1 Combined Heat and Power (CHP) Background

***Clean Energy Project Analysis: RETScreen® Engineering & Cases** is an e-textbook for professionals and university students. This chapter covers the analysis of potential combined heat and power (cogeneration or Power | Heating | Cooling) projects using the RETScreen Clean Energy Management Software, including a technology background and a detailed description of the algorithms found in the RETScreen Software. A collection of project templates and case studies, with assignments, worked-out solutions and information about how the projects fared in the real world, is available.* The worked-out solution is the data file selected from within the RETScreen Project Database. *The user automatically downloads the Project Database file while downloading the RETScreen software.*

The principle behind combined heat and power (or "cogeneration" or simply CHP) is to recover the waste heat generated by the combustion of a fuel (see note 1) in an electricity generation system. This heat is often rejected to the environment, thereby wasting a significant portion of the energy available in the fuel that can otherwise be used for space heating and cooling, water heating, and industrial process heat and cooling loads in the vicinity of the plant. This cogeneration of electricity and heat greatly increases the overall efficiency of the system, anywhere from 25-55% to 60-90%, depending on the equipment used and the application.

Combined heat and power systems can be implemented at nearly any scale, as long as a suitable thermal load is present. For example, large scale CHP for community energy systems and large industrial complexes can use gas turbines (***Figure 1***), steam turbines, and reciprocating engines with electrical generating capacities of up to 500 MW. Independent energy supplies, such as for hospitals, universities, or small communities, may have capacities in the range of 10 MW. Small-scale CHP systems typically use reciprocating engines to provide heat for single buildings with smaller loads. CHP energy systems with electrical capacities of less than 1 kW are also commercially available for remote off-grid operation, such as on sailboats. When there is a substantial cooling load in the vicinity of the power plant, it can also make sense to integrate a cooling system into the CHP project (see note 2). Cooling loads may include industrial process cooling, such as in food processing, or space cooling and dehumidification for buildings.

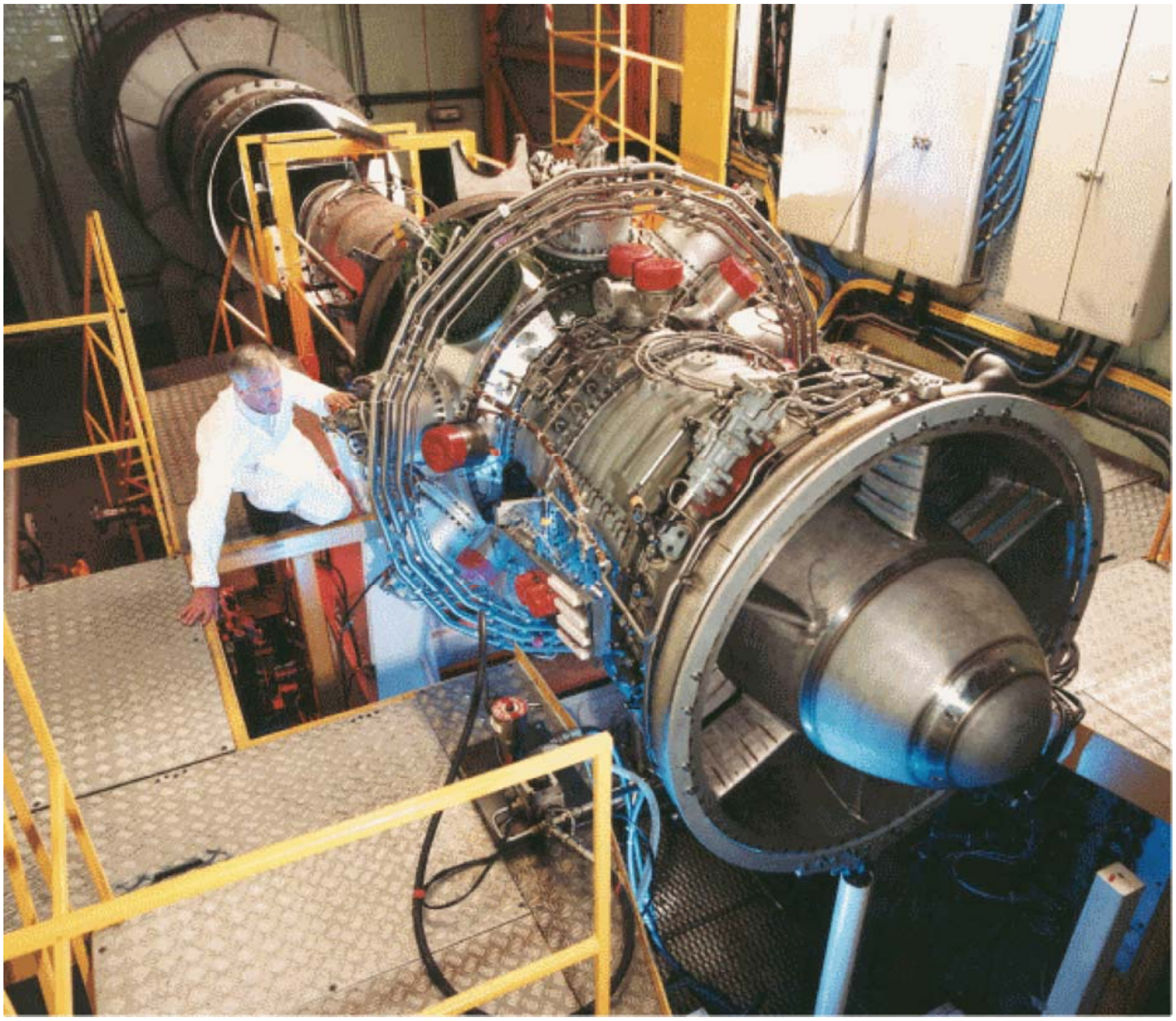


Figure 1: Gas Turbine

Photo Credit: Rolls-Royce plc

The electricity generated can be used for loads close to the CHP system, or located elsewhere by feeding the electric grid. Since heat is not as easily transported as electricity over long distances, the heat generated is normally used for loads within the same building, or located nearby by supplying a local district heating network. This often means that electricity is produced closer to the load than centralized power production. This decentralized or "distributed" energy approach allows for the installation of geographically dispersed generating plants, reducing losses in the transmission of electricity, and providing space & process heating and/or cooling for single or multiple buildings (***Figure 2***).

Figure 2: Combined Heat & Power, Kitchener's City Hall, Ontario, Canada

Photo Credit: Urban Ziegler, NRCan

A CHP installation comprises four subsystems: the power plant, the heat recovery and distribution system, an optional system for satisfying heating (see note 3) and/or cooling (see note 4) loads and a control system. A wide range of equipment can be used in the power plant, with the sole restriction being that the power equipment (see note 5) rejects heat at a temperature high enough to be useful for the thermal loads at hand. In a CHP system, heat may be recovered and distributed as steam (often required in thermal loads that need high temperature heat, such as industrial processes) or as hot water (conveyed from the plant to low temperature thermal loads in pipes for domestic hot water, or for space heating).

Worldwide, CHP systems with a combined electrical capacity of around 240 GW are presently in operation. This very significant contribution to the world energy supply is even more impressive when one considers that CHP plants generate significantly more heat than power. Considering that most of the world's electricity is generated by rotating machinery that is driven by the combustion of fuels, CHP systems have enormous potential for growth. This future growth may move away from large industrial systems towards a multitude of small CHP projects, especially if a decentralized energy approach is more widely adopted and the availability of commercial products targeted at this market.

1. Such as fossil fuels (e.g. natural gas, diesel, coal, etc.), renewable fuels (wood residue, biogas, agricultural byproducts, bagasse, landfill gas (LFG), etc.), hydrogen, etc.

2. In such case, the CHP project becomes a "combined cooling, heating and power project."
3. Heating equipment such as waste heat recovery, boiler, furnace, thermal fluid heater, heat pump, etc.
4. Cooling equipment such as compressor, absorption chiller, heat pump, etc.
5. Power equipment such as gas turbine, steam turbine, gas turbine-combined cycle, reciprocating engine, fuel cell, etc.

2 RETScreen CHP (Cogeneration or Power | Heating | Cooling) Project Model

The primary goal of the RETScreen Combined Heat and Power (CHP) model is to calculate the amount of energy delivered, in various forms, by an energy system. More specifically, a CHP system can satisfy heating, cooling and power loads by using a combination of base, intermediate and peak power, cooling and heating systems (See ***Figure 3***) using various fuels and operating modes. The challenges of the model are therefore to:

1. assess the system's energy needs in terms of heating, cooling and power generation;
2. estimate how those needs can be met by the various energy systems that are ultimately chosen.

Consequently, the model is devoted to calculating the system's load and energy use (see note 6) and to evaluating how they can be met. The algorithm used by the model is schematically shown in ***Figure 3***.

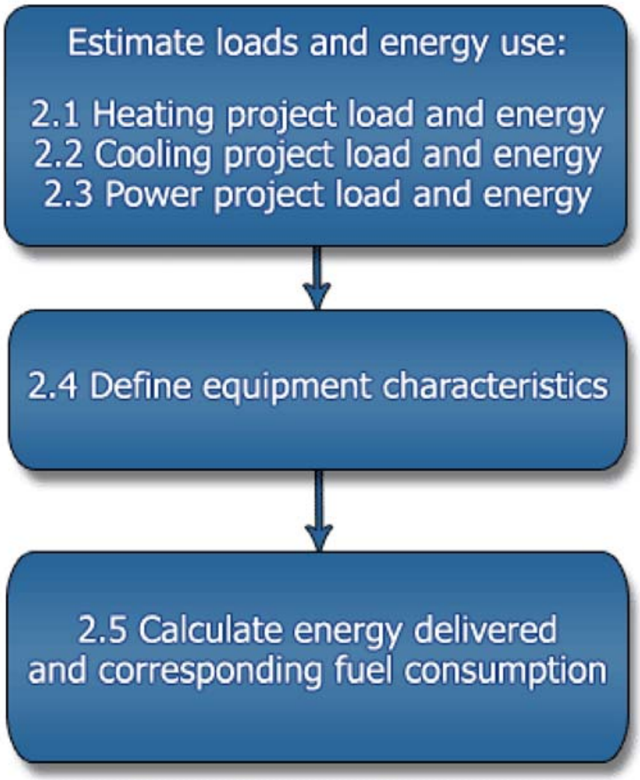


Figure 3: Algorithm of CHP Model

The various sections of this chapter each deal with a particular aspect of the calculation. Section 2.1 explains how *heating* load and energy use are calculated; section 2.2 considers the same calculation for *cooling* load and energy use, and section 2.3 addresses the calculation of *power generation* load and energy use. Section 2.4 gives a detailed description of the combined heat and power equipment that can be used. Finally, section 2.5 provides an overview of the possible operating strategies and calculates the energy delivered by the base, intermediate and peak systems.

Section 2.6 deals with calculations not covered in the previous sections, such as correlation formulae to estimate building loads or the heating value of fuels. Validation studies, summarized in sections 2.7 and 2.8, describe how the model was validated against other models and experimental data.

6. *Load* refers to instantaneous values (power, expressed in W for example), whereas *energy use or needs* refers to integrated values (energy, expressed in J or in Wh for example). For example, the *heating load* of a building refers to the heat that it requires at any given time, whereas its *energy use or needs* refers to the amount of energy it requires over a month or a year. Both are of interest for energy calculations: knowing the load is necessary to properly size the equipment, and knowing the *energy use* is necessary to evaluate the annual fuel consumption. Loads will be referred to by the symbol P throughout this chapter; *energy use or needs* will be referred to by the symbol Q . Average monthly loads will be referred to by the symbol $\overline{P}$.

2.1 Heating Project Load and Energy Calculation

Three kinds of heating loads are considered by the RETScreen CHP model: space heating, domestic hot water heating, and process heating. The annual total heating energy use of the system, Q_H , is the sum of the energy use for space heating, Q_{SH} , the energy use from domestic hot water heating, Q_{DHW} , and the energy use from process heating, Q_{PH} . Therefore:

$$Q_H = Q_{SH} + Q_{DHW} + Q_{PH} \qquad (1)$$

Space heating is calculated by using the concept of heating *degree-days*. This concept is explained in section 2.1.1. The concept can be extended to include domestic hot water heating, as explained in section 2.1.2. Calculation of the peak heating load is covered in section 2.1.3. The peak heating load and the monthly heating degree-days can then be used together to calculate the heating load duration curve, as explained in section 2.1.4. The duration curve is then converted to *monthly average loads* and a *peak load period* (section 2.1.5). Process loads can be added as described in section 2.1.6. The calculation of the equivalent full load hours is found in section 2.1.7 and the impact of energy efficiency measures is briefly reviewed in section 2.1.8.

2.1.1 Site climatic conditions

Site conditions for heating are defined through two user-entered parameters:

- the *heating design temperature*, and
- the *monthly heating degree-days*.

The heating design temperature corresponds to the temperature of an exceptionally cold day in the area. It is often specified by the local building code. For example ASHRAE (1997) defines it as the minimum temperature that has been measured for a frequency level of at least 1% over a long period of record (usually 20 to 30 years), for the specified location. In Sweden it is defined as the coldest/warmest temperature that is expected once every 20 years. The capacity of the building's heating equipment typically depends on the design heating temperature since the equipment needs to be sized to keep the building comfortable under the coldest conditions. The heating design temperature is used to determine the *peak heating load* and to size the heating system (section 2.1.3).

Heating degree-days, on the other hand, help determine the heating energy use. Heating degree-days are defined as the sum of daily differences between a set temperature T_{set} (usually 18°C) and the average daily temperature below the set temperature. Mathematically:

$$HDD_i = \sum_{k=1}^{N} \max\left(T_{set} - T_{a,k}, 0\right) \qquad (2)$$

where HDD_i is the monthly heating degree-days for month i , N_i is the number of days in month i , and $T_{a,k}$ is the average daily temperature for day k of the month. The annual heating degree-days HDD is calculated by adding the monthly heating degree-days:

$$HDD = \sum_{i=1}^{12} HDD_i \qquad (3)$$

The main advantage of using heating degree-days is that in a first approximation for space heating, the heating needs of a building can be assumed to be proportional to the number of heating degree-days (a refinement of this will be shown in section 2.1.5). Degree -days can also be used to describe hot water consumption, as will be seen in the next section.

2.1.2 Equivalent degree-days for hot water heating

The RETScreen CHP model allows the user to include domestic hot water as part of the energy needs met by the heating system. The domestic hot water demand is assumed constant throughout the year and is expressed by the user as a fraction d of the annual heating use (excluding process heat). Thus if Q_H is the annual heating use excluding process heat, Q_{SH} the portion of the energy use corresponding to space heating, and Q_{DHW} the portion of the energy use corresponding to domestic hot water heating, one has:

$$Q_{DHW} = d\,Q_H \qquad (4)$$

$$Q_{SH} = (1-d)Q_H \qquad (5)$$

and therefore:

$$Q_{DHW} = \frac{d}{(1-d)} Q_{SH} \qquad (6)$$

Since the space heating needs is roughly proportional to the number of heating degree-days, the model defines an *equivalent* number of heating degree-days corresponding to the domestic hot water demand. If HDD is the number of degree-days for heating from equation (3), the equivalent degree-days for domestic hot water demand HDD_{DHW} follows the same relationship as equation (6):

$$HDD_{DHW} = \frac{d}{(1-d)} HDD \qquad (7)$$

The equivalent heating degree-days is often expressed as their average daily value by dividing equation (7) by the number of days in a year. This leads to a value hdd_{DHW} which is expressed in heating degree-days per day:

$$hdd_{DHW} = \frac{1}{365} \frac{d}{(1-d)} HDD \qquad (8)$$

The use of hdd_{DHW} in establishing a heating load duration curve for the chosen location will be shown in section 2.1.4. It should be noted that the model takes into account domestic hot water demand in a rather coarse way. For example the model assumes that the domestic hot water demand is the same for every day of the year. This may be a reasonable approximation for a large district energy system, but may be inappropriate for, say, a school where there will be no domestic hot water load during the night, weekends and holidays. Similarly, the hot water load varies over the course of the year, both because input water is colder during the winter months and because hot water consumption may be reduced during the summer months. The DHW load can be as much as 30 to 50% more in the winter compared to the summer. This is not modeled in the RETScreen CHP model.

2.1.3 Calculation of peak heating load

The peak load for space heating usually occurs under very cold conditions, although it depends not only on outside weather conditions (temperature, wind, etc) but also on other parameters such as the thermal mass of the building and the infiltration rate.

In the RETScreen CHP Project Model, the peak heating load for a building (or a cluster of buildings with identical thermal properties) is a value $p_{SH,j}$ expressed in Watts per square metre of heated floor area. This value is entered by the user and depends on the heating design temperature for the specific location (see section 2.1.1) and on the building design (insulation, ventilation, etc.). Typical values are given in section 2.6.1. The total peak heat load $P_{SH,j}$ for the j the cluster of buildings is calculated as:

$$P_{SH,j} = p_{SH,j} A_j \qquad (9)$$

where A_j is the total heated area of the j the cluster of buildings. The total peak heating load P_{SH} seen by the heating system is:

$$P_{SH} = \sum_j P_{SH,j} \qquad (10)$$

where the summation is done on all clusters. Up to 14 different building clusters can be specified by the user.

2.1.4 Heating load duration curve

The peak heating load occurs only for a limited time of the year - usually during short and very cold spells. For the majority of the year, depending upon climatic conditions, the heating load of the system is only a fraction of the peak heating load. A *heating load duration curve* is used to describe how heating loads vary over the year and it is explained in this section. The heating load duration curve will be used to calculate the heating use for the system, as will be seen in section 2.1.5.

The heating load duration curve shows the cumulative duration for different loads in the system over a full year. An example of a heating load duration curve is shown in ***Figure 4***. The load for a district heating system (excluding any process load, which will be treated in section 2.1.6) consists of three main contributions, namely: distribution losses, domestic hot water and building heating load. Distribution losses correspond to loss of heat from the buried pipes to their environment and stay fairly constant over the year (slightly higher in the winter as the supply and return temperatures are higher and the ground temperature is lower). The domestic hot water load is also fairly constant over the year, with a reduction during the night and during summer months (see section 2.1.2). Finally, the building heating load is the dominating load for most of the year and follows the seasonal variations of the climate.

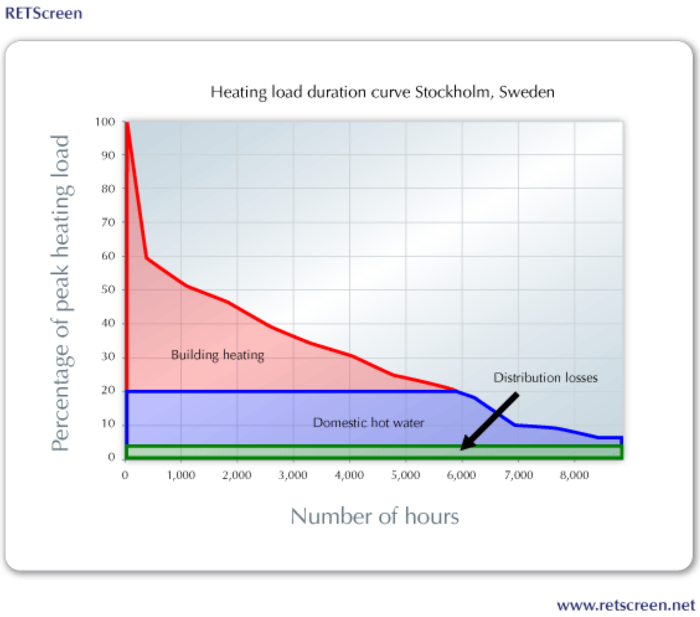
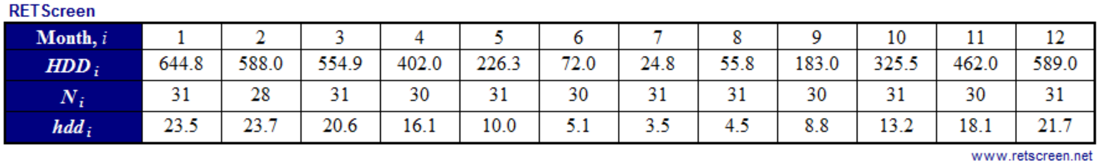


Figure 4: Example of Heating Load Duration Curve for Stockholm, Sweden

In principle the heating load duration curve should be derived from hourly loads to show all possible variations to the system. However, this information is rarely available for a system in the design or feasibility stage. For that reason, a method has been developed to derive the load duration curve from monthly degree-days. The data used to develop the method is taken from very detailed studies of a relatively large system in Uppsala, Sweden (Larsson, 2003). It includes empirical monthly factors that represent the influence of solar gains, wind, and occupants' habits on the energy requirements of the building.

The algorithm is described below and is illustrated on an example that of a heating system for Stockholm, Sweden. The heating design temperature (see note 7) is -19.4° C; heating degree-days can be obtained from RETScreen's Climate Database and are given in ***Table 1***. The domestic hot water demand is equal to 19% of the annual heating energy use (excluding process heating). According to ***Table 1*** the annual heating degree-days for space heating only is equal to 4,128.8; equation (8) enables to calculate the equivalent number of degree-days per day for domestic hot water heating; the value is 2.65 ºC·d/d.



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Month, i	1	2	3	4	5	6	7	8	9	10	11	12
HDD_i	644.8	588.0	554.9	402.0	226.3	72.0	24.8	55.8	183.0	325.5	462.0	589.0
N_i	31	28	31	30	31	30	31	31	30	31	30	31
hdd_i	23.5	23.7	20.6	16.1	10.0	5.1	3.5	4.5	8.8	13.2	18.1	21.7

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Table 1: Heating Degree-Days for Stockholm, Sweden

1. The first step is to calculate the monthly heating degree-days per day hdd_i (this is to eliminate the effect of months having different number of days), including in this quantity the equivalent degree-days for domestic hot water heating hdd_{DHW} calculated through equation (8):

$$hdd_i = \frac{HDD_i}{N_i} + hdd_{DHW} \qquad (11)$$

where HDD_i is the number of degree-days for month i and N_i the number of days in the month. The values calculated for the example are shown in ***Table 1***.

2. The monthly degree-days per day are sorted in ascending order. Let hdd'_i (with i = 1, …, 12) be the sorted array of monthly degree-days per day and N'_i the number of days per month sorted in the same order. The values of hdd'_i and N'_i for the example are shown in ***Table 3***. It should be noted in the example that January has the most degree-days, followed by December and February. However, February has more degree-days per day than both January and December.

3. Fourteen cumulative durations $C_0, C_1, \ldots, C_{13}$ are defined as:

$$C_0 = 8760\ hours \qquad (12\text{-}0)$$

$$C_1 = C_0 - N'_1 \cdot \frac{24}{2} \qquad (12\text{-}1)$$

$$C_2 = C_1 - (N'_1 + N'_2) \cdot \frac{24}{2} \qquad (12\text{-}2)$$

$$C_3 = C_2 - (N'_2 + N'_3) \cdot \frac{24}{2} \qquad (12\text{-}3)$$

…

$$C_{12} = C_{11} - (N'_{11} + N'_{12}) \cdot \frac{24}{2} \qquad (12\text{-}12)$$

$$C_{13} = C_{12} - N'_{12} \cdot \frac{24}{2} = 0 \qquad (12\text{-}13)$$

Physically, C_0 corresponds to the full year, C_1 to C_{12} correspond to the middle of the sorted months (see later in ***Figure 5***). The C_i calculated for the example are shown in ***Table 3***.

4. Fractions of peak load $D_0, D_1, \ldots, D_{13}$ corresponding to the cumulative durations $C_0, C_1, \ldots, C_{13}$ are calculated as:

$$D_0 = \frac{hdd'_1}{\Delta T_{des}} F_1 \cdot 100 = D_1 \qquad (13\text{-}0)$$

$$D_1 = \frac{hdd'_1}{\Delta T_{des}} F_1 \cdot 100 \qquad (13\text{-}1)$$

$$D_2 = \frac{hdd'_2}{\Delta T_{des}} F_2 \cdot 100 \qquad (13\text{-}2)$$

…

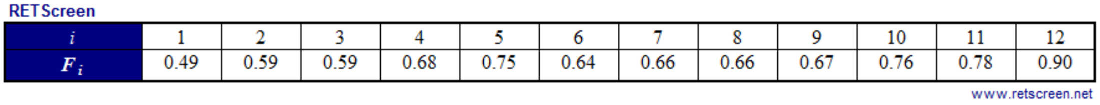
$$D_{12} = \frac{hdd'_{12}}{\Delta T_{des}} F_{12} \cdot 100 \qquad (13\text{-}12)$$

$$D_{13} = 100\ \% \qquad (13\text{-}13)$$

where hdd'_i (with i = 1, …, 12) is the sorted array of monthly degree-days per day including domestic hot water as per equation (8), $F_1, F_2, \ldots, F_{12}$ are twelve empirical monthly factors found in ***Table 2***. ΔT_{des} is the difference between the set point temperature (T_{set} = 18°C) and the heating design temperature T_{des} for the specified location (see section 2.1.1):

$$\Delta T_{des} = T_{set} - T_{des} \qquad (14)$$

The fourteen points (C_i, D_i) define the heating load duration curve expressed as a percentage of the peak heating load. The calculation of coefficients D_i for the example is shown in ***Table 3*** and the resulting load duration curve is shown in ***Figure 5***.



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i	1	2	3	4	5	6	7	8	9	10	11	12
F_i	0.49	0.59	0.59	0.68	0.75	0.64	0.66	0.66	0.67	0.76	0.78	0.90

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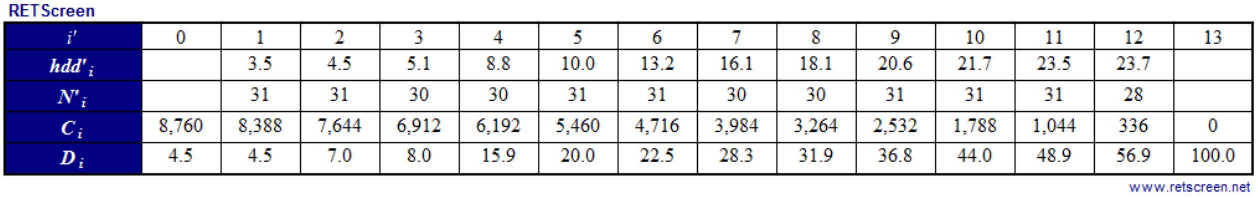
Table 2: Empirical Factors F_i for Heating



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i'	0	1	2	3	4	5	6	7	8	9	10	11	12	13
hdd'_i		3.5	4.5	5.1	8.8	10.0	13.2	16.1	18.1	20.6	21.7	23.5	23.7	
N'_i		31	31	30	30	31	31	30	30	31	31	31	28	
C_i	8,760	8,388	7,644	6,912	6,192	5,460	4,716	3,984	3,264	2,532	1,788	1,044	336	0
D_i	4.5	4.5	7.0	8.0	15.9	20.0	22.5	28.3	31.9	36.8	44.0	48.9	56.9	100.0

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Table 3: Example of Coefficient Calculation

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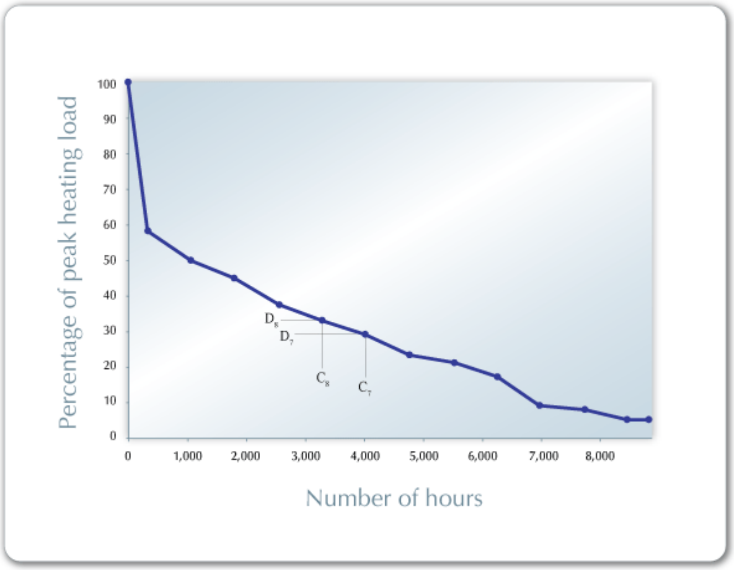

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Figure 5: Example of Heating Load Duration Curve

2.1.5 Monthly average load and peak load period

Monthly average heating load
The area under the curve in ***Figure 5***, when multiplied by the peak heating load calculated in section 2.1.3 , represents the heating energy use of the system over the whole year. Since the points on the curve of ***Figure 5*** represent individual months, sorted by decreasing degree-days per day, it is possible to calculate the monthly heating use from this curve. Continuing with the example from the previous section, a sample calculation is shown in ***Figure 6*** for the point (C_8 , D_8); the shaded area multiplied by the peak load is equal to the energy use for that month. Referring to ***Table 3*** and ***Table 1***, one observes that the month represented by the point (C 8 , D 8) is the month of November.

The same procedure can be applied for all months. A trapezoidal rule could be used to calculate the shaded area in ***Figure 6.*** Using this method, the peak heating load is related to the month with the highest number of degree-days. Moreover, the duration of that peak heating load is dependant on that month. This leads to a variable peak load duration and is not reliable. However, rather than calculate the monthly use directly this way, an approximation of the monthly average heating load, which is valid for most months, is to assume that the average heating load for the month is D_i multiply by the peak heating load, or:

$$\overline{P}_{SH,i} = D_i \cdot P_{SH} \qquad (15)$$

where $\bar{P}_{SH,i}$ is the average monthly space heating load (including domestic hot water for month *i*), D_i is the fraction of peak load from section 2.1.4, and P_{SH} is the peak space heating load (including domestic hot water) calculated in section 2.1.3.

The only month for which this approximation is not valid is the month corresponding to (C_{12} , D_{12}), the month in the leftmost part of ***Figure 6***, since the heating load exhibits a very large peak for that month. One could modify equation (15) to include the peak in the calculation of the average load for that month; however due to the limitations listed above, another method is preferred, one which treats the peak separately, as will now be explained.

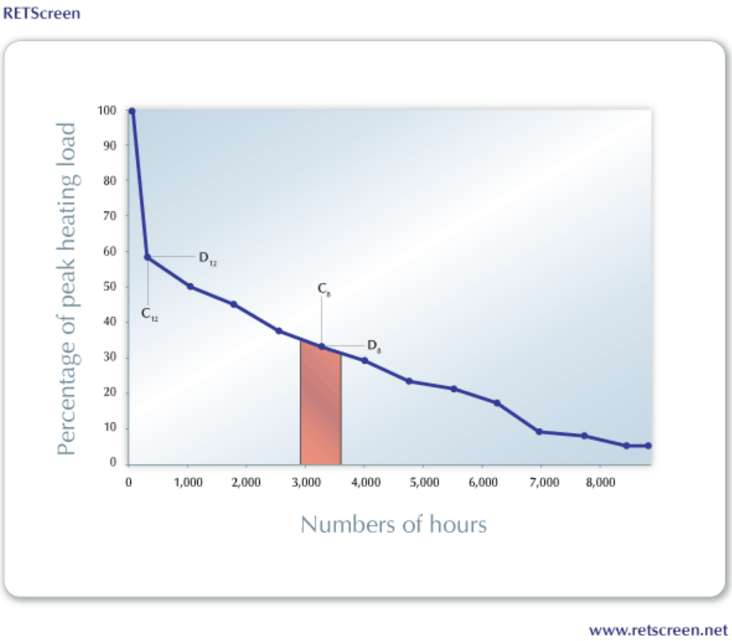
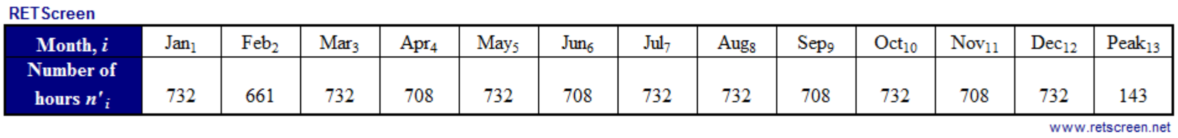


Figure 6: Example of Monthly Heating Energy Use Calculation

Peak heating load period

As mentioned, the method described in section 2.1.4 calculates the duration of the peak period as a function of the number of days in the month with the highest number of heating degree-days per day. However, in CHP systems the occurrence of the peak period can be highly variable. Depending on heating, cooling and power needs, it can happen in any month and have variable duration. For this reason an additional, fictitious 'peak period' is added to the calculation (this peak period is hidden from the user and is used for calculations only; it does not appear in the results of the workbook.) Tests have shown that a reasonable duration for the peak period is somewhere between 140 and 150 hours.

Of course, a side effect of this additional peak period is to make the year slightly longer which then needs to be corrected. The simplest method is to reduce the apparent length of each individual month. In RETScreen, the length of each month is reduced by 12 hours, except for February which, being a shorter month, is reduced by only 11 hours. The length of the peak period is thus set to 143 hours (11 months × 12 hours plus one month × 11 hours) so that the total number of hours in the year remains equal to 8,760. The monthly load curve, derived using the method described in section 2.1.5, and the additional peak period, are shown in ***Figure 5***. The corrected number of hours n'_i in each month and in the peak period are summarized in ***Table 4***.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Month, i	Jan_1	Feb_2	Mar_3	Apr_4	May_5	Jun_6	Jul_7	Aug_8	Sep_9	Oct_{10}	Nov_{11}	Dec_{12}	$Peak_{13}$
Number of hours n'_i	732	661	732	708	732	708	732	732	708	732	708	732	143

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Table 4: Corrected Number of Hours in Each Month and in the Peak Period

Total energy needs

It is now possible to proceed with the calculation of the total space heating needs (including domestic hot water heating) Q_{SH} . It is simply the area under the curve in ***Figure 7***, or:

$$Q_{SH} = \sum_{i}^{12} \bar{P}_{SH,i} \cdot n'_i + P_{SH} \cdot n'_{13} \qquad (16)$$

where P_{SH} is the peak space heating load, $\overline{P}_{SH,i}$ is the net monthly average space heating load (including domestic hot water heating) as per equation (15), n'_i is the corrected number of hours per month as per ***Table 4*** and n'_{13} is the number of hours of the peak period (143).

This completes the estimation of space and domestic hot water heating load and use for the system: peak heating load is defined by equation (10), monthly average heating loads are defined by the method exposed in section 2.1.5, equation (15), and yearly heating use is calculated by equation (16). Process heating is weather independent, and is therefore treated separately.

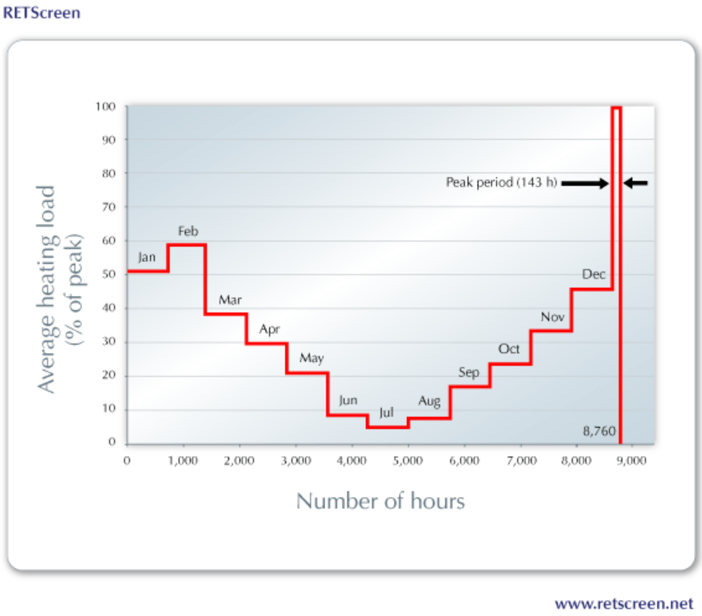

Figure 7: Average Monthly Heating Loads and Additional Peak Period

2.1.6 Process heat

So far the calculations have dealt only with space heating and domestic hot water heating (through the equivalent degree-days). It is now time to consider process loads as well.

Process heating loads are entered by the user through one of two methods, "standard" or "detailed." In the standard method the user enters the equivalent full load duration hours for the process. In the second method, the user inputs the percentage of time, for each month, that process load is operating. In both cases, the user also specifies the peak process heating load.

The process heating peak load is assumed to occur during the same period of time as the space heating peak load. This may or may not be the case in practice, but this assumption in RETScreen represents a 'worst case' scenario for which the system is designed. The process heating peak load is therefore simply added to the space heating peak load calculated through equation (10):

$$P_H = P_{SH} + P_{PH} \qquad (17)$$

where P_H is the total peak heating load, P_{SH} is the peak heating load for space heating and domestic hot water heating from equation (10), and P_{PH} is the peak process heating load entered by the user.

In the "standard" method, the process heating load is equal to the peak load P_{PH} during the peak period defined in section 2.1.5, and is set to a constant value $\overline{P}_{PH}$ during all months of the year so that the total annual heating use is equal to the peak load times the equivalent full load duration hours specified by the user. When the "detailed" method is used, the user inputs of the equivalent percentage of time per month that process load is operating at full load. The monthly average load $\overline{P}_{PH,i}$ is calculated as:

$$\overline{P}_{PH,i} = P_{PH} \cdot e_i \qquad (18)$$

where e_i is the equivalent percentage of time in month i that the process load is operating at full load.

The peak process heating load P_{PH} and the monthly average process loads $\overline{P}_{PH}$ or $\overline{P}_{PH,i}$ are then added to their space-heating (and domestic hot water heating) equivalents in equation (16) to calculate the total annual energy use for heating, Q_H .

2.1.7 Equivalent full load hours

Equivalent full load hours E_{flh} can be described as the amount of hours a system designed exactly for the peak heating load would operate at full load during one year. It is simply calculated as:

$$E_{flh} = \frac{Q_H}{P_H} \qquad (19)$$

with Q_H the total annual energy use, given by equation (1), and P_H total peak load given by equation (17).

2.1.8 Energy efficiency measures

When energy efficiency measures are considered, they simply reduce both the load and the energy use by the percentage specified by the user.

7. Note that this value is colder than the design temperature in the RETScreen climate database, which is -14.4 °C. The -19.4 °C value corresponds to a more conservative design.

2.2 Cooling Project Load and Energy Calculation

Cooling load and energy calculation is treated very much the same way as heating load and energy use, with a few variations as explained below.

2.2.1 Site climatic conditions

As in the heating case, site climatic conditions use the concepts of design temperature and degree-days - this time *design cooling temperature* and *cooling degree-days*. The former represents an exceptionally warm day and corresponds to the maximum temperature that has been measured for a frequency level of at least 1% over the year, for a specific area [ASHRAE, 1997]; it is useful to determine cooling loads. The latter is useful to determine cooling needs and is defined as the sum of daily differences between the average daily temperature and a set temperature T_{set} (10°C in the RETScreen CHP model). Mathematically:

$$CDD_i = \sum_{k=1}^{N_i} \max\left(T_{a,k} - T_{set}, 0\right) \tag{20}$$

where CDD_i is the monthly cooling degree-days for month i , N_i is the number of days in month i , and $T_{a,k}$ is the average daily temperature for day k of the month. The annual degree-days CDD is calculated by adding the monthly degree-days:

$$CDD = \sum_{i=1}^{12} CDD_i \tag{21}$$

Again, the main advantage of using degree-days is that in first approximation, the cooling needs of a building can be assumed to be proportional to the number of cooling degree-days.

2.2.2 Equivalent degree-days for base load cooling

Base load cooling represents non-weather dependent process cooling needs such as internal cooling loads or constant cooling loads. The base load cooling is entered by the user as a fraction d of the annual space cooling energy use (including base load cooling, but excluding process cooling energy use).

The method used in section 2.1.2 can be used again to define equivalent cooling degree-days for base load cooling. The equations are identical, with the base cooling use replacing the domestic hot water demand and cooling degree-days replacing heating degree-days. The final result is:

$$cdd_{CL} = \frac{1}{365} \frac{d}{(1-d)} CDD \tag{22}$$

where cdd_{CL} is the equivalent cooling degree-days corresponding to the base cooling load. Here again the model takes into account constant cooling loads in a rather coarse way. The model assumes that this load is constant for every day of the year. In a cold climate the cooling might be completely turned off during the heating season and the factor d should be set to zero.

2.2.3 Calculation of peak space cooling load

The space cooling load is entered directly by the user as a value in Watts per square metre of cooled floor area. Formulae (9) and (10) have their direct equivalents for cooling:

$$P_{sc,j} = p_{sc,j} A_j \tag{23}$$

where $P_{sc,j}$ is the total peak cooling load for the j the cluster of buildings, $p_{sc,j}$ is the peak cooling load per unit area entered by the user, A_j is the total cooled area of the j the cluster of buildings. The total peak space cooling load for all the clusters of buildings P_{sc} seen by the system is:

$$P_{sc} = \sum_{j} P_{sc,j} \tag{24}$$

where the summation is done on all clusters of buildings. Details about the estimation of the peak cooling load per unit area can be found in section 2.6.2.

2.2.4 Cooling load duration curve

A cooling load duration curve can be derived using a method similar to the one described in section 2.1.4 for heating. The only difference is that the empirical coefficients $F_1, F_2, \ldots, F_{12}$ will be different. In the RETScreen CHP cooling model the coefficients are all set to one, which is equivalent to say that the heating load for all months is directly proportional to the number of cooling degree days (as shown by equations (13-0) to (13-13)). The rest of the calculation is similar to the heating case.

2.2.5 Peak load period, total energy use, etc.

As was done for the heating load analysis in section 2.1.5, a peak load period is added to represent the time of year where the cooling system works at full capacity. The rest of the calculation of the cooling use is in all points similar to that of the heating use, with cooling loads replacing heating loads in all equations.

2.2.6 Process cooling

Process cooling is treated exactly the same way as process heating. Formulae similar to equations (17) to (19) can be written, except that they apply to cooling processes rather than heating processes.

2.3 Power Project Load and Energy Calculation

The calculation of load and energy for the power project is somewhat simpler than those for the heating and cooling projects, since twelve values of the average monthly power loads $\overline{P}_{P,1}$, $\overline{P}_{P,2}$, …, $\overline{P}_{P,12}$ are specified directly by the user. The user also specifies the system peak electricity load over maximum monthly average:

$$\frac{P_P}{\max(\overline{P}_{P,i})} \tag{25}$$

which enables the calculation of the peak electricity load P_P . The peak electricity load is assumed to happen for the duration of the peak period defined in section 2.1.5. The electricity use $Q_{P,13}$ during the peak period is then given by:

$$Q_{P,13} = n'_{13} \cdot P_P \tag{26}$$

and the electricity use $Q_{P,i}$ for each individual month i is given by:

$$Q_{P,i} = n'_i \cdot \overline{P}_{P,i} \tag{27}$$

where the n'_i represent the modified number of hours in each month as per ***Table 4***. Finally the total annual electricity use Q_P is:

$$Q_P = \sum_{i=1}^{13} Q_{P,i} \tag{28}$$

The use of electricity for non heating and cooling purposes also varies over the year. The variation can depend on more light being required during the winter period, or on activities and usage changes between the seasons. For existing systems it is recommended that the electricity bills be used to calculate a load profile. Note that if electricity is used for either heating or cooling, it should be included in the figures used for this calculation; the amount of electricity used for heating or cooling purposes is deducted on a monthly basis from the gross values entered by the user to calculate a net power monthly average. For example if an average power $\overline{P}_{P\to C,i}$ is used by a compressor for space cooling for month i , and the gross average power load for the month specified by the user is $\overline{P}_{P,i}$, then the *net* average power load for the month is only:

$$\overline{P}_{P,net,i} = \overline{P}_{P,i} - \overline{P}_{P\to C,i} \tag{29}$$

2.4 Equipment for Combined Heat and Power

Now that the heating, cooling and power generation loads and use are known, it is possible to estimate how they are met by the various energy devices that the system includes. But first it is necessary to explain the basics of heat and power generating equipments, and how their fuel consumption and heating capacity can be estimated.

The RETScreen CHP model is able to calculate a number of combined heat and power options, including steam turbines, steam turbines with extraction port, gas turbines, and combined cycle gas turbines. The model also covers (although not with the same degree of detail) reciprocating engines, fuel cells, etc.

2.4.1 Steam turbine

Background
A steam turbine uses high pressure and saturated or superheated steam produced in a boiler, and converts the thermal energy by expanding it in the turbine to generate shaft power that drives a generator to produce electricity.

Turbines can be of two types, radial or axial flow. Axial flow is the most common for power generation. The steam is directed by nozzles to rotating blades or buckets mounted radially on a rotating wheel. The length of the blades is short in proportion to the radius of the turbine. Several stages of expansion are used in high efficiency turbines. Vacuum exhaust can be achieved by mounting the different stages on a single shaft, and supporting the nozzles of all the stages from a continuous housing. Large turbines must not be operated in conditions where the exhaust steam contains more than 10 to 13% water. Water droplets can seriously erode nozzles and blades. Some turbines may have special stages designed for the removal of moisture. This type of design is used when the superheated steam temperature is limited. The moisture content of the exhaust is dependent on the inlet steam pressure combination.

Superheating the steam increases the cycle efficiency. Reheat is sometime used to further increase the efficiency. The steam is then re-superheated after partial expansion.

Back pressure operation refers to non-condensing steam turbines designed to utilize the exhaust steam for heating or a process. In a condensing turbine the steam exhausts to a condenser and the latent heat of the steam is transferred to the cooling water. The condensed steam is returned to the boiler as feed water.

Extraction, controlled automatic operation, refers to a steam turbine designed to permit a controlled extraction steam flow to be matched to the steam demand; steam can be used for heating or process purposes. Steam that is not extracted is condensed. Large steam turbines might have more than one extraction port. The RETScreen CHP model only allows the user to use one extraction port.

Thermodynamic cycle
In the RETScreen CHP model the steam turbine is assumed to be an isentropic device. In practice it is not an ideal device, and efficiencies will be introduced later to account for that fact.

The diagram for a steam turbine is shown in ***Figure 8***. The corresponding thermodynamic cycle (known as the Rankine cycle) is shown in ***Figure 9***. The four phases of the cycle are:

1 to 2: heat transfer to the working fluid. The heat is provided by the combustion of fuel. Water enters the boiler, receives heat provided by the combustion of fuel, and exits as superheated vapour.

RETScreen

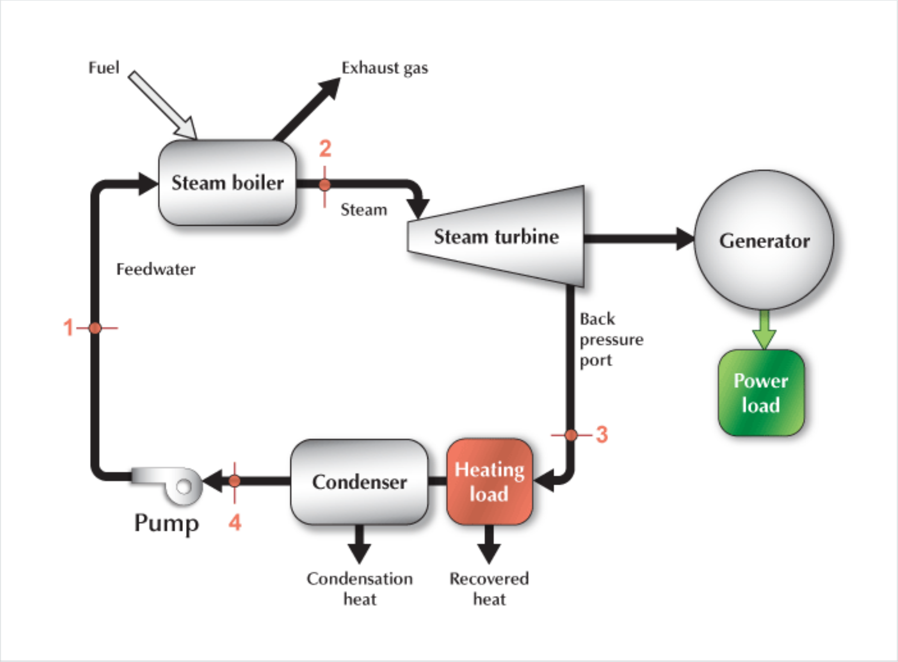

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Figure 8: Steam Turbine

RETScreen

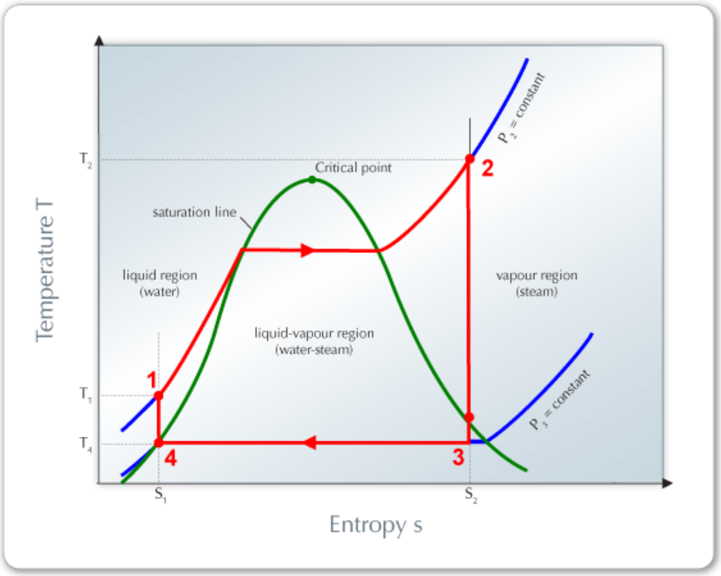

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Figure 9: Ideal Rankine Cycle with Superheating

2 to 3: expansion. The steam is expanded in the turning turbine, converting the enthalpy in the working fluid into work.

3 to 4: transfer of heat to the environment. As the water condenses it rejects heat to the environment. This usually takes place in a condenser. Heat can also be extracted by co-generation loads.

4 to 1: isentropic pressure increase. The pump is used to increase the pressure of the working fluid. The water enters the pump as a saturated liquid and exits it as a subcooled liquid. The process requires work, and a small fraction of the work generated by the turbine (typically 5%) is used to power the pump.

Calculation of work, heating capacity, and fuel consumption
The turbine's specific work (work per mass), or Rankine cycle work, is simply given by:

$$w_{ideal} = h_2 - h_3 \qquad (30)$$

where w_{ideal} is the Rankine cycle work or theoretical steam rate, h_2 is the input steam enthalpy and h_3 is the exhaust steam enthalpy. The enthalpies h_2 and h_3 correspond to phases 2 and 3 shown on ***Figure 9***, which have the same entropy. The actual steam turbine specific work w or actual steam rate is calculated with:

$$w = \eta_s \cdot w_{ideal} \qquad (31)$$

where η_s is the isentropic efficiency of the turbine.

Equation (30) requires the knowledge of input steam and exhaust steam enthalpy. The enthalpy h_2 and entropy s_2 of the input steam can be calculated from the operating pressure P_2 and the superheated temperature T_2 (both specified by the user) of the input steam. The enthalpy h_3 at the back port can be calculated from the back pressure P_3 (also specified by the user) and the back port entropy ($s_3 = s_2$ since the process is assumed to be isentropic). The formulae used to calculate steam and water properties for the RETScreen CHP model are those published by the International Association for the Properties of Water and Steam (IAPWS, 1997) (see note 8).

In practice the system does not behave ideally, and additional inefficiencies have to be taken into account. The actual steam rate can be calculated from the total turbine generator package efficiency:

$$w = \eta_{tg} \cdot w_{ideal} \qquad (32)$$

where η_{tg} is the combined total efficiency of the turbine generator set. The efficiency is in reality dependent upon many factors in the steam path including exhaust size. However to simplify the amount of inputs for the RETScreen CHP model (for example the energy lost to power the pump), these efficiencies have been combined into one overall number, which is entered by the user.

The total amount of power (electricity) produced from a turbine can now be calculated by multiplying with the mass flow of steam:

$$W = m \cdot w \qquad (33)$$

where W is the power produced by the steam turbine generator, m is the mass flow of steam feeding the turbine and w the actual steam rate for the turbine generator set. The heating capacity W^{th} of the turbine is:

$$W^{th} = m \cdot (h_3 - h_4) \cdot w \qquad (34)$$

Finally the fuel consumption for the steam cycle can be defined by the difference of enthalpy of the water returning to the boiler and the enthalpy of the steam produced, divided by the boiler's seasonal efficiency:

$$W^f = m \cdot \frac{(h_2 - h_1)}{\eta_b} \qquad (35)$$

where W^f is the boiler fuel consumption, m is the mass flow of the input steam, h_2 is the input steam enthalpy, h_1 is the return water enthalpy and η_b is the seasonal boiler efficiency including blow-down losses (i.e. due to the periodic removal of water to get rid of accumulated solids or sludges).

Steam quality
If the entropy is between fluid and vapour entropy at the exit pressure, the exit quality of the steam mixture is calculated from the two phase mixture as:

$$x_3 = \frac{s_3 - s_1}{s_v - s_1} \qquad (36)$$

where, x_3 is the exit quality, s_3 the entropy of the exhaust steam, s_1 the entropy of the fluid feeding the boiler, but at the exit pressure and s_v the entropy of saturated steam at the exit pressure. When the steam quality is less than one, a warning message is displayed to the user to indicate that the steam is wet.

2.4.2 Steam turbine with extraction port

The RETScreen CHP model also allows the calculation of a turbine that has one extraction port as seen in ***Figure 10***. The corresponding thermodynamic cycle is shown in ***Figure 11***.

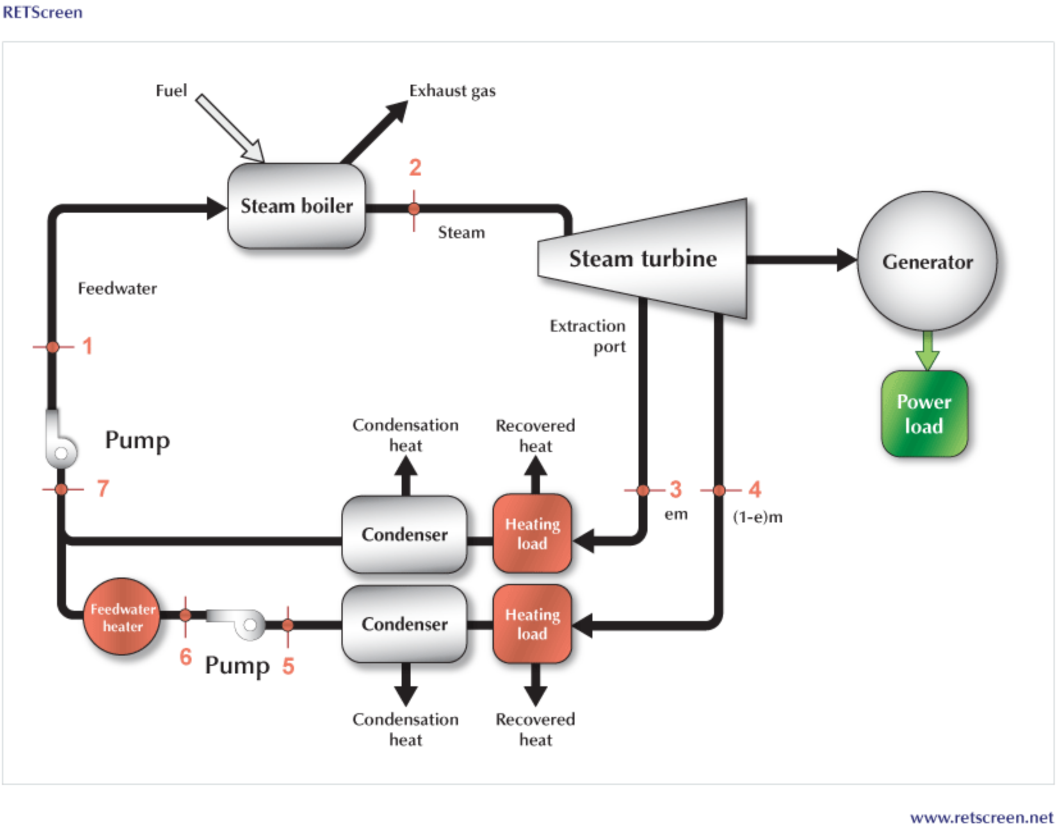


Figure 10: Steam Turbine with Extraction

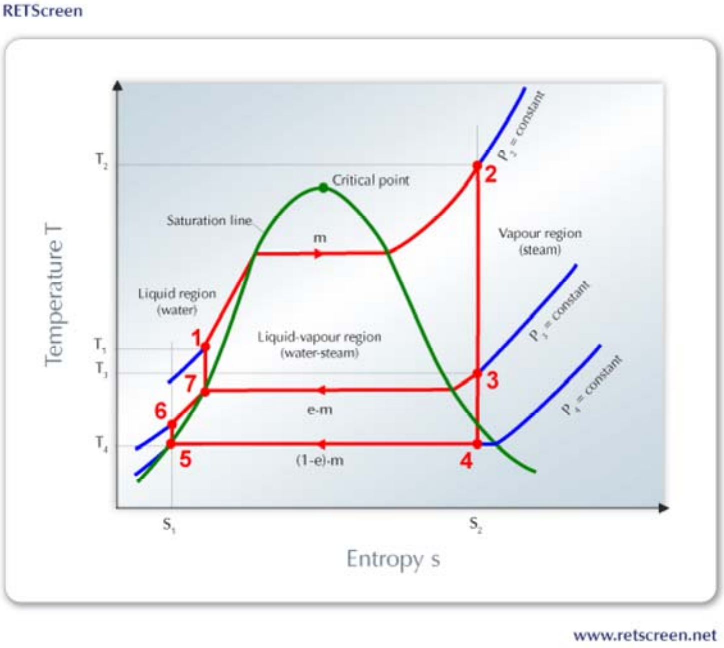


Figure 11: Ideal Rankine Cycle with Superheating and Steam Extraction

The power produced by an extraction turbine depends on rate of extraction. The steam turbine will always need to have a minimum flow to the back pressure port. The maximum extraction is specified by the turbine design and the pressure and size of the extraction port. The minimum and maximum power generated are:

$$W_{Min} = m \cdot \eta_{tg} \cdot \{e \cdot (h_2 - h_3) + (1-e) \cdot (h_2 - h_4)\} \quad (37)$$

$$W_{Max} = m \cdot \eta_{tg} \cdot (h_2 - h_4) \quad (38)$$

where W is the power generated, m is the mass flow of the input steam, e is the maximum allowable extraction rate, expressed as a fraction, h_2 is the input steam enthalpy, h_3 is the extraction steam enthalpy, h_4 is the exhaust steam enthalpy and η_{tg} is the combined total efficiency of the turbine generator set. The extraction enthalpy h_3 and the exhaust steam enthalpy h_4 an be readily calculated from user inputs using formulae similar to the ones used in section 2.4.1.

Maximum and minimum available heating capacities for this turbine are:

$$W^{th}_{Max} = m \cdot (e \cdot (h_3 - h_1) + (1-e) \cdot (h_4 - h_1)) \quad (39)$$

$$W^{th}_{Min} = m \cdot (h_4 - h_1) \quad (40)$$

where W^{th} is the available heating capacity as a function of the fraction e of steam extracted. The maximum heating capacity of this turbine will be during operation at full extraction.

The fuel consumption of the system is calculated with the same equation as in the steam turbine case (see equation (35)).

2.4.3 Gas turbine

Background
A gas turbine is a machine that compresses a gas (typically air), and then adds heat energy into the compressed gas. The heat can be added either firing (combusting) a fuel in the compressed air or transferring the heat via a heat exchanger. This is followed by the expansion of the hot pressurized gas to produce work. Part of the work produced is used to compress the gas, and the remaining part can either drive a generator for electricity production or some other machinery. An aircraft jet engine is a gas turbine where the useful work is produced as trust from the exhaust.

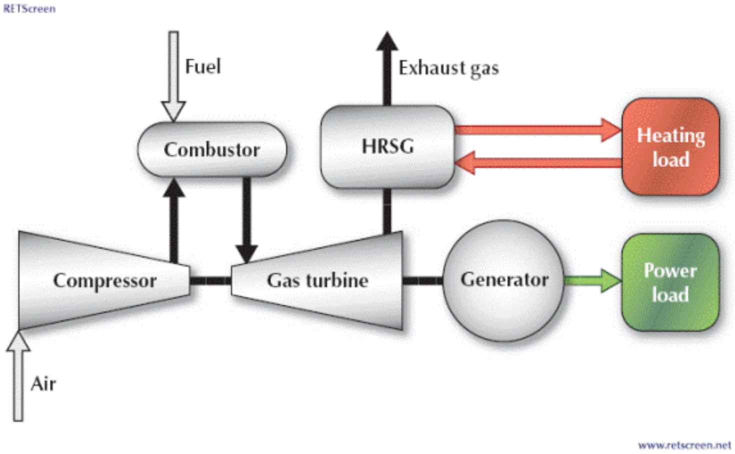


Figure 12: Typical Gas Turbine System with Heat Recovery

There are two types of land based gas turbines namely, heavy frame engines and aero derivative engines. Heavy frame engines are larger and typically operate at lower compression rates than the smaller and more compact aero derivative engines.

In the RETScreen CHP model the gas turbine is characterized by its power capacity [kW], its minimum capacity [%], its heat rate [kJ/kWh] or [Btu/kWh] and its heat recovery efficiency [%].

Power capacity or output of the generating equipment is measured in [kW]. The power capacity is the output to the grid. All efficiency factors such as altitude, atmospheric conditions, generator, transformer etc. are assumed to have been already deducted from the power capacity entered by the user.

Minimum capacity is sometimes also referred to as turndown ratio. The minimum capacity (load) for the equipment selected is entered in percent of total capacity. If the system selected cannot be turned down to the anticipated load, the electricity either has to be sold or the turbine stopped. A warning will be shown if the system is too large to follow the system load. If the user selects several smaller turbines, load following can typically be achieved. If the monthly load is less than the minimum capacity, the model will assume that the system is off during that period. Then the load for that period will need to be met by the intermediate or peak load systems.

The *heat rate* and the *heat recovery efficiency* are used to specify the efficiency of the power producing equipment. The heat rate is a measure of fuel consumption per unit of power output: the higher a turbine's efficiency, the lower its heat rate. Heat rate is typically described in [kJ/kWh] but other units are also used (see note 9). Heat recovery efficiency in percent is used to specify the amount of available heat that can be recovered by the proposed system. All heat that is produced cannot be recovered, as sometimes the temperature of the available heat is too low.

Calculation of work, heating capacity, and fuel consumption
From the quantities defined above, and from the gas turbine power capacity W, it is fairly easy to calculate the thermal output and the fuel consumption. Indeed one has by definition:

$$HR = \frac{W^f}{W} \qquad (41)$$

where HR is the heat rate and W^f is the gross total fuel input; and:

$$\eta^{th} = \frac{W^{th}}{W^f - W} \qquad (42)$$

where η^{th} is the efficiency of the heat recovery system and W^{th} is the heating capacity of the system. As a consequence,

$$W^f = HR \cdot W \qquad (43)$$

and:

$$W^{th} = \eta^{th} \cdot W \cdot (HR - 1) \qquad (44)$$

HR, η^{th} and W are specified by the user.

2.4.4 Combined cycle gas turbine

The exhaust from a stationary gas turbine can be recovered to generate heat or steam for power generation in a steam turbine. In the combined cycle arrangement the heat is converted to steam in a heat recovery steam generator. This steam is then typically used to produce power.

In some systems duct firing is used; this means that supplementary fuel is burned to increase the output of steam produced. Note also that, as shown in ***Figure 13***, the model allows the use of one extraction port of the steam turbine. In more complex CHP plants, steam turbines have more than one extraction port, but the RETScreen CHP model only models one.

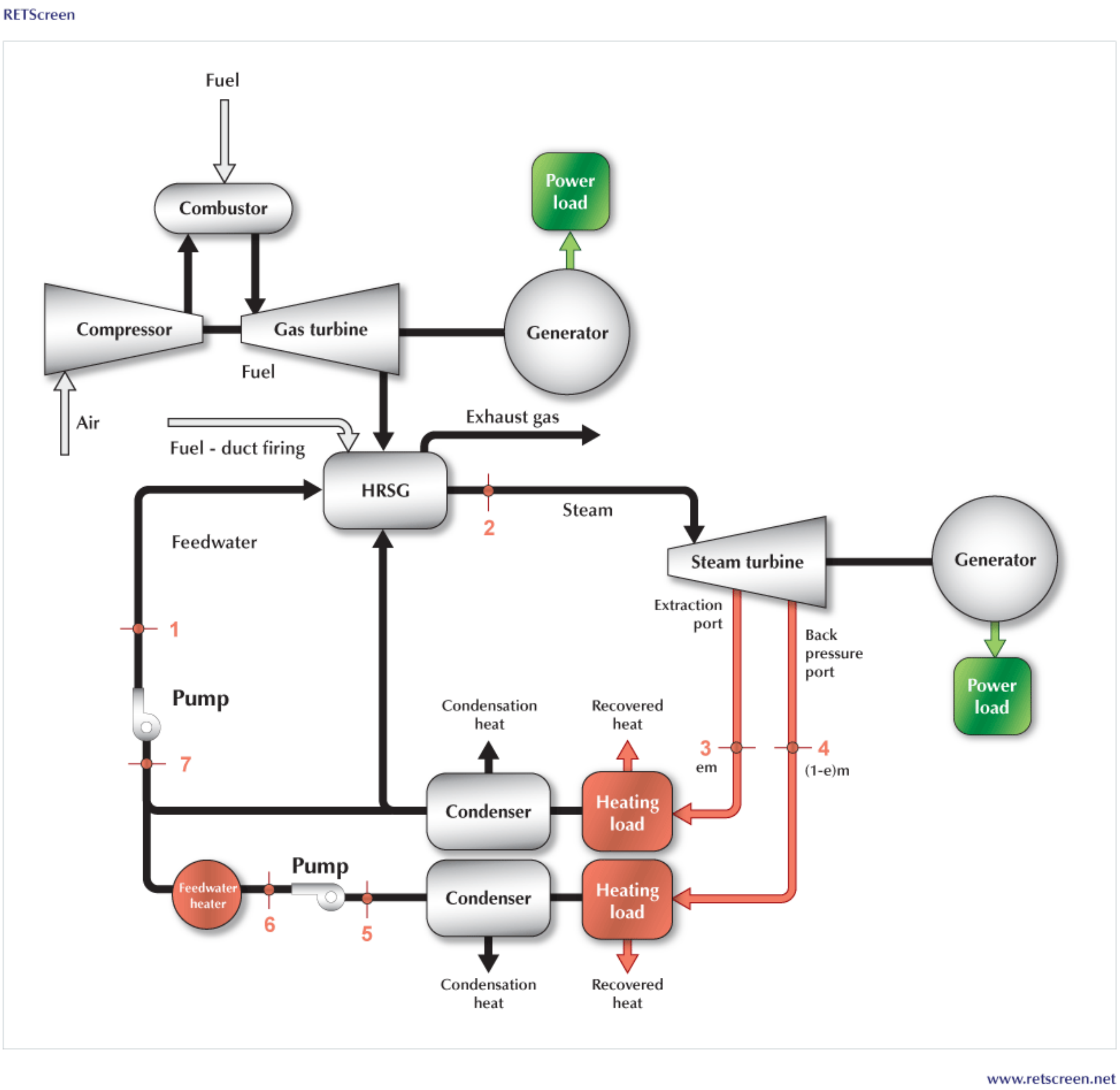


Figure 13: Typical Combined Cycle Gas Turbine System with Duct Firing and Extraction on the Steam Turbine

When duct firing is not used, equations (43) and (44) can still be used to calculate the gross fuel input W^f and the thermal output W^{th} of the system, as a function of the gas turbine's electrical output W. If duct firing is present in the system these equations have to be replaced with:

$$W^{th} = \eta^{th} \cdot W \cdot (HR - 1) + W^{DuctFiring} \qquad (45)$$

and:

$$W^f = HR \cdot W + W^{DuctFiring} \qquad (46)$$

where $W^{DuctFiring}$ is the gross duct firing fuel input.

The calculation of the steam turbine side of the system then proceeds in a very similar fashion to what was exposed previously in sections 2.4.1 and 2.4.2. The only difference is that the thermal input to the steam turbine W^{th} is known, rather than the steam mass flow rate m. The following relationship relates the two:

$$m = \frac{W^{th}}{h_1 - h_2} \qquad (47)$$

where h_1 is the return water enthalpy and h_2 is the input steam enthalpy (these two quantities are, as in sections 2.4.1 and 2.4.2, calculated from the operating pressure, superheated temperature, extraction rate and pressure, and back pressure).

The total combined cycle gas turbine power capacity is

$$W = W^e_{GasTurbine} + W^e_{SteamTurbine} \qquad (48)$$

where W is the total electrical capacity of the combined cycle gas turbine, $W^e_{GasTurbine}$ is the electrical capacity of the gas turbine and $W^e_{SteamTurbine}$ is the electrical capacity of the steam turbine.

In some cases the gas turbine and steam turbine are packaged and only the *total* heat rate for the combined cycle system is known. The heat rate is then calculated as:

$$HR = \frac{W^f}{W^e_{GasTurbine} + W^e_{SteamTurbine}} \qquad (49)$$

where HR is the gross total heat rate, W^f is the gross total fuel input, $W^e_{GasTurbine}$ is the electrical capacity of the gas turbine and $W^e_{SteamTurbine}$ is the electrical capacity of the steam turbine. In the RETScreen CHP model, if the combined cycle heat rate is known and no extra duct firing nor extraction is required, the "gas turbine" section can be used to evaluate the combined cycle plant.

2.4.5 Reciprocating engine, fuel cell, or other power equipment consuming fuel

All these systems are calculated with the same inputs (power capacity, heat rate, and heat recovery efficiency) as the gas turbine. The equations used in section 2.4.3 apply as well.

2.4.6 Geothermal system

The geothermal system is treated as a steam turbine, with the difference that the steam is produced through geothermal means, not by burning fuel; therefore there is no calculation of the fuel needed.

8.In that reference, of particular interest are equations 7 for entropy and enthalpy in the liquid stage, 15, 18 and 19 in the vapour stage, and 31 for saturation temperature.
9.The Tools worksheet contains methods to convert between the different methods published by equipment manufacturers.

2.5 Energy Delivered and Fuel Consumption

Now that the heating, cooling and power loads and use have been defined (sections 2.1, 2.2 and 2.3) and that the characteristics of the CHP equipment are known (section 2.4), it becomes possible to calculate how loads and energy use are met by the base, intermediate and peak systems. This is described in section 2.5.1. Power generating system availability and operating strategy considerations are treated in sections 2.5.2 and 2.5.3, respectively.

2.5.1 Load met by the base, intermediate and peak systems

The average monthly and peak loads for heating, cooling and power generation, as determined in sections 2.1 to 2.3, are met by base, intermediate, and peak load systems. Typically, the lowest cost energy is used to produce the base load. Then the intermediate load system, if applicable, is dispatched to meet most of the rest of the energy needs. Finally, the peak load system meets the top portion of the annual energy needs during peak periods. The fraction of the total needs met by each system depends on their respective sizes; for example the heating load of ***Figure 5*** can be met by a waste heat recovery system (base), a biomass heating system (intermediate), and a gas-fired boiler (peak). This is illustrated in ***Figure 14***. In this figure, the base heating system can meet 10% of the peak load, the intermediate heating system meets another 30%. Together these two systems meet the heating load for all months except during the months of December, January and February and during the peak period. The boiler supplies the rest of the load during those times.

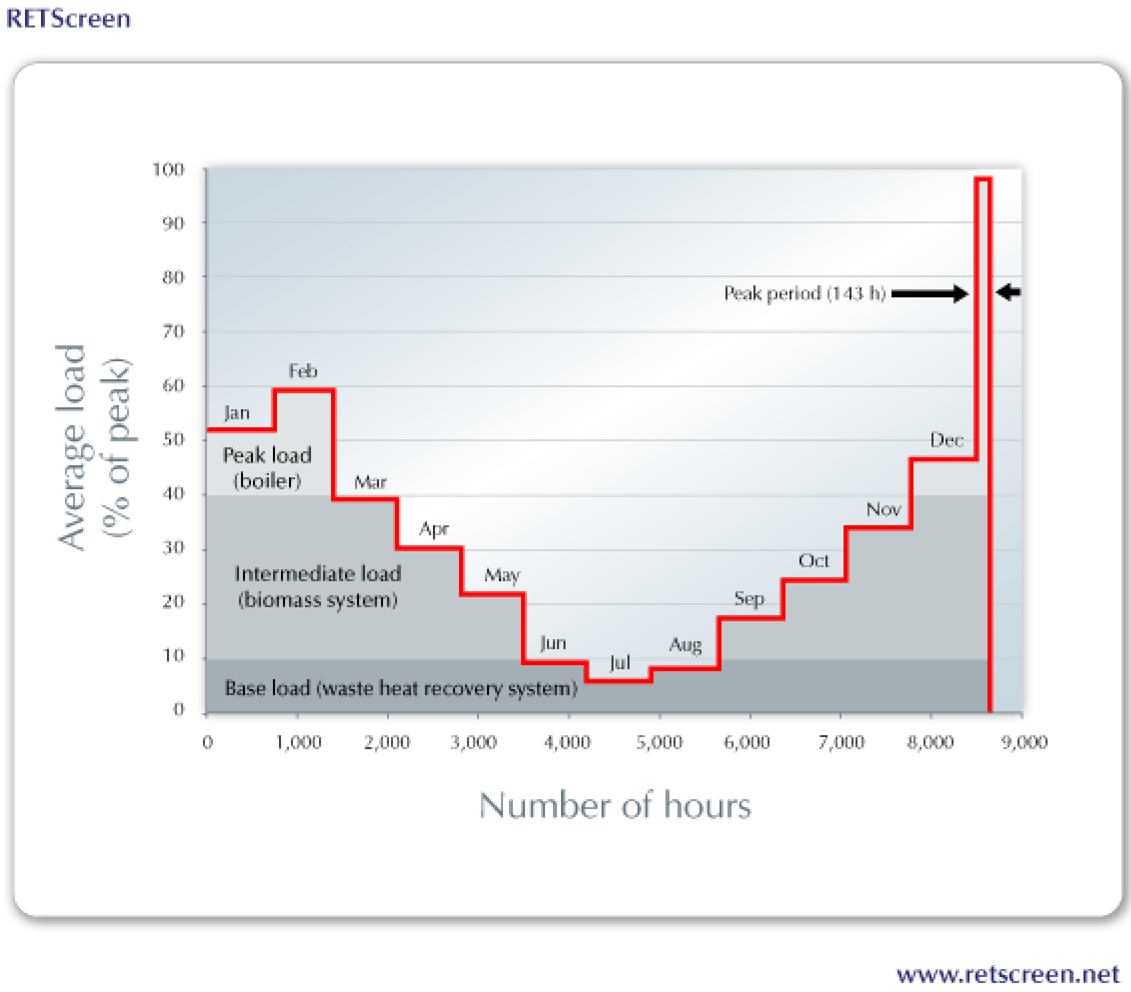


Figure 14: Parts of the Heating Load Met by Various Energy Systems

The calculation of the load met by the base, intermediate and peak load systems will be first illustrated in the case of the heating systems. The case of cooling system is very similar. The calculation of the power generating system is slightly more complicated because of the minimum capacity at which the system has to be run.

Heating system

Let $\overline{P}_{H,i}$ be the average heating load for period i (i ranges from 1 to 12 for individual months and is equal to 13 for the peak period), and let P_H^{Base} , P_H^{Inter} and P_H^{Peak} be the capacities of the base, intermediate and peak heating systems. The energy needs $Q_{H,i}^{Base}$ met by the base heating system for period i is:

$$\begin{array}{ll} \text{if } \overline{P}_{H,i} \le P_H^{Base} & Q_{H,i}^{Base} = \tilde{N}_i \cdot \overline{P}_{H,i} \\ \text{if } \overline{P}_{H,i} > P_H^{Base} & Q_{H,i}^{Base} = \tilde{N}_i \cdot P_H^{Base} \end{array} \qquad (50)$$

where $\tilde{N}_i$ is the corrected number of hours in the period i (see ***Table 4***). The load not met by the base heating system for that period i is simply:

$$\overline{P}'_{H,i} = P_{H,i} - \frac{Q^{Base}_{H,i}}{\tilde{N}_i} \tag{51}$$

The energy needs $Q^{Inter}_{H,i}$ met by the intermediate heating system for period i is then:

$$\begin{aligned} &\text{if } \overline{P}'_{H,i} \le P^{Inter}_{H} && Q^{Inter}_{H,i} = \tilde{N}_i \cdot \overline{P}'_i \\ &\text{if } \overline{P}'_{H,i} > P^{Inter}_{H} && Q^{Inter}_{H,i} = \tilde{N}_i \cdot P^{Inter}_{H} \end{aligned} \tag{52}$$

The load not met by the either the base of the intermediate heating systems for that period i is then:

$$\overline{P}''_{H,i} = \overline{P}'_{H,i} - \frac{Q^{Inter}_{H,i}}{\tilde{N}_i} \tag{53}$$

and finally the energy needs $Q^{Peak}_{H,i}$ met by the peak heating system during period i is:

$$\begin{aligned} &\text{if } \overline{P}''_{H,i} \le P^{Peak}_{H} && Q^{Peak}_{H,i} = \tilde{N}_i \cdot \overline{P}''_{H,i} \\ &\text{if } \overline{P}''_{H,i} > P^{Peak}_{H} && Q^{Peak}_{H,i} = \tilde{N}_i \cdot P^{Peak}_{H} \end{aligned} \tag{54}$$

(in this last case, the peak load is not met and a warning is displayed to the user). The heating use delivered by the base, intermediate and peak heating systems over the year is obtained simply by summing the contributions of all 13 periods.

Power generating system

In the case of a power generating system, the turndown of cogeneration equipment sometimes limits the operating conditions. For example if m^{Base}_{P} is the minimum capacity of the base power system under consideration, then the energy needs $Q^{Base}_{P,i}$ it meets during period i is:

$$\begin{aligned} &\text{if } P_{P,i} > P^{Base}_{P} && Q^{Base}_{P,i} = \tilde{N}_i \cdot P^{Base}_{P} \\ &\text{if } P_{P,i} \le P^{Base}_{P}: && \\ &\qquad \text{if } P_{P,i} < m^{Base}_{P} \cdot P^{Base}_{P} && Q^{Base}_{P,i} = 0 \\ &\qquad \text{if } P_{P,i} \ge m^{Base}_{P} \cdot P^{Base}_{P} && Q^{Base}_{P,i} = \tilde{N}_i \cdot P_{P,i} \end{aligned} \tag{55}$$

where $P_{P,i}$ is the power load for period i (i =1,…,13), P^{Base}_{P} is the capacity of the base power system, and $\tilde{N}_i$ is the corrected number of hours in period i (see ***Table 4***). Subsequent calculations, such as (51), are automatically adjusted for the change in the value of $Q_{P,i}^{Base}$.

2.5.2 Power generating system availability

For the base and intermediate power generating systems, the user enters the estimated availability in hours or percent of the year. The model calculates the electricity (and co-generated heat) delivered based on the availability. The amount of energy that is not produced by the base load system, because the availability is less than 100%, needs to be produced by the intermediate and/or peak load systems. Heating and cooling systems have an assumed availability of 100%.

Typical values for availability expressed in hours for a new generating system are between 8,000 (91.3%) and 8,400 hours (95.9%) per year. The values may be lower for used and older equipment. If down time can be scheduled to low load times the availability hours can be increased as the model deals with the average monthly load.

The model assumes that the down time is spread equally over the year; so if a_P^{Base} is the fraction of time that the base power generating system is available, the energy delivered by the base system for every period, as calculated by (55), has to be multiplied by a_P^{Base} . Subsequent calculations, such as (51), are again automatically adjusted for the change in the value of $Q_{P,i}^{Base}$. Note that the amount of co-generated heat that can be reclaimed varies in the same proportion.

2.5.3 Operating strategy

The user selects the operating strategy for the base or intermediate load system as either *Full power capacity output*, *Power load following*, or *Heating load following*. When the operating strategy is set to follow either heating or power load, and the load required is less than produced for 100% output but more than then minimum capacity of the generating equipment, the output of the generating equipment will be reduced according to:

$$P_{P,i,m} = P_P \cdot m_i \qquad (56)$$

where m_i is the capacity in percent required to meet the load in period i, P_P is the capacity of the generating equipment and $P_{P,i,m}$ is the reduced output to meet the load in the period i. Both heating and power output will be reduced on a linear basis. Improved or reduced performance on part load is not calculated for any type of equipment.

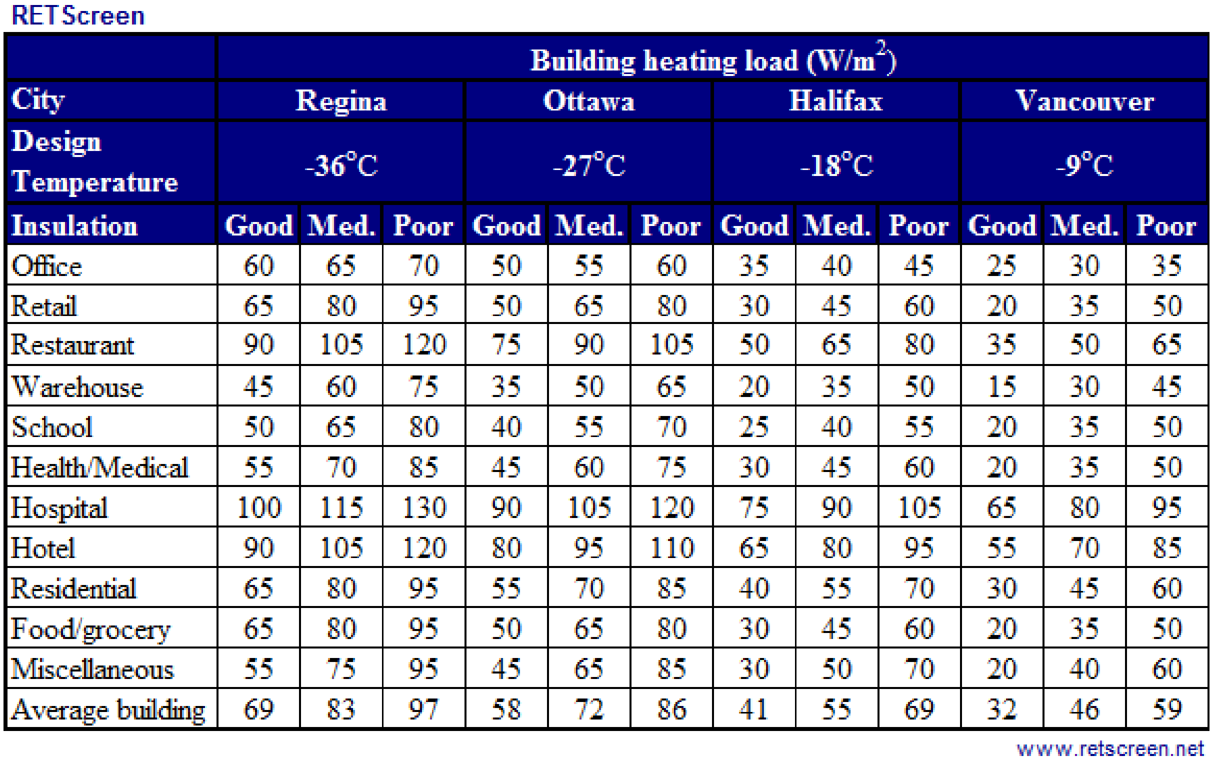
Note finally that when more heat is available than required to meet the heating load, this heat is assumed disposed by a cooling system.

2.6 Tools and Other Algorithms

This section contains a description of some tools and algorithms that are not central to the RETScreen CHP model. Some subsections detail algorithms that are part of the *Energy Model* or *Load and Network* worksheets; other refer to auxiliary algorithms found in the *Tools* worksheet.

2.6.1 Calculation of peak heating load

In the RETScreen CHP Project Model, the peak heating load for a building (or a cluster of buildings with identical thermal properties) is a value p_{Hj} expressed in Watts per square meter of heated floor area. This value is entered by the user and depends on the design temperature for the specific location (see section 2.1.1) and on the building insulation efficiency. Typical values for average buildings range from 30 to 100 W/m^2, as shown in ***Table 5*** (Ciavaglia, L., 2003). This table can also be used to estimate peak heating loads for various kinds of buildings in several Canadian locations. The peak heating load as a function of design temperature is also shown in graphical form in ***Figure 15***.



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	Building heating load (W/m^2)											
City	**Regina**			**Ottawa**			**Halifax**			**Vancouver**		
Design Temperature	-36°C			-27°C			-18°C			-9°C		
Insulation	**Good**	**Med.**	**Poor**	**Good**	**Med.**	**Poor**	**Good**	**Med.**	**Poor**	**Good**	**Med.**	**Poor**
Office	60	65	70	50	55	60	35	40	45	25	30	35
Retail	65	80	95	50	65	80	30	45	60	20	35	50
Restaurant	90	105	120	75	90	105	50	65	80	35	50	65
Warehouse	45	60	75	35	50	65	20	35	50	15	30	45
School	50	65	80	40	55	70	25	40	55	20	35	50
Health/Medical	55	70	85	45	60	75	30	45	60	20	35	50
Hospital	100	115	130	90	105	120	75	90	105	65	80	95
Hotel	90	105	120	80	95	110	65	80	95	55	70	85
Residential	65	80	95	55	70	85	40	55	70	30	45	60
Food/grocery	65	80	95	50	65	80	30	45	60	20	35	50
Miscellaneous	55	75	95	45	65	85	30	50	70	20	40	60
Average building	69	83	97	58	72	86	41	55	69	32	46	59

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Table 5: Building Heating Load for Sample Cities (Ciavaglia, L., 2003)

The values in ***Table 5*** are estimates only; the building types may be described as follows:

Office:	Government, data processing, financial centre, post office, office with retail (except food), real estate, computer centre, etc.
Retail:	Strip mall, hardware store, department store, furniture store, drugstore, car dealership, multi retail buildings.

Restaurant:	Full service, cafeteria, carry out, food related sales and service.
Warehouse:	Storage, agricultural storage, stand alone barns, etc.
School:	Educational buildings, colleges, Universities, etc.
Health / Medical:	Medical clinic, dental clinic, veterinary clinic, out-patient care, rehabilitation centre.
Hospital:	Medical care hospital, mental care facility.
Hotel:	Motel, hotel, short-term residential, tourist home.
Residential:	Apartments, condominiums, (may be used for single family homes).
Food / Grocery:	Retail food, supermarket, farmer's market, specialty food stores.
Miscellaneous:	Fire/police station, library, religious assembly, amusement arcade, museum, art gallery, concert hall, theatre, gas station, jail, shelter home, civic assembly, passenger terminal, etc.

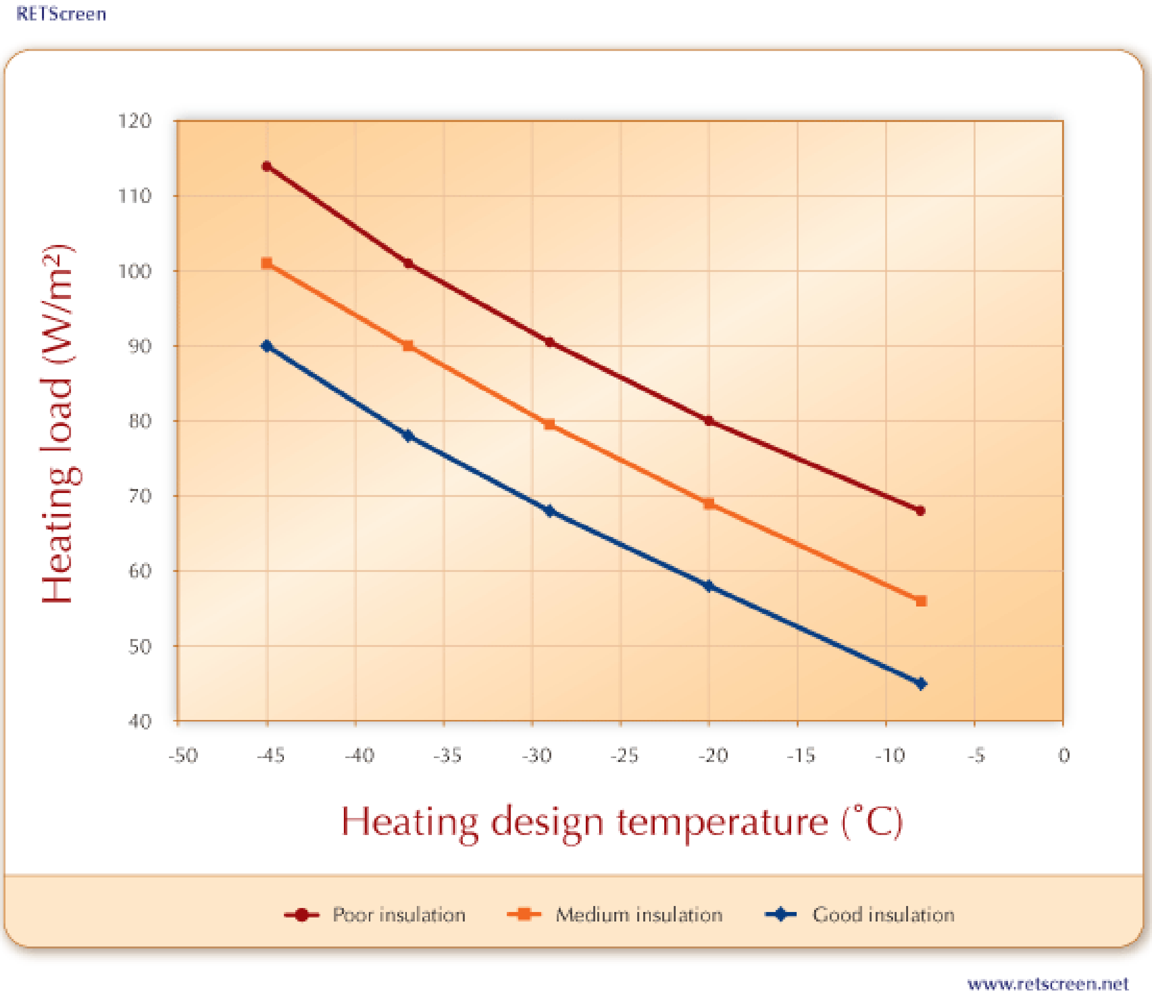


Figure 15: Building Heating Load Chart (CET, 1997)

2.6.2 Calculation of peak cooling load

In the same way, the peak cooling load per unit area is entered by the user and depends on the design temperature for the specific location (see section 2.2.1) and on the building insulation efficiency. ***Figure 16***

(CET, 1997) can be used as a guide to estimate peak cooling load as a function of location and building insulation.

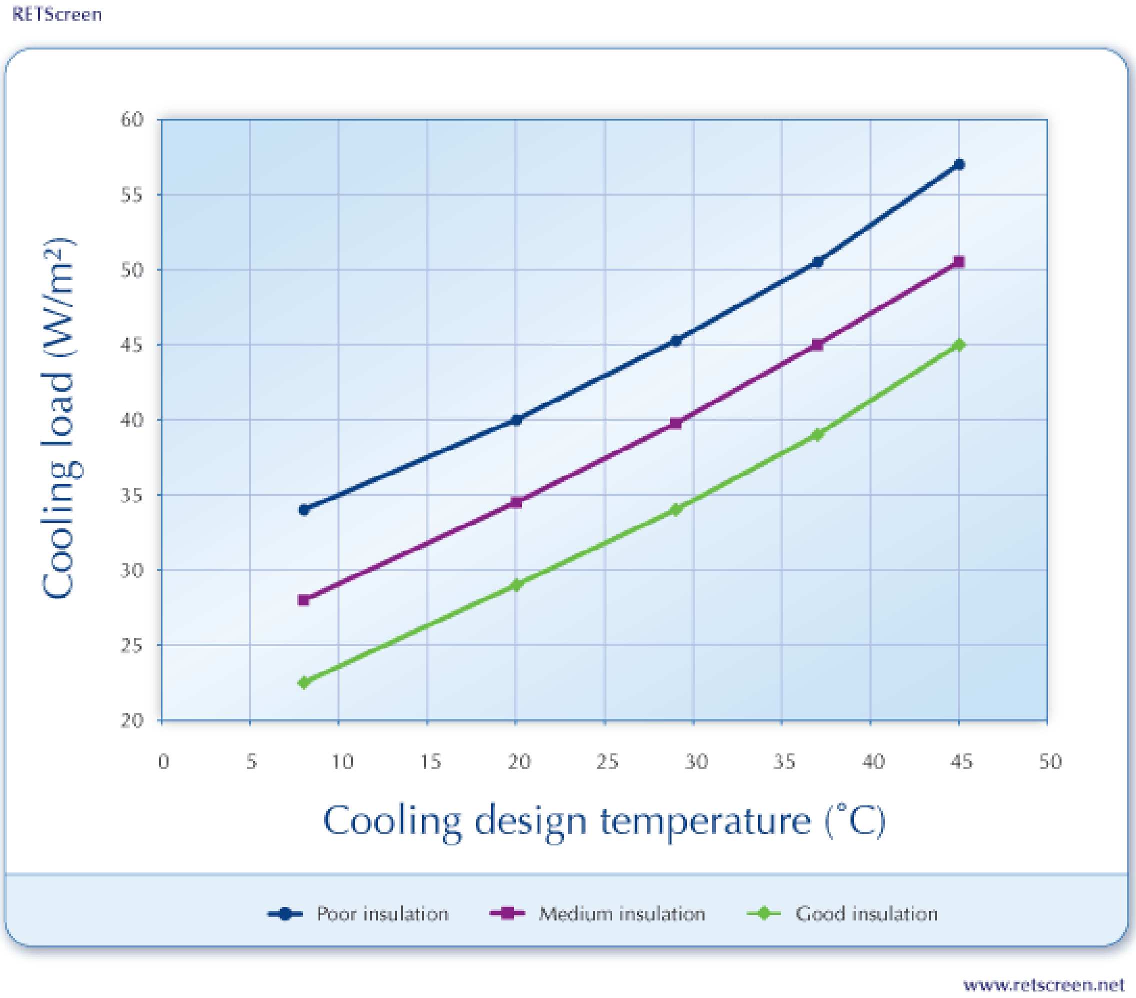
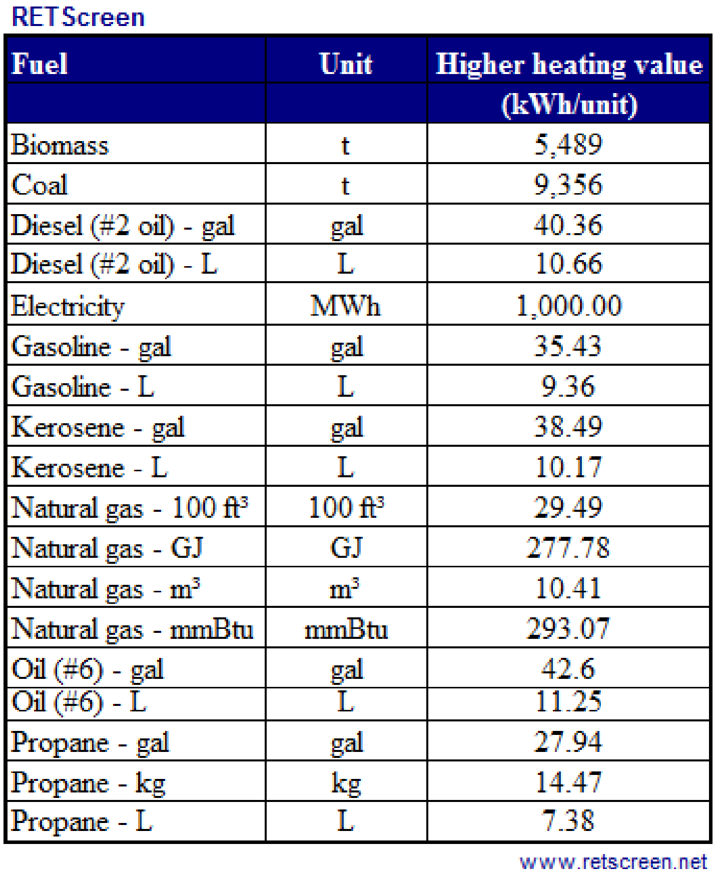


Figure 16: Building Cooling Load Chart (CET, 1997)

2.6.3 Calculation of base case fuel consumption

To evaluate the financial benefits of the proposed system, one has to calculate the quantity of fuel that would be used if the proposed system were not installed. This is what is called the *alternative fuel consumption*, or what is referred to as the *base case system*.

Units used to measure fuel consumption and heating values depend on the type of fuel used. ***Table 6*** summarizes the units and heating values for the different fuel types in RETScreen.



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Fuel	Unit	Higher heating value (kWh/unit)
Biomass	t	5,489
Coal	t	9,356
Diesel (#2 oil) - gal	gal	40.36
Diesel (#2 oil) - L	L	10.66
Electricity	MWh	1,000.00
Gasoline - gal	gal	35.43
Gasoline - L	L	9.36
Kerosene - gal	gal	38.49
Kerosene - L	L	10.17
Natural gas - 100 ft³	100 ft³	29.49
Natural gas - GJ	GJ	277.78
Natural gas - m³	m³	10.41
Natural gas - mmBtu	mmBtu	293.07
Oil (#6) - gal	gal	42.6
Oil (#6) - L	L	11.25
Propane - gal	gal	27.94
Propane - kg	kg	14.47
Propane - L	L	7.38

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Table 6: Units and Heating Values of Various Fuels

The heating alternative fuel consumption (HAFC) is calculated as:

$$M_{HAFC} = \frac{Q_H}{\eta_{hs,se} \cdot C_f} \qquad (57)$$

where M_{HAFC} is the heating alternative fuel consumption [units: m^3, L or MWh, as per ***Table 6***], $\eta_{hs,se}$ is the heating system seasonal efficiency [expressed without units] entered by the user, C_f is the heating value for the selected fuel type [kWh/unit, as per ***Table 6***], and Q_H is the heating energy use of the building or cluster of buildings [expressed in kWh]. The same formula applies to the calculation of the cooling alternative fuel type consumption M_{CAFC}:

$$M_{CAFC} = \frac{Q_C}{\eta_{cs,se} \cdot C_f} \qquad (58)$$

where $\eta_{cs,se}$ is the cooling system seasonal efficiency [expressed without units] entered by the user, and Q_C is the cooling energy use of the building or cluster of buildings [expressed in kWh].

When the electricity is used for heating or cooling, the net amount of electricity used on a monthly basis is added to the amount of electricity used for heating or cooling purposes in order to calculate the gross monthly average power load. This can be shown mathematically as:

$$P_{Pi,gross} = \overline{P}_{Pi} + P^{e}_{C,i} + P^{e}_{H,i} \qquad (59)$$

$$P^{e}_{H,i} = \frac{\overline{P}_{H,i}}{\eta_{hs,se}} \qquad (60)$$

$$P^{e}_{C,i} = \frac{\overline{P}_{C,i}}{\eta_{cs,se}} \qquad (61)$$

where $P_{Pi,gross}$ is the gross monthly average power load, $\overline{P}_{Pi}$ is the monthly power net average load specified by the user, $P^{e}_{H,i}$ is the monthly power load for the heating system, $\overline{P}_{H,i}$ is the monthly average heating load using electricity as a fuel, $\eta_{hs,se}$ is the heating system seasonal efficiency, $P^{e}_{C,i}$ is the monthly power load for the cooling system, $\overline{P}_{C,i}$ is the monthly average cooling load using electricity as a fuel and $\eta_{cs,se}$ is the cooling system seasonal efficiency.

2.6.4 Calculation of fuel heating value of biomass fuels

The calorific value or heating value of fuel is the measure of heat released, per unit weight of fuel, during the complete combustion of the fuel. The *higher heating value* (also referred to as *HHV* or *gross heating value*) refers to the maximum energy that can be released, per unit weight of *dry* fuel, from burning dry fuel (see note 10) . The *lower heating value* (also referred to as *LHV* or *net heating value* or *as fired heating value*) of the fuel subtracts the energy in the water vapour produced from the water in the fuel and in the water vapour produced from the hydrogen in the fuel; it is expressed per unit weight of wet fuel.

High moisture content biomass fuel reduces system efficiency, because the vaporization of water to steam requires heat. As flue gases are rarely condensed in small biomass system, this energy which otherwise would be useful in heat production is thus diverted to drying the wood fuel in the combustion system prior to actually burning it. Higher moisture content in the fuel means lower net heating value of the fuel. Typical as fired heating values for biomass range from 10,800 to 15,900 MJ/tonne of biomass on a wet basis.

The heating value of biomass fuels depends on the nature of the fuel considered. In the CHP heating model of RETScreen, the user selects the type of biomass fuel from a list, and specifies the moisture content. The *moisture content* of biomass fuel on the *wet basis* is the weight of water in a wood sample divided by the total weight of the sample:

$$MCWB = \frac{W_{water}}{W_{water} + W_{drywood}} \cdot 100 \qquad (62)$$

where $MCWB$ is the moisture content wet basis, expressed in %, W_{water} is the weight of water, and $W_{drywood}$ is the weight of dry wood. In RETScreen $MCWB$ is entered by the user.

The *ultimate analysis* of a fuel describes its elemental composition as a percentage of the sample's dry weight. Typically the ultimate analysis tests for hydrogen, carbon, oxygen, nitrogen, sulphur and ash (the amount of sulphur in biomass fuels is typically very low or non existent). ***Table 7*** shows sample analysis of various biomass fuel types.

A *proximate analysis* describes the volatiles, fixed carbon and ash present in the fuel as a percentage of dry fuel weight. The amount of volatiles and fixed carbon directly affect the heating value of the fuel, flame temperature and the process by which combustion is achieved. The ash content is important in the design of air emission control equipment, combustion systems and ash handling systems.

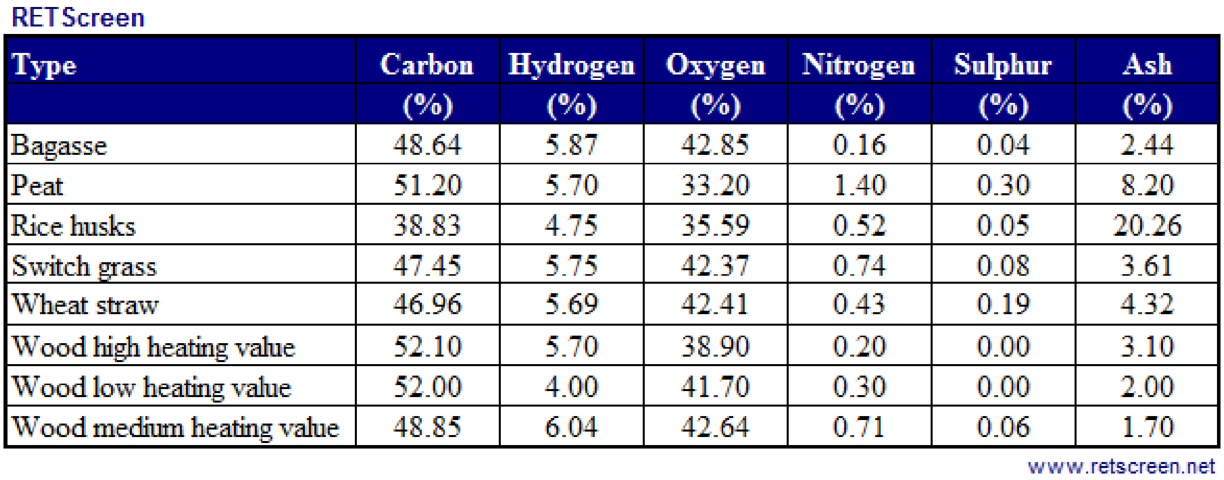
Analytically formulae have been developed for the prediction of the higher heating value of coal and other fossil fuels. Exact calculations are available for all components of biomass fuel which will oxidize. However, it is very difficult to quantify the contribution of volatiles to the heating value. From experience the following formula has proven to be reliable for biomass, and is used in the RETScreen model:

$$HHV_{Biomass} = 34.1C + 123.9H_2 - 9.85O_2 + 6.3N_2 + 19.1S \qquad (63)$$

where $HHV_{Biomass}$ is the higher heating value [MJ/kg], and C , H_2 , O_2 , N_2 and S are the weight percentage for carbon, hydrogen, oxygen, nitrogen, and sulphur respectively in the dry fuel. The corresponding lower heating value LHV (as fired), in MJ/kg, is given by:

$$LHV = (HHV - 21.92H_2)(1 - MCWB/100) - 0.02452\,MCWB \qquad (64)$$

where $MCWB$ is the moisture content wet basis expressed in %. The value from equation (63) is used to calculate the annual biomass requirements of the heating system.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Type	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)	Ash (%)
Bagasse	48.64	5.87	42.85	0.16	0.04	2.44
Peat	51.20	5.70	33.20	1.40	0.30	8.20
Rice husks	38.83	4.75	35.59	0.52	0.05	20.26
Switch grass	47.45	5.75	42.37	0.74	0.08	3.61
Wheat straw	46.96	5.69	42.41	0.43	0.19	4.32
Wood high heating value	52.10	5.70	38.90	0.20	0.00	3.10
Wood low heating value	52.00	4.00	41.70	0.30	0.00	2.00
Wood medium heating value	48.85	6.04	42.64	0.71	0.06	1.70

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Table 7: Sample Ultimate Analysis of Biomass

The *Tools* worksheet contains a tool allowing the user to enter a user defined solid or gas fuel. The fuel entered in these tools will appear in the fuel database available through a drop-down list in the software.

The higher heating value for fossil fuels may be approximated by Dulong's formula:

$$HHV_{FossilFuel} = (14{,}544C + 62{,}028(H_2 - \frac{O_2}{8}) + 4{,}050S) \cdot 2.326 \qquad (65)$$

where $HHV_{FossilFuel}$ is the higher heating value [kJ/kg], and C, H_2 , O_2 and S are the mass percentage for carbon, hydrogen, oxygen, and sulphur respectively in the fuel.

The higher heating value for gas fuels is also calculated using Dulong's formula (equation (65)). The *Tools* worksheet formula is considering the amount of methane CH_4 , ethane C_2H_6, carbon-dioxide CO_2 , oxygen O_2 and nitrogen N_2 in the gas. As an example, for a gas that has 50% methane and 50% carbon-dioxide, the mass percentage for carbon, hydrogen, oxygen are:

$$X = 12.011(1 \cdot x_{CH_4} + 1 \cdot x_{CO_2}) + 2.016(2 \cdot x_{CH_4}) + 31.999(1 \cdot x_{CO_2}) \qquad (66)$$

$$C = \frac{12.011(1 \cdot x_{CH_4} + 1 \cdot x_{CO_2})}{X} \qquad (67)$$

$$H_2 = \frac{2.016(2 \cdot x_{CH_4})}{X} \qquad (68)$$

$$O_2 = \frac{31.999(1 \cdot x_{CO_2})}{X} \qquad (69)$$

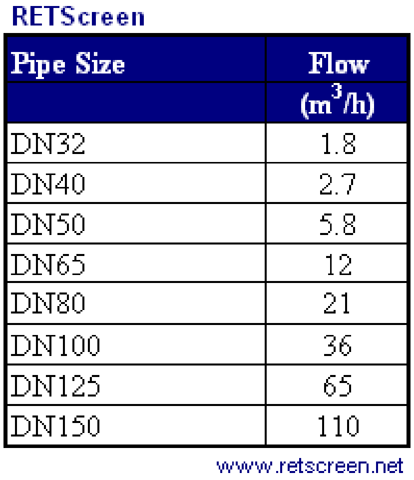
where X is the total mole mass, x_{CO_2} and x_{CH_4} are the mass percentage of carbon-dioxide and methane respectively and C , H_2 , O_2 , N_2 and S are the mass percentage for carbon, hydrogen, oxygen, nitrogen, and sulphur respectively in the fuel.

2.6.5 Network design

District heating and cooling network design is included in the RETScreen CHP model so that the user can do a preliminary sizing of the pipes and cost the installation. The calculation takes place in the *Load and Network* worksheet; however its results have no influence on the energy calculation part of the worksheet.

A district heating/cooling piping distribution system consists of an underground hot/cold water distribution network with supply and return line pipes in a closed circuit. Each building is connected to the network via a building heat/cooling transfer station that regulates and measures the energy taken from the distribution system. The network comprises a *main distribution line* which connects several buildings, or clusters of buildings, to the heating/cooling plant, and *secondary distribution lines* which connect individual buildings to the main distribution line. The pipe network is usually oversized to allow a future expansion of the system. In RETScreen the over-sizing factor is specified by the user.

For preliminary sizing of the network pipes a simplified method has been used in the RETScreen CHP model. It has been assumed that the head loss is not to exceed 20 mm H_2O or 200 Pa per meter of pipe; and for dimension larger than 400 mm a maximum velocity of 3 m/s is to be used. Standard formulae (Avallone & Baumeister, 1987) for pressure head loss in pipes as a function of water velocity and pipe diameter have been used to calculate maximum flow values shown in ***Table 8***.



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Pipe Size	Flow (m^3/h)
DN32	1.8
DN40	2.7
DN50	5.8
DN65	12
DN80	21
DN100	36
DN125	65
DN150	110

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Table 8: Maximum Allowable Flow in Selected Pipe Sizes, for a Maximum Friction Loss of 200 Pa/m

The total heating load carried in a pipe in the main distribution line can be calculated as:

$$P_{pipe} = \rho V c_p \Delta T_{s-r} \qquad (70)$$

where V is the volumetric flow of water, ρ the density of water, c_p its specific heat (set to its value at 78°C, 4,194 J/(kg °C) for heating pipes and at 5°C, 4.205 J/(kg °C) for cooling pipes), and ΔT_{s-r} is the differential temperature between supply and return, specified by the user. This relationship can be inversed to find, given the peak load of the building cluster (quantity $P_{H,j}$ from equation (10)), the volumetric flow of water that the pipe will be required to carry:

$$V = \frac{\rho c_p \Delta T_{s-r}}{P_{H,j}} \qquad (71)$$

The actual formula used in RETScreen includes a factor for pipe over-sizing; if κ is the main pipe over-sizing factor, expressed in %, entered by the user, equation (71) becomes:

$$V = \frac{\rho c_p \Delta T_{s-r}}{(1+\kappa/100)P_{H,j}} \qquad (72)$$

Then, a lookup in ***Table 8*** provides the desirable pipe size given the flow. In the case where several clusters of buildings are served by the same main distribution line pipe, the load in equation (72) should naturally be replaced by the sum of the relevant loads.

Finally, a similar relationship holds for secondary distribution lines piping. The denominator of equation (72) is then replaced with a load $P'_{H,j}$ given by:

$$P'_{H,j} = \frac{P_{H,j}(1+\kappa'/100)}{N_j} \qquad (73)$$

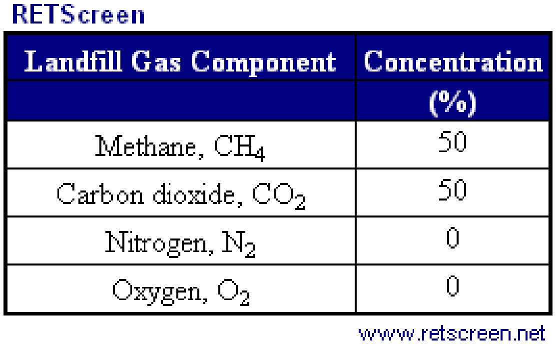
where κ' is the secondary pipe network over-sizing factor specified by the user, and N_j is the number of buildings in the cluster.

2.6.6 Landfill gas generation

The *Tools* worksheet in RETScreen includes a section to estimate landfill gas availability. This section explains the models used for this calculation.

Landfill gas is generated by the biological decomposition of wastes placed in a landfill. The composition of landfill gas is highly variable and depends on a number of site-specific conditions including solid waste composition, density, moisture content, and age. The specific composition of landfill gas varies significantly from landfill to landfill and even from place to place within a single landfill. However, landfill gas is typically comprised of methane and carbon dioxide, approximately 50 percent each by volume with trace quantities of other compounds including hydrogen sulphide, mercaptans, and non-methane organic compounds (NMOC).

Two other gases that may be present in landfill gas in varying quantities are nitrogen and oxygen. The presence of nitrogen and oxygen in a sample of landfill gas is often an indication that there is intrusion of ambient air into the landfill gas collection or delivery system. When in the presence of methane or other combustible gases, a gas mixture containing oxygen is considered to be explosive when the concentration of oxygen is between 5 and 15 percent by volume. A suitable source of landfill gas for flaring or utilization purposes attempts to maximize the concentration of methane and minimize the amount of oxygen and nitrogen in the mixture. For the purposes of a technical feasibility assessment of the use of landfill gas in a combined heat and power project as a fuel source, the concentration of oxygen and nitrogen in the gas fuel are assumed to be zero. Methane is the primary component of landfill gas which contributes to the gas's heating value. The heating value of methane is typically defined on a volume basis.



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Landfill Gas Component	Concentration (%)
Methane, CH_4	50
Carbon dioxide, CO_2	50
Nitrogen, N_2	0
Oxygen, O_2	0

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Table 9: The Standard Default Concentrations for Typical Components of Landfill Gas

Modeling landfill gas generation

There are numerous models available for estimating rates of landfill gas generation, however accepted industry standard models are generally first order kinetic models that rely on a number of basic assumptions. These models are used to predict the variation of landfill gas generation rates with time for a typical unit mass of solid waste. This generation rate curve is then applied to records, or projections, of solid waste filling at a site to produce an estimate of the site's landfill gas generation over time.

The Scholl Canyon model, with defined default parameters is the empirical, first-order decay model most widely accepted and used by industry and regulatory agencies, including Environment Canada and the United States Environmental Protection Agency (USEPA). There are many more detailed models available for the estimation of landfill gas generation rates, however, these models require more specific knowledge of the waste quantities, waste composition, and landfilling practices associated with the site than is generally available, especially for older landfill sites where such records were not required.

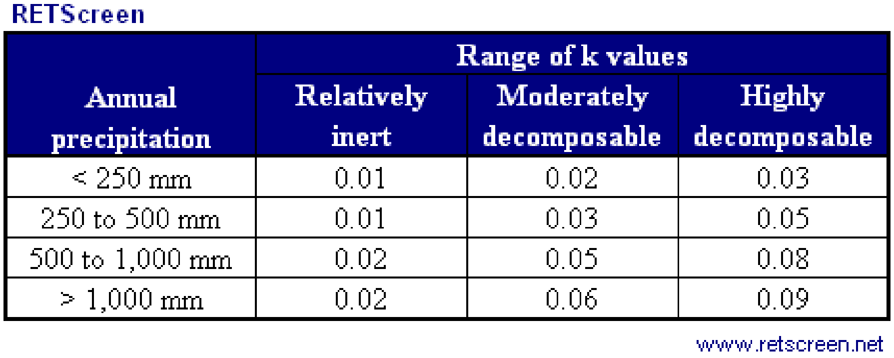
The Scholl Canyon model is based on the assumption that there is a constant fraction of biodegradable material in the landfill per unit of time, and is an estimate of the generation of methane from this biodegradable material. The first-order equation is given below:

$$Q_{CH4_i} = kL_0 m_i e^{-kt} \tag{74}$$

where Q_{CH4_i} is the volume of methane produced in year i from a section of waste, k the methane generation constant, L_0 the methane generation potential, m_i the waste mass disposed of in year i, t the years after closure of landfill.

It is typical practice to assume that the volume of landfill gas generated consists of 50 percent methane and 50 percent carbon dioxide so that the total volume of landfill gas produced is equal to twice the volume of methane calculated from equation (74). The volume of landfill gas estimated may be adjusted for any concentration of methane in the same manner.

The k constant represents the first-order biodegradation rate at which methane is generated following the placement of biodegradable wastes. This constant is influenced by moisture content, the availability of nutrients, pH, and temperature. The moisture content of the waste within a landfill is one of the most important parameters affecting the landfill gas generation rate. The moisture content of waste within a landfill is influenced primarily by the infiltration of precipitation through the landfill cover, the initial moisture content of the waste, the design of the leachate collection system, and the depth of waste in the site. Typical values for k range from 0.02 for dry sites to 0.07 for wet sites.



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Annual precipitation	Range of k values		
	Relatively inert	Moderately decomposable	Highly decomposable
< 250 mm	0.01	0.02	0.03
250 to 500 mm	0.01	0.03	0.05
500 to 1,000 mm	0.02	0.05	0.08
> 1,000 mm	0.02	0.06	0.09

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Table 10: Range of k Values by Annual Precipitation

The methane generation potential, L_0 , represents the total yield of methane expressed in units of m^3 of methane per tonne of waste. The value of L_0 is dependent on the composition of the waste, in particular, the fraction of organic matter present in the waste. The value of L_0 may be estimated based on the carbon content of the waste, the biodegradable carbon fraction, and a stoichiometric conversion factor. Typical values for L_0 range from 125 m^3 of methane/tonne of waste to 310 m^3 of methane/tonne of waste. The default value for L_0 of 170 m^3 of methane/tonne of waste recommended by the USEPA in their New Source Performance Guidelines (NSPS Tier 1 default, 1994), is considered to be a fairly conservative value, which is representative of a majority of domestic and municipal solid waste landfills in the United States. Selection of a different value for the methane production potential L_0 should be based on the users specific knowledge and experience with the landfill site that is being assessed.

The quantity (in tonnes) of typical waste landfilled in a particular year is represented by variable m_i in equation (74). In landfills where there are good data indicating a significant portion of inert or non-decomposable waste, such as construction and demolition debris, this parameter may be reduced to represent only the amount of waste that is not inert. However, in many cases there is insufficient data to make this determination. A specific reduction of m_i should only be made if there is a readily discernible portion of the waste that is different from the typical waste received at most conventional mixed solid waste landfills. The default assignment of L_0 already recognizes that there is a mixture of decomposable organic wastes and inorganic wastes being deposited in a typical fill site.

Another important factor is the assumed lag time between the placement of waste in a landfill and the beginning of the anaerobic decomposition of the waste mass, i.e., production of landfill gas. A typical lag time between the placement of waste and the start of methane generation is 1 year.

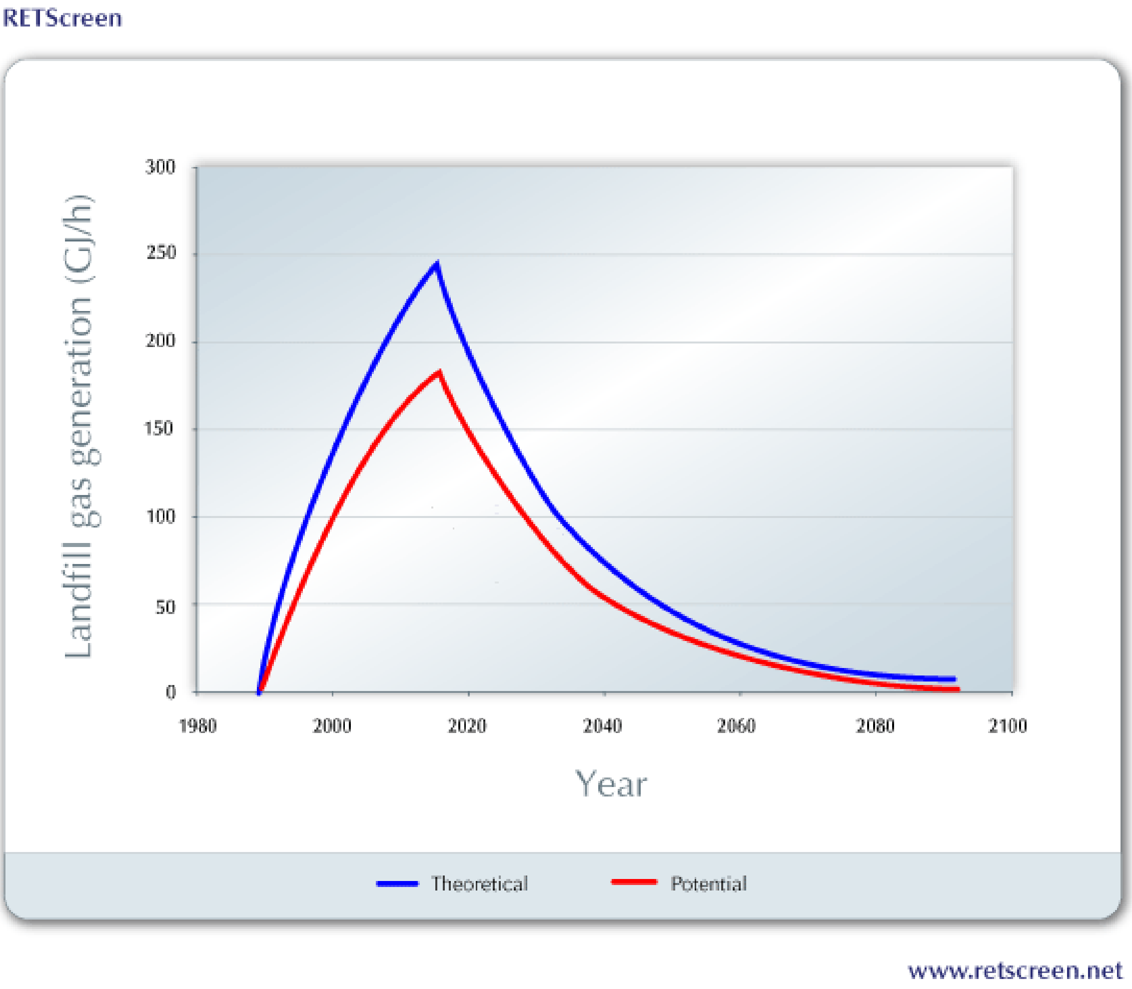

Figure 17: Example of Landfill Gas Generation Curve

Figure 17 provides a landfill gas generation curve produced using the Scholl Canyon model with the conservative USEPA default values used for a preliminary site assessment for a relatively dry site (less than 625 mm (25 inches) of rain), with a constant fill rate of 500,000 tonnes per year for 25 years (from 1990 to 2015), using a value for k of 0.05, L_0 of 170 m^3 of methane per tonne of waste. The figure shows two curves, the theoretical total amount of landfill gas generated using the Scholl Canyon model and the landfill gas collected assuming a typical collection system efficiency of 75 percent.

It is important to note that the results obtained from these models represent estimated production rates. Actual recovery rates will vary as dictated by the actual landfill gas generation rate and by the recovery efficiency of the landfill gas collection system. Reported recovery efficiencies range from 60 to 80 percent, and 75 percent is generally assumed in the absence of site-specific data.

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10. The higher heating value is defined in ASTM Standard "Standard Test Method for gross calorific value of solid fuel by the adiabatic bomb calorimeter."

2.7 Validation

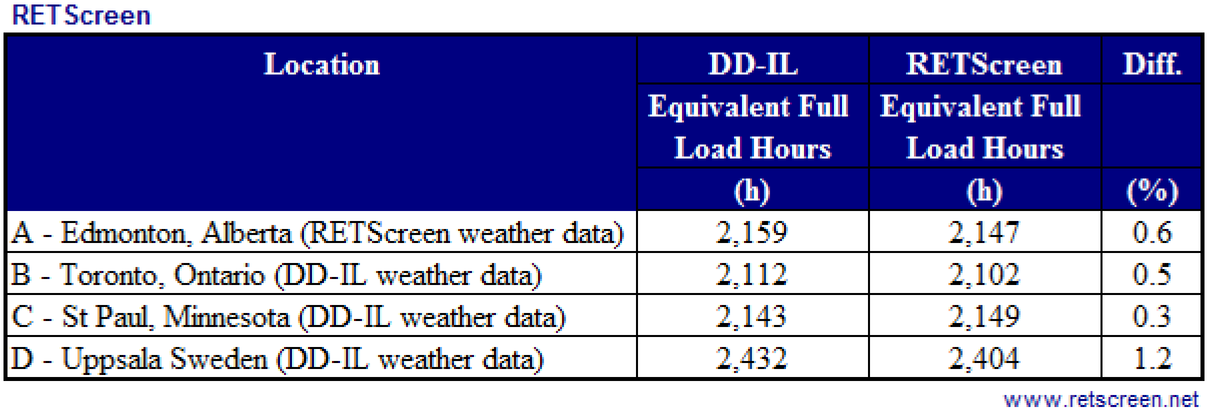
Numerous experts have contributed to the development, testing and validation of the RETScreen CHP Project Model. They include CHP heating modeling experts, cost engineering experts, greenhouse gas modeling specialists, financial analysis professionals, and ground station and satellite weather database scientists.

Validation of parts of the RETScreen CHP Project Model was done against other models used in the industry. The validation focused on three areas: calculation of the load duration curve (section 2.7.1), calculation of the heating value of biomass (section 2.7.2), and heating network pipe sizing (section 2.7.3). A more global validation is shown in section 2.8, Validation by an Independent Company.

2.7.1 Validation of load duration curve

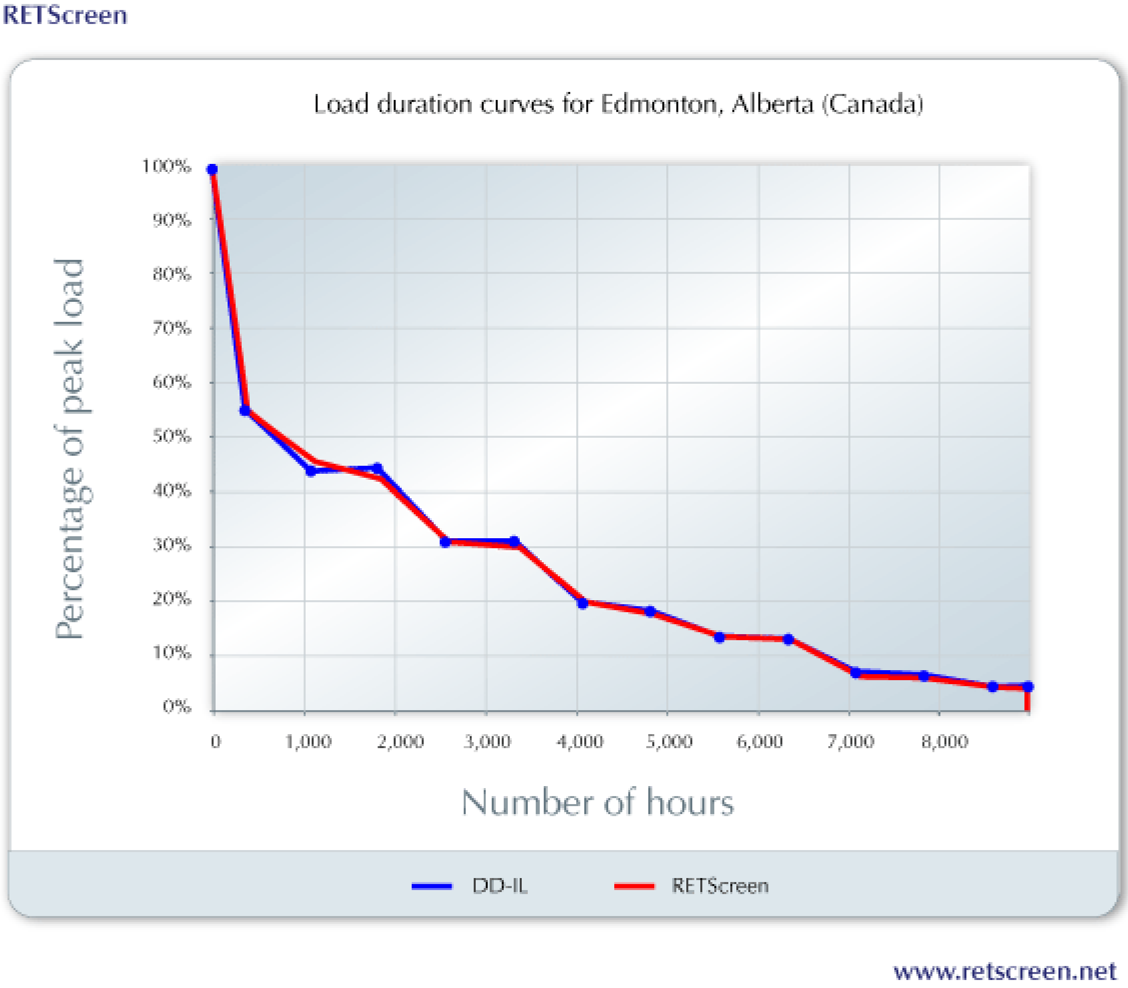
To validate the load duration curve generated by RETScreen (see section 2.1.4), a comparison was made with a computer model developed by Mr. Ingvar Larsson at FVB District Energy Consultants in Sweden. Mr. Larsson's model, hereafter named "DD-IL," was developed using extensive records from two large and closely monitored district heating systems (St. Paul, MN, USA and Uppsala, Sweden). The RETScreen model was tested against DD-IL with data for four different cities: Edmonton, Alberta (Canada), Toronto, Ontario (Canada), St. Paul, Minnesota (USA), and Stockholm (Sweden). For all cities, degree-days data from DD-IL were used in RETScreen (rather than degree-days from the RETScreen Climate database) to eliminate artificial differences that could result from using weather data from different sources in the two programs. The only exception is for Edmonton where data from the climate database of RETScreen were used in DD-IL. Load duration curves were generated for the four cities using a 2.74 °C-d/d (1,000 degree-days annually) equivalent degree-days for domestic hot water heating, except for Uppsala where a value of 2.88 °C-d/d (1,050 degree-days annually) was used.

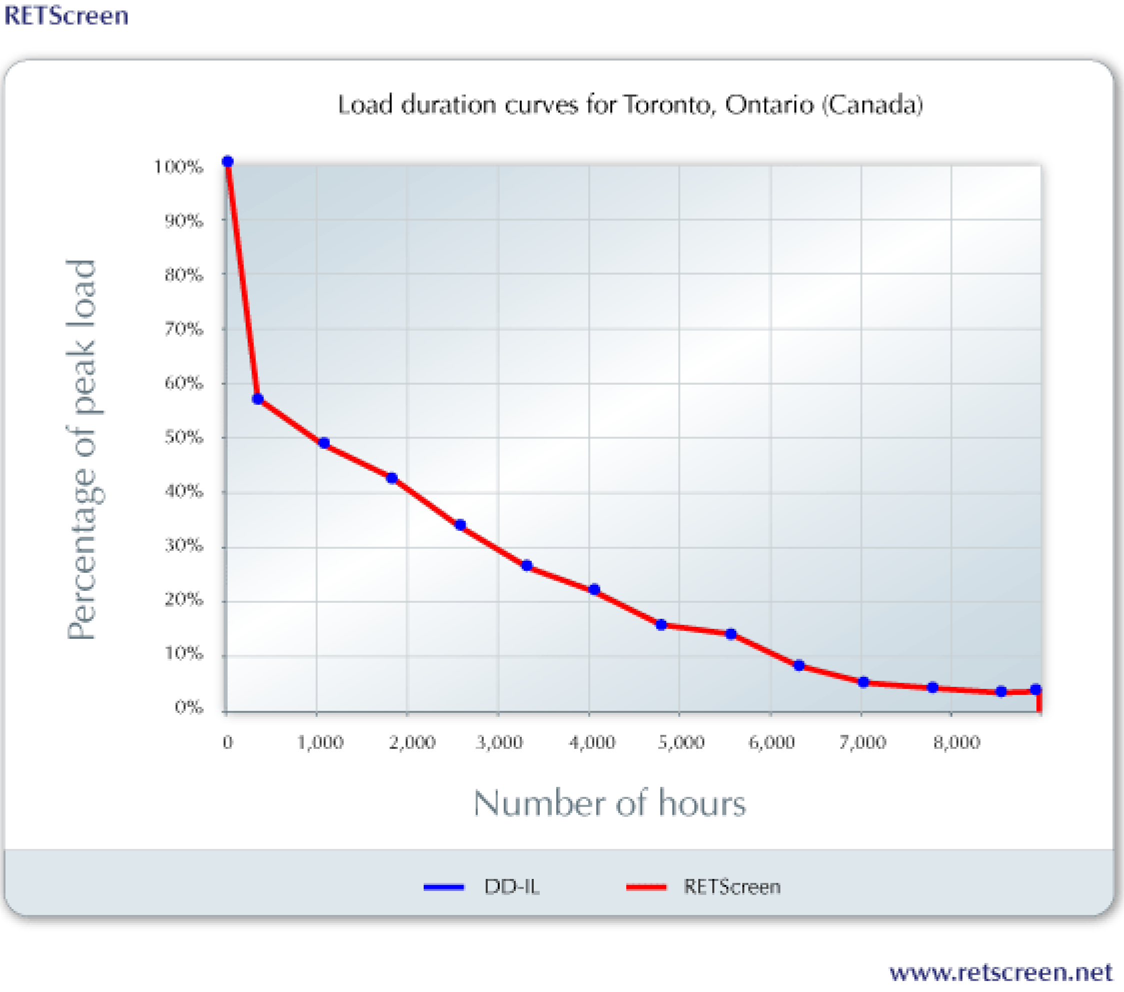
Table 11 compares the equivalent full load durations calculated by the two programs for the four locations. The results are very similar (less than 1% difference). ***Figure 18***. shows the load duration curves calculated by the two programs. Again the differences are minute. For Toronto and Uppsala the two programs generate exactly the same curves. For Edmonton and Saint Paul the generated curves are very close.

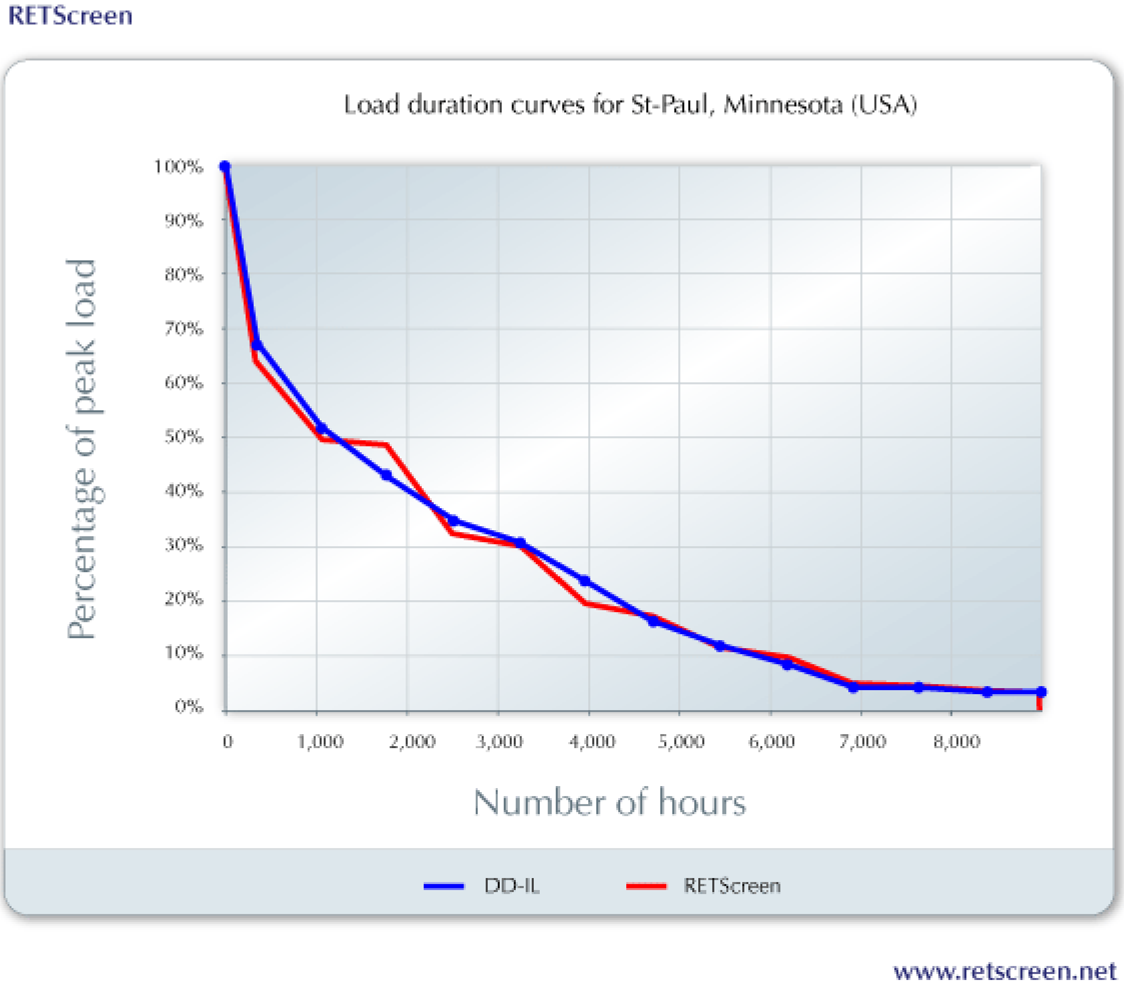


Location	DD-IL	RETScreen	Diff.
	Equivalent Full Load Hours	Equivalent Full Load Hours	
	(h)	(h)	(%)
A - Edmonton, Alberta (RETScreen weather data)	2,159	2,147	0.6
B - Toronto, Ontario (DD-IL weather data)	2,112	2,102	0.5
C - St Paul, Minnesota (DD-IL weather data)	2,143	2,149	0.3
D - Uppsala Sweden (DD-IL weather data)	2,432	2,404	1.2

Table 11: Comparison of Equivalent Full Load Duration Hours for Different Communities


RETScreen
Load duration curves for Edmonton, Alberta (Canada)
Percentage of peak load
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Number of hours
DD-IL
RETScreen
www.retscreen.net


RETScreen
Load duration curves for Toronto, Ontario (Canada)
Percentage of peak load
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Number of hours
DD-IL
RETScreen
www.retscreen.net


RETScreen
Load duration curves for St-Paul, Minnesota (USA)
Percentage of peak load
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Number of hours
DD-IL
RETScreen
www.retscreen.net

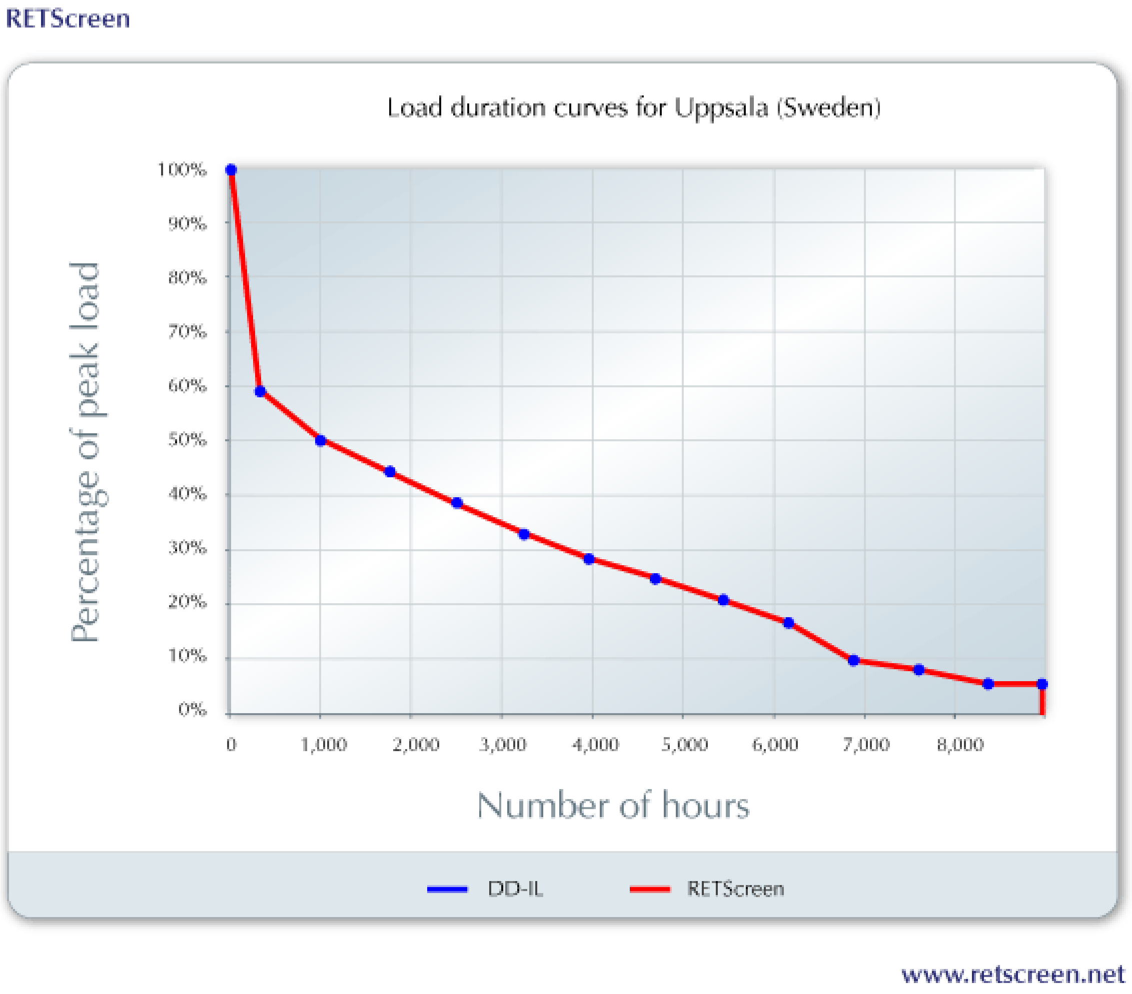


Figure 18: Load Duration Curves Calculated with DD-IL and RETScreen for Four Different Cities

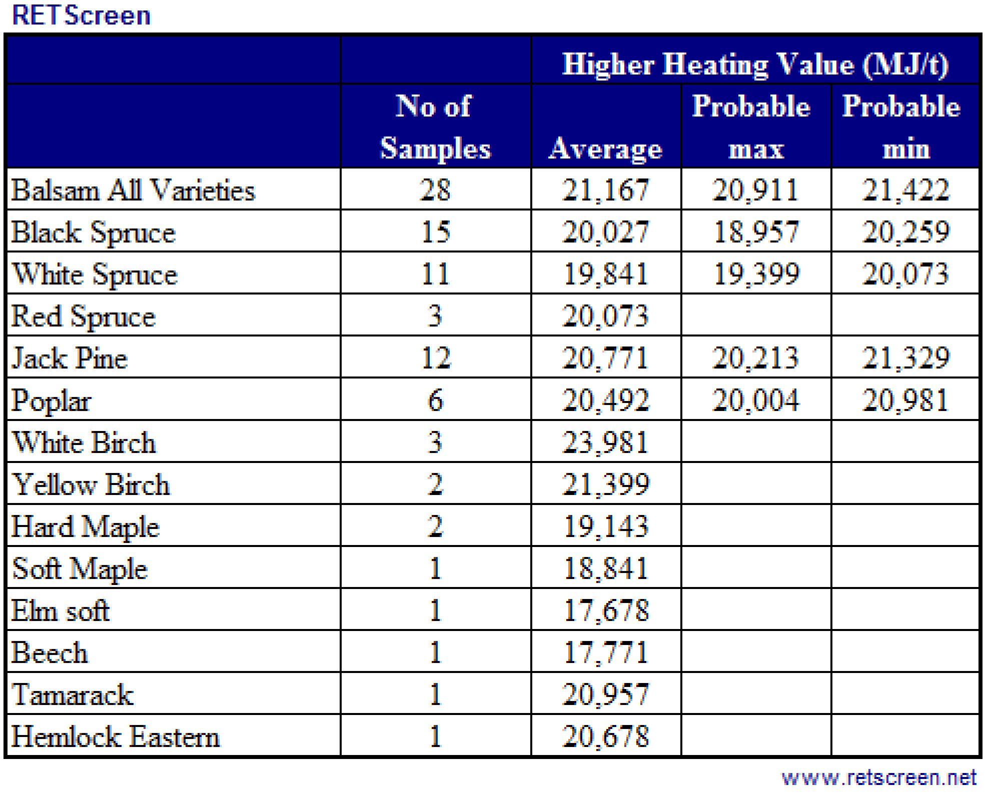
2.7.2 Validation of heating value algorithm

To validate the heating value algorithm used by RETScreen (see section 2.6.4), its predictions were compared to findings reported in the Summer Meeting of the Technical Section, Canadian Pulp and Paper Association, Quebec, Quebec, Canada, June 6 to 8, 1955. In the paper called *Determination of Bark Volumes and Fuel Properties*, data was collected from thirty mills by the Forest Products Laboratories of Canada and the Federal Department of Mines and Technical Surveys. The chemical analyses (proximate and ultimate) from the samples were all performed by one laboratory. The heating values were statistically analyzed by the Forest Products Laboratories with the following results:

Age: no correlation between heating value and the age of the tree was noticeable.

Geographical area: analyses of tests did not reveal any significant differences among heating values due to area.

Species: the tests show a significant difference in the heating value among the various species in the following order (highest first): 1 - Balsam, 2 - Jack Pine, 3 - Poplar, 4 - Spruce.



RETScreen

		Higher Heating Value (MJ/t)		
	No of Samples	Average	Probable max	Probable min
Balsam All Varieties	28	21,167	20,911	21,422
Black Spruce	15	20,027	18,957	20,259
White Spruce	11	19,841	19,399	20,073
Red Spruce	3	20,073		
Jack Pine	12	20,771	20,213	21,329
Poplar	6	20,492	20,004	20,981
White Birch	3	23,981		
Yellow Birch	2	21,399		
Hard Maple	2	19,143		
Soft Maple	1	18,841		
Elm soft	1	17,678		
Beech	1	17,771		
Tamarack	1	20,957		
Hemlock Eastern	1	20,678		

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Table 12: Measured Heating Values of Eastern Canadian Bark

Table 12 summarizes the heating values measured in the test. These values should be compared to those proposed by RETScreen for the heating value of wood waste, which range from a low of 17,723 MJ/t to a high of 19,760 MJ/t with an average of 18,673 MJ/t. The variation according to this test is +/- 3% for Jack Pine and up to -5% for Black Spruce. The estimate given by RETScreen is amply sufficient at the pre-feasibility stage of a project.

The higher heating value algorithm of RETScreen (equation (63)) was also tested against 55 samples measured by the US National Renewable Energy Laboratory (NREL) under Subcontract TZ-2-11226-1 in February 1996. ***Figure 19*** compares measured values against values predicted by RETScreen. The average difference between the laboratory tests and the RETScreen model is 3.41% with a standard deviation of 3.75%. The difference between the results is again quite acceptable; one has to keep in mind, for example, that the typical variation in moisture content over a year for a biomass fuel can be more than 15%.

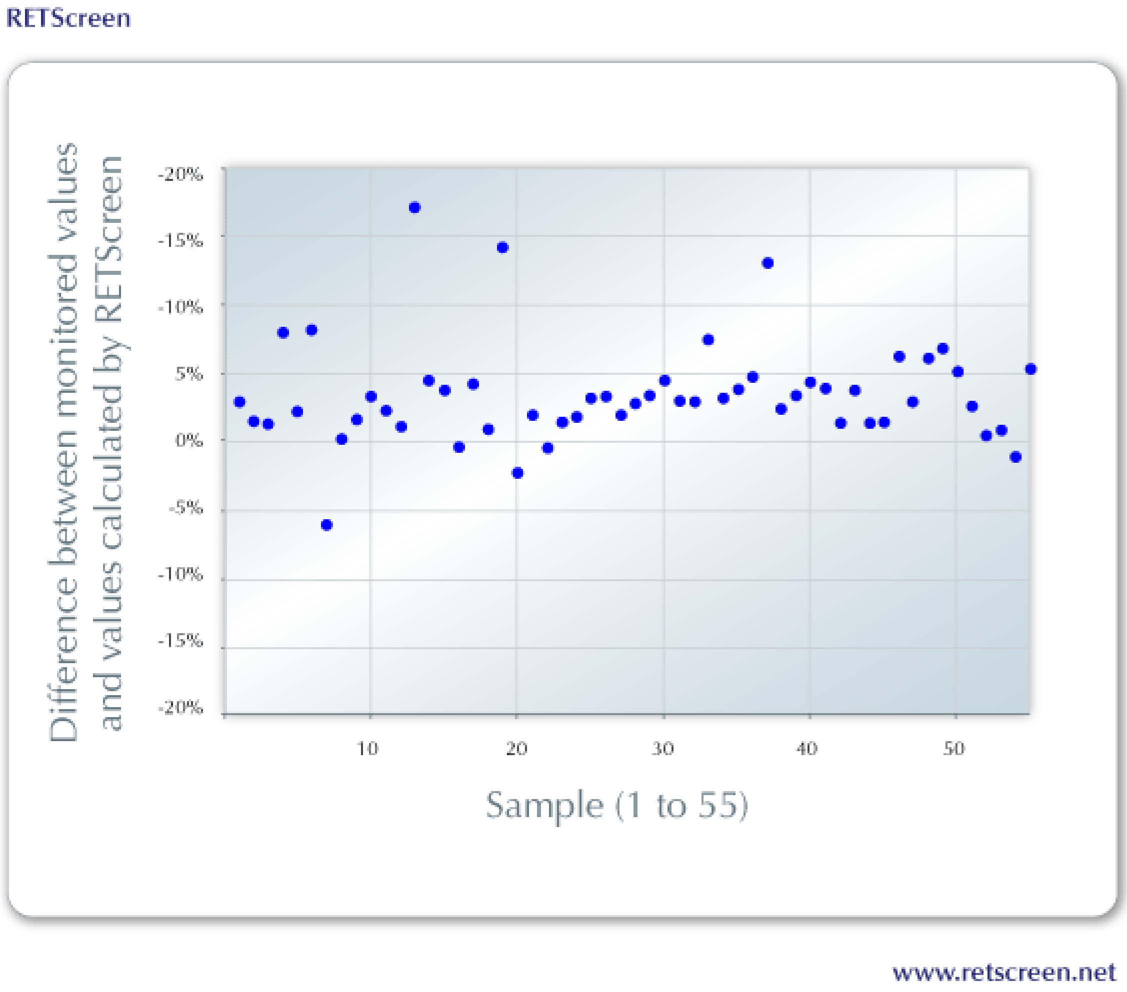


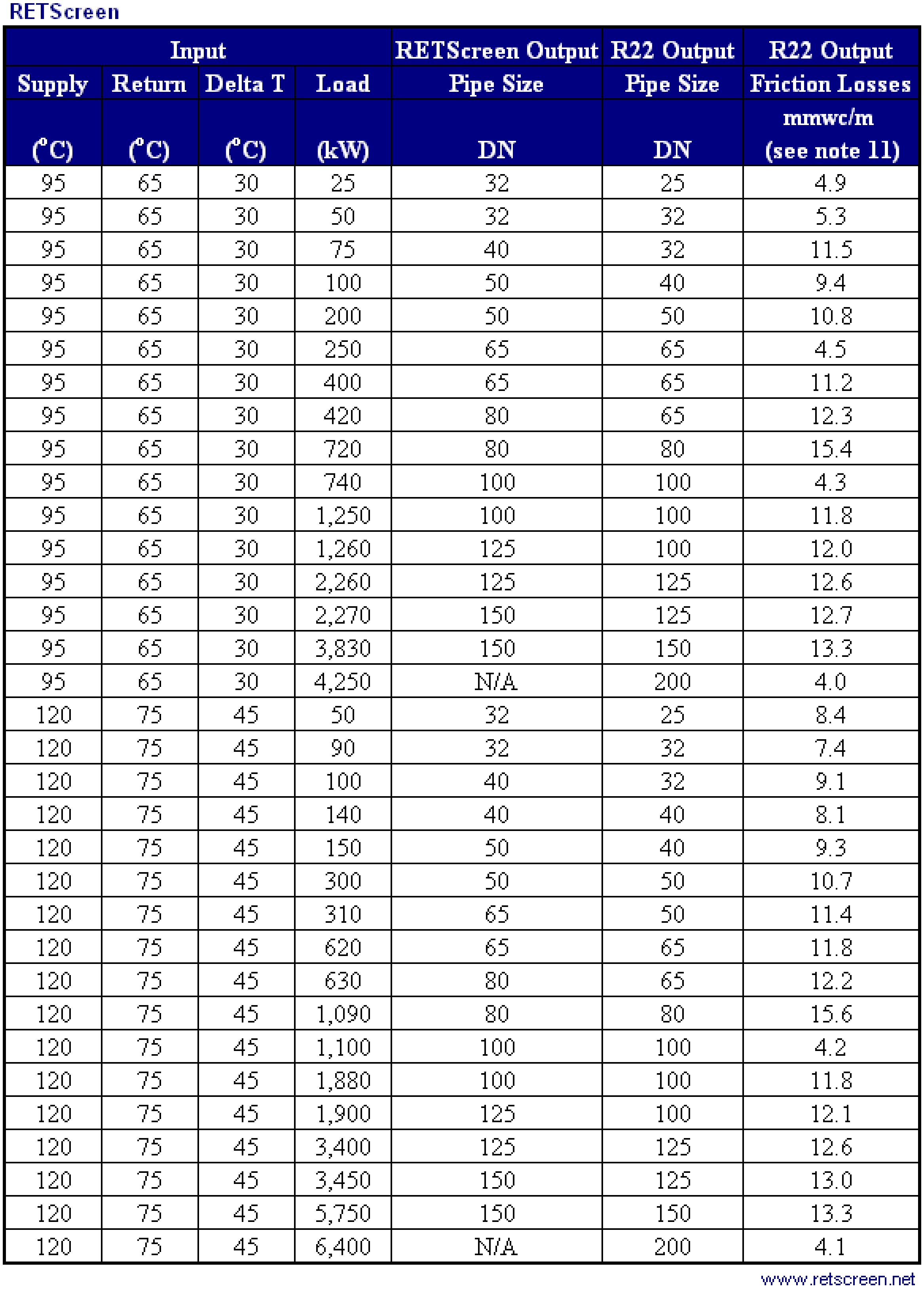
Figure 19: Differences between Measured Higher Heating Value and Values Predicted by RETScreen for 55 Wood Samples

2.7.3 Validation of district heating network design

The district heating network design algorithms of RETScreen (see section 2.6.5) were validated with the help of ABB's R22 computer program. The R22 computer program developed by ABB Atomic Division for sizing pipe distribution systems has been used extensively in the Scandinavian countries for design of district heating networks.

Table 13 shows pipe sizes calculated by the RETScreen model and values calculated by the R22 program. The values calculated by the two programs compare well. The RETScreen model tends to be more conservative than the R22 model. This is intentional, as the R22 model is a tool for detailed design, whereas the RETScreen is a pre-feasibility tool. The selected pipe size is also a function of how much money can be spent on the project. If money is restricted the designer typically allows for higher friction losses. The sizing is still very safe with respect to sound and erosion problems.

Theoretically the main distribution pipes should be sized with low friction losses and allow higher losses in the secondary distribution pipes to minimize required pumping load and investment costs. However, in reality it is common that space is limited and capital costs needs to be controlled resulting in a small main line. As for the secondary line it is typically oversized, as the customers heating load is not well defined and to avoid noise problems.



RETScreen

Input				RETScreen Output	R22 Output	R22 Output
Supply	Return	Delta T	Load	Pipe Size	Pipe Size	Friction Losses
(°C)	(°C)	(°C)	(kW)	DN	DN	mmwc/m (see note 11)
95	65	30	25	32	25	4.9
95	65	30	50	32	32	5.3
95	65	30	75	40	32	11.5
95	65	30	100	50	40	9.4
95	65	30	200	50	50	10.8
95	65	30	250	65	65	4.5
95	65	30	400	65	65	11.2
95	65	30	420	80	65	12.3
95	65	30	720	80	80	15.4
95	65	30	740	100	100	4.3
95	65	30	1,250	100	100	11.8
95	65	30	1,260	125	100	12.0
95	65	30	2,260	125	125	12.6
95	65	30	2,270	150	125	12.7
95	65	30	3,830	150	150	13.3
95	65	30	4,250	N/A	200	4.0
120	75	45	50	32	25	8.4
120	75	45	90	32	32	7.4
120	75	45	100	40	32	9.1
120	75	45	140	40	40	8.1
120	75	45	150	50	40	9.3
120	75	45	300	50	50	10.7
120	75	45	310	65	50	11.4
120	75	45	620	65	65	11.8
120	75	45	630	80	65	12.2
120	75	45	1,090	80	80	15.6
120	75	45	1,100	100	100	4.2
120	75	45	1,880	100	100	11.8
120	75	45	1,900	125	100	12.1
120	75	45	3,400	125	125	12.6
120	75	45	3,450	150	125	13.0
120	75	45	5,750	150	150	13.3
120	75	45	6,400	N/A	200	4.1

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Table 13: Comparison of the RETScreen Pipe Sizing with the ABB R22 Computer Program

11. mmwc/m: millimeters water column per meter of pipe.

2.8 Validation by an Independent Company

2.8.1 Methodology

FVB Energy conducted a validation of the RETScreen CHP model, based on the approach described below.

FVB in-house load calculations were used to compare equivalent full load hour values calculated by the RETScreen CHP module, based on the equations contained in this e-textbook. Process loads and baseloads were set to zero to first compare the core energy calculations, then the same baseload values were added to again compare full load hours calculated.

Heating values of various fuels identified in the user manual were checked against published values. Deviations were flagged.

FVB in house distribution pipe sizing methods were used to calculate pipe sizes for the same loads the RETScreen CHP module was used to calculate pipe sizes.

Steam properties calculated by the RETScreen CHP module were compared to calculated values based on ASME 1999 steam table data.

Steam Turbine performance calculated by the RETScreen CHP module was compared to steam turbine performance using GE Energy process simulation software called GE Enter Gatecycle. This commercially available software establishes design point efficiency and performance for any type of steam turbine based on Spencer Cotton Cannon performance correlations.

Gas turbine performance is represented by the heat rate, published for each individual gas turbine. The heat rate data points presented in the user manual for use by the user to input into the gas turbine performance section of the module were compared to published heat rate information found in the 2003 Gas Turbine World Handbook.

Reciprocating Engine heat rates presented in the user manual for use by the user were compared to the heat rates of engines FVB have been involved in specifying and purchasing for CHP projects in Canada.

FVB's in-house energy calculation model for CHP systems was used to compare the amount of heat recoverable that the RETScreen CHP module calculated.

Chiller and boiler seasonal efficiency ranges identified in the user manual were compared to efficiency data compiled in the FVB project database.

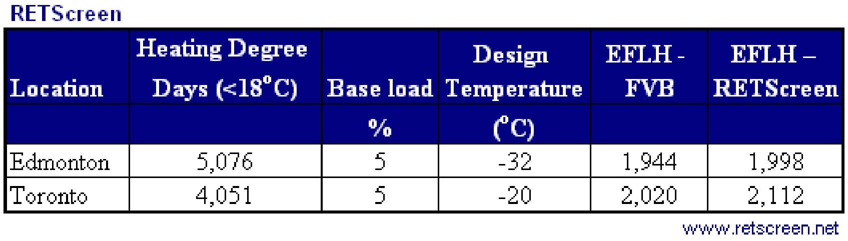
FVB did not validated the performance of the following systems within the RETScreen CHP module:

- Geothermal power
- Photovoltaic
- Wind turbine
- Desiccant cooling
- Hydro turbine

2.8.2 Load and energy calculations

The range of heating and cooling energy use values per unit floor area of a building provided in the user manual fall within the majority of heating and cooling customers encountered by FVB on various projects. The range of unit building heating and cooling loads is reasonable for North American type buildings.

The use of weather data to estimate the amount of energy consumed for heating and cooling over the period of a year is an industry accepted method to establish the core energy consumptions. Added to this core consumption is any base energy loads due to ongoing processes occurring in the building and or domestic hot or cold water uses. These base energy loads are typically specific to each building and should be estimated by the user of the RETScreen CHP module. The following two tables compare two Canadian cities and their Equivalent Full Load Hours as calculated by FVB in-house software and the RETScreen CHP module.



RETScreen

Location	Heating Degree Days (<18°C)	Base load	Design Temperature	EFLH - FVB	EFLH – RETScreen
		%	(°C)		
Edmonton	5,076	5	-32	1,944	1,998
Toronto	4,051	5	-20	2,020	2,112

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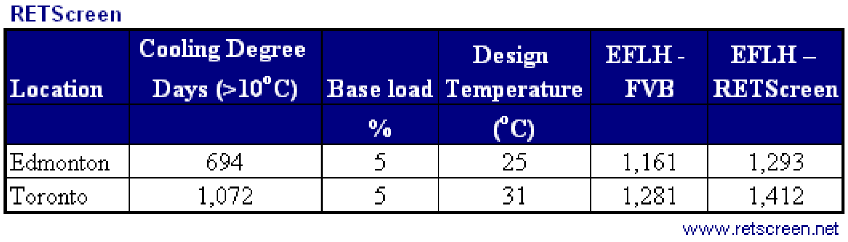
Table 14: Comparison of Heating EFLH Calculations



RETScreen

Location	Cooling Degree Days (>10°C)	Base load	Design Temperature	EFLH - FVB	EFLH – RETScreen
		%	(°C)		
Edmonton	694	5	25	1,161	1,293
Toronto	1,072	5	31	1,281	1,412

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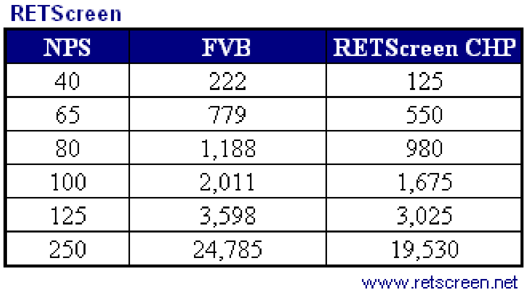
Table 15: Comparison of Cooling EFLH Calculations

The heating EFLH comparison shows good agreement between FVB calculated values and RETScreen CHP module calculated values. The cooling EFLH shows good agreement as well. According to FVB, the values calculated by the RETScreen CHP module for EFLH are reasonable given the use of the module as a CHP screening tool.

2.8.3 Distribution pipe sizing

Various distribution pipe sizes calculated by the RETScreen CHP module were tested to see what the maximum heating and or cooling capacity could be transmitted through the pipe at a design condition of 40°C temperature difference, and 200 Pa/m pressure drop. The comparison is presented in ***Table 16***. A similar comparison is presented in ***Table 17*** for cooling pipes, assuming a 8°C temperature difference and a 200 Pa/m pressure drop.



RETScreen

NPS	FVB	RETScreen CHP
40	222	125
65	779	550
80	1,188	980
100	2,011	1,675
125	3,598	3,025
250	24,785	19,530

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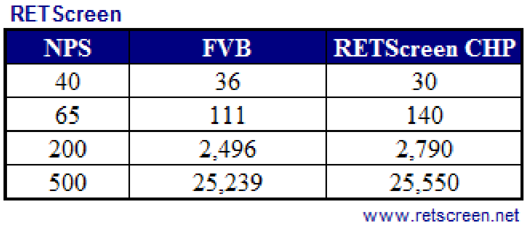
Table 16: Pipe Heating Capacity in kW at 200 Pa/m and 40°C Delta T



NPS	FVB	RETScreen CHP
40	36	30
65	111	140
200	2,496	2,790
500	25,239	25,550

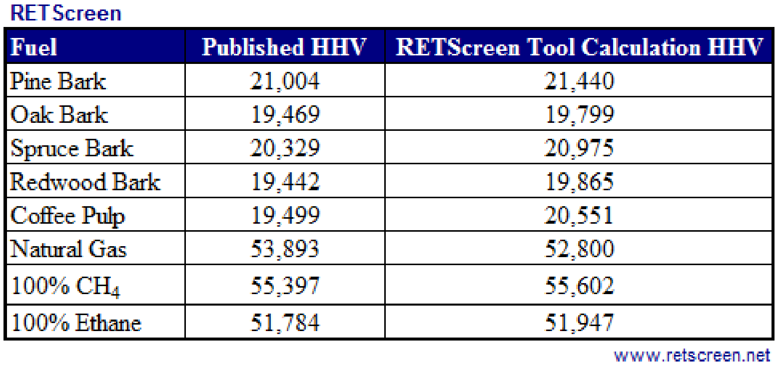
Table 17: Pipe Cooling Capacity in kW at 200 Pa/m and 8.3°C Delta T

The RETScreen CHP model calculated pipe sizes are more conservative than FVB's for heating, and very similar for cooling. The comparison shows the validity of the pipe sizing calculations in the RETScreen CHP model.

2.8.4 Fuel heating values

The fuel heating content values provided in the user manual were compared to published values.

The fuel analysis calculators for solid and gaseous fuels, found in the Tools worksheet were tested. By entering the analysis for each fuel into the calculators, a HHV was calculated and compared to the published values associated with each analysis. The following table compare the results and show that there is a reasonable agreement between calculated and published values.



Fuel	Published HHV	RETScreen Tool Calculation HHV
Pine Bark	21,004	21,440
Oak Bark	19,469	19,799
Spruce Bark	20,329	20,975
Redwood Bark	19,442	19,865
Coffee Pulp	19,499	20,551
Natural Gas	53,893	52,800
100% CH_4	55,397	55,602
100% Ethane	51,784	51,947

Table 18: Fuel Analysis Comparison; MJ/tonne

Ultimate analysis data for the wood fuel was sourced from published analysis found in Babcock and Wilcox Steam Textbook, 40th Edition. Coffee heating values and ultimate analysis was based on FVB project data, and based on actual analysis from CANMET labs. Pure hydrocarbon heating values were obtained from the Gas Processors Society of America (GPSA) data book, 10th Edition.

2.8.5 Reciprocating engine

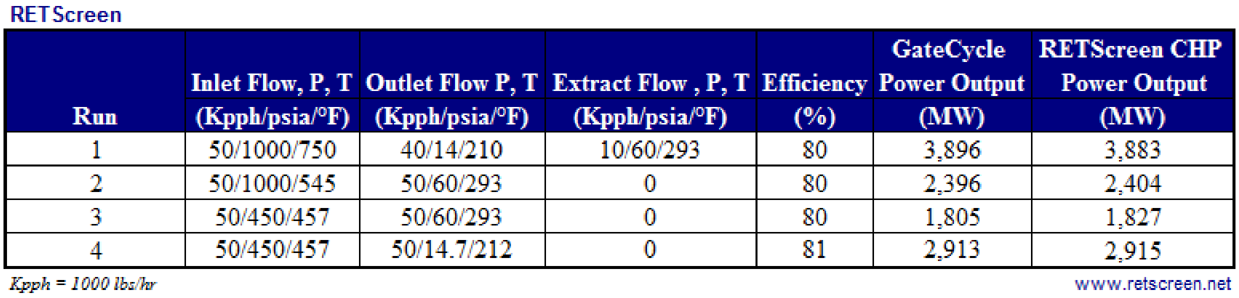
The industry standard is to quote reciprocating engine heat rates on a lower heating value basis. The heat rates identified in the user manual are representative of the engines that FVB have been involved with on CHP projects. The heat rate figures were assumed to be converted to HHV basis using natural gas as fuel.

2.8.6 Gas turbine

The industry standard is to quote combustion gas turbine heat rates on a lower heating value basis. The heat rates identified in the user manual are representative of the gas turbine data presented in the publication 2003 Gas Turbine World Handbook. The heat rate figures were assumed to be converted to HHV basis using natural gas as fuel.

2.8.7 Steam turbine

Steam Turbine simulation software (GE Enter Gatecycle) was used to calculate unit performance in order to compare to the RETScreen CHP module steam turbine performance calculations. The following table compares the results from the two.



RETScreen

Run	Inlet Flow, P, T (Kpph/psia/°F)	Outlet Flow P, T (Kpph/psia/°F)	Extract Flow , P, T (Kpph/psia/°F)	Efficiency (%)	GateCycle Power Output (MW)	RETScreen CHP Power Output (MW)
1	50/1000/750	40/14/210	10/60/293	80	3,896	3,883
2	50/1000/545	50/60/293	0	80	2,396	2,404
3	50/450/457	50/60/293	0	80	1,805	1,827
4	50/450/457	50/14.7/212	0	81	2,913	2,915

Kpph = 1000 lbs/hr

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Table 19: Steam Turbine Performance Calculation Comparison

The calculated power output shows very good agreement between the two software performance models.

2.8.8 Chillers

FVB agrees with the efficiency data presented in the user manual. Efficiencies are representative of chillers performance based on FVB experience in North America.

2.8.9 Steam properties

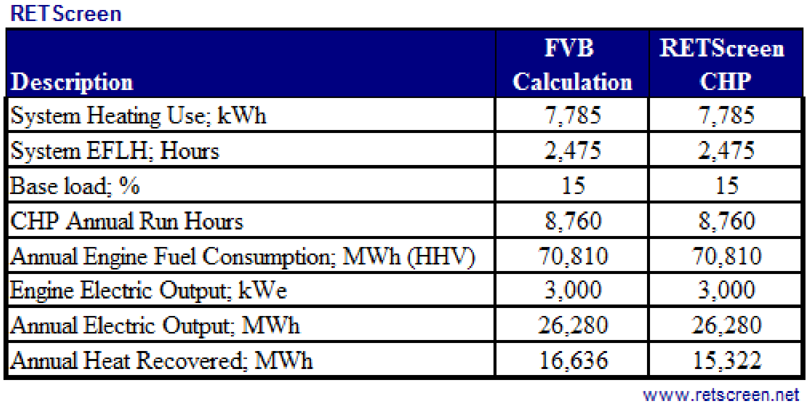
The steam properties calculated by the RETScreen CHP module for a given steam pressure and temperature were compared to the steam properties calculated by the GE Enter GateCycle software for the same conditions. The GE software utilizes the ASME 1999 steam data as the basis for its calculations.

The very good level of agreement that was seen in the steam turbine performance validation is due to the very good agreement in steam properties calculated by both programs.

2.8.10 CHP system energy allocation

FVB utilized its in-house CHP system model to estimate the amount of recovered heat energy from a CHP project that could be delivered to the consumer over the year. This useful recovered heat energy was compared to the amount calculated by the RETScreen CHP Module.

The following table summarizes the comparison of the two approaches.



RETScreen

Description	FVB Calculation	RETScreen CHP
System Heating Use; kWh	7,785	7,785
System EFLH; Hours	2,475	2,475
Base load; %	15	15
CHP Annual Run Hours	8,760	8,760
Annual Engine Fuel Consumption; MWh (HHV)	70,810	70,810
Engine Electric Output; kWe	3,000	3,000
Annual Electric Output; MWh	26,280	26,280
Annual Heat Recovered; MWh	16,636	15,322

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Table 20: CHP Energy Allocation Comparison

The amount of energy recovered and used compares very well between the two calculation methods. The FVB approach calculates approximately 8.5% more recovered thermal energy than the RETScreen CHP module.

2.8.11 Conclusions

The RETScreen CHP module software, user manual and e-textbook are intended to serve as an initial technical screening tool for users to conceptually assess the technical and financial feasibility of potential CHP projects. Based on the good agreement found between the RETScreen CHP module technical calculations and calculation processes normally utilized by FVB Energy, it is FVB Energy's opinion that the module will satisfactorily fulfill this purpose.

2.9 Summary

The RETScreen CHP Project Model uses a combination of algorithms to predict the energy delivered, on a yearly basis, by a combined heating, cooling and power system. Peak heating and cooling loads are calculated from building descriptions entered by the user. Load duration curves are derived from monthly degree-days data; domestic hot water is included in the load by defining equivalent degree-days for hot water heating. The load duration curve is then used to calculate the energy use on a monthly basis and during a fictitious 'peak period'. Algorithms for steam turbines (without or with extraction), gas turbines, combined cycle gas turbines, and other systems, are used to calculate power capacity, recoverable heat and fuel consumption. The monthly energy use are used to predict what fraction of the needs is met by base, intermediate and peak systems given their respective capacities.

Various parts of the algorithm have been validated against other programs or against values published in the literature. Despite the simplicity of the model, the accuracy of the model proves acceptable at the pre-feasibility stage, when compared with other software tools or with published data.

References

Avallone E. A. and Baumeister T III, ***Marks Standard Handbook for Mechanical Engineers***. McGraw-Hill, Inc., 1987.

ASHRAE, ***Handbook, Fundamentals***, ***SI Edition***, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA, 30329, USA, 1997.

Community Energy Technologies, CANMET Energy Technology Centre-Ottawa, Natural Resources Canada, 1997.

Ciavaglia, L., "Personal communication," CANMET Energy Technology Centre-Ottawa, Natural Resources Canada, 2003.

IAPWS (1997) ***Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam*** . The International Association for the Properties of Water and Steam, Erlangen, Germany, September 1997.

Larsson, I. Personal communication. FVB Energy, Stockholm, Sweden, 2003.