Renewable Energy for Heat & Power Generation and Energy Storage in Greenhouses

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Greenhouses Considered as Examples in the Study

(1) Altman Specialty Plants, a 1.4 million ft^2 (32 acre) specialty plant nursery for ornamental succulents with on-site natural gas-fired hot water plants for radiant heating that account for the vast majority of natural gas usage at the facility

(2) Gunnison Gardens, a cold-climate single-gable roof greenhouse designed for energy efficiency and minimal heating and cooling inputs to support year-round production of seasonal crops.

(3) Welby Gardens, a wholesale greenhouse operation consisting of several round roof gutter-connected greenhouses and hoop houses totaling 350,000 ft^2 for year-round propagation of annuals, perennials, ornamental grasses, organic vegetables, and herbs

(4) Zapata Seeds, a 7,020 ft^2 covered growing operation where 81% of energy use goes toward maintaining a 60°F indoor temperature for seed potato production

Summary of Findings

Supporting widespread growth of the agricultural greenhouse industry requires innovative solutions to meet the unique energy challenges and demands of each farm with sustainable and cost-effective strategies and technologies. This study examines renewable energy for heat and power generation and storage at four greenhouses located in Colorado. Results outline key considerations for energy demand characteristics and the renewable energy technologies and strategies available to meet energy needs more sustainably, reliably, and economically and are broadly applicable to greenhouses across the world.

Snapshot

- This study considered four greenhouse farms in Colorado as examples to understand energy needs and opportunities in controlled environmental agriculture (CEA).
- Energy audits from 2016 to 2020 for each of the facilities were made available to understand the unique energy consumption profiles of each operation.
- Although some commonalities can be found across the studied farms, no "one-size-fits-all" solution should be applied across all cases. An appropriate combination of technical and nontechnical solutions to sustainably meet energy demands with clean and renewable sources should consider how characteristics like the crop system, climate control technologies, cultivation practices, and greenhouse structural design influence energy demand and opportunities to optimize solutions for each unique context.

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Introduction

Agricultural greenhouses could improve food system resilience in the face of climate change, farmland degradation, population growth, water scarcity, and other challenges. This type of controlled environment agriculture (CEA) can significantly improve water and land use efficiency for food production by sheltering crops from adverse weather conditions and pests; carefully and precisely controlling water and nutrient cycles; and optimizing internal environmental conditions to maximize crop productivity (Esmaeli and Roshandel 2020). In remote and extreme environments, including arid, arctic, and urban locations, some form of CEA may be required to overcome inhospitable conditions and enable more reliable, high-quality yields (McCartney and Lefsrud 2018).

However, due to the degree of control needed for greenhouses, they can be extremely energy-intensive compared to traditional open-air agricultural systems (Gorjian et al. 2021). Most of this energy demand is currently served by fossil fuels. The growing environmental and economic costs associated with energy use raise concerns about the sustainability of greenhouse cultivation in the future (Gorjian et al. 2021). Energy access and reliability can also be a substantial challenge for many greenhouses in rural areas, where grid power may be unavailable or unreliable (Hassanien et al. 2016). Many greenhouse crops are particularly sensitive to sudden changes in the environment; therefore, ensuring stable, reliable, and resilient energy to protect against outages and potential crop failure is a key priority (Esmaeli and Roshandel 2020).

While floriculture maintains a dominant portion of the greenhouse industry, greenhouse cultivation for food production is growing across the United States. In a five-year span, from 2012 to 2017, the total number of greenhouses nationwide growing food increased by nearly 34%. In the same time frame, the overall number of agricultural greenhouses increased by nearly 8%. By 2017, the land area for greenhouse

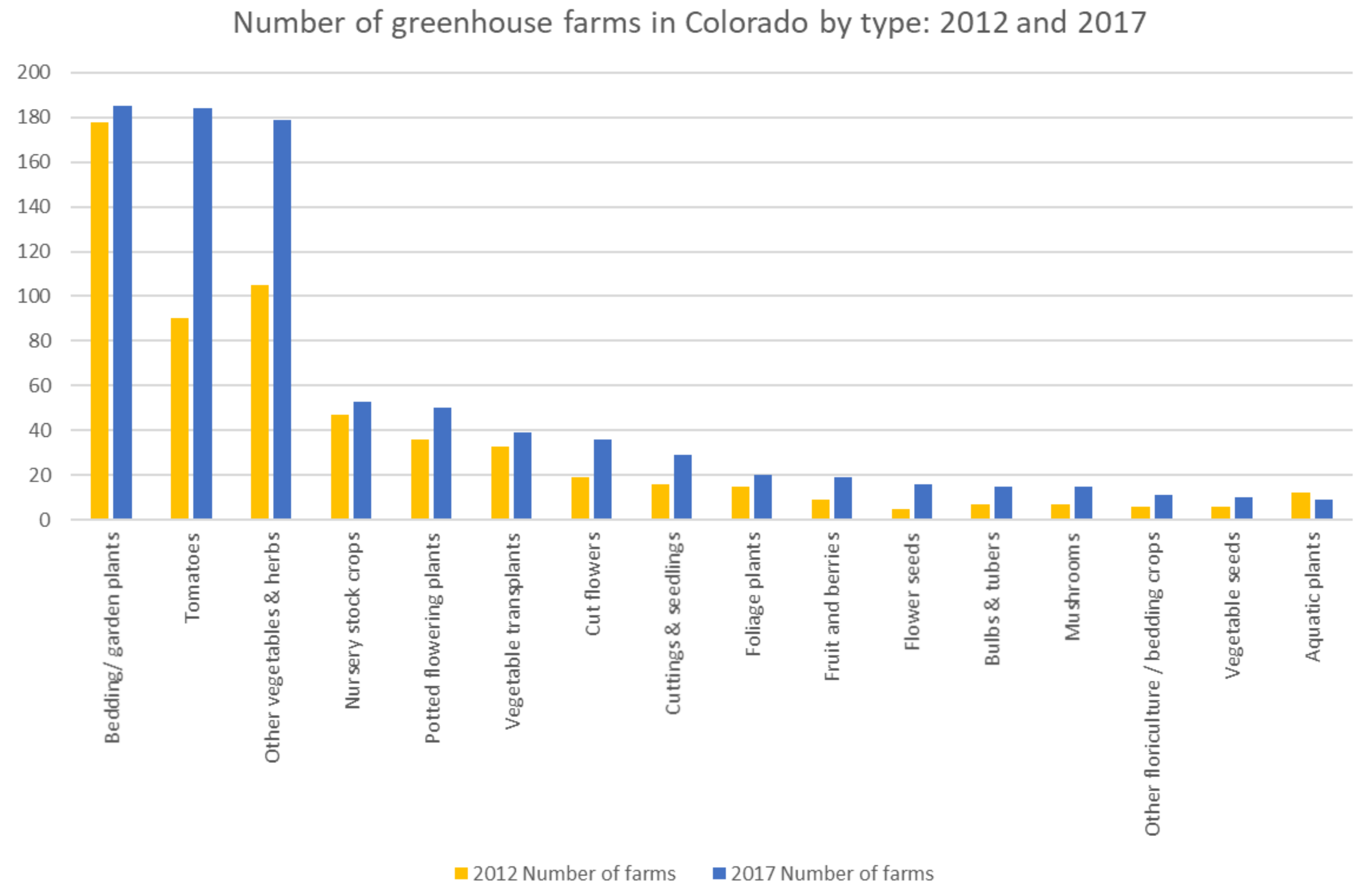

Figure 1. Number of greenhouse farms in Colorado by type in 2012 (yellow bar) and 2017 (blue bar). State-wide data from *Table 39. Floriculture and Bedding Crops, Nursery Crops, Propagative Materials Sold, Sod, Food Crops Grown Under Glass or Other Protection, and Mushroom Crops: 2017 and 2012* of the 2017 Census of Agriculture (USDA 2019).

food production reached 3,600 acres, and the land area overall for all greenhouse crops reached 32,000 acres. Nursery crops, including nursery stock and aquatic plants, accounted for the single largest increase in greenhouse land area, adding nearly 1,150 acres from 2012 to 2017 (USDA 2019).

The greenhouse industry in Colorado is also growing with a 47% increase in the total number of agricultural greenhouse farms from 2012 to 2017 (USDA 2019). The largest growth in land area occurred in sectors producing cuttings and seedlings, which grew by 17.5 acres in 5 years. During the same time, the number of greenhouse tomato farms more than doubled from 90 to 184, and the number of other vegetable and fresh herb greenhouse farms grew by 70% from 105 to 179 (USDA 2019).

Passive or active technologies and strategies can be used to regulate light, temperature, humidity, and carbon dioxide (CO_2) levels in greenhouses.

Passive strategies operate without any external energy supply, often using aspects of building design to capture and utilize “free” solar energy.

Active strategies rely upon external technologies and devices to increase capture and utilization beyond what can be achieved through passive strategies.

To keep pace with this growth and realize the potential benefits of CEA, solutions are needed to meet the unique energy challenges and demands of each farm with sustainable and cost-effective strategies and technologies. Several interdependent factors impact greenhouse energy requirements including shape and size, building materials, technology utilization, crop selection, and cultivation methods (Esmaeli and Roshandel 2020). Sustainable greenhouse design can be used to optimize greenhouse productivity and energy consumption efficiency with the appropriate combination of strategies, technologies, and systems to meet the unique energy and environmental demands of the location.

Energy Demands in Agricultural Greenhouses

Energy demands in agricultural greenhouses center around maintaining optimal internal microclimatic conditions for plant growth, crop productivity, and off-season cultivation (Ezzaeri et al. 2018). Microclimate controls can include various passive and active technologies and strategies to maintain a stable indoor environment. The electrical energy consumption characteristics of a greenhouse will vary according to several factors, including the geographic location, climate, crops, cultivation practices, structural design, and technologies employed in the greenhouse (Hassanien et al. 2016; Shen et al. 2018; Yano and Cossu 2019). With most of this energy demand currently served by fossil fuels, the high costs, supply vulnerabilities, and environmental harms associated with greenhouse energy could be reduced by more sustainable and resilient energy solutions for these key areas of demand (Gorjian et al. 2021).

Temperature

Temperature regulation typically accounts for most of the primary energy demand for agricultural greenhouses. Conventional materials used in greenhouse facades are designed to maximize solar light transmittance to crops at the expense of thermal performance, creating the need for auxiliary heating and cooling systems to maintain suitable internal climate conditions (Gorjian et al. 2021). Thermal regulation can be achieved through active, passive, or hybrid systems.

The plants, soil, and equipment involved in crop production also influence the heating and cooling needs of greenhouses. The absorption of incoming sunlight and artificial light by plant leaves; latent and convective heat exchanges between crop surfaces and the ambient air; and heat exchanges between plant, soil, and building surfaces all influence the overall energy balance of the greenhouse. Characteristics such as the leaf area index, crop spacing, indoor and outdoor temperature, humidity, and light availability can significantly impact these heat exchange rates. Peak heating and cooling energy demands for agricultural greenhouses will therefore be influenced by the growing systems and operation parameters of the greenhouse, which may vary daily or even hourly, depending on environmental conditions and management decisions (Talbot and Monfet 2020).

Lighting

Lighting is an important aspect of greenhouse energy management. Plant growth and fruit production depend on the rate at which plants photosynthesize, which depends on the amount of photosynthetically active radiation (PAR, 400–700nm wavelength range) reaching plant leaves (Yano and Cossu 2019). However, excessively high light intensity can also disrupt photosynthesis (Hassanien et al. 2016). Crops are typically classified as high, medium, or low light-demanding, depending on the average daily light requirements for optimal growth and production. Fruit-producing horticultural crops such as cucumber, sweet pepper, and tomato tend to be in the high light-demanding category, while ornamental and floricultural crops such as poinsettia and kalanchoe tend to be in the low light-demanding category. Even small deviations above or below these optimal lighting levels can affect crop yields (Cossu et al. 2020). Growers also need to regulate the day length, or photoperiod, to control plant physiological and morphological developments, such as the onset of flowering and fruit production (Hassanien et al. 2016).

Both natural and artificial lighting systems are used in agricultural greenhouses to maintain optimal light levels for crop growth and production. Greenhouses often use supplemental lighting during low-light conditions to extend the growing season, regulate plant development, and maintain optimal photosynthesis rates. In some settings and conditions, energy demands and operational costs for supplemental lighting can rival heating and cooling costs (Yano and Cossu 2019). When solar radiation levels exceed optimal light intensities for crops, shade curtains or other means of reducing sunlight intensity may be required to prevent overheating and sun damage (Hassanien et al. 2016).

Humidity

Within the controlled environment of a greenhouse, relative humidity typically increases as temperature decreases, and vice versa. When relative humidity drops too low, many crops respond by closing stomata to prevent excessive moisture loss, restricting gas exchange between plant leaves and the environment, and negatively impacting photosynthesis and other key physiological processes. Excessively high humidity, however, can lead to fungal diseases, inhibit flower pollination, and promote development of certain types of crop pests (Ezzaeri et al., 2018). Particularly in cold climates, a failure to regulate temperature and humidity can result in condensation on leaves, fruits, and the internal surfaces of the building, contributing to crop damage and disease and potentially damaging the structural integrity of the greenhouse. Maintaining ideal humidity levels is therefore a critical function of greenhouse heating, ventilation, and air conditioning (HVAC) equipment (Talbot and Monfet 2020).

Crop-air interactions, along with certain greenhouse design and management decisions, including crop selection, moisture-holding capacity of interior surfaces, light and temperature regulation, and irrigation practices can significantly impact relative humidity and need to be considered when selecting and sizing both passive and active humidity regulation and HVAC systems (Talbot and Monfet 2020).

CO_2

Along with light availability, ambient temperature, and relative humidity, ambient CO_2 concentrations within the greenhouse directly influence plant photosynthetic rate. Ideal CO_2 levels, as with other internal microclimatic parameters, are partially a function of the crop and horticultural system in use. Lettuces, for instance, do best with CO_2 concentrations between 700–1,000 ppm, which can be maintained with forced air circulation and CO_2 enrichment systems that, together, facilitate optimal gas exchange at the leaves (Talbot and Monfet 2020). Maintaining these optimal gas exchange rates to manage plant metabolism and development involves a dynamic balance of internal environmental parameters, including temperature, relative humidity, airflow and ventilation rates, light intensity, and photoperiod (Ezzaeri et al. 2018; Talbot and Monfet 2020).

Mechanical Equipment

Mechanical equipment constitutes a fourth major component of agricultural greenhouse energy consumption. Depending on the crop and cultivation system, these may include irrigation pumps and sprayers, mechanical harvesters, transplanting and potting machines, product packaging and labeling equipment, autoclaves, refrigerators or coolers, and other farm equipment and facilities. While these energy demands are typically small compared to microclimatic control systems, utilizing renewable energy to supply all or part of the energy demands for these smaller applications can be an environmentally and economically attractive option, particularly in areas where grid electricity is unreliable or unavailable (Hassanien et al. 2016).

Solar Technologies to Meet Energy Demands in Solar Greenhouses

Solar energy technologies and strategies could sustainably and reliably meet the energy demands of agricultural greenhouses, reduce operating costs, improve farm competitiveness, and alleviate competing land development pressures for energy and food production (Hassanien et al. 2016; Cossu et al. 2020). Both passive and active solar technologies can be used by agricultural greenhouses.

Passive Solar

Passive solar greenhouses use siting and design strategies to maximize efficient capture, storage, and utilization of incoming solar energy. The amount of solar energy absorbed depends on factors such as latitude and season; greenhouse size, dimensions, and orientation; local climate and other characteristics of the installation site; and the materials used in exterior walls and facades. Passive solar greenhouses can also include thermal collection units to capture and store excess incoming solar radiation in heat storage mediums and minimize diurnal temperature fluctuations. While many passive strategies are primarily available for new construction, some strategies can be incorporated into existing structures.

Active Solar

In active solar greenhouses, solar technology systems, such as photovoltaic (PV) panels or solar thermal collectors, are used to produce electricity and/or improve thermal performance beyond what can be achieved through passive design strategies alone—both solar PV or solar thermal technologies are available (Gorjian et al. 2021).

Solar PV

Solar PV systems convert sunlight directly to electricity, which can then be used to power mechanical and electrical systems within the greenhouse or other on-site facilities, sold back to the electric grid, or stored in battery cells for later use. Greenhouse solar PV systems include both on-grid and off-grid configurations.

On-grid systems are connected to the local power grid and can either access grid-supplied power when greenhouse energy demands exceed PV electricity generation or sell excess power back to the grid. Off-grid systems are more common in settings where a utility connection is not available, such as remote or isolated locations, and typically incorporate other backup power sources, such as fossil-fueled generators or battery banks, to ensure stable and reliable energy supplies (Gorjian et al. 2021).

Wall- and roof-mounted PV modules allow for co-production of energy and crops without incurring some of the negative land development pressures and ecological consequences associated with large ground-based solar farms in rural and agricultural areas (Castellano 2014). However, there are energy production and crop yield trade-offs to consider. For each 1% increase in the PV cover ratio (the ratio of projected area of PV panels on the ground to the total greenhouse floor area), the cumulative global radiation within the greenhouse decreases by 0.8%, limiting the amount of sunlight available to support plant development and potentially impacting crop yields (Cossu et al. 2020). Conversely, greenhouses in hot climates can benefit from shading and cooling provided by roof-mounted solar PV modules, which can improve indoor greenhouse microclimatic conditions, reduce cooling demand loads, and positively impact crop yields (Gorjian et al. 2021).

To balance trade-offs between energy productivity and crop productivity, PV cell type, module design, and module installation patterns on the rooftop should be considered. Dominant PV cell types used in greenhouses include opaque and semi-transparent PV cells. Opaque cell types are a more conventional technology for rooftop solar, but they result in more shading effects and typically require other system configuration and/or operational strategies to mitigate any adverse impacts to crop productivity. Replacing some or all of the PV modules with semi-transparent PV cells can help optimize the shading impacts of PV modules to balance crop photosynthetic requirements, electricity generation, and management of interior microclimatic conditions, in some cases improving both crop and energy productivity by capturing both incident and ground-reflected radiation (Cossu et al. 2016).

Other system design parameters include the use of sun-tracking systems to produce dynamic shading and improve electric generation efficiency (Gorjian et al. 2021), the installation pattern of PV panels on the roof, and the total PV cover ratio (Cossu et al. 2020). The optimal combination of these various parameters depends upon characteristics of the local climate, crop production method, and greenhouse design.

Photovoltaic solar panels installed on a greenhouse. *Photo from iStock 1207270991*

Solar Photovoltaic Technologies

Technology / Approach	**Grid-connected (on-grid) solar PV system**
Description	Excess energy generated by PV modules is fed into the power grid
Example Applications	This is the most common system configuration in agricultural greenhouses. Notable exceptions include remote and/or geographically-isolated locations where grid power may be inaccessible or unreliable. In some parts of the world, such as Italy and China, greenhouse-generated electricity makes up a substantial portion of renewable energy on the local grid
Benefits	Potential revenue generation opportunity for greenhouses with excess solar insolation Grid backup power reduces the need for additional backup generators or batteries
Drawbacks	Requires utility connection and policies (e.g. net metering) to allow sale of excess power to the grid

Technology / Approach	**Semi-transparent / bifacial panels**
Description	PV modules with PV cells on the front (sky-facing) and back (ground-facing) sides to capture incoming sunlight and ground-reflected irradiance
Example Applications	Technology to mitigate shading impacts of rooftop PV Balancing light demands for energy and crop production
Benefits	Well-established technology Allows partial transmittance of sunlight to crops
Drawbacks	Higher capital and O&M costs Total power production varies depending on the amount of light transmitted by the panels and the amount of light reflected from the ground

Technology / Approach	**Organic PV (OPV) cells**
Description	PV cells using molecular or polymeric absorbers rather than silicon
Example Applications	Incorporated in semi-transparent solar blind systems, bifacial modules, and hybrid PVT systems as an alternative to conventional Si-PV
Benefits	Smaller life-cycle environmental impacts and shorter energy and carbon payback times compared to Si-PV Thin and lightweight Low production costs Can be designed to create colored or transparent PV modules that use non-PAR wavelengths for electricity generation and transmit PAR wavelengths to crops
Drawbacks	New technology is difficult to obtain Further efficiency improvements are needed to make OPV cost-competitive with traditional Si-PV

Technology / Approach	**Dynamic PV shading controls**
Description	Movable PV modules such as venetian blind-type systems or sun-trackers
Example Applications	Incorporated in semi-transparent solar blind systems, bifacial modules, and hybrid PVT systems as an alternative to conventional Si-PV
Benefits	Sun-trackers prioritize electricity production, blind-type systems can be automatically or manually adjusted to meet crop or energy production needs
Drawbacks	Higher capital and operations and maintenance costs relative to stationary modules; an area of ongoing research and design optimization

Technology / Approach	**Near-infrared (NIR)-reflective coatings**
Description	NIR-reflective greenhouse roof coating allows PAR wavelengths to reach crops and reflects NIR portion of sunlight to a PV system positioned to capture the reflected light
Example Applications	Prototype greenhouse with circular trough reflector integrated in the greenhouse roof constructed in 2007 in the Netherlands
Benefits	Allows simultaneous utilization of sunlight for energy and food production NIR reflection prevents overheating of greenhouse interior
Drawbacks	Requires solar tracking and complex custom greenhouse design Curved roof structures accumulate snow

Technology / Approach	**Checkerboard PV configurations**
Description	Opaque or semi-transparent PV modules alternated with conventional clear roof panels in a checkerboard pattern to create more uniform shading of the greenhouse interior
Example Applications	Creation of more uniform shading pattern; High light-demanding crops (tomato, cucumber, sweet pepper) or medium light-demanding crops (asparagus, basil, lettuce, strawberry, spinach, chrysanthemum, rose, ficus) requiring PV cover ratio < 60%
Benefits	Simple design approach compatible with conventional technologies; more uniform shading patterns can improve greenhouse microclimate and crop yields compared to unshaded greenhouses
Drawbacks	Tradeoff between energy and crop production

Solar Thermal

Solar thermal technologies convert incoming sunlight to heat, which can be used for space and water heating, or transferred to a storage medium for later use. These systems can achieve high energy conversion efficiency and energy storage density at relatively low cost, making them a promising alternative to fossil fuel-fired heating systems (Gorjian et al. 2021). Systems typically consist of a solar collector to absorb incoming solar radiation and convert it to heat, and a thermal energy storage unit to deposit excess heat for colder periods. When used alongside PV panels in hybrid PV-thermal systems, solar thermal technologies can improve the electric conversion efficiency of PV systems by efficiently transferring waste heat away from the PV panels toward productive low- to medium-temperature applications, cooling the panels and preventing overheating in the process (Gorjian et al. 2021). Hybrid systems combining thermal collectors with heat pumps can more sustainably and reliably meet greenhouse heating demands (Hassanien et al. 2018; Awani et al. 2015).

Thermal Collectors

Thermal collectors can be categorized according to the collector type and heat transfer medium. Non-concentrating collectors include flat-plate and evacuated tube collectors or concentrating (e.g., parabolic and Fresnel lens concentrators). Solar concentrators using reflectors or refractors to focus sunlight from a wider collection area onto a single point or line, such as a fluid-filled pipe, achieving higher thermal and optical efficiencies and making them particularly attractive options for cold climates or situations where competing demands for light and/or space are constraints (Gorjian et al. 2021; Wu et al. 2019). Non-concentrating flat-plate collectors and evacuated tube collectors can supply a substantial portion of greenhouse heating demands with short payback periods in certain settings, especially in moderate climatic conditions or when using large collector areas (Gorjian et al. 2021; Hassanien et al. 2018).

Solar Thermal Technologies

Technology / Approach	**Hybrid photovoltaic-thermal (PVT) systems**
Description	Combined PV modules for electricity production with thermal collectors to capture excess heat for low- to medium-temperature applications
Example Applications	Greenhouse solar dryers PV modules at risk of overheating Space- and/or light-constrained systems
Benefits	More efficient in both heat and electricity production than either system alone Cooling medium extracts excess heat from PV modules, improving overall electric efficiency and capturing usable heat
Drawbacks	Reflectors, lenses, and solar tracking mechanisms increase system complexity and cost More research is needed on controlling the temperature provided by concentrators

Technology / Approach	**Latent thermal energy storage (LTES)**
Description	Storage of excess heat in phase-change materials (PCMs) that transition between solid and liquid states as energy is absorbed and released
Example Applications	Heating and cooling applications High temperature (e.g., concentrated solar power) and low temperature applications Seasonal and short-term storage Frequently integrated with other thermal technologies to enhance overall energy utilization efficiency Can be integrated in the greenhouse structure or exist in stand-alone storage tanks
Benefits	Large amounts of energy can be stored and released without changing the temperature of the storage medium PCMs can be selected based on the desired thermochemical characteristics
Drawbacks	Most systems are more expensive and complex compared to sensible thermal energy storage systems

Technology / Approach	**Sensible thermal energy storage (STES)**
Description	Storage of excess heat generated during the day in common materials with high thermal capacity, typically rocks, water, and/or soil. The heated materials then dissipate the heat at night or during cloudy / cooler periods
Example Applications	Heating and cooling applications High temperature (e.g., concentrated solar power) and low temperature applications Seasonal and short-term storage Frequently integrated with other thermal technologies to enhance overall energy utilization efficiency Can be integrated in the greenhouse structure or exist in stand-alone storage tanks
Benefits	Inexpensive design and simple operation Long lifetime and short repayment period Widely available materials with high thermochemical and mechanical stability Positive secondary impacts on greenhouse microclimate, pest suppression, and crop yield
Drawbacks	Lower energy density than phase-change materials System efficiency may be dependent on weather conditions

Technology / Approach	**Concentrating solar collector**
Description	Modules use curved reflectors or refractors to focus solar energy on a single point (point-focus) or line (line-focus) where the heat transfer medium absorbs and transmits the collected solar thermal energy
Example Applications	Parabolic trough collectors Fresnel lens collectors Parabolic dish collectors Compound parabolic collectors
Benefits	Result in the most thermally and electrically efficient hybrid PVT systems when integrated with PV technology Less crop shading impact for rooftop systems compared to flat-plate collectors
Drawbacks	Reflectors, lenses, and solar tracking mechanisms increase system complexity and cost More research is needed on controlling the temperature provided by concentrators

Technology / Approach	**Non-concentrating solar collector**
Description	Systems collect heat in air or liquid transfer mediums without the use of concentrating reflectors or refractors
Example Applications	Flat-plate collectors Evacuated tube collectors
Benefits	Simple, inexpensive design Easier control of operating conditions compared to concentrating solar collectors Flat-plate collectors can more easily be mounted on greenhouse facades or tilted roofs, offering beneficial shade protection
Drawbacks	Supplying the full thermal demand of the greenhouse may require increased collector area, auxiliary heat supplies, and/or integration of thermal energy storage

Colorado Greenhouse Technology Considerations

The four greenhouse farms considered as examples for this study are Altman Specialty Plants, Gunnison Gardens, Welby Gardens, and Zapata Seed Company. They span a wide range of cultivation techniques, existing on-site energy resources, structural designs, and climate control strategies, collectively demonstrating a diverse set of energy needs and challenges. Each of these greenhouses received an energy audit from an outside agency and the results of the audit were used as the basis to suggest solar energy technologies that could be implemented at each of the greenhouses to meet energy challenges or address the greatest energy consuming areas of the greenhouse identified through the audit. Further study and assessment should be conducted before implementing any of these technology suggestions. The appropriate combination of technical and nontechnical solutions will vary according to the unique characteristics of each operation, including current state of operations and factors such as light, water, and temperature requirements of crops, the use of different passive and active climate control technologies, and the site's access to sunlight, grid power, and other energy resources. Careful consideration of the different benefits and challenges of various solar energy options, as well as the potential synergistic benefits of different combinations of active and passive solar power and solar thermal solutions, could deliver multiple energy and non-energy benefits to help reduce operating costs, improve farm competitiveness, and improve the sustainability and resilience of agricultural yields from controlled environment agriculture (in the face of a changing climate and evolving industry.

Non-concentrating solar hot water collector system. *Photo by Dennis Schroeder, NREL 48515*

Greenhouse Name and Characteristics	Primary Challenges/ Greatest Energy Consuming Areas Identified through Energy Audits	Solar Energy Technology Suggestions from Case Study
Altman Specialty Plants *Location:* Peyton, CO *Size:* 1.4 million ft² (32 acre) *Main Crop:* Ornamental Succulents *Current Heat & Power Source:* Electricity and Natural Gas *Audit conducted by:* Nexant *Audit date:* Nov. 19, 2020	**Space heating** • Four 9,300kW boilers (18,600kW per greenhouse) **Water pumps** • Five 10 horsepower well water pumps (27.7 million gallons per year) • Four 20 horsepower irrigation pumps **Other mechanical systems** • Small (<1 horsepower) motors for roof vents, conveyor system, curtains	**a.** Repair/ replace existing equipment, opting for energy-efficient upgrades where possible to reduce overall electric and heating loads. Repair curtain controls to regulate light on-demand, consider centralizing controls for irrigation, roof vents, curtains, and heating system to facilitate more dynamic energy and water use regulation. **b.** Replace boilers with liquid-type photovoltaic thermal system to produce both hot water and electrical energy to power the radiant heat system. Concentrating Photovoltaic Thermal collectors (e.g., parabolic trough collectors or Fresnel lenses) offer higher thermal and electric efficiencies (Gorjian et al. 2021), but partially covered flat plate water collectors can also be suitable for hot water production (Sultan and Ervina Efzan 2018). **c.** Incorporate thermal energy storage to improve overall heating system efficiency and reduce diurnal / seasonal indoor temperature fluctuations (see Vadiee and Martin 2013 for an assessment of different TES options to cover seasonal and daily heating and cooling demands). **d.** Advanced option: replace thermal curtain with solar PV or Photovoltaic Thermal blind system using bifacial or semi-transparent PV panels as blind slats. Blinds can be operated manually or with automated controls regulated by indoor air temperature, humidity, and lighting conditions (see Li et al. 2020, Vadiee and Yaghoubi 2016 for example configurations).

Greenhouse Name and Characteristics	Primary Challenges/ Greatest Energy Consuming Areas Identified through Energy Audits	Solar Energy Technology Suggestions from Case Study
Gunnison Gardens *Location:* Gunnison, CO *Size:* single gable roof greenhouse *Main Crop:* Seasonal Crops *Current Heat & Power Source:* Electricity *Audit conducted by:* GDS Associates, Inc. *Audit date:* Dec. 29, 2016	**Space heating** • Two 1.5kW electric radiant space heaters in seed starting room **Fans** • 1.36kW climate battery fans • 1 horsepower exhaust fan for summer ventilation (planned) **Lighting** • Twenty-one 68 W grow lights • 156 W and 90 W fluorescent lights (seed starting room) • Five 51 W LED flood lights (storage area) • 66 W LED string work lights (storage area)	These recommendations are based on an energy audit performed in 2016, some upgrades may have already occurred since then. **a.** Replace electric radiant space heaters with a solar Photovoltaic Thermal system to provide space heating for the seed starting room and electricity for fans, lighting, and other equipment. A free-standing system with concentrating collectors (e.g., parabolic trough collectors) could be an efficient use of impervious area adjacent to the two primary site structures (see Sultan and Ervina Efzan 2018 for a review of various Photovoltaic Thermal options). **b.** Upgrade fluorescent grow lights to high efficiency LED grow lights to reduce overall electricity demand. **c.** Incorporate thermal energy storage for the seed starting room to reduce nighttime and wintertime heating demand. Due to the significant energy demand spikes in winter, seasonal storage in underground thermal energy storage may be appropriate (Vadiee and Martin 2013). **d.** If wintertime electricity demand continues to exceed supply from Photovoltaic Thermal system, consider a residential battery storage system to capture and store any excess electricity produced during warmer and sunnier periods.

Greenhouse Name and Characteristics	Primary Challenges/ Greatest Energy Consuming Areas Identified through Energy Audits	Solar Energy Technology Suggestions from Case Study
Welby Gardens - Westwoods *Location:* Arvada, CO *Size:* 350,000 ft² *Main Crop(s):* Propagation of Annuals, Perennials, Ornamental Grasses, Organic Vegetables, and Herbs *Current Heat & Power Source:* Electricity and Natural Gas *Audit Conducted by:* GDS Associates, Inc. *Audit date:* May 31, 2017	**Greenhouse heating** • Central steam boiler (natural gas) • Several hydronic Modine unit heaters **Fans** • 142 exhaust fans (1.1 kW each) • 17 horizontal air flow fans (0.1 kW each)	These recommendations are based on an energy audit performed in 2017, some upgrades may have already occurred since then. **a.** Replace (or supplement) boiler with efficient rooftop solar Photovoltaic Thermal system to provide wintertime space heating for the gutter-connected greenhouses and hoop houses as well as electricity to power fans, cooling pad pumps, walk-in coolers, and other equipment. Concentrating Photovoltaic Thermal collectors (e.g., parabolic trough collectors or Fresnel lens collectors) could be used to maximize solar thermal energy capture while still allowing sufficient light penetration into the greenhouse (Gorjian et al. 2021). A feasibility study including an assessment of available and sufficient solar resource should be conducted before installing any concentrating solar power systems. **b.** Conduct a feasibility study to see how much of the annual heating demand could be met by solar thermal, especially if investing in concentrators and/or thermal energy storage to improve the overall efficiency and overcome some of the mismatch between peak demand times and peak solar thermal energy production times. **c.** Incorporate seasonal soil heat storage units with greenhouse solar photovoltaic thermal systems to reduce seasonal thermal energy demand fluctuations, serve wintertime heating demand, and improve overall Photovoltaic Thermal system efficiency (see Awani et al. 2017 and Zhang et al. 2015 for potential system designs with and without a ground-source heat pump, respectively). **d.** Advanced option: install thermal curtains on greenhouses with solar PV or Photovoltaic Thermal blind system using bifacial or semi-transparent PV panels with flat-plate collectors as blind blades. Blinds can be operated manually or with automated controls regulated by indoor air temperature, humidity, and lighting conditions to reduce nighttime heat losses, provide shading while generating electricity during sunny periods, and prevent overheating in the summer (see Li et al. 2020, Vadiee and Yaghoubi 2016 for sample configurations. Note that this included modeling for a photovoltaic thermal system with flat plat collectors on a much smaller greenhouse with single polycarbonate glazing; other critical site data such as roof pitch and load capacity might preclude rooftop PV systems).

Solar photovoltaic panel built on the roof of aerial vegetable greenhouse. *Photo from iStock 1131751289*

Greenhouse Name and Characteristics	Primary Challenges/ Greatest Energy Consuming Areas Identified through Energy Audits	Solar Energy Technology Suggestions from Case Study
Zapata Seed Company *Location:* Hooper, CO *Size:* 7,000 ft² *Main Crop:* Seed Potatoes *Current Heat & Power Source:* Electricity and Liquid Propane *Audit conducted by:* GDS Associates, Inc. *Audit date:* Dec. 6, 2017	**Greenhouse heating** • Modine overhead liquid propane gas unit heaters in each greenhouse **Lighting** • 45 high-pressure sodium greenhouse grow lights (465 W each) • 68 fluorescent overhead light fixtures (90-180 W each) • Three CFL fixtures in walk-in cooler (18 W each) **Fans** • Eight 0.2 kW greenhouse HAF fans • Four 1.6 kW greenhouse exhaust fans • 0.7 kW head house exhaust fan **Misc. heating, cooling, motors, etc.** • 1.5 kW ductless split unit (front office) • Furnace style forced air system (grow room / head house backup heating) • Overhead liquid propane unit heater (west head house backup heating) • Two 0.1 horsepower greenhouse vent motors • Three 1 horsepower cooling pad / well pumps • 12.1 horsepower autoclave • 5 horsepower condensing unit, evaporator coil and standard motors (walk-in cooler	These recommendations are based on an energy audit performed in 2017; some upgrades may have already occurred since then. **a.** Replace greenhouse overhead liquid propane gas unit heaters with rooftop or ground mounted photovoltaic thermal system to provide space heating for greenhouses and attached headhouse, west headhouse, and second office as well as electricity to power lights, fans, evaporative cooling pad pumps, and walk-in cooler. Concentrating photovoltaic thermal modules (e.g., parabolic trough collectors or Fresnel lens collectors) generally offer the greatest optical and thermal efficiencies (Gorjian et al. 2021) **b.** Incorporate seasonal soil heat storage (SSHS) unit for long-term storage of excess thermal energy generated during warm months to use for wintertime greenhouse heating (see Awani et al. 2017 and Zhang et al. 2015 for potential system designs with and without a ground-source heat pump, respectively). Short-term (diurnal) rock-bed or water thermal energy storage units can also help reduce daily temperature fluctuations and improve overall thermal efficiency (Gorjian et al. 2021) **c.** Upgrade grow lights and fluorescent lights to high efficiency LED lights to reduce overall electricity demand. **d.** Advanced option: install thermal curtains on greenhouses with solar PV or photovoltaic thermal blind system using bifacial or semi-transparent PV panels with flat-plate collectors as blind blades. Blinds can be operated manually or with automated controls regulated by indoor air temperature, humidity, and lighting conditions to reduce nighttime heat losses, provide shading while generating electricity during sunny periods, and prevent overheating in the summer (see Li et al. 2020, Vadiee and Yaghoubi 2016 for sample configurations. Note that this included modeling for a Photovoltaic Thermal system with flat plat collectors on a much smaller greenhouse with single polycarbonate glazing; other critical site data such as roof pitch and load capacity might preclude rooftop PV systems).

Conclusion

Solar energy technologies represent a promising solution to sustainably and reliably meet energy demands of agricultural greenhouses. The technologies described in this study represent some of the most promising options for sustainable, reliable, and economical heat and power generation in an expanding and diversifying agricultural greenhouse industry. Some of these technologies were suggested as possible solutions to address energy challenges and requirements at four greenhouses in Colorado but could be applied in greenhouse farms across the world. The appropriate combination of technical and nontechnical solutions will depend upon characteristics like the crop system, climate control technologies, cultivation practices, and greenhouse structural design. While there are no one-size-fits-all solutions to the energy challenges of indoor agriculture, these technologies and strategies create promising opportunities to reduce operating costs, improve farm competitiveness, and alleviate competing land development pressures for energy and food production.

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Solar PV panels on a greenhouse. *Photo from iStock 1129147050*

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