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Multiphysics Energy Systems Demand Modelling for Community-Scale Greenhouses

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Abstract— Greenhouses allow for local food production, protecting plants from the external environment and maintaining optimal growing conditions. This paper presents a modelling methodology for integrating renewable energy and storage into community-scaled greenhouse operations. By adopting a heating demand model for building envelopes, the capabilities of energy modelling tool OSeMOSYS can be extended to represent the energy system of such a greenhouse. Using real solar and temperature hourly data, the results capture meaningful aspects of the design, operation, and costs that may otherwise be lost in averaged modelling approaches.

I. Introduction

Greenhouses may be assumed to provide a potential solution to address food insecurity in more extreme climate zones. By sheltering plants from the external environment, greenhouses may be able to maintain optimal growing conditions and allow for local food production. There is considerable interest in implementing greenhouses in hot and arid regions [1]. In contrast, more northern latitudes experience highly seasonal levels of natural sunlight and low external temperatures. In all such extreme conditions, greenhouses can do little to extend the growing season without external energy inputs [2]. Many remote communities in Canada, however, lack access to electricity grid networks, creating a reliance on diesel generators. Using renewable energy to support greenhouses would, therefore, reduce reliance on fossil fuels.

This paper presents a modelling methodology to represent an energy system of a community-scale greenhouse, typical of remote communities, integrating renewable energy and storage in the open-sourced modelling tool OSeMOSYS. Given the energy demand-based nature of OSeMOSYS, time-dependent data preprocessing is required. Therefore, model linking is necessary to accurately represent a greenhouse's energy demands. A system with PV, solar thermal generation, and electrical and thermal storage is linked to a lighting and heating demand model of the greenhouse which takes into account its thermal characteristics. With access to solar irradiance and temperature data, this methodology can be applied to any location. In this paper, two locations in Canada are selected to highlight the impact of different regions.

II. Background

In northern latitudes, traditional agriculture has always been challenging due to long periods of low temperatures and limited growing seasons. Access to locally grown food is poor, making many northern communities dependent on imported and processed food at extremely high prices. In 2023, remote communities in northern BC reported 16.6% of households living in food insecurity, with 10.7% in moderate to severe food insecurity [3].

Typical greenhouse infrastructure may be either passive, grid-connected, or powered by generators and heated by kerosene space heaters. An increasingly popular small-scale community greenhouse structure uses a geodesic dome shape designed for energy efficiency and strength, ranging between 14 m^2 and 27 m^2 [4], see Fig. 1.

Fig. 1: Growing Dome [5]

The domes are more resistant to wind, hail, and snow due to their aerodynamic shape and the use of strong triangular beam structures, making them more appropriate for colder climates. The curved outer envelope allows for even heat distribution throughout the day as the sun moves and minimises heat loss by reducing surface area by 40% compared with rectangular structures [4].

Communities intent on implementing greenhouses and integrating renewable energy into their systems face

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high capital costs and intimidating technical decisions. Studies to date, however, focus on parameter and climate control modelling for greenhouses [6]–[11]. Small solar-powered ventilation fans and other low-cost strategies for heat conservation are implemented in many of projects, but there is a reliance on fossil fuels to power the greenhouses.

Many communities express interest in solar power and batteries to support the growing season [5]. To support such investment planning for community greenhouses, energy modelling provides essential information on the scale and cost of potential energy solutions. However, given the nature of community greenhouse initiatives, these modelling tools must have low financial input, be relatively easy to set up, provide sufficient detail to inform useful results, and have accessible data input requirements. OSeMOSYS optimises the integration and mix of energy sources included in the system and minimises overall costs. The open-source nature of this tool makes it an appropriate choice for this use.

III. Methodology

For such northern locations, the simulated system comprises a community-scaled greenhouse supplied by PV panels, flat-plate solar thermal collectors (STC), lithium-ion battery storage, and water tank-based thermal energy storage, see Fig. 2. These technologies are selected due to the need for heat and light, their accessibility, ease of installation and maintenance, relatively low cost, and scalability suitable for community-scale greenhouses. Furthermore, northern locations often have good solar irradiance for half the year, making solar energy the most appropriate renewable energy. The design of the system under consideration, presented below, would vary depending on the heating and cooling requirements of different climates. A growing dome is used as a reference for the size of a community-scaled greenhouse, the largest of which is a 12.5 m dome with a floor area of 127 m^2 and at its centre has a height of 5 m [12]. Fig. 2 shows the proposed system diagram for colder climates, where the energy generated by the PV and STC panels is delivered directly to the greenhouse or stored for later use in the battery and thermal storage systems. A controller technology, although necessary for such systems, is not shown in Fig. 2 as the OSeMOSYS model determines and optimises the flow of energy between the energy generation technologies, the storage systems, and the greenhouse. Controller technologies are, therefore, not necessary in the simulations. No grid connection or diesel generator is included at this stage on the basis that such remote greenhouses should be able to function if grid connections are unstable or generators are unavailable and to explore the feasibility of greenhouses operating solely on solar energy and storage. To meet the thermal and electrical energy demands, the model optimises the sizing of the components to provide the most cost-effective solution.

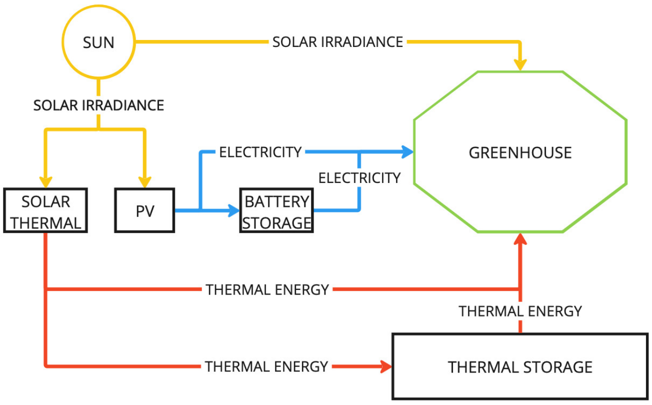


Fig. 2: System Component Diagram

Table I shows the general range of parameters for optimum crop growth. For colder climates, we are assuming the ventilation and humidity loads for community-scaled greenhouses to be passive, requiring manual or negligible power input relying on convection draft ventilation. Therefore, the modelling concentrates on light intensity and temperature.

TABLE I: Optimum Crop Growth Conditions [13]

Temperature	20°C - 25°C
Light intensity	20 - 100 $W/m^2/hr$
Relative humidity	60% - 80%
Carbon dioxide level	800 - 1500 ppm

A. Lighting Demand and Control

For consistent plant growth, a minimum of between 10 and 12 hours of light exposure per day is required, either natural sunlight or artificial daylight spectrum LED supplementary lighting. Using historical location-dependent hourly solar irradiance data [14], a two-step condition is applied. First, each 24-hour period is assessed against the minimum daily solar irradiance threshold of 840 W/m^2 per day [13]. If lighting is required for that day, each hour is then compared to the minimum hourly threshold of 70 W/m^2, which meets the requirements for most plant types. A supplementary lighting demand is calculated if this hourly threshold is not met, using Equation 1 [15].

$$D = A * (MSI - (SI * T)) \tag{1}$$

Where: D = lighting demand (W/m^2), A = area of greenhouse (m^2), MSI = minimum solar irradiance ($W/m^2/hr$), SI = solar irradiance ($W/m^2/hr$), T = transmittance factor of greenhouse envelope (%)

Supplementary lighting is supported by the PV panels and the battery storage in an islanded system, which may be part of a microgrid. For the purposes of system design, no assumption is made regarding the scale of the PV system, therefore the panels may support the required supplementary lighting during daylight hours.

However, if the minimum daily solar irradiance threshold is not met, battery energy storage is required to provide lighting during periods of no natural light or low light conditions when the panels are not able to meet the demand directly.

B. Heating Demand Modelling

The heating demand in cold climates must account for the behaviour of the thermal inertia of the structure and the absorption of solar irradiance over the course of a day while allowing for any heat loss or gain through the envelope. [17] presents a model for this in the context of heating and cooling demand for liveable buildings. The model can be tailored with a specific solar gain for the envelope and heat retention, along with a number of other coefficients. This model is chosen as it may be adapted to represent a greenhouse structure and its heating demand, noting that many modern buildings have high window-to-wall ratios. The output of this model provide the heating demand inputs for the OSeMOSYS model. Table II shows the full list of tailorable coefficients, their descriptions and the selected values for each.

The optimum temperature for common vegetable growth is between 20°C and 25°C. This range is therefore represented in the heating and cooling thresholds in Table II. The smoothing variable represents the structure's ability to retain thermal energy over multiple days, and the effect that energy has on the current temperature. As the greenhouse structure has significantly less envelope insulation than residential buildings, this value is reduced from the default to 0.1 per day. The solar gains, however, are increased from the default to 0.03°C per W/m^2 as the greenhouse is encased in transparent cladding, aiming to allow maximum sunlight into the structure. Similar to the smoothing effect, the limited envelope insulation of greenhouses limits their ability to retain heat against wind chill. Therefore, this variable is increased from the default to -0.4°C per m/s. Finally, the humidity discomfort factor is decreased to 0°C per g/kg, as typically plants require higher levels of humidity than humans may find comfortable.

Similar to the lighting system, discussed above, the heating system is also islanded. The STC may provide heat directly to the greenhouse or via the thermal storage system, to meet the greenhouse heating demand. However, the optimum temperature range and the long thermal time constant implies that thermal storage is essential to meet the heating demand and in design optimisation this can be scaled appropriately and could be incorporated in the greenhouse structure.

IV. Results

The results below showcase two case study locations demand profiles, representing the outputs of the methodology detailed above. Selected results are also presented from the OSeMOSYS modelling, highlighting how this methodology contributes to the overall energy modelling of the greenhouses system.

A. Demand Profiles

Fig. 3a shows the daily lighting demands for two geographically extreme case study locations, Simon Fraser University in British Columbia (BC), 49.276N 122.916W, and Sachs Harbour in Northwest Territories (NT), 71.99N 125.242W, representing temperate oceanic and sub-arctic climates of Canada, respectively. As shown in the NT lighting demand, shown in orange, there are consistently high winter lighting demands, as Sachs Harbour experiences periods of no sunlight. In the summer months, however, the demand drops to zero for prolonged periods. The BC location experiences a smaller range of lighting demand. However, it lacks periods of consistent sunlight in the summer and has a widely varying lighting demand throughout most of the year.

Fig. 3b shows the year-long daily heating demand for the same two case studies, BC and NT. As can be seen from this graph, the most northern location has a significantly higher heating demand throughout the year, as expected, reaching a peak demand of over 300 kWh per day at the end of January. However, neither location achieves consistently high temperatures that would allow for no added heating, resulting in some daily demands throughout the summer months.

B. OSeMOSYS Outputs

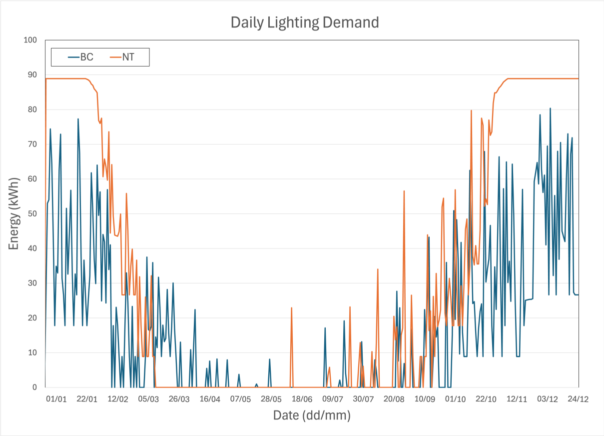
Due to the lack of sunlight for in the winter in NT, this location has no year round feasible solution given the off-grid energy generation technology selected. A feasible solution is obtained for BC, see Table III.

Fig. 4a shows the daily electricity use and production by the simulated system to meet the lighting demand over 48 hours for the BC location in February. The shorter days result in a lighting demand in the morning of both days, which is met by the battery storage system. Due to cloudy conditions, the first day shows fluctuating lighting demands even during the day. This demand is met by both the battery storage and directly by the PV panels. The second day experiences more consistent levels of solar irradiance, allowing the PV panels to charge the battery and meet demand without the need of the storage system in the afternoon.

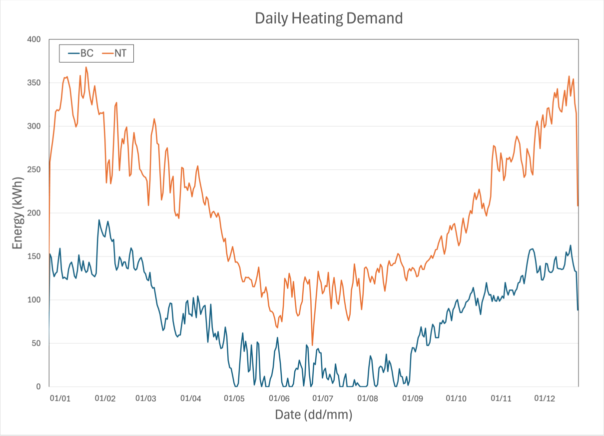
Fig. 4b shows the same 48 hour period as Fig. 4a with the daily heating use and production. Due to the more constant heating demand the thermal storage system is required to meet the demand throughout the night. The lower levels of solar irradiance experienced in February result in the need for thermal storage to assist heating the greenhouse during the day. The second day experiences higher levels of solar irradiance, however, neither day results in sufficient levels for storage to recharge. Given the downward trend of the demand, it can be assumed that the improving weather and the solar gain of the greenhouse result in the steady decreasing of heating

TABLE II: Heating Demand Model Variable Inputs [16]

Variable	Description	Default Values	Model Input
Heating threshold	Temperature below which heating is required.	14°C	20°C
Cooling threshold	Temperature above which cooling is required.	20°C	25°C
Base power	The base level of demand when it is neither hot nor cold.	0 kW	0 kW
Heating power	The additional demand for heat as temperature falls below the threshold..	0.3 kW/°C	0.3 kW/°C
Cooling power	The additional demand for cool as temperature rises above the threshold.	0.15 kW/°C	0.15 kW/°C
Smoothing	This represents the building's thermal inertia: the influence that temperatures on the previous two days have on the current temperature index.	0.5 /day	0.1 /day
Solar gains	This represents solar gains in the building: the influence greater sunshine has on increasing perceived temperature.	$0.012°C/W/m^2$	$0.03°C/W/m^2$
Wind chill	This represents wind chill in the building: the influence greater wind speed has on reducing perceived temperature. .	-0.2	-0.4 $°C/m/s$
Humidity discomfort	This represents the added discomfort from humidity: the influence greater humidity has on moving perceived temperature further from the desired level.	0.05 $°C/g/kg$	0 $°C/g/kg$



(a) Lighting



(b) Heating

Fig. 3: Year-Long Daily Lighting and Heating Demands for BC and NT Locations

TABLE III: OSeMOSYS System Outputs for BC

PV (KW)	STC (KW)	Battery (kWh)	Thermal Storage (kWh)	Cost (CAD)
395	122	115	2,417	716,251

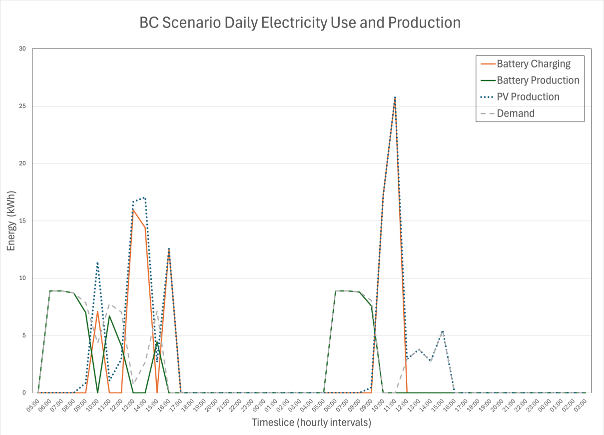
requirements. The OSeMOSYS optimisation controls the timing of storage charging and the scale of storage system and STC to ensure demand is met throughout the year. The storage system is therefore charged on days with sufficient solar irradiance, see Fig. 4c.

V. Discussion

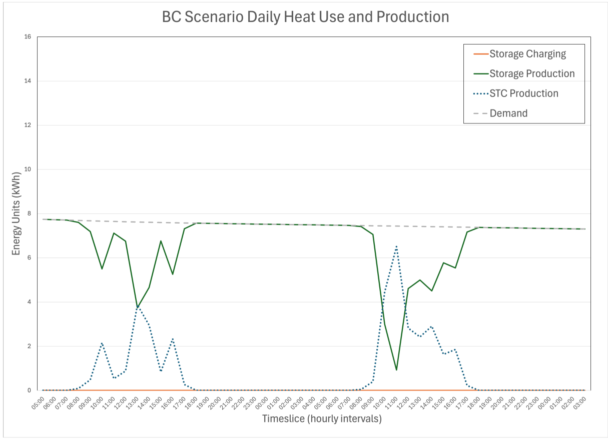
The BC solution required unexpectedly high battery and thermal storage capacities. With grid connections available it is probable that commercial growing in BC depends on such grid energy inputs. At the same time, fossil fuel heating, such as natural gas, is necessary for the thermal system. However, when considering the detailed results, as shown above, and the annual demand profiles, Fig.3a and Fig. 3b, it is clear that the temperate climate of the region does not make up for the variable and irregular solar irradiance levels. Indeed, commercial greenhouses in BC may often be seen with lights on. There is, therefore, a heavy reliance on the storage systems to meet both the lighting and heating demands. During the summer, when solar irradiance levels are higher, the over-installed PV could be monetised or the microgrid energy system extended. Solutions for the NT location were obtained for growing periods less than year long. 6 months, 183 days, for example resulted in a system cost of $276,325, with a modest battery capacity requirement, highlighting the more consistent solar irradiance levels for much of the year, Fig. 3a.

As the global population is estimated to reach 9.8 billion by 2025, food demand is projected to increase by as much as 62% in that time [18], [19]. Clearly, the benefits obtained by developing the system infrastructure enables extensions of the natural growing seasons. Specific high-value crops, such as arugula, for example, have specific optimal conditions and seed-to-harvest lengths. These may include varying temperatures dependent on the growth stage and are likely to include different light spectra and intensities. By extending the growing season, it may be possible to have multiple plantings and harvests over a long period, even after the apparent season has ended.

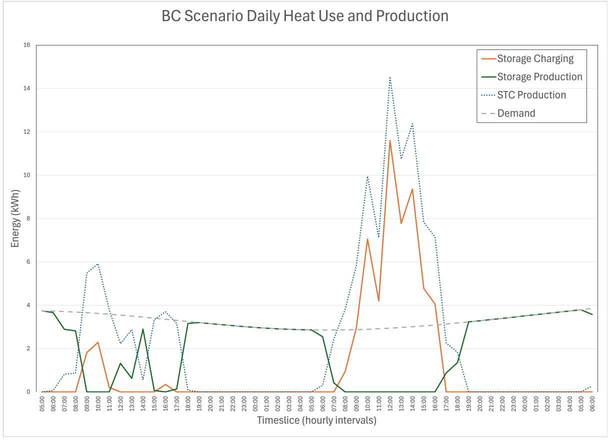
The methodology presented above enables consider



(a) Electricity (February)



(b) Heating (February)



(c) Heating (April)

Fig. 4: BC Location Daily Electricity and Heating Use and Production

infrastructure options for greenhouse energy systems, taking into consideration the location specific demands and the nature of the greenhouse envelope. The system costs and capacities provide sufficient detail to inform decision making and expansion planning, including grid connection options and microgrid integration. This methodology framework allows the exploration of further retrofitting and refinement of the greenhouse envelope and thermal storage options. This would require further preprocessing intervention and multiple OSeMOSYS optimisation runs. Alternative energy sources, such as wind and geothermal, can also be explored and integrated into the framework. Fossil fuel based heaters may also be attractive, adding CO_2 and humidity. Costing the these benefits, however, would require further information on crop management, typical of commercial scale greenhouse operations.

VI. Conclusions

Adapting OSeMOSYS provides an opportunity for operational analysis of a greenhouse energy system and is suitable for optimal investment expansion planning. Data preprocessing and the addition of an open-source external building envelope model allow OSeMOSYS to consider and accurately represent the greenhouse's envelope, thermal behaviour, and plant growth demands. By using real solar and temperature hourly data from 2015, the optimised system presented above captures meaningful aspects of the design and operation that may otherwise be lost in an averaged modelling approach. Incorporating multi-year data could further increase the reliability of these results. However, as this methodology is based on location-driven solar irradiance data, it can be easily adapted to other case studies integrating renewable energy.

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