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Energy Consumption Model for Indoor Cannabis Cultivation Facility

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ABSTRACT The recent legalization of cannabis is facilitating very rapid growth in the cannabis cultivation industry, with the energy intensive indoor cultivation facilities becoming more prevalent. This presents a challenge to utilities as the high energy demand from this industry can overburden the existing utility infrastructure. Hence, from both planning and operational perspectives, it is crucial to understand the energy consumption of the rapidly growing load. This paper proposes a deterministic energy consumption model for indoor cannabis cultivation operations for the two major loads in these facilities, i.e., lighting and HVAC, over a 24-hour period based on equipment specifications and operational requirements of the facility. This model can further be used to estimate or forecast short-term and long-term energy demands and costs of indoor cannabis operation(s). The proposed model successfully simulated the environmental conditions in a real-world cannabis facility, and the model's energy consumption output is validated using actual measurements taken from this facility as well as model output using GridLab-D.

INDEX TERMS Energy management, farming, humidity control, power demand, temperature control.

I. INTRODUCTION

CANNABIS cultivation is an energy-intensive sector and with the recent legalization of this industry, such as in Canada and a growing number of US states, the cannabis sector is growing very rapidly and consequently, so is the energy demand. For example, in 2014, Denver saw a 1.2% increase in electricity use, and 45% of that increase in demand came from cannabis cultivation, i.e., 0.54% of Denver's electricity use [1]. In 2018, 4% of Denver's electricity usage is attributed to the cannabis industry. In California, indoor Cannabis production consumes 3% of California's total electricity, and 1% of total US electricity [2]. While the demand from cannabis operations can help flatten the load profile during off-peak periods, it can also overburden existing utility infrastructure. Hence, from both planning and operational perspectives, it is important for the system operators and utilities to understand this load's energy consumption.

The energy consumption from the grid required for cannabis cultivation facilities is dependent on several factors such as, facility type, lighting fixtures used, and HVAC (temperature and humidity) settings and efficiencies. Facility type has an impact on the energy consumed for cannabis cultivation due to differences in the involved processes [3]. While outdoor cannabis cultivation is far less energy intensive than indoor operations, many choose to grow cannabis indoors or in greenhouses to boost productivity and lower risk to yields resulting from unpredictable and/or extreme weather conditions. Fig. 1 shows that energy is used differently in

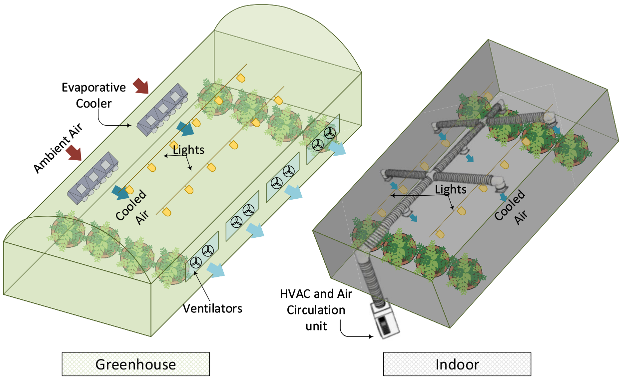


FIGURE 1. **Difference in energy use in greenhouse and indoor cannabis cultivation operations.**

greenhouse, and indoor cultivation operations. While lighting in greenhouses supplement natural sunlight, in indoor operations, lighting loads are much higher because high power lights are used to replace sunlight. In turn, these high-power lights in indoor operations generate significant heat, which needs a high capacity HVAC system to maintain optimal growing conditions for cannabis plants. These reasons support the need for a different model for indoor grow facilities.

In legal markets, indoor and greenhouse cultivation is more prevalent [3]. In 2017, approximately 60% of electricity usage in legal cannabis cultivation in the US was associated with indoor operations, while 37% was associated with greenhouse production [3]. The total energy costs for indoor cannabis grow operations typically varies between 20%-50% of total operating costs (approximately 150 kWh of electricity/yr/sq.ft). In comparison, energy use in a medium size or larger brewery accounts for about 6-12% of total operating costs [4].

Cannabis cultivation requires three stages: the seedling (or propagation) stage, the vegetative stage, and the flowering stage, all of which have different energy requirements based on the lighting, temperature, and humidity level they need. Typically, for indoor and greenhouse operations, the flowering stage has the highest energy consumption, while the seedling stage has the lowest [3]. Fig. 2 shows the electricity use breakdown for a typical indoor cannabis grow operation which shows that most of the electricity consumed is due to HVAC (ventilation, air conditioning, and dehumidification) (51%) and lighting (38%) [2]. In comparison, electricity represents only 10-15% of a typical greenhouse grower's total energy consumption [5].

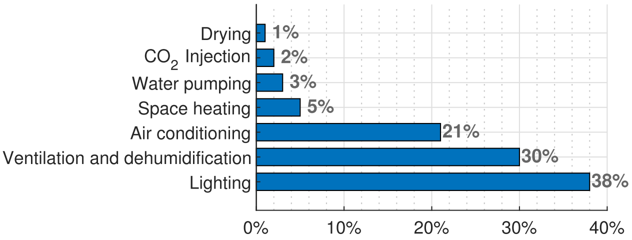


FIGURE 2. Electricity use breakdown for a typical indoor cannabis cultivation operation.

There are limited works in the literature that address energy management and consumption in greenhouses using mathematical models, such as [6]–[9], while others present an overview of the energy use of the new, emerging energy intensive cannabis industry [1], [3], [4], [10]. In [11], the technical report presents estimates and forecasts of energy consumption by indoor cannabis facilities in Ontario; however, the load profile considered for an indoor cannabis facility was assumed to be the same as an greenhouse cannabis facility. This assumption may underestimate the energy consumption of an indoor cannabis facility, based on the field data presented in [3]. To the best of our knowledge, there are no works to date proposing energy consumption models targeting cannabis grow operations in particular.

In view of the above discussions, this paper focuses on developing a deterministic energy consumption model for indoor cannabis cultivation facilities accounting for the two major energy loads, i.e., lighting and HVACs. This paper makes a number of contributions. Firstly, an energy consumption model for indoor cannabis facilities is developed and presented, considering the scheduling and operational requirements of lighting and HVAC equipment, respectively. Secondly, the proposed energy consumption model computes the daily peak demand, 24-hr power profile for each stage and entire facility, and the daily cost of electricity used by the facility based on time-of-use (TOU) rates for a real-world indoor cannabis facility demonstrating the capability of the model. Finally, temperature control in each grow room is modeled based on the energy balance equation considering sensible (lighting) and latent (evapotranspiration) heat contributions as well as the ventilation, conduction, convection, and infiltration losses. Furthermore, humidity control in each grow room is modeled based on the mass balance equation considering evapotranspiration, ventilation, and infiltration contributions as well as the moisture removed through dehumidification.

The proposed energy consumption model can be used by power system planners and operators to estimate/forecast long-term energy demands posed by indoor operations of this emerging industry, and maintain the security and reliability of the overall system. Utilities can also use this model to estimate short-term energy demands from their existing/future customers, identify limitations posed by the grid, and design specific strategies targeting cannabis grow operations to participate in demand response programs as well as offer incentives to achieve higher energy efficiency. Cannabis facility owners can use this energy consumption model to better understand the current energy consumption in their facility as well as the cost of consumed electricity; future upgrades to improve the energy efficiency of their facility (e.g., HPS to LED lights) can be evaluated as well.

The objective of the energy consumption model is to determine the daily energy consumed by a given indoor cannabis facility to maintain the grow rooms within the specified temperature and relative humidity thresholds, based on the physical parameters of the grow rooms, lighting and hvac equipment specifications, and operational requirements.

The remainder of this paper is organized as follows: The lighting and environmental requirements for the different stages of cannabis cultivation are discussed in Section II. The developed energy consumption model is presented and discussed in Section III. The parameters of the real-world indoor cannabis cultivation facility and simulation results of the proposed model's application to this real-world facility are presented and discussed in Section IV. Finally, the main conclusions and contributions of this paper are highlighted in Section V.

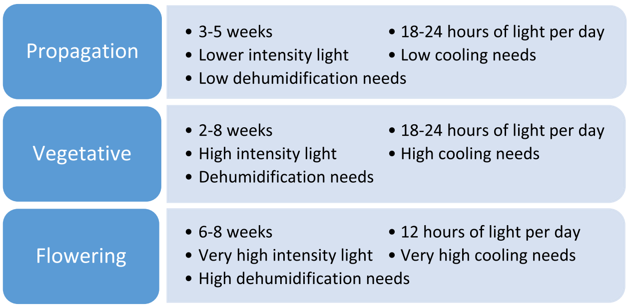


FIGURE 3. Requirements for different stages of cannabis cultivation.

II. STAGES OF CANNABIS CULTIVATION

The lighting and environmental requirements for the different stages of cannabis cultivation are shown in Fig. 3. The initial phase of cannabis cultivation is the process of replicating a genetic strain, typically done through cloning from living stock, known as the seedling or propagation stage. This stage of the cultivation generally represents less than 5% of overall electricity use [3]. Clone plants are generally kept under lower-wattage lights (5-40 W/sq.ft.) 18-24 hours a day for 1-2 weeks. T5HO fluorescents are preferred for this stage. Optimal temperature and relative humidity levels for cannabis cultivation are $24 - 26°C$ and 70-75% relative humidity [12]. Generally, split air-conditioning units are sufficient for this stage.

In the next stage, known as the vegetative stage, the clones are transplanted to an area that has higher intensity light and different environmental conditions. This stage consumes approximately 30-40% of total electricity use [3]. Historically, High-Pressure Sodium (HPS) lights and Metal-Halide (MH) lamps were preferred for the vegetative state, though now, LEDs and CMH fixtures are seeing increased adoption. Depending on strain and grower preference, plants remain in this stage for about 2-3 weeks (indoor cultivation) or 4-6 weeks (greenhouse cultivation) with lights (15-70 W/sq.ft.) on for generally 18 hours a day [3]. 600 W or 1000 W MH HID lighting is preferred because their spectra contains more blue, but HPS fixtures are also used for this stage. Optimal temperature and relative humidity levels for cannabis cultivation are $24 - 26°C$ and 65-70% relative humidity [12]. Generally, rooftop units are used in this stage for temperature and humidity control.

Lastly, in the flowering stage, the light schedule is changed to induce a hormonal response in the plant towards flower proliferation. This stage results in the highest energy consumption of all the stages estimated to be 50-65% of total facility electricity consumption [3]. This stage of cannabis cultivation uses 12 hours of light per day, which typically spans 7-11 weeks. This stage is when the photosynthesis rates peak and hence, the lighting intensity requires is high as well (40-70 W/sq.ft.) [3]. Owing to increasing cost and changing perceptions towards LEDs in this stage, the lighting mix in this stage appears to be changing from the conventional HPS lighting. 1000 W HPS fixtures are conventionally used for this stage because of their concentration of yellow or red spectra. Optimal temperature and relative humidity levels for cannabis cultivation are $24 - 26°C$ and 60-65% relative humidity [12]. Generally, rooftop units and standalone dehumidifiers are used in this stage for temperature and humidity control.

III. PROPOSED ENERGY CONSUMPTION MODEL

In a typical indoor cannabis cultivation facility, the total energy consumption results from these energy consuming loads - supplementary lighting, climate control of temperature, relative humidity, and CO_2 levels, air ventilation and circulation, space heating, drying, and irrigation systems. The energy demand of these loads varies with different stages of cannabis cultivation.

A. ASSUMPTIONS

In the proposed energy consumption model, only electricity consumption due to lighting, ventilation, and HVAC (temperature and humidity control) in the each of the stages are considered. It is also assumed that the installed HVAC equipment for temperature and humidity control are sized appropriately for the facility. The grow rooms are assumed to be well-sealed and well-insulated to minimize leakage of thermal energy and moisture. The temperature and relative humidity in the rooms during each computation interval are assumed to be constant, as the intervals are in the order of 1-5 minutes. The cooling and heating capacities as well as the air flow rates for the HVAC and dehumidifiers are assumed to be continuous variables in this model.

B. DESCRIPTION OF ENERGY CONSUMPTION MODEL

The model computes the power demand and energy consumed due to lighting, air circulation, and HVAC (temperature and humidity control) in each room $r \in N_r$ and cultivation stage $s \in S$ in time step dt over a given time horizon $t \in T$ as follows:

1) LIGHTING

Based on the lighting schedule $(T_{r,s}^{L,on}, T_{r,s}^{L,off})$ for each cultivation stage, the power consumed by lighting loads in each stage and room $P_{t,r,s}^{L}$ is computed for each time interval t:

$$P_{t,r,s}^{L} = \sum_{LT} n_i^L \cdot P_i^L \quad \forall\, t \in [T_{r,s}^{L,on}, T_{r,s}^{L,off}) \tag{1}$$

The power consumed by lighting loads in each cultivation stage $P_{t,s}^{L}$ is then computed:

$$P_{t,s}^{L} = \sum_{N_r} P_{t,r,s}^{L} \tag{2}$$

The power consumed by lighting loads in the facility P_t^L is then computed:

$$P_t^L = \sum_{S} P_{t,s}^{L} \tag{3}$$

Finally, the total energy consumed by lighting loads in the facility during the given time horizon E^L is computed:

$$E^L = \sum_{T_{r,s}^{L,on}}^{T_{r,s}^{L,off}-1} P_t^L \cdot dt \tag{4}$$

2) AIR CIRCULATION

Based on the operational requirements of the facility, the power consumed by the fans used for air circulation in each room and stage $P_{t,r,s}^C$ is computed for each time interval t:

$$P_{t,r,s}^C = n^{fan} \cdot P^{fan} \tag{5}$$

Similarly, the power consumed by the air circulation system in each cultivation stage $P_{t,s}^C$ and facility P_t^C is computed for each time interval t:

$$P_{t,s}^C = \sum_{N_r} P_{t,r,s}^C \tag{6}$$

$$P_t^C = \sum_{S} P_{t,s}^C \tag{7}$$

Finally, the total energy consumed by air circulation loads in the facility during the given time horizon E^C is computed:

$$E^C = \sum_{T_{r,s}^{fan,on}}^{T_{r,s}^{fan,off}-1} P_t^C \cdot dt \tag{8}$$

3) HUMIDITY CONTROL

Cannabis operations generally monitor and control the relative humidity (RH) inside the grow rooms within a specific range to promote optimal growth of plants and protect the plants from mold or mildew. It is important to note that RH ϕ is a function of temperature and inversely proportional, i.e., if the temperature increases, RH decreases and vice versa.

$$\phi = \frac{P^v}{P^{sat}} \tag{9}$$

where P^v is the partial pressure of water vapour, and P^{sat} is the saturation vapour pressure.

Partial pressure of water vapour can be computed either by using (9), if RH and temperature are known, or using the humidity ratio as follows:

$$P^v = \left(\frac{p \cdot R^d}{R^v}\right) \cdot \omega \tag{10}$$

where p is the atmospheric pressure (=101325 Pa), R^d is the gas constant for dry air (=287 J/kg.K), R^v is the gas constant for water vapour (=462 J/kg.K), and ω is the humidity ratio, which is the ratio of mass of water vapour to the total mass of air, and expressed in kg_{water}/kg_{air}. Saturation vapour pressure at a given temperature K (in Kelvin) is given by [13]:

$$P_{sat} = 610.78 \cdot \exp\left(\frac{17.08\,(K - 273.15)}{234.175 + (K - 273.15)}\right) \tag{11}$$

In the energy consumption model, the mass balance equation is used, which is an application of conservation of mass to physical systems, and accounts for the mass of moisture entering and leaving the grow room. In the context of cannabis cultivation, humidity control in each grow room is simulated based on this mass balance equation considering moisture contributions through evapotranspiration, ventilation, and infiltration as well as moisture removed through dehumidification during each time interval [14]. Hence, the steady-state mass balance equation in each time interval t is represented for each room r and stage s, as follows:

$$\begin{aligned}\Delta\omega_{t,r,s} &\\ = \Big(\dot{M}_{t,r,s}^{trans} + \dot{M}_{t,r,s}^{vent} \cdot \omega_t^O + \dot{M}_{t,r,s}^{inf} \cdot \omega_t^H - \dot{M}_{t,r,s}^{D} \cdot \omega_{t,r,s}\Big) \cdot dt &\end{aligned} \tag{12}$$

where $\Delta\omega_{t,r,s}$ is the change in humidity ratio (kg_{water}/kg_{air}) in grow room r and stage s in time interval t, $\dot{M}_{t,r,s}^{trans}$ is the mass flow rate (kg_{water}/hr) of water due to evapotranspiration, $\dot{M}_{t,r,s}^{vent}$ is the mass flow rate of air due to ventilation, ω_t^O is the humidity ratio of the outside air, $\dot{M}_{t,r,s}^{inf}$ is the mass flow rate of air due to infiltration, ω_t^H is the humidity ratio of the hallway air, $\dot{M}_{t,r,s}^{D}$ is the mass flow rate of air due to dehumidification. The mass flow rate is the mass of air/water (kg) which passes a point per unit of time (hr) and therefore, the product of humidity ratio and mass flow rate of air, in the case of ventilation, infiltration, and dehumidification, gives the mass flow rate of water. Note that ventilation brings in moisture along with the fresh air from outside, infiltration brings in moisture from the hallway outside the grow rooms, and dehumidification removes moisture from the room air and, therefore, the respective humidity ratios have been used in (12).

The change in humidity ratio in a given time interval t can be expressed as:

$$\Delta\omega_{t,r,s} = \rho_{t,r,s} \cdot V_{r,s} \cdot \Big(\omega_{t+1,r,s} - \omega_{t,r,s}\Big) \tag{13}$$

where $\rho_{t,r,s}$ is the humid air density (kg/m^3) of grow room r in stage s in time interval t, and $V_{r,s}$ is the volume of air (m^3) in the room r in stage s. The humid air density is a function of the partial pressure of water vapour P^v and temperature K, and can be expressed as:

$$\rho_{t,r,s} = \frac{\left(p - P_{t,r,s}^v\right) \cdot M^d + P_{t,r,s}^v \cdot M^v}{R \cdot K_{t,r,s}} \tag{14}$$

where M^d is the molar mass of dry air (=0.028964 kg/mol), M^v is the molar mass of water vapour (=0.018016 kg/mol), R is the universal gas constant (=8.314 J/K.mol), and $K_{t,r,s}$ is the temperature (in Kelvin) of grow room r in stage s in time interval t. Using (13) to compute the change in humidity ratio $\Delta\omega_{t,r,s}$ and (10) to compute the humidity ratio in room r and stage s in the current time interval t, the humidity ratio in time interval $t+1$ is computed using (13). To compute the change in humidity ratio for any time interval t in (12), the different contributions are computed as follows. Water vapour added by plant evapotranspiration is computed using:

$$\dot{M}^{trans}_{t,r,s} = F^{trans}_{s} \cdot n^{plants}_{r,s} \cdot F^{L}_{t,r,s} \tag{15}$$

where F^{trans}_{s} is the transpiration rate per plant in stage s (kg_{water}/hr), $n^{plants}_{r,s}$ is the number of plants in room r and stage s, and $F^{L}_{t,r,s}$ is the light factor. When the lights are on, it causes the plants to transpire more ($F^{L}_{t,r,s} = 1$); however, when the lights are off, the plants still transpire at a lower rate ($F^{L}_{t,r,s} = 0.3$) [15]. For the proposed energy consumption model, the transpiration rate is assumed to be 0.25 $kg/plant/hr$ in the seedling/propagation stage, 0.38 $kg/plant/hr$ in the vegetative stage, and 0.5 $kg/plant/hr$ in the flowering stage [16].

Water vapour added due to grow room ventilation is computed using:

$$\dot{M}^{vent}_{t,r,s} \cdot \omega^{O}_{t} = \left(\psi^{vent} \cdot \dot{V}^{hvac}_{t,r,s} \cdot \rho^{O}_{t}\right) \cdot \omega^{O}_{t} \tag{16}$$

where ψ^{vent} is the ventilation factor (percentage of fresh air mixed in with circulated air), $\dot{V}^{hvac}_{t,r,s}$ is the HVAC air flow rate (m^3/hr), and ρ^{O}_{t} is the air density of outside air (kg/m^3) computed using (14). Water vapour added due to air infiltration when the door opens is computed using:

$$\dot{M}^{inf}_{t,r,s} \cdot \omega^{H}_{t} = \left(\dot{V}^{inf}_{t,r,s} \cdot \rho^{H}_{t}\right) \cdot \omega^{H}_{t} \tag{17}$$

where $\dot{V}^{inf}_{t,r,s}$ is the air infiltration flow rate (m^3/hr) and ρ^{H}_{t} is the air density of hallway air (kg/m^3) computed using (14), which uses partial pressure and temperature of the hallway. The infiltration of air into the grow room from the hallway occurs due to the pressure difference between these zones when the door opens. The air infiltration rates used are different for peak and off-peak times, similar to a warehouse [17]. Water vapour removed through dehumidification is computed using:

$$\dot{M}^{D}_{t,r,s} \cdot \omega_{t,r,s} = \left(\alpha^{D}_{t,r,s} \cdot n^{D}_{r,s} \cdot \dot{V}^{D}_{t,r,s} \cdot \rho_{t,r,s}\right) \cdot \omega_{t,r,s} \tag{18}$$

where $\alpha^{D}_{t,r,s}$ is the state of dehumidifier operation based on the relative humidity setting of dehumidifier in room r and stage s ($=1,\ \forall\ \phi_{t,r,s} > \phi^{set}_{r,s}$; 0, otherwise), $n^{D}_{r,s}$ is the number of dehumidification units in room r and stage s, $\dot{V}^{D}_{t,r,s}$ is the air flow rate of the dehumidification unit (m^3/hr), and $\rho_{t,r,s}$ is the humid air density inside room r and stage s (kg/m^3).

It is important to note that the dehumidification requirement depends on the relative humidity level in the room. Hence, to compute the dehumidifier air flow rate $\dot{V}^{D}_{t,r,s}$ for the time interval t in room r and stage s, the change in humidity ratio without dehumidification $\Delta\omega'_{t,r,s}$ for the same is computed using:

$$\Delta\omega'_{t,r,s} = \left(\dot{M}^{trans}_{t,r,s} + \dot{M}^{vent}_{t,r,s} \cdot \omega^{O}_{t} + \dot{M}^{inf}_{t,r,s} \cdot \omega^{H}_{t}\right) \cdot dt \tag{19}$$

The resulting humidity ratio without dehumidification at time interval $t+1$ $\omega'_{t+1,r,s}$ in room r and stage s is then computed using:

$$\omega'_{t+1,r,s} = \frac{\Delta\omega'_{t,r,s}}{\rho_{t,r,s} \cdot V_{r,s}} + \omega_{t,r,s} \tag{20}$$

If the dehumidifier(s) in room r and stage s is *ON* in the time interval t and the humidity ratio exceeds the upper limit ($\omega'_{t+1,r,s} - \bar{\omega} > 0$), then the dehumidifier air flow rate $\dot{V}^{D}_{t,r,s}$ can be computed using:

$$\omega'_{t+1,r,s} - \bar{\omega} = \frac{\dot{V}^{D}_{t,r,s} \cdot \rho_{t,r,s} \cdot \omega_{t,r,s}}{\rho'_{t,r,s} \cdot V_{r,s}} \tag{21}$$

If the computed dehumidifier air flow rate $\dot{V}^{D}_{t,r,s}$ exceeds the rated dehumidifier air flow rate ($\dot{V}^{D,rated}_{r,s}$), then the dehumidifier air flow rate is set to $\dot{V}^{D,rated}_{r,s}$. Therefore, the power consumption by dehumidification units $P^{D}_{t,r,s}$ in each room and stage is computed in proportion to the computed dehumidifier air flow rate as follows:

$$P^{D}_{t,r,s} = \frac{\dot{V}^{D}_{t,r,s}}{\dot{V}^{D,rated}_{r,s}} \cdot P^{D,rated}_{r,s} \cdot \alpha^{D}_{t,r,s} \tag{22}$$

where $P^{D,rated}_{r,s}$ is the aggregate rated power of the dehumidifier(s) in room r and stage s.

The power consumption by dehumidifiers in each stage s, $P^{D}_{t,s}$, and time interval t, P^{D}_{t}, is computed as follows:

$$P^{D}_{t,s} = \sum_{N_r} P^{D}_{t,r,s} \tag{23}$$

$$P^{D}_{t} = \sum_{S} P^{D}_{t,s} \tag{24}$$

Finally, the total energy consumed by the dehumidification system in the facility during the given time horizon E^D is computed:

$$E^{D} = \sum_{T} P^{D}_{t} \cdot dt \tag{25}$$

4) TEMPERATURE CONTROL

Cannabis operations monitor and control the temperature inside grow rooms within a specific range to promote optimal growth of plants. In the proposed energy consumption model, temperature in grow rooms is simulated using the energy balance equation, which accounts for the thermal energy added and lost in a room over a time interval [14]. This energy balance equation considers thermal energy contributions through HVAC, sensible heat (thermal energy added due to supplemental lighting), latent heat (thermal energy added due to plant evapotranspiration) as well as thermal energy lost/removed through conduction and convection, ventilation, and door opening events. Hence, the steady-state energy balance equation in each time interval t is represented for each room r and stage s, as follows:

$$\begin{aligned}\Delta Q^{stored}_{t,r,s} &\\ &= \left(Q^{hvac}_{t,r,s} + Q^{L}_{t,r,s} + Q^{trans}_{t,r,s} - Q^{C}_{t,r,s} - Q^{vent}_{t,r,s} - Q^{inf}_{t,r,s}\right)\end{aligned} \tag{26}$$

where $\Delta Q^{stored}_{t,r,s}$ is the change in stored thermal energy $(W \cdot hr)$ in grow room r and stage s in time interval t, $Q^{hvac}_{t,r,s}$ is the thermal energy contribution of the HVAC system (positive when operating in heating mode and negative when in cooling mode), $Q^{L}_{t,r,s}$ is the thermal energy contribution due to lighting, $Q^{trans}_{t,r,s}$ is the thermal energy contribution due to evapotranspiration, while $Q^{C}_{t,r,s}$ is the thermal energy lost due to conduction and convection, $Q^{vent}_{t,r,s}$ is the thermal energy lost due to ventilation requirements, and $Q^{inf}_{t,r,s}$ is the thermal energy lost due to air infiltration resulting from door opening events. The change in stored thermal energy $\Delta Q^{stored}_{t,r,s}$ in room r and stage s in time interval t can also be expressed as:

$$\Delta Q^{stored}_{t,r,s} = (1/3.6) \cdot C^{air}_{p} \cdot V_{r,s} \cdot \rho_{t,r,s} \left(K_{t+1,r,s} - K_{t,r,s} \right) \tag{27}$$

where C^{air}_{p} is the specific heat capacity of air $(kJ/kg.K)$ and $K_{t+1,r,s}$ is the temperature of grow room r and stage s in time interval $t+1$. Using (26) to compute the change in stored thermal energy $\Delta Q^{stored}_{t,r,s}$ and (14) to compute the humid air density $\rho_{t,r,s}$, the temperature in time interval $t+1$ is computed using (27). To compute the change in stored thermal energy $Q^{hvac}_{t,r,s}$ for any time interval t in (26), the different contributions and losses are computed. Thermal energy added/removed by HVAC is computed using:

$$Q^{hvac}_{t,r,s} = \begin{cases} Q^{hvac,heat}_{t,r,s}, & \forall \gamma^{H}_{t,r,s} = 1 \\ -Q^{hvac,cool}_{t,r,s}, & \forall \gamma^{H}_{t,r,s} = 2 \\ 0, & \forall \gamma^{H}_{t,r,s} = 0 \end{cases} \tag{28}$$

where $Q^{hvac,heat}_{t,r,s}$ is the thermal energy contributed by the HVAC system in heating mode, $Q^{hvac,cool}_{t,r,s}$ is the thermal energy removed by the HVAC system in cooling mode, and $\gamma^{H}_{t,r,s}$ is the HVAC mode of operation in time interval t in room r and stage s.

The HVAC mode of operation in time interval t is determined as follows:

$$\gamma^{H}_{t,r,s} = \begin{cases} 1, & \forall \left(K_{t,r,s} < \underline{K_{r,s}} \right) \\ & \cup \left(\forall \gamma_{t-1,r,s} = 1 \cap K_{t,r,s} < K^{set}_{t,r,s} \right) \\ 2, & \forall \left(K_{t,r,s} > \overline{K_{r,s}} \right) \\ & \cup \left(\forall \gamma_{t-1,r,s} = 2 \cap K_{t,r,s} > K^{set}_{t,r,s} \right) \\ 0, & otherwise \end{cases} \tag{29}$$

where $\underline{K_{r,s}}$ is the lower temperature limit in room r and stage s, $\overline{K_{r,s}}$ is the upper temperature limit in room r and stage s, and $K^{set}_{t,r,s}$ is the temperature setting of the HVAC(s) in room r and stage s. Thermal energy added due to lighting is computed using:

$$Q^{L}_{t,r,s} = P^{L}_{t,r,s} \cdot F_{SA} \cdot dt \quad \forall\, t \in \left[T^{on}_{r,s}, T^{off}_{r,s} \right) \tag{30}$$

where $P^{L}_{t,r,s}$ is the aggregate power consumed by all operational lighting fixtures in room r and stage s in time interval t, and F_{SA} is the special allowance factor which depends on the type of lighting fixture used (For T5HO fluorescent, $F_{SA} = 0.87 - 1.15$ [14]; for MH and HPS, $F_{SA} = 1.1$ [14]; for LED, $F_{SA} = 0.79$ [18]). The special allowance factor is the ratio of lighting fixtures' power consumption, including lamps and ballast, to the normal power consumption of the lamps. Thermal energy added due to evapotranspiration is computed using:

$$Q^{trans}_{t,r,s} = n^{plants}_{r,s} \cdot F^{trans}_{s} \cdot L_{v} \cdot F^{L}_{t,r,s} \cdot dt \tag{31}$$

where L_v is the specific latent heat of water for vapourization $(= 628\ W.hr/kg)$. Thermal energy lost due to conduction and convection is computed using:

$$Q^{C}_{t,r,s} = \left(\frac{K_{t,r,s} - K^{O}_{t}}{R^{eq,window}_{r,s}} + \frac{K^{leaf} - K^{air}}{R^{eq,convection}_{r,s}} \right) \cdot dt \tag{32}$$

where $R^{eq,window}_{r}$ is the absolute thermal resistance (K/W) of windows, $R^{eq,convection}_{r}$ is the absolute thermal resistance due to convection, and $(K^{leaf} - K^{air})$ is the temperature difference between the surface of the leaf and air in the room ($\approx 2°C$ [19]). The absolute thermal resistance of windows is computed using [20]:

$$R^{eq,window}_{r,s} = \frac{d^{window}_{r,s}}{A^{window}_{r,s} \cdot u^{window}_{c}} = \frac{Rvalue^{window}_{r,s}}{A^{window}_{r,s}} \tag{33}$$

where $d^{window}_{r,s}$ is the thickness of window(s) (m) in room r and stage s, $A^{window}_{r,s}$ represents the total surface area (m^2) of all the windows in room r and stage s, u^{window}_{c} is the thermal conductivity of the window $(W/m.K)$, and $Rvalue^{window}_{r,s}$ is the windows' resistance to heat transfer $(K.m^2/W)$ [21]. Similarly, the absolute thermal resistance of the roof and walls of the room can be computed as well. The absolute thermal resistance due to convection is computed using [20]:

$$R^{eq,convection}_{r,s} = \frac{1}{A^{canopy}_{r,s} \cdot h^{int}_{c}} \tag{34}$$

where $A^{canopy}_{r,s}$ is the surface area of the plant canopy (m^2) in room r and stage s, and h^{int}_{c} is the internal convection coefficient ($=7\ W/m^2.K$ [22]). Thermal energy lost due to ventilation is computed using:

$$Q^{vent}_{t,r,s} = \left(dt/3.6 \right) \cdot \psi^{vent} \cdot \dot{V}^{hvac}_{t,r,s} \cdot \rho_{t,r,s} \cdot C^{air}_{p} \cdot \left(K_{t,r,s} - K^{O}_{t} \right) \tag{35}$$

Thermal energy lost due to air infiltration is computed using:

$$Q^{inf}_{t,r,s} = \left(dt/3.6 \right) \cdot \dot{V}^{inf}_{t,r,s} \cdot \rho^{H}_{t,r,s} \cdot C^{air}_{p} \cdot \left(K_{t,r,s} - K^{H}_{t} \right) \tag{36}$$

where $\rho^{H}_{t,r,s}$ is the density of air in the hallway, and K^{H}_{t} is the temperature of the hallway. It is important to note that the cooling or heating requirement depends on the temperature in the room. Hence, to compute the HVAC thermal energy added/removed in heating/cooling mode ($Q^{hvac,heat}_{t,r,s}/Q^{hvac,cool}_{t,r,s}$) respectively for time interval t in room r and stage s, the change in stored thermal energy without HVAC contribution $\Delta Q'^{stored}_{t,r,s}$ is computed:

$$\Delta Q'^{stored}_{t,r,s} = \left(Q^{L}_{t,r,s} + Q^{trans}_{t,r,s} - Q^{C}_{t,r,s} - Q^{vent}_{t,r,s} - Q^{inf}_{t,r,s} \right) \tag{37}$$

The resulting temperature without HVAC contribution at time interval $t + 1$ $K'_{t+1,,r,s}$ in room r and stage s is then computed:

$$K'_{t+1,r,s} = \frac{3.6 \cdot \Delta Q'^{stored}_{t,r,s}}{C^{air}_{p} \cdot \rho_{t,r,s} \cdot V_{r,s}} + K_{t,r,s} \tag{38}$$

If the HVAC(s) in room r and stage s is in heating mode during time interval t and the resulting temperature is lower than the lower temperature limit ($\underline{K}_{r,s} - K'_{t+1,r,s} > 0$), then the thermal energy added by hvac $Q^{hvac,heat}_{t,r,s}$ can be computed using:

$$\underline{K}_{r,s} - K'_{t+1,,r,s} = \frac{3.6 \cdot Q^{hvac,heat}_{t,r,s}}{C^{air}_{p} \cdot \rho_{t,r,s} \cdot V_{r,s}} \tag{39}$$

If the computed HVAC(s) thermal energy $Q^{hvac,heat}_{t,r,s}$ exceeds the total rated heating capacity of the HVAC system $Q^{hvac,heat,rated}_{r,s}$ in room r and stage s, then the added HVAC thermal energy is set to $Q^{hvac,heat,rated}_{r,s}$.

If the HVAC(s) in room r and stage s is in cooling mode during time interval t and the resulting temperature exceeds the higher temperature limit ($K'_{t+1,r,s} - \overline{K}_{r,s} > 0$), then the thermal energy removed by hvac $Q^{hvac,cool}_{t,r,s}$ can be computed using:

$$K'_{t+1,r,s} - \overline{K}_{r,s} = \frac{3.6 \cdot Q^{hvac,cool}_{t,r,s}}{C^{air}_{p} \cdot \rho_{t,r,s} \cdot V_{r,s}} \tag{40}$$

Similar to the heating mode, if the computed HVAC(s) thermal energy $Q^{hvac,cool}_{t,r,s}$ exceeds the total rated cooling capacity of the HVAC system $Q^{hvac,cool,rated}_{r,s}$ in room r and stage s, then the removed HVAC thermal energy is set to $Q^{hvac,cool,rated}_{r,s}$. Therefore, power consumption of hvac system $P^{hvac}_{t,r,s}$ in time interval t in room r and stage s is computed as follows:

$$P^{hvac}_{t,r,s} = \frac{Q^{hvac}_{t,r,s}}{Q^{hvac,rated}_{t,r,s}} \cdot P^{hvac,rated}_{r,s} \cdot \gamma^{H}_{t,r,s} \tag{41}$$

where $P^{hvac,rated}_{r,s}$ is the rated power of the HVAC system in cooling mode. The power consumption of the hvac system $P^{hvac}_{t,s}$ in each stage s for each time interval t is then computed:

$$P^{hvac}_{t,s} = \sum_{N_r} P^{hvac}_{t,r,s} \tag{42}$$

The power consumption of the hvac systems in the facility P^{hvac}_{t} in each time interval t is then computed:

$$P^{hvac}_{t} = \sum_{S} P^{hvac}_{t,s} \tag{43}$$

Finally, the total energy consumed by the HVAC system in the facility during the given time horizon E^{hvac} is computed:

$$E^{hvac} = \sum_{T} P^{hvac}_{t} \cdot dt \tag{44}$$

IV. SIMULATION RESULTS AND MODEL VALIDATION

A. REAL-WORLD INDOOR CANNABIS CULTIVATION FACILITY

Simulations were performed using facility and equipment parameters from a real-world indoor cannabis operation with a flowering space of approximately 4000 sq. ft., using a time interval (dt) of 1-min. Table 1 outlines the facility specifications.

TABLE 1. Real-world indoor cannabis cultivation facility specifications.

Stage (Rooms)	Lighting Fixture (Qty)	HVAC Type
Seedling/Propagation (1)	54W T5HO fluorescent (48)	Split AC unit
Vegetative (1)	1000 W MH (45)	Rooftop unit
Flowering (3)	1000 W HPS (48/65/64)	Rooftop unit

The temperature and RH in the hallway is assumed to be 25°C and 60%, respectively. The hourly temperature and RH profile of the outside air is taken for September 23, 2019 to facilitate comparison of the model output with the available measurements for the same day from the real-world facility.

The heavily insulated and well-sealed walls and roof as well as the absence of windows in the grow rooms of the chosen real-world facility have a negligible effect on loss of heat and moisture through their windows, walls, and roof, and hence, these losses have negligible impact in the computation of energy consumption for this facility. However, this may not be in the case in other indoor cannabis operations. Furthermore, this facility does not draw in outside air directly into the grow rooms through the HVAC system as part of their cultivation process, and therefore, $\psi^{vent} = 0\%$. The lighting schedule in the grow rooms are staggered to lower the daily peak demand as follows: 6:00 am - 12:00 am (Seedling and flowering room 1); 2:00 am - 8:00 pm (vegetative room); 12:00 pm - 12:00 am (flowering room 2); and 12:00 am - 12:00 pm (flowering room 3). Furthermore, the peak times used for door opening events in these grow rooms are 7-8 pm, 12-1 pm, and 5-6 pm, while the rest of the hours between 6 am - 7 pm are off-peak times [17]. Ontario's 2019 Summer TOU rates [23] are used to compute the cost of electricity consumed by the facility.

B. RESULTS AND DISCUSSION

For a time horizon of 24 hours, simulations were performed for time intervals of 1 minute to compute important metrics for the facility, particularly for lighting, HVAC, and dehumidification loads.

1) CLIMATE CONTROL

Fig. 4 presents the temperature and RH profiles for a flowering stage grow room using a time step of 5 min to clearly show

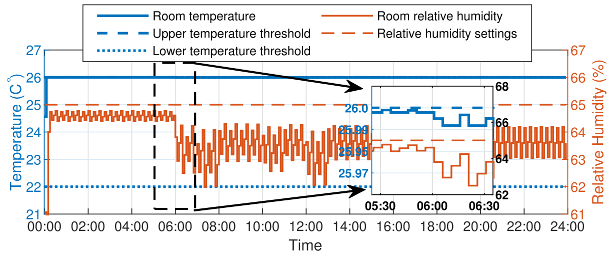
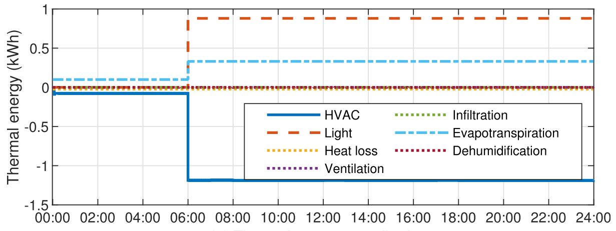
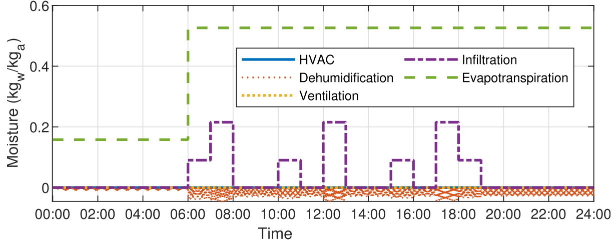


FIGURE 4. **Temperature and RH profiles for a grow room in the flowering stage.**



(a) Thermal energy contributions



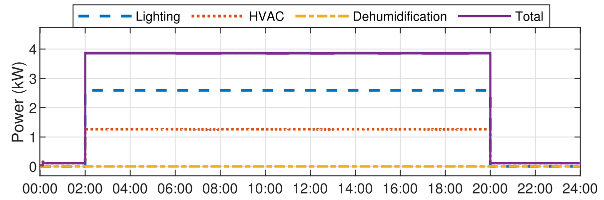
(b) Moisture contributions

FIGURE 5. **(a) Thermal energy and (b) Moisture profiles for a grow room in the flowering stage.**

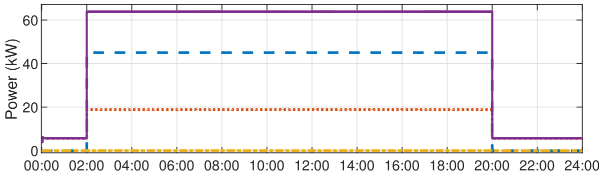
the temperature and RH regulation. It can be seen that the HVAC in the grow room keeps the room temperature within the specified limits. Similarly, the dehumidifier in the grow room regulates the relative humidity based on a maximum RH setting. Furthermore, Fig. 5 shows a breakdown of thermal energy and moisture contributions from different sources. It can be seen that the largest source of thermal energy is the lighting in the room, while plant evapotranspiration is the largest contributor of moisture inside the room. In this facility, thermal energy loss through conduction/convection (heat loss), ventilation, and infiltration are not significant. This may be because of the well-sealed and heavily insulated grow rooms and minimal temperature difference between the hallway and grow room.

2) POWER DEMAND PROFILE

For the given day, the peak power demand for the entire facility is computed to be 237.1 kW. The power demand profile for lighting, HVAC, and dehumidification loads in different stages of cannabis cultivation are shown in Fig. 6. In this figure, it can be seen that the flowering stage has the highest power consumption of the three stages, while propagation stage has the lowest. Furthermore, HVAC and dehumidification power consumption is less than lighting loads, which may be attributed to the well-insulated and well-sealed grow rooms reducing the leakage of cool air through conduction, resulting in higher HVAC efficiency. Fig. 7 presents the operation state and power consumed by



(a) Propagation Stage



(b) Vegetative Stage

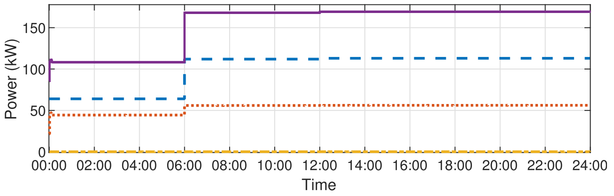
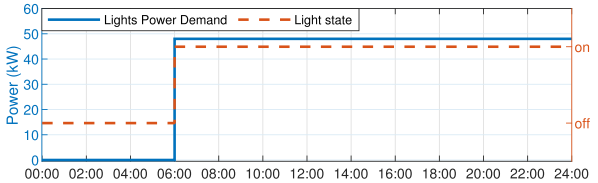
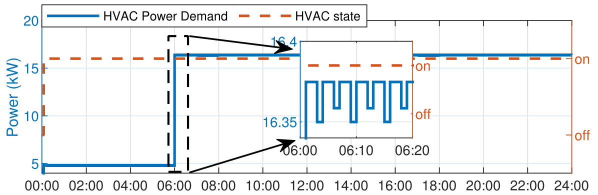


FIGURE 6. **Power demand profiles for lighting, HVAC, and dehumidification loads in different stages in a real world indoor cannabis facility.**



(a) Lights power consumption



(b) HVAC power consumption

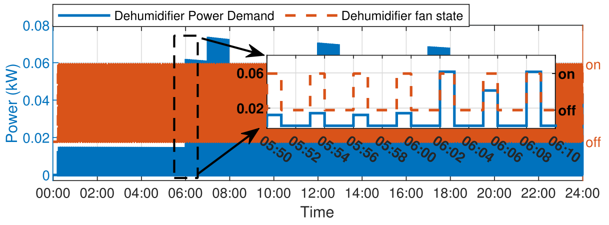


FIGURE 7. **Operation state and power consumed by lighting, HVAC, and dehumidifier in a grow room (flowering stage).**

lighting, HVAC, and dehumidifier in a flowering stage grow room. It can be seen that the HVAC cooling and dehumidification loads are the highest when the lights are on. This is because the heat emitted by the lights increases transpiration of water from the plants.

3) ENERGY CONSUMPTION PROFILE

The 15-min average energy consumption profiles for each cultivation stage in the facility is shown in Fig. 8, which is computed using the energy consumption of lighting, HVAC, and dehumidification loads in each stage. The profiles follow a similar trend as the power demand profiles. It is important to note that the determination of the power profiles and the total energy consumed by the facility only considers the lighting, HVAC, and dehumidification loads; other loads have not been considered but may be estimated based on the percentages given in Fig. 2. The breakdown of the total energy consumed by the facility by load and stage for a 24-hour period is shown in Table 2. The results show that the contribution of lighting, HVAC, and dehumidification towards the total energy consumption is 66.14%, 33.83%, and 0.03%, respectively.

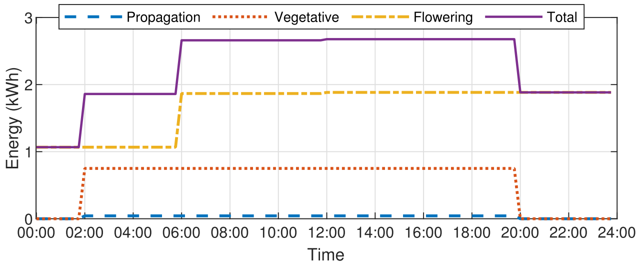


FIGURE 8. **Energy profile of the facility in 15-min intervals.**

TABLE 2. **Energy Consumption by Indoor Cannabis Facility for a 24-h period (kWh).**

Stage	Lighting	HVAC	Dehumidification	Total
A	46.7	23.4	0.0	70.1 (1.4%)
B	810.0	372.5	0.5	1183.0 (23.9%)
C	2412.0	1276.0	1.2	3689.2 (74.6%)
Total	3268.7	1671.9	1.7	**4942.0**

4) ELECTRICITY COST

Based on the computed energy consumption for the facility, the cost of consumed electricity is computed using TOU rates (current pricing plan for facility) and the results are presented in Table 3.

TABLE 3. **Cost of electricity consumed by Indoor Cannabis Facility for a 24-h period (CAD).**

Stage	Lighting	HVAC	Dehumidification	Total
A	4.6	2.3	0.0	6.9
B	79.1	35.3	0.0	114.4
C	223.0	115.9	0.1	339.0
Total	306.7	153.5	0.1	**460.3**

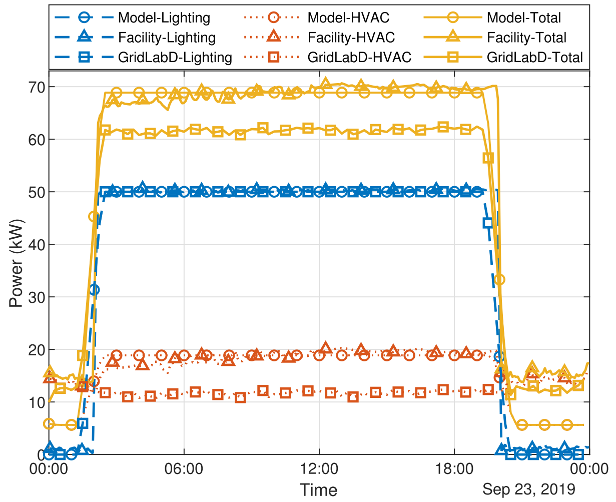


FIGURE 9. **Comparing the power demand profile of the model with the real-world facility and GridLab-D.**

5) ELECTRICITY INTENSITY

This is a commonly used benchmark by cannabis facility owners to measure their facility's electricity consumption per unit of flowering canopy area, and is measured in kWh/sq.ft. For this facility, with a flowering canopy area of approximately 4000 sq.ft. and 24-hour total energy consumption of 4942 kWh, the electricity intensity for this facility is computed to be 1.24 kWh/sq.ft/day.

C. MODEL VALIDATION

In order to validate the proposed model, the one-day power demand profile generated by the model, as shown in Fig. 9, is compared with: 1) the power demand profile collected from the real-world indoor cannabis growing facility; 2) a simulation of the facility's demand produced using GridLab-D [24] simulation software.

1) VALIDATION USING ACTUAL MEASUREMENTS FROM A REAL-WORLD FACILITY

Actual measurements from a real-world indoor cannabis cultivation facility data are used to validate the proposed model. The facility meets certain optimal conditions for indoor cannabis cultivation, such as well-sealed and heavily insulated grow rooms, climate and lighting control in grow rooms, blocking out windows in grow rooms, and so on. The parameters of one growing room in the vegetative stage in that facility are provided in Table 4 in the Appendix. Voltage, current, and phase angle measurements at the grow room panel were collected using Braingrid [25] sensor devices.

The cultivation at the cannabis facility was in the infancy stage at the time of model development, and the cannabis plants were still in the vegetative stage then. Hence, this comparison is for the power demand of the vegetative stage only, that is Grow Room 2.

2) VALIDATION USING GridLab-D

The model of the cannabis facility was built using GridLab-D [24]. In this model, grow rooms are modeled separately using the residential house model the has no windows and very good insulation level. The facility's grow rooms parameters are used as inputs to their counterparts in the model such as the floor area, the ceiling height, and the door size. However, the aggregate size of the HVAC units and fans is used in the model since the software does not model multiple units. The other model parameters such as the power requirements and the number of lighting fixtures, lighting schedules, and heating and cooling setpoints are set according to the facility's data given in Table 4. Finally, all the simulations are run using the outside temperature and relative humidity values as measured at the real-world facility.

The comparison in Fig. 9 shows the lighting power consumption, HVAC power consumption, and total power consumption profiles. From the figure, it can be seen that the output generated by the proposed model is closer to the actual measurements, compared to the GridLab-D results. The results show that the proposed model is able to estimate the lighting load with an average error of -0.6% when compared to the actual facility measurements; however, in the case of HVAC load, the average error is higher at $+1.2\%$. This can be attributed to deviation of real-world conditions from assumptions made in the proposed model, with respect to entry and exit frequency in the room as well as the number of plants in the room on the given day. If the actual entry and exit frequency or the actual number of plants in the grow room on the chosen day are significantly higher than the model assumptions, HVAC power consumption will be higher due to increased temperature and humidity fluctuation resulting from opening and closing of doors and increased evapotranspiration, respectively.

3) LIMITATIONS OF THE PROPOSED MODEL

The error in the model output can be attributed to the following limitations of the model:

- Due to the diversity of HVAC equipment utilized by indoor cannabis cultivators, it is impossible to model the HVAC equipment exactly for each individual facility. Hence, some error is introduced into the model because the model is based on heating/cooling functions of the HVAC and applied in the energy and moisture balance equations.
- This model assumes 80% efficiency for the HVAC equipment, as this information was not available in the manufacturer datasheets. Hence, if the actual HVAC efficiency is different from the assumed efficiency, this would introduce an error. Furthermore, in longer established indoor cannabis operations, the HVAC equipment efficiency can vary based on the age of the equipment, technology, and regularity of maintenance. This is another factor that can introduce errors in the output of this model.
- In this model, the transpiration rates for cannabis plants in each stage are assumed to be a constant with a unit of kg/hour/plant. In reality, the transpiration rate of cannabis plants (or evapotranspiration) can vary as temperature and relative humidity conditions at the leaf surface and the resulting vapour pressure deficit changes [26], [27]. The higher the temperature in the room, the more the plants transpire; the model uses different transpiration constants for when the lights are on and off. Hence, for the purpose of this model, the constants [16] are sufficient; however, if the actual evapotranspiration rates are significantly different from the assumed rates, this would introduce an error in the model output.
- The lag times in heating and cooling of the room when the lights turn on and off, respectively, are not considered in this model. However, it can be seen in the HVAC power consumption profiles plotted using measurements that the lag times do not have a significant impact on the power consumption profile, as the measurement vs model output plots are very close in pattern.
- The number of plants in any grow room may change on a day-to-day basis. However, to estimate the energy consumption of the facility in the proposed model, the maximum plant capacity of grow rooms is used.

V. CONCLUSION

The proposed deterministic energy consumption model used the energy and mass balance equations to simulate temperature and humidity control, respectively, in the grow rooms. Based on the temperature and humidity simulations and operational requirements of the facility, the proposed model computed the total energy consumption and electricity cost of the facility, as well as for each room and cultivation stage of the indoor cannabis operation. In addition, power profiles were computed for each room, stage, and entire facility, based on the physical parameters of the grow rooms, equipment specifications, and operational requirements. The proposed model also computed the cost of electricity used by the real-world facility. The results of the proposed energy consumption model, applied to a real-world indoor cannabis facility, show that lighting is the highest energy consuming load, and of the three cannabis cultivation stages, flowering has the highest energy consumption. The proposed model was validated using actual power consumption measurements from the real-world facility as well as GridLab-D simulation software.

APPENDIX

The following parameters for the vegetative grow room in the real-world facility were used to the validate the model output:

TABLE 4. **Parameters of a real-world cannabis facility's vegetative grow room.**

Vegetative Grow Room	
Dimensions (m)	15.7×8.4×3
Surface area of windows	0
Surface area of doors (m^2)	1.95
Plants	1000
Lighting	
Fixture type	Metal Halide
Quantity	50
Rated power (W)	1000
Operation Schedule	2 am–8 pm
HVAC	
HVAC type	Rooftop
Number of units	2
Rated power (W)	11900
Max Cooling capacity (W)	42788
Max Heating capacity (W)	57149
Coefficient of performance	80%
Ventilation requirement factor	0%
Number of fans	2
Fan rated power (W)	1596
Fan max airflow rate (m^3/h)	7132
Temperature Setting (°C)	23
Temperature bandwidth (°C)	22–25
Dehumidification	
Number of units	2
Rated power (W)	8350
Max cooling capacity (W)	19713
Max airflow rate (m^3/h)	7132
Relative humidity setting	70%

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REFERENCES

[1] Massachusetts Department of Energy Resources. *Cannabis Energy Overview and Recommendations*. Accessed: May 10, 2020. [Online]. Available: https://mass-cannabis-control.com/wp-content/uploads/2018/03/Presentation_Cannabis-Energy-Overview-to-CCC.pdf

[2] E. Mills, "The carbon footprint of indoor Cannabis production," *Energy Policy*, vol. 46, pp. 58–67, Jul. 2012.

[3] New Frontier Data. *The 2018 Cannabis Energy Report*. Accessed: May 10, 2020. [Online]. Available: https://newfrontierdata.com/product/2018-cannabis-energy-report/

[4] N. Cowley, "A budding opportunity: Energy efficient best practices for Cannabis grow operations," Southwest Energy Efficiency Project, Boulder, CO, USA, Tech. Rep., 2017. [Online]. Available: https://www.swenergy.org/data/sites/1/media/documents/publications/documents/A%20Budding%20Opportunity%20%20Energy%20efficiency%20best%20practices%20for%20cannabis%20grow%20operations.pdf

[5] S. Sanford, "Reducing greenhouse energy consumption—An overview," *Energy*, vol. 3907, no. 1, pp. 1–16, 2011. [Online]. Available: https://www.northcentralsare.org/content/download/61997/845719/ENC07-098_Reducing_Greenhouse_Energy_Consumption.pdf

[6] P. Zhuang, H. Liang, and M. Pomphrey, "Stochastic multi-timescale energy management of greenhouses with renewable energy sources," *IEEE Trans. Sustain. Energy*, vol. 10, no. 2, pp. 905–917, Apr. 2019.

[7] M. C. Bozchalui, C. A. Canizares, and K. Bhattacharya, "Optimal energy management of greenhouses in smart grids," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 827–835, Mar. 2015.

[8] Q. Zou, J. Ji, S. Zhang, M. Shi, and Y. Luo, "Model predictive control based on particle swarm optimization of greenhouse climate for saving energy consumption," in *Proc. World Automat. Congr.*, Sep. 2010, pp. 123–128.

[9] H. Shimizu and S. Moriizumi, "Simulation of greenhouse energy consumption," in *Proc. 41st SICE Annu. Conf. (SICE)*, vol. 2, Aug. 2002, pp. 1342–1345.

[10] *Energy use in the Colorado Cannabis Industry*, Cannabis Conservancy, Denver, CO, USA, 2018. [Online]. Available: https://resourceinnovation.org/wp-content/uploads/2019/12/18-CEO-MJ32-Energy-Cannabis-Report_FINALWEB.pdf

[11] *Greenhouse Energy Profile Study*, Posterity Group, Rockville, MD, USA, Sep. 2019. [Online]. Available: http://www.ieso.ca/-/media/Files/IESO/Document-Library/research/Greenhouse-Energy-Profile-Study.pdf

[12] M. J. Wells. *Expert Opinion: How Humidity Works*. Accessed: May 8, 2020. [Online]. Available: http://magazine.cannabisbusinesstimes.com/article/july-2017/moisture-matters.aspx

[13] G. van Straten, G. van Willigenburg, E. van Henten, and R. van Ooteghem, *Optimal Control of Greenhouse Cultivation*. Boca Raton, FL, USA: CRC Press, 2011.

[14] *2017 ASHRAE Handbook—Fundamentals (SI Edition). ASHRAE*, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Inc., Atlanta, GA, USA, 2017.

[15] Desert Aire. *Understanding HVAC & Plant Dynamics in Grow Rooms*. Accessed: May 8, 2020. [Online]. Available: https://pugetsoundashrae.org/wp-content/uploads/2018/01/Seattle-ASHRAE-Grow-Room-Presentation.pdf

[16] G. Yetisgen. *Design of Grow Rooms and Facilities*. Accessed: Apr. 2, 2020. [Online]. Available: http://ashraemontreal.org/ashrae/data/files/ashrae_montreal.pdf

[17] H. Cho, B. Liu, and K. Gowri, "Energy saving impact of ASHRAE 90.1 vestibule requirements: Modeling of air infiltration through door openings," Pacific Northwest Nat. Lab. (PNNL), Richland, WA, USA, Tech. Rep. PNNL-20026, 2010. [Online]. Available: https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-20026.pdf

[18] J. R. Benya. *Lighting Applications*. Accessed: Apr. 4, 2020. [Online]. Available: https://www.mouser.ca/applications/lighting_calculations/

[19] J. A. Nelson and B. Bugbee, "Analysis of environmental effects on leaf temperature under sunlight, high pressure sodium and light emitting diodes," *PLoS ONE*, vol. 10, no. 10, 2015, Art. no. e0138930.

[20] E. Atam and L. Helsen, "Control-oriented thermal modeling of multi-zone buildings: Methods and issues: Intelligent control of a building system," *IEEE Control Syst. Mag.*, vol. 36, no. 3, pp. 86–111, 2016.

[21] Natural Resources Canada. *Ratings and Certification*. Accessed: Apr. 2, 2020. [Online]. Available: https://www.nrcan.gc.ca/energy/products/categories/fenestration/buying/13978

[22] W. F. F. Ilahi, "Evapotranspiration models in greenhouse," M.S. thesis, Dept. Irrigation Water Eng. Group, Agricult. Biores. Eng., Wageningen Univ., Wageningen, The Netherlands, Aug. 2009.

[23] Ontario Energy Board. (2019). *Electricity Prices Remain Virtually Unchanged Starting May 1*. Accessed: May 2, 2020. [Online]. Available: https://www.oeb.ca/newsroom/2019/electricity-prices-remain-virtually-unchanged-starting-may-1

[24] D. P. Chassin, K. Schneider, and C. Gerkensmeyer, "GridLAB-D: An open-source power systems modeling and simulation environment," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Exposit.*, Apr. 2008, pp. 1–5.

[25] Technology Company. *BrainGrid*. Accessed: May 13, 2020. [Online]. Available: http://braingrid.io

[26] S. Chandra, H. Lata, I. A. Khan, and M. A. Elsohly, "Photosynthetic response of Cannabis sativa L. To variations in photosynthetic photon flux densities, temperature and CO_2 conditions," *Physiol. Mol. Biol. Plants*, vol. 14, no. 4, pp. 299–306, Oct. 2008.

[27] L. Breit, M. Leavitt, and A. Boyd, "Understanding VPD and transpiration rates for Cannabis cultivation operations," *Cannabis Sci. Technol.*, vol. 2, no. 2, pp. 52–61, 2019.

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