EFFICIENT ENERGY:

A Framework for Efficient, Practical, and Scalable Energy Technologies with Agrivoltaics Exemplifying Enhanced Energy Sector Decarbonization

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Senior Thesis: Efficient Decarbonization of the Energy Sector

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CHAPTER 1

STRATEGIES FOR EFFICIENT DECARBONIZATION OF THE ENERGY SECTOR

INTRODUCTION:

The climate crisis is here and pressing, and decarbonization is the talk of the moment. Overall, it is understood that to mitigate the effects of climate change, the degree of global warming needs to decrease immediately and dramatically. In 2015, the Paris Agreement was signed by 196 parties to set a long-term temperature goal of keeping the rise in global surface temperatures below 1.5°C (3.6°F) above pre-industrial levels.[1] One part of actualizing this goal is reducing greenhouse gas emissions.

Greenhouse gases, including water vapor, carbon dioxide (CO2), and methane (CH4), collect in Earth's atmosphere. The gases allow short-wave (high-frequency) radiation from the sun to enter the atmosphere but block long-wave (low-frequency) infrared radiation from leaving the atmosphere.[2] This contributes to the Greenhouse Effect, where radiation collects in the atmosphere, contributing to the rise of global surface temperatures. In 2022, CO_2 was responsible for around 80% of the U.S. total gross greenhouse gas emissions (6,343 million tonnes).[3]

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[1] *Paris Agreement*, 12 December 2015, United Nations Framework Convention on Climate Change (UNFCCC), https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.
[2] "What are greenhouse gases and how do they affect the climate?" *U.S. Energy Information Administration*, 2 May 2024, https://www.eia.gov/tools/faqs/faq.php?id=81&t=11#:~:text=Greenhouse%20gases%20are%20transparent%20to,and%20warms%20the%20planet's%20surface.
[3] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022," *United States Environmental Protection Agency*, 2024, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

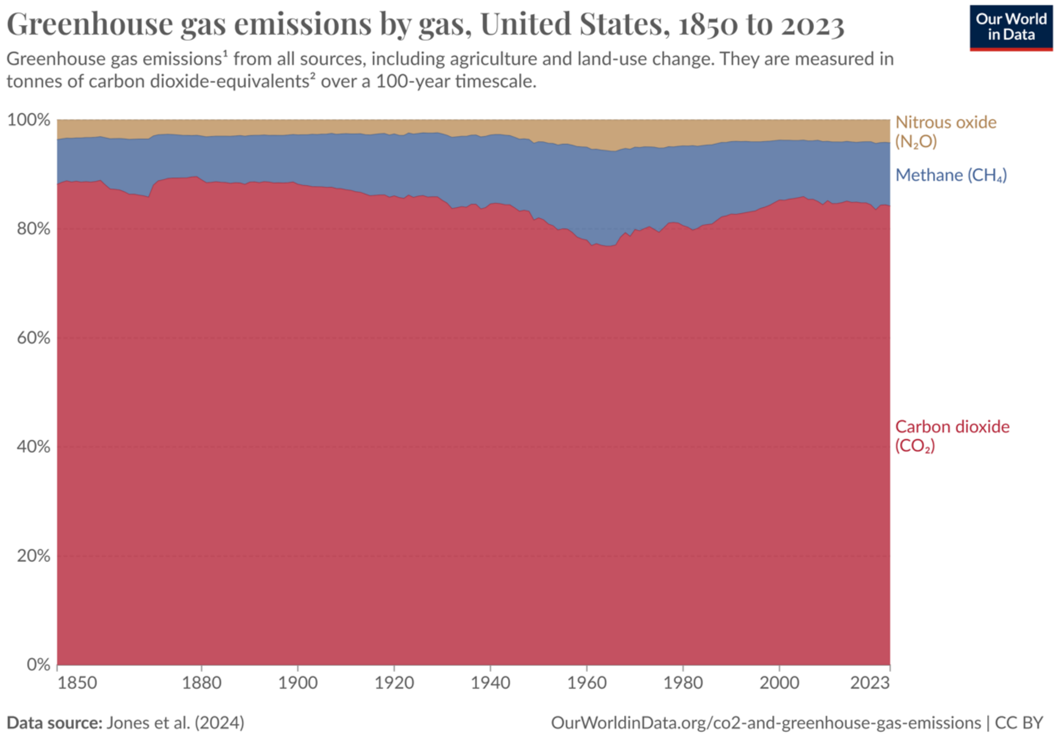

Figure 1: Greenhouse gas emissions by gas, United States, 1850 to 2023 (Our World in Data)

Due to its prevalence and immense impact on global warming in the U.S., reducing CO_2 emissions is a primary focus for climate activists, the Department of Energy (DOE), and the technology sector.

However, before decarbonizing anything, the first step is to find the source of the CO_2 emissions, typically by sector.

In 2021, CO_2 emissions in the U.S. by sector (tonnes per year) showed Electricity/Heat (around 39%) and Transportation (around 35%) as the two sectors with the highest emissions[4]. The energy sector, comprised of Electricity/Heat, Transportation, Buildings, Other Fuel

[4] "CO2 Emissions Global," *Climate Watch*, 2025, https://www.climatewatchdata.org/data-explorer/historical-emissions

Consumption, Manufacturing/Construction, and Fugitive Emissions, has been responsible for over 75% of total annual CO_2 emissions in the US since 2016[5].

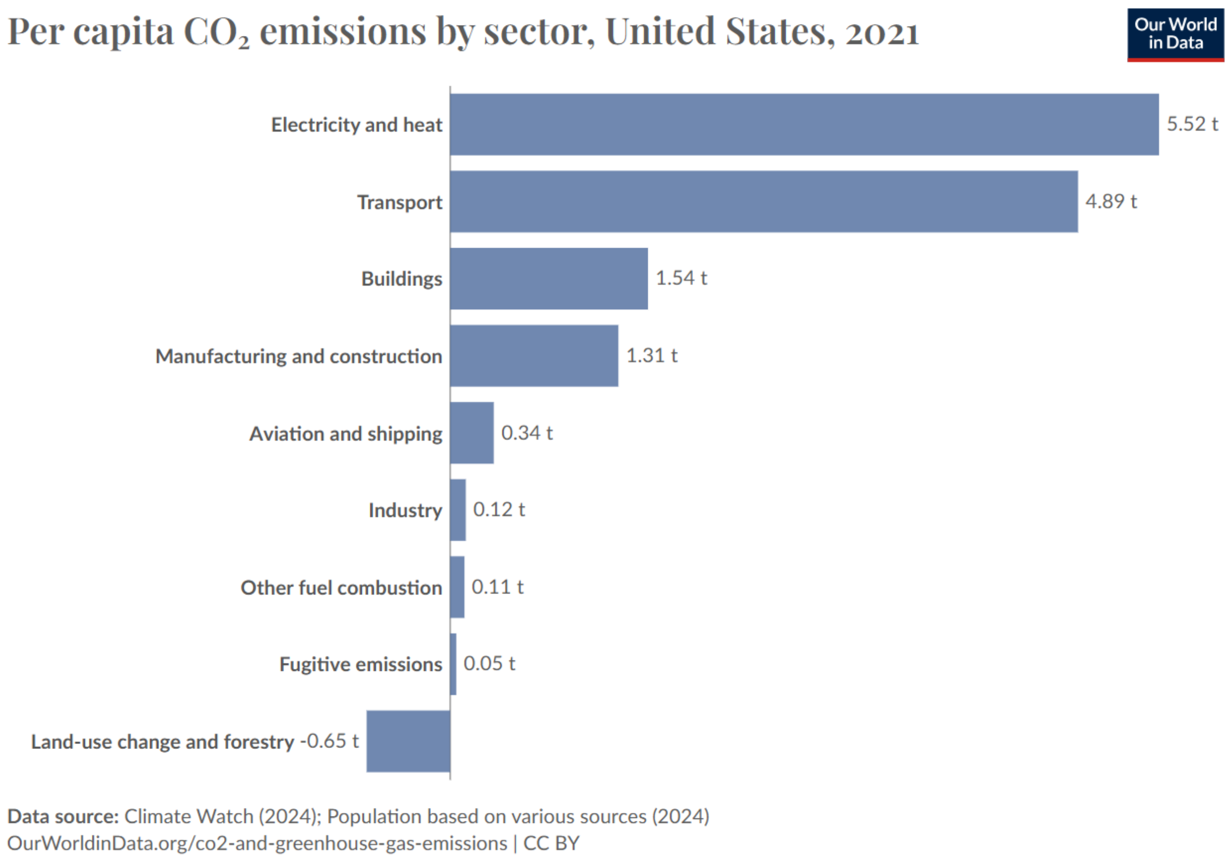

Figure 2: Per capita CO2 emissions by sector, United States, 2021 (Our World in Data)

In the past few years, the federal government and DOE have taken steps toward decarbonizing the energy sector, including increasing publications such as Advanced Nuclear, Innovative Grid, and Next-Generation, and advanced pilot demonstrations of Enhanced Geothermal Systems (EGSs) and budgeted funding for additional superhot EGSs[6]. In May 2024, Phase 2 of the National Interest Electric Transmission Corridor (NIETC) Designation Process

[5] "Main sources of carbon dioxide emissions," *CO2 Human Emissions*, 13 December 2017, https://www.che-project.eu/news/main-sources-carbon-dioxide-emissions.
[6] Holly Reuter et al, "Decarbonizing the U.S. power sector: Progress and opportunities," *Clean Air Task Force*, 19 August 2024, https://www.catf.us/2024/08/decarbonizing-us-power-sector-progress-opportunities/.

began to relieve congestion and cost to electricity ratepayers and unlock the potential of low-carbon energy sources[7].

From the funding side of things, the DOE has recently budgeted $3.46 billion for 58 Grid Resilience and Innovation Partnerships (GRIPs), $3.8 billion to build/upgrade transmission lines, and over $375 million for rural clean energy project identification through the Rural and Remote Areas Program.[8].

As of 2024, the United States invests just over $100 billion more into clean energy (energy efficiency and end-use, power grids and storage, renewable power, etc.) than into fossil fuels.[9] The money is in the right place, but change is still not happening quickly enough to meet the 1.5°C goal. This is where efficiency comes into play.

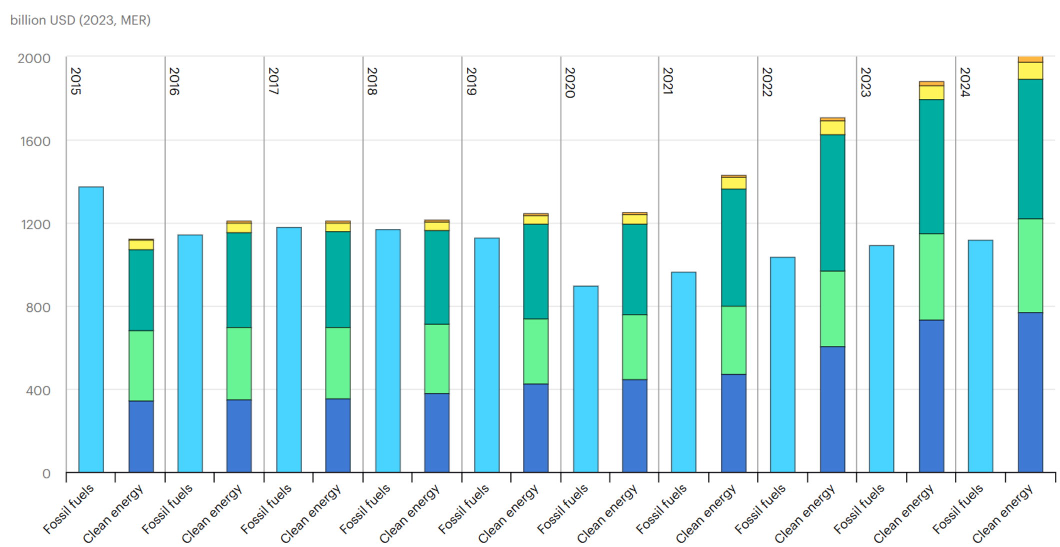

Figure 3: Global investment in clean energy and fossil fuels, 2015-2024 (International Energy Agency)

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[7] "National Interest Electric Transmission Corridor Designation Process," *U.S. Department of Energy*, https://www.energy.gov/gdo/national-interest-electric-transmission-corridor-designation-process.
[8] Holly Reuter et al, "Decarbonizing the U.S. power sector: Progress and opportunities."
[9] "Overview and key findings," *International Energy Agency*, 2024, https://www.iea.org/reports/world-energy-investment-2024/overview-and-key-findings.

If the money and effort are being put toward renewable energy and decarbonizing the energy sector, finding ways to accelerate that decarbonization is now essential. This report details and analyzes several strategies for increasing the efficiency of decarbonization technologies in several areas, including storage, distribution, and sequestration.

STRATEGY I: leveraging existing infrastructure

One such strategy is to develop technologies that can be scaled easily by leveraging existing infrastructure. Energy infrastructure is typically defined as "a facility, and associated equipment, used for (1) the generation or transmission of electric energy; or (2) the production, processing, and delivery of fossil fuels, fuels derived from petroleum, or petrochemical feedstocks".[10] This means these low-carbon technologies, once developed and ready for public use, can easily be swapped into energy infrastructure and systems where less efficient energy technologies are currently being used.

One example of this concept is the product from NET Power. NET Power has created a novel natural gas combustion process that sequesters the resulting CO_2 to produce electricity and ends with high-purity CO_2 that can be sold to industry.

[10] "ENERGY INFRASTRUCTURE REINVESTMENT," *U.S. Department of Energy*, https://www.energy.gov/lpo/energy-infrastructure-reinvestment.

The technology first separates air into components, particularly oxygen, argon, and nitrogen. The resulting oxygen is combusted with natural gas to produce CO_2 and water vapor. This high-pressure CO_2, combined with recirculated CO2, expands and turns a turboexpander, an axial-flow turbine, to produce electricity before the CO_2 goes into a heat exchanger to cool.[11] After the water is finally removed from the CO_2 mixture, a small amount of the CO_2 is repressurized to be sequestered and sold. At the same time, the rest of the gas goes through the other end of the heat exchanger to be reheated and recycled into the process. Throughout the cycle, nearly all CO_2 is ultimately captured.

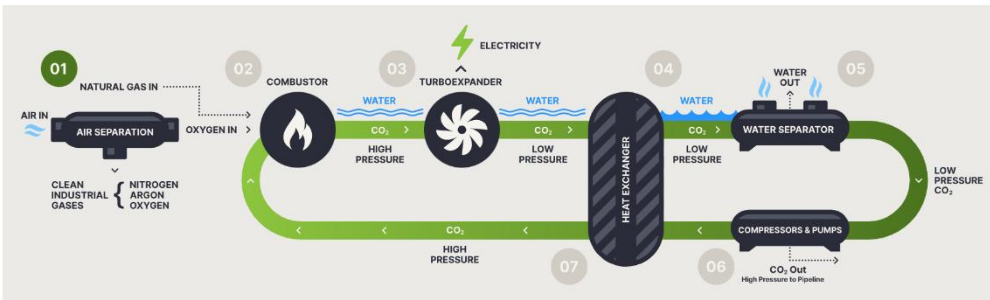

Figure 4: NET Power Cycle (NET Power)

The NET Power technology is more easily scalable because it fits existing infrastructure. Natural gas is already being burned across the country, and this technology can be applied to existing combustion infrastructure. By minimizing the need for extra components such as facilities for combustion, ways to harness and transport electricity, etc., the NET Power cycle can be more easily deployed and is less likely to be seen as not worth the effort.[12]

Another more commonplace example of renewable energy technologies leveraging existing infrastructure is solar photovoltaics (PVs). Especially in places that receive a significant

[11] "Gas turboexpanders," *Ipieca*, June 2023, https://www.ipieca.org/resources/energy-efficiency-compendium-online/gas-turboexpanders-2023.
[12] Ben Kroposki, " Renewable Energy Integration," *National Renewable Energy Laboratory (NREL)*, https://www.nrel.gov/grid/renewable-energy-integration.html.

amount of direct sunlight, PVs have been increasingly installed in small-scale residential settings, typically on rooftops. In 2022, small-scale solar energy produced ten times more than in 2012.[13] Residential solar uses the existing land and connection to the power grid in most homes

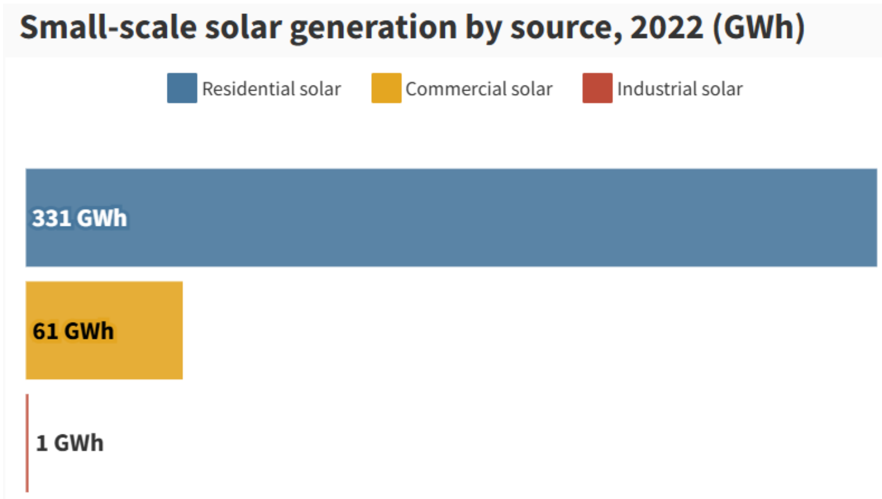

Figure 5: Small-scale solar generation by source, 2022 (Environment America)

to easily provide energy, unlike typical solar farms, which require large amounts of land and new grid systems, which can be costly.[14]

Some pitfalls of using existing infrastructure to speed up the deployment of sustainable technologies are a switch from reliable power to power that possibly has short-term variability (particularly in the case of wind and solar), and ensuring enough power is being generated to allow the scale-back of traditional power sources.[15]

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[13] Johanna Neumann and Tony Dutzik, "Rooftop solar on the rise," *Environment America*, https://environmentamerica.org/center/resources/rooftop-solar-on-the-rise/.
[14] Emily Potts, "Barriers to solar energy transition identified by researchers," *Innovation News Network*, https://www.innovationnewsnetwork.com/barriers-to-solar-energy-transition-identified-researchers/38395/.
[15] Ben Kroposki, " Renewable Energy Integration."

Integrating new energy technology with existing energy infrastructure makes large-scale deployment of new technologies much more feasible, practical, and approachable. However, such integration often requires adding new infrastructure, which can still be costly.

STRATEGY II: leverage existing supply chains

The second primary way to increase the scalability of a technology meant to help decarbonize the energy sector is by using existing supply chains. This strategy capitalizes on using existing supply chains mainly for the processing and dissemination of the technology.

Typically, supply chains in the energy sector refer to how the materials necessary for clean energy technologies are produced. However, it relates to how the technologies are used in this case. Though some technologies, such as solar panels and wind, are proving relatively cost-effective, other technologies, such as batteries and carbon capture and storage (CCS), are expensive to manufacture and deploy.[16] [17] High deployment cost usually involves high complexity, a need for customization, and specialized and complicated installation.[18] Utilizing existing supply chains can help with that. If the finished product can be transported and implemented by some previously existing supply chain, or a new product can be manufactured using a supply chain already set up for another product, it can be efficiently scaled.

An example of this is a company called Andes. The Andes consist of beneficial microorganisms deposited into farmland and agricultural seeds, mainly corn, soybeans, and wheat. The microorganisms can convert calcium cations (Ca^{2+}) in the soil and CO_2 into inorganic

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[16] "Rapid rollout of clean technologies makes energy cheaper, not more costly," *International Energy Agency*, 20 May 2024, https://www.iea.org/news/rapid-rollout-of-clean-technologies-makes-energy-cheaper-not-more-costly.
[17] Katrin Sievert et al, "Why the Cost of Carbon Capture and Storage Remains Persistently High," *International Institute for Sustainable Development*, September 2023, https://www.iisd.org/system/files/2023-09/bottom-line-why-carbon-capture-storage-cost-remains-high.pdf.
[18] Katrin Sievert et al, "Why the Cost of Carbon Capture and Storage Remains Persistently High."

carbons such as calcite, calcium carbonate, and other calcium carbonate equivalents (CCEs).[19] Furthermore, the microorganisms grow along with the plant roots to accelerate the conversion

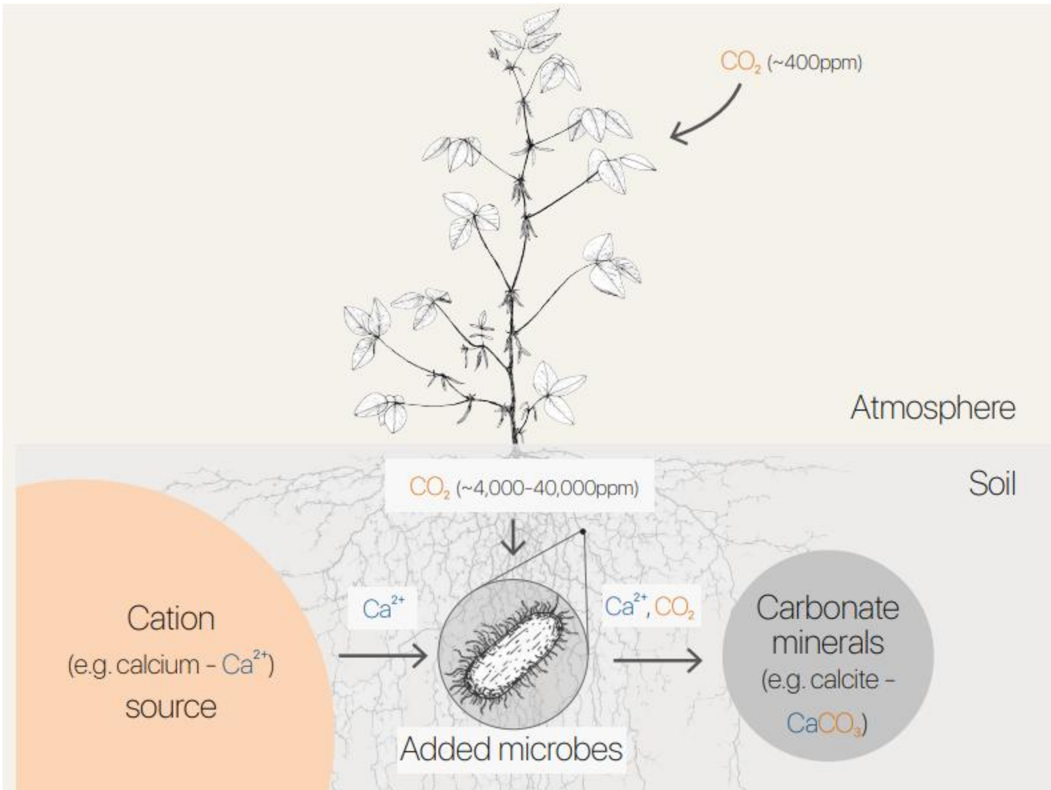

Figure 6: Illustration demonstrating use of microbes for carbon dioxide removal (Andes)

and increase the nitrogen-fixing capabilities of the plant, reducing the need for traditional fertilizers that are not good for the environment.[20] [21]

The feature of this technology that fits into the supply chain efficiency framework is that, since the microorganisms are part of the crop seeds, farmers and agricultural companies can

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[19] "Methodology for Quantification and Crediting of Carbon Dioxide Removal," *Andes*, September 2023, https://static1.squarespace.com/static/57a7b2f8f5e231cfd157e7fc/t/6610722cb9cf6879d8674421/1712353844509/Microbial+Carbon+Mineralization+Methodology+v1.0.1_September+2023.pdf.
[20] "About Us," *Andes*, https://www.andes.bio/.
[21] Facundo Calvo, "Why we must rethink the use of nitrogen fertilizers," *International Institute for Sustainable Development*, 24 March 2022, https://www.iisd.org/articles/analysis/tackling-hunger-nitrogen-fertilizers.

purchase the seeds directly and continue cultivating them as usual.[22] In other words, the Andes seeds just slot into the spot in the agriculture supply chain where traditional seeds would typically be, meaning that they do not require additional materials or labor later down the supply chain, all the way to implementation.

One other example of a technology that fits into this framework is Anthro, a company making ultra-dense batteries that can be manufactured in existing gigafactories.[23] This framework encapsulates any more efficient technology because it easily integrates into an existing supply chain.

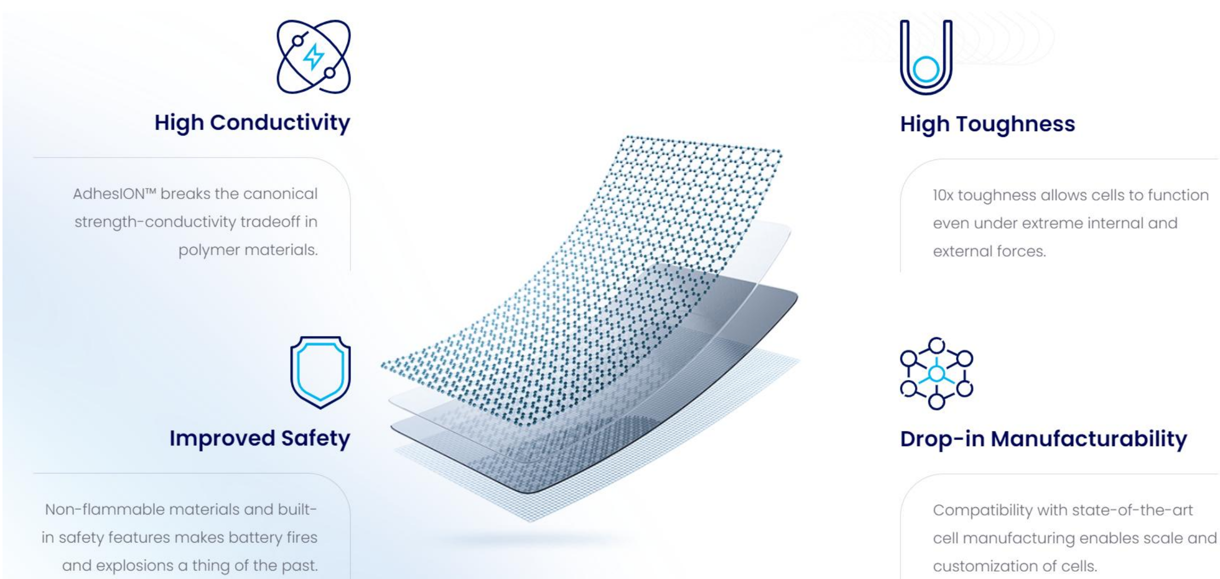

Figure 7: Anthro Energy technology and characteristics (Anthro Energy)

STRATEGY III: focus on modular technologies

[22] Lauren Manning, "Andes Ag is integrating seeds with beneficial microbes to combat inherent delivery challenges for biologics," *AG Funder News*, 9 June 2020, https://agfundernews.com/andes-ag-is-integrating-seeds-with-beneficial-microbes-to-combat-inherent-delivery-challenges-for-biologics.
[23] "Home," *Anthro Energy*, https://www.anthroenergy.com/.

Modular technologies are energy solutions that can be expanded or compounded upon. In other words, they have small, combinable parts that can make larger products. These solutions are scalable because they are typically less expensive to produce and can be easily added to each other. This means that if you have one of the products, it is relatively easy to get more.[24]

Modular technology can show up in a couple of different ways, either in energy production or storage. The first example is from Lydian, which produces more sustainable jet fuel. The process begins with the raw ingredients, CO_2 from the environment, renewable energy, and water, all easily accessible and sustainable ingredients. These products are then focused on the production of syngas, a synthetic gas combination of hydrogen gas (H_2) and carbon monoxide (CO).[25] Then, the syngas is used for a proprietary fuel synthesis process to produce fuel for planes and jets, fuel which is then burned, producing carbon dioxide, a raw fuel ingredient.[26] The synthesis steps in the process are modular, meaning that as raw materials in a particular setup of the process become more abundant, it is easy to scale the synthesis technology to match.

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[24] "What is Modular Construction," *Modular Building Institute*, https://www.modular.org/what-is-modular-construction/.

[25] Kara Rogers, "Syngas | Description, Production, Uses, Advantages, & Disadvantages," *Encyclopedia Britannica*, 30 June 2023, https://www.britannica.com/topic/syngas.

[26] "Home," *Lydian Labs*, https://www.lydianlabs.com/technology.

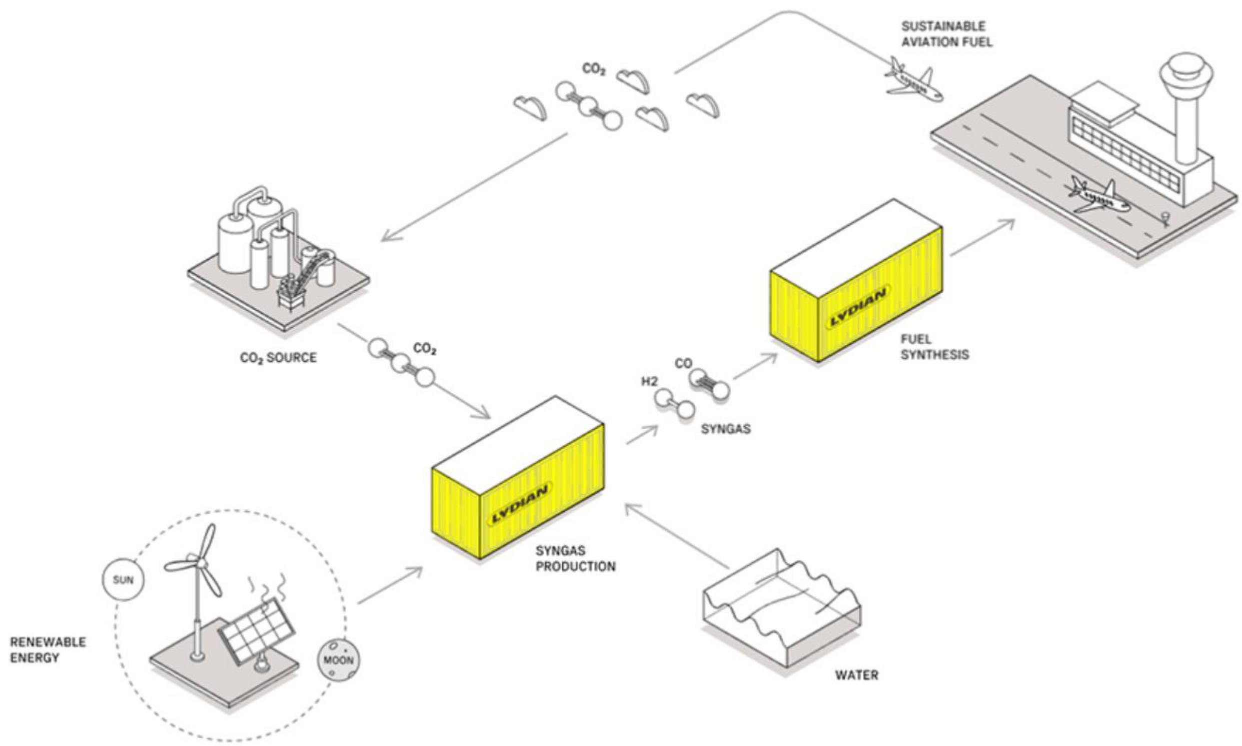

Figure 8: Lydian Labs process and characteristics (Lydian Labs)

The second example centers around story energy more efficiently and more sustainably than with batteries. The Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle (ENDURING) project stores extra energy produced during the day by sustainable sources (solar panels) as heat to be deployed as electricity when needed.

The cycle begins with the extra electricity from the grid being used to power an electric heater, which sits at the top of a set of silos filled with silica beads. Silica beads are easy to manufacture, easy to heat, and inexpensive, so they are used to hold thermal energy. The beads are then fed into the insulated silos, where they await use. When it is time for the energy to be deployed, the beads pass through a heat exchanger, where they heat up stored gas and steam. The pressurized gas and steam are then used to turn generators and produce electricity to be pushed back into the grid.[27]

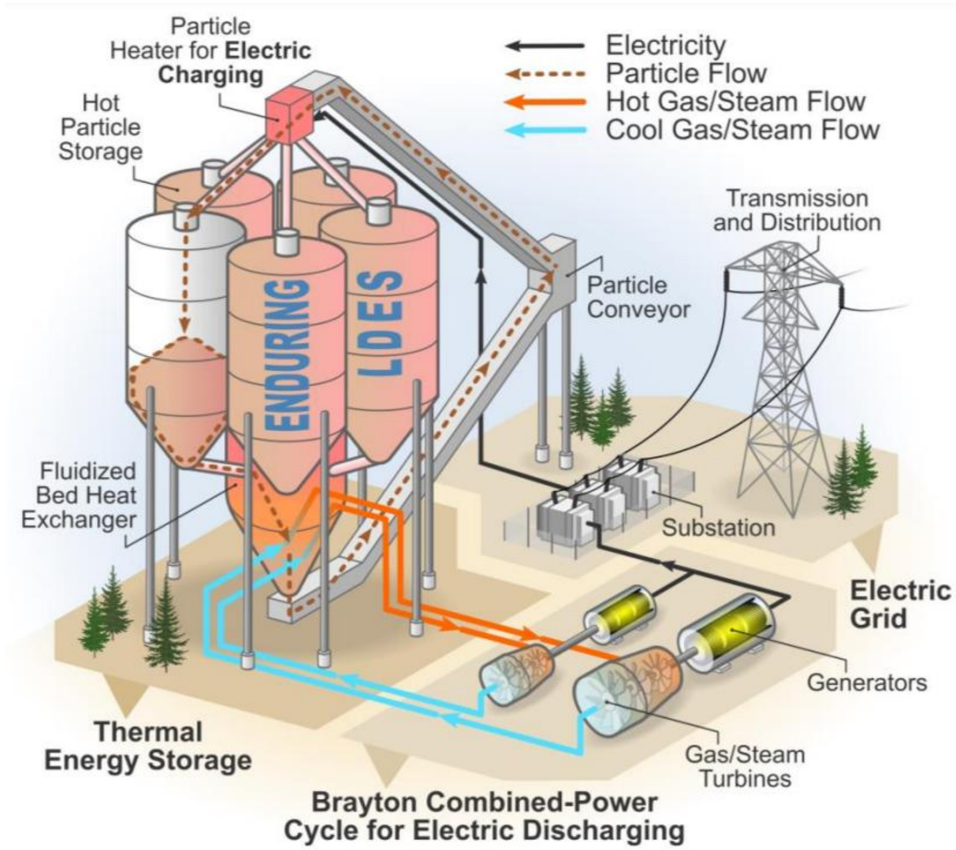

Figure 9: ENDURING energy solutions design and characteristics (ENDURING)

The modular component of this technology is the silos, as the number of silos can be changed easily to account for the amount of energy to be stored. Furthermore, this solution also utilizes existing infrastructure because it can be built using retired coal and natural gas plants to reduce costs and waste materials.

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[27] "Modular, Cost-Effective, Build-Anywhere Particle Thermal Energy Storage Technology," *National Renewable Energy Laboratory (NREL)*, 30 August 2021, https://www.nrel.gov/news/program/2021/nrel-options-a-modular-cost-effective-build-anywhere-particle-thermal-energy-storage-technology.html.

Modular technologies are one of the simplest energy solutions because it is typically apparent how they can be scaled easily. Modular technologies can also satisfy one of the other scalable solution criteria. This would make it easy and efficient to produce more parts, not just convenient and practical.

STRATEGY IV: integrated intelligence to improve efficiency

One part of the energy sector that has not yet been addressed is energy usage in manufacturing. Typically, decreasing environmental impact in this area revolves around minimizing the amount of excess energy wasted. Integrated intelligence is making it even easier to do this.

An example of this can be seen in technology from the company Alcemy, which works to improve efficiency in concrete development systems. Skilled workers and manual quality control in concrete plants typically optimize this process. However, as new concretes are developed that require closer monitoring, technology can step in. With the Alchemy machine learning technology, ready-mix concrete plants have seen fewer water additions (more water conserved), more target accuracy, and more.[28]

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[28] "Product," *Alcemy*, https://alcemy.tech/en/produkt/beton.

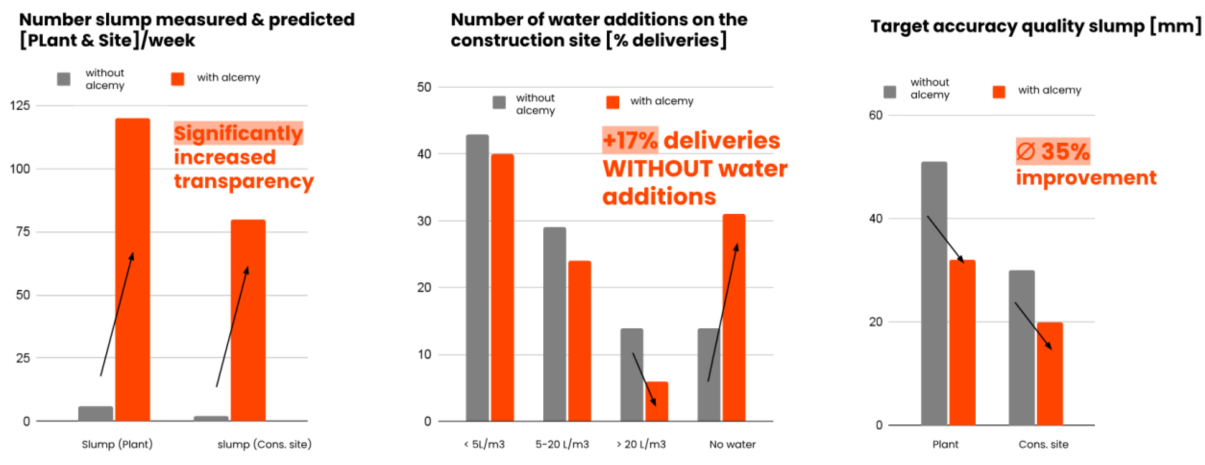

Figure 10: Improvements to Development with Alcemy Technology (Alcemy)

This added intelligence fits into this bucket of efficiency strategies and is scalable because it uses existing infrastructure. Since Alcemy requires no hardware installation, it can be dropped straight into existing factories and into the processes already completed by quality control.

STRATEGY V: accelerate deployment of existing energy technologies

With so many viable energy technologies on the market that may or may not fall into one of the efficiency brackets above, some focus must be put on making existing technologies more efficient. These strategies fall into two major categories: policy and technology.

From a policy perspective, money and effort being put into specific projects and sectors are most helpful. For example, the Energy Ready program is sponsored by the Department of

Energy (DOE) and helps local governments with tech assistance and improvements in planning, zoning, and permitting.[29]

Energy Ready combines three programs to help streamline energy efforts. First is SolSmart, which was established in 2016 and funded by the DOE's Solar Energy Technologies Office. It provides technical support to help communities adopt solar with a target of 1000 communities by 2027.[30] Charging Smart is the second program and is funded by the DOE's Vehicle Technologies Office with a focus on equitable expansion of EVs and charging infrastructure by reducing soft costs (permitting, inspection, load service requests, etc.) nationwide. Finally, Distributed Wind Smart, launched in Fall 2024 (funded by DOE's Wind Energy Technologies Office), develops best practices for zoning, planning, inspecting, etc., for wind energy with a goal of 200 jurisdictions by 2027.[31]

Though this report focuses on energy in the United States, some up-and-coming programs are occurring in Europe, particularly those put forward by the European Commission.[32]

The Commission is introducing temporary measures to accelerate renewable energy deployment, reinforcing efforts under the European Green Deal and addressing the ongoing energy crisis. With the urgency heightened by disruptions in fossil fuel supply, mainly from Russia, the proposal aims to simplify and fast-track permitting for solar installations, repowering aging renewable plants, and expanding heat pump adoption. Renewable energy projects will be

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[29] "Energy Ready Program Launches to Accelerate Local Clean Energy Deployment," *U.S. Department of Energy*, 20 September 2024, https://www.energy.gov/eere/articles/energy-ready-program-launches-accelerate-local-clean-energy-deployment.
[30] "SolSmart," *International City/County Management Association (ICMA)*, 6 November 2023, https://icma.org/programs-and-projects/solsmart.
[31] "Energy Ready Program Launches to Accelerate Local Clean Energy Deployment."
[32] "Consolidated Version of the Treaty on European Union", 7 July 2016, Official Journal of the European Union, *EUR-Lex*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A12016M%2FTXT.

granted "overriding public interest" status, helping eliminate bureaucratic delays and speeding up implementation. These steps are designed to immediately cut fossil fuel reliance, stabilize energy prices, and enhance energy security across the EU.

The proposal focuses on rapidly deployable technologies like solar photovoltaics, heat pumps, and wind energy repowering, ensuring minimal legal and environmental hurdles. Specific solar installations, such as rooftop panels and small-scale projects, will be exempt from environmental impact assessments to streamline approvals. Repowering older wind and solar farms will enhance efficiency without requiring additional land use. While the plan does not alter existing renewable energy targets, it aims to remove regulatory roadblocks. It supports a record-breaking expansion of over 50 GW of renewable capacity in 2022 and sets the stage for even faster growth to meet 2030 sustainability goals.[33]

The second part of making existing technologies more efficient is the technological side. One example is the company Charge Robotics. Charge is dedicated to reducing the primary barriers to solar power: installation and labor logistics. Charge Robotics reports that the technology is keeping pace with a traditional crew of about eighty people and only a small crew of operators, drivers, and technicians.[34]

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[33] "Questions and Answers on Emergency Measures to Accelerate the Deployment of Renewable Energy," *European Commission*, 8 November 2022, https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_6658.
[34] Adele Peters, "This Solar-Building Robot Is Designed to Solve One of the Industry's Biggest Problems," Fast Company, 19 April 2024, https://www.fastcompany.com/91108331/these-solar-assembling-robotic-arms-could-solve-one-of-the-industrys-biggest-problems.

Figure 11: Solar Installation Robot from Charge Robotics (Charge Robotics)

In all, though developing new technologies with the efficiency framework in mind can increase the odds of a technology being scalable, some strategies can be used after the fact to make existing technologies more efficient as well.

STRATEGY VI: new, bigger, innovative technologies

The final strategy detailed in this report is using technologies pushing the bounds of what we know is possible in terms of scale. For example, there has been a global push for more research into space-based solar, which would turn an intermittent power source (only available during the day) into continuous power. The technology would use energy-transmitting satellites fitted with solar panels and mirrors to reflect solar rays onto small solar collectors. The energy is then transmitted to Earth through microwave or infrared radiation.[35]

Microwave transmitting satellites must be in geostationary orbit around 35,000 km from Earth. Laser satellites, due to their smaller size, would orbit in clusters around 400 km away from the Earth.[36] For reference, the moon is around 384,400 km away from Earth.[37]

Of course, there are numerous challenges with both types of solar. Laser solar would require groups or even fields of satellites to emit significant energy, while microwave satellites would be too far away from Earth to maintain once set out reasonably.[38]

Another technology of interest is small modular fission reactors (SMRs). These facilities could produce 300 MW(e) per unit, but given their smaller footprint, they would be suitable for places where traditional fission facilities would not be possible. They would typically be fabricated and manufactured at a different location and shipped to the installation location, which may not have the same grid connectivity. This makes the SMRs suitable for places with less grid connectivity.[39]

In all, technologies are being developed worldwide to provide novel and ever more scaled solutions to the energy problem, including versions of existing technologies that fit into this efficiency framework.

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[35] "Space-Based Solar Power," *U.S. Department of Energy*, 2025, https://www.energy.gov/space-based-solar-power.
[36] "Space-Based Solar Power."
[37] "How Far Away Is the Moon?" *Royal Museums Greenwich*, 2025, https://www.rmg.co.uk/stories/topics/how-far-away-moon.
[38] "New Study Updates NASA on Space-Based Solar Power," *NASA*, 11 January 2024, https://www.nasa.gov/directorates/stmd/space-based-solar-power-report/.
[39] "What Are Small Modular Reactors (SMRs)?," *International Atomic Energy Agency*, 13 September 2023, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs.

CONCLUSION:

Global warming and climate change are ever-pressing issues in our modern world, and steps must be taken to address these challenges. In 2023, the US had the 13th-largest per capita CO_2 emissions worldwide.[40] Of that, the vast majority are due to the energy sector.[41] Though increasing money is being invested into decarbonizing the energy sector, progress is not happening fast enough to put the US on track to reach the decarbonization goals set in the Paris Climate Accords.

This efficiency framework strives to change that. By researching and categorizing the characteristics of energy technologies that make them most efficient, practical, and scalable, money feeding into the energy sector can have more meaningful influences on the state of the climate crisis today.

The prescribed framework, however, is incomplete. Only six possible strategies are detailed, while numerous others exist and can be analyzed, including cheap/abundant feedstocks and technologies with room for development.

Importantly, it is a start. It makes it possible to pick a technology and ask, "Which strategies does this technology use? Does that make it scalable?" It is a framework for critical thinking and cost-benefit analysis. It is a step toward understanding how to maximize the impact of funding. It is the future of energy technology development.

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[40] "Per Capita CO_2 Emissions," *Our World in Data*, 2024, https://ourworldindata.org/grapher/co-emissions-per-capita.
[41] "Main sources of carbon dioxide emissions."

CHAPTER 2

AGRIVOLTAICS AS A CASE STUDY FOR EFFICIENT DECARBONIZATION

INTRODUCTION:

Agrivoltaics is one of the many strategies used across the United States to decarbonize the energy sector. The setup combines aspects of solar farms with traditional agriculture by planting crops that thrive under partial shade environments between, under, or on the perimeter surrounding solar panels. This leads to both benefits and drawbacks depending on the environment. In general, agricultural land need not be pulled out of food production for renewable energy, but changes in crops are to be expected. In arid climates, the protection of the panels may result in higher yield and lower watering requirements, while water distribution would need to be managed carefully in wetter conditions.[42]

Furthermore, specific considerations are necessary when planning for agrivoltaics. Two or more groups must be in conjunction to handle both the agricultural and energy aspects, possibly increasing the cost. However, resources such as those at the National Renewable Energy Laboratory (NREL) are researching and providing support to maximize the output of such setups.[43]

Agrivoltaics, in particular, falls under several of the efficient decarbonization strategies outlined above. Firstly, it utilizes existing infrastructure, which is the land. Land requirement is

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[42] "Agrivoltaics," *National Renewable Energy Laboratory*, 3 April 2025, https://www.nrel.gov/solar/market-research-analysis/agrivoltaics.html.
[43] "Agrivoltaics."

one of the most significant limiting factors for solar power and solar farms, so by using land that is already prepped for agriculture, the solar farm land can be put to double use.[44] Solar farms are modular in that when more land becomes available, the connection to the grid, layout, crop choice, and panel configuration are already fixed, and adding new solar panels is relatively affordable.[45] In the past, fixed-angle solar panels were the norm. However, new research is being done on how angle adjustments in residential and industrial solar panels can increase power yield up to 25 kW/m^2, leaving an opening for integrated intelligence to optimize the technology.[46] Finally, agrivoltaics are making existing technology, such as solar farms, more efficient by using the above strategies.

Agrivoltaics exemplify many of the efficient decarbonization strategies outlined in Chapter 1, but still face several optimization problems. Firstly, solar PVs require direct sun without obstructions to their South, the direction in which panels typically face to maximize output.[47] Furthermore, several calculations must be done to find the optimal fixed-angle panel in a typical field.[48] However, as soon as plants are added, energy is not the only thing that has to be maximized; it also has to be used for plant growth.

The project uses a scale agrivoltaics model to run a 2-vector maximization of solar energy output and plant growth (measured by height) to discover the optimal solar panel angle in

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the setup's specific conditions. The purpose of the project is an exploration of electrical wiring and engineering, practice with data collection and analysis, and steps toward analyzing the sunlight-height relationship of a specific agrivoltaics scenario.

MATERIALS & PROCEDURE:

The agrivoltaics rig wiring involved six solar panels (11 cm by 6 cm, 5V, 0.2 A), an Arduino Mega, an Arduino micro-SD card reader, micro-SD cards, breadboard jumper wires, breadboard, resistors (33 ohms), red LEDs, a power cable for the Arduino, and a 10V DC downgrade adapter for wall power.

Throughout the process, the Arduino was powered externally using DC wall power. For each solar panel, the positive terminal of the panel was connected to an analog input pin on the Arduino to measure the voltage off the panel. A 33-ohm load resistor is placed in series with the solar panel, the output of which is connected to another analog input pin on the solar panel (to measure current). Due to the low voltage and amperage of the panel, the necessary shunt resistor is nearly negligible in resistance. For this reason, a red LED was used since the internal resistance of the LED is negligible and serves as a shunt resistor. The red LED is placed in series with the connection to the second analog input pin before running to ground. Figure 12 below shows a complete wiring diagram of one solar panel to the Arduino.

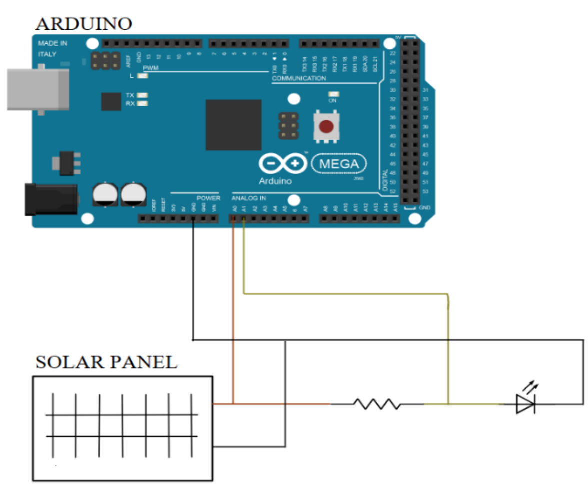

Figure 12: Wiring diagram for one solar panel to Arduino

The Arduino was wired identically to five other solar panels and directly to the SD-card reader through the following connections: VCC to 5V, GND to GND, MOSI to pin 51, MISO to pin 50, SCK to pin 52, and CS to pin 53. The Arduino was programmed to collect data on each solar panel's voltage and amperage every ten minutes and write that data to the micro-SD card in a .csv file. The exact code used is available upon request.

To build the frame and stand for the panels, wooden planks were used with a metal bar across the top at 8 inches (Figure 13). The solar panels were then attached to the metal bar at various angles relative to the vertical, east-facing window. They were placed vertically, 20

Figure 13: Image of complete solar panel stand

degrees from the window, 40 degrees from the window, 60 degrees from the window, horizontally, and a control panel was placed vertically.

Mung beans were utilized for the plants. A batch of mung beans was soaked for 24 hours to prepare for sprouting. Then, they remained damp and covered in a cool, dark spot for three days until roots were visible on all the seeds. After three days, 15 similar and mature seeds were hand-picked to be planted, three in each container, just below the soil's surface. The plants were allowed to grow for 17 days in south-facing sunlight with identical daily waterings before placing them in the rig, one under each of the five test solar panels and one without a panel as a control (Figure 14). Initial height measurements (average of the three plants in each of the five containers) were recorded. Height was measured from the soil level to the highest point on the plant. At this point, the data collection started with voltage and amperage being measured every 30 minutes and the height of the plants (individual and average for each solar panel) being measured every 24 hours, 5 days a week, for 10 days total.

Figure 14: Image of complete agrivoltaic rig

Throughout, wiring and coding went generally to plan. However, the initial plan involved using lima beans as the plant. Numerous attempts to sprout the lima beans continuously molded or simply did not lead to sprouting, so mung beans were used as a replacement. Mung plants, though slimmer and daintier than lima plants, have the same quick-growing, hardy properties as lima beans.

DATA AND RESULTS:

For 10 days, voltage and amperage measurements were taken every 30 minutes, and height measurements were taken every 24 hours; the raw data is available upon request. The data was cleaned and visualized using Python (code available upon request). Figure 15 shows the voltage readings over the entire length of the studies for each of the six panels (five test panels and one control). Figure 16 shows the average daily voltage for each solar panel. Figure 17 shows the daily change in height of each plant. Note that April 26 and April 27 show a change in height of 0 because no data was recorded on those days due to the weekend. Finally, Figure 18 shows the total average daily change in height of each plant plotted against the total average voltage for the corresponding panel for the five test panels.

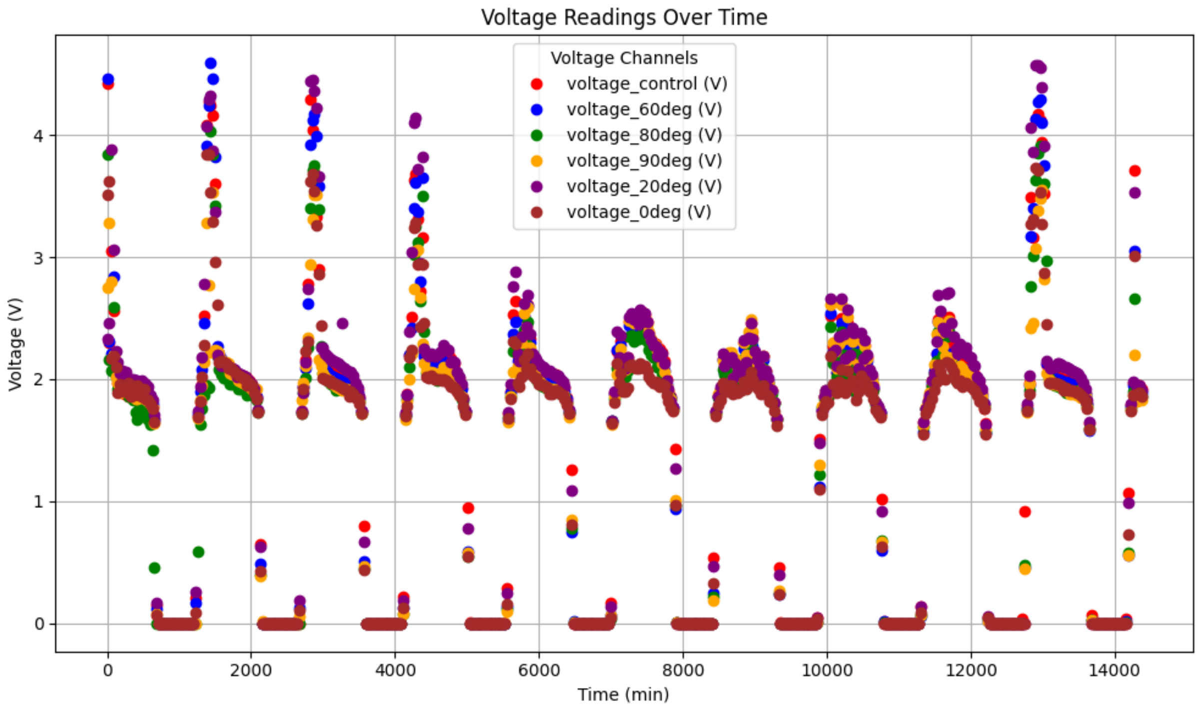

Figure 15: Voltage for each panel over time

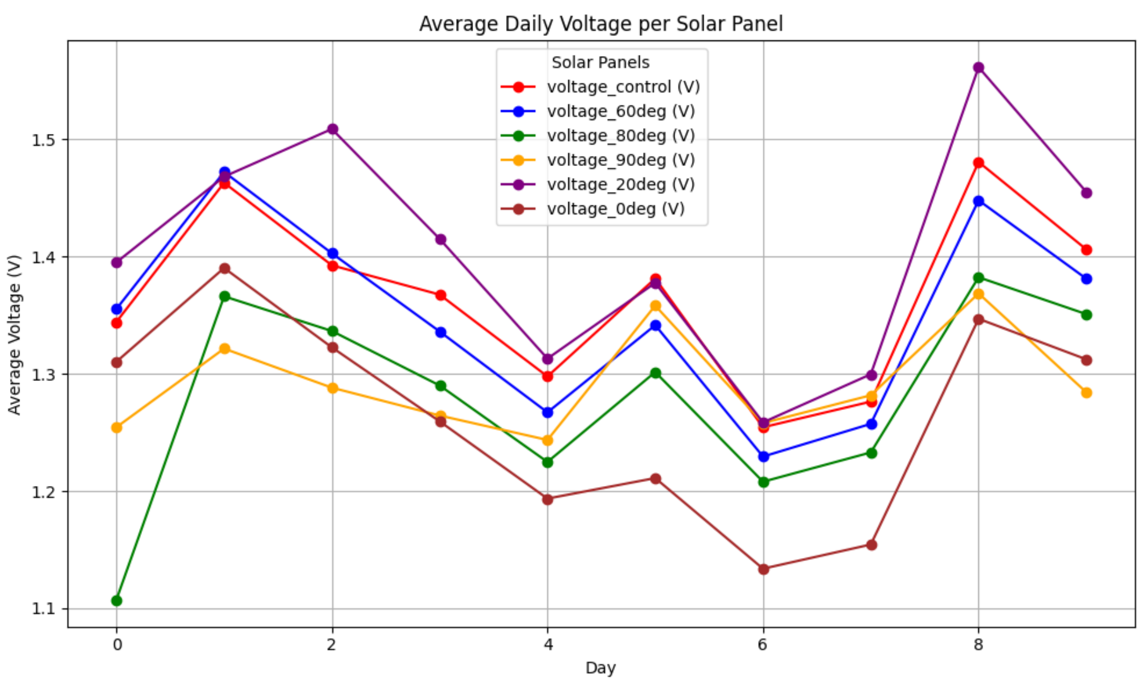

Figure 16: Average daily voltage of each panel over time

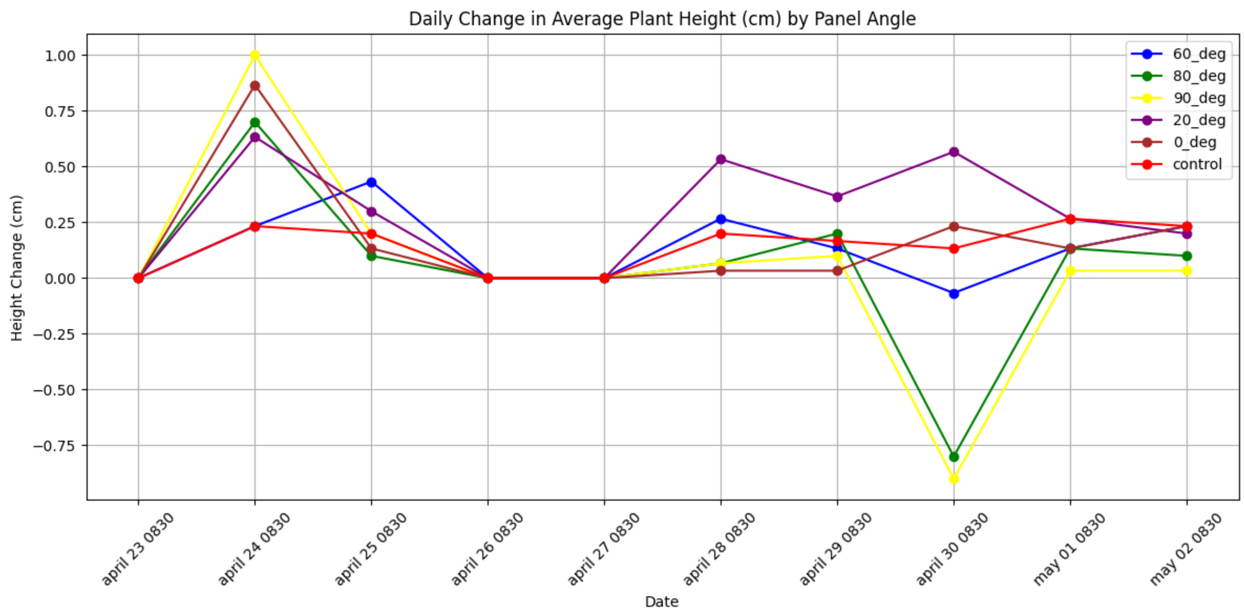

Figure 18: Daily change in height of each plant over time

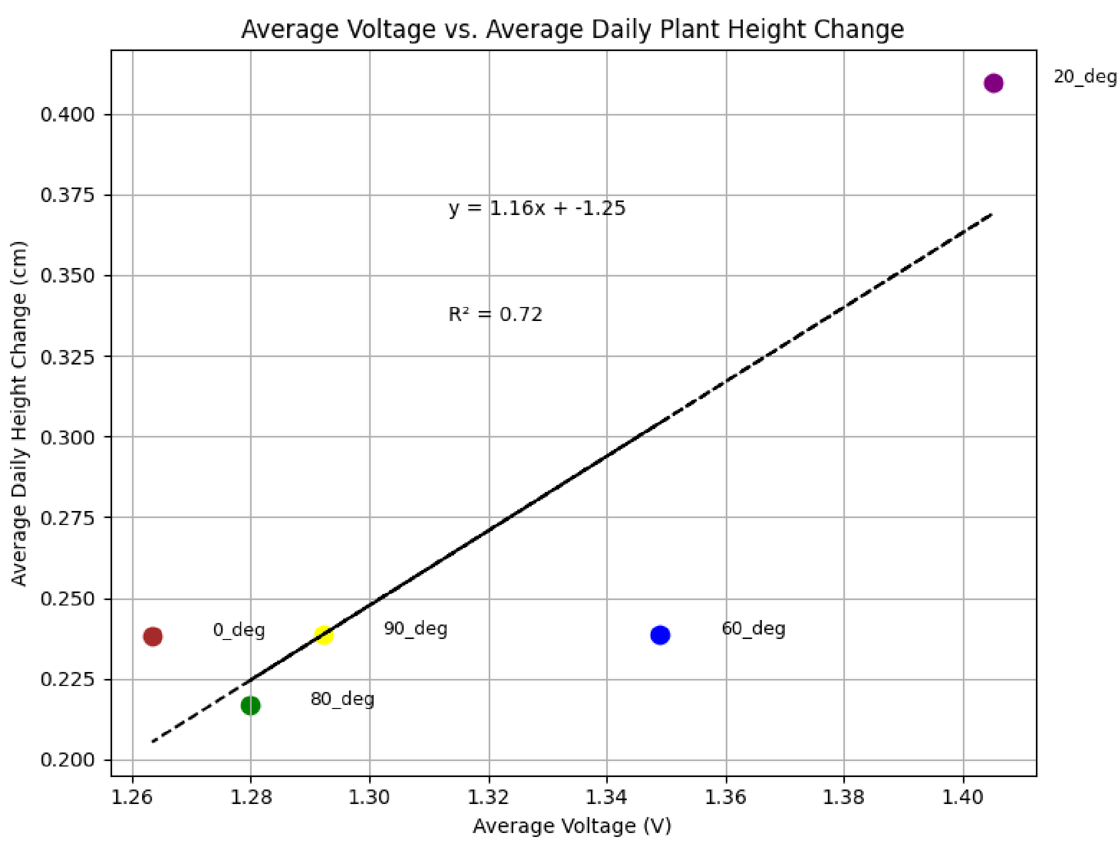

Figure 17: Average voltage of each panel related to average daily change in height for each corresponding plant

ANALYSIS AND DISCUSSION:

Figure 13 above provides little information to answer the experimental question of which angle of the panel maximizes both the growth of the plant and the resultant solar energy. However, it does show the efficacy of the voltage collection with the voltage maintaining clear day-night cycles. Figure 14 shows that, as expected, the panels that were more vertical (control, 20° from the window) had higher daily voltages on average. However, unexpectedly, the 0° panel, which was in the same angular orientation as the control panel, did not have a voltage similar to that of the control panel. Figure 15 illustrates that all five test plants initially grew at comparable rates. However, as time went on, the plants with more vertical panels (20°, 0°) grew more than the plants with more horizontal panels (80°, 90°), which decreased in height due to visible wilting.

Figure 16 shows a moderate positive linear correlation between the voltage of the panel and the plant's growth, but illustrates that the 20° panel had the best plant growth and average daily height change of all of the test panels.

It is essential to recognize the flaws and shortcomings of this experiment. Firstly, there is bound to be variation when experimenting with live plants, which was exacerbated by the lack of repetition in this process. For example, the 20° plant and panel performed better than the control panels (which were set up optimally), which is unexpected and likely due to variability in the plant growth and slight variations in the voltages recorded by the panels.

If this experiment were to be repeated, it could be improved by collecting more data and standardizing the panels' voltages before the experiment's beginning. Measuring heights from the soil level to the last leaf node in the plant would also reduce variability that could result from the movement of plants toward the sun.

CONCLUSION:

In this particular agrivoltaics setup, it is clear that solar panels angled at 20° away from the vertical window maximize both plant growth and solar energy harvested. Furthermore, the panels that are closer to horizontal (90°, 80°) led to lower voltages and much lower plant growth, and even wilting of the plants.

In the future, this experiment could be improved by collecting more data, calibrating the voltage of the independent panels, and adding more repetition to reduce random error. The experiment can be expanded using machine learning and advanced data analysis to quantify the relationship between energy harvested and plant growth. Furthermore, a larger-scale project would more accurately model real-world scenarios.

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