California ISO

EXTERNALLY-AUTHORED REPORT

Variable Operations and Maintenance Cost

December 26, 2018

This report was developed by an external party at the request of the California Independent System Operator for posting to the CAISO website in conjunction with a Stakeholder-involved initiative or similar activity. The document was not produced by the CAISO and therefore does not necessarily reflect its views or opinion.

Background

Variable Operations and Maintenance (VOM) costs are used in default energy bids and minimum load costs as per MWh dollar amounts that are intended to capture the variable, non-fuel costs associated with running a generator. The VOM has been refined since 2009 with the CAISO reviewing VOM adders every three years as indicated in the BPM for Market Instruments Attachment D.5.4. In 2012, the category of VOM values was expanded from two categories to ten categories based on a consultant study of the various types of generating plants operating in the CAISO Control Area. The CAISO reviewed the ten categories in 2015 and retained the values established in 2012.

Tariff Section 39.7.1.1.2 details the current default VOM values: "The default value for the variable operation and maintenance cost portion will vary by fuel source or technology as follows: (1) solar $0.00/MWh; (2) nuclear $1.00/MWh; (3) coal $2.00/MWh; (4) wind $2.00/MWh; (5) hydro $2.50/MWh; (6) natural gas-fired combined cycle and steam units $2.80/MWh; (7) geothermal $3.00 WMh; (8) landfill gas $4.00/MWh; (9) combustion turbines and reciprocating engines $4.80/MWh; and (10) biomass $5.00/MWh. Resource specific values may be negotiated with the CAISO or the Independent Entity charged with calculating the Default Energy Bid. Default operation and maintenance values as well as any negotiated values will also be used to calculate Minimum Load Costs pursuant to Section 30.4."

The CAISO has engaged Nexant consulting for the 2018 review of VOM. The 2018 review is a detailed review of the costs associated with VOM and consistent with the definition of VOM as the variable non-fuel costs that may include raw water, water and wastewater disposal expenses, chemicals and other consumable materials and supplies. The CAISO has been identifying and refining generator commitment and energy costs through a series of stakeholder initiatives including Commitment Costs Enhancements Phases 1 through 3, Bidding Rules Enhancements Phase 1 & 2 and Commitment Costs and Default Energy Bid Enhancements (CCDEBE) and this detailed review of VOM is consistent with those initiatives.

The ISO is starting a review process to update, as applicable, the adders for VOM. During this process, stakeholders will have an opportunity to review and comment on the methodology used to calculate VOM. Nexant's report includes a review of the data sources and methodology used to determine VOM considering the generating fleet and resource technologies in the Western Interconnect.

Revision History

Date	Version	Description	Author
12/26/2018	1.0	Initial Version	Nexant

REPORT

Nexant

Reimagine tomorrow.

Variable Operations and Maintenance Costs Report

Submitted to: California Independent System Operator

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Contents

1 Introduction and Background

1.1 Objectives and Requirements

The CAISO engaged Nexant to assist them to review and to potentially update the variable operations and maintenance cost values that are used in their market processes. The CAISO's overall objectives for this engagement are as follows:

1) To perform a review of the variable operations and maintenance costs (VOM) of generators in order to help ensure that the cost inputs used in CAISO markets are reasonable reflections of expected costs.

2) To potentially revise the current technology types and default values for VOM in its Tariff to reflect the current technology and technology-specific VOM costs in the Western Interconnection.

In addition, listed below are a few other requirements that went into the development of the VOM default cost values:

- VOM values should be developed for generator types that have a significant market presence in the Western Interconnection
- VOM values should adhere to the CAISO's definition of Variable Operations and Maintenance costs.
- Since VOM values developed will be used by the CAISO as default values in the CAISO market they should be representative of a large fraction of the generators in the class - for generators whose variable O&M costs are different the default VOM value, the CAISO is expected to continue its past practices of working with generator owners to develop generator-specific VOM values.
- To the extent possible, VOM values should be developed using publicly available information.
- The VOM costs developed should be representative of the costs in the year 2019. To accomplish this, the project included the development of a methodology to escalate cost data from years prior to 2019 (i.e. in 2009 dollars) to cost in 2019 dollars.

1.2 Report Overview

This report summarizes the work that was performed to the meet objectives while meeting the requirements listed above – namely the review and potential revision of the default VOM values used in the CAISO market.

This draft report is organized into the following sections:

- **Section 2:** Cost Definitions, Data Sources and Methodology for Cost Development
- **Section 3:** Cost Information for Generating Plants

2 Cost Definitions, Data Sources and Methodology for Cost Development

2.1 Cost Definitions

We note that in the course of searching for data and developing the various costs factors, there are no standard definitions for what operations and maintenance costs should be considered variable vs. what costs should be considered fixed. Further, there are no standard definitions regarding what costs should be considered variable with respect to energy production (MWh) or plant starts or plant operating hours. This report utilizes the following CAISO definitions (directly or indirectly) in characterizing cost information in this report. They are intended to be consistent with the CAISO's definition related to VOM costs as they are designed to be used in the CAISO market processes.

2.1.1 Variable Operations and Maintenance (VOM)

Variable Operations and Maintenance (VOM) costs are the portion of the O&M costs that are a function of the level energy production (MWh) of the generating unit over any period of interest. In other words, the portion of O&M costs (excluding fuel costs) that varies directly with the MWh production of the generating unit. To be consistent with how the VOM costs are used in the CAISO market, the VOM values developed in this report include only costs associated with consumables and waste disposal. The VOM values do not include any major maintenance (MM) costs or other maintenance (OM) Costs (which are described below).

The use of the term VOM in industry and in many of the data sources available is not standardized. In some cases, VOM is defined in same way that the CAISO defines it (consumable and waste related costs) and in other cases VOM values provided in industry reports include MM and/or OM costs[1]. All references to VOM cost in this report are based upon the CAISO definition unless otherwise stated.

Examples of costs that are included in the VOM values per the CAISO definition are costs for:

- Raw water
- Waste and wastewater disposal expenses
- Chemicals, catalysts and gases
- Ammonia for selective catalytic reduction
- Lubricants whose use depends upon energy production
- Consumable materials and supplies

[1] A good example of an industry report that for the most part includes Major Maintenance and Other Maintenance in their VOM values is the U.S. Energy Information Authority's Annual Energy Outlook (AEO) report which has been published since1979.

2.1.2 Major Maintenance Costs (MM)

Major Maintenance Cost (MM) is the cost of performing periodic O&M work required to maintain the generating unit in an efficient and reliable condition. This work is normally performed during extended periods of shut down of the generating unit lasting multiple weeks. These costs generally include for example:

- Scheduled major overhaul expenses for maintaining prime mover
- Major maintenance labor expenses
- Major maintenance spare parts costs
- Balance-of-Plant (BOP) major maintenance costs that cannot be done with routine maintenance or while in commercial operation

These costs are not included in the VOM values in this report.

2.1.3 Other Maintenance Costs (OM)

Other Maintenance Cost is the cost of performing other periodic O&M work required to maintain the generating unit in an efficient and reliable condition. This work is normally not performed during extended periods of shut down of the generating unit but performed during short shutdowns (e.g. weekends). These costs generally include, for example:

- Maintenance of equipment such as water circuits, feed pumps, main steam piping, and demineralizer systems
- Maintenance of electric plant equipment, which includes service water, DCS, condensate system, air filters, and plant electrical
- Maintenance of miscellaneous plant equipment such as communication equipment, instrument and service air, and water supply system

These costs are not included in the VOM values in this report.

2.2 Data Sources

2.2.1 General

Generally, data that could be used to develop O&M values often come from reports that were developed for generation planning or analysis. As such, they are focused heavily on capital costs and the O&M costs are normally treated at a high level. In these sources, O&M cost is not generally segregated into categories that are useful to developing a CAISO VOM default value – in general MM and OM costs are not shown as individual items and VOM, particularly in recent years contains MM and OM costs in many reports. For developing VOM costs that are consistent with the CAISO market design, emphasis was placed upon finding data sources that segregated the costs related to consumables and waste disposal from other costs making it possible to more accurately estimate VOM costs for use in the CAISO market. The various sources referred to in the course of developing the default VOM values are listed below.

2.2.2 Independent System Operators' Cost of New Entry (CONE) Study Reports

Independent System Operators that operate capacity markets in the US (Example: New York ISO, PJM, and ISO New England) periodically perform Cost of New Entry (CONE) studies to develop the demand curve for their capacity auctions. Typically, the ISOs hire an Independent Consultant to develop the inputs for the demand curve, including the cost of a new peaking unit. These studies involve the detailed development of construction cost estimates, operating cost data and plant operating characteristics by an engineering firm or based on inputs from an engineering, procurement and construction (EPC) company. In these studies, the CONE for two types of plants are typically developed – peaking plants which include simple cycle aeroderivative combustion turbines, frame combustion turbines and reciprocating internal combustion engines (RICE) and combined cycle power plants using 1x1 or 2x1 configurations of frame combustion turbines.

In addition to capital costs for new units, the fixed operating and maintenance (O&M) costs and variable O&M costs are also developed in these studies. Typical fixed plant expenses include plant staff labor cost, routine O&M, routine planned maintenance, and administrative and general costs. Variable O&M costs are directly related to plant electrical generation and start-ups and consist of two components. One variable operating cost component includes the consumables such as ammonia for the Selective Catalytic Reduction (SCR), chemicals, and lube oil for the RICEs, water, and other production-related expenses including SCR and oxidation catalyst replacement. This component is similar to the CAISO VOM definition. The other variable operating cost component is major equipment maintenance. For the simple cycle combustion turbines, the major maintenance variable cost component is for the combustion turbine. For the RICE plant, the major maintenance variable cost component is for the engine major maintenance. For the combined cycle plants, the major maintenance variable cost component also includes the major steam cycle equipment such as the steam turbine, heat recovery steam generator, and condenser. These major maintenance costs (parts and labor) associated with gas turbine, steam turbine, and HRSG are provided as a separate line item in these reports but are not included in the VOM values developed in this report.

The CONE reports for NYISO and PJM can be accessed using the links below. NYISO and PJM have performed these CONE studies every three years.

https://www.nyiso.com/installed-capacity-market

https://www.pjm.com/markets-and-operations/rpm.aspx

2.2.3 Sargent and Lundy

Sargent & Lundy published the "New Coal Fired Power Plant Performance and Cost Estimates report" in August 2009. This one-time report which was produced for the EPA provides a detailed breakdown of the variable O&M components for coal plants in a manner that is consistent with the CAISO VOM definition. This disaggregation of O&M costs allows for the calculation of VOM associated with consumables and waste only which enables a bottom-up

calculation of VOM values. This data is used for the many coal fueled power plants in the report as well as a reference to other fossil fueled plants with similar water and emission control systems.

https://www.epa.gov/sites/production/files/2015-08/documents/coalperform.pdf

2.2.4 EPA Compilation of Air Pollutant Emissions Factors (AP-42)

Compilation of Air Pollutant Emissions Factors (AP-42) has been published by EPA since 1972 as the primary compilation of EPA's emission factor information. It contains emissions factors and process information for more than 200 air pollution source categories. A source category is a specific industry sector or group of similar emitting sources. The emissions factors have been developed and compiled from source test data, material balance studies, and engineering estimates. Data from this source was used to compare/develop estimates for consumables related to emission controls for various generation types including coal, natural gas and biomass.

https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf

2.2.5 DOE Utility-Scale Solar Reports

The DOE Utility-Scale Solar Report, published annually since 2011, provides an overview of developments and trends in the U.S. solar power market. This report summarizes the trends in the solar industry related to installation, technology, performance, cost and solar power purchase agreement (PPA) prices. In addition to capital costs, this report also provides a detailed summary of O&M costs. Berkeley Lab, the primary author of this report, has compiled limited O&M cost data for 40 solar projects in the United States, totaling 800 MW and with commercial operation dates of 2011 through 2016. Although the data sources do not all clearly define what items are included in O&M costs, in most cases the reported values include the costs of wages and materials associated with operating and maintaining the solar project, as well as rent. Other ongoing expenses, including general and administrative expenses, taxes, property insurance, depreciation, and workers' compensation insurance, are generally not included.

https://emp.lbl.gov/sites/default/files/lbnl_utility_scale_solar_2018_edition_report.pdf

2.2.6 DOE Wind Technologies Market Reports

The DOE Wind Technologies Market Report published annually since 2005 provides an overview of developments and trends in the U.S. wind power market. These reports summarize the trends in the wind industry related to installation, technology, performance, cost, wind power price and policies. In addition to capital costs, this report also provides a detailed summary of O&M costs. Berkeley Lab, the primary author of this report, has compiled limited O&M cost data for 164 installed wind power projects in the United States, totaling 14,146 MW and with commercial operation dates of 1982 through 2016. These data cover facilities owned by both IPPs and utilities, although data since 2004 are exclusively from utility-owned projects and so may not be broadly representative. The treatment of O&M costs for wind projects is similar to

the treatment of O&M costs for solar projects as described in the previous section in that data sources do not all clearly define what items are included in O&M costs but generally include or exclude the same type of costs as listed in the previous section.

https://www.energy.gov/sites/prod/files/2018/08/f54/2017_wind_technologies_market_report_8.15.18.v2.pdf

2.2.7 NREL O&M Cost Reports

The National Energy Renewable Laboratory periodically publishes detailed reports on the O&M costs associated with wind and solar PV plants. These reports give a detailed breakdown of the O&M cost components for wind and solar plants and can be used to determine the costs that are variable and fixed as per CAISO's definition. These reports, in conjunction with the DOE reports can be used for estimating the MM and other O&M costs for wind and solar plants.

https://www.nrel.gov/docs/fy08osti/40581.pdf

https://www.nrel.gov/docs/fy17osti/68023.pdf

2.2.8 EIA Annual Energy Outlook Reports

The U.S. Energy Information Authority (EIA) has been publishing the Annual Energy Outlook (AEO) since 1979. Projections for the AEO report are obtained from the North American Energy Modeling System (NEMS), a model developed and maintained by the Office of Energy Analysis of the U.S. EIA. NEMS has several modules of which the Electricity Market Module (EMM) is one. The NEMS Electricity Market Module (EMM) represents the capacity planning, dispatching, and pricing of electricity. Based on fuel prices and electricity demands provided by the other modules of NEMS, the EMM determines the most economical way to supply electricity, within environmental and operational constraints. The cost and performance characteristics of new generating technologies are inputs to the EMM electricity capacity planning submodule. EIA maintains an archive (https://www.eia.gov/outlooks/aeo/archive.php) of assumptions used in the NEMS model. These assumptions are available for the years 1996 and later.

Every three years on average, the EIA commissions an external consultant to update current cost estimates for certain utility scale electric generating plants. The external consultant reports from 2010, 2013, and 2016 are available on EIA's website. The focus of these studies is to gather information on the engineering, procurement and construction costs, operating costs, and performance characteristics for a wide range of generating technologies. Where possible, costs estimates are based on information derived from actual or planned projects known to the consultant.

Non-fuel operations and maintenance (O&M) costs associated with each of the power plant technologies are also evaluated in these external consultant studies. The O&M costs that do not vary significantly with a plant's electricity generation are classified as fixed, while the costs incurred to generate electricity are classified as variable. However, in these reports, all the major maintenance costs are included under variable O&M costs.

EIA scales the costs using a cost adjustment factor for the years that an external consultant's report is not produced. The cost adjustment factor, based on the producer price index for metals and metal products, allows the overnight costs (capital costs) to fall in the future if this index drops, or rise further if it increases. It should be noted that the methodology for calculating the various costs has been consistent only for the past 10 years. Older data, while available should be used with caution since the methodology used for classifying various costs followed a different approach. In addition, the most recent studies are generally high level and do not go into the detailed engineering analysis that one finds in the NY CONE studies or the Sargent and Lundy coal studies discussed above.

2.2.9 Geothermal H_2S Abatement Costs

A paper titled "Geysers Power Plant H_2S Abatement Update" by John Farison, Brian Benn, Brian Berndt, Calpine Corporation; was published in the Geothermal Research Council Transactions, Vol. 34, 2010. The paper deals with hydrogen sulfide treatment at the Geysers Power Plant in northern California including effluent abatement and the operations and maintenance costs associated with the H_2S treatment. A link to the paper is included below. This source was used to develop default VOM values for geothermal generating units.

https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1028816

2.2.10 Black & Veatch

This report (COST AND PERFORMANCE DATA FOR POWER GENERATION TECHNOLOGIES, 2012) was prepared for the National Renewable Energy Laboratory NREL (NREL) for comparison of cost of conventional technologies vs. renewable technologies. NREL contracted Black & Veatch to provide the power generating technology cost and performance estimates that are described in this report. This data was used to compare against other sources of cost for renewable generation plants. Some of the cost data in this report is based upon EIA reports.

https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf

2.2.11 Wood Fuels Handbook

Report prepared by Dr. Nike Krajnc and published by the Food and Agriculture Organization of the United Nations (FAO-UN), 2015. This report provides data on various biomass fuels and their detailed analysis. This handbook was used in estimating the Biomass VOM.

https://roycestreeservice.com/wp-content/uploads/Wood-Fuels-Handbook.pdf

2.2.12 Lazard's Levelized Cost of Energy

Lazard regularly publishes LCOE reports that include capital and O&M costs. However these reports do not provide detailed breakdown of cost components. This source was used as a source of O&M data for nuclear plant O&M costs.

https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

2.2.13 EPA Combined Heat and Power

EPA published a Catalogue of CHP Technologies in partnership with ORNL and ICF in September 2017. It provides O&M cost breakdown for various generation technologies, including IC engines and Fuel Cells.

https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf

2.2.14 Parson Brinkerhoff Report

Parson Brinkerhoff Report for the CCS O&M costs - July 2012 by Parsons Brinkerhoff for IEA Environmental Projects, 2012. This report estimates O&M costs of carbon capture from combined cycle plants. Developed for IEA, it was used to estimate the cost of Carbon Capture and Sequestration costs.

https://ieaghg.org/docs/General_Docs/Reports/2012-08.pdf

2.2.15 IRENA (Renewable Power Generation Cost Reports)

The O&M cost review for some solar, wind, and small and large hydro plants were performed using the IRENA Renewable Power Generation Cost Reports. These reports are published regularly by IRENA and are developed from a cost database that includes 15000 data points for LCOE from projects around the globe, representing over 1000 gigawatts (GW) of power generation capacity. An additional auctions database encompasses over 7,000 projects with nearly 300 GW of capacity. A link to the report is included below.

https://www.irena.org/publications/2018/jan/Renewable-Power-Generation-Costs-in-2017

2.3 Methodology Used to Develop VOM Costs

The overall approach taken to develop the VOM cost estimates was to first find public sources, if possible, that included VOM type information that is consistent with the CAISO's definition of VOM costs. When possible this was done with sources that disaggregated VOM costs from other types of O&M costs (MM, OM and other fixed costs) thus allowing a type of bottom up estimation methodology. In cases where such data was found, the next steps was to revise the data, if required, to reflect CAISO's requirement of establishing VOM default values that are representative of the VOM costs that would be applicable to many of the units for this type of generator. As indicated earlier, the expectation is that if there are plants that have VOM costs different than the default VOM value, that the plant owner/operator can approach the CAISO to develop a unit specific VOM value.

It was possible in the case of most generation types to use the approach previously described. In a few cases when a bottom up approach was not possible, VOM costs were estimated using aggregated O&M costs that were then partially disaggregated into VOM and other costs using engineering judgement. An example of this approach was the method used to develop the VOM default value for an Advanced Combined Cycle Plant with Carbon Capture and Sequestration.

Finally, these VOM costs which represent data for years prior to 2018 were adjusted to be representative of the costs in the year 2019 – the target year for all potential revised VOM values. This simple methodology used for escalating a cost from a prior year to 2019 is described below.

2.3.1 Escalating Costs to 2019 Target Year

We reviewed the various cost components in the VOM and the range of types of costs in various VOM values and observed that these costs can include a range of chemical costs, a range of disposal costs, some labor costs and some disposal fees.

Based upon that review of the components of VOM costs and their escalation over time, it was decided that the best, as well as the simplest approach to escalate costs from a previous year (for example, 2016) to the 2019 was to use the US Consumer Price Index (CPI) published periodically by the US Bureau of Labor Statistics (BLS). In this approach, the ratio of the CPI for the two years of interest (i.e., CPI_{2019}/CPI_{2016}) is used to escalate the VOM value from 2016 to the year 2019. A link to the CPI used is provided below.

https://www.bls.gov/cpi/tables/detailed-reports/home.htm

2.4 Generators Included in Report

As requested by the CAISO, the types and subtypes of units covered in this report are intended to include those types and subtypes that are representative of the generation technology installed in the Western Interconnect or those that are likely to be installed in the near future. Thus, generating plants that are one of kind or one of a few may not be represented in the report results because they do not meet the “significant market presence” criteria discussed earlier.

3 Cost Information for Generating Plants

The potential Variable Operations and Maintenance Cost default values for all generating plants covered by this report are shown in several tables in this Section 3. The generators have been grouped such that similar generators are listed in the same section and cost table. The information in each grouping includes:

- Name of the Generator Group
- Discussion of the generators in the group
- A brief discussion of the costs included
- A brief discussion of the key sources used to develop the VOM value for generators in the group
- A table that list the Generator Types included in the Group and the VOM costs in $/MWh in 2019 dollars

3.1 Coal and Natural Gas Generators

Generators in this group include plants that are fueled by coal or natural gas in a variety of configurations. The group includes coal and natural gas-fired, sub-critical conventional plants, supercritical and ultra-supercritical coal units, an advanced supercritical coal unit with 90% carbon capture and sequestration (CCS) and an Integrated Gasification Combined Cycle (IGCC) plant.

The variable costs associated with this group of generators includes: 1) water used in water/steam cycle and other processes in the generation facility that utilize water (e.g., coal pile management), 2) chemicals associated with the plant emissions control processes and 3) waste treatment and disposal.

Chemicals that are included for this group (as appropriate to each plant) are:

- Limestone Reagent (dry FGD)
- Activated Carbon (AC) – for mercury control
- Ammonia – for NOx control
- SCR Catalyst Replacement
- Bags for Baghouse
- Other miscellaneous consumables and waste costs

Waste treatment and disposal that are included (as appropriate to each plant) are:

- Bottom Ash Disposal
- Fly Ash Disposal
- Gypsum Disposal
- AC Waste Disposal

In keeping with the aim to develop default VOM values, the variable costs for this group of generator types do not include costs for obtaining NOx or SO2 allowances and do not reflect the revenue associated with the sales of waste products.

The primary sources of data used to develop these VOM cost estimates included:

- Sargent and Lundy Report
- EPA Compilation of Air Pollutant Emissions Factors (AP-42) - Emissions of criteria pollutants were used to estimate NOx emissions and NOx emission control related consumables for various thermal plants.

Table 3-1: Variable Operations and Maintenance Costs – Coal and Natural Gas Plants (2019$)

Plant Type	Variable O&M Cost
Coal Plant - Pulverized Coal – Subcritical	$2.69 MWh
Coal Plant - Pulverized Coal – Supercritical	$2.64 MWh
Coal Plant - Ultra-Super-Critical Coal Plant	$2.60 MWh
Coal Plant - Super-Critical with 90% Carbon Capture and Sequestration (CCS)	$5.21 MWh
Integrated Coal Gasification Combined-Cycle (IGCC)	$1.57 MWh
Oil/Gas Steam Plant – Subcritical	$0.32 MWh

3.2 Combustion Turbine and Combined Cycles Generators

Generators in this grouping include a range of combustion turbine generator types in a both simple and combined cycle arrangements and advanced arrangements with carbon sequestration. They include:

- Combined Cycle (CC) Heavy Duty Frame F – This category represents the majority of the existing CCs in WECC. The values were derived based on a 328 MW Siemens 1 x 1 x 1 SGT6-5000F Combined Cycle Power Plant.
- Combined Cycle Heavy Duty Frame H – This category represents the new CCs entering into service. The values were derived based on a 383 MW Siemens 1 x 1 x 1 SGT6-8000H Combined Cycle Power Plant.
- Advanced Combined Cycle with Carbon Capture and Sequestration. This category represents advanced power plants that use the latest combined cycle technology along with 90% Carbon Capture and Sequestration Technology. The plant size is 860MW Gross and 789 MW net.
- Combustion turbines - E Class - This category represents the older frame gas turbines that are in service (Frame B/E) in WECC. The values were derived based on a 74MW, GE Frame 7000E Simple Cycle Power Plant.
- Combustion turbines - F Class - This category represents the majority of the frame gas turbines in WECC. The values were derived based on a 250 MW Siemens SGT6-5000F Simple Cycle Power Plant Cycle Power Plant.

- Combustion turbines - H Class - This category represents the new frame combustion turbines entering the WECC region. The values were derived based on a 337 MW GE 7HA.02 Simple Cycle Power Plant Cycle Power Plant.
- Combustion turbines (Aeroderivative) – This category represents the majority of the aeroderivative combustion turbines (LM6000 and earlier). The values were derived based on a 51 MW GE LM6000PA Simple Cycle Power Plant.
- Combustion turbines (Aeroderivative) LMS100 – This category represents the new/recent aeroderivative combustion turbines in the WECC region. The values are based on a 100 MW GE LMS100 PA Simple Cycle Power Plant.

The variable costs associated with this group of generators includes: 1) water used in water/steam cycle and 2) chemicals associated with the water and plant emission's control processes, 3) chemicals required for CO2 capture for the Advanced Combined Cycle with CCS Unit and 4) other miscellaneous consumable costs

The primary sources of data used to develop these VOM cost estimates included:

- The ISO CONE Reports
- Parson Brinkerhoff Report for the CCS O&M costs.

Table 3-2: Variable Operations and Maintenance Costs – Combustion Turbines and Combined Cycle Plants (2019$)

Plant Type	Variable O&M Cost w/o SCR	Variable O&M Cost SCR
Combined Cycle CC Heavy Duty Frame F	$0.17 MWh	$0.26 MWh
Combined Cycle Heavy Duty Frame H	$0.17 MWh	$0.38 MWh
Advanced Combined Cycle with Carbon Capture and Sequestration		$2.64 MWh
Combustion Turbines - E Class	$0.47 MWh	$1.58 MWh
Combustion Turbines - F Class	$0.29 MWh	$0.82 MWh
Combustion Turbines - H Class	$0.29 MWh	$0.82 MWh
Combustion turbines (Aeroderivative) LM6000	$0.70 MWh	$1.88 MWh
Combustion turbines (Aeroderivative) LMS100	$0.72 MWh	$1.82 MWh

3.3 Nuclear and Advanced Nuclear

This group includes existing conventional nuclear plants with ratings of about 1100 MW and an advanced nuclear plant with a rating of 1137 MW.

The primary source of data used to develop these VOM cost estimates is the EIA reports.

Table 3-3: Variable Operations and Maintenance Costs – Nuclear Plants (2019$)

Plant Type	Variable O&M Cost
Nuclear Plant Size 1100 MWs	$1.87 MWh
Advanced Nuclear Plant	$1.96 MWh

3.4 Renewable Generating Units with VOM

The plants in this group are all renewable in nature, except the Fuel Cell and the Internal Combustion Engine generator which are primarily fueled by natural gas. The group includes VOM costs of geothermal plants, biomass plants operating on agriculture waste, two solar thermal power plants one with and one without storage, a fuel cell, a land fill gas generation plant and an internal combustion plant.

Table 3-4: Variable Operations and Maintenance Costs – Renewable Generators with VOM (2019$)

Plant Type	Variable O&M Cost
Geothermal Power Plant	$1.16 MWh
Biomass Power Plant	$1.65 MWh
Solar Thermal Power Plant w/o storage	$0.24 MWh
Solar Thermal Power Plant with storage	$0.26 MWh
Fuel Cell	$37.7 MWh
Land Fill Gas	$1.21 MWh
Internal Combustion Engine	$1.10 MWh

The primary sources of data used to develop these VOM cost estimates included:

- Geothermal H2S Abatement Report
- Sargent and Lundy
- EPA Air Pollutant Emissions Factors (AP-42)
- EIA 2016 Report
- EPA CHP Report

VOM costs for these generators will vary based on type or renewable energy and technology. The following is the list of VOM components for each type of generating units.

- Geothermal Power Plant – costs associated with H2S removal, and chemicals and water for the steam cycle cooling and other miscellaneous consumables and waste costs.
- Biomass Power Plant – costs associated with water for the steam cycle and for cooling system, ammonia and SCR for NOx control, ash disposal costs and other miscellaneous consumables and waste costs.
- Solar Thermal Power Plant w/o storage – Cost of water and water chemicals for the steam cycle and cooling tower and other miscellaneous consumables costs.
- Solar Thermal Power Plant with storage – Cost of water and water chemicals for the steam cycle and cooling tower, cost of Nitrogen (or inert gas) blanketing of the molten salt storage tanks and other miscellaneous consumables
- Fuel Cell – cost of fuel cell stack (or membrane) replacement that is directly proportional to MWh generated
- Land Fill Gas – cost associated with NOx control (ammonia and SCR catalyst) and other miscellaneous consumables and waste costs.
- Internal Combustion Engines - cost associated with NOx control (ammonia and SCR catalyst), and other miscellaneous consumables costs.

3.5 Plants without Variable Operations and Maintenance Costs

There are a number of types of generation plants that do not have variable operations and maintenance cost that meet the CAISO definition of VOM. That is, they don't have costs that are a function of the level of production (MWhs) that are consumables and waste related. The generation types that are in this category include:

Table 3-5: Generating Plants without Variable Operations and Maintenance Costs

Plant Type
Small Hydro
Large Hydro
Pumped Storage
Solar PV of all sizes
Wind Generators
Battery Storage Units

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