Design of Various Solar Tracking Systems for Net-Zero Off-The-Grid Residential Retrofitting

Analyzing the Faults in the American Energy Grid System to Determine How Off-the-Grid Renewable Energy Can Help

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Country-wide electricity access has been a pillar of American society for decades and helped establish the United States as a global superpower (Tuttle et al., 2016, p. 6). However, today most of the grid is long past its initial life expectancy, and the United States experiences the most power outages of any developed country in the world (Chrobak, 2020, n.p.). The values of equality and access established during grid development have not been upheld for the modern-day grid, and profits have been consistently put ahead of the wellbeing of the consumers. The concept of living "off-the-grid" is almost as old as the grid itself, with records dating back to the 70s in the Oxford English Dictionary (2021, n.p.), showing that independence from these systems is not a new concept. The negative impacts that drive the shift away from the grid today include contributions to climate change, exploitation of marginalized populations, inaccessibility, and the compromised integrity of an aging grid system.

The most popular and effective method for energy generation off-the-grid is solar energy, and the optimization of solar has become a massive industry (US Energy, n.p.). Increasing the efficiency of solar panels allows for better, more affordable solar energy systems for a range of applications, causing solar prices to drop dramatically whilst becoming increasingly popular, shown in the plot below (Solar Industry).

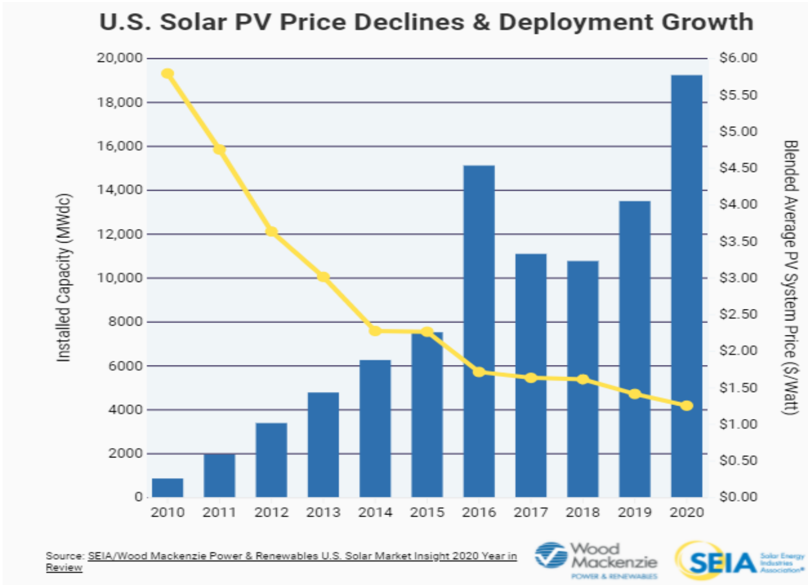

Figure 1: Solar prices and installation trends over time (US Energy, n.p.). In just 10 years prices have decreased around 82% with a 1800% increase in installation capacity.

One way to increase the efficiency of solar panels is to install solar trackers that move the panels to follow the sun throughout the sky. Solar tracking was first invented in 1962, and while the technology has progressed with the popularization of solar panels, it remains a niche market (Nsengiyumva et al., 2018, p. 252). My capstone team will develop and analyze multiple systems for the technical project to determine what benefits they can bring to the renewable energy market.

The solar trackers are being developed as a segment of a larger project to develop a net-zero off-the-grid home from an existing building, with a focus on retrofitting residential structures. The concept of off-the-grid living isn't new, but it's meaning and role within society has developed significantly. The proposed thesis will analyze the faults of the current grid system that have pushed the off-the-grid movement for the STS topic to see how solutions such as renewable energy can help bridge the gaps and help repair the system.

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Solar panels are most efficient when the sunlight hits it at exactly 90 degrees (Nsengiyumva et al., 2018, p. 250). The vast majority of solar panels used in residential applications are stationary meaning the panels are not operating at peak efficiency almost all of the time. Solar trackers address this problem by moving the panels throughout the day, either rotating them on one or two axes to follow the sun. The high costs of solar systems are one of the main barriers for households, and increased energy efficiency of panels over the past decades is the leading factor driving solar prices down (Vernay et al., 2019, p. 225). Therefore, increases in efficiency of up to 56% due to solar trackers could help make these systems more accessible (Seme et al., 2020, p. 19). Current technology surrounding solar trackers is focused on commercial applications and while there have been various studies done on these different systems, the effectiveness of solar trackers has ranged drastically by over 40% efficiency, even with similarly modeled systems (Seme et al., 2020, p. 19). On top of that, no single study has compared these different varieties of solar trackers side by side to get a true comparison of their performance. Efficiency can depend on weather conditions and location so comparing multiple studies done in different places provides little conclusive value (Seme et. al, 2020, p. 1).

The proposed project will analyze a single axis tracking system, following the sun from east to west throughout the sky every day. Four different panel setups will be created and tested to compare energy efficiency, cost effectiveness, and overall aesthetic of the designs. The first panel will be a control fixed panel to emulate the current technology for a residential application. The second panel system utilizes an open loop system, which has a motor that is connected to a computer that uses an algorithm to track where the sun is in the sky based on the location of the panel and the time. The third panel has a closed loop system that utilizes a sensor to actively track the sun, instead of the algorithm, and adjust the panel accordingly. The last system is a passive system, meaning it uses no electrical parts. The panel will have connected copper tubes on each side with a low boiling point liquid inside. As the sun hits one side of the tubing, the fluid will boil, creating a pressure difference between the two sides. This pressure difference causes the liquid to be pushed towards the shaded side, causing gravity to rotate the panel. The basic set up between the two types of tackers, active and passive, are shown in Figure 2 below.

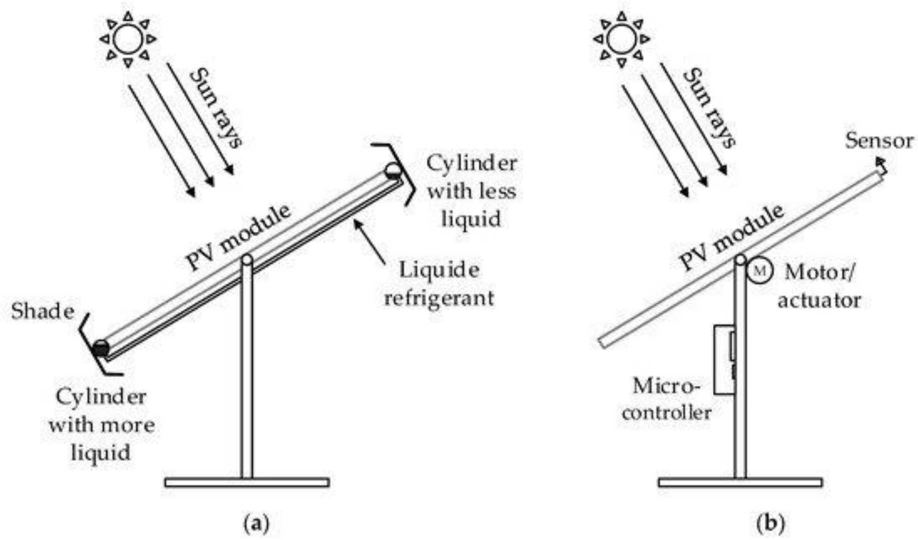

Figure 2: Passive tracking (a) and closed loop active tracking (b) solar system set up (Seme et al., 2020, p.7). The closed loop active tracker will be the same as (b) but without the sensor, and the rig set up will be different for all 4 panels.

The designs of all three systems have a general basis in previous work, utilizing algorithms already developed and using the same cylinder design as shown in figure 2. A large-scale comparison of pervious work is detailed by Seme et al. (2020) and Nsengiyumva et al. (2018), and this project seeks to build off of this existing knowledge. A key difference for this project is the application of the tracking systems, meant for off-grid residential settings rather than commercial solar farms. The most popular design for these commercial rigs is shown below in Figure 3, utilizing free standing mounts which are unsuitable for rooftop installation. This project proposes the design of a sleeker rig, shown in Figure 4, that could be used for residential rooftop energy generation.

Figure 3: Existing design for commercial solar tracker (Solaris). Not designed for roof installation.

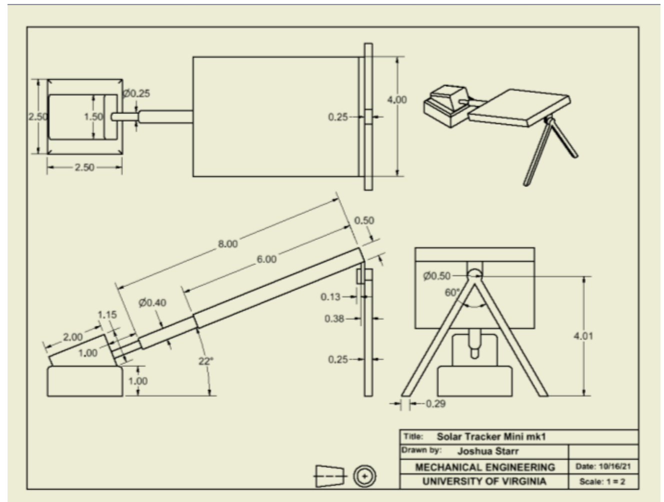

Figure 4: Proposed rig design for rooftop residential application. (Created by Joshua Starr)

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The main push behind today's societal shift towards renewable energy is due to the current grid's contributions to climate change. The US produced 1,448 million metric tons of CO2 in 2019 alone from the electric power sector, whereas solar panels produce no emissions at all (FAQ, 2020, n.p.). Climate change isn't the only reason to go "off-the-grid" though, and some of the first references of the term didn't even mention renewable energy, just simply systems independent from the main grid (Oxford English Dictionary, 2021, n.p.). A large part of the failures in the grid system are due to the unreliability of the aging infrastructure, as well as the lack of flexibility or competition.

The winter storm that hit Texas in February 2021 is a great example of many of these deficiencies. According to NASA, climate change has already begun to cause more extreme weather and natural disasters, which indicates that instances of record-shattering temperatures, such as those in Texas, will become more common (Hansen, 2021, n.p.). Texas's state-wide grid system failed, partially due to natural gas shortages that the power generation stations rely on, and resulted in outages spanning the entire state, as shown in the map below (Hansen**,** 2021, n.p.). According to the Texas State Department, there were over 200 confirmed deaths that resulted from the February winter storm (2021, n.p.).

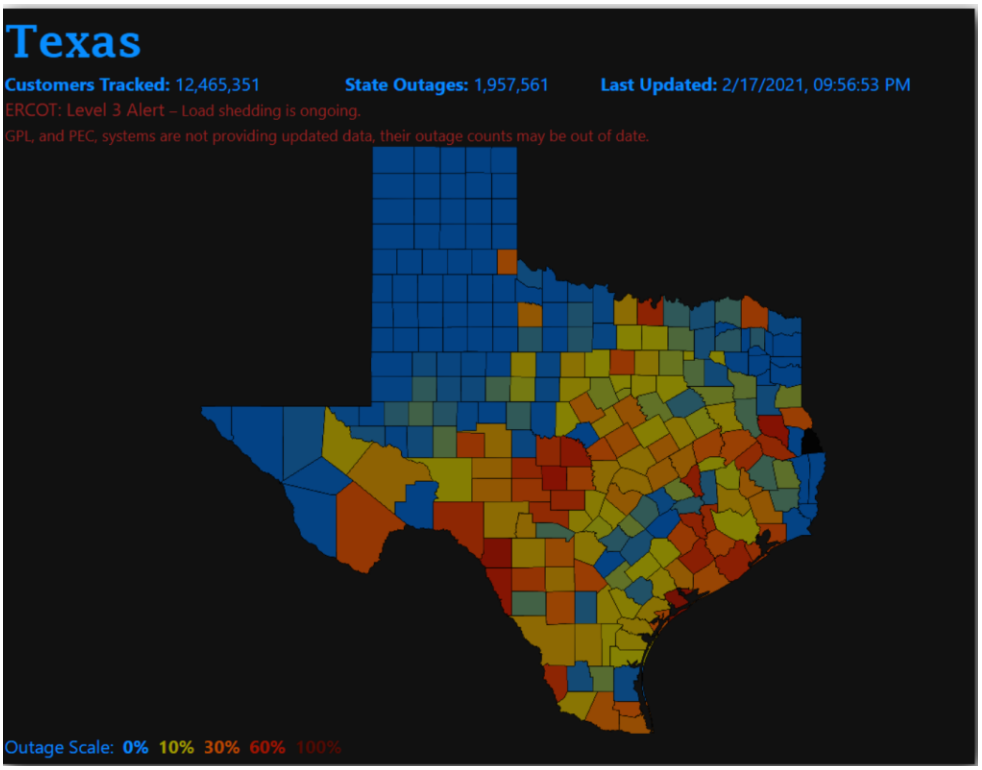

Figure 5: Map of power outages in Texas from the February 2021 storm (Hansen**,** 2021, n.p.). The majority of the state, including the most populated cities, experienced varying levels of outages.

As storms like this become more common with climate change and unreliable grids, another problem arises that bridges the problem from a technical failure, to a fault in the grid's economic system. During the Texas storm, prices for electricity had hit the maximum legal amount, $9000 per megawatt-hour, which meant a 75 times increase in price for the average household (Adams-Heard, 2021, n.p.). These prices are exploitative of the low-income households that cannot afford a massive increase in their bills, especially since access to electricity and heat during a winter storm is a necessity for survival. Additionally, most households had no alternatives to the grid system and the high prices.

Another example of the failings of the current grid system, and potential for renewables, is the case of energy access for the Navajo Nation. The Navajo Nation has over 30,000 remote off-grid tribal members that electrical companies have deemed cost-prohibitive to provide utilities to (Begay, 2018, p. 1). While these communities are traditionally off-the-grid, developments of modern society have made energy access vital in these areas, and many community members are resorting to outdated and unsafe practices to help fill the need. This includes the use of kerosene lamps, coal stoves for heating, and a lack of running water or sewage systems (Begay, 2018, p. 4). Solar energy systems have begun to fill this gap, as detailed by Begay, which can be analyzed for further applications.

Unfortunately, though, this problem extends beyond the Navajo Nation, as "there are approximately half a million Americans without basic electricity service, or who live in energy poverty" (Begay, 2018, p. 6). This is mainly due to either lack of access, or the inability to afford enough electricity to fulfill an individual's needs. Renewable energy can be used to address both of these problems, as it does not require grid access, and after initial costs of renewable energy systems are paid, the system begins to pay for itself.

There are still many barriers when using renewable energy to address these gaps within the current grid system. This includes the initial cost of renewable energy as well as inconsistencies in renewable energy production, and further research is necessary to address all of these issues. In the case of the Texas storm, "significantly more natural gas and coal went offline than renewables," but overall, the performance of renewables in adverse weather conditions could use more data and is a dominant source of public uncertainty with renewables (Domonoske, 2021, n.p.). The development of micro-grids, small localized grid systems with independent energy generation, is a key part of a potential solution to a lot of the large-scale failures of the national grid system (Spector, 2016). Renewables play a large part in the localized energy generation, and the connection of independently functioning systems within different communities can help address many issues. The complexities of addressing the grid goes beyond the technical feasibilities of other energy generation set-ups, and as the case studies have shown, energy is embedded into our society in a cultural sense, not just its technical capabilities, which warrants a network of analysis into the sociotechnical systems at play.

Conclusion

On the technical side, my capstone group will analyze four different solar panels to determine which system provides the most benefits from financial, aesthetic, and efficiency perspectives. These panels will be retrofitted to an existing structure to help create a fully functioning net-zero building. The accompanying STS research will provide a thorough evaluation of the faults in the current national grid system that can help determine the role renewable energy can play. This will include the wide variety of actors, such as government entities, utility companies, individuals without grid access, micro-grids, and the limits of renewable energy technology that exists today. More efficient and accessible solar panels improve the renewable energy field as a whole, and the comparative viability data behind these systems is essential and can help leverage the shift towards these systems as the national grid continues to age (Nsengiyumva et al. 2018, p. 275).

References

Adams-Heard, R. (2021, February 25). *Why Texas broke: The crisis that sank the state has no easy fix*. Retrieved October 26, 2021, from https://www.bloomberg.com/news/features/2021-02-25/texas-blackouts-what-went-wrong-with-ercot-and-state-power-grids.

Begay, S. K. (2018). Navajo Residential Solar Energy Access as a global model. *The Electricity Journal*, *31*(6), 9–15. https://doi.org/10.1016/j.tej.2018.07.003

Chrobak, U. (2020, August 17). *The US has more power outages than any other developed country. here's why.* Retrieved October 28, 2021, from https://www.popsci.com/story/environment/why-us-lose-power-storms/.

Climate change evidence: How do we know? (2021, October 12). Retrieved October 21, 2021, from https://climate.nasa.gov/evidence/.

Domonoske, C. (2021, February 18). *No, the blackouts in Texas weren't caused by renewables. here's what really happened*. Retrieved October 28, 2021, from https://www.npr.org/sections/live-updates-winter-storms-2021/2021/02/18/968967137/no-the-blackouts-in-texas-werent-caused-by-renewables-heres-what-really-happened.

Frequently asked questions (faqs). U.S. Energy Information Administration (EIA). (2020, December 15). Retrieved October 14, 2021, from https://www.eia.gov/tools/faqs/faq.php.

Hansen, K. (2021, February 7). *Extreme winter weather causes U.S. blackouts*. Retrieved October 26, 2021, from https://earthobservatory.nasa.gov/images/147941/extreme-winter-weather-causes-us-blackouts.

Nsengiyumva, W., Chen, S. G., Hu, L., & Chen, X. (2018). Recent advancements and challenges in solar tracking systems (STS): A Review. *Renewable and Sustainable Energy Reviews*, *81*, 250–279. https://doi.org/10.1016/j.rser.2017.06.085

Off-the-grid. (2021, September). *Oxford English Dictionary*. Retrieved October 2021, from https://www.oed.com/view/Entry/34180481?redirectedFrom=off-the-grid&.

Seme, S., Štumberger, B., Hadžiselimović, M., & Sredenšek, K. (2020). Solar photovoltaic tracking systems for electricity generation: A Review. *Energies*, *13*(16), 4224. https://doi.org/10.3390/en13164224

Solar Industry Research Data. (n.d.). Retrieved October 21, 2021, from https://www.seia.org/solar-industry-research-data.

Solaris Technology Industry Inc. (n.d.). *Zomeworks Utrf-120 Passive Solar Tracker*. Solar Panel Kits and Products. Retrieved November 1, 2021, from https://cdn10.bigcommerce.com/s-3yc5xwvk/products/1620/images/1940/230_0059__22118.1423352186.1280.1280.jpg?c=2.

Spector, J. (2016, January 22). *Microgrids Might Be Ready for the Big City*. Retrieved October 26, 2021, from https://www.bloomberg.com/news/articles/2016-01-22/mit-study-microgrids-can-handle-real-world-urban-energy-demands.

Texas Department of State Health Services. (2021, October 22). *News updates*. Retrieved October 26, 2021, from https://dshs.texas.gov/news/updates.shtm#wn.

Tuttle, D. P., Gulen, G., Hebner, R., King, C. W., Spence, D. B., Andrade, J., Wible, J. A., Baldick, R., & Duncan, R. (2016). "The History and Evolution of the U.S. Electricity Industry. *The University of Texas Austin Energy Institute*.

U.S. Energy Information Administration - EIA - independent statistics and analysis. (n.d.). Retrieved October 21, 2021, from https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.02A#/?f=A&start=1949&end=2020&charted=2-1--4-.

Vernay, A.-L., Sohns, M., Schleich, J., & Haggège, M. (2019). Commercializing sustainable technologies by developing attractive value propositions: The case of photovoltaic panels. *Organization & Environment*, *33*(2), 220–244. https://doi.org/10.1177/1086026619853797