Undergraduate Thesis Prospectus

Design of a Thermal Conductivity Measurement Device for Cryogenic Applications

(technical research project in Mechanical Engineering)

The Making of Data Center Alley: Proponents and Critics

(sociotechnical research project)

by

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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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General Research Problem

How can computing efficiency be improved?

Since their public release less than five years ago, generative artificial intelligence (AI) programs have become mainstream with remarkable speed. However, the computationally intensive nature of these products – Goldman Sachs (2023) estimates that one ChatGPT search uses 6-10 times the power of a traditional Google search – compels us to improve their efficiency to meet sustainability goals. There are countless methods to pursue more efficient computing. Some, like campaigns that promote the use of traditional searches over AI products, rely on social rather than technical innovations. Other solutions use cutting-edge tech like quantum computers, which Villalonga et al. (2020) proved can solve complex math problems with 50,000 times less energy than standard supercomputers. Regardless, to promote energy security and carbon neutrality, efficiency concerns must be addressed if we are to meet the rapidly increasing demand for computing resources.

Design of a thermal conductivity measurement device for cryogenic applications

How can thermal conductivity of materials be measured in a 1K freezer?

For the mechanical engineering capstone, our eight-member group[1], advised by Professor Ethan Scott, will manufacture and test a vacuum-sealed insert to test material properties like thermal and electrical conductivity while submerged in a 1 Kelvin dilution freezer. The work's primary application is in quantum computing, which requires millikelvin-range temperatures to function. Therefore, understanding material properties at cryogenic temperatures is essential for designing future quantum technology.

[1] The capstone group includes Grace Milton, Jacqueline Harkins, Mehki Rippey, Kyle Holden, Erik McKenna, Madalyn Yates, Matthew Crowe, and me.

Quantum computing is expected to revolutionize scientific research by solving previously intractable problems in drug design, machine learning, cryptography, weather predictions, and countless others. Despite this, Troyer et al. (2023) note that the technology will fall short of its potential without global governance standards, equal access to the product, and deployment toward critical issues like food insecurity.

Both the technical project and its applications are limited by the cryogenic operating temperatures they require. For example, project prototypes will be tested in a dilution freezer that chills helium until it condenses at 4K and releases clouds of very expensive helium gas each time the freezer is unsealed. The project's success is further endangered by the metal chamber that holds samples in a vacuum, as it absorbs large amounts of heat from the surface.

Van der Linden and Behnia (2003) overcame these constraints to measure thermal conductivity below 1K and in high magnetic fields. Their probe used a vacuum chamber equipped with temperature sensors and expensive RuO resistors to measure thermal conductivity. However, replicating their assembly for large-scale applications would be cost prohibitive.

More recently, in 2020 physics researchers at MIT observed the coldest temperature ever recorded, less than one nanokelvin, with state-of-the-art collisional cooling methods that "immerse molecules of cold sodium lithium in a cloud of even colder sodium atoms" which act as a refrigerant (Son, 2020). Their work suspends materials of interest with laser cooling and rotating magnetic fields (magneto-optical traps), revealing quantum atomic properties but cannot determine thermal conductivity.

Seeking inspiration, the capstone group studied the Physics department's dilution freezer and prior dipper probes. After this visit, four subgroups formed to tackle the electrical, vacuum, structural, and sample mount design constraints. Teams meet on their own and in biweekly integration meetings with the advisor to update CAD designs, calculate heat transfer through the assembly, and ensure the subsystems fit together. The probe design is nearly complete, and its components will be ordered by the end of November. In the spring, the group will focus on manufacturing and testing, learning relevant machining skills (lathe, drill press, etc.) by February so sufficient time remains to build and test the probe.

In conclusion, the capstone group will design and test a low-cost thermal conductivity measurement probe for a cryogenic freezer to address the knowledge gap in material properties in the 1K range, for quantum computing applications.

The Making of Data Center Alley: Proponents and Critics

In Virginia, how have advocates and critics of new data centers advanced their agendas?

Virginia has the largest concentration of data centers in the world, with over 35% of all hyperscale centers operating within the state (Barnett, 2024). “Data Center Alley” emerged from a confluence of factors, including proximity to federal agencies/contractors, a favorable business climate, and relative safety from natural disasters, but also inspired a highly organized opposition. Groups like the Piedmont Environmental Council oppose further data center construction, taking part in a complex interaction that also includes utility providers, facility operators, local governments, and tech corporations. Due to the detached nature of modern computing (e.g. North Dakota Twitter users access data stored on Northern Virginia servers), the outcomes of this interaction have nationwide implications for computing access and efficiency.

Similar dynamics govern opposition to infrastructure development and data center construction. Cohen et al. (2013) identify many welfare decreasing aspects of new infrastructure that are similar across project types and foment public opposition, including “noise, pollution, ecological change, decreased property values and others," while defining social acceptance of infrastructure as occurring when the project's "welfare increasing aspects leave each agent *at worst* welfare neutral and indifferent, or better off and supportive of the project." Cohen also suggests avoiding areas with high environmental value, compensation for those with diminished property values, and including the public in planning processes to improve renewable energy project acceptance. Virginia state and corporate officials promote new data centers with insufficient consideration of developer-public relations, citing economic benefit to quell opposition.

Applying Jevon's paradox for computing efficiency is another powerful strategy for data center opponents to refute industry claims of sustainability. Woodruff et al (2023) calls this phenomenon "rebound," noting that computing efficiency gains from 2000-2005 were more than offset by increased server loads worldwide, generating a power consumption increase of 260%. Due to rebound, the authors recommend that tech companies transition quickly to renewable energy, a suggestion that Virginia data center developers have publicized but not yet embraced.

Powerful technology corporations like Amazon are the primary drivers of data center development as their cloud computing and AI products continue to expand. Since 2011, Amazon Web Services has spent an eyewatering $63 billion building a footprint in Virginia, with plans to invest $35 billion more by 2040 (Swinhoe, 2024). Corporate leaders tout these figures as victories for the state, saying that they create "hundreds or even thousands of jobs to build and run their data centers," developing a workforce of "cloud engineers, electricians, fiber optic cable splicers, and more" (Swinhoe). Meanwhile, Amazon makes a windfall taking advantage of

Virginia's generous sales tax exemptions and subsidies, with the most recent AWS earnings statement showing a $10.45 billion profit last quarter (CNBC, 2024).

Amazon's massive physical footprint in Virginia has drawn the attention of national advocacies like Greenpeace, whose 2019 report detailed how the company turned its back on transitioning to 100% renewable energy. The report casts Amazon's relationship with Dominion (Virginia's utility provider) as concerning because it created additional pressure to build the Atlantic Coast Pipeline and accelerated Dominion's shift toward natural gas (Greenpeace, 2019). In doing so, Greenpeace calls attention to Amazon's "greenwashing" to slow further expansion efforts and prevent environmental degradation.

At a local level, community organizations like Citizens for Fauquier County often pursue legal action to block new data center construction, citing non-compliance with zoning ordinances, tree removal, traffic, noise, and potential property value loss as concerns. (Schumaker, 2024; PEC 2024). Since these projects usually receive final approval from town/county legislators, lawsuits and direct appeals to elected officials are valuable, accessible tools for citizens concerned about the expansions. Other local groups like the Coalition to Protect Prince William County appeal directly to fellow citizens' emotions, decrying data centers' threats to natural and historical sites. They even compare the takeover of land to forest destruction in Dr. Seuss's The Lorax, posting the whole story on their website (Protect PWC, 2023).

In 2010, Virginia legislators created the largest economic development incentive in the state, an exemption for state sales and use tax for data centers if they led to:

- $150 million in new capital investment and
- 50 new jobs located at the data center associated with the facility's operation or maintenance, where each job must be paid >150% of the annual average wage. (VEDP)

As one of 11 incentives for attracting computing facilities, the measure has helped Virginia keep its status as America's data center capital, but growing electricity and water footprints have prompted recent reevaluation. Last year the state's Joint Legislative Audit and Review Commission began a study about the industry's effects on energy infrastructure, considering citizens' concerns and noting that policy changes may be in order if current incentives are not effective (JLARC, 2023).

Even with recent efficiency improvements, data centers form a large fraction of energy consumption in Virginia, and the Electric Power Research Institute estimates that this portion could reach 46% of the state's overall electricity use in high growth cases (EPRI, 2024).

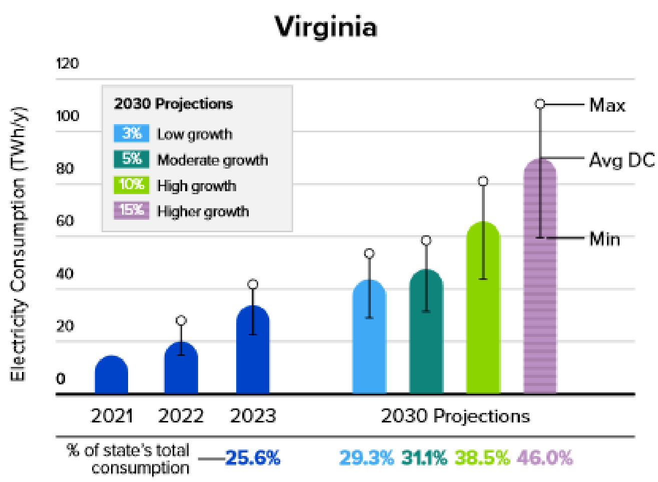

Figure 1: Data center electricity use could range from 29.3 to 46.0% of Virginia's total by 2030, depending on growth rate (EPRI, 2024)

Some environmental advocacy groups like Appalachian Voices and the Southern Environmental Law Center allege that Dominion purposely inflates its growth forecasts to justify new power plant development. Last year, AV and SELC lobbied the state to reject Dominion's official Integrated Resource Plan, claiming that since most of Dominion's forecasted growth comes from just five companies, it is too risky to pursue increased grid capacity (Vogelsong, 2024).

Dominion's IRP was eventually approved, but SELC has valid concerns that power consumption is too highly concentrated among a few corporations: in 2019 Amazon alone used 1.7GW of capacity in Virginia in 2019, the equivalent of more than 3 large coal power plants (Greenpeace). The SELC therefore warns Virginians could face electricity price shocks if the relationship between Amazon and Dominion were to worsen.

Data centers tend to exist outside the public eye due to their unremarkable appearance, yet they form an increasingly vital part of our modern infrastructure. Therefore, lobbying, lawsuits, and state environmental & financial reports become important tools for data center proponents and critics to quietly advance their agendas.

(1691 words)

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