Distributed Energy Resource Valuation and Optimization

Combined Heat and Power Use Cases

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Technical Update, December 2021

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ABSTRACT

Distributed Energy Resources Value Estimation Tool (DER-VET™) provides a free, publicly accessible, open-source platform for calculating, understanding, and optimizing the value of distributed energy resources (DER) based on their technical merits and constraints. An extension of EPRI's StorageVET® tool, DER-VET supports site-specific assessments of energy storage and additional DER technologies—including solar, wind, demand response, electric vehicle charging, internal combustion engines, and combined heat and power (CHP)—in different configurations, such as microgrids. CHP application is a mature end use of decentralized fueled distribution generation (DG) that produces electricity and useful thermal energy concurrently from a single source of energy. For many large commercial and industrial customers, CHP application is central for serving thermal and electric loads. This report focuses on the CHP and thermal load modeling functionalities of DER-VET. Thermal loads, such as those for domestic hot water, steam, and cooling, are now being implemented within DER-VET. This report explains how thermal loads and technologies are modeled in DER-VET and includes three reference use cases to exemplify how users can model CHP in stand-alone and microgrid scenarios. This report describes use cases only for analyzing sites with known electric and thermal loads as well as size of the CHP. Sizing CHP is the next planned development for thermal technologies in DER-VET. An overview of DER-VET and the user guide can be found on www.der-vet.com.

Keywords
Boilers
Chillers
Combined heat and power
DER-VET
Distributed energy resources
Distributed generation
Microgrids

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1 INTRODUCTION

Distributed Energy Resources Value Estimation Tool (DER-VET™) provides a free, publicly accessible, open-source platform for calculating, understanding, and optimizing the value of distributed energy resources (DER) based on their technical merits and constraints. An extension of EPRI's StorageVET® tool, DER-VET supports site-specific assessments of energy storage and additional DER technologies—including solar, wind, demand response, electric vehicle charging, internal combustion engines, and combined heat and power (CHP)—in different configurations, such as microgrids. It uses load and other data to determine optimal size, duration, and other characteristics for maximizing benefits based on site conditions and the value that can be extracted from targeted use cases. Customers, developers, utilities, and regulators across the industry can apply this tool to inform project-level decisions based on sound technical understanding and unbiased cost-performance data. Funded by the California Energy Commission, DER-VET Version 1.0 was released in April 2021. EPRI plans to support continuing updates and enhancements and has since released Version 1.1 in September 2021.

The technologies modeled in DER-VET include various types of energy storage, intermittent renewable generation (solar, wind), fueled generation (internal combustion engines), controllable loads, electric vehicles, and CHP. These energy resources can be used in any combination to improve grid reliability, improve customer resilience by providing backup to local critical loads, decrease the electricity bill incurred by the site, participate in wholesale service markets, and provide demand response or resource adequacy—or some allowable combination of these.

CHP application is a mature end use of decentralized fueled distribution generation (DG) that produces electricity and useful thermal energy concurrently from a single source of energy. Instead of obtaining electricity from centralized generation and producing thermal energy on-site, customers can use CHP cogeneration systems to meet both energy requirements with a single fuel, which increases the overall efficiency of the process. For many large commercial and industrial customers, CHP application is central for serving thermal and electric loads. Many prime mover technologies can be configured for CHP applications, including steam turbines, combustion turbines, reciprocating internal combustion engines, microturbines, and fuel cells.

This report focuses on the CHP and thermal load modeling functionalities of DER-VET. Thermal loads, such as those for domestic hot water, steam, and cooling, are now being implemented within DER-VET. This report first explains how thermal loads and technologies are modeled in DER-VET. This report includes three reference use cases to exemplify how users can model CHP in stand-alone and microgrid scenarios. The reference cases also include thermal and electric load data that are modeled after realistic sites. The cases are part of the initial efforts for modeling thermal loads and thermal technologies in DER-VET. This report describes use cases only for analyzing sites with known electric and thermal loads as well as size of the CHP. Sizing CHP technologies requires more validation because different prime movers have different characteristics and performance for serving thermal loads. Sizing CHP is the next planned development for thermal technologies in DER-VET. Consequently, standard engineering judgments are being left out of the current implementation, relying on user inputs instead. In the future, after more validation and testing, more use cases and reference cases could become available to the users. EPRI intends to include thermal load and technologies in the next DER-VET update.

An overview of DER-VET and the user guide can be found on www.der-vet.com.

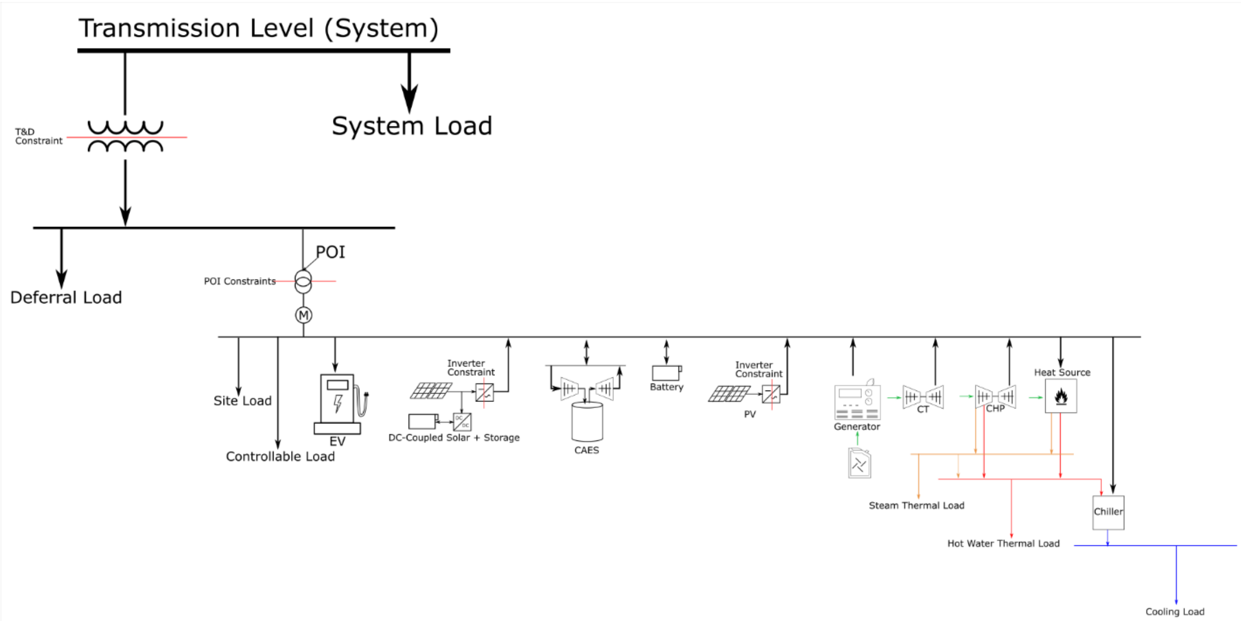

Figure 1-1
Visual depiction of DER technologies that DER-VET can model

2

THERMAL TECHNOLOGIES AND LOADS IN DER-VET

This section briefly describes how thermal technologies and loads are currently modeled in DER-VET. This section describes the flags, parameters, optimization variables objective terms, and constraints for each thermal technology. This information is more pertinent to users who are interested in learning about the formulation of thermal technologies and loads in DER-VET. CHP use cases are illustrated in the section after.

Each object of the DER class must have the following binary flags to indicate the type of power that it either takes in or outputs.

- Is_electric: This flag will be equal to one if the DER either consumes or generates electric power
- Is_hot: This flag will be equal to one if the DER either consumes or generates heat
- Is_cold: This flag will be equal to one if the DER either consumes or generates cooling power
- Is_fuel: This flag will be equal to one if the DER consumes fuel

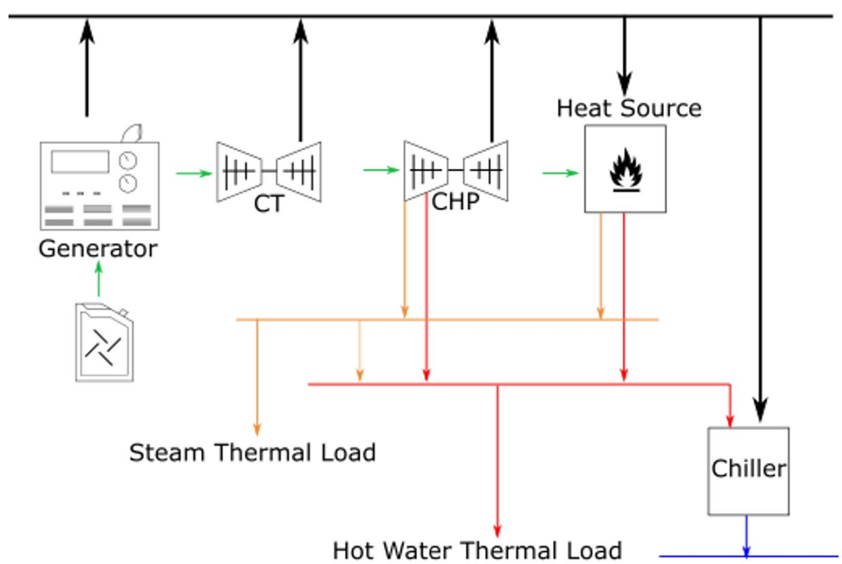

Figure 2-1
Thermal technologies and loads in DER-VET

Thermal Site Loads

Heat is broken down into 2 components: hot water and steam. Breaking down heat into hot water and steam allows DER-VET to capture the quality of heat, which is useful for modeling thermal requirements and technology characteristics. As Figure 2-1 shows, steam is a higher quality of heat than hot water, and the respective loads are served specifically by the types of heat generated. Generated steam can serve hot water loads but generated hot water cannot serve steam loads.

DER-VET will accept the following 3 thermal site loads, and each is converted to kW.

- Site Hot Water Thermal Load (MMBtu/hr)
- Site Steam Thermal Load (MMBtu/hr)
- Site Cooling Thermal Load (tons)

Combined Heat and Power System

A CHP plant is able to recover thermal power whenever electric power is being generated. Generally, CHP can be more efficient at supplying a combined thermal and electric load than obtaining two loads separately. This model will represent the amount of thermal power that can be recovered as proportional to the electric power being generated. CHP plants are modeled as a fixed-size generator. CHP plans are assumed to have constant electric power to heat ratio, and it applies even if generating at part load. The sizing process consists in determining the number of units to be used, although this functionality is not yet validated.

Flags

- Is_electric = 1
- Is_hot = 1
- Is_fuel = 1

Table 2-1
Parameters and optimization variables for modeling a combined heat and power system in DER-VET

Parameters			
Parameter	**Notation**	**Units**	**Description**
Electric Heat Ratio	EHR	kW-electric/ kW-heat ratio	The ratio of electricity produced to heat generated
Heat Rate	HR	MMBtu/MWh (converted to MMBtu/kWh)	HHV heat rate of electric energy generated
Minimum Loading	P_{min}	kW	Minimum electric power that can be generated by the unit
Variable O&M	$VAR\_O\&M$	$/kWh	Variable operational cost, without fuel
Fixed O&M	$Fixed\_O\&M$	$/year	Fixed operational cost
Rated capacity	P_{max}	kW/generator	Maximum electric power that the unit can generate
Unit cost	$Cost$	$	Cost of a unit of the technology
Fuel Type	FT	--	One of: liquid | gas | other, and used to set a fuel cost from the corresponding price in the Finance tag
Maximum Steam Ratio	MSR	Steam/Hot-Water ratio	The maximum ratio of instantaneous steam to hot water thermal power (a value of 0 means only hot water generation). Used to control the maximum amount of steam the CHP can produce.
Optimization Variables			
Variable	**Notation**	**Type**	**Description**
Electric power	P_t^i	Nonnegative	Electric power (kW) output at every time t
Hot Water Generated	$P_{HotWater,t}$	Nonnegative	Hot Water (kW) output at every time t
Steam generated	$P_{Steam,t}$	Nonnegative	Steam (kW) output at every time t
Number of units	N_units	Integer	Number of CHP units of the same type
Unit is on	on_t^i	Binary	Unit i is on at time t

Table 2-2
Objective terms and constraints for modeling a combined heat and power system in DER-VET

Objective Terms	
Description	**Expression**
Capital cost	$N\_units * Cost$
O&M cost	$Fixed\_O\&M + VAR\_O\&M * \sum_t \sum_i P_t^i * \Delta$
Fuel cost	$HR \sum_t CF_t * \sum_i P_t^i * \Delta$
Constraints	
Description	**Expression**
Max power limit	$P_t^i \leq on_t^i * P_{max}$, for all i, t
Min power limit	$P_t^i \geq on_t^i * P_{min}$, for all i, t
Total number of units	$\sum_i on_t^i \leq N\_units$, for all t
Max number of units	$N_{units} \leq N\_max$
Heat recovery	$\sum_i P_t^i = EHR * (P_{HotWater,t} + P_{Steam,t})$, for all t
No excess steam	$P_{Steam,t} \leq MSR * P_{HotWater,t}$, for all t

Chiller

A chiller can serve only a cooling load. It can be powered in three ways:

- From electricity (an electric chiller)
- From gas (a natural gas chiller)
- From heat (heat provided by CHP or a boiler)

Flags

- Is_cold = 1
- Is_hot = 1 only for absorption chiller
- Is_electric = 1 only for electric chiller
- Is_fuel = 1 only for natural gas chiller

Table 2-3
Parameters and optimization variables for modeling a chiller in DER-VET

Parameters			
Parameter	**Notation**	**Units**	**Description**
Coefficient of performance	COP	Btu/hr cooling / Btu/hr [electric|gas|heat] ratio	Ratio of cooling provided to the power input
Fixed O&M	$Fixed\_O\&M$	$/year	Fixed operational cost
Unit cost	$Cost$	$	Cost of a unit of the technology
Power Source	$Power\_Source$	--	One of: electricity | gas | heat
Rated Power	P_{max}	tons/chiller (but converted to kW/chiller)	Maximum power that the unit can generate (cooling capacity)
Optimization Variables			
Variable	**Notation**	**Type**	**Description**
Cooling generated	$P_{Cooling,t}$	Nonnegative	Cooling (kW) output at every time t

Table 2-4
Objective terms and constraints for modeling a chiller in DER-VET

Objective Terms	
Description	**Expression**
Capital cost	$N\_units * Cost$
O&M cost	$Fixed\_O\&M * \Delta$
Fuel cost (*only for natural gas chiller*)	$\frac{1}{COP}\sum_t CF_t * \sum_i P^i_{Cooling,t} * \Delta$
Constraints	
Description	**Expression**
Maximum cooling power limit	$P^i_{Cooling,t} \leq P_{max}$, for all i, t
Cooling power balance	$P^i_{Cooling,t} \geq Site\_Cooling\_Load$

Notes

- An electric chiller consumes electricity, which manifests as an increase in the electrical bill. A constraint is modified so that the aggregate electric power flow (in) accumulates electric power from a chiller by its generation divided by its COP ($\frac{P^i_{Cooling,t}}{COP}$). The electric site load also increases by this amount.
- An absorption chiller consumes heat in the form of hot water (from a Boiler or CHP). A constraint is modified so that the hot water load will increase by its generation divided by its COP ($\frac{P^i_{Cooling,t}}{COP}$). It is understood that a chiller does not only consume heat in the form of hot water, and can also consume steam, with an increased COP. This is currently not modeled in DER-VET yet.

Boiler

A boiler can serve only a heating load (hot water and/or steam). It can be powered in two ways:

- From electricity (an electric boiler)
- From gas (a natural gas boiler)

Flags

- Is_hot = 1
- Is_electric = 1 only for electric boiler
- Is_fuel = 1 only for natural gas boiler

Table 2-5
Parameters and optimization variables for modeling a boiler in DER-VET

Parameters			
Parameter	**Notation**	**Units**	**Description**
Coefficient of performance	COP	Btu/hr heating / Btu/hr [electric|gas|heat] ratio	Ratio of heating provided to the power input
Fixed O&M	$Fixed\_O\&M$	$/year	Fixed operational cost
Unit cost	$Cost$	$	Cost of a unit of the technology
Power Source	$Power\_Source$	--	One of: electricity | gas
Rated Power	P_{max}	MMBtu/Boiler (but converted to kW/boiler)	Maximum power that the unit can generate (heating capacity)
Optimization Variables			
Variable	**Notation**	**Type**	**Description**
Hot Water generated	$P_{HotWater,t}$	Nonnegative	Hot Water (kW) output at every time t
Steam generated	$P_{Steam,t}$	Nonnegative	Steam (kW) output at every time t

Table 2-6
Objective terms, and constraints for modeling a boiler in DER-VET

Objective Terms	
Description	**Expression**
Capital cost	$N\_units * Cost$
O&M cost	$Fixed\_O\&M * \Delta$
Fuel cost (*only for natural gas boiler*)	$\frac{1}{COP}\sum_t CF_t * \sum_i (P^i_{HotWater,t} + P^i_{Steam,t}) * \Delta$
Constraints	
Description	**Expression**
Maximum heating power limit	$(P^i_{HotWater,t} + P^i_{Steam,t}) \leq P_{max}$, for all i, t
Hot Water power balance	$P^i_{HotWater,t} \geq Site\_Hot\_Water\_Load$
Steam power balance	$P^i_{Steam,t} \geq Site\_Steam\_Load$

Notes

- An electric boiler consumes electricity, which manifests as an increase in the electrical bill. A constraint is modified so that the aggregate electric power flow (in) accumulates electric power from a boiler by its generation divided by its COP ($\frac{(P^i_{HotWater,t}+ P^i_{Steam,t})}{COP}$). The electric site load also increases by this amount.

3

DER-VET CASE STUDIES FOR VALIDATION

The section examines 3 case studies for utilizing CHP for site-specific analysis – wastewater treatment plant, industrial site, and a hospital. In two of the three cases, the CHP is sized based on the thermal load requirement and it eliminates the need of a boiler.

For all three reference cases, the primary grid service is bill savings from onsite generation and increased efficiency of cogeneration. These cases assume no export, and no interconnection constraints.

Reference Case 1: Wastewater Treatment Plant

The first case is a wastewater treatment plant with hot water, steam thermal loads, and a site electric load. Figure 3-1 and Figure 3-2 illustrate scenarios with and without CHP.

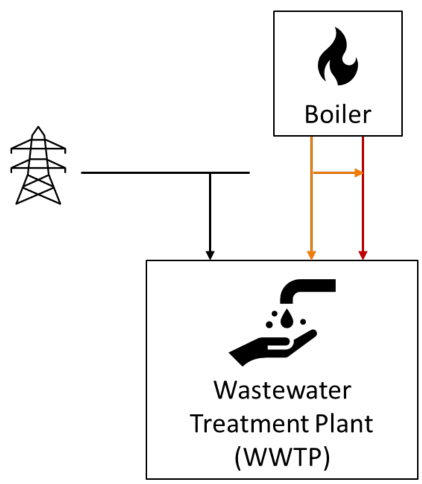

Figure 3-1
Base case configuration for a wastewater treatment plant

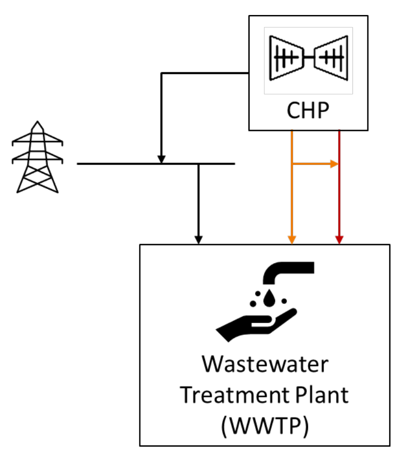

Figure 3-2
Change case configuration with CHP system for a wastewater treatment plant

Electric and Thermal Loads

Figure 3-3 illustrates hourly profile of the electric and thermal loads of the wastewater treatment plant site, which contains converted units to kW. It should be noted that DER-VET accepts thermal loads for hot water and steam in MMBtu/hour and cooling load in tons of cooling. The site has some seasonal variations for hot water between winter and summer months, but other loads are relatively consistent throughout the year. The wastewater treatment plant is assumed to not have any cooling load.

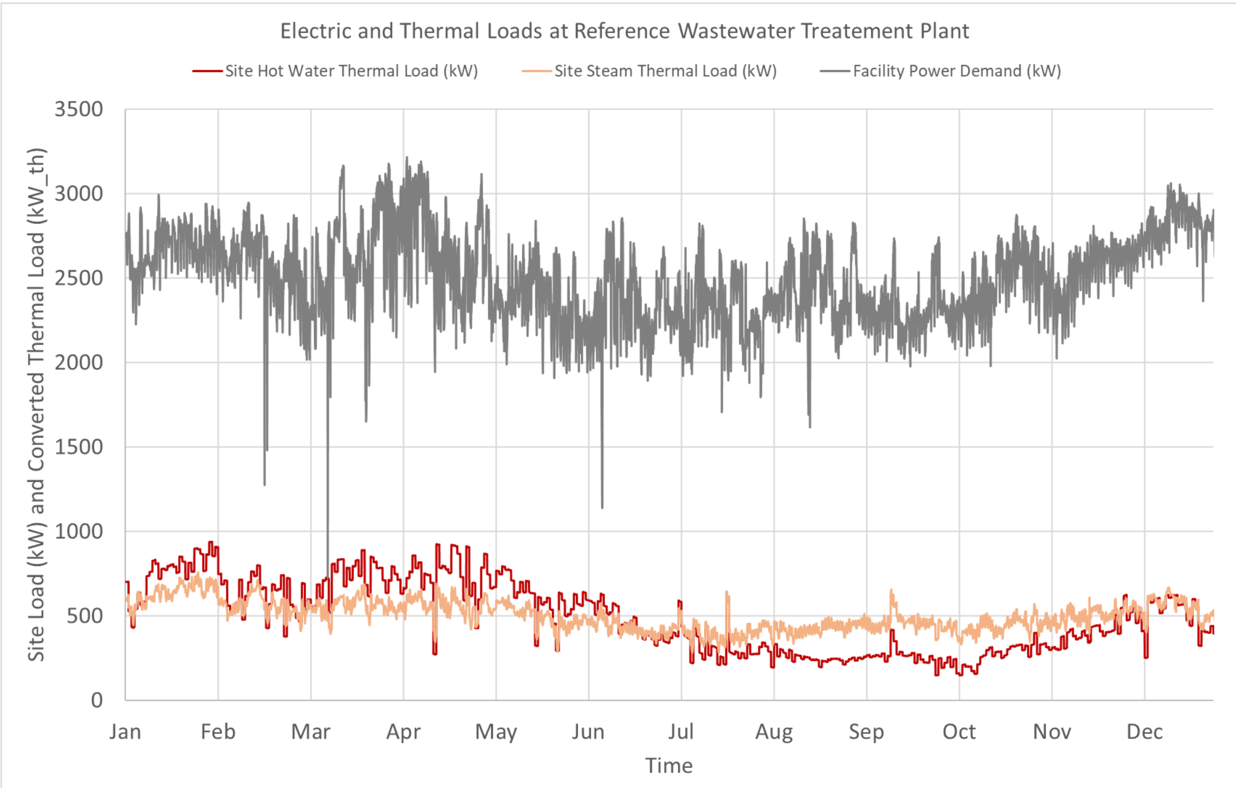

Figure 3-3
Electric and thermal loads at a hypothetical wastewater treatment plant

Specifications of Thermal Technologies

In the base case, the electric load is served by the grid, and the hot water and steam loads are served by a larger boiler. In the change case, a CHP system is installed and sized based on the maximum thermal load, eliminating the need of the boiler. Most of the electric load is served by the CHP, and additional electricity can be purchased from the grid if needed, depending on the hour.

Table 3-1
Summary of Inputs for Reference Case 1

	Base Case	Change Case with CHP
Grid-connected	Yes	Yes
Boiler	Yes 6 MMBtu/hr $\eta = 80\%$	No
CHP	No	Yes 1.75 MW $\frac{P}{H} = 1$ $MSR = 1$
Chiller	Not applicable	Not applicable

Results

Figure 3-4 shows the site load for three winter days in January. The CHP mostly serves as a base load and does not export. Figure 3-5 illustrates the thermal loads, converted to $kW_{thermal}$, for the wastewater treatment plant.

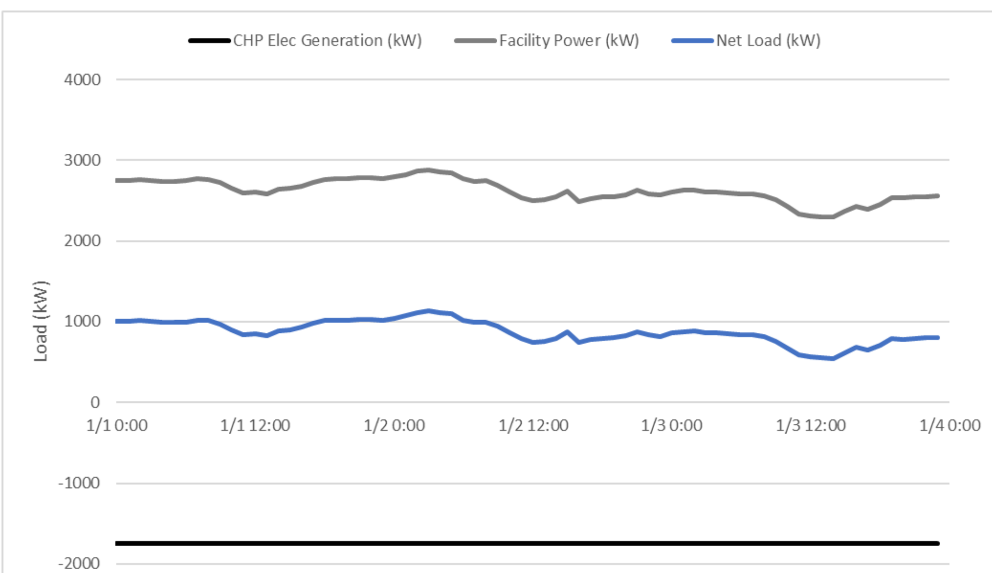

Figure 3-4
Original site load and net load after installing a CHP system, for the wastewater treatment facility

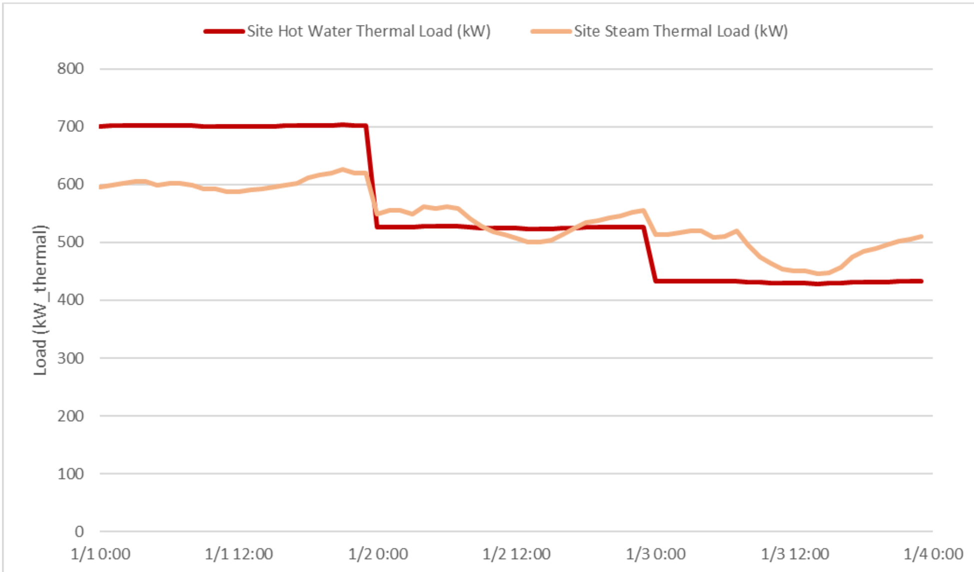

Figure 3-5
Thermal loads for the wastewater treatment plant

Using a reference tariff with energy and demand charges in California, savings from reduced energy and demand charges from the CHP generation can be observed, as much as 70% savings from energy charge and 61% savings from demand charges. If the CHP is sized correctly and if the site didn't have a boiler already, CHP also eliminates the need for a boiler entirely, yielding additional savings from the capital costs of boiler. The CHP system does have almost double the fuel costs as the boiler, but still less than the savings from energy and demand charge costs.

Reference Case 2: Industrial Site

The second case is an industrial site with only steam and cooling thermal loads, with an electric site load. Figure 3-6 and Figure 3-7 show configurations for an industrial site with and without CHP.

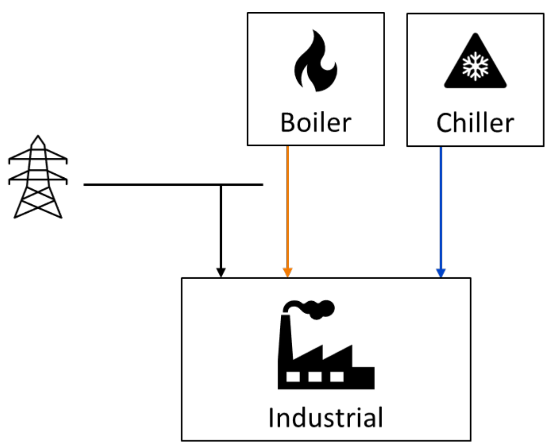

Figure 3-6
Base case configuration for an industrial site

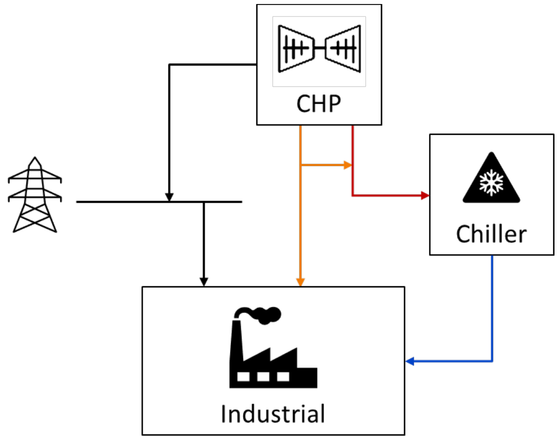

Figure 3-7
Change case configuration with CHP system for an industrial site

Electric and Thermal Loads

Figure 3-8 and Figure 3-9 show hourly profile of the electric and thermal loads of a large industrial site used in this reference case. As an industrial site, the load profile has little seasonal variations for electric and steam loads, and no hot water load. Cooling load varies with climate, so it is the highest during the summer months.

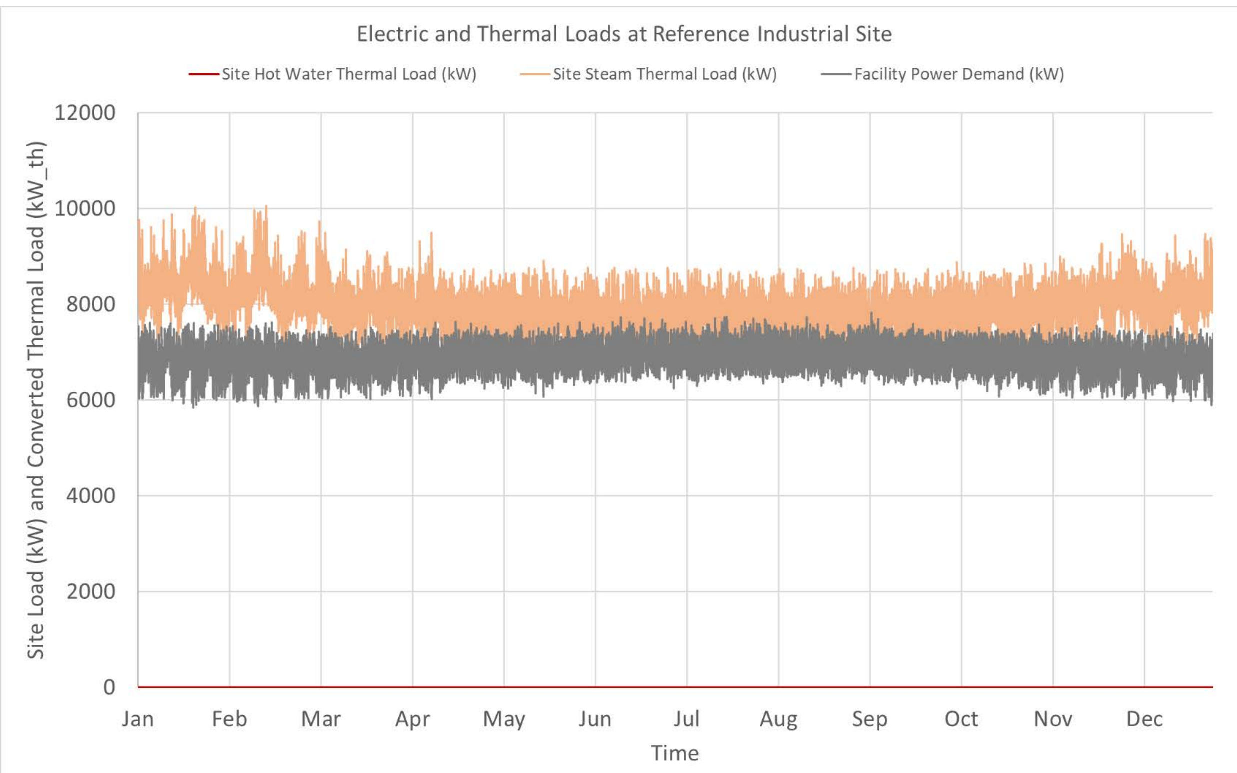

Figure 3-8
Electric, hot water and steam loads at a hypothetical industrial site

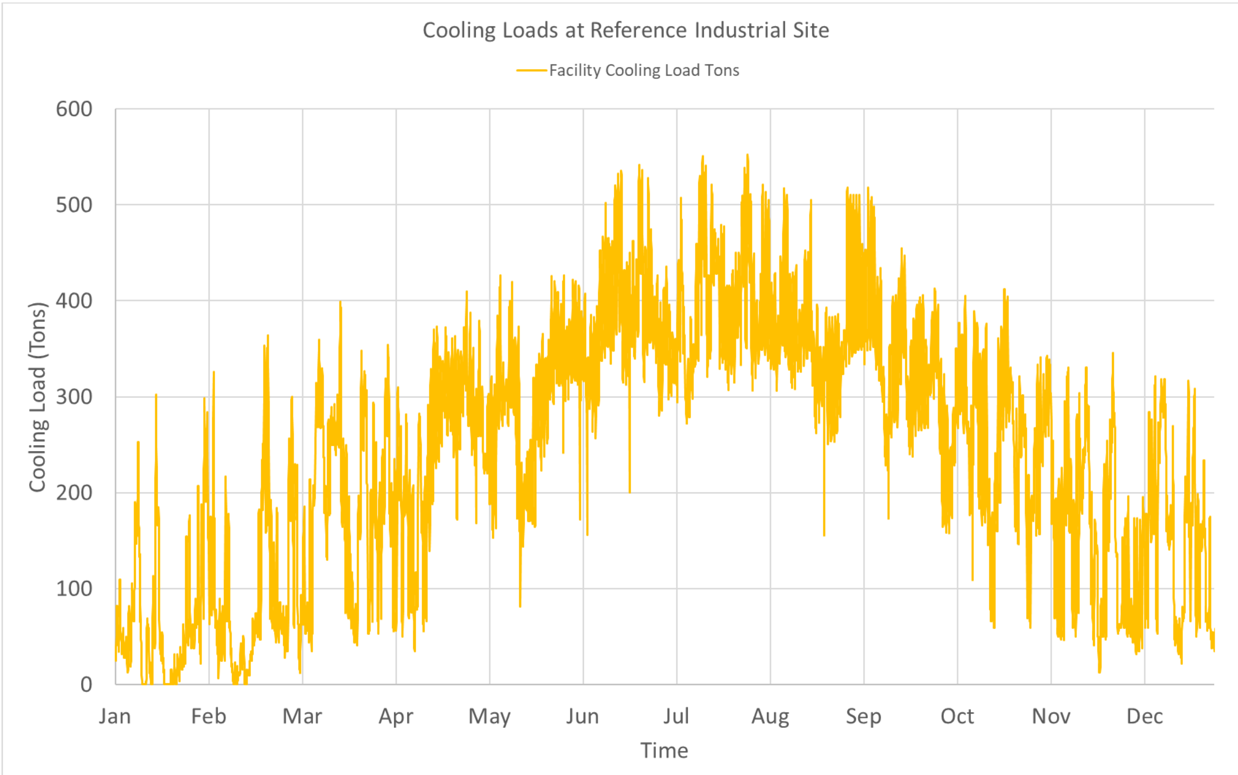

Figure 3-9
Cooling loads at a hypothetical industrial site

Specifications of Thermal Technologies

In the base case, the electric load is served by the grid, the steam load is served by a larger boiler, and the cooling load is served by a chiller. In the change case, a CHP system is installed and sized based on the maximum thermal load, eliminating the need of the boiler. An absorption chiller utilizes heat from the CHP system and serves the cooling load. Most of the electric load is served by the CHP, and additional electricity can be purchased from the grid if needed, depending on the demand of hour.

Table 3-2
Summary of Inputs for Reference Case 2

	Base Case	Change Case with CHP
Grid-connected	Yes	Yes
Boiler	Yes 35 MMBtu/hr η = 80%	No
CHP	No	Yes, gas turbine 6 MW $\frac{P}{H} = 0.5$ $MSR = 10^4$
Chiller	Yes, electric chiller 560 ton COP = 5	Yes, absorption chiller powered by CHP COP = 1.42

Results

Figure 3-10 shows the site load for a summer day in July. The CHP mostly serves as a base load, as it is not exporting. Figure 3-11 illustrates the thermal loads, converted to $kW_{thermal}$, for the industrial site, which have all hot water, steam, and cooling load. The hot water is generated from the CHP in order to serve the absorption chiller for the cooling load. The cooling load is proportionally smaller compared to the steam load required, which is typical for an industrial customer, such as a manufacturing site.

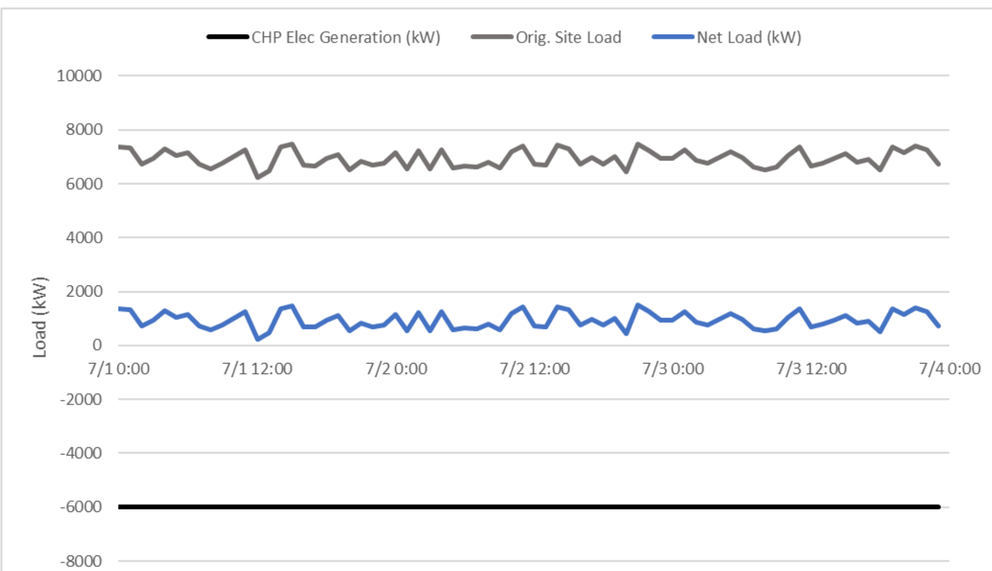

Figure 3-10
Original site load and net load after installing a CHP system, for the industrial facility

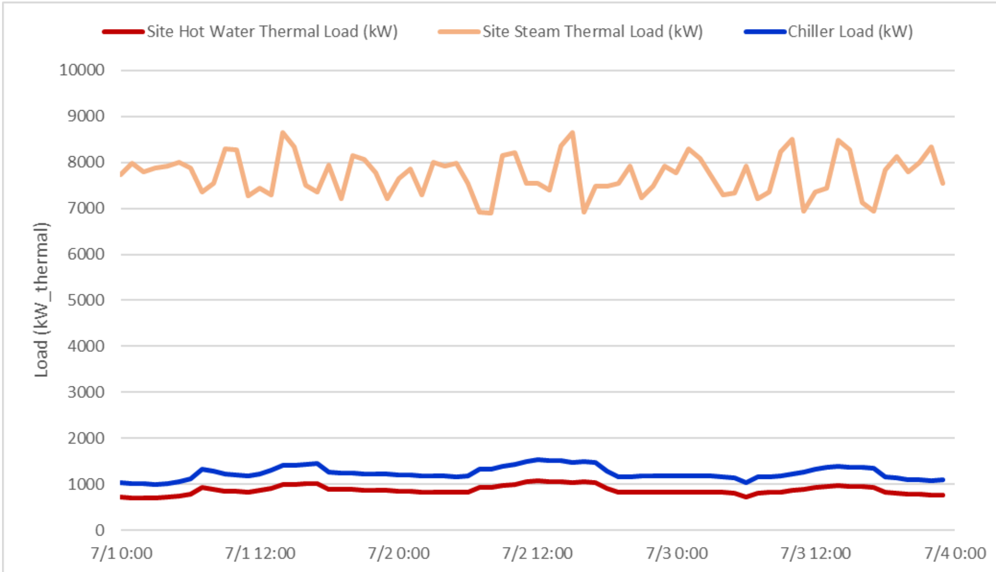

Figure 3-11
Thermal loads, including steam, hot water and cooling, for the industrial site with a CHP system.

An electric chiller is used in the base case, which accounts for 3% of the total energy and demand charges of the total site load. Using a reference tariff with energy and demand charges in California, savings from reduced energy and demand charges from the CHP generation can be observed. Configuration with CHP can save as much as 88% from energy charge and 79% from demand charges. The savings from eliminating the boiler and the associated capital cost are also assumed here, which means the CHP is sized correctly and the site didn't have a boiler already. The CHP system sees an increase of 77% in fuel costs, associated with operating the larger CHP as opposed to the boiler alone. However, the combined costs of fuel, energy, and demand charges see a decrease of 64% on an annual basis, compared to those for operating an electric chiller and boiler separately.

Reference Case 3: Hospital Building

The third case is a hospital with hot water, steam, cooling, and site loads. Figure 3-12 and Figure 3-13 depict the hospital load with and without a CHP configuration.

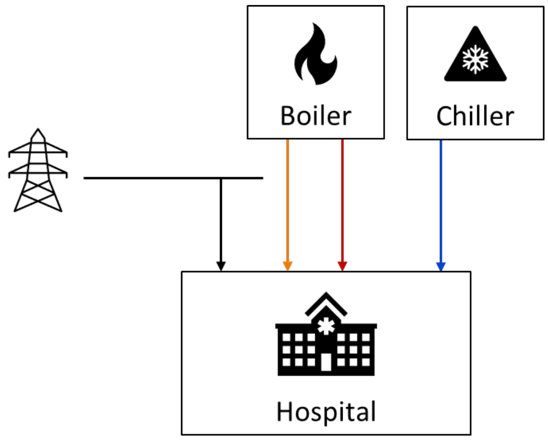

Figure 3-12
Base case configuration for a hospital with all types of thermal loads and an electric load

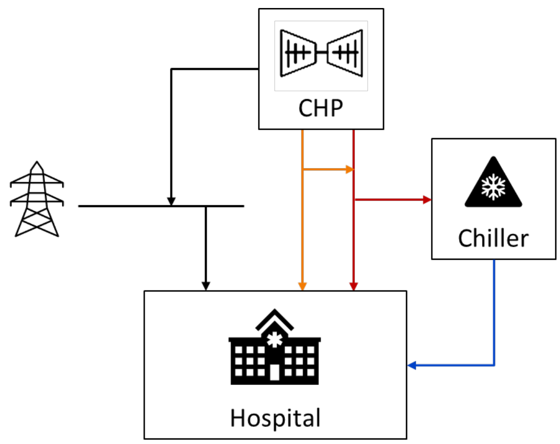

Figure 3-13
Change case configuration with CHP system for a hospital site

Electric and Thermal Loads

Figure 3-14 and Figure 3-15 show hourly profile of the electric and thermal loads of a large hospital with 500 beds in this reference case. As a large hospital, there is consistent need for steam, where the hot water load is driven by season need. The cooling load is evidently tied to seasonal variations, being the highest during the summer when temperature is likely higher.

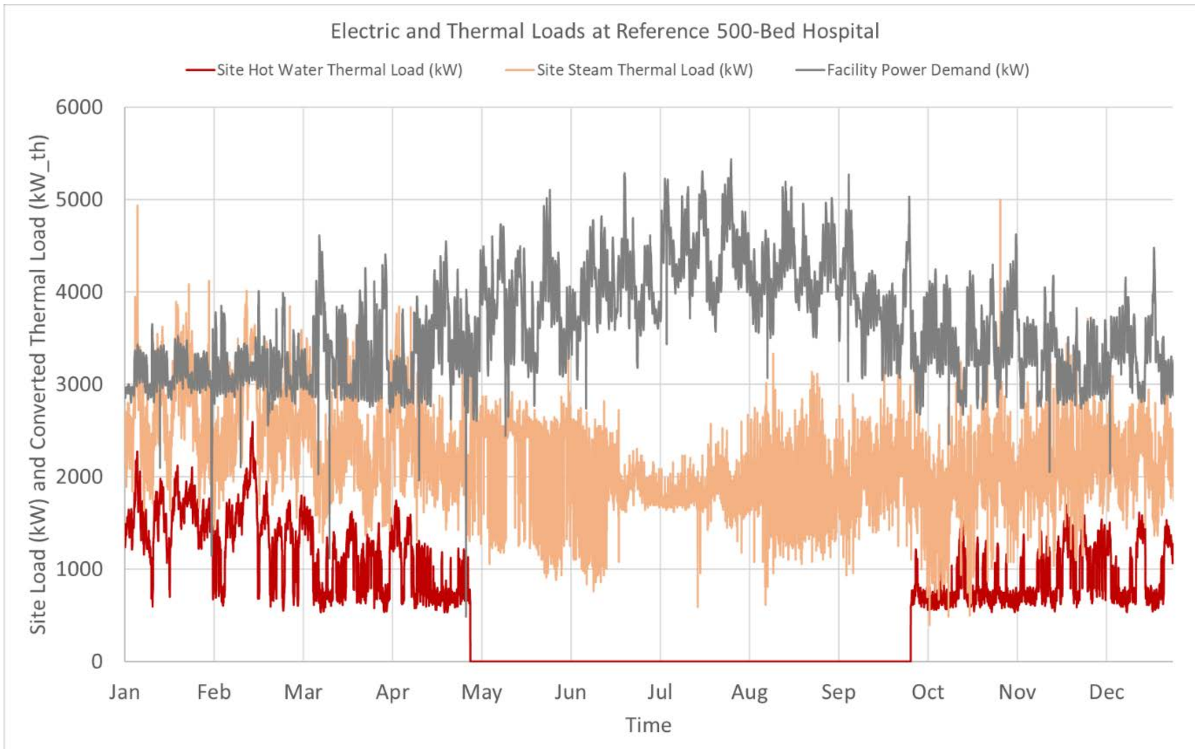

Figure 3-14
Electric, hot water and steam loads at a hypothetical 500-bed hospital

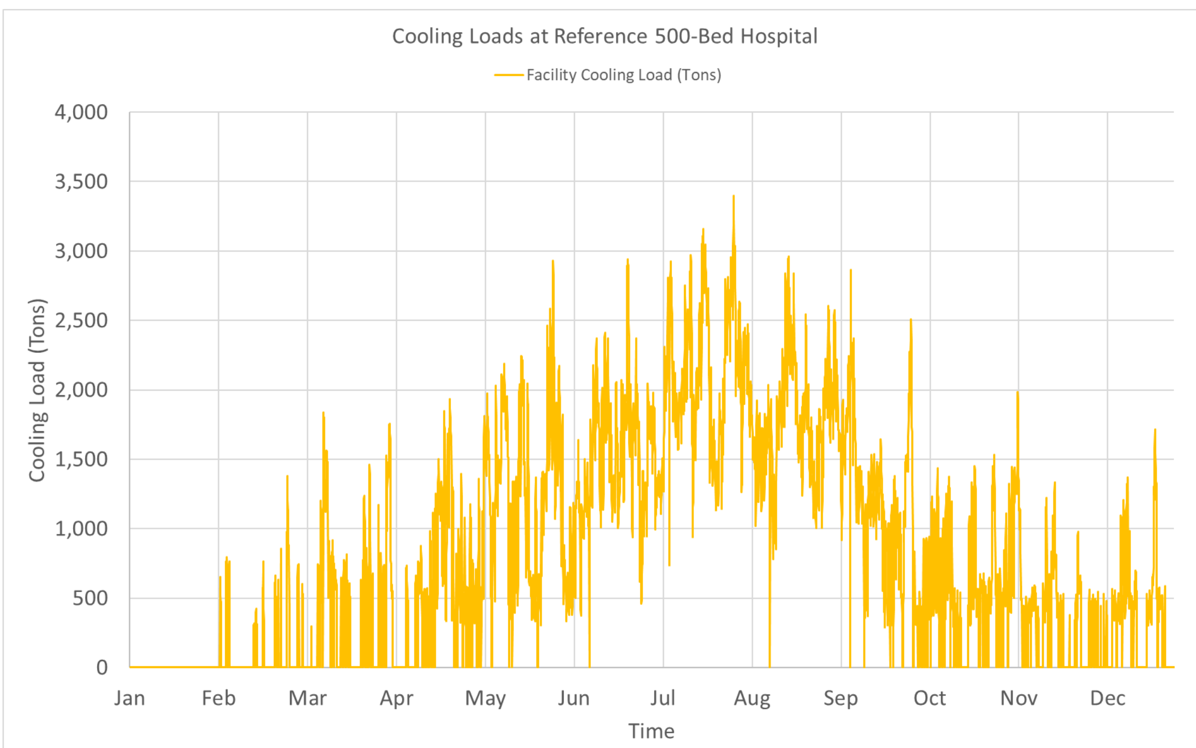

Figure 3-15
Cooling loads at a hypothetical 500-bed hospital

Specifications of Thermal Technologies

In the base case, the electric load is served by the grid, the steam and domestic hot water loads are served by a larger boiler, and the cooling load is served by a chiller. In the change case, a CHP system is installed and sized based on the maximum load of the combined steam and hot water, and the site base load. Unlike the other two reference cases, the boiler cannot be eliminated, and a smaller boiler is still needed to meet all the thermal loads. An absorption chiller utilizes heat from the CHP system and serves the cooling load. About half of the peak demand of the electric load is served by the CHP, and additional electricity needs to be purchased from the grid, depending on the demand of hour.

Table 3-3
Summary of Inputs for Reference Case 3

	Base Case	Change Case with CHP
Grid-connected	Yes	Yes
Boiler	Yes 25 MMBtu/hr $\eta = 80\%$	Yes 9 MMBtu/hr $\eta = 80\%$
CHP	No	Yes, gas turbine 3.3 MW $\frac{P}{H} = 0.45$ $MSR = 10^2$
Chiller	Yes, electric chiller 3400 ton COP = 5	Yes, absorption chiller powered by CHP COP = 1.42

Results

Figure 3-16 shows the original site load, and net load after CHP's electricity generation.

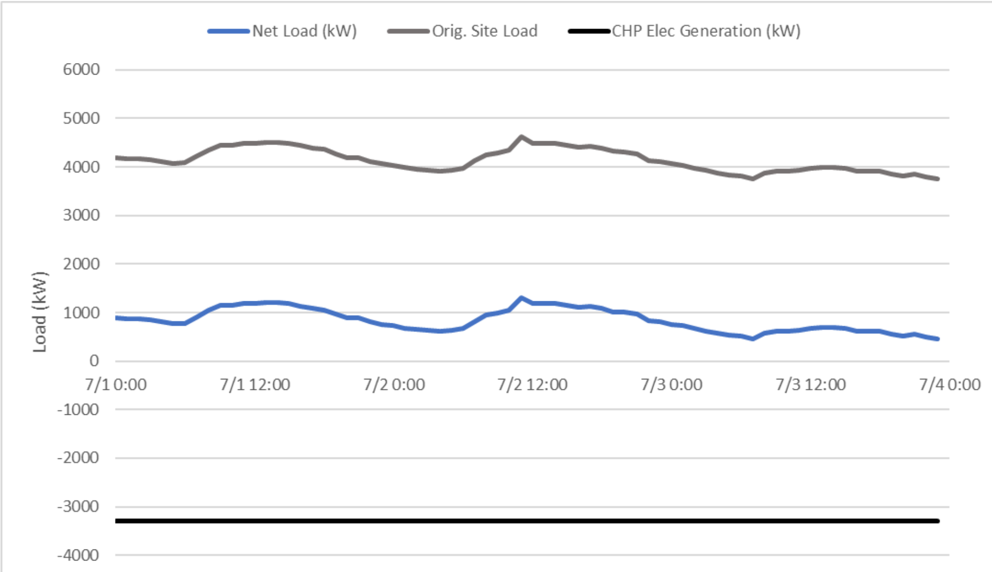

Figure 3-16
Original and net site load with CHP system

Figure 3-17 shows the original thermal and cooling loads on three summer days in July. In the original case, the hospital site requires no hot water. Figure 3-18 shows the thermal and cooling loads for the same days for the change case, with the CHP deployed. In this scenario, the hot water generation is increased in order to power the absorption chiller required to serve the cooling load.

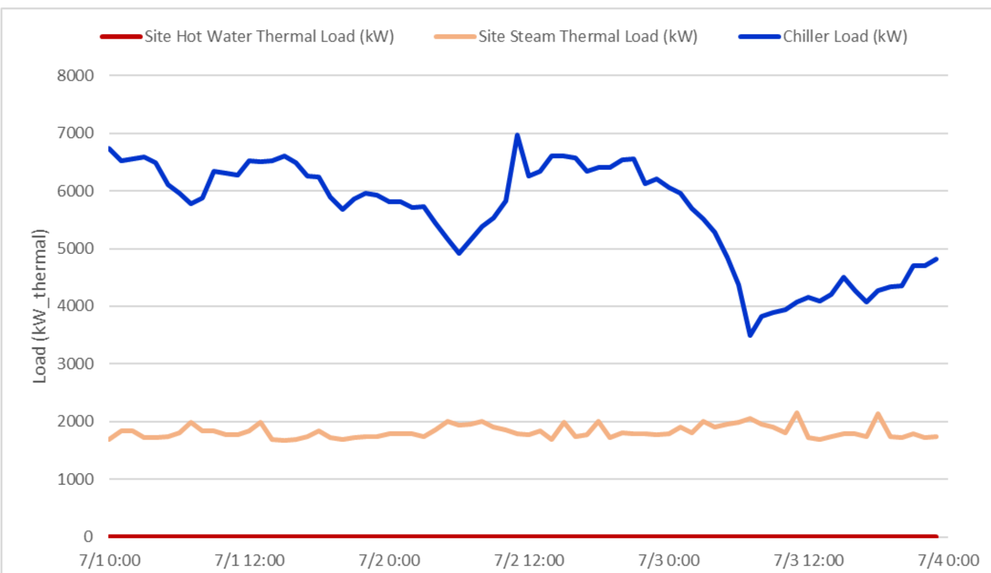

Figure 3-17
Thermal loads, including hot water, steam and chiller for base case.

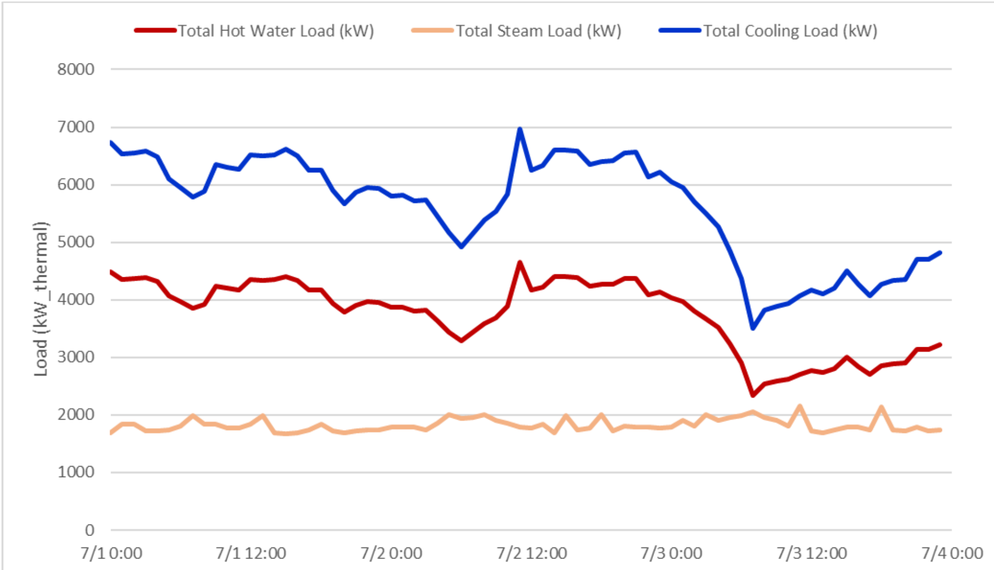

Figure 3-18
Thermal loads, including hot water, steam and chiller for the change case with CHP and absorption chiller.

An electric chiller is used in the base cases, which accounts for 17% of the total energy and 33% of the total demand charges of the site load. Using a reference tariff with energy and demand charges in California, savings from reduced energy and demand charges from the CHP generation can be determined. Configuration with CHP can save as much as 90% from energy charge and 77% from demand charges. Although the boiler was not entirely eliminated, it is not used frequently. Of 8760 hours in a year, it is only used 401 hours, or a capacity factor of 5%, in order to meet the peak thermal loads (heat and cooling combined). However, there are still savings from downsizing the boiler and the associated capital cost reduction. The CHP system and boiler combined see a 4-times increase in fuel costs, associated with operating the CHP as a base load and boiler at 5% capacity.The combined costs of fuel, energy, and demand charges see a decrease of 46% on an annual basis, compared to those for operating an electric chiller and boiler separately.

4
FUTURE DEVELOPMENT FOR CHP IN DER-VET

In conclusion, CHP has been a mature and efficient DG technology for decades, allowing customers to cogenerate electric and thermal energy on site. This report provides three reference cases for evaluating CHP systems at specific sites, with known electric load, thermal loads, and thermal technology system sizes. The reference cases utilized realistic commercial and industrial loads, with hourly electric site, hot water, steam and/or cooling load profiles. The current CHP implementation in DER-VET establishes the foundation of evaluating thermal loads and thermal technologies in the model. However, future development is required for sizing and potentially helping users selecting technologies, such as specific prime movers of CHP. Various CHP prime mover technologies have different performance and heat generation characteristics that need to be accounted for in DER-VET, including engineering judgements that typically facilitate technology selection and sizing. Additionally, other emerging and less commercialized DG technologies would require validation, such as fuel cells, hydrogen-blended natural gas engines, and more. Low carbon fuel distributed generation technologies are also gaining interests in recent years, and how these developments would impact CHP landscape, and subsequently how they are modeled in DER-VET, should be monitored.

Users are welcomed to provide feedback or participate in improving DER-VET's open-source model on EPRI's Github and the DER-VET website.

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