Greenhouse Energy Model
User Guide

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Contents

1 Introduction:

GEM: A Computerized Tool to Optimize Electrical and Thermal Energy Uses in New York State Controlled Environment Agriculture Greenhouses

Controlled Environment Agriculture (CEA) has created a new paradigm for plant growth in closed environments, specifically in year-round vegetable production in single-storied, glazed greenhouses. CEA has demonstrated how controlling more environmental parameters, more precisely than was possible in previous practice, leads to unprecedented biomass productivity and control of product composition, quantity, and quality. For example, the commercial greenhouse developed by the Cornell CEA program near Ithaca can produce lettuce, per unit growing area, at a yearly rate approximately twenty times the yearly rate of California outdoor lettuce production. Additionally, the facility provides year-round work opportunities for its employees, which are not always available for agricultural workers in New York State.

Environmental manipulation is a powerful mechanism enabled by CEA technologies to control plant growth and development. Light is a key environmental regulator of plant growth and can be delivered precisely to the crop every day of the year using an algorithm patented through Cornell University to control supplemental lights, movable shades, and the carbon dioxide concentration (Albright, 1998 and Albright, et al., 2000, 2007, 2009.) Supplemental lighting and its control are critical for optimum plant growth during the cloudy winters of New York State.

Serious consequences can arise from an inability to develop and work with objective data to predict the magnitudes and timing of energy flows among the subsystems within CEA facilities. One is the inability to correlate design and control decisions with reliable outcomes. Another is the inability of potential and current CEA facility operators to develop dependable business plans and convince lending agencies and other capital sources regarding how an investment in a specific energy technology can permit or increase greenhouse production and how one option can be preferred to another, seemingly comparable option. Together, these consequences translate into lost knowledge, lost efficiency, lost profitability, and lost opportunities.

Optimum energy management is central to successful CEA operations, for CEA depends greatly on energy inputs – electrical as well as thermal – in New York State climate zones. The purpose of the GEM software program is to provide a user-friendly, flexible, computerized tool to assist existing and potential greenhouse operators to design and control CEA greenhouses, optimally, based on local climate, greenhouse physical characteristics, energy rate schedules, and the crop needs. Other possible users include students, commercial and private investors, utility engineers, land-use planners, and governmental agencies.

2 Software Installation:

2.1 Requirements:
- Windows Operating systems with a 64 bit processor
- Approximately 500 Mb of hard-drive storage space.
- Connection to the Internet (to download program files. Once the program is installed, no internet connection is necessary).

On a windows 10 machine you can verify whether you have a 64 bit system by right clicking on the "Start" button and then selecting "System". System type should state "64-bit Operating System". See Figure 1.
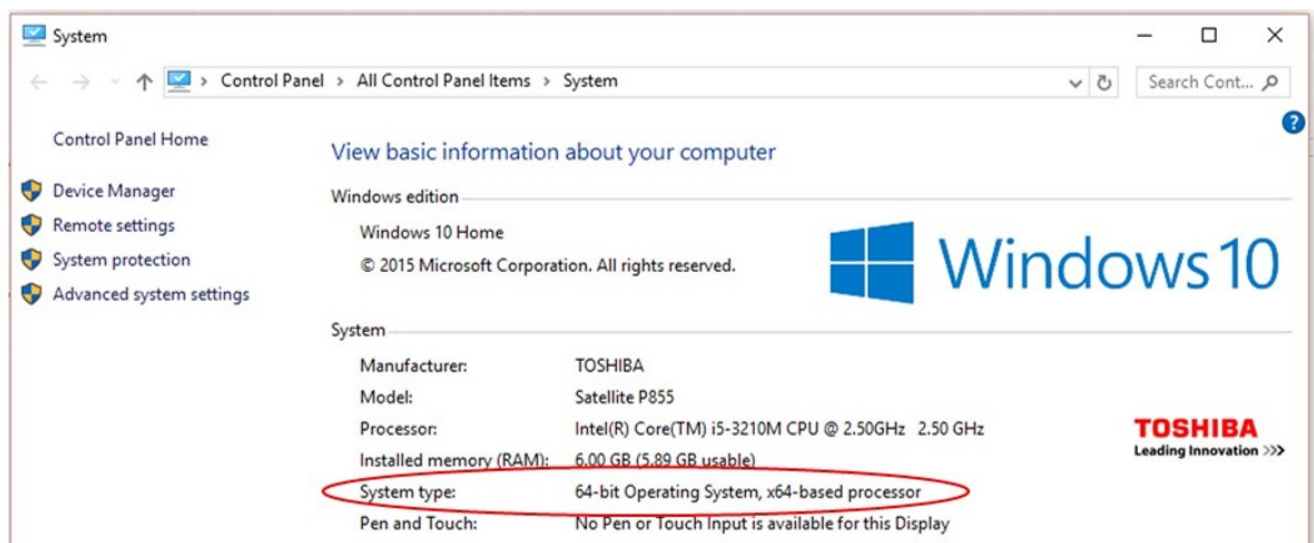
Figure 1: How to determine if you have a 64-bit computer.

2.2 Overview
GEM was written using the Matlab™ programming language both to take advantage of computer code previously developed by the Cornell CEA group, and the Graphical User Interface Development Environment (GUIDE) within Matlab™. Matlab™ is typically a subscription service software, however it also has the capability to create executable files, which permit Matlab™ programs to run on computers that do not have Matlab™ installed on them.

To enable GEM to run on a machine, it is necessary to download the Matlab™ runtime (which allows Matlab™ programs to run on machines without Matlab™), and then the GEM program itself.

2.2.1   Matlab runtime

The Matlab™ runtime is required to allow Matlab™ programs to run on computers without Matlab™ installed on them. It is available to download for free from the Matlab™ website. Please download only the version from the link provided below, as the program requires that you use the runtime specific to a 64 bit windows machine, and the R2013b release of Matlab™. The GEM program may not work otherwise.

https://www.mathworks.com/supportfiles/downloads/R2013b/deployment_files/R2013b/installers/win64/MCR_R2013b_win64_installer.exe

The download is approximately 400 Mb in size as this file contains all of the necessary components to run a Matlab™ program.

Once you have download the Matlab™ Runtime file, click on it and you will be prompted about where you would like to install the program. Select any location you would like, and then click "Install". Once the installation is complete, there is no need to retain the downloaded Matlab™ runtime file, however you may wish to do so, if you plan on reinstalling the program on another machine in the future.

2.2.2   Downloading Program File:

The GEM program file can be downloaded from the Cornell CEA website at the following link.

www.cornellcea.com/

The GreenhouseEnergyModel.exe file you download for the GEM program is approximately 30 MB in size and contains the climate data for select NY state locations. Place this file in a directory where you would like information to be saved. The GreenhouseEnergyModel.exe file will need to be run every time you wish to use GEM.

2.3   Starting GEM

Once you have installed the Matlab™ runtime and downloaded GreenhouseEnergyModel.exe into a suitable directory, you can start GEM by clicking on GreenhouseEnergyModel.exe. If the installation was successful, GEM should start up. Note, it has been observed that on some computers it can take several seconds for the program to load. If you do not immediately see the program start up, please wait ~5 to 10 seconds before clicking on the GreenhouseEnergyModel.exe file again.

3   User Interface:

3.1   Overview

The user interface for GEM was developed using the Graphical User Interface Development Environment (GUIDE), which is a toolbox available from Matlab™. GUIDE provides a relatively straightforward means to creating graphical user interfaces that can be used to interface with Matlab™ function and other file types.

The start screen, displayed in Figure 2, is the first screen that appears when the program starts. This is the main screen from which all input and output windows are accessed, and closing this screen will close the program.
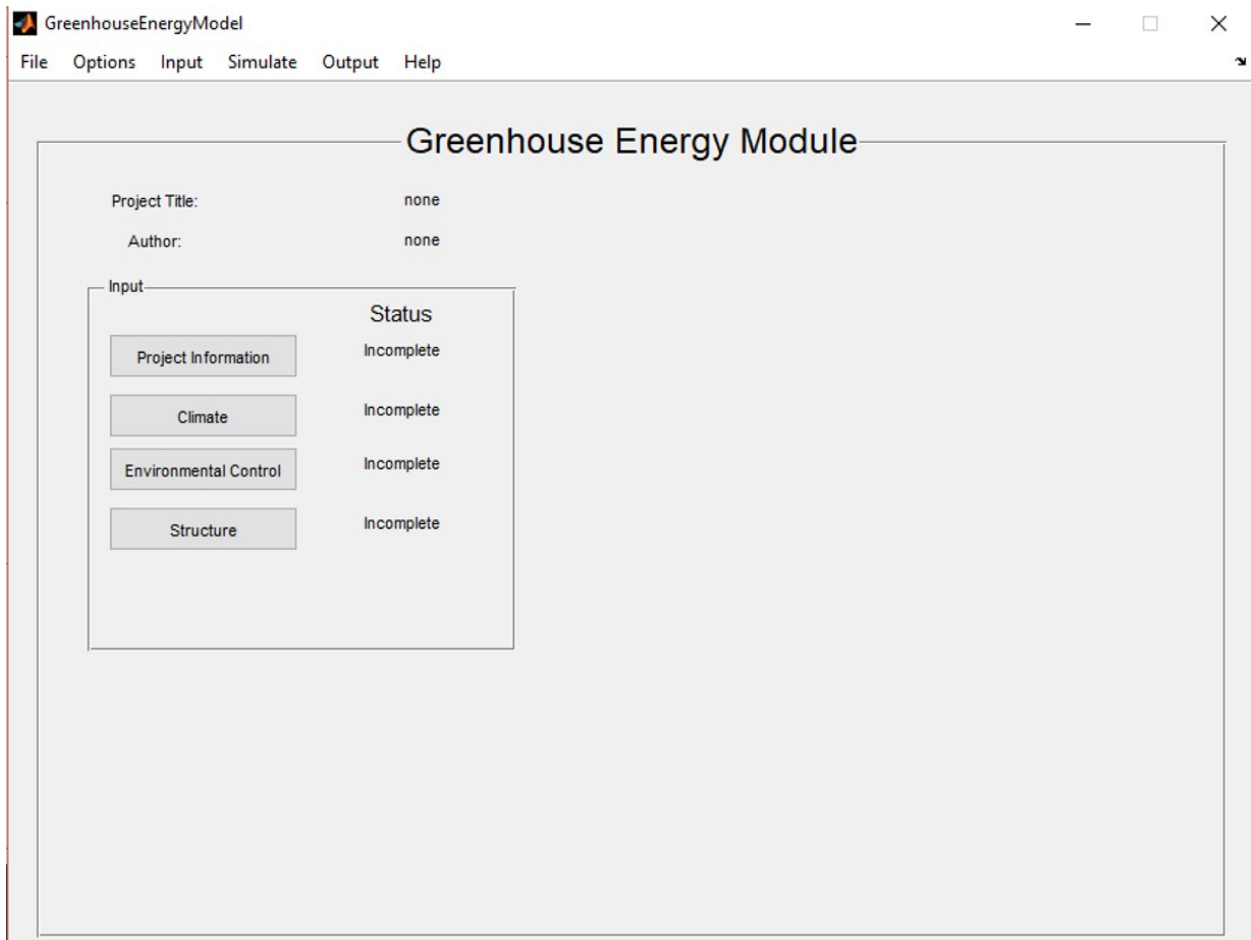

Figure 2: GEM Start screen and primary user interface window

Data is input to the program through separate screens, specific to each topic. To access the input screens, you can either click on the buttons on the left (e.g. "Project Information", "Climate", etc.) or through the main menu at the top of the screen under "Input".

Separate input windows will pop up for each of the input categories, into which you can enter values regarding the greenhouse setup you wish to model.

The programs tracks to see whether you have entered all of the required information for each section, and when you have done so, the "Status" next to the button will change from "incomplete" to "complete". Once all of the major categories of data information have changed to "complete", you will have the option to access the "simulation" screen, from which you can launch the actual simulation. Once the simulation has run, yearly summarizing output will appear on the main screen, with the option to access more detailed information on subsequent output screens, as well as the ability to export data to excel files for further analysis. It is not possible to run the simulation without entering all of the necessary data. Care should be taken when entering values for the input as reasonability checks are frequently incorporated wherever possible, but they are not exhaustive.

It is recommended that you proceed in a linear fashion starting with "Project information" and proceeding down to "Structure", though you are not required to do so. The program will automatically suggest values for several of the parameters necessary for the model based on information you have previously entered, but will not over-ride values you have previously entered.

3.2   Main Menu:

The Main Menu, (

Figure *3*) provides a means to access typical windows file functions through the "File" drop down menu, options to change the units under the "Options" menu, a way to access individual input screens, the "Simulate" screen and Output screens directly.
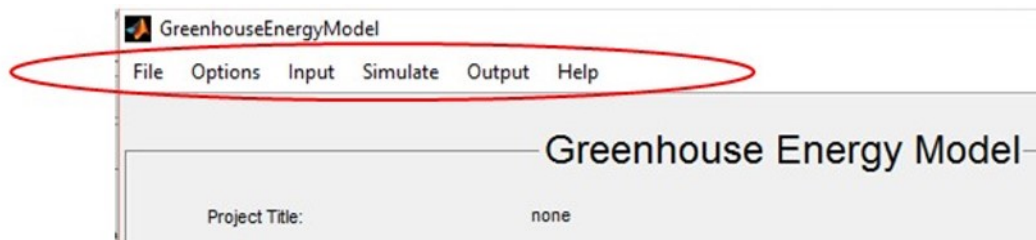

Figure 3: GEM Main menu

3.2.1   File Menu:

Figure 4: File Menu

The file menu (Figure 4) has similar functions to most windows based programs. Within the file menu you can perform the following functions related to file management.

3.2.1.1   Open:

Use the "Open" option to load previously saved files, such as the included "example.mat" file. Clicking on the "Open" option will pull up a dialog to prompt you to select the file to open. Only valid .mat files previously saved by GEM can be opened in this way (i.e. you cannot open additional data files, or other Matlab™ .mat files with this function.

3.2.1.2   New:

Use the "New" option to clear any data from the program. This will reset the program and you will lose any unsaved information. This function is equivalent to shutting down and restarting the program.

3.2.1.3   Save:

Use the "Save" option to save the data you've entered and if you've run the simulation, the results you've generated. If you have not previously entered a file name to save the data to, you will be prompted to enter a filename. Once you have saved the data in a .mat file, you will be able to load your data by using the "Open" function. Once you have saved your data, you can close the program, or send the .mat file to another user.

3.2.1.4   Save as:

Similar to the "Save" function, however you will be prompted to enter a new filename to save the current data to.

3.2.1.5   Exit:

The exit button will close the main GEM window. Any unsaved data will be lost, so be sure to use the "save" or "save as" functions before exiting. Alternatively you can also click the small "X" in the upper right corner of the main GEM screen.

3.2.2   Options:

In the options menu you can select whether you would prefer to use Metric or US Customary Units. You may change this at any time while using the program and the values you have already entered will be converted for you.

Note: Data is stored in metric, and during conversion it is possible that small rounding errors from conversion may show up. (You may not see US customary values as round numbers, following loading.)

3.2.3   Input:

Use the "Input" drop down menu to access specific data input screens directly, without having to proceed through the usual hierarchy of other input screens that you encounter when pressing the corresponding input buttons (e.g. "Climate" or "Project Data") on the main screen.

3.2.4   Simulate:

Use the "Simulate" drop down menu to access the "Simulate" input window. This is functionally the same as pressing the "Simulate" button on the main input screen. Note: this function is disabled until data input has been completed, and the status of all of the various input categories is "Complete".

3.2.5   Output:

Use the "Output" drop down menu to access the "Output" windows directly. This is functionally the same as pressing the "Detailed Output" button on the main input screen. Note: this function is disabled until data input has been completed, and the status of all of the various input categories is "Complete", and the Simulation has been run.

3.2.6   Help:

Help for specific pages is accessed by clicking the "Help" button located in the top right corner of every input page. By pressing the "help" button you will be taken to a separate page that indicates the corresponding page in the user manual. If you would like to access help from another page, select the "Help" drop down menu which will allow a user to access all of the individual help screens (without first opening the respective input or output windows.)
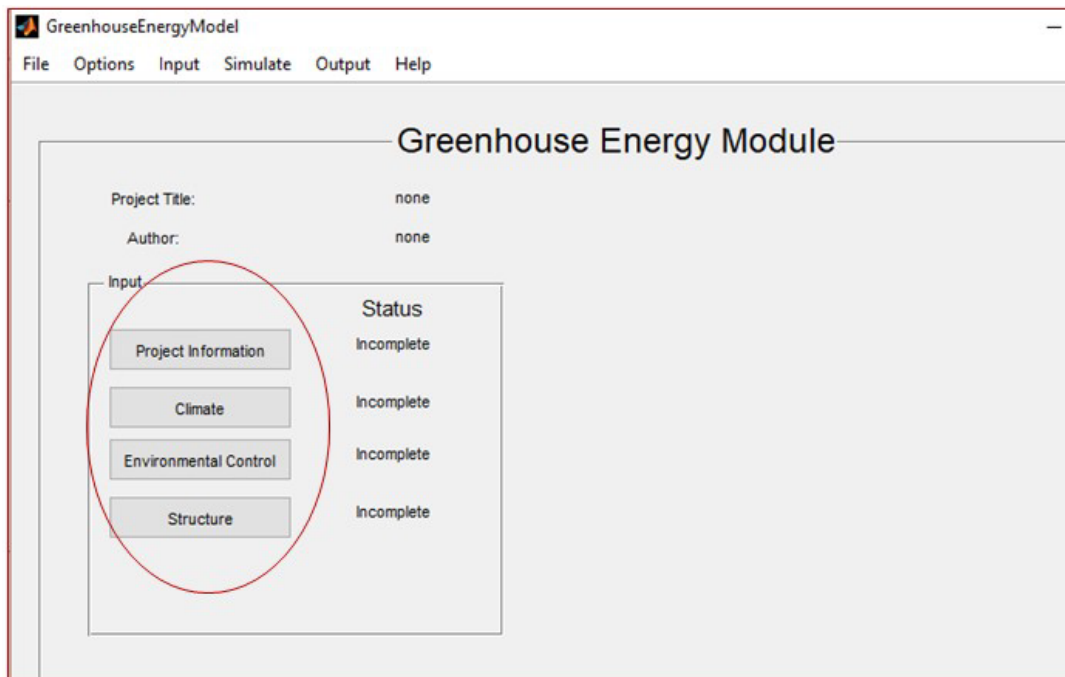
4 Program Input:

4.1 Overview

Figure 5: Program Input

The first steps of using GEM are to enter information about the greenhouse project you wish to model (Figure 5). This information forms the basis for the simulation, and care should be taken to ensure accurate estimates of values are used.

To assist in entering data, the program attempts to suggest values for parameters based on previously entered data. However this functionality depends on the user starting data entry with "Project Information" and then proceeding through "Climate", "Environmental Control" and finally "Structure". Selecting options for environmental control will enable entering information about equipment usage in the Structure. Many of the sizes and numbers of equipment are based on the dimensions of the greenhouse, however if you wish you can directly input information into the program in any order you wish, and the program will not automatically overwrite your entries. Suggestions are only placed into areas where no information has yet been input by the user.

The program temporarily stores the values you've entered when you hit the "Set" button located at the bottom of data input screens. Hitting the "Set" button, will store the values you've entered into the memory of the program, however this should be distinguished from saving the file. Saving the file will write your data to a .mat file so you can come back after the program has been shut down and reload the values. Information that has been temporarily stored by the use of the "Set" button is lost when the program closes.

The "Set and Close" button has the same functionality as the "Set" button, however the input window is closed as well.

The "Close" button will close the current window and any information you have not previously "Set" will be lost. There is no check to see if "Set" values have changed, and so no warning to verify that you've properly "Set" the values entered.

The "Help" button brings up the "Help" page specific to the page you pressed the button on which in turn indicates the relevant section in the user manual. If you would like to access help from another page, select the "Help" drop down menu which will allow a user to access all of the individual help screens (without first opening the respective input or output windows.)

4.2   Project:

By clicking on the "Project Information" button on the GEM main screen, the user will be brought to the "Project Information" input window (Figure *6*) and prompted to input basic information about the project as well as information about utility rates. The basic project description is meant to assist in keeping project files organized, and should be used to input notes about specific runs of the model. I.e. if one simulation considered using glass or plastic a user could note this in the project information section.
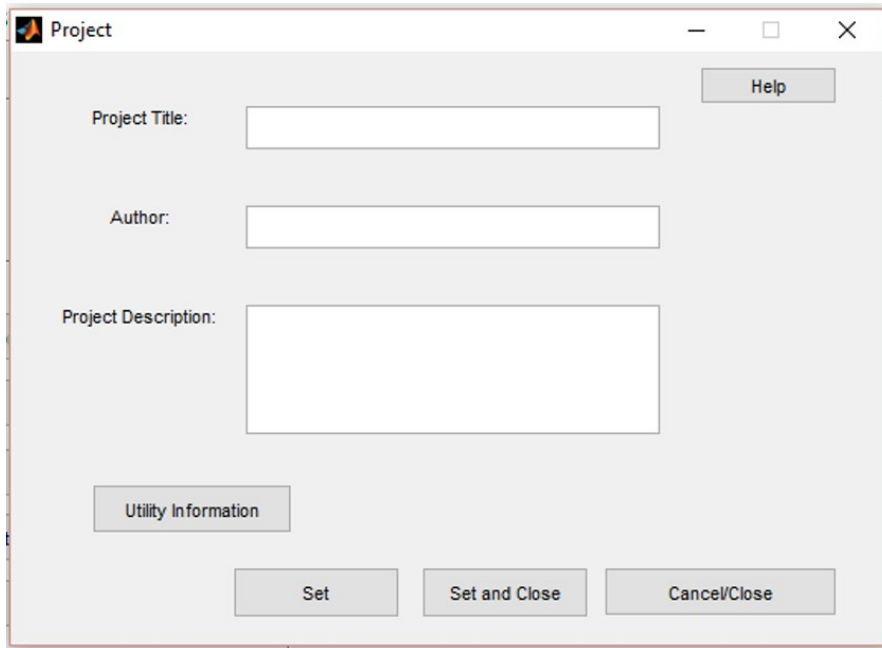

Figure 6: Project Information Input Screen

4.2.1 Project Title:

The Project title is a required field (i.e. you must enter a value to be able to run the simulation). Project names are envisioned to be relatively simple, with more detail about the particular simulation placed into the "Project Description" field. The Project title is displayed on the main GEM screen after the user has hit the "Set" button.

4.2.2 Author:
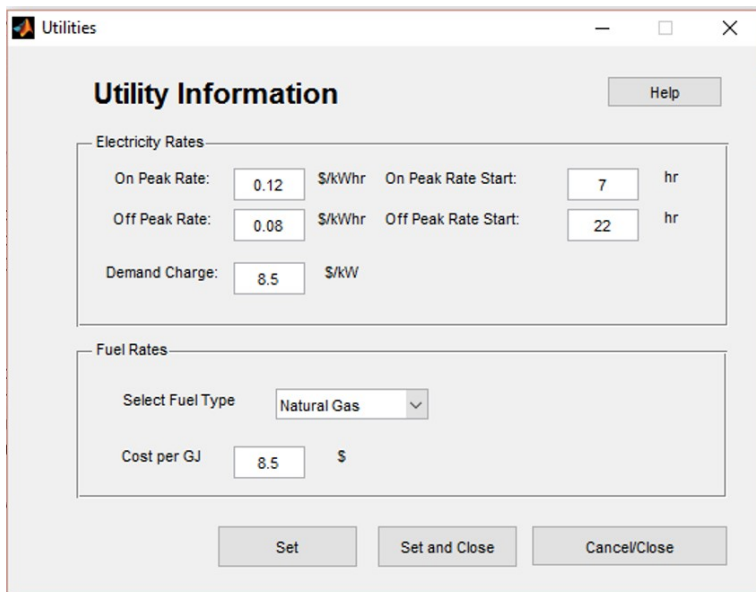
The Author field is where the name of the person who is working on the project should be entered. The Author field is also a required field, which if not filled out, will prevent the simulation from being run.

4.2.3 Project Description:

The "Project Description" field is where the user should enter a brief description of the project or variation on a project that is being worked on. You can include as much, or as little detail here as is necessary. The "Project Description" field does not require information to be entered to proceed with the simulation.

4.2.4 Utility Information:

To access the "Utilities" input screen, press the "Utilities" button located on the "Project Information" input screen. A new input window (Figure 7) will pop up where you will be prompted to input the following information. On this screen you can enter information about the project Energy Provider. This function also allows the user to adjust utility cost rates to see the effect on monthly and yearly costs. This functionality may be useful when comparing the costs of providing energy when you are uncertain of what the rates may be, or the relative energy savings/costs of implementing different management or infrastructure options.

Figure 7: Utility Information Input Screen

4.2.4.1   Electricity Rates:

In this section the user can enter prices for on and off peak electricity pricing, as well as the hour of the day that on peak and off peak rates start. If on peak/off peak pricing is not available, just enter the same price for on peak as off peak and leave the hours they apply at the defaults. It should be noted that the time of day information uses a 24 hour format (i.e. 10:00 pm is 22, 2:00 am is 2, etc.) Since the simulation is based on an hourly time step, only the hour is considered (minutes are not).

The user can also enter the demand charge paid for supply of electricity. This is typically the price you pay for the peak 15 minute usage (kW) during a billing cycle. It should be noted that this program is based on hourly time steps and so the estimated demand may vary from what you would experience in reality. The program determines the peak hourly electricity usage during the month and then multiplies the demand charge, to arrive at the monthly demand cost.

4.2.4.2   Fuel Rates:

In this section the user can enter information about the type of fuel that provides heat to the greenhouse, along with the cost of providing the heat. Users can select a fuel type from a drop down menu, with the options of: Natural Gas, Propane, Fuel Oil, Kerosene, Wood Pellets, or Other. The program will automatically fill in the cost of the fuel, however you may wish to change the suggested value to represent more current or local pricing, or to see what varying the cost of fuel will have on operational costs. Costs are given based on a $/MMBtu or $/GJ basis.

4.3   Climate:

Pressing the "Climate" button on the GEM main screen will bring up the Climate information input window (*Figure 8*). The Climate information screen is used to select the Typical Meterological Year Data to use with the simulation. Typical Meterological Year data is derived from historic data for locations around the United States, and is often used for design purposes. More information can be found at the following link:

http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Per the NREL website

"The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories. Because they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location."

Data for all available New York Sites is pre-loaded in the program, however if the user wishes to consider another location outside of New York, they can download the TMY3 data file that most closely represents their location through the above link. The website contains data for 1020 sites around the United States.
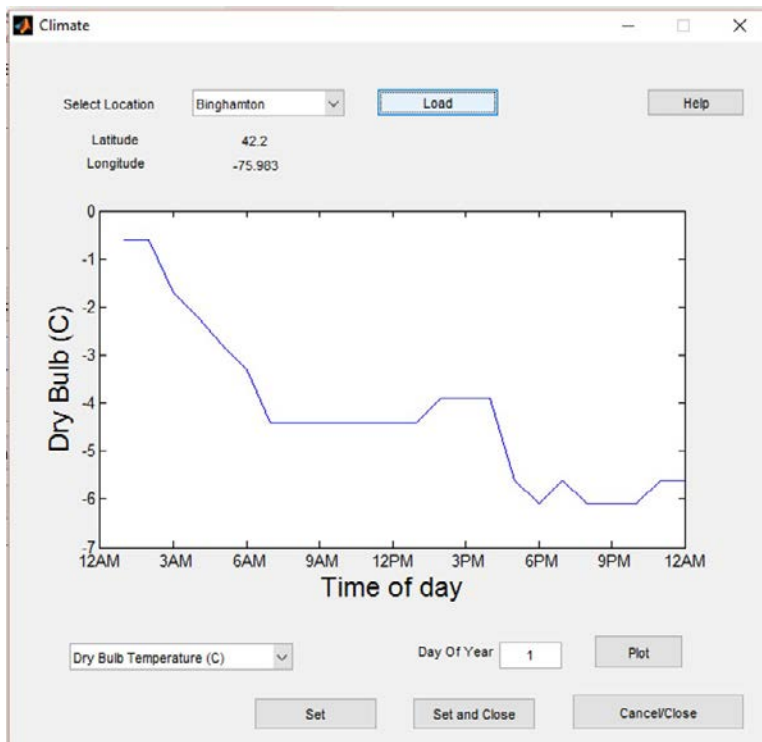
Figure 8: Climate Information Input Screen

4.3.1   Location:

You can select from one of the 17 NY locations (plus Erie, PA) by using the "Select Location" drop down menu and then pressing the "Load" button. The program is pre-loaded with all of the data for these locations. If you wish to use an alternate location, select "Select TMY3 From File" and then press the "Load" button. A file dialog box will pop up and prompt the user to select the TMY3 file that they wish to use for the project simulation.

Additional TMY3 are readily available for 1020 locations around the United States from the following link: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

4.3.2   Display:

Once you have successfully loaded a TMY3 data file (either from preloaded or custom locations), the latitude and longitude of the location will be displayed, along with a plot of the Dry Bulb temperature on the first day of the year.

To change the parameter displayed on the chart, use the drop down menu located in the bottom left corner of the Climate Information input window. The user can select from displaying Dry Bulb Temperature, Wind Speed, Humidity, and Light intensity. After selecting the parameter, press the "Plot" button located at the lower right hand corner of the input window, and the new parameter should be displayed.

To view data from a different day of the year, change the value of the "Day of Year" field (between 1 and 365) and then press the "Plot" button as above.

4.4   Environmental Control:

Pressing the "Environmental Control" button on the main GEM window will bring up the "Environmental Control" input screen (Figure 9). From here a user can select further input screens to input control settings for: Light, Shading, and CO_2 supplementation, Heating, and Cooling.
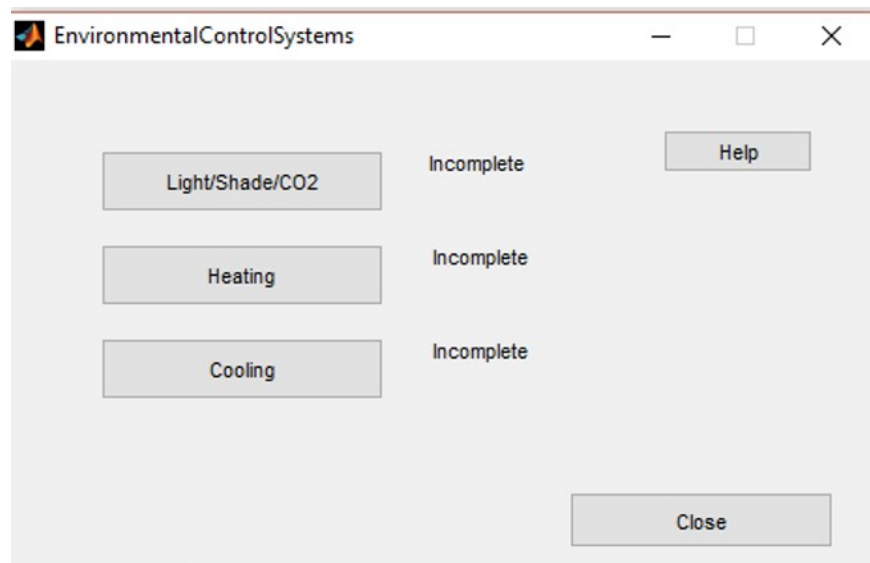

Figure 9: Environmental Control Input Screen

Users must enter information for all three control systems to be able to run the simulation. As information for each category of control is input, the status next to each category of control will update to "Complete" from "Incomplete". When all three categories are "Complete", the status of Environmental Control, on the main GEM page will update to "Complete".

4.4.1   Light/Shade/CO2:

Providing supplemental lighting in the Northeastern United States represents a significant portion of the energy costs of a commercial greenhouse with year round production. Providing consistent lighting year round is fundamental to maintaining a consistent level of production. Currently greenhouses generally rely on some variation of either time-clock or threshold based light control, which may or may not include the ability to turn off the lights when a set target daily light integral has been achieved. A major effort at Cornell has been the development of a lighting control algorithm that seeks to maintain a constant daily light integral year round, while also delaying supplemental lighting until the less expensive, off peak periods of the day (Albright 1998). This algorithm, LASSI (Light and Shade System Implementation) is included as an option for light control.

Once the user clicks the Light/Shade/ CO_2 button on the Environmental Control Screen, the Light/Shade/ CO_2 input window (*Figure 10*) appears. The user can then enter information about supplemental CO_2 use, supplemental light use and Shade use. Though the user can enter information about these systems in any order, it is advised that they proceed in a top/down order starting with the CO_2 control method.
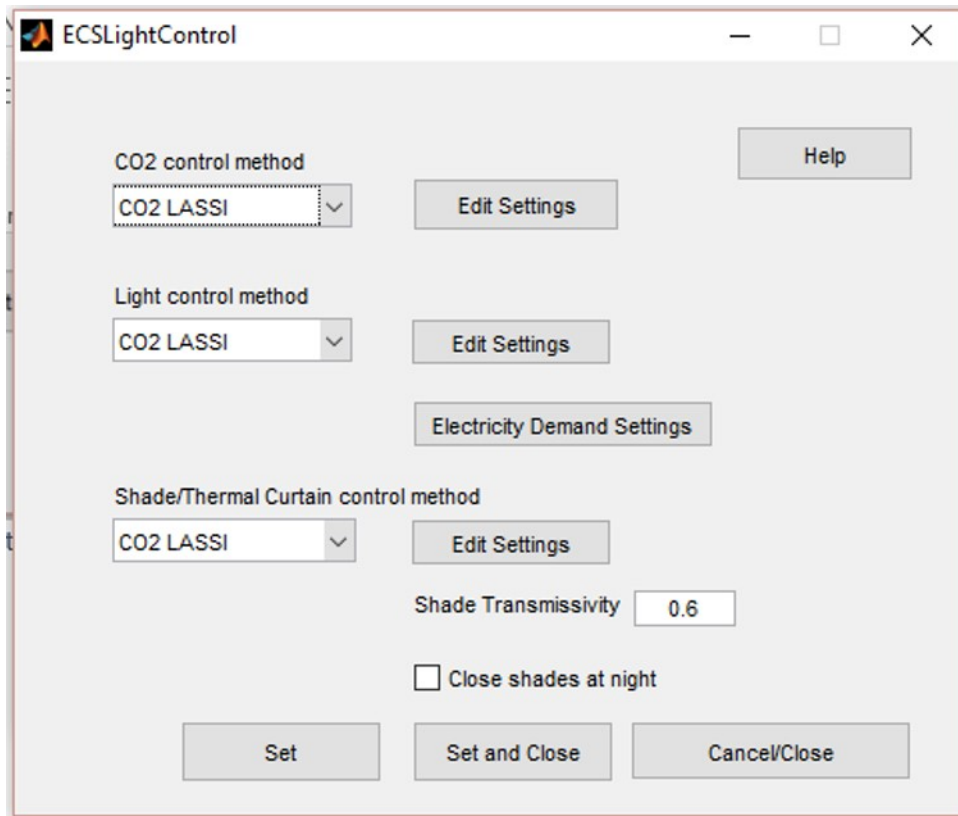
Figure 10: Light, Shade and CO_2 Control Settings Input Screen

4.4.1.1 Supplemental CO_2 Control Method:

The two CO_2 control methods available are none (natural) and CO_2 LASSI, which can be selected from the Drop down menu.

4.4.1.1.1 None (Natural):

"None" corresponds to no supplemental CO_2, with the assumption that CO_2 levels within the greenhouse are maintained at ambient.

4.4.1.1.2 CO_2 LASSI:

Selecting CO_2 LASSI from the drop down menu will automatically bring up the input screen for CO_2 LASSI Control Settings (*Figure 11*). Once the CO_2 LASSI control settings window has been closed, it can be accessed by pressing the "Edit Settings" button to the right of the drop down menu. Selecting CO_2 LASSI will also automatically select CO_2 LASSI for light and shade control, as these are fundamental to the performance of the CO_2 LASSI control method. However if you wish to select a different shade control method you may do so (though it is recommended that if a greenhouse has a shade system, that it employ the LASSI or CO_2 LASSI algorithm for shade control. The ability to change shade settings from other than CO_2 LASSI or LASSI was included so that users could examine the option of having no shade control.

The two main inputs of the CO_2 LASSI control screen are when during the year CO_2 LASSI should operate, and then the control settings and setup it should operate with.

Figure 11: CO_2 LASSI Control Settings

CO_2 Supplementation Controlled By:

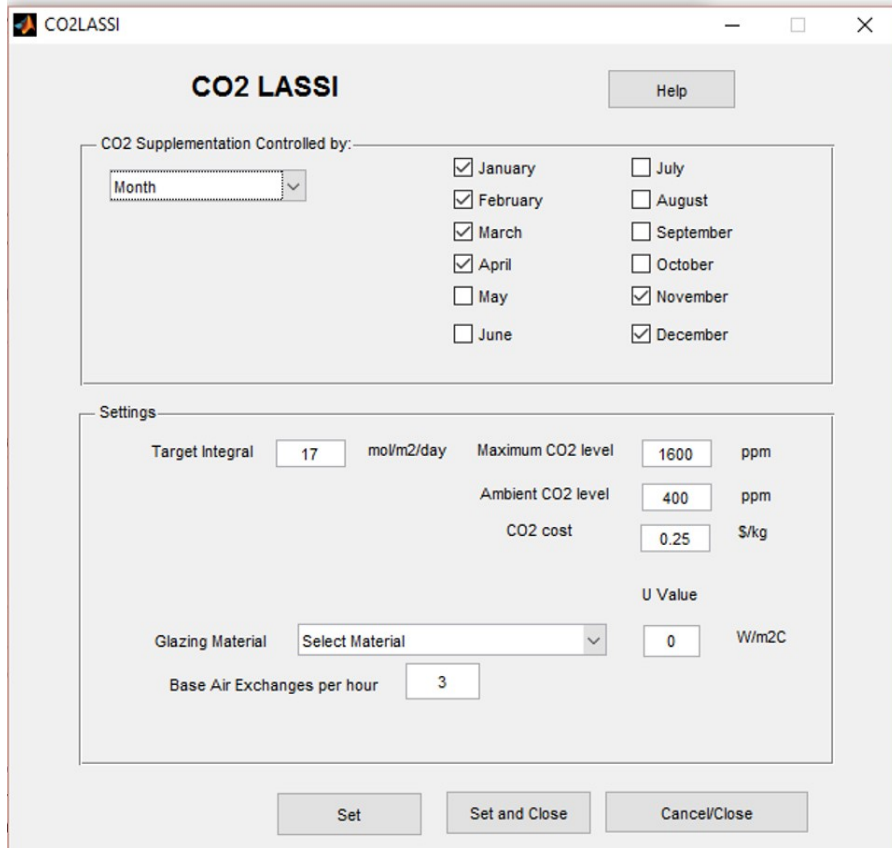Since CO_2 supplementation is generally not necessary during the summer months, and in other months, CO_2 losses due to ventilation may make CO_2 LASSI less economical than regular LASSI. During months that CO_2 LASSI is not in operation, control defaults to regular LASSI.

The two options for controlling when CO_2 LASSI operates are by Julian day of the year, and by month. Selecting "Day of year" from the drop down menu will display input fields where the user can put in the day to start and stop using the CO_2 LASSI Control Algorithm. Selecting "Month" from the drop down menu will display the months of the year with checkboxes next to each month. The user can then check the box next to each month they would like CO_2 LASSI to operate.

Settings:

The most important setting in CO_2 LASSI (and regular LASSI) is the target daily integral. The target integral is the amount of light that the crop should receive in Mols of photons of Photosynthetically Active Radiation (PAR) per m2 per day. Reducing daily light integral will generally reduce the yield of a crop, whereas increasing the integral will increase yield. However for some crops such as lettuce, there is a maximum daily light integral, beyond which the amount of light may be damaging to the crop, if it is exposed to considerably higher levels of light for prolonged periods. For CO_2 LASSI, the daily target integral is actually the "Virtual Integral", or the equivalent combination of Light Integral and CO_2 supplementation that would produce the same growth as straight Light Integral.

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Less light is required to produce the same amount of growth if CO_2 is supplemented above ambient conditions.

The next parameter that the user needs to enter is the maximum level of CO_2 Concentration to evaluate. Generally, in the experience of Cornell University experiments, levels above 1600 ppm are not economical. Values should be entered in increments of 100 ppm.

The next parameter that the user can modify is the ambient concentration (default setting is 400 ppm). Generally, in 2016, 400 ppm is considered to be the approximate ambient environmental concentration of CO_2.

A goal of the CO_2 LASSI algorithm is to reduce the cost of providing growth, whether that be through supplemental lighting or CO_2. As such, the CO_2 LASSI algorithm needs to know the cost of providing CO_2 supplementation (the cost of lighting is based on the cost of electricity, and the number of lights in the greenhouse, a factor which is determined from information entered in the "Structure" input section. The user can use the default cost of CO_2, or enter their own cost.

The CO_2 LASSI program uses a simplified model to predict the temperatures in the greenhouse over the course of the next hour, and thus whether ventilation is likely to occur. If the ventilation rate is too high, the cost of maintaining CO_2 at the target concentration will become uneconomic and CO_2 supplementation will be disabled for the hour. The simplified temperature model uses a simplified heat transfer factor (U Value), to predict temperatures. The user can select a material from the drop down menu and the corresponding U value for that material will automatically populate the U value field. If the user wishes to use a different U value, they can change the value within the U value input field.

The final field that needs to be entered is the "Base Air Exchanges per Hour". This is basically a measure of the tightness of the greenhouse, and represents how much air exchange occurs naturally between the interior of the greenhouse and the ambient air outside the greenhouse (with no ventilation.) Typically older, poorly sealed single glazed greenhouses can have air exchanges as high as 3 to 4 per hour, whereas tight, newly constructed plastic houses are typically around 0.5 air exchanges per hour. The air exchanges per hour affects how the concentration of CO_2 within the greenhouse decays over time.

4.4.1.2   Light Control Method:
The user can select from 7 options in the light Control Drop down menu. The 7 options are: None (Natural), LASSI, CO_2 LASSI, Supplemental, Fixed Interval, Manually Specified, and Day ahead Market Price. Once a user has selected a light control method, generally the input screen corresponding to their selection will pop up. To access the input screen later, the user can press the "Edit Settings" button next to the light control drop down menu.

A button labelled "Electricity Demand Settings" will appear if any control option other than "None (Natural)" is selected (*Figure 12*). This button is used to disable on peak lighting during any particular month of the year. Generally this is done to avoid expensive demand charges during times of the year when there is generally enough light to achieve daily target integral using off peak lighting only. Without disabling on peak lighting it is possible that even a single day of lighting with some on peak power can trigger an entire month of demand charges. The default is that on peak lighting is allowed during all months of the year.
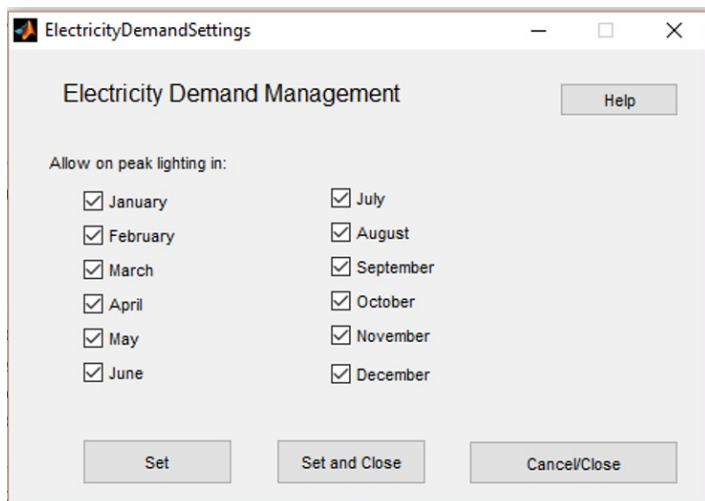
Figure 12: Supplemental Lighting Demand Management Input Screen

4.4.1.2.1   None

None (Natural) lighting means that there is no supplemental lighting available and the crop relies on whatever natural light enters the greenhouse. There are no settings associated with this control method, since there is no control.

4.4.1.2.2   LASSI

Light and Shade System Implementation (LASSI) is a Cornell University developed control algorithm that seeks to control the light levels in the greenhouse to a year-round consistent target daily integral. Another goal of the LASSI control algorithm is to shift any supplemental lighting into cheaper, off-peak power price periods.
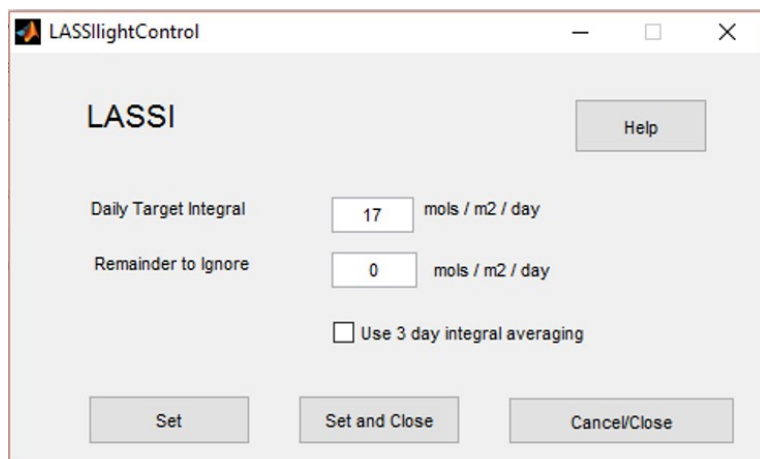
Figure 13: LASSI light control settings Input Screen

The main control setting, is the daily target integral, which is how much light the crop should receive over the course of a day. Typically for lettuce the daily target integral is 17 Mols /m2/day. A daily integral less than this will result in slower growth and productivity. A larger daily integral could result in excess light and a damaging physiological condition called "tip-burn" which can quickly render a crop unsaleable.

The next field a user can modify is the "Remainder to Ignore". In many greenhouses, supplemental lighting is provided by high pressure sodium lighting, which while boasting some of the highest efficiencies, has the drawback of a long warm up period, and shortened life from repeated on/off cycles. The "Remainder to Ignore" parameter seeks to reduce the on/off cycling by allowing the control algorithm to not turn on the lights if there is only some fraction of the daily light integral remaining. Note this is only triggered if the lights are off, and would need to turn on for some small fraction; if the lights are already on and less than an hour's worth of light is required, the lights will stay on for that fractional hour.

The next control option is to enable 3 day averaging. 3 day averaging seeks to smooth out the imperfections of the control algorithm and spread any over or under shoots of control, by adjusting the current daily target to take into account the differences. For example if the daily target integral yesterday was 17 Mols/m2/day and was undershot by 1 Mol/m2/day and the achieved target was only 16 Mol/m2/day, the daily target for the current day would be adjusted to 18 Mol/m2/day. There is a hard-coded 5 Mol/m2/day maximum limit to how much correction can take place.

4.4.1.2.3 CO_2 LASSI

Selecting CO_2 LASSI, will automatically change the CO_2 supplementation mode to "CO_2 LASSI", and pull up the "CO_2 LASSI input screen". For information about CO_2 LASSI please see "CO_2 LASSI", page 18.

4.4.1.2.4   Supplemental:

Supplemental Light Mode turns the lights on based on the natural light level. Typically whenever the light level drops below a set value, the control system will trigger the supplemental lights to turn on. The lights will turn off when the light level at the crop reaches a set level. For the purposes of this simulation the program looks at the expected natural light level for the current hour (which is an average over the hour) and then decides whether the supplemental lights should be turned on for that hour. The supplemental Lighting Input screen is shown in *Figure 14*.

The fields that the user can adjust are:

"Turn Lights on if light below", which is the light level (in umol/m2/s) below which the control algorithm will trigger the lights to turn on.

"Turn Lights Off if light above", which is the light level (in umol/m2/s) above which the control algorithm will turn the lights off.

Typically there is a deadband of at least 100 to 200 umol/m2/s between these two levels, depending on the system of supplemental lights that is installed.

The next field corresponds to when the lights should first turn on. The default check box is the lighting control algorithm will engage at sunrise. If the user wishes to specify a time, they can uncheck the "Start light at sunrise?" check box, when they will be presented with a field to input the time at which they want the control system to become active. Note this field uses a 24 hour clock.

The next field corresponds to when the lighting control system should be disabled. The default is at sunset, however by unchecking the box, the user can then gain access to an input field where they can put the hour of the day when they would like the control system to stop.

The final entry field is "Control to Integral". The default option is to not control to integral as this is how most unsophisticated control systems work. However, if the user checks the "Control to Integral" checkbox, they will be prompted to enter a target daily integral (in mol PAR/m2/day.) When the target integral is achieved, future lighting for the day will be disabled.
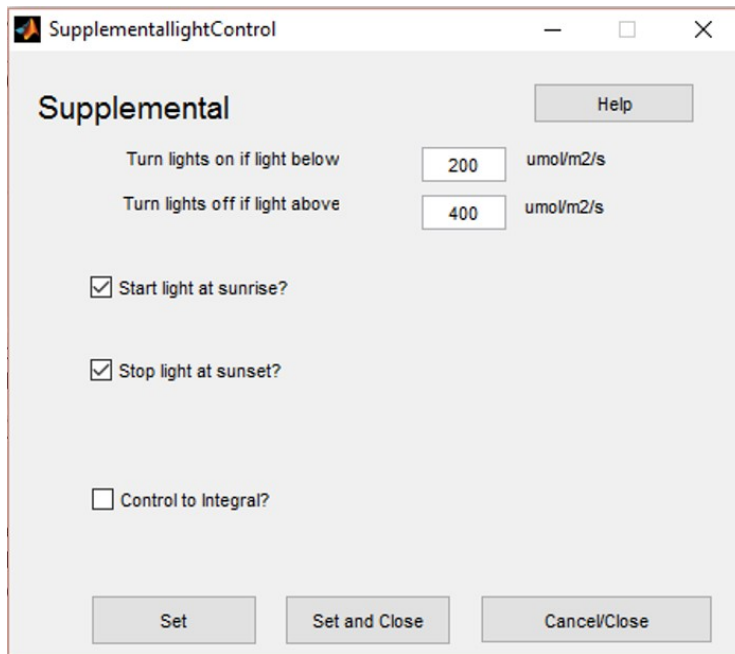
Figure 14: Supplemental Lighting Control Input Screen

4.4.1.2.5   Fixed Interval

Fixed interval mode is used to turn the lights on and off at specific times of the day (Figure *15*). In a greenhouse setting this would typically be controlled by a simple on/off time clock type controller. Typically such greenhouses do not measure the level or amount of light that the crop receives.

The options within Fixed interval lighting control mode are:

Start lighting at sunrise:

To turn the supplemental lights on at sunrise, check the box labelled "Start light at sunrise" (default mode), otherwise if this box is unchecked, a field will be displayed where the user will be prompted to enter the hour of the day for supplemental lighting to begin. Note, the time clock uses a 24 hour clock and only considers whole hours.

Stop lighting at sunset:

To turn the supplemental lights off at sunset, check the box labelled "Stop light at sunset" (default mode), otherwise if this box is unchecked, a field will be displayed where the user will be prompted to enter the hour of the day for supplemental lighting to end.

Most Fixed Interval or time clock controllers do not have a light sensor associated with them, however GEM includes the option of turn off the supplemental lighting when a target integral is met. If the "Control to Integral" box is checked, a user entry field will appear where a target integral value can be entered.
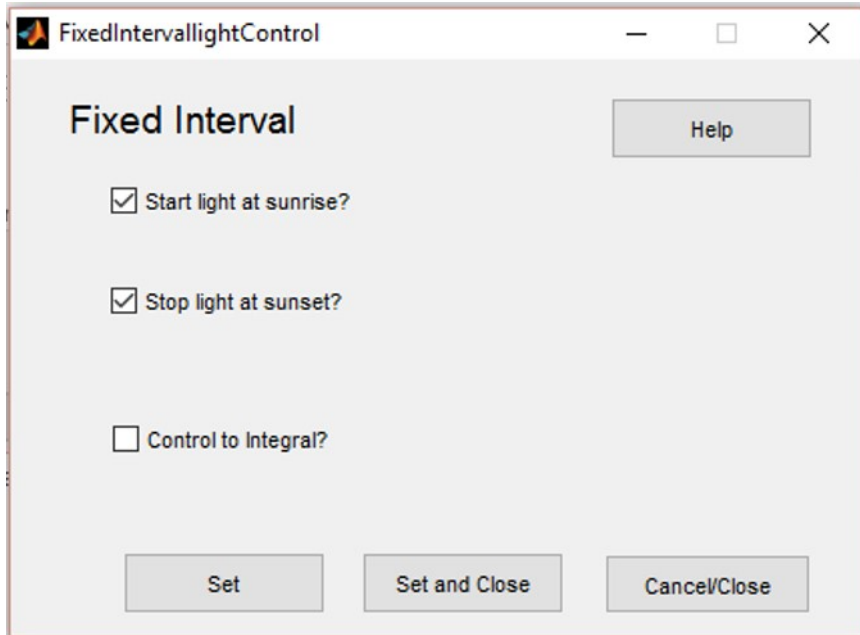
Figure 15: Fixed Interval Lighting Control Input Screen

4.4.1.2.6   Manually specified

Manual light mode is where the user can define which hours of the day the supplemental lights are either on or off for. It is similar to the fixed interval mode, however the lights can be turned on/off multiple times per day (rather than just defining and on/off time) (Figure 16).

To set the hours for supplemental lighting, select the check boxes corresponding to the hours of the day for the lights to be on. Unselecting a box will turn (or leave) the lights off for that hour.

Once the hours for supplemental lighting are selected, the user can then choose which days of the year those settings should apply to. If the user would like to store the same values for each day of the year, set the start day to 1, the stop day to 365, and then press the "Store" button. You can modify any day ranges you would like, using the same procedure. Any undefined days will default to no lighting.

To check what values apply to a specific day, enter the day in the "View day" input field, and then press the "View" button. The values stored for that day will be displayed.
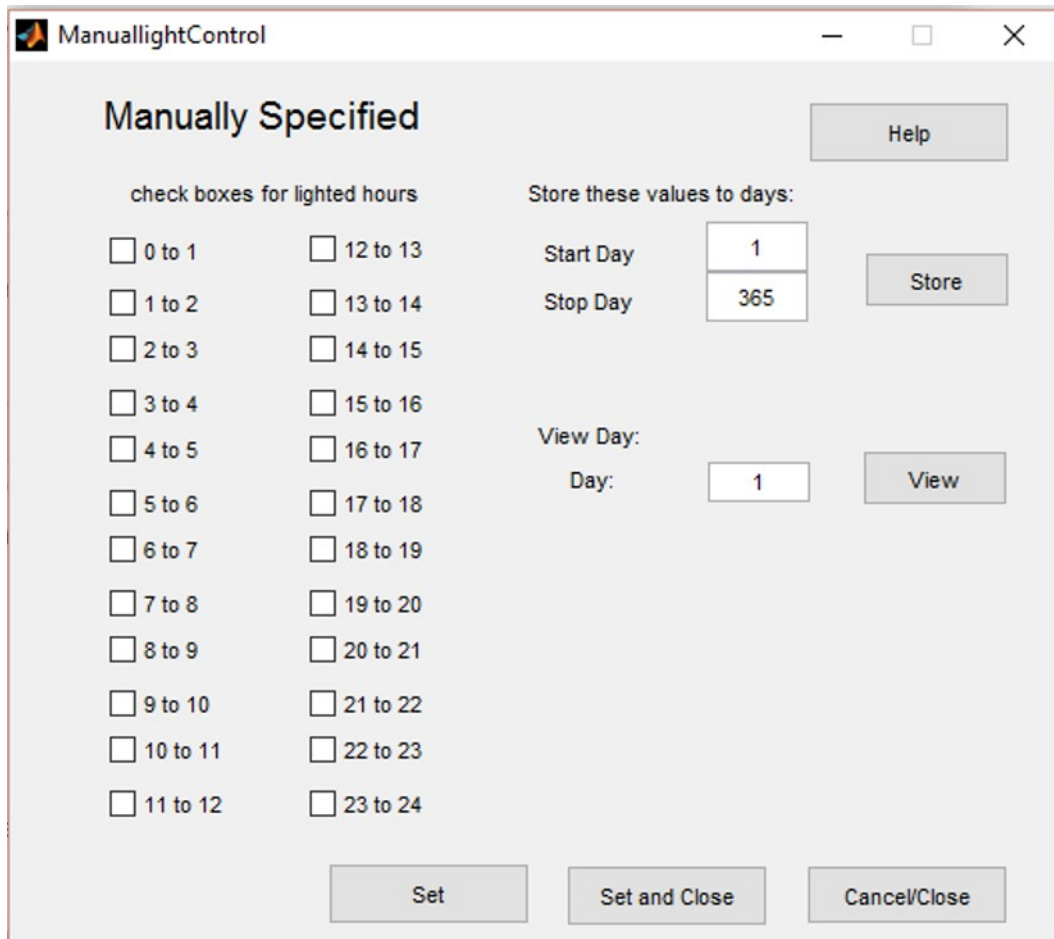
Figure 16: Manually Specified Lighting Control Input Screen

4.4.2   Heating Control:

After pressing the "Heating" button on the Environmental Control Systems input screen, (*Figure 9*), the user will be able to enter the heating setpoints for the greenhouse. If the user has previously selected a crop, the heating setpoints will automatically be filled in with suggested values. The user does not have to use these values and can change them to reflect different cultural practices, or energy saving considerations.

There are three modes for controlling temperature in the greenhouse:

4.4.2.1   *Constant Temperature:*

From the Temperature Target Method drop down menu, select "Constant, and a field for entering the constant temperature will appear (Figure 17).

Figure 17: Constant Temperature

4.4.2.2 Night/Day Temperature:

Typically greenhouse producers use different day and night temperature settings to save energy on heating at night. To use day/night temperature control, select "Day and Night" from the Temperature Target method drop down menu (*Figure 18*).
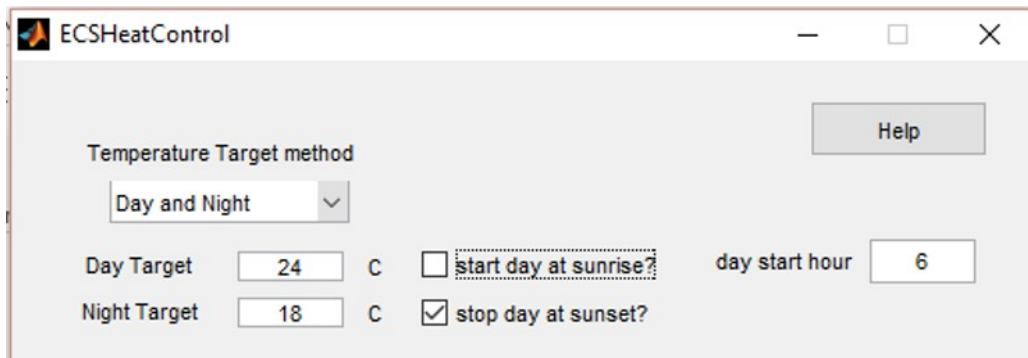
Figure 18: Day and Night Temperature

The user will then be prompted to enter the day and night temperatures, and to define when the day/night start and end. The user can either select for the day to start at sunrise, or else to define the start time explicitly by unchecking "start day at sunrise?" and entering the hour the day starts. Use the same procedure for defining the end of the day.

4.4.2.3 Manually Specified:

A grower may wish to employ a more sophisticated schedule for temperature control, with extended periods of "ramping" where temperature adjustments between day and night are more gradual. To use this more detailed temperature control method select "Manually specified" from the Temperature Target Method drop down menu (*Figure 19*).
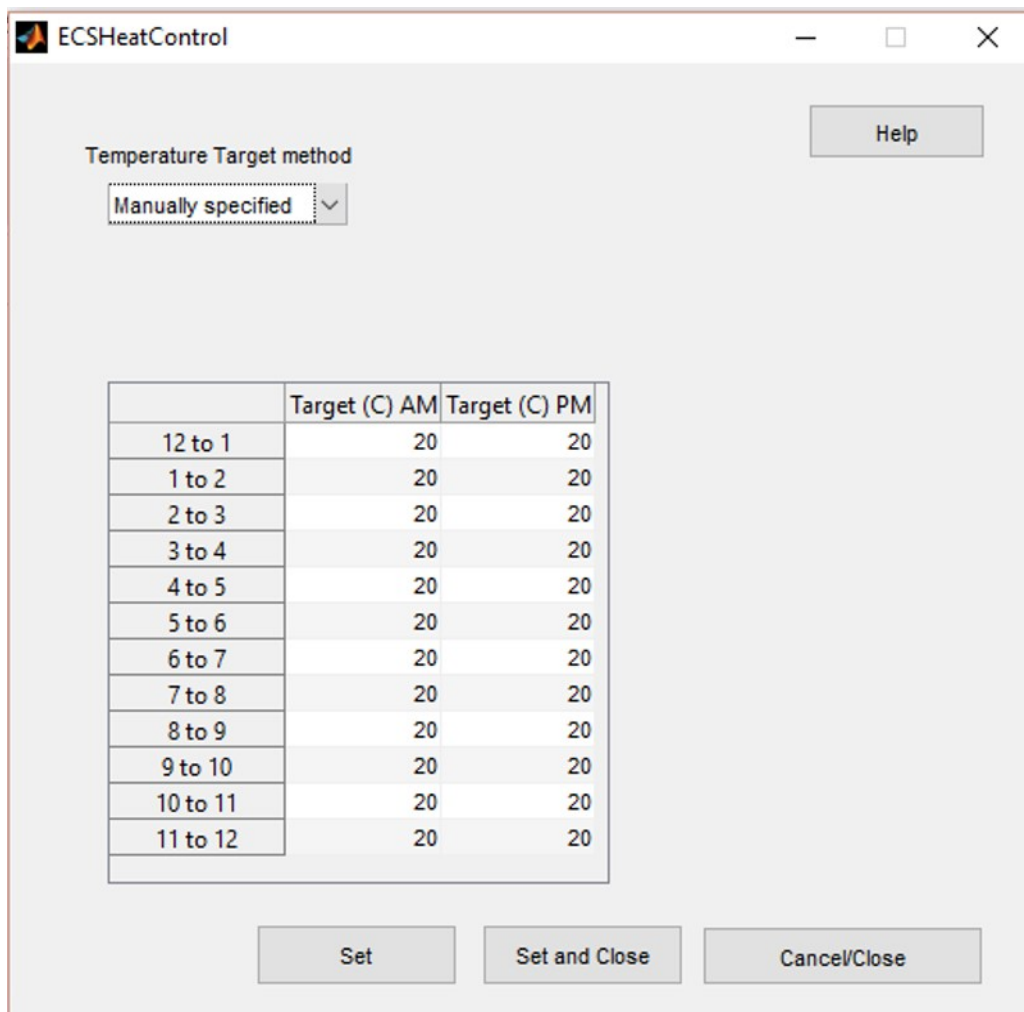
Figure 19: Manually Specified Temperature

A table will appear with 24 fields, corresponding to the 24 hours of the day for which a temperature will need to be specified. The rows of the temperature input table correspond to the 12 hours of the day, and the two columns correspond to the AM and PM hours.

The user can now enter target temperatures for each of the 24 hours of the day.

4.4.3   Cooling Control:

After pressing the "Cooling/Venting" button on the Environmental Control Systems input screen, (*Figure 9*), the user will be able to enter information about some of the cooling Options for the greenhouse.

The cooling control option that can be set on the cooling input screen (*Figure 20*).
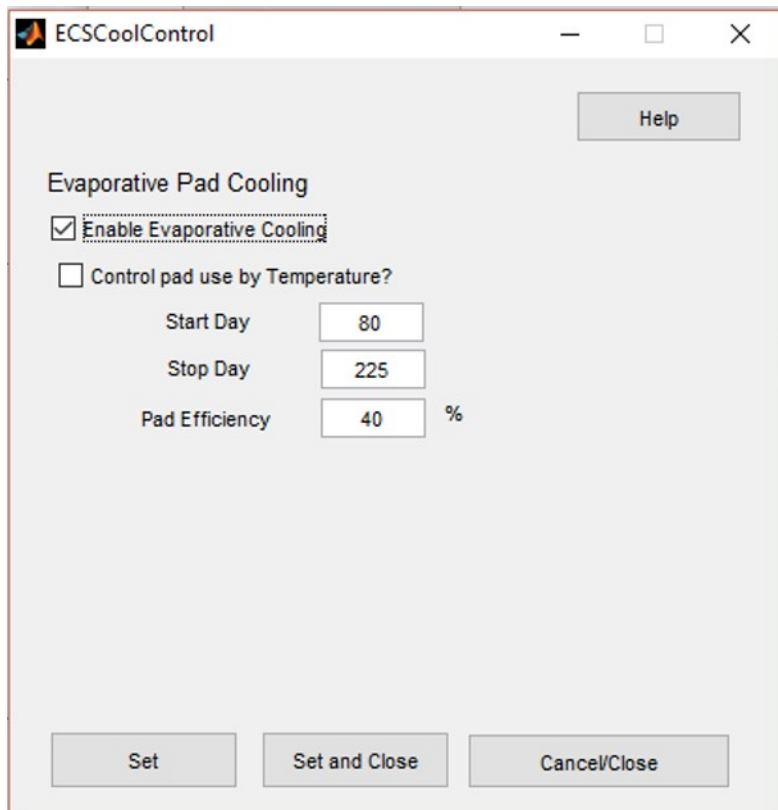
Figure 20: Cooling Control User Input

4.4.3.1   Evaporative Pad Cooling:

In the Northeast, a common method of cooling the incoming ventilation air is to use evaporative cooling. In an evaporative cooling system, water is run over a large porous surface area through which the incoming air to the greenhouse is drawn. Some of the water evaporates, and the dry bulb temperature of the air is reduced proportionally (the moisture content of the air is increased.) Typically evaporative cooling is only used in the summer months when ambient temperatures are high.

The user can select to have the greenhouse air cooled by evaporative cooling pads by checking the "Enable Evaporative Cooling" checkbox. Once the "Enable Evaporative Cooling" checkbox has been checked, an additional checkbox, "Control pad use by Temperature?" will appear.

The default is to control pad use by day of the year, ("Control pad use by Temperature" unchecked). If "Control pad by Temperature" is unchecked, the user will be prompted to enter a starting and stopping day of the year on which the pad will be in operation. Enter a Julian day between 1 and 365 for these fields. Note, the stop day must be greater than the start day.

If 'Control pad by Temperature?' is checked the input fields change so that the user will have the option of putting in a value for the ambient temperature above which the pads will be active. On days when the average ambient temperature is above the user setpoint, pad cooling will be active.

The other user information required for pad cooling is the efficiency of the pad. The default value is 40%.

4.5   Structure:

The "Structure" user input screen (*Figure 21*) is where specifics about the dimensions of the greenhouse, its construction materials, and the equipment installed within it. It is recommended that the "Structure" input screen be completed last, after the other inputs. This is both to take advantage of GEM presenting suggested values for some fields based on previously input information, as well as displaying only relevant input options (i.e. if a user has not selected to use evaporative pad cooling, then information about the size(s) of evaporative cooling pumps will not be displayed.

Similarly it is recommended that the user proceed from the top down, within the Structure information input window, starting with Dimensions, proceeding to Materials, and then finishing with Equipment. It is important to enter Dimensional data first as in the Dimensions input screens there will the option to select whether there is a knee wall, or a head house adjoining the greenhouse. This information will then be used by the Materials input window to display (or not) information about kneewalls and adjoining headhouses. In addition, in the equipment information input screen, GEM suggests values (number and size) for several types of equipment based on the area, of the greenhouse.
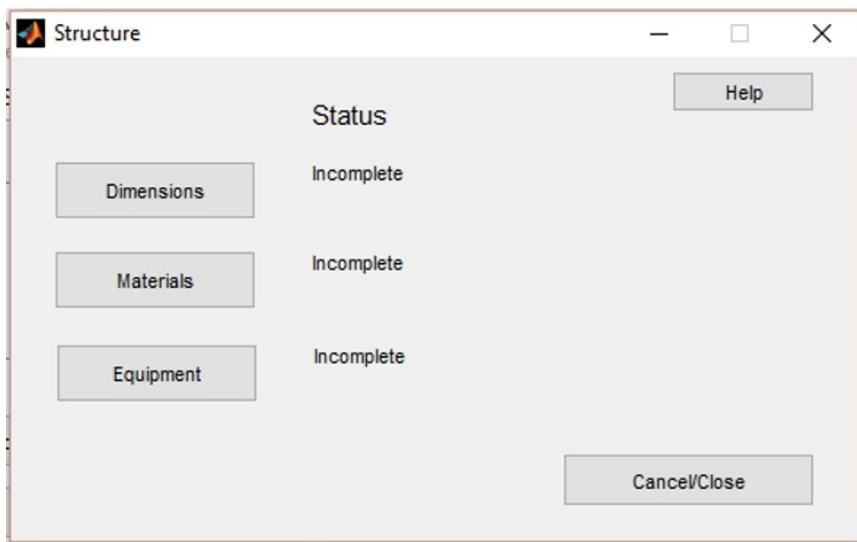
Figure 21: Structure information input screen

On the Structure information screen you can select which aspect of the structure you would like to enter information about. The three choices are, Dimensions, Materials, and Equipment.

4.5.1   Dimensions:

The dimensions screen (*Figure 22*) defines the shape as well as some of the characteristics of the walls of the greenhouse. The required input information can be broken down into four main areas: Overall dimensions, Roof Characteristics, Adjoining headhouse information, and Kneewall information.

The overall dimensions of the greenhouse consist of the Width, Length, Gutter Height, and the Growing area.

The width and length are arbitrarily defined as the length being larger than the width, however this convention does not have an effect on the calculations, if you wish to define walls differently. It should be noted that end walls are associated with the width of the greenhouse, and side walls with the length.

Figure 22: Greenhouse Dimensions Input Screen

The gutter height is defined as the distance from grade level to the lowest part of the roof (typically where drainage gutters are installed on multi-bay greenhouses).

The user can also define how much of the greenhouse consists of growing area. Typically a significant portion of a greenhouse area is taken up by alleys and walkways that provide access to the crop. A default value of 85% of the footprint of the greenhouse is assumed as the growing area, though the user can change this to any value less than the total footprint of the greenhouse. The growing area is used in some of the simulation calculations, particularly in the calculation of evapotranspiration.

4.5.1.2   Roof:

The dimensions and style of the roof can be defined in the Roof section of the Structure dimensions input screen.

In large area greenhouses, the roof is generally broken into several peaks. The user can enter a value for the number of peaks in the "Number of Peaks" entry field.

The peak height is defined as the distance from grade to the highest part of the greenhouse. This value must be greater than the gutter height value, entered in the overall greenhouse dimensions section.

Select either "Constant slope" or "Arch" from the "Roof Style" drop down menu. The profile of "arch" is defined as an ellipse, for the purposes of the calculation of roof area.

Also relevant to the calculation of roof area is the checkbox entitled "Roof runs parallel to length". Check this box if the ridgeline of the roof runs parallel to the length of the greenhouse, uncheck it if the roofline runs parallel to the width of the greenhouse. For the purposes of this program, the length of the greenhouse is defined as the long side of the greenhouse (ie. the length is greater than the width.)

4.5.1.3   End Walls:

In the walls section of the Greenhouse Dimensions input screen, it is possible to define whether the entire, or portion of the walls abut (adjoin) a headhouse. For the purposes of simulation, if a portion of the greenhouse adjoins the headhouse, the user will be prompted in the "Materials" input screen to enter what temperature the headhouse is maintained at (it is assumed that the temperature of the headhouse is constant.)

The user can check the box "headhouse abuts" for each of the walls that a headhouse abuts (adjoins), after which an entry field will appear into which the user can enter the length of the wall that the headhouse adjoins. This length must be less than the overall length of the particular wall. It is also assumed that the headhouse adjoins the greenhouse for the full height of the greenhouse.

Walls are defined for the purposes of GEM as the "End" walls are associated with the width (which is generally less than the length), and the "Side" walls are associated with the length of the structure.

4.5.1.4   Knee Walls:

Knee walls are the lower part of greenhouse walls that are generally constructed of materials more durable, less expensive, and with better insulating properties, than the upper glazing portion of the wall.

If knee walls are used on any of the walls, the user should check the "Knee walls Used" checkbox. Once the checkbox has been checked, entry fields where the user can input the height of the kneewalls will appear. The kneewall heights must be less than the gutter height of the greenhouse.

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4.5.2 Materials:

In the "Structure Materials" input screen (*Figure 23*), the user can choose the materials and properties of the materials, from which the greenhouse is constructed. Generally the user will have the option of selecting a material from a drop down menu, which will then autofill the thermal properties for that particular material. The user will then have the option of keeping the suggested value, or changing it to better represent the situation they wish to simulate.

The entry fields the user will have to select/complete depend on information entered on the "Dimensions" input screen. For example if no kneewalls were selected in the Dimensions input screen, the user will not be prompted to input material information about kneewalls. Similarly for whether any of the walls adjoin a headhouse.

Figure 23: Structure materials information Input Screen

The user will always have to enter information about the walls and roof of the greenhouse. The first information to be entered are the materials, and thermal property of the walls. If no knee walls are present, the walls are referred to as End walls, or side walls (end walls correspond to the width of the greenhouse, side walls to the length). If knee walls are present, the first entries regard the upper end and side walls.

If knee walls were defined in the "Dimensions" input screen, any non-zero knee wall height will trigger the need to input information about the knee wall (material and thermal property). Only knee walls with non-zero heights will need to be input.

Headhouse materials data input is treated similarly to knee wall input. If any portion of a wall has been defined to abut (adjoin) a headhouse, then the user will be prompted to enter information about the material and thermal property of the material that separates the greenhouse from the headhouse. The user will also be prompted to enter the Temperature at which the headhouse is maintained. For the purposes of the simulation it is assumed that this temperature is constant, year round.

The user will also always have to enter information about the material of the roof (material and thermal property.) If the user previously selected shade control, the user will also have to input

information about the thermal properties of the roof with the shade deployed. Suggested values are generated based on the material chosen for the roof, however the user has the option of changing this value to better reflect the situation they are simulating.

Also related to the selection of a roof material is the greenhouse tightness, and transmissivity of light.

The tightness of the greenhouse is defined as the number of air exchanges that occur between the air within the greenhouse and outdoor ambient air over the course of an hour. The tightness can vary considerably depending on the type of material the greenhouse is constructed of, as well as how well that material is maintained (as well as outdoor environmental conditions.) Typically on the low end, greenhouse tightness can be 0.25 air exchanges per hour, up to 4 or more for poorly maintained greenhouses.

When the user selects a material for the roof, an average greenhouse tightness is automatically filled into the input field. The user is encouraged to change this value if they have better knowledge of the condition and performance of the greenhouse system they are modelling.

The final piece of information in the materials input window is the transmissivity of the greenhouse to light. This is broken down into three parts; the glazing transmissivity, the structural transmissivity, and the overall transmissivity. The overall transmissivity is the most important as this si the value used in the simulation calculations. It is a product of the glazing transmissivity and the structural transmissivity. The glazing transmissivity is automatically filled based on the choice of roof material selected by the user. The user can change this based on any better knowledge they have of the transmissivity of the material they are interested in modelling. The structural transmissivity is the transmissivity of the structure of the greenhouse to light. Often support structures, light fixtures, heat pipes, or any other overhead materials will block a portion of the light incident on the crop, and this is defined in the structural transmissivity entry field. A default value of 0.8 (80%) is assumed, though the user can change this value.

4.5.3 Equipment:

Equipment is defined for the purposes of GEM as the energy (fuel, or electricity) using equipment associated with the greenhouse. Depending on where the equipment is located it may or may not contribute to the thermal load of the greenhouse as energy used by equipment (or at least a portion), may be converted to heat. In addition, electricity represents a significant portion of the cost of greenhouse production, and GEM seeks to provide an estimate of energy use, and the cost associated with the use of that energy.

Suggested values and quantities for equipment are automatically populated when the user enters the dimensions of the greenhouse. The user can keep these suggested values or else enter values more specific to the project they wish to simulate. However it should be noted that if the user changes the dimensions of the greenhouse, the values entered for equipment will not change (suggested values will only be populated into a project that has not previously had values entered.)

On Greenhouse Equipment screen (*Figure 24*) the user can enter information about the equipment associated with the greenhouse.

Figure 24: Equipment information input screen

The Greenhouse Equipment Input Screen is divided into two sections:

4.5.3.1 Continuous Use Equipment:

Continuous use equipment is typically operating at all times, and its energy usage will remain relatively constant throughout the year. Categories that are explicitly defined are: Nutrient Solution pumps, Air Circulation fans, Control computers and Miscellaneous. For the Nutrient Solution pumps, air circulation fans and control computers, the user is prompted to enter the number of each type of item, as well as the size (individual energy use) of each item.

Miscellaneous is a catch all field in which the user can enter the energy use of any equipment that runs continuously.

If the user previously entered dimensions for the greenhouse, GEM will automatically input suggested values for the equipment. The user may keep or modify these values as they see fit.

4.5.3.2   Periodic Use Equipment:

Periodically used equipment is equipment that is not used 100% of the time (i.e. not in continuous use.) This equipment might be seasonal or daily use, however when it is turned on is controlled by the GEM simulation, based on input settings the user has chosen.

This input section is divided into two components, Supplemental Lighting and Heating and Cooling.

4.5.3.2.1   Supplemental Lighting:

The supplemental lighting field is automatically filled in based on growing area that was entered in the "Dimensions" data entry screen. The user may wish to enter more relevant information based on the use of different fixtures and fixture efficiencies. For the purposes of the GEM model to keep input simple, the user can modify the number of fixtures, the size (energy use) of the individual fixtures, and the light output at Crop level, of the fixtures. Generally higher output fixtures would mean that few fixtures would be needed to provide the same level of light at Crop level as a smaller fixture, however that is also a function of reflector design. For energy use of the fixtures, the "wall plug" usage should be entered, so as to properly capture the energy use of any ballasts or cooling fans associated with each fixture.

4.5.3.2.2   Heating and Cooling:

Within the "Heating and Cooling", periodic use equipment section there are three items.

4.5.3.2.2.1   Heating Infrastructure:

Pressing the "Heating Infrastructure" button will bring up the Heating System Equipment screen (*Figure 25*) where information can be entered to describe the equipment used for providing heat to the greenhouse. It is assumed that any waste heat from this equipment is not dissipated in the greenhouse aerial environment.

The first step is for the user to select the type of equipment used to provide heat from the drop down menu labelled "Heater Type". The options to choose from are Boiler, Unit Heaters, and Custom heat source.

"Boilers": If the user selects "Boilers" from the drop down menu, they will be prompted to enter further information about the number of boilers, the size (capacity) of the boilers, and the efficiency of the boilers.

In addition the user will be prompted to enter information about the pumps and fans used to disperse the heat from the boilers. Boiler loop pumps distribute water between and within boilers and typically operate continuously when the boiler is in operation.

Heat Circulation pumps move the heated substrate (typically water or steam) into the greenhouse for distribution. It is assumed that when the greenhouse is calling for full heat, the pumps work at 100% of rated capacity, and are then scale proportionately lower as less heat is called for.

If any fans are used to distribute the heat (heat distribution fans are considered separate from circulation HAF fans), the user can enter information about them here. It is assumed that these fans operate at the same time as the boiler is operational (i.e. continuously during heating system use).

Figure 25: Heating System Equipment Input Screen

"Unit Heaters": If the user selects "Unit Heaters" from the drop down menu they will be prompted to enter further information about the number of unit heaters, the size (capacity) of each heater, and the efficiency of the heaters.

In addition the user will be prompted to enter information about the fans used to disperse the heat in the greenhouse space, in the "Heat Distribution Equipment" entry fields. For the purposes of the simulation it is assumed that the "Heat Distribution Equipment" works at 100% whenever the heat is called for (whether or not 100% heat is called for or not.)

"Custom Heat Source": If the user selects "Custom Heat Source" from the drop down menu they will be prompted to enter further information about the number of custom heat sources, the size (capacity) of each heat source, and the efficiency of the heaters.

In addition the user will be prompted to enter information about the fans used to disperse the heat in the greenhouse space, in the "Heat Distribution Equipment" entry fields. For the purposes of the simulation it is assumed that the "Heat Distribution Equipment" works at 100% whenever the heat is called for (whether or not 100% heat is called for or not.)

4.5.3.2.2.2   Ventilation Fans:

Pressing the "Ventilation Fans" button will bring up a screen (*Figure 26*) in which information can be entered about the fans used for ventilation. The information required is the number, size and capacity of the fans, as well as the threshold (temperature above set point) that they activate.
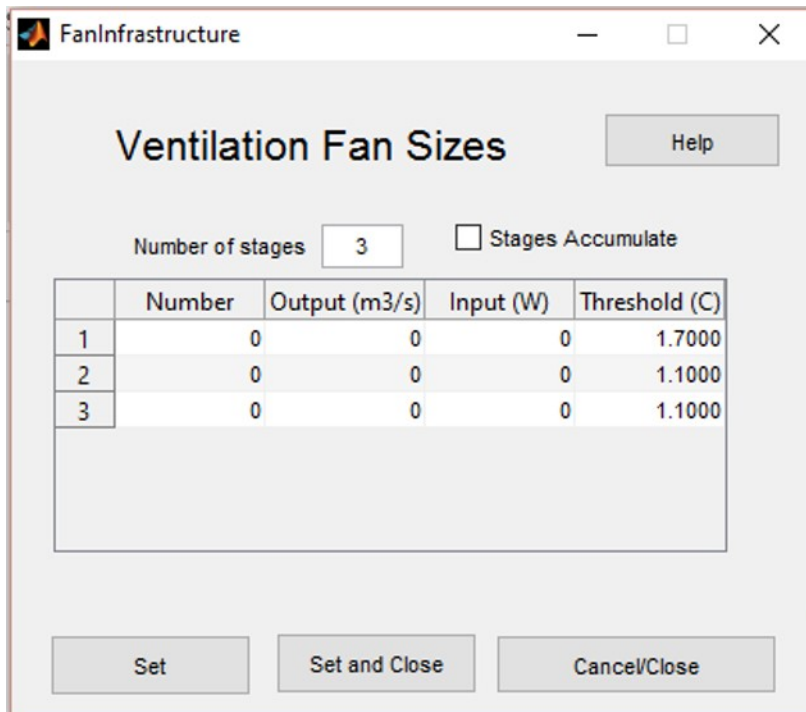
Figure 26: Ventilation fan sizes and threshold for use

Typically, in modern greenhouses fans are controlled by "stages", to provide an airflow more closely matched to the greenhouse need. Single stage greenhouses may cause premature wear of the fans if large fans that are sized for peak summer usage are switched on/off frequently during periods of the year when ventilation requirements are low.

On the Ventilation fan size input screen, the user is presented with an input field prompting for the number of stages present. The user can enter the number of fan stages present (from 1 to 6), and the table below will update to provide the space to enter further information about each stage.

Number:
In the number column, enter the number of fans of the same size associated with a particular stage.

Output:
Enter the output in terms of air flow of the same sized fans for each stage.

Input:

Enter the electrical energy input of the individual fans in each stage.

Threshold:

The threshold is the temperature above the greenhouse aerial temperature set point above which the stage will activate.

Stages Accumulate Checkbox:

If the user selects the "Stages Accumulate" checkbox, as the temperatures in the greenhouse rises and further ventilation stages are called for, all previously called for stages will remain active. If the checkbox is unchecked, only the stage corresponding to the temperature threshold will activate (i.e. only a single stage will be active at a time).

4.5.3.2.2.3   Evaporative Cooling:

If the user selected "Enable Evaporative Cooling" on the Cooling Venting input screen, (*Figure 20*), the user will be prompted to enter the number and size of the water pumps used to circulate water over the evaporative cooling pads. It is assumed for the purposes of the GEM simulation that the circulation pumps run continuously for the days that Evaporative cooling is enabled (i.e. they do not shut down at night.)

5 Simulation:

Before the user can view the estimated energy use of their particular greenhouse, the program must use the input information to simulate the greenhouse and predict the energy usage. The simulation runs through every hour of the year and predicts the electricity usage, and how heat flows in and out of the structure and stores this information for later viewing by the user. Only after running the simulation will the user be able to access the output data to examine the performance of their greenhouse.

Once all necessary data has been entered or is loaded and the "Project Data", "Climate", "Crop", "Environmental Control" and "Structure" status indicators read "Complete", the Simulate Button will appear on the main GEM GUI window. Also at this time the ability to access the simulation page through the main menu will become active (Figure 27).
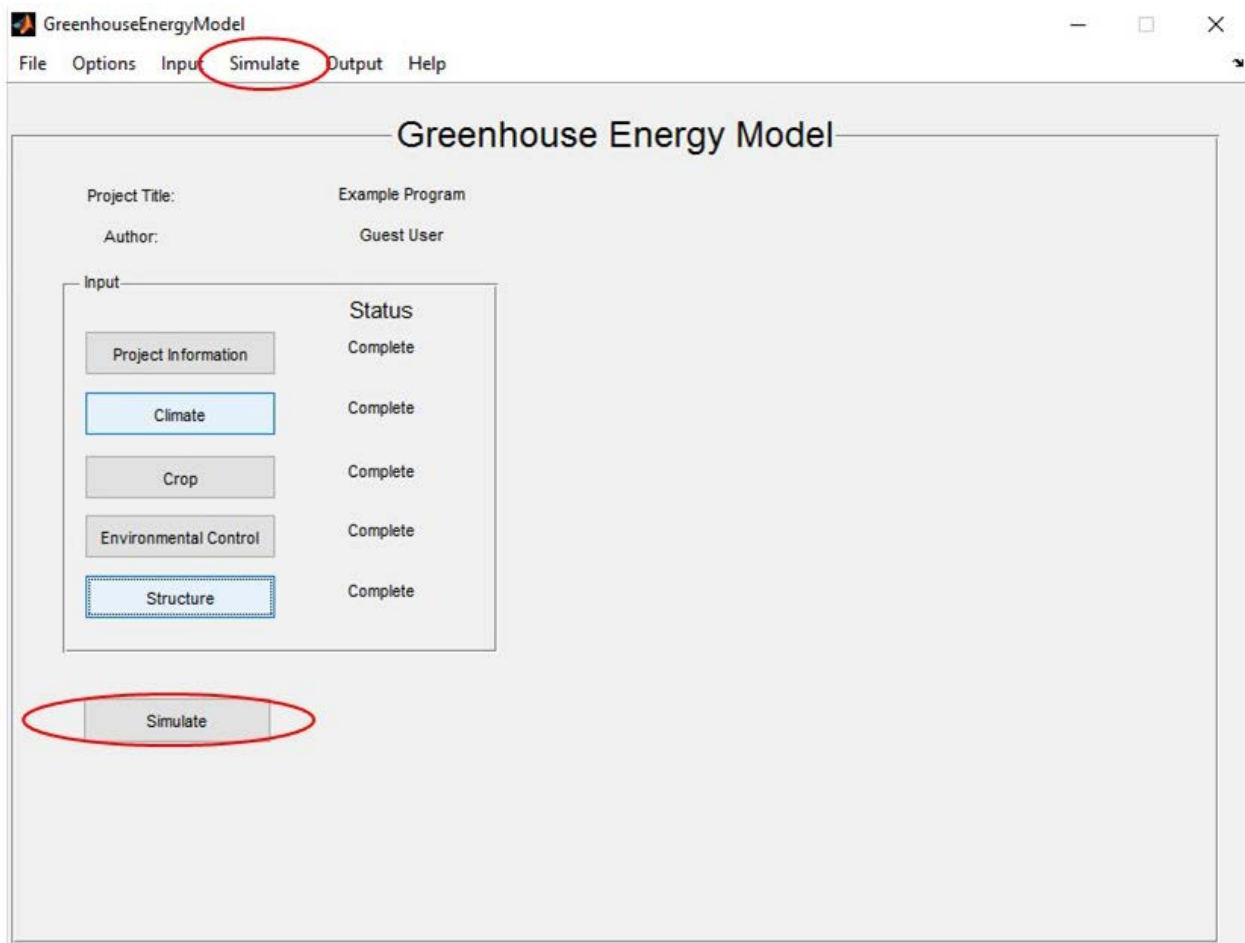

Figure 27: The Simulate page can be accessed through pressing the "Simulate" button, or through the main menu

5.1 Simulation Algorithm

To predict the energy usage (heat and electricity) of the greenhouse, the simulation steps through each hour of the year, and then estimates makes estimations based on the previous conditions in the greenhouse, setpoints and environmental conditions for that particular hour. There are a number of steps that the program goes through, and these are outlined in (Figure 28)
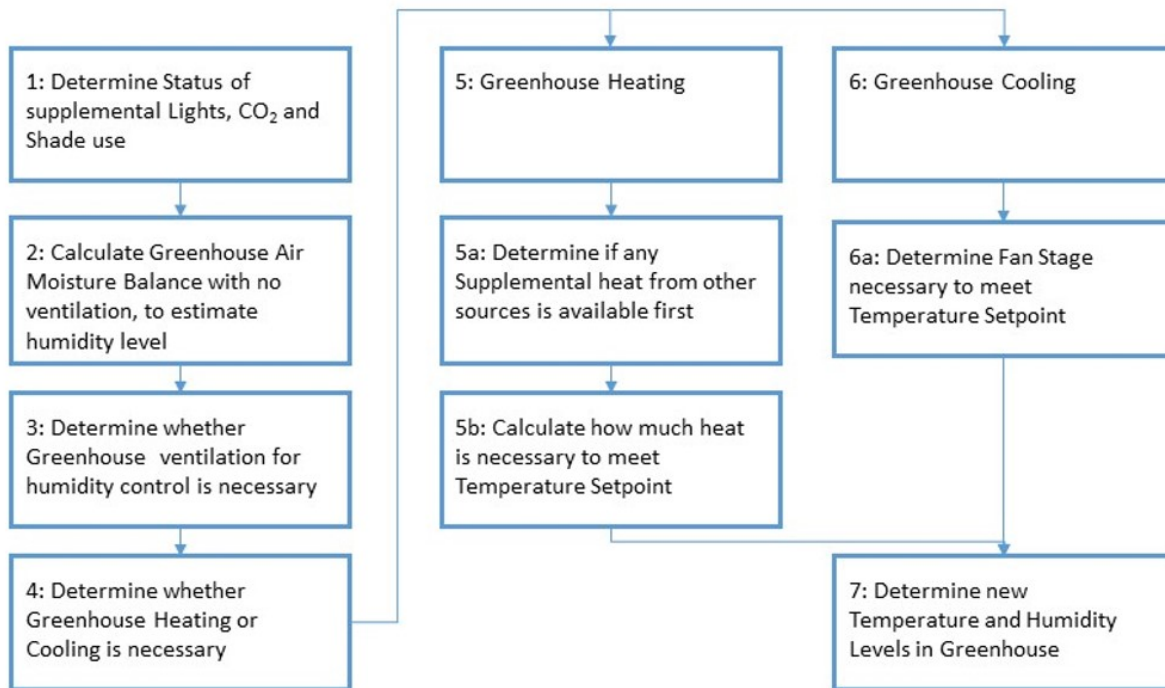
```
┌─────────────────────────┐      ┌─────────────────────────┐      ┌─────────────────────────┐
│ 1: Determine Status of  │      │ 5: Greenhouse Heating   │      │ 6: Greenhouse Cooling   │
│ supplemental Lights, CO2│      │                         │      │                         │
│ and Shade use           │      │                         │      │                         │
└─────────────────────────┘      └─────────────────────────┘      └─────────────────────────┘

┌─────────────────────────┐      ┌─────────────────────────┐      ┌─────────────────────────┐
│ 2: Calculate Greenhouse │      │ 5a: Determine if any    │      │ 6a: Determine Fan Stage │
│ Air Moisture Balance    │      │ Supplemental heat from  │      │ necessary to meet       │
│ with no ventilation, to │      │ other sources is        │      │ Temperature Setpoint    │
│ estimate humidity level │      │ available first         │      │                         │
└─────────────────────────┘      └─────────────────────────┘      └─────────────────────────┘

┌─────────────────────────┐      ┌─────────────────────────┐      ┌─────────────────────────┐
│ 3: Determine whether    │      │ 5b: Calculate how much  │      │ 7: Determine new        │
│ Greenhouse ventilation  │      │ heat is necessary to    │      │ Temperature and         │
│ for humidity control is │      │ meet Temperature        │      │ Humidity Levels in      │
│ necessary               │      │ Setpoint                │      │ Greenhouse              │
└─────────────────────────┘      └─────────────────────────┘      └─────────────────────────┘

┌─────────────────────────┐
│ 4: Determine whether    │
│ Greenhouse Heating or   │
│ Cooling is necessary    │
└─────────────────────────┘
```

Figure 28: Flow diagram of GEM Simulation algorithm

5.1.1 Status of Supplemental Lights, CO_2, and Shade Use:

Because the use of supplemental lights and shading systems can have a significant effects on the heat balance of the greenhouse, and light level is the environmental factor of prime importance, the first step in the simulation algorithm is to determine the status of the supplemental lighting and shade systems. The status of the supplemental CO_2 control system (if used) is also determined at this time as it affects the growth and transpiration of the crop and in turn the moisture balance of the greenhouse air.

Depending on the light control mode selected, the program makes a decision to turn on the lights/supplement with CO_2, or open/close the shades as described in section 4.5, Program Input, Light/Shade/CO2:.

If CO_2 supplementation is used, the program will determine the target CO_2 concentration, or if CO_2 supplementation was used in a previous hour, but not the current, the program will calculate the new CO_2 concentration (however the new CO_2 concentration is performed later, when greenhouse ventilation rates have been calculated.)

5.1.2 Greenhouse Air Moisture Balance:

Once the status of the supplemental lights, shades and CO_2 systems have been determined, a moisture balance of the greenhouse air can be determined. The moisture balance is a sum of all the sources and sinks of moisture in the greenhouse air. Starting with the initial moisture conditions of the greenhouse, sources and sinks of moisture are:

5.1.2.1 Crop Evapotranspiration:

Crop Evapotranspiration is estimated using the Penman Monteith equation (Allen et al, 1998). The Penman Monteith equation is a widely used means of estimating reference evapotranspiration from a crop based on the incident radiation (light), wind velocity above the crop and several psychrometric parameters that can be determined from the Dry bulb temperature and Relative Humidity.

5.1.2.2 Outdoor Air Infiltration:

With even well maintained, tightly sealed modern greenhouses, air infiltration can be significant. Air infiltrating into the greenhouse carries in moisture from the air outside of the greenhouse.

5.1.2.3 Greenhouse Air Exfiltration:

When outdoor air infiltrates a greenhouse, an equivalent volume of air must be forced out of the greenhouse. As a simplification in determining the moisture that is leaving the greenhouse in this air, it is assumed that the air has the psychrometric properties of the greenhouse air at the beginning of the hour (initial moisture conditions.) In reality, the air of the greenhouse is constantly being mixed as outdoor air is brought in, and other processes adjust the moisture content.

5.1.3 Ventilation for Humidity Control:

Once the net gain/loss of moisture in the greenhouse air has been determined, the relative humidity can be estimated by using the new moisture content of the air, and the target air temperature. With these two parameters the psychrometric properties of the air can be determined, of which the relative humidity is one.

The newly calculated relative humidity is then compared against the target relative humidity to determine if venting for humidity control is necessary. If the humidity is below the target, no ventilation is necessary. If the humidity is above the target, then outside air must be brought in to reduce the humidity level within the greenhouse.

The first step in determining the volume of outside air that must be exchanged to bring the relative humidity down to the target setpoint, is to calculate the surplus amount of moisture in the greenhouse air (i.e. the mass of water that must be removed).

The next step is to calculate the moisture difference between 1 m3 of outside air and 1 m3 of inside greenhouse air. The total mass of moisture to be removed can then be divided by the calculated difference in moisture content between inside and outside air to provide the volume of air that must be exchanged.

The program then determines the ventilation rate necessary, and matches it to a corresponding fan stage/duration. If the volume is greater than the fan capacity, it is assumed that the fans run at full capacity.

5.1.4 Heating or Cooling Status:

Once the moisture balance has been completed, and the ventilation rate necessary for humidity control determined, an energy balance on the greenhouse air can be performed to determine if heating or cooling is necessary.

GEM can determine the energy balance using two different methods; a modified ASABE, and a custom GEM balance that incorporates radiative exchange.

The modified ASABE energy balance is based on the ASABE standard : ASABE 2008. The standard uses the inside and outside temperatures as well as heat loss coefficients (U factors) for the building materials to estimate the heat exchange with the ambient environment. To improve on the ASABE standard, GEM includes taking into account; solar gain and sensible heat from electrical equipment within the greenhouse such as lights, fans and pumps. Electrical equipment can represent a significant portion of the heat added to a greenhouse, which in turn has important implications on heating/cooling.

If the result of the energy balance indicates a net flow of heat out of the greenhouse, then the greenhouse heating section of the program takes over. A net flow in, and the cooling section becomes active.

5.1.5 Greenhouse Heating:

Once the energy balance has been calculated and it has been determined that there is a net flow of heat out of the greenhouse, the greenhouse heating portion of the algorithm determines the amount of heat necessary to maintain temperature, and the amount of fuel (or additional supplemental heat) necessary to provide that heat. The amount of fuel necessary is determined by dividing the required amount of heat by the efficiency of the heat conversion equipment (boiler, unit heater etc.)

5.1.6 Greenhouse Cooling:

If there is a net flow of heat into the greenhouse, cooling may be necessary. Cooling is handled differently than heating in that some tolerance is given for drifting above the greenhouse temperature setpoint.

Initially the program calculates what the greenhouse temperature will be given the heat flow into the greenhouse and no fan use (there are still air-exchanges due to natural ventilation). This temperature is then compared against the threshold for the first stage of fans. If it is below the threshold, the fans remain off. If it is above the threshold temperature of the first stage of fans, the program re-calculates what the temperature would be at maximum ventilation for the first stage. If the temperature is still above the threshold, additional stages of fans are necessary, and the process is repeated for the next stage of fan, up until the threshold is no longer exceed for a particular stage, or the final stage of ventilation is exceeded.

If the predicted temperature is below the above the threshold of the next stage, the program determines the volume of air necessary to balance the temperature, and then determines the portion of the hour the fan stage would need to operate by dividing that volume by the total volume that stage of fan could provide over the full hour.

If the temperature can't be maintained due to excess heat coming in, it is assumed that the fans run at maximum on the final stage.

5.1.7   New Temperature and Humidity Levels:

Once the heating and cooling status of the equipment is determined, the temperature and relative humidity for the current hour are determined. These values will be the starting point for calculations in the following hour (ie. if the greenhouse is unable to maintain temperature during a particular hour due to an undersized boiler, the greenhouse will start the next hour below the target setpoint.

5.2   Simulation Process:

The simulation runs based on day of the year with the day starting at sunrise of the 1st day, and going through sunrise on day after the last day of the year (as days in the greenhouse lighting are generally calculated on a sunrise to sunrise basis.) Data for the night of the final day (midnight to sunrise) is taken from the first day of the year.

As the simulation runs and calculations are being performed, the progress of the simulation is displayed in the Simulation Progress Bar (Figure 29). It is important that you do not close window until the simulation bar is complete (at which point it will close itself), otherwise the simulation may not have finished.

It should be noted that the progress bar does not always move at a constant rate, because under differing times of year and conditions, certain control options may come into play requiring more calculations to be performed.

Once simulation completes, yearly summary data is displayed on the GEM main GUI window.
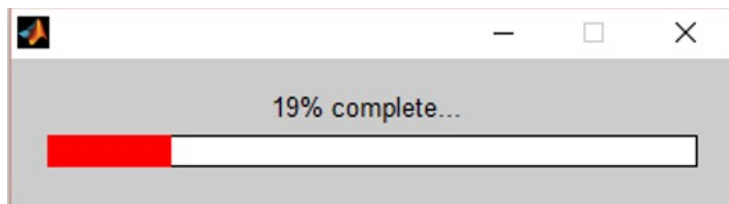

Figure 29: Simulation Progress Bar

6   Program Output:

The product of GEM is the output the simulation generates which the user can examine to compare different control strategies, greenhouse construction and location effects on energy usage. Quick comparisons can be made by looking at overall yearly energy usage, or more in depth analyses are possible through examining daily and hourly values.

Once the simulation has completed running, the output generated will be accessible by the user. Output is available in two forms, displayed by GEM onscreen, or exported to an Excel™ file for more in depth analysis/comparison.

Yearly summary data is placed on the main GEM screen, and additional summary data can be accessed by pressing the "Detailed Output" button on the main GEM screen (*Figure 30*).

6.1   Yearly Summary

Yearly output data is initially displayed on the main GEM window (*Figure 30*). This yearly data quickly summarizes the major energy usage of the greenhouse in terms of heat used to maintain temperature, and electricity use (both overall and for lighting). The yearly summary also summarizes the performance of the lighting control system, which is typically a major energy user, and a key component of a year round productive greenhouse system.
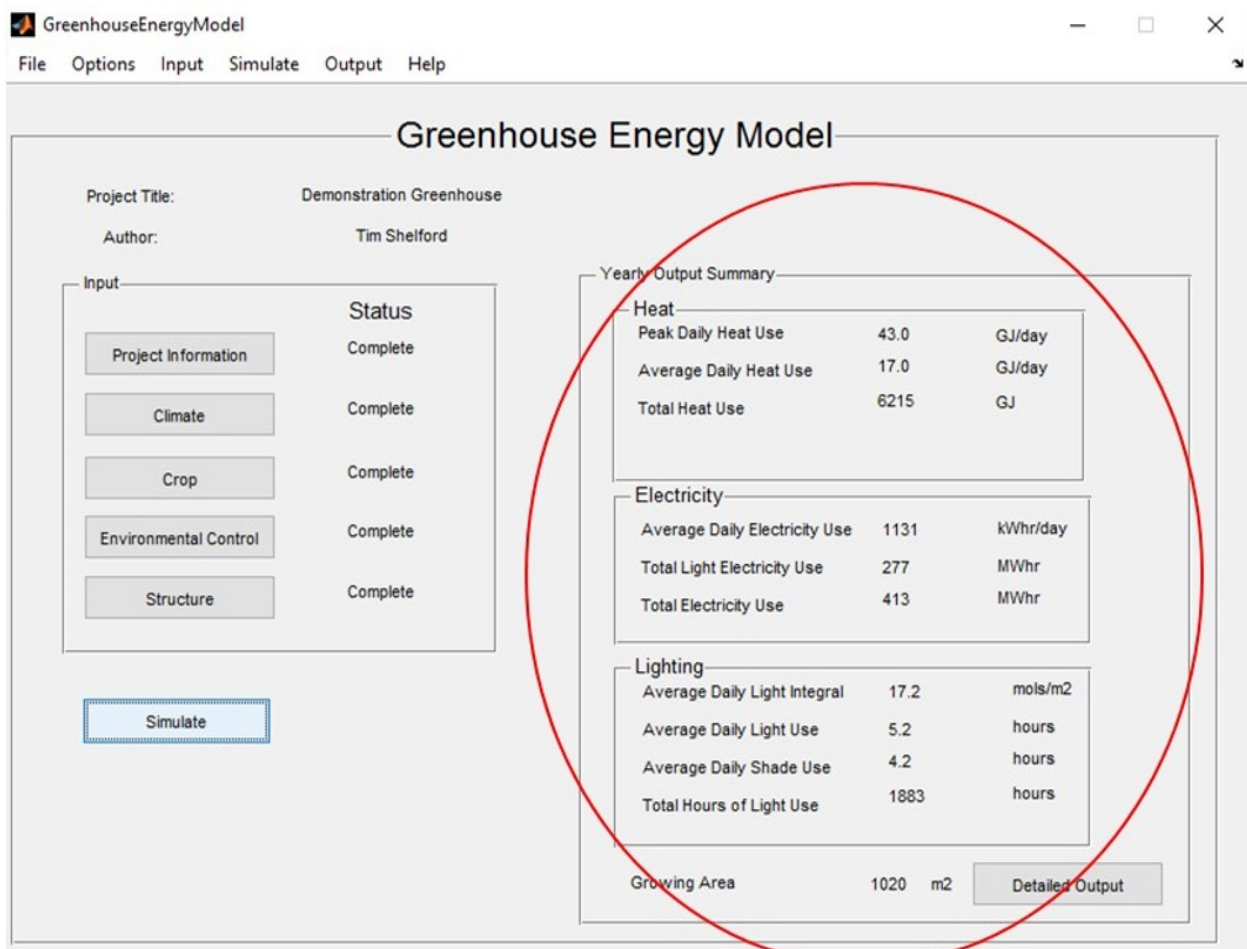

Figure 30: Yearly Output Summary

To change the units of display, select "Options" from the main menu, and then select "Preferences" and then select "Units". Default is metric, but the user can switch to U.S. customary units if that is their preference.

To access more detailed output, the user can either press the "Detailed Output" button located at the bottom right corner of the main GEM window (immediately under the yearly summary data), or by selecting "Output" from the main menu.

6.2 Detailed Output Screen:

Once the user presses the "Detailed Output" button, or selects "Output" from the main menu, the Detailed Output screen is displayed (*Figure 31*). The "Detailed Output" screen displays the output of GEM on both a monthly (table) and daily (plot) basis. In addition the user has the option of exporting the results of the simulation to Microsoft Excel™ should they wish to examine hourly values more closely, or perform additional calculations.
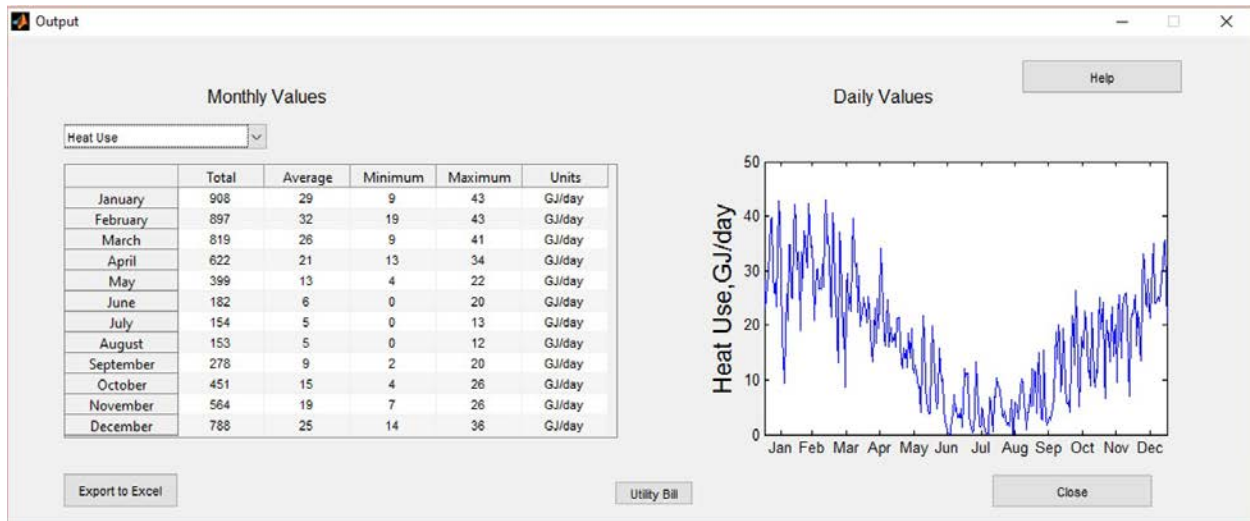

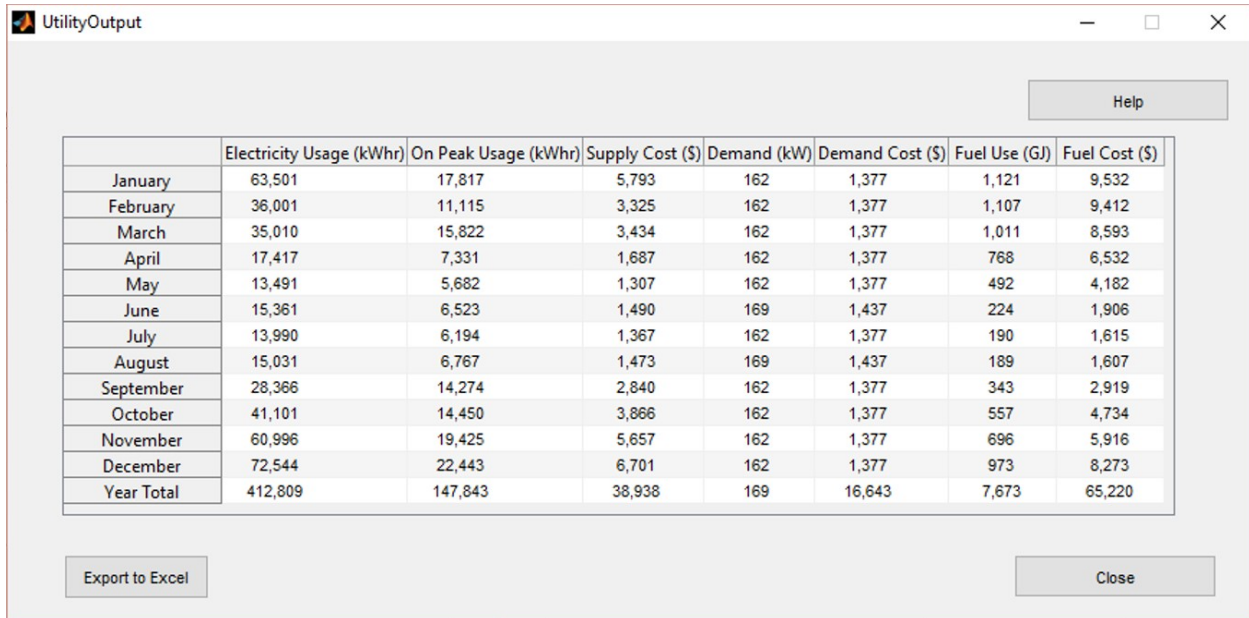Figure 31: Detailed Output Screen

Data Display:

To change the data displayed in the table and the plot, select the parameter to be displayed from the drop down menu, located in the upper left hand corner of the window. The options are: Heat Use, Electricity Use, Light Electricity Use, Light Integral, Light Use, Shade Use and CO2 use. The default display is the Heat Use.

Export Output to Excel:

For more detailed analysis, the user may wish to export the results of the simulation to Microsoft Excel™. To do so, press the "Export to Excel" button following which the user will be prompted to select a location and a filename for where to place the data. Complete hourly data for the simulation will be output.

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6.3   Utility Bill

To aid in making comparisons between different simulation runs, GEM provides the option to output a "Utility Bill" style output screen (*Figure 32*). The "Utility Bill" provides a monthly summary of the electrical and fuel use, and the cost of providing both. In addition the yearly totals are available at the bottom row of the "Utility Bill".

	Electricity Usage (kWhr)	On Peak Usage (kWhr)	Supply Cost ($)	Demand (kW)	Demand Cost ($)	Fuel Use (GJ)	Fuel Cost ($)
January	63,501	17,817	5,793	162	1,377	1,121	9,532
February	36,001	11,115	3,325	162	1,377	1,107	9,412
March	35,010	15,822	3,434	162	1,377	1,011	8,593
April	17,417	7,331	1,687	162	1,377	768	6,532
May	13,491	5,682	1,307	162	1,377	492	4,182
June	15,361	6,523	1,490	169	1,437	224	1,906
July	13,990	6,194	1,367	162	1,377	190	1,615
August	15,031	6,767	1,473	169	1,437	189	1,607
September	28,366	14,274	2,840	162	1,377	343	2,919
October	41,101	14,450	3,866	162	1,377	557	4,734
November	60,996	19,425	5,657	162	1,377	696	5,916
December	72,544	22,443	6,701	162	1,377	973	8,273
Year Total	412,809	147,843	38,938	169	16,643	7,673	65,220

Figure 32: Utility Bill Output Screen

Electricity is broken down into use, supply and demand charges, whereas Fuel use is broken down into use and supply cost. Values displayed are monthly totals, with the exception of the demand column which is the maximum hourly electricity demand for the month.

For further analysis the user can press the "Export to Excel" button, after which the user will be prompted to select a filename for the file to save the exported data to (note this filename should be different than the file name for the GEM output data. If the filename is the same the output data will be overwritten.)

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