PURSUING SUSTAINABILITY

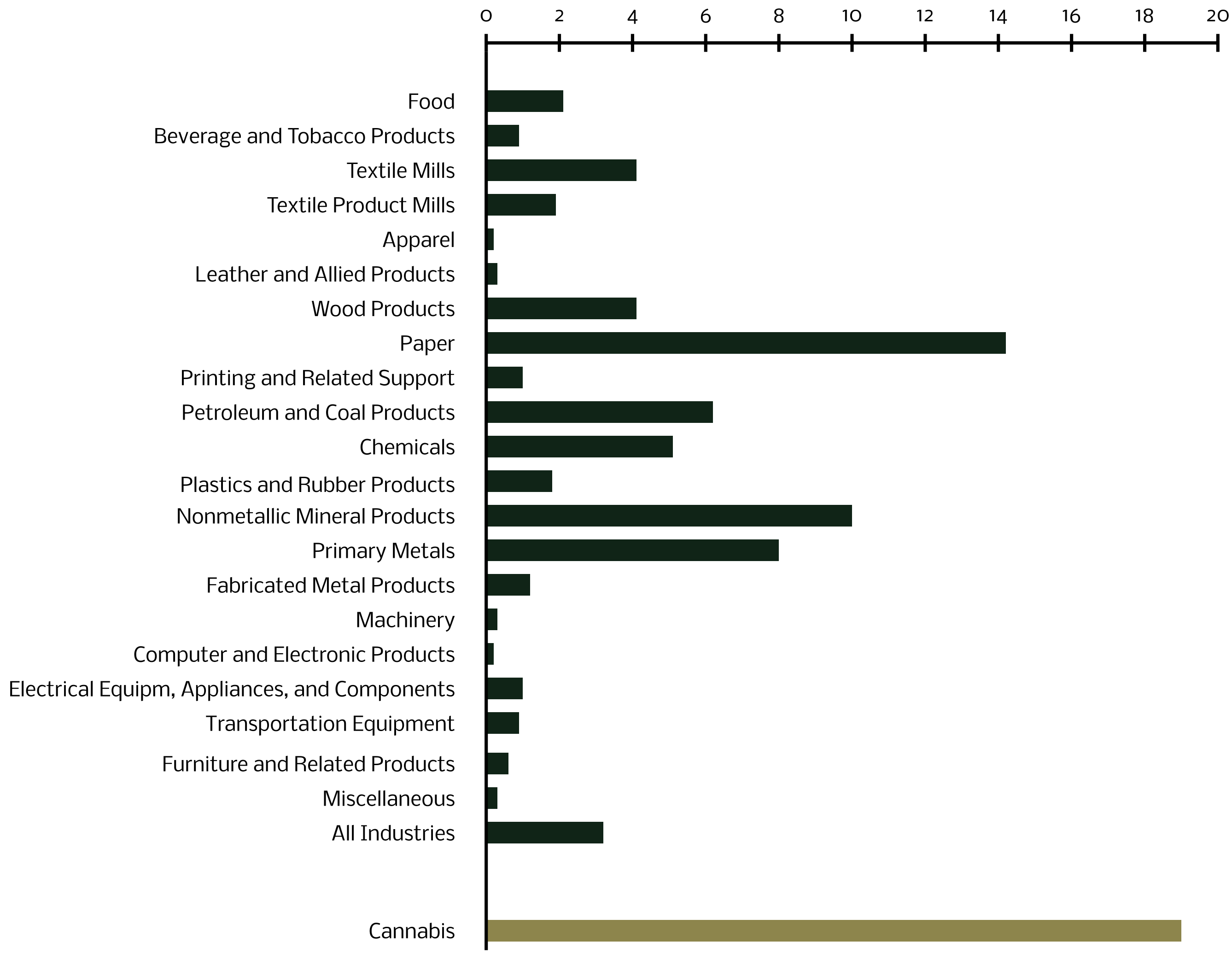
THE WEIGHT OF IMPACTFUL DESIGN CHOICES

Legal cannabis is one of the least environmentally friendly agricultural crops in the world [9]. While the majority of cannabis is cultivated in some permutation of controlled environment agriculture (CEA), indoor production generates the highest product quality and is the dominant method of production in North America [5]. Sole-source lighting and mechanical systems are required to maintain acceptable indoor-growth conditions and demand intensive amounts of energy, creating high carbon footprints [27]. Asparagus and similar highly-perishable, air-freighted crops are the only agricultural commodities which surpass indoor cannabis productions carbon footprint [11].

It is estimated that producing a single kilogram of indoor cannabis generates between 2,283kg-5184 kg equivalent of CO_2 emissions (CO_2eqv) [19, 25]. Location is the major determining factor affecting a cultivation facility's carbon foot print, resulting from the energy generation method of the power plant supplying the facility and the facility's proximity to the generation

COMPARATIVE ENERGY INTENSITIES BY SECTOR, MJ/$1000

Comparison of energies required to generate $1000 of product. 1 kilowatt hour is 3.6 megajoules.



site [25] To put this in perspective, Colorado produces over 530 metric tons of cannabis per year, meaning all indoor cultivation facilities in this single state generate somewhere between 605 million kg CO_2eqv to 1.373 billion kg CO_2eqv per year, the same as burning 68.07 million to 155.8 million gallons of gasoline.

Due to cannabis' Federal scheduling status, there is little to no regulatory oversight of energy usage or carbon emissions by indoor cannabis cultivation facilities [25]. Many inputs and processes used in cannabis cultivation generate substantial amounts of "greenhouse gases." Greenhouse gases are gaseous chemicals that trap heat in earth's atmosphere, leading to climate change. These gases include CO_2, methane, nitrous oxide and many fluorinated compounds. While little is understood about total greenhouse gas (GHG) emissions generated by indoor cannabis facilities in the United States, the total environmental impact of indoor cannabis production extends far beyond GHG emissions generated by energy usage [12, 27, 6, 14, 15]. Indoor hydroponic production requires high levels of water, fertilizer, pesticides, media, and supplemental CO_2 while generating large amounts of solid and liquid waste [12, 14, 19, 25]. Consumption of these inputs and their associated waste products come with their own environmental cost, however quantifying and compounding their environmental impact to finished flower is difficult [28].

SUCCESSFUL CULTIVATORS WILL WEATHER MARKET COMPRESSION BY DEVELOPING SUSTAINABLE PRODUCTION MODELS FOCUSED ON MINIMIZING ENERGY CONSUMPTION, INPUT CONSUMPTION, AND CARBON EMISSIONS.

As legalization spreads in the United States, the environmental impact of indoor cannabis production in the US will increase exponentially until Federal regulations around energy usage efficiency, water and fertilizer consumption, and waste generation are enacted. With little regulatory oversight of energy usage efficiency or resource management at the state level, MSO's and small cultivators often purchase inexpensive, inefficient equipment to keep start-up costs low and hit pro-forma benchmarks. As both large and small cultivation facilities begin their climb out of startup mode, operators often fail to make a paradigm shift from survival mode towards a forward-thinking focus on process efficiency and process improvement [16]. If the goal is to quickly sell their business, many operators see minimal incentive to direct capital expenditure towards retrofitting wasteful facilities or to develop sustainable management practices for their resources. If the goal is to create a profitable business, many cultivators focus too narrowly on growth and minimizing debt, opting to double down on their original cost-engineered model. As time goes on, market saturation makes it increasingly harder for operators to sell through their inventory or maintain necessary margins and many cultivators begin a violent collapse towards default, unable to cover their normal operational costs.

Creating a cultivation model, centered around efficient equipment and sustainable cultivation practices can help new and existing operators to avoid this scenario. Successful cultivators will weather market compression by developing sustainable production models focused on minimizing energy consumption, input consumption, and carbon emissions.

TOTAL ENERGY CONSUMPTION OF A CULTIVATION FACILITY BY USAGE CATEGORY

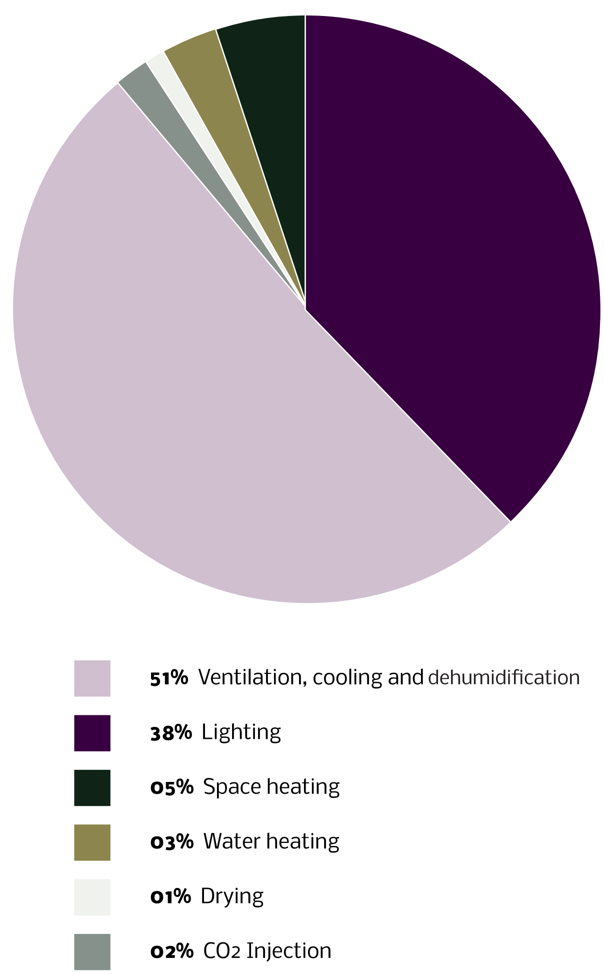
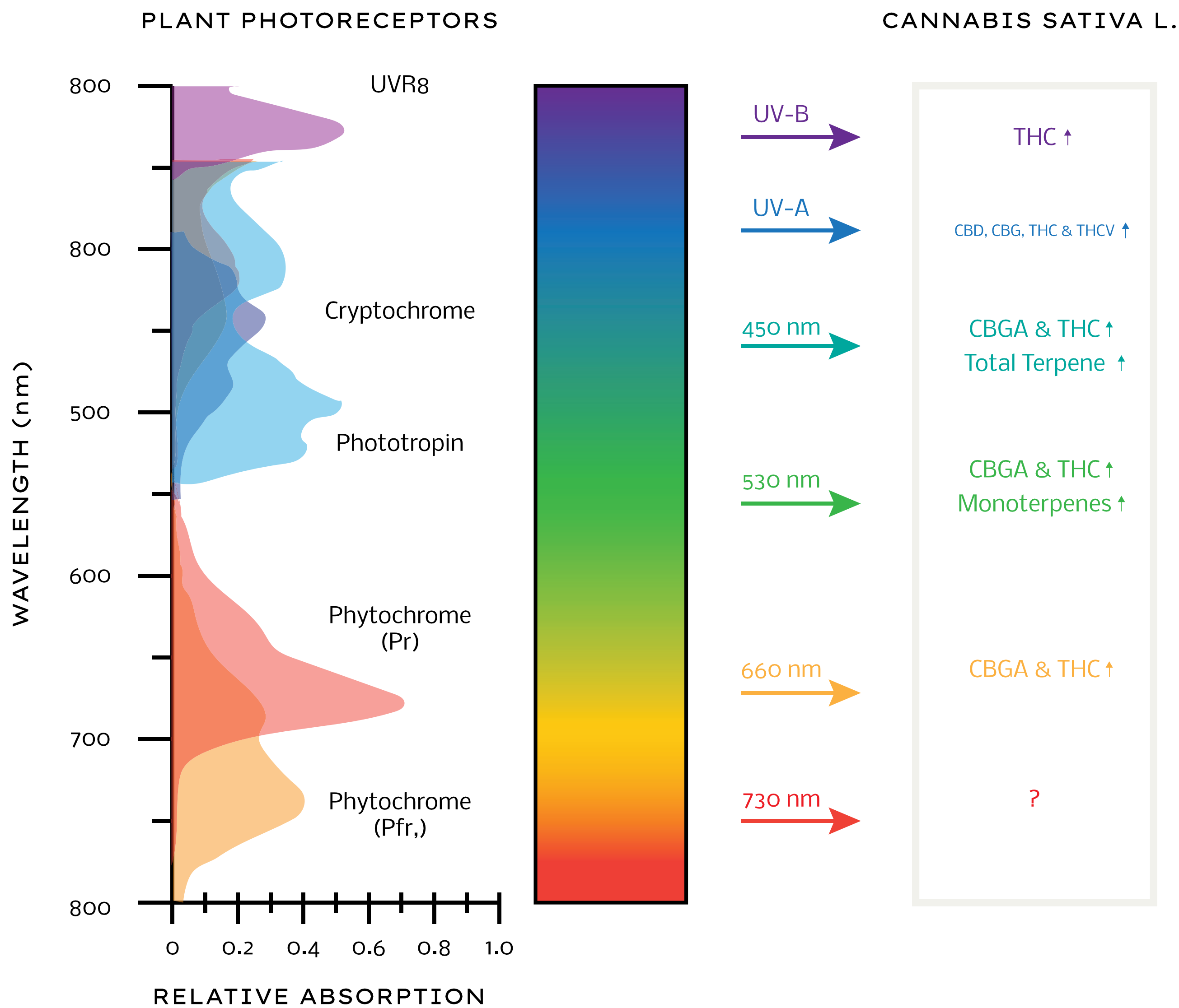


PHOTO-PROTECTANT MANIPULATION TO ENHANCE CANNABIS SATIVA L. PHYTOCHEMISTRY

Exposing cannabis to higher quantities of specific light wavelengths upregulates expression of various secondary phytochemicals.



LIGHTING

Equipment choice is the most impactful aspect of facility design when examining carbon emissions and energy efficiency, with lighting and HVACD having the highest upfront and operational cost. Lighting is usually the first energy-consuming equipment chosen and sets the tone in designing the facility around it. High intensity discharge (HID) lighting has been the standard for indoor production until recent years. Due to HID fixtures high volume of light generation, large coverage area, and low upfront cost, many cultivators still opt to go this route despite HID fixtures low lighting efficacy and intense heat generation.

Growers that base their lighting selection around fixture efficacy set themselves up for success during the rest of the design phase. This choice heavily influences margins,

with energy accounting for up to 50% of operating costs [17]. Upfront cost can be high with LED lighting, however some LED lighting manufacturers have programs to help growers secure multiple rebates at the federal, state, and local level for purchasing energy efficient lighting fixtures.
Almost all commercially available LED lighting options have a substantially higher lighting efficacy than HID lighting and offer growers more flexibility in their cultivation design [23]. LED lighting allows growers to cultivate in standard single tier systems or vertical systems in both vegetative and flowering rooms. Highly efficacious LED fixtures minimize HVAC requirements in single tier applications: when more energy is converted to light, less waste-energy is emitted as heat. Low radiant energy emissions from LED fixtures necessitates higher ambient temperatures in cultivation rooms to maintain proper leaf surface temperatures, further decreasing HVAC demand in single tier applications [10, 17] Advances in lighting optics have also made LED fixture coverage comparable to HID fixtures, with many manufacturers offering “1:1 replacements”. Simply put, 1:1 replacements are LED fixtures that generate equivalent light levels when installed in the same layout as the HPS fixtures they are replacing. Additionally, LED lightings’ low radiant energy generation allows fixtures to be placed closer to plants, creating higher light levels than are achievable with HID lighting [10].

> **“ GROWERS THAT BASE THEIR LIGHTING SELECTION AROUND FIXTURE EFFICACY SET THEMSELVES UP FOR SUCCESS DURING THE REST OF THE DESIGN PHASE.**

All of these LED benefits have also made vertical production economical and easily applied. In many instances, LED fixtures can be used in a phased approach, allowing operators to start cultivation operation in a single level and later transition the same area to a vertical system while utilizing the same fixture. Many cost savings benefits of LED lighting are seen specifically in phased approaches to vertical production or conversion from HID fixtures to LED fixtures. Phasing from single tier production to vertical production with LEDs allows growers to start generating revenue, which can help demonstrate proof of concept to investors or they can help facilitate self-funding of vertical racking systems. In many cases growers are relegated solely to the confines of their existing structures with no ability to expand their buildings’ footprint, leaving vertical space as their only means of expanding their production capacity.

> **“ HIGHLY EFFICACIOUS LED FIXTURES MINIMIZE HVAC REQUIREMENTS IN SINGLE TIER APPLICATIONS: WHEN MORE ENERGY IS CONVERTED TO LIGHT, LESS WASTE-ENERGY IS EMITTED AS HEAT.**

LEDs also surpass HID lighting in spectral quality [10, 23]. They are offered in full spectrum or narrow spectrum configurations. Full spectrum LED fixtures are engineered to provide light in a spectrum more comparable to the sun, while narrow spectrum fixtures are designed with specific combinations of white, blue, and red LEDs. Some manufacturers also include ultraviolet and far-red emitting diodes in their fixtures. Both types of LED fixtures offer superior spectral quality over HID lighting and have been shown to increase nutritional content and brix levels in plants when compared to plants grown under HID lighting [10, 20]. While full spectrum LEDs are efficient and efficacious lighting choices, narrow spectrum fixtures offer many advantages over both HID and full spectrum LED lighting. Narrow spectrum fixtures arrays can surpass full spectrum LEDs in lighting efficacy and have been shown to generate higher overall yields in plants when compared to full spectrum LED fixtures and HID lighting fixtures [27, 20]. Blue red and far-red LEDs have reached efficacies of 2.42 μmol/Joule, 3.14 μmol/Joule, and 3.5 μmol/Joule compared to double ended HPS fixtures efficacy of 1.7 [18]. This translates to energy savings of up to 50%. Additionally, narrow spectrum fixtures can be tailored to steer cannabis to produce photomorphogenic responses [10] In simple terms, photomorphogenesis is a sustained developmental response to light. Spectrum can be used to manipulate photosynthetic rates, plant height, internodal distance, leaf area, leaf thickness, florescence morphology, florescence dry mass, root mass, rooting rate of cuttings, terpene production, cannabinoid production, and flavonoid production in cannabis [10, 27, 20].

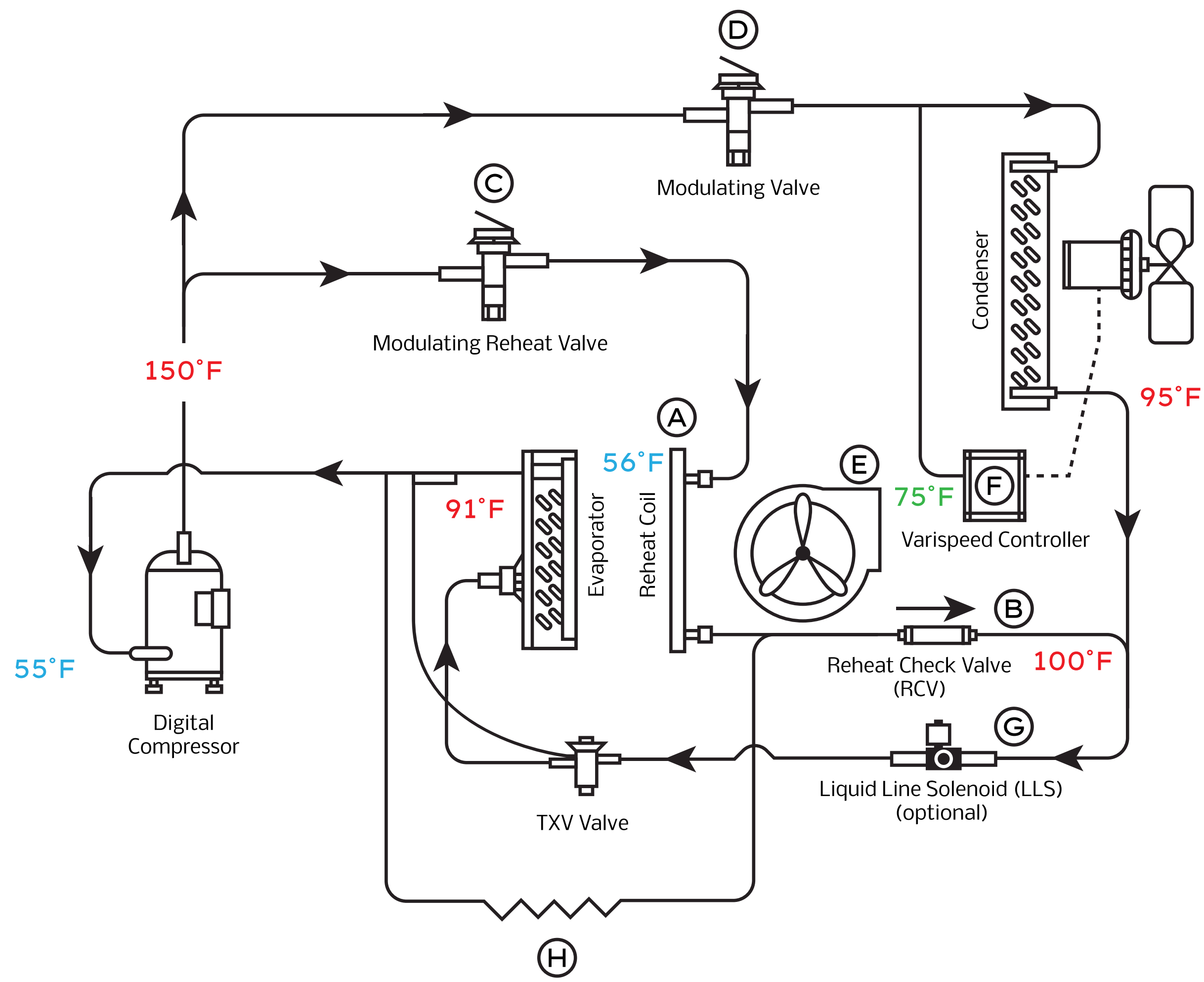
HVAC

HVAC systems are the second largest choice that affects the sustainability of indoor cultivation facilities [21, 17, 19]. HVAC systems must address three major problems created by indoor cultivation: High sensible load, high latent load, and odor. Sensible load is the dry heat load in the cultivation spaces and latent load is wet heat load of moisture in the same space [4]. The system must be able to efficiently handle the sensible demands of daytime and nighttime conditions while accounting for infiltration and exfiltration [21]. The system must also be able to efficiently handle the large latent demands of cultivation rooms, again accounting for infiltration and exfiltration [21]. The system must also be able to contain odors and volatile organic compounds generated by the cultivation process [7].

Operators often choose to utilize HVAC systems that are inappropriate for their application or are inefficient mechanically [8] These decisions are most often attributed to cost cutting efforts and/or inexperience with indoor cultivation. Small facilities, and even some larger facilities, will opt for light commercial mini split systems, variable refrigerant flow (VRF) systems, two stage RTU or AHU systems, and standalone dehumidification units [8]. Equipment choices like these become disastrous due to the performance demands of cultivation spaces and controls that are inadequate for cultivation applications. These systems most often yield weak performance and low levels of control which results in low yields, crop failure, and high energy consumption.

> **THESE SYSTEMS MOST OFTEN YIELD WEAK PERFORMANCE AND LOW LEVELS OF CONTROL WHICH RESULTS IN LOW YIELDS, CROP FAILURE, AND HIGH ENERGY CONSUMPTION.**

Hydronic systems are the most efficient choice for cultivation facilities [3, 22]. Most often these systems consist of two chiller plants, and air handlers. Hydronic systems use simple piping loops, variable frequency drives (VFDs) and sets of circulation pumps to move hot and cold water from boilers and chillers to air handlers. Some air handlers for hydronic systems can also be fitted with hot gas reheat for moisture removal. Inside air handlers, high-surface area transfer coils



System diagram of a typical RTU with digital scroll compressors and Modulating Hot Gas Reheat.

allow energy exchange between air and liquid. Hot and cold piping loops most often contain 100% water, but in some situations, water and propylene glycol mixtures are used. All of these components are sequenced in rotating lead-lag configurations to minimize wear and tear amongst components, create redundancy, and minimize total system downtime during repairs and preventative maintenance. Hydronic systems provide highly precise environmental control while offering flexibility in situations when cultivation plans must deviate from the original design parameters [5].

Hydronic systems can be designed with many energy saving features. Water side economizers take advantage of "free cooling" by using cold outside air instead of mechanical cooling during cooler months of the year however they are not suitable for all applications [21, 5] To utilize water side economizers, cultivation facility must be located somewhere with low relative humidity for evaporative chiller plants or temperatures that get below the temperature of chilled water returning to dry chiller plants. Boiler plants for hot water loops and hot gas reheat use natural gas burners for heating, a more efficient solution than using electric heating elements. Hydronic systems carry high price tags, making ROI justification difficult in some situations.
In projects with short timelines or limited

ancillary space, packaged RTU systems or split systems with indoor AHUs and rooftop mechanical units are often better solutions. Packaged systems and split systems are efficient alternatives to hydronic systems for smaller cultivation spaces [3, 5] They carry a lower price tag than hydronic systems and come with a variety of options to decrease energy usage. These systems use compressors, condensers and refrigerant for cooling. Compressor based systems cool effectively and shine in applications with high latent loads when equipped with properly sized modulating hot gas reheat coils [3]. In compressor systems, refrigerant is run through a direct expansion coil to cool return air, outside air, or a combination of the two. As the hot, humid air is cooled, water condenses on the DX coil and is “dried out.” Once cooled, the air must often be reheated to further remove moisture and reach the desired discharge temperature setpoint. MHGRH uses a portion of hot gas, supplied by the discharge refrigerant line and channeled into a reheat coil, to dehumidify and heat cool air without using energy from mechanical heating.

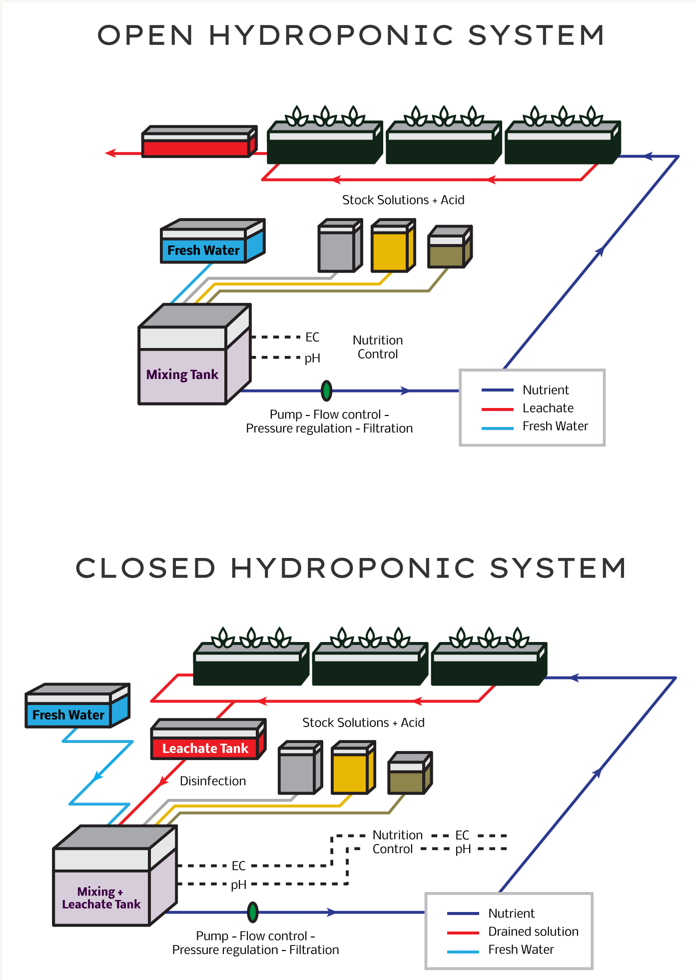
“

OPERATORS CAN CHOOSE PACKAGED AND SPLIT SYSTEMS WITH AIRSIDE ECONOMIZERS TO LOWER ENERGY CONSUMPTION.

Operators can choose packaged and split systems with airside economizers to lower energy consumption. Airside economizers use outside air to provide lower cost cooling. Airside economizers modulate dampers, allowing a desired percentage of outside air to enter the air handler. Airside economizers provide the most energy savings in areas with cool, dry winter months. In units equipped with airside economizers, operators can also choose to install enthalpy wheels (EWs.) Enthalpy wheels are unique economization systems that allow transfer of both latent and sensible energy, a feature no other economization system offers. EWs consist of a rotating disk coated with porous materials such as silica gel or molecular sieve. The EW is positioned so that half of the wheel is in the supply stream and the other half in the return or exhaust stream. This allows energy to be transferred through a heat and moisture gradient as the wheel rotates. During cooler months when economizers bring in cool, dry outside air, waste heat energy is used to assist in heating and humidifying outside air decreasing the need for mechanical heating. Gas burners are the most efficient way to provide primary heating in these systems [3]. Gas heat can also be used as a backup reheat source when MHGRH is not enough to heat or dry supply air. As gas is burned to provide heat, a certain portion of energy from the combustion process is released as water vapor and exhaust heat out of the gas burner’s flue. Gas burner flues can be equipped with a secondary heat exchanger to further recycle energy that would otherwise be discharged to the atmosphere as waste heat.

CONTROLS

Control systems are an often-overlooked tool that can be utilized to increase efficiency of HVACD systems. Large scale indoor cultivation is still a relatively novel manufacturing process, lacking application specific control and monitoring systems. Most often, HVACD systems for indoor cultivation facilities are driven by manufacturer supplied controls and logic intended to manage office building or warehouse environments. These control systems do not provide a complete building



management system (BMS) that addresses all aspects of indoor cultivation needs [22]. Greenhouse controls will often be brought in to address shortcomings of traditional BMS systems in CEA applications. In these situations, multiple systems must then be concerted to successfully control the same HVACD system, convoluting control sequences and creating more opportunities for control failure. Greenhouses most often use simple mechanical systems controlled by analog signal to manipulate simple equipment and cultivation conditions. Analog communication uses excessive amounts of hardware and communication channels, leaving communication signals open to noise and a high level of communication error. Mechanical systems used in indoor cultivation demand robust controls capable of harmonizing multiple complex systems, many of which require digital communication protocol. Digital systems allow high volumes of encoded digital signals to be transmitted through a low volume of hardware and communication channels, creating a highly secured network while minimizing energy usage in the control process. Digital control systems' ability to quickly transmit and receive large volumes of data allow complex algorithms to be used in system management. This minimizes deviation from control setpoints and subsequently decreases the need of mechanical systems to consume high amounts energy in aggressive course-corrections.

Digital control systems are also able to efficiently manage complex fertigation systems used for indoor cultivation [21, 14]. "Crop steering" is a technique in hydroponic production utilizing manipulation of hydroponic solution concentration, rhizospheric conditions, precision irrigation, and precision environmental control to maximize crop yields [13]. As a summative science, hydroponic cultivation has reformed CEA methodologies to match those of lean manufacturers. Precision hydroponics empowers the transformation of non-arable land into bountiful farms with a biocapacity that is unachievable in field production [12]. Additionally, hydroponic cultivation methods can do all this using up to 95% less water and 50% less fertilizer when utilizing crop-steering practices [12]. Effective crop steering requires intelligent control of fertilizer injection systems to dilute concentrated nutrient stock solutions into irrigation water to produce a final fertilizer solution with a specific concentration based on the stage of plant growth during a production cycle [14]. This increased productivity, however, can come with severe repercussions if used inappropriately.

Highly concentrated hydroponic effluent has a high biochemical oxygen demand (BOD) [12, 15]. Hydroponic wastewater requires heavy treatment to effectively mitigate the harmful effects it can exert on nearby ecosystems [5, 14, 15, 28]. Excessive nitrogen, phosphorous, heavy metals, and phytosanitary chemicals found in high EC hydroponic solution can cause eutrophication of surface and subsurface water [15, 28].

IRRIGATION

Many hydroponic cannabis cultivators opt for open irrigation systems due to the high initial cost of water treatment equipment required by recirculating systems [12]. Drain to waste drip irrigation systems are inexpensive to install compared to closed systems, but the volume of fertilizer and water required to satiate the nutritional demands of high-volume cannabis production quickly negate cost-savings. Furthermore, regular discharge of high BOD effluent from drain to waste operators tax the remediation capabilities of municipal water treatment facilities and often-times hydroponic wastewater is not adequately treated before it is discharged to the environment [14, 15, 28]. Imprecise control during fertigation events leads to wasteful application of fertilizer solution and excessive liquid waste generation; digital controls help to minimize these scenarios [15].

When recirculating irrigation systems are installed with digital controls, fertilizer pollution and liquid waste generation can be minimized. In recirculating systems, leachate from irrigation events is collected, sterilized, and then re-adjusted with a small portion of fresh water and fertilizer to a specific EC for reuse [14, 15]. Recollecting leachate minimizes high BOD discharge events and operators can coordinate effluent disposal with proper waste management facilities or notify their receiving wastewater treatment facilities of discharge events to prevent undertreatment of wastewater [14].

Outdoor organic cultivation is similar in environmental impact to greenhouse hydroponic cultivation when conducting life cycle analysis [15, 28]. Indoor cultivation is exponentially more detrimental to the environment than outdoor or greenhouse cultivation irrespective of organic or conventional strategies but cultivating organically can help to minimize the overall environmental impact of indoor cultivation. Organic cultivation systems are difficult to execute indoors but produce a substantially lower amount of liquid waste when compared to indoor hydroponic systems [1].

MOIST SOIL, 30 MIN. AT	ORGANISMS KILLED
120° F (49°C)	Watermolds (oomycetes)
145° F (63°C)	Most plant pathogenic fungi, bacteria, and viruses, worms, and slugs
160° F (71°C)	Plant pathogenic bacteria, soil insects
180° F (82°C)	Weed seeds
212° F (100°C)	Heat resistant plant viruses and weed seeds

Target temperatures needed to kill specific organisms for moist soil or potting medium heated to the target for a minimum of 30 minutes

Cultivating organically indoors establishes plants in finite volumes of soil, limiting the size of plants' rootzones and nutritional supply [1,2]. As such, growers most often generate little to no leachate and which poses a much smaller burden on wastewater treatment facilities than hydroponic cultivators. Additionally, organic cultivation relies on fertilizers which are often plant-based and have sequestered carbon before they were processed for use [28]. While using plant-based fertilizer indoors does not negate GHG emissions used to produce the fertilizer, it does help to minimize the overall volume produced by its use [28]. GHG emission volumes from production and use of organic fertilizer are lower than GHG emissions from production and use of conventional fertilizer [6, 9]. Some organic fertilizers are generated as waste products of agriculture and animal husbandry and show promising use in cultivation systems [1]. Inputs such as blood meals, bone meals, composted animal manures, compost, and fish hydrolysates are all saved from waste streams and repurposed in a conscientious fashion [1, 9, 28].

Indoor organic cultivators often reutilize their cultivation media, which helps prevent sending large amounts of solid waste to landfills. Organic cultivators that recycle media also help prevent nutrient pollution and fertilizer waste while minimizing their production input cost. Many hydroponic cultivators can also benefit from reutilizing cultivation media [12]. Growers who utilize peat-based media can recycle their media for up to two years before noticing a decrease in media performance. Coco coir can be reused in a similar manner and needs much less calcium to buffer it for reuse in subsequent cycles. Growers who cultivate in rockwool can reuse their media indefinitely. Enzymatic products can be used to degrade root tissue in blocks and slabs and plastic coverings can be re-applied. It is recommended to steam sterilize soil and soilless media for reuse to prevent the spread of bacterial and fungal diseases. Steam generators can be purchased from many agricultural equipment distributors to facilitate media reuse. Facilities using hydronic HVAC systems can often add small additional boilers to their boiler room during facility design and buildout for minimal cost.

CONCLUSION

As discussed, there is much room for improvement within industry standards for indoor cultivation design and practices. Additionally, there are many ways for new and existing operators to start the journey to becoming sustainable businesses that will be able to meet the inevitable demands of regulatory agencies like the EPA and USDA. Oftentimes sustainable equipment and input choices can provide substantial ROI and concomitantly establish ethical core values visible to employees and consumers alike. Efficient lighting, HVACD equipment, and digital controls can decrease operating costs and help to increase yields. Drip irrigation can help hydroponic producers to minimize water usage, but closed irrigation systems can substantially decrease liquid waste and minimize negative effects on ecosystems and water sources. Growers can also recycle their media, preventing thousands of cubic yards of landfill waste every year. As science continues to improve and develop technologies used in cultivation, operators must actively seek out ways to utilize them to keep their costs and impact on the environment low. There is no way to thrive and stay relevant in the rapidly maturing cannabis market if operators are unwilling to do their part to improve consumer's perception of practices deemed to be outdated or inappropriate for commercial cultivation facilities. It takes a conscious effort from the top down and bottom up to fully embrace sustainability in cultivation: growers at all levels have an innate responsibility to give back to the earth that has given them the plant they cultivate.

ABOUT THE AUTHOR

Alex Stanish has over a decade of experience in horticulture, he has led cultivation departments across various states, specializing in cultivation facility design and launching cultivation operations for large scale medical facilities. Alex holds a B.S. in Horticulture from Penn State's College of Agricultural Sciences and has spearheaded multiple independent research projects examining plant genomics for crop improvement and secondary plant metabolites and their effects on human health.

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