Distributed Smart Solar Charge Controller for UVA Solar Car

Investigating Data Center Development in Northern Virginia

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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

Every year the UVA Solar Car team competes in the Formula Sun Grand Prix to see which team can complete the most laps over three days of racing. For my technical capstone, my team is working with the UVA Solar Car team to design a solar charge controller that will draw more power from the car's solar panels so that the car can drive further and win the race. However, we hope our project can be applied to much more than racing. Solar charge controllers are vital to the longevity and efficiency of all solar systems including systems for homes, IOT devices in remote areas, agriculture, and more (Yellowlite, 2024). Solar charge controllers manage the power transfer from the solar panels to the battery, preventing the battery from overcharging, from undercharging due to a load, and protecting the panels from reverse current. "America is getting nearly 12 times more energy from the sun than we did a decade ago" (Neumann, 2023), so it is important the best solar charge controllers are used in these energy systems.

For my sociotechnical capstone, I will investigate the state of data center development in Northern Virginia and if it is being carried out in an ethical and sustainable manner. This is important because Virginians should have a say on some of the largest infrastructure developments in the state and should be informed as soon as possible as it is easier to influence development projects before they begin. Northern Virginia is home to the most data centers in the world and growing (Kidd, 2023). Located near the capital with plentiful land, data center tax incentives, few natural disasters, and an advanced fiber optic network, Northern Virginia has been an ideal place for data center development. However, some of these incentives are becoming exceedingly finite, creating complex conflicts over land-use, water-use, power-use, and noise pollution, for companies, governments, and residents.

Global power demand is growing more than forecasted with electricity consumption by data centers, artificial intelligence, and cryptocurrency sectors expected to double by 2026 (Eren et al., 2024). This is important because demand could overpass supply in the mid to long-term, leading to power shortages. My capstone's technical and socio technical components address power demand, a local-level solution and a state-level problem. At the local level, I aim to make power generation systems more efficient, and at the state level, I investigate data center development to support fair and equitable development through spreading awareness among Virginia residents.

Distributed Smart Solar Charge Controller for UVA Solar Car

For my technical capstone, I plan to design a solar charge controller based on architectures typically only found in research for the UVA Solar Car team. We hope that our design will increase the power transferred from the car's solar panels to the car's batteries. More power will allow the UVA Solar Car team to drive further, faster, and win the annual Formula Sun Grand Prix.

Solar charge controllers (SCCs) are integral to any solar system. A solar system is generally made up of solar panels, batteries, and loads that are powered by the batteries. The SCC manages this system and protects its components. SCCs manage the battery charging process. They work to draw the maximum power from solar panels that the battery can safely handle, they prevent reverse current from damaging the solar panels, and they cut off charging even when power is available to prevent battery overcharging (Zientara, 2024). SCCs also manage the battery discharging process. They allow loads to use the battery when the battery is charged and cut off access before the battery becomes too undercharged (Zientara, 2024).

Without SCCs to manage a solar system, components would be more prone to damage and the system would be less efficient.

We hope to see our SCC integrated into UVA's Solar Car. However, the SCC can be used for a wide range of solar applications. The US Energy Information Administration forecasts that "solar will be the fastest-growing source of electricity in 2024 and 2025" (Antonio, 2024). Solar power is a vital part of efforts to transition towards renewable energy systems. Thus, advancing the development of SCCs is crucial in securing solar power's role in energy production at a pivotal moment in the makeup of the US energy grid.

There have been many advances in solar charging that have brought significant increases in charging efficiencies, which is why it is important to quickly adopt advances in research. Our team's SCC design stems from Stuart Watkinson's 1985 invention of the first MPPT SCC (AERL, 2024). SCCs change the voltage-current output from the solar panel until the panel reaches a combination that will produce the maximum power. An MPPT controller, compared to previous PWM controllers, converts excess voltage into current leading to a 5-30% increase in energy extraction efficiency (Morningstar, 2013). Future advancements in SCCs have focused on the algorithms that determine the best voltage-current combination and the architecture of the whole system.

The current industry standard for conventional systems is to connect the solar panels in series forming a solar array and use a central controller that determines the operating point for all panels combined with a simple non-intensive algorithm. This setup works fine in uniform systems where the solar panels experience similar conditions and have similar max operating points, but it is not the most efficient. Over time, solar panels develop imperfections from normal environment exposure and under varied sun exposure, solar panels will have different optimal operating points. The SCC can only optimize for one operating point, leading to an inefficient power charging process.

My project introduces controllers at each panel, with the output in series called module cascaded converter (MCC) architecture (Al-Smadi et al., 2020). This allows each controller to optimize for a single panel power output. The SCCs feed into Solar Car's current SCC, extending the current system. This will increase Solar Car's power charging capability because the sum of local maximum power point charging is greater than global maximum power point charging. The project will be a proof of concept with documentation to help Solar Car implement the charging system. To make the integration process as easy as possible we designed the system to be modular, supporting any number of solar panels at different sizes and robust, providing protections for the solar panel. To validate the system we will compare our design using a smart algorithm with the conventional central converter design using a perturb and observe algorithm. The data will be presented on a metrics dashboard built with Django for realtime and historical analysis.

Investigating Data Center Development in Northern Virginia

Data center demand from AI and cloud computing is insatiable, with data creation expected to increase at a 23% compound annual growth rate through 2030 (Batson, 2024). A lot of this growth is happening in Northern Virginia, the largest data center market in the world. Data centers have a major impact on the lives of Virginia residents because of this prevalence, impacting the economy, environment, local infrastructure, and resident well being.

This subject is complicated because data centers are not inherently bad. They are actually a major benefit to the local economy. Data centers are a significant economic driver in Prince William County (PWC) bringing in $34.1 million in taxes annually (PFM Group, 2022, p. 45).

Data centers provide employment opportunities with $236.1 million in total labor income from direct, indirect, and induced employment (PFM Group, 2022, p. 40). Data centers attract investments in power infrastructure like Dominion Energy investing $9 billion to build a wind farm in Virginia beach (Parson et al., 2024, p. 13). Data centers attract businesses like AWS that offer cloud services with ultra-low latency. Data center development brings a lot of benefits so Virginia counties have been quick to cater to this development. For instance, PWC has created a Data Center Opportunity Zone Overlay District (DCOZOD) where development regulations are more favorable and support the county's mission of “Targeted Industries for New, and Expanding Companies” (Stantec, 2021).

With counties quick to embrace development, the unintended consequences and conflicts have become apparent because many stakeholders are involved. Utility stakeholders for cabling, water, sewer, and power generally support development, but want a say in the project planning and development location (Stantec, 2021, pg. 1). However, utility companies like Dominion Energy, a primary energy provider in the area, has reported that its power grid infrastructure has not kept up with data center growth, straining power demand and leading to temporary proposals like the Virginia Department of Environmental Quality’s attempt to waive air quality rules that was eventually disbanded by criticisms from residents (Judge, 2022). Environmental stakeholders like the Sierra club argue that land preservation needs to be a higher priority (Stantec, 2021, pg. 9). Historic stakeholders like the American Battlefield Trust argue that historical landmarks like battlefields are being neglected (Stantec, 2021, pg. 4). Local stakeholders like towns or cities are concerned about whether their infrastructure can support a data center (Stantec, 2021, pg. 6). There are many interests at play, and I plan to investigate, quantify, and unravel key traits of equitable and sustainable data center development.

There is a lot of conflict around the actual development of data centers, but there is also a real concern about the health effects of living near a data center among residents. A new data center development in Loudoun County, another prominent data center hub in Virginia, brought over 40 noise complaints. Residents interviewed described the noise as a “low frequency sound” and “loud drone hovering above 24/7” (Lover, 2023). A comprehensive review in the Journal of Exposure Science & Environmental Epidemiology argues that noise pollution should be taken seriously as it has a wide range of consequences including cardiovascular problems, behavioral problems, neurological problems, increased levels of obesity, and more (Hahad et al., 2024). Luckily in this case, resident action led the company to review their practices and reduce their fan power needs by 20% (Lover, 2023).

I am investigating data center development because equitable and sustainable development is possible and community engagement can lead to change. I will analyze data centers from a holistic perspective using Actor-Network Theory. From the breadth of stakeholders impacted and the information technology industry that data centers support, data centers are not singular developments, but part of a wide network to supply companies with secure low-latency cloud services. This network can be seen in AWS’s data center architecture. The AWS Global infrastructure is made up of Availability Zones that consist of 1 or more data centers and Regions that consist of at least 3 isolated Availability Zones (Amazon Web Services, 2024). I will use Actor-Network Theory to analyze the actor’s involved, how data center development has been shaped as a result, and evaluate the policies in place locally so Virginia residents can speak up to shape these policies (Mattison et al., 2005). I plan to review sources ranging from market analysis reports, sustainability models, county interviews with stakeholders, news articles, noise pollution medical journals, and environmental impact analyses. I also plan to interview local environmental groups like the Piedmont Environmental Council. After investigating data center development holistically, I will analyze a current development, using Lkyou's data center sustainability model to quantify the environmental, societal, and operational impact of a single data center. I hope my research will inform Virginia residents and provide them with the tools to speak out on local developments close to home.

Conclusion

I plan to ease power demand at the local level and curb development that affects power demand at the county and state level because with the inevitable reliance on technology and increased use of technology in our lives, power demand will continue to rise. My technical project to design a distributed smart solar charge controller aims to bring controller architectures typically found in research to a more general audience. To do this, I will prioritize modularity, scalability, and robustness of the system, allowing clients to use a wide range of panels and any number of panels, with the added confidence of built-in protections for the panels. My sociotechnical project aims to guide data center development so that new development is power efficient and doesn't strain the power grid in the local area. To do this, I will investigate the data center landscape of Northern Virginia and its major stakeholders, analyze the current data center developments, and equip Virginia residents with the tools to create policy changes. An increasingly digital world will face power challenges, so I hope my research paper supports efforts to create new and better power avenues.

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