

From Forest Nursery Notes, Winter 2011

98. Virtual Grower: software to calculate heating costs of greenhouse production in the United States. Frantz, J. M., Hand, B., Buckingham, L., and Ghose, S. HortTechnology 20(4):778-785. 2010.

Technology and Product Reports

Virtual Grower: Software to Calculate Heating Costs of Greenhouse Production in the United States

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ADDITIONAL INDEX WORDS. decision support, energy efficiency, floriculture, glazing, covering

SUMMARY. Greenhouses are used in many climates for season extension or year-round production and can be expensive to heat. Greenhouse users and growers are often faced with management decisions that rely on an understanding of how temperature settings, heating systems, fuel types, and construction decisions influence overall heating costs. There are no easy-to-use programs to calculate heating costs associated with these factors over full cropping seasons. A computer program called Virtual Grower was created that helps calculate heating costs at many U.S. sites. The program uses a weather database of typical hourly temperature, light, and wind information of 230 sites from the National Renewable Energy Laboratory in the calculations. A user can define unique design characteristics such as building material and construction style. The user also defines the type of heating system and heating schedule, and then the program will predict heating costs based on typical weather at the selected location. Shorter-term predictions with weather forecasts of 2 days or less can be made with the software if there is an internet connection through integration with local weather forecasts. Virtual Grower can serve as a platform from which many other features can be added, such as plant growth and scheduling. Continued development will improve the software and allow users to perform baseline analysis of their heating costs, identify areas in their production to improve efficiency, and take some of the guesswork out of energy analysis in unique greenhouses.

In many parts of the United States, plants are produced in greenhouses in colder times of the year, for early marketing of ornamental crops (Moccaldi and Runkle, 2007) or early/year-round vegetable production (Hochmuth and Hochmuth, 1993). For this reason, energy costs are second only to labor costs as the most expensive factor in indirect costs of greenhouse production. While oil and natural gas prices fluctuated by 100% or more in the last 3 years, generally, fuel prices have risen by

50% over the last 10 years (U.S. Department of Energy, 2009), and represents a large cost that is often difficult to predict. Greenhouse accounting software has pooled this number in variable cost estimates, typically on an area per time basis (Brumfield, 1992), or requires the user to input this cost (Fisher and Donnelly, 2002). Thorough analyses or even a basic understanding of factors that contribute to this cost are complex and can be difficult to work through on long-hand worksheet

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calculations (Aldrich and Bartok, 1994; Brumfield, 1992). These worksheets are excellent references in and of themselves, but getting a grower or specialized consultant to perform them can be time consuming, difficult, expensive, or all of these.

The National Renewable Energy Laboratory (NREL) has a database of typical weather for 230 U.S. locations, including hourly temperature, wind speed, and solar radiation (Marion and Urban, 1995). Combining this resource with standard methods of calculating energy balance in a greenhouse could yield useful information about energy requirements of different structures and allow for simulations in different locations and cropping periods.

A computer program was developed called Virtual Grower that combines the NREL database with standard energy calculations for greenhouse heating needs. The program also provides methods of estimating typical commercial-scale heating system efficiencies and air infiltration values. Flexibility in how a greenhouse is heated allows a user to estimate typical heating costs associated with a variety of realistic heating schedules or evaluate potential savings through changing methods, upgrading systems, or switching to an alternative fuel source. Even though typical hourly data are used in this program, accurate predictions of heating of a greenhouse have been achieved when longer-term (several month seasons, for example) time frames are simulated.

Program description

When the software is opened, the main design page is viewed (Fig. 1). At the top of the page, there are clickable tabs labeled "Design," "Heating Schedule," "Lighting," "Costs," "Plant Growth," and "Real Time Data." By clicking on the tabs, those sections will appear. Note that this article describes all of these tabs except "Lighting" and "Plant Growth."

In the main design page, four boxes are outlined: "Current Greenhouses," "Edit Greenhouse," "Find Site," and "Edit Site." The "Current Greenhouses" box displays a list of greenhouses that have been created within Virtual Grower. Upon opening the program, there are no greenhouses in the list. When the button "Add New Greenhouse" is clicked once, a greenhouse name appears in

this list next to a box that can be checked or unchecked by clicking on the greenhouse name in the "Current Greenhouses" list. This activates or deactivates the greenhouse for a simulation. A user can also load previously developed greenhouses from other Virtual Grower sessions by clicking "File-Load Settings," and selecting from a list of saved greenhouses. When a greenhouse is added to this list, the "Total Square Feet" of all greenhouses (simulated and not simulated) is shown at the bottom left corner.

The user chooses a location in the lower left side of the main page by choosing the state and closest city or by searching for the nearest site by typing in the zip code. This is an important step that provides the weather information for the core of the calculations. Making a selection loads the historical weather information, including temperature, humidity, wind, and solar radiation for that location. It is important to note that the weather information is not average values for a period of time, but typical or representative values for that date and time. For example, a location might use data from Feb. 1987 followed by Mar. 1982 because these months were deemed most representative of the weather at that location (Marion and Urban, 1995). The value of this, as opposed to using averages, is that typical daily fluctuations are simulated; if averages were used instead, it would always be a blend of sunny, overcast, rainy, windy, calm, etc. A single day's simulation, therefore, may not accurately predict that day every year, but simulations over longer periods of time would likely predict that site with reasonable precision yet show typical variability from

month to month or week to week that can be expected at that location.

The "Edit Greenhouse" box allows a user to name and define the size and shape of that greenhouse. By clicking in each section ("Name," "Length," "Width," "Kneewall Height," "Material," "Fuel Type," and "Fuel Price"), you can type in the information specific for that greenhouse. Virtual Grower comes with a material database containing 15 commonly encountered greenhouse materials (Table 1) selectable through a drop-down menu with the material names for selection. If selected here, the greenhouse is constructed assuming that the *entire greenhouse*, other than the kneewall, is made of that material. Rarely are greenhouses built with such uniformity, so to refine the greenhouse materials and other features, a user would click on the "Advanced Design Options" button displaying a different pop-up window (Fig. 2). Virtual Grower has a feature that allows a user to enter unique materials with associated insulation and light-transmittance values allowing for testing of new, unique, experimental, or theoretical materials easily.

In addition to allowing for unique combinations of materials for different walls, roof types, and kneewalls, a user can change the sidewall and center heights, greenhouse style, and if a gutter-connected greenhouse is being constructed, choose the number and width of spans within the structure.

At the bottom of this screen is a picture of the greenhouse style (roof type) that is being constructed and a color-coded diagram that correlates with the different terms. A two-bay gutter-connected house is always shown, but it does not mean all greenhouses are gutter connected. There are seven roof styles that can be simulated, including Quonset-style greenhouses,

which can be built by setting the height at the edge to zero and selecting the roof shape as "Arched."

Currently, each greenhouse is treated as a stand-alone structure with no shared walls with other houses or structures. This would influence heat loss or gain and potentially have a significant impact on the overall costs of heating your greenhouses (Giacomelli and Roberts, 1993; Simpkins et al., 1984).

Another option within the "Edit Greenhouse" box is to define the air leakage or air infiltration of the greenhouse. In a careful energy audit, known amounts of trace gases such as carbon dioxide (CO₂) are added to a greenhouse and the "decay" rate or disappearance of these gases is measured to compute leakage in a similar manner as a closed CO₂ gas exchange system (Wheeler, 1992). Some common or typical values are reported in Aldrich and Bartok (1994) for new and old construction made of glass, fiberglass, or polyethylene film. Using these values as a starting place, estimates were made for commonly observed greenhouse conditions such as malfunctioning or missing vent covers, gaps, or tears in the glazing, and uninsulated partitions between greenhouse sections. Baseline conditions were simulated for greenhouses containing these conditions, and air infiltration rates were further modified so that the model output matched with grower heating bills. This empirical method of matching rough descriptors lacks the rigor of a trace gas leak test, but allows a user to quickly describe their facility and approximate their conditions.

In Virtual Grower, a user is allowed to select characteristics such as approximate number of large and small gaps (with photographic examples given), broken vent covers, and descriptions of the partitioning

We thank the Toledo Area Flower and Vegetable Growers' Association and Maumee Valley Growers for helpful discussions in the development of the software, and James Altland, James Locke, Douglas Sturtz, and anonymous reviewers for helpful review comments.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
1.0551	Btu	kJ	0.9478
3.6246	cord	m ³	0.2759
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
0.0283	ft ³	m ³	35.3147
3.7854	gal	L	0.2642
0.4536	lb	kg	2.2046
105.4804	therm	MJ	0.0095
0.9072	ton(s)	Mg	1.1023
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

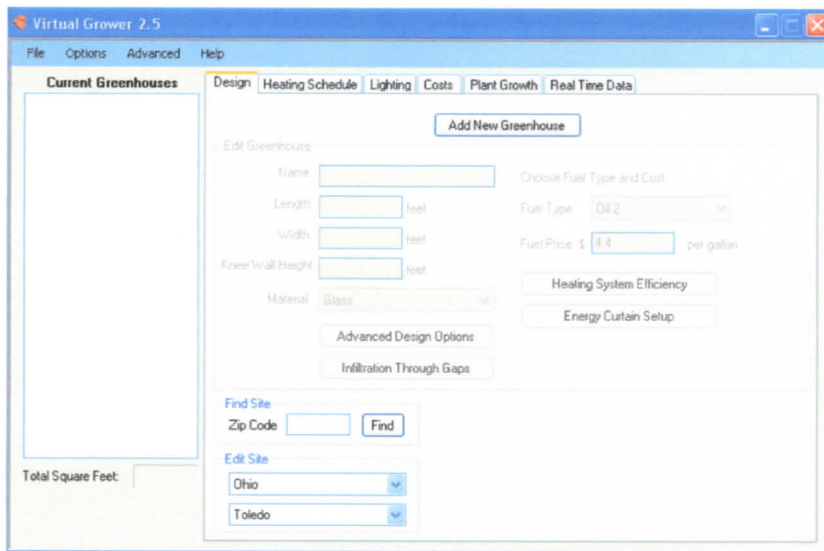


Fig. 1. When a user begins using Virtual Grower software, this is the main design page and opening screen view. The “Add New Greenhouse” button populates the middle of the window with values for greenhouse name, length, width, knee wall height, materials, fuel types, infiltration, and heating system efficiency. Users can then change these values in the drop-down windows, or describe the house in more detail through additional buttons on this screen. Additional areas of Virtual Grower are accessible through the tabs at the top of the screen; 1 ft = 0.3048 m, 1 gal = 3.7854 L.

Table 1. List of greenhouse materials in the database used by Virtual Grower, their unit area thermal conductance value (U-value), and light transmittance properties. Users can select from the different materials to construct a greenhouse and use different materials for different greenhouse walls. Values are based on those from Aldrich and Bartok (1994). Note that U-value is the inverse of the thermal resistance value (R-value) commonly used in the building industry.

Material	U-value (Btu/h/ft ² per °F) ^a	Light transmittance (%)
Glass	1.13	75
Glass double layer	0.65	70
Fiberglass	1.00	75
Corrugated polycarbonate	1.20	75
Polyethylene	1.15	65
Polyethylene double layer	0.70	60
Polycarbonate biwall	0.65	60
Polycarbonate triple-wall	0.58	56
Acrylic biwall	0.65	60
IR film ^b	1.00	65
IR film double layer	0.61	60
Solid insulation foam	0.23	0
Concrete block	0.51	0
Poured concrete	0.75	0
Insulated concrete	0.13	0

^a1 Btu = 1.0551 kJ, 1 ft² = 0.0929 m², (°F-32)/1.8 = °C.
^bInfrared-blocking polyethylene film.

between greenhouse areas. Each selection adds a known amount of air exchanges as an approximation of system leakage (Table 2). A tight, well-sealed greenhouse is considered to have an air exchange rate of 0.5 air exchange per hour, while an extremely leaky greenhouse has a rate of 5.1 air exchanges per hour. While this may

provide a user a better description of their system, a careful energy audit may reveal a different estimate, which can be entered directly by overriding the matrix-generated value in the lower corner of this window. If nothing is selected in this section, the program has default values of 1.3 air exchanges per hour, which is representative of a

medium-aged greenhouse with a few holes throughout.

A description of the overall heating system’s efficiency is also possible, and is set up in a similar manner as the air infiltration section. Again, a careful energy audit by qualified personnel would result in a more accurate description of the heating system efficiency. The method of assigning heating efficiency values was performed by measuring a number of heating systems’ combustion and output efficiencies in situ. This informal survey comprised of several high-efficiency boilers, power-vented and gravity vented boilers, and unit heaters, all comprised of several ages and maintenance schedules. The most uncertain aspect in the development of the decision matrix was delivery of the heat to the plants. Maintenance frequency was not weighted heavily because there is considerable overlap in the effect of maintaining a heater and our measured efficiency values in the survey. Finally, three to five grower heating bills were compared with baseline simulations to ensure that larger errors were accounted for in the matrix.

Working through the heating efficiency matrix, a user can choose simple descriptions of their system in Virtual Grower and help “dial in” an estimate for this important term. By choosing a combination of heater types and ventilation, heat delivery method, and some description of age and maintenance performed on the system (with photographs to help a user make appropriate selections), a single efficiency (from 0% to 100%) is calculated. These three sections each have an efficiency value (Table 3) and are multiplied together to estimate the overall system efficiency. Similar to the air infiltration section, a user can override the matrix-generated value and enter a value from 0% to 100%. Some matrix combinations are not possible. For example, if a user has a standard unit heater, it is not possible to select heated floors as a delivery method. If the user does not select anything in this section, the program uses default values of 45%, which is typical of a forced-air system with no assistance to distribute that heat.

The user has the option of selecting the fuel source for their heating system from a drop-down list of 31 fuel types (Table 4). These values are expressed in terms of British thermal

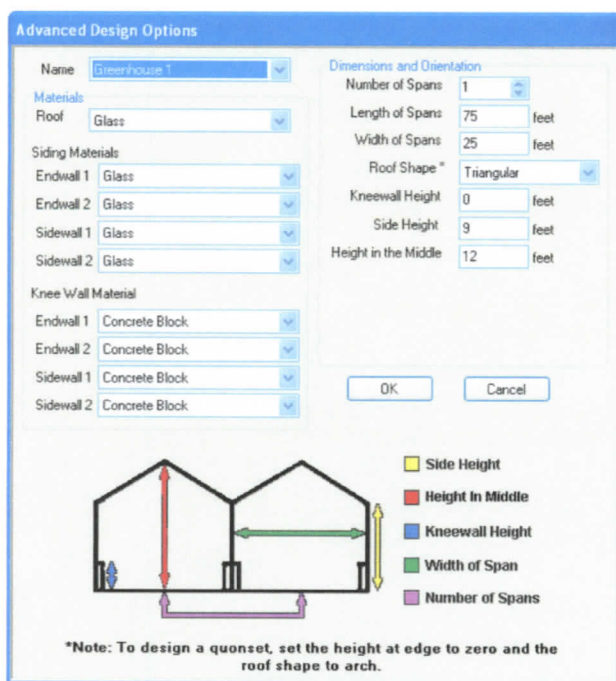


Fig. 2. Advanced design options window in Virtual Grower, version 2.5. From this screen, a user can describe their greenhouse design and materials in detail, tailoring each wall to match their existing or planned structure. The diagram of the greenhouse at the bottom changes depending on the overall style of greenhouse that is selected; 1 ft = 0.3048 m.

Table 2. In the section for air infiltration within Virtual Grower software, a user can describe their greenhouse air leakage based on size and abundance of gaps, characteristics of ventilation systems, and other construction designs. The value of air exchanges that each category/item adds to the baseline air exchange rate of 0.5 air exchanges per hour is shown.

Leakage source	Additional selection criteria	Air exchanges added (no.)
Large gaps	None	0.0
	Few	0.3
	Several	0.6
	A lot	1.2
Small gaps	None	0.0
	Few	0.15
	Several	0.3
	A lot	0.6
Outside air intakes		0.75
Gaps between greenhouse and vents		0.25
Malfunctioning vent covers		0.5
Office, headhouse, retail area, and shipping area ^z	Connected, but insulated area	0.25
	Connected and not insulated	0.5

^zBaseline, default value is to assume this is a separate building.

unit content in units most commonly associated with that fuel type. The original source for British thermal unit value (Bartok, 2005; Knaebe, 2004) assumed 70% to 80% combustion efficiency, but do not state which ones were assumed to be 70% or 80%. Because the user estimates heating

system efficiency independently, Virtual Grower corrects for the assumption of 70% to 80% efficiency by dividing the source material British thermal unit value by 0.75 (an average or compromise between the 70% and 80% efficiencies) before it is used to calculate heating costs.

When a fuel is selected, a cost for that material per unit is loaded, but can be changed by the user. As with greenhouse materials, there is a feature that allows a user to add a fuel with unique energy contents and costs, thus experimental or theoretical materials can be tested easily.

Describing the heating schedule

After clicking on the “Heating Schedule” tab, a user can set temperatures of the different greenhouses. There are four preprogrammed “classes” of schedule options: “No Heating,” “Its Day When The Sun Is Up,” “Its Day When I Say It Is,” and “Constant Temperatures.” The “No Heating” setting simply does not heat that greenhouse for the time frame selected, and no cost is calculated, while the “Constant Temperature” setting sets a single temperature for the period of the year selected.

In the “Its Day When The Sun Is Up” setting, the daytime temperature setpoint is activated when the sun comes up, based on your location in the country. When the sun is not up, the night temperature is maintained. In this selection, the thermoperiod matches the natural photoperiod or light period. The “Its Day When I Say It Is” setting allows for the daytime temperature to be set to a specific time period in the day. This time period does not change from one day to the next, unless the user changes the settings for that day.

In addition to the preprogrammed sections, a user can define a “Custom Schedule,” programmable for individual hours in the day. This allows for programming different day and night temperature treatments (DIF), or temporary, short-term drops in temperature just before sunrise (DIP) treatments for certain crops or certain times of the year (Erwin et al., 1994). All schedules are savable, thereby allowing a user to have that schedule for future greenhouse designs. The program allows for complex, realistic scheduling for entire greenhouses, but currently does not permit subdividing greenhouse sections with temporary partitions as is a common practice in greenhouse production.

Calculating heating costs

Once a greenhouse is created and a heating schedule is assigned to

Table 3. Heating system efficiency is estimated in Virtual Grower software by a matrix of ventilation type, heat delivery method, and maintenance frequency. Efficiency values are shown for each possible selection within the matrix. A user selects one term from each section (“Ventilation,” “Heat delivery,” and “Maintenance”), the three values are multiplied, and a final system efficiency is estimated. Note that in “Heat delivery,” there are three sections for delivery method, but only one type is used from forced air, exposed pipes, or in floor.

<i>Ventilation type, heating system type, and resulting efficiency (%)</i>				
Heater type	Gravity	Power or fan-assisted	Condensing	Separate
Standard unit heater	65	78	—	80
High-efficiency unit heater	70	80	—	82
Hot water boiler	68	82	93	84
Steam boiler	65	78	90	80
<i>Heat delivery method, location, and resulting efficiency (%)</i>				
Heater type	Forced air			
	Above bench	Below bench	Inflatable tubes above bench	Inflatable tubes below bench
Standard unit heater	60	65	65	70
High-efficiency unit heater	65	70	75	80
Heater type	-Or- Exposed pipes			
	Perimeter	Below bench	Finned perimeter	Finned below bench
Hot water pipes	85	88	87	90
Steam pipes	80	83	82	85
Heater type	-Or- In floor			
	Not insulated	Insulated		
Heated floors	80	90		
<i>Maintenance frequency, age of heating system, and resulting efficiency (%)</i>				
Age	Weekly or monthly	Annually	Every few years	Never
New (1–2 years)	100	99	98	97
Intermediate (3–5 years)	99	96	94	92
Old (over 6 years)	98	94	92	90

that greenhouse, costs can be calculated. To do this, heat gained by solar radiation (if daytime) is added to heat lost through conduction and convection (if temperature outside is lower than the set point) for each hour of the day. The equations used are from Aldrich and Bartok (1994) and are described in detail therein and briefly below.

For an estimate of heat gained by solar radiation, the light energy per area (from weather database) is multiplied by the total footprint of the greenhouse. To account for reflection and evapotranspiration, it is assumed that one-third is reflected from the greenhouse materials and half of the remainder is used for evaporating water from plants and substrate surfaces with that evaporated water leaving the greenhouse (assumption used in Aldrich and Bartok, 1994). This means that only 33% of the sun’s energy heats the greenhouse.

To calculate conduction over any greenhouse surface, four values are

used: the temperatures on either side of the surface (usually the temperature set point of the greenhouse and the current temperature outside), the area of the surface, and a constant known as the unit area thermal conductance value (U-value) of the surface material. By multiplying these values together, the amount of heat per hour that is lost to that surface can be found. This value can be multiplied by a correction factor based on wind speed, reported by Bartok (2005), to account for the effects of wind.

To calculate convection for any particular greenhouse, four values are used: the temperatures on the inside and outside of the greenhouse, the volume of air within the greenhouse, and a correction factor representing the relative leakiness of the greenhouse structure. By multiplying the difference between the two temperatures by the volume and the correction factor, an estimate of heat loss can be obtained. As with conduction, an additional correction factor to

account for the effects of wind can be applied.

For the entire structure, conduction is calculated for each wall, knee-wall, and the roof, while convection is calculated for the whole structure. Adding the results together with solar gain provides the net energy lost at a given temperature. If the result is negative (i.e., the greenhouse is cooling off), the number of British thermal units lost is assumed to be the number of British thermal units added to the greenhouse by its heaters, to keep it at its current temperature.

Cost is then calculated by dividing British thermal units lost by the amount of heat gained from burning one unit of selected fuel, adjusted for the given heater and combustion efficiencies. This gives us the amount of fuel needed to keep the greenhouse up to temperature. Finally, the cost to heat the structure is calculated by multiplying the units of fuel burned by the cost per unit specified for that greenhouse. Cost is expressed per

Table 4. List of fuel types, energy content, and default units in the database used by Virtual Grower. Users can select from the different fuel types and assign different fuels to different greenhouses to simulate fuel consumption based on other user-defined selections. All values were obtained from Bartok (2005) and Knoebe (2004).

Fuel type	Energy (Btu) ^z	Unit for energetic amount ^z
Fuel oil #2	138,500	gal
Fuel oil #4	145,000	gal
Fuel oil #6	153,000	gal
Natural gas	100,000	therm
Propane	92,500	gal
Hard coal	26,000,000	ton
Soft coal	24,000,000	ton
Electricity	3,412	kWh
Methane	1,000	ft ³
Methanol	57,000	gal
Landfill gas	500	ft ³
Butane	130,000	gal
Ethanol	76,000	gal
Kerosene	135,000	gal
Waste oil	125,000	gal
Biodiesel	120,000	gal
Gasoline	125,000	gal
Soft wood	12,500,000	cord
Hard wood	21,000,000	cord
Hogged wood	18,000,000	ton
Sawdust (green, 45% moisture)	9,000,000	ton
Sawdust (dry)	16,000,000	ton
Wood chips	7,600,000	ton
Bark	9,750,000	ton
Wood pellets (10% moisture)	16,000,000	ton
Rubber pellets	33,000,000	ton
Plastic	19,000	lb
Corn shells	16,000,000	ton
Corn cobs	16,500,000	ton
Switchgrass	11,625,000	ton

^z1 Btu = 1.0551 kJ, 1 gal = 3.7854 L, 1 therm = 105.4804 MJ, 1 ton = 0.9072 Mg, 1 ft³ = 0.0283 m³, 1 cord = 3.6246 m³, 1 lb = 0.4536 kg.

year and per month on a square foot and total basis.

An alternative method of calculating a building's heat requirements is the use of a "Heating Degree Day" model. This method bases heat needs on the average temperature during a day. If the average temperature at the specific location is below 65 °F, heating is required. A list of heating degree days for different locations can be found online (Cornell University, 2010). The heating degree days that Virtual Grower predicts and this database does are in close agreement (typically less than 1% variation). On some days, however, the heating degree day model predicts no heat is needed when Virtual Grower would predict some heat is needed. For example, assume your greenhouse has a set point of 65 °F. If a location

(hypothetical) has an average temperature of 65 °F, has a 12-h day of 75 °F, and a nighttime of 55 °F, Virtual Grower would heat the house for 12 h (during the night) and the heating degree day model would predict that no heat is needed.

GENERATING A REPORT. From the "Costs" page, a text-based report can be generated, copied, and saved in any word-processing program. The report describes the current settings (greenhouse design considerations, fuel types, etc.) and costs associated with heating that greenhouse.

REAL-TIME DATA. For long simulation periods, historical data has value, but for immediate, short-term predictions and validation, the "Real Time Data" feature can allow a user to control costs for heating over the next 2 d, provided the user has an active

internet connection. In this section, there is a box into which a zip code can be typed. Once entered, pressing the "Calculate Heating Costs" button retrieves the 2-d forecast from a website (National Oceanic and Atmospheric Administration, 2010) that is specific to that zip code. In a few seconds, the forecast appears in the top part of the window, broken down in 3-h increments, and the costs for each selected greenhouse and its British thermal unit usage will appear in the bottom box. The heating costs prediction depends on the greenhouses simulated and heating schedule. This feature is only functional for U.S. sites, except Alaska.

The "Calculate Heating Costs" button is inactivated for a few minutes after each web service call to the web server. This will cut down on users inadvertently making multiple data requests and save on bandwidth.

At any time during simulation or "constructing" a greenhouse, the user can save the greenhouse setting from the "Main" page by clicking "File-Save Settings" and naming the greenhouse data file (.gdf). This enables a user to reload the greenhouse in other Virtual Grower sessions. Exiting out of the program at any point will also prompt the user to save the settings.

Virtual Grower allows the choice of U.S. or metric units. From any page, a user can choose U.S. or metric; default settings are in U.S. units. Making the change will convert the units to that convention throughout the program.

MODEL USE AND VALIDATION. Extensive field validation in commercial greenhouses has been done in some locations of the United States. In the midwestern U.S., the Center for Innovative Food Technology (Toledo, OH) conducts energy assessments at greenhouse operations and their engineers have used Virtual Grower to analyze energy consumption for winter heating at several different sites in Ohio. These evaluations have included single-span and gutter-connected multiple-span structures constructed of glass, polyethylene, polycarbonate, and fiberglass, and those operated under full season and partial season schedules. Four examples of field validation are presented as case studies below.

CASE STUDY 1: HEATER REPLACEMENT. A 2.5-acre greenhouse operation in Delta, OH, has heating

Table 5. Virtual Grower was used to simulate baseline conditions in commercial greenhouses and those predicted costs were compared with actual heating bills. Following baseline description, Virtual Grower was used to simulate a change in operating conditions and evaluate for financial savings. After implementation, heating bills were compared with predicted values for assessment of differences. N/A = not applicable in this case due to new construction. All facilities used heating from 1 Sept. to 31 May.

Case study	Baseline conditions			Change or savings		
	Model (\$)	Actual (\$)	Difference (%)	Model (\$)	Actual (\$)	Difference (%)
Heater replacement ^a	34,000	32,200	5.6	8,520	8,100	5.1
Side curtains ^b	5,700	6,120	-6.8	300	350	-12.5
Heater replacement ^c	61,800	59,280	4.4	15,450	15,500	-0.3
Boiler selection ^d	N/A	N/A	N/A	55,900	50,000	11.9

^aModel assumptions: each house 180 × 30 ft (54.9 × 9.1 m), single span, double polyethylene sides and walls, day/night 60/55 °F (15.6/12.8 °C), propane at \$1.50 per gal (\$0.40/L), 60% heating efficiency (baseline), 80% heating efficiency (savings), Toledo, OH, weather database.

^bModel assumptions: four-bay gutter connected house, each bay 120 × 27 ft (36.6 × 8.2 m), glass sidewalls (baseline), double layer walls (savings), double polyethylene roof, day/night 65/60 °F (22.0/15.6 °C), natural gas at \$0.70 per therm (\$0.0066/MJ), Toledo, OH, weather database.

^cModel assumptions: gutter connected houses [four bay and five bay, each approx 3200 ft² (297.3 m²)], double layer polyethylene, day/night 60/55 °F, natural gas at \$0.95 per therm (\$0.0090/MJ), 60% heating efficiency (baseline), 80% efficiency (savings), Toledo, OH, weather database.

^dModel assumptions: gutter connected glass house with 14 bays, each bay 432 × 40 ft (131.7 × 12.2 m), 65 °F constant temperature, wood chips at \$25 per ton (\$27.55/Mg), 80% heating efficiency, Cleveland, OH, weather database, 25% space utilization in September and October, 50% space utilization in November and December.

needs from October to the end of March. The portion of the greenhouse slated for upgrading consists of a combination of single-span and gutter-connected houses, all with double-layer polyethylene glazing on the walls and roof. The facility uses propane, which was assumed to be \$1.50 per gal, an approximate 3-year average for this facility. Baseline conditions were modeled at a day/night temperature of 60/55 °F, with overall heating system efficiency of 60% due to older heaters, gravity-vented ventilation, and good heat distribution system from inflated poly-tubes under the bench. Virtual Grower estimated a cost of \$34,000 for propane in a typical year (Table 5). A 3-year average cost using the facility's fuel bills yielded an estimate of \$32,200 cost for fuel or a difference of 5.6%.

A heating system upgrade was simulated by the changing heating system efficiency from 60% to 80%. Virtual Grower estimated a savings of \$8520 per year. After heater installation, separate engineering estimates and measurements of fuel consumption for the initial year predicted an annual savings of around \$8100 or a difference of 5.1%.

CASE STUDY 2: SIDE-WALL CURTAINS. A 0.5-acre gutter-connected facility in Bowling Green, OH, was investigating the practicality of saving energy by inexpensive temporary side curtains. The facility has a combination of twin-wall polycarbonate and double-polyethylene roof, but mostly single-layered glass walls. The heating season in this greenhouse is from December to March, and uses natural gas-fired unit heaters. Baseline heating costs at day/

night temperature settings of 65/60 °F were estimated to be \$5700 assuming \$7 per million Btu, a 3-year average gas cost (Table 5). Actual gas costs over the previous 3 years were \$6120 or a difference of 6.8%.

A change in the model from single layer glass walls to double layer (glass or different plastic materials) predicted possible savings of \$300 per year, with little variation due to the choice of material to be temporarily hung on the glass walls. With this information, the operation installed a plastic sheet on the west glass wall to enhance insulation through this winter operation. The installation was simple and low-cost and the curtain is manually lifted and lowered. Cost savings estimated from the grower confirms that the fuel savings from this installation are in the range of \$300 to \$400, or a difference of about 12.5% (assuming \$350 actual savings).

CASE STUDY 3: HEATER REPLACEMENT. Twenty old gravity-vented unit heaters in Swanton, OH, were in need of replacement with high-efficiency power-vented models. The heaters were located in two gutter-connected ranges with double-layer polyethylene glazing, and were operated under varying heating schedules through winter and spring using natural gas-fired unit heaters. The two ranges were modeled at 60% heating efficiency and were assumed to cost \$9.50 per million Btu, a 2-year average cost for that facility. The model predicted those ranges to have a cost of around \$61,800, which corresponded well to the previous years and engineering estimates for consumption

breakdown for the houses, estimated at around \$59,280 (a difference of 4.4%; Table 5). The model was re-run with heating efficiencies of 80% to reflect the upgraded heaters, and showed a savings of around \$15,450 per year. Separate engineering estimates also confirmed annual savings of about \$15,500 per year with the heater replacement, or a difference of -0.4%.

CASE STUDY 4: BOILER SIZING AND SELECTION. A new 5-acre commercial greenhouse facility was being planned in Avon, OH. The glass-glazed gutter-connected facility incorporated the latest energy-efficient features including zone control, thermal and shade curtains, efficient hydronic warm-floor and overhead heating system, and efficient irrigation and material handling systems. Energy modeling with Virtual Grower was performed to estimate the benefits of the renewable fuel heating system, wood chip biomass over conventional natural gas-fired system. Virtual Grower assumed waste biomass (locally sourced waste saw dust, bark, and chips) at \$25 per ton, and used individual bays (part of the gutter connected houses) for September to December. The model predicted a cost of heating to be about \$56,000 per year compared with the actual operational cost for the biomass heating system over the last two heating seasons of about \$50,000 per year, a difference of 11.9% (Table 5).

In general, these case studies illustrate that when full seasons or years are simulated, predictions have been found to be within about 12% of actual costs with greenhouses maintained at fairly consistent temperatures

and heating schedules. Additionally, a range of different project scopes can be simulated, from new construction to smaller greenhouse modifications, with adequate results. Our experience shows that when shorter time frames are simulated, variations up to 50% have resulted at sites where greenhouse space is occupied and heated progressively with growing schedules through the season relying on the historical databases (2 weeks to 1 month). This may be due to seasonal or short-term deviations from the “typical” historical weather data used in Virtual Grower. The historical perspective of the climate and solar databases for different sites used by Virtual Grower and the resulting model predictions are therefore most useful for comparative analysis of efficiency improvement features over multiple seasons and to derive baseline operational characterizations.

Future software development

Virtual Grower continues to be developed. Adding plant growth and development models will allow for scheduling and an assessment of plant quality. Facing increasing fuel costs, growers are always looking for ways to reduce their heating bills, sometimes to the detriment of crops. In fact, intuition that tells growers to lower a setpoint to curb energy use may make the problem worse. Runkle et al. (2009) have calculated that in some crops and for some markets, more cost-effective and energy-efficient crops can be grown in warmer greenhouses than cooler houses due to delays in development. That is, slower development in cooler greenhouses leads to longer production times, so even though the per day energy consumption is lower, the total energy consumption is higher to finish the crop.

Improving the realism in heating systems and partitioning of greenhouses would provide more realistic simulation opportunities. For example, early in growing seasons, growers hang temporary plastic “curtains” between greenhouse sections and heat only parts of large ranges. These can be simulated in the current software only through complex, non-intuitive “work-arounds,” so adding this as a design or scheduling option would be helpful.

Increasingly, growers have multistage heating systems with different

heaters and potential fuel sources to provide baseline or emergency heat. The current version only applies a single heating system and fuel type for a greenhouse, so a multitiered heating system option would add more flexibility and realism for simulations, and help to identify the investment value of these systems.

Carbon footprints could be calculated from the existing software’s framework, and predictions of plant pest outbreaks and water use could also be folded in, with linkages to the historical weather database already used. There are advantages to keeping these models separate (simplicity, for example), but a significant advantage of observing interactions and potential for determining the impacts of optimizing for one feature (plant growth, for example) that may occur on other features (energy consumption and likelihood of pest outbreaks) would be possible.

Setup requirements

Virtual Grower 2.5 was written in Visual Basic.NET (Microsoft, Redmond, WA) architecture and uses Access (Microsoft) database files. It is only compatible with computers running Windows 98, ME, 2000, XP, Vista (Microsoft), or later. It does not operate on 64-bit processors, though current efforts on the program are making the software platform independent. User “help” is provided through a comprehensive manual through the program as well as with an e-mail address (USDA-ARS@utoledo.edu). The latest versions of the software can be downloaded for free from the internet (U.S. Department of Agriculture, 2006).

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