from the first year to the ninth year, PEM cases have overall O&M costs higher than those of the alkaline ones. The difference is mainly due to the fixed costs in terms of maintenance, which is nearly related to the TPC. In addition, the difference in TPC also led proportionally to different insurance and local tax costs. Finally, a minor contribution of this O&M cost difference is due to the variable costs in terms of electricity and raw water, related to the specific requirements of the technology.
- Considering the electrolysis system cases at the 10th year of operation, the consideration made above is again applicable, while the cost for stack replacement is now added. The cost of replacement for PEM is greater than that of the alkaline one, mainly due to the lower maturity of the technology.
- Considering cases with the same target hydrogen-production capacity, fixed costs prove to be higher for gasification-based alternatives; what mainly impacts this difference is the maintenance cost of a more complex plant.
- As a general trend, comparing cases with the same hydrogen-production capacity, variable costs of SMR are higher than the gasification-based ones. This is mainly due to the feedstock price and feed rate demand. While coal cases require a higher feed flow rate (see Table 7), coal price still is nearly half of that of natural gas, determining such a trend. This holds true even more for the biomass cases (Cases 13 and 14), which require higher electricity costs, in line with the electric demand reported in Table 7.

Table 15. Hydrogen-production technologies—O&M (electrolysis)

wood.	Case 1 1st to 9th Year US$/Year	Case 1 at 10th Year US$/Year	Case 2 1st to 9th Year US$/Year	Case 2 at 10th Year US$/Year	Case 3 1st to 9th Year US$/Year	Case 3 at 10th Year US$/Year	Case 4 1st to 9th Year US$/Year	Case 4 at 10th Year US$/Year
Fixed Costs **Direct Labor**	100,000	100,000	200,000	200,000	100,000	100,000	200,000	200,000
Adm./Gen Overheads	70,800	70,800	636,300	636,300	88,300	88,300	1,361,800	1,361,800
Insurance and Local Taxes	118,000	118,000	1,664,800	1,664,800	164,000	168,400	3,760,800	3,760,800
Replacement Stack	-	831,200	-	17,795,200	-	1,544,400	-	45,455,600
Maintenance	136,100	136,100	1,920,900	1,920,900	194,300	193,400	4,339,400	4,339,400
Subtotal	**424,900**	**1,256,100**	**4,422,00**	**22,217,200**	**551,000**	**2,095,400**	**9,662,000**	**55,117,600**
Variable Costs (Capacity Factor = 90%) **Electricity (1)**	1,356,800	1,356,800	44,335,700	44,335,700	1,435,700	1,435,700	47,173,900	47,173,900
Raw Water Makeup	6,300	6,300	193,700	193,700	7,300	7,300	239,800	239,800
Chemicals	2,040	2,040	166,200	166,200	2,040	2,040	166,200	166,200
Wastewater Disposal	4,400	4,400	145,600	145,600	4,400	4,400	145,600	145,600
Subtotal	**1,369,540**	**1,369,540**	**44,841,200**	**44,841,200**	**1,449,440**	**1,449,440**	**47,725,500**	**47,725,500**
Total O&M Costs	**1,794,440**	**2,625,640**	**49,263,200**	**67,058,400**	**2,000,440**	**3,544,840**	**57,387,500**	**102,843,100**

Case 1	Alkaline Electrolysis	1,500 kg/day
Case 2	Alkaline Electrolysis	50,000 kg/day
Case 3	Proton Exchange Membrane (PEM) Electrolysis	1,500 kg/day
Case 4	Proton Exchange Membrane (PEM) Electrolysis	50,000 kg/day

Note: Proton exchange membrane is another term for the polymer electrolyte membrane.

1. $50/MWh electric; $0.39/Liter water; Chemicals depend on technology - these are defined in the report

Table 16. Hydrogen-production technologies—O&M (SMR and gasification)

wood.	Case 7 US$/Year	Case 8 US$/Year	Case 9 US$/Year	Case 10 US$/Year	Case 11 US$/Year	Case 12 US$/Year	Case 13 US$/Year	Case 14 US$/Year	Case 15 US$/Year
Fixed Costs Direct Labor	3,400,000	3,400,000	4,300,000	4,300,000	4,500,000	9,000,000	4,500,000	4,500,000	4,500,000
Adm./Gen Overheads	1,443,000	2,370,000	1,948,800	3,418,500	3,774,000	11,436,000	3,829,000	3,520,000	3,800,000
Insurance and Local Taxes	1,222,000	3,900,000	1,903,200	6,149,000	5,377,000	19,539,000	5,535,000	4,870,000	5,386,000
Maintenance	1,410,000	4,500,000	2,196,000	7,095,000	8,079,000	29,120,000	8,263,000	7,234,000	8,166,000
Subtotal	7,475,000	14,170,000	10,348,000	20,962,500	21,730,000	69,095,000	22,127,000	20,124,000	21,852,000
Variable Costs (Capacity Factor = 90%) Feedstock	12,970,000	78,207,400	15,089,800 (1)	90,538,600 (1)	7,724,600	58,064,100	5,455,500	4,503,300	27,234,500
Electricity	1,155,000	6,859,100	2,093,200	12,827,300	2,838,200	0	9,421,400	8,238,800	7,213,900
Water Makeup	66,400	398,200	30,700	184,500	239,800	2,081,600	212,200	178,300	196,800
Chemicals and Catalysts	100,000	598,400	119,000	712,000	674,800	5,073,200	480,600	458,000	413,600
Waste Disposal	–	–	–	–	173,400	1,277,200	44,700	167,100	101,700
Subtotal	**14,291,400**	**86,063,100**	**17,332,700**	**104,262,400**	**11,650,800**	**66,496,100**	**15,614,400**	**13,545,500**	**35,160,500**
Total O&M Costs	**21,766,400**	**100,233,100**	**27,680,700**	**125,224,900**	**33,380,800**	**135,591,100**	**37,741,400**	**33,669,500**	**57,012,500**

1. Including fuel (price of natural gas = $4.4/mmbtu)

Case 7	SMR "Advanced Technology"	50,000 kg/day
Case 8	SMR "Advanced Technology"	300,000 kg/day
Case 9	SMR "Traditional Technology"	50,000 kg/day
Case 10	SMR "Traditional Technology"	300,000 kg/day
Case 11	Coal Gasification	50,000 kg/day
Case 12	Coal Gasification	300,000 kg/day
Case 13	Biomass Gasification—ABSL Technology	50,000 kg/day
Case 14	Biomass Gasification—Nexterra Technology	50,000 kg/day
Case 15	Plastic Gasification—ABSL Technology	50,000 kg/day

Ammonia Synthesis

Table 17 provides a summary of the O&M costs for the ammonia-synthesis study cases. The O&M costs trend for ammonia-synthesis cases is in line with the increased capacity of the ammonia production.

Table 17. Ammonia synthesis—O&M

wood.	Case 1 US$/Year	Case 2 US$/Year
Fixed Costs **Direct Labor**	7,100,000	7,100,000
Adm./Gen Overheads	3,952,600	5,392,300
Insurance and Local Taxes	5,265,400	9,424,500
Maintenance	6,075,500	10,874,400
Subtotal	**22,393,500**	**32,791,200**
Variable Costs (Capacity Factor = 90%)		
Feedstock	49,817,300	124,544,300
Electricity	5,006,300	12,535,600
Water Makeup	123,900	309,900
Chemicals and Catalysts	1,000,000	1,700,000
Subtotal	**55,947,500**	**139,089,800**
Total O&M Costs	**78,341,000**	**171,881,000**

Case 1	Ammonia production via Haber Bosch	1,000 tonnes/day
Case 2	Ammonia production via Haber Bosch	2,500 tonnes/day

Power Generation Technologies

Table 18 provides a summary of the O&M costs for the power generation technology study cases. The primary conclusions that can be drawn for the four cases are the following:

- O&M costs are largely affected by the variable price of the feedstocks and their need to meet the targeted power demand of the case—the higher the power demand, the higher the variable cost of the fuel.
- Case 3 shows the highest O&M costs; this is mainly due to the large amount of ammonia required for this case and its related unitary cost.
- Case 2 shows the highest fixed costs; this is mainly due to the additional complexity of the combined-cycle power plant, compared to the other technologies of the study.

Table 18. Power generation technologies—O&M

wood.	Case 1 US$/Year	Case 2 US$/Year	Case 3 US$/Year	Case 4 US$/Year
Fixed Costs **Direct Labor**	800,000	2,300,000	800,000	800,000
Adm./Gen Overheads	644,700	5,964,000	1,876,800	802,200
Insurance and Local Taxes	759,000	6,119,000	3,275,000	1,010,000
Maintenance	1,349,000	17,580,000	5,456,000	1,874,000
Subtotal	**3,552,700**	**31,963,000**	**11,407,800**	**4,486,200**
Variable Costs (Capacity Factor = 90%) **Feedstock**	64,579,000	554,656,700	752,821,300	115,288,600
Water Makeup	43,000	1,466,700	61,500	–
Catalysts	–	1,134,000	1,225,800	168,300
Subtotal	**64,622,000**	**557,257,400**	**754,108,600**	**115,456,900**
Total O&M Costs	**68,174,700**	**589,220,400**	**765,516,400**	**119,943,100**

Case 1	New aeroderivative hydrogen CT	40 MWe
Case 2	New advanced class hydrogen 1x1 CTCC	550 MWe
Case 3	New advanced class ammonia/H_2 blend CT	400 MWe
Case 4	New Ammonia Reciprocating Engine	50 MWe

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