# Controlled-Environment Agriculture and the Geography of Food, Energy and Water Resilience in the United States

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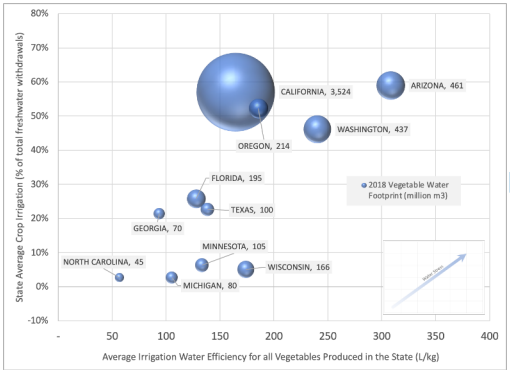
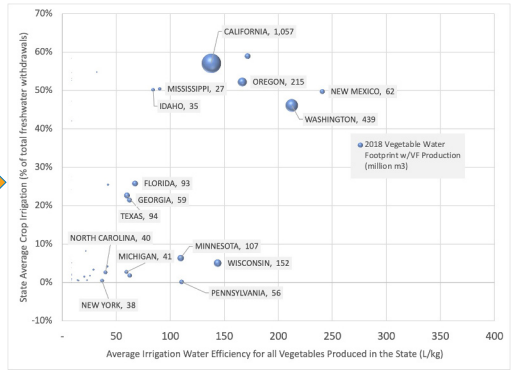



| Crop | 2018 total production (M kg) | Wt fraction of Total Production | Total VF production (M kg) | VF water use L/kg |
|---|---|---|---|---|
| Cabbage | 880 | 3% | 501 | 5.11 |
| Cucumbers | 701 | 2% | 402 | 11 |
| Lettuce, head | 1,840 | 5% | 1,060 | 1.5 |
| Lettuce, leaf | 487 | 1% | 280 | 1.5 |
| Lettuce, romaine | 1,330 | 4% | 756 | 1.5 |
| Peppers, bell | 585 | 2% | 335 | 11 |
| Peppers, chile | 121 | 0% | 69 | 11 |
| Spinach | 368 | 1% | 211 | 1.5 |
| Tomatoes | 12,600 | 36% | 7,180 | 10.8 |
| Total | 18,900 | 55% | 10,790 | 8.6 |

***Supporting data for this study. VF cultivation would reduce the total vegetables needed by reducing supply chain losses.*** *Sources: "USDA ERS - Food Availability (Per Capita) Data System" 2020, USDA 2021, NREL analysis*

*(Right) 2018 vegetable water footprint. 90% of vegetable crops are grown in 11 states, mostly in the arid West. California alone accounts for 60%.*

*(Left) Reduced water footprint with distributed production of crops amenable to cultivation in controlled-environment agriculture (CEA) vertical farms (VF). The remaining crops are grown in their original locations.*

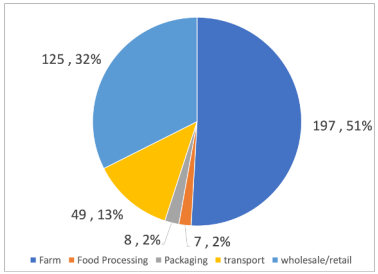
*Sources: "USDA/NASS QuickStats Ad-Hoc Query Tool" accessed 11/19/2021, "USDA ERS - Food Availability (Per Capita) Data System" 2020, USDA 2021, Dieter and Linsey 2017, NREL analysis*

## Controlled-environment production of some vegetable crops could reduce water use by 53%; from 5.8 billion m$^3$ (4,200 Mgal/day) to 2.8 billion m$^3$ (2,000 Mgal/day).

- The water savings in California alone would be equivalent to the water use for ~13.7 million people (35% of the population of California). Distributed production reduces water stress and increases water resilience by:
  - Shortening the supply chain for the VF-grown vegetables resulting in a 23% reduction in overall vegetable food loss.
  - Moving production to less water-stressed regions.
  - Increasing water efficiency of the vegetable supply from an average of 18,000 L/person to 8,000 L/person.

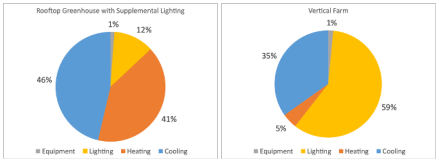
## Distributed cultivation in vertical farms would increase electricity consumption in cities while decreasing supply chain energy use by ~50%.

- Literature values for energy use for VFs varies widely depending on the crops grown, lighting technology, location, and degree of building integration. For this scenario, energy use could vary between 200 and 1,000 kWh/person in comparison to about 700 kWh/person for the existing supply chain.




***Per capita supply chain energy use for fresh vegetables in the United States in 2002 (kWh/person, %). Extrapolating the growth rate of 4% per year, the total in 2018 would be about 725 kWh/person.*** *Source: Canning et al. 2010.*

*Van Ginkel (Van Ginkel et al. 2017) found that irrigation accounted for about half of on-farm energy use for tomato cultivation in California. Drip irrigation for the same crop would reduce water use by 34%.*



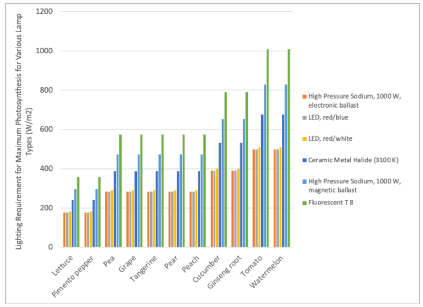

***Energy use breakdown for modeled controlled-environment rooftop greenhouse (left) and vertical farm (right) growing tomatoes in New York.*** *Sources; Benis, Reinhart, and Ferrão 2017, NREL analysis.*

*Lighting consumes the majority of energy in vertical farms. Ongoing research focuses on reducing energy use by;*

- *Tuning LED lights to maximize their output of photosynthetic wavelengths of light*
- *Pulsing lights to synchronize with plants' light conversion kinetics*

*Vertical farm light requirements are well-suited to integration with renewable energy sources because the required photoperiod can be adjusted to match renewable output and lighting can be turned on and off to compensate for other energy consumption variability.*

*Full integration of farm heating, cooling, and $CO_2$ systems into existing buildings could save 18% to 36% of HVAC energy use (Sanyé-Mengual et al. 2018).*




***Light requirements for various vegetable crops and lighting technologies. Lighting requirements vary by the type of plant and length of growing period.*** *Sources; Chart data calculated from O'Sullivan et al. 2019, Nelson and Bugbee 2014, NREL analysis*

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