SMR and Solar Hybrid Energy Systems for Rural Electricity Demands

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Introduction and Literature Review

Currently, in the United States, access to energy remains a huge issue among many communities–specifically those in a rural setting. Unlike cities with modern infrastructure, rural communities suffer from outdated power grids and electricity sources. These systems are too expensive to provide upgrades, and therefore not future-proof like many other solutions. Currently, they cannot handle the growing energy demands across the country. This makes it harder for people to run businesses, removes access to educational opportunities, and makes it difficult for many to heat their homes properly. Fixing this is about making sure everyone is given the tools to grow alongside the country into a sustainable and green future.

To address these matters, nuclear energy has been an appealing solution. Utilizing smaller and cheaper Small Modular Reactors (SMRs) and solar energy together, could make energy more accessible. SMRs are newer and safer than old nuclear systems, and they do not possess the same negative outlook. Combining SMRs and solar energy into what's known as a hybrid system, can provide steady electricity around the clock. Solar has already been implemented nationwide and continues to grow due to its renewable, increasingly affordable, and popular status. Together, SMRs and solar can create energy systems that are dependable and environmentally friendly. This study will explore whether this hybrid approach can truly help these rural communities, where the need for innovative solutions is pressing.

The Importance of Energy Equity

Energy problems in rural communities aren't new. They've been around for decades, but the urgency to fix them is growing as the country moves toward decarbonization. Right now, many of these rural settings have older grids. These older grids have outages quite frequently, and are therefore expensive to maintain and repair–it's time to upgrade. For families and businesses in these areas, unreliable electricity isn't just frustrating—it affects everything from farm production to keeping the lights on in schools. According to the Department of Energy, most rural households spend about 25% more on energy than urban households, which has stood as a large burden for lower income families.

Energy equity has been targeted by programs such as REAP, or the Rural Energy for American Program, which has funded renewable energy projects. But these efforts often focus on solar or wind without addressing the reality that these energy sources can't run 24/7 without backup. Hybrid systems—where SMRs provide consistent power and solar handles peaks—might be the missing piece that bridges this gap.

Hybrid Systems

Why hybrid systems? It's simple. Solar power is great because it's renewable and getting cheaper, but it can't generate electricity at night or during cloudy weather. SMRs solve that issue by providing consistent, low-carbon power, day or night. Together, they create a balanced system that can handle both regular energy needs (base-load) and the spikes that happen during high-demand times (peak-load).

Hybrid systems are also versatile. For example, research by Rath and Morgan (2020) found that pairing a 200 MW SMR with solar panels could reduce emissions by 50% compared to traditional fossil fuels. And unlike building entirely new grids, these systems are easier to set up in remote areas. Studies like this underline the potential, but they rarely focus on rural U.S. communities, which have unique challenges like limited budgets and rugged terrain.

Nuclear and Solar Energy Historically

In order to clarify why these technologies (SMRs and solar) function so well together, it is essential to look back at how the technologies first started. Nuclear energy has been a major player in the US since the 1950s, with reactors growing massively until the 1990s. At its peak usage in the 1980s, it provided over 20% of the nation's electricity, but safety concerns and its price led to a decline. Accidents like Chernobyl in 1986 and Fukushima in 2011 created a negative social stigma toward nuclear energy, despite the proven safety of today's reactors. According to organizations like the World Nuclear Association, the modern SMR designs include passive (no human intervention) safety systems which help them stand out as secure and reliable, unlike previous reactor designs which put human lives at risk (WNO, 2022). In addition to this, solar power has become significantly more popular, as the cost of the panels have seemingly dropped 89% since 2010 (International Energy Agency, 2022). This has made it one of the most accessible energy solutions, though it isn't perfect. One major drawback of solar is that it relies on sunlight alone , making in ineffective during harsh winter weather and during night time. A good way to address this is to pair it with SMRs, which would cover its lacking aspects.

What's Being Done Right Now

In recent times, the U.S. government has begun to pay more attention to the various ideas, but the progress is still not as fast as needed. The Inflation Reduction Act (2022) included billions in tax credits for renewables like solar and wind, but nuclear energy hasn't received the same level or any truly relevant amount of funding. For context, the Department of Energy allocated only $6 billion to support existing nuclear plants (which are also currently aging and reaching the end of their lifetime) and fund SMR research under the Bipartisan Infrastructure Law (2021). Compare that to the $12 billion for wind and $7 billion for solar, and it is clear how nuclear energy is struggling to keep up (World Nuclear Association, 2022).

That said, there's been a recent shift. With more support from both political parties, there have been initiatives pertaining to advanced nuclear technologies. Additionally many policymakers are recognizing the importance of SMRs, and their role in transition America to clean energy. Committees like the Nuclear Regulatory Commission (NRC) have started to approve many SMR designs, and some states, including Wyoming and Utah, are looking at different hybrid systems like my proposed one, that include both nuclear energy and renewable energy. These efforts seem effective, but they're mostly focused on urban settings. Rural communities, where hybrid systems could have a major impact, still aren't a major focus.

Research Gap

While there is much interest surrounding the implementation of Small Modular Reactors in the united states, as well as solar energy, they are currently treated as two separate solutions. Most existing research for SMRs focus on urban implementation and how it can build on top of already solid energy infrastructure. The gap that needs addressing is a proper analysis of how SMRs and solar energy could be combined to aid rural communities in the US that lack access to a reliable grid.

This is important as rural communities possess unique needs, and rural communities are the foundation for America, particularly with agriculture. Rural communities often also face very harsh weather, suffer significantly higher electricity cost, and possess little resources for large infrastructure-shifting projects. If there is no research to form a basis for their implementation, it stands difficult to earn the investment to support the hybrid systems. Filling this gap has real world implications, particularly for energy equity, and meeting the US's sustainability goals.

Hybrid Systems Moving Forward

Moreover, the hybrid SMR and solar systems support the United States' clean energy and sustainability goals. The

Department of Energy (DOE) hopes to reach a net-zero emissions state nationwide by 2050, and the hybrid system could aid in achieving this goal by reducing fossil fuel emissions in areas that currently have a heavy reliance on them (which rural communities do). In addition to this, the systems contribute to the UN's Sustainable Development Goals (SDGs)–Mainly Goal 7, which is Affordable and clean energy for all.

The economic standpoint of the issue is clear, with the nuclear industry already supporting over 500,000 jobs in the U.S., and contributing over $60 billion to the GDP every year as of 2021 (U.S. Office of Nuclear Energy, 2021). The smaller and more compact aspect of SMRs, along with their quick deployment times, could provide even more economic benefits to these rural settings. Joining together SMRs and solar energy would add to a dying job market, creating jobs needed for the manufacturing, construction, and maintenance of these plants.

Investigating The Need/Gap

Overall, the SMR and solar hybrid system could be an important part of aiding energy needs. By taking advantage of solar energy's daytime strengths (base load), and pairing it with SMRs, the system can effectively supply reliable energy to these rural communities across the United States. Regardless of the impact shown, there has not been too much research on the matter, and current studies focus on SMRs and solar energy separately. This research gap leaves a very important question that I hope to answer: How can a hybrid energy system containing Small Modular Nuclear Reactors and solar energy effectively support the electricity needs of rural communities with aging electrical infrastructure?

The study hopes to address the gap by looking into the reliability of the SMR and solar system for rural communities. By analyzing technical (specifically base and peak load needs), social, and financial factors, this paper looks to bring forth a promising solution to a pressing nationwide energy crisis. In addition to this, the research also aims to help the nation's and world's goal of a sustainable future, enabling communities with clean and reliable energy who have been left behind in an era of energy innovation.

Methods

My research project utilizes various methods. I will be looking at case studies from different rural towns in America, performing a comparative evaluation of electricity/power needs, as well as modeling some scenarios to show the potential of my proposed energy system. As discussed previously, these rural areas have distinct energy challenges, which do not mirror the solutions provided for urban settings. Therefore, I had to take on a more diverse approach, to truly gain an insightful understanding on the technical feasibility, the social implications, and economic impact of the proposed system.

Case Study Method

I chose 4 rural communities to perform in-depth case studies available (these were some with publicly available data as well). They include:

- Nome, Alaska
- Beaver Island, Michigan
- Navajo Nation, Arizona
- McDowell County, West Virginia

These were each chosen to show the different levels of grid accessibility, as well as the energy burden and environmental conditions (Nome is snow covered and Navajo is the polar opposite). The goal was in-turn to show how these varying location factors such as isolation, dependence on the existing grid, diesel use, and solar effectiveness influenced the practicality of my proposed system.

Each of the four case studies goes into:

- Their current energy systems and how reliable or safe they are
- Price of energy compared to the system
- Access to energy, or grid availability
- Solar energy feasibility
- Socioeconomic status of the area (financials are one of the major downsides to this project)
- What the impact of the hybrid system could have

By looking at various areas across the US, all in distinct rural settings, my research contains a much more in-depth and broader understanding of how the hybrid system applies in these conditions.

Comparative Analysis

I utilized a comparative analysis, looking at the hybrid system's predicted energy output and performance, and comparing it to the traditional diesel and coal based systems. Some of the metrics I used to compare include:

- The Levelized Cost of Energy (LCOE) *or the average cost of producing energy over energy sources lifespan*
- The energy burden, including the percentage that these households already spend on their power
- How carbon emissions can be reduced
- The resilience of the system compared to the current ones, and how reliable they will stand

This section of the research can help to show more than just a technical standpoint. It helps by showing the economic as well as social benefits the hybrid system enables.

Scenario Modeling

In terms of this approach, I modeled scenarios that predict the performance of the system in different weather conditions (very general). These include addressing:

- The variation of solar energy performance in different seasons
- The need for backup power in emergency power outages
- The growth in demand for energy as population increases
- The change (increase or decrease) in diesel and fossil fuel prices (new political party may make a shift towards this)

This way, this study can cover the long-term effects of the project, and make for a more holistic perspective of the proposed system's feasibility. This model makes the assumption that the SMR output remains the same and the solar input changes according to the past seasonal data provided by the National Renewable Energy Laboratory (NREL, 2024).

Criteria For Rural Community Choice

The case studies selected were made for the four communities due to the following:

- Data Availability: Much data is not available on other rural communities, so it was convenient that this data was made public recently
- Current Energy Source Dependency: Communities with a heavy diesel or coal reliance were chosen as this is where a cleaner alternative truly stands to aid
- Access to Grid: Communities with absolutely no grid access like Nome, to those with poor grids but still available like McDowell were chosen.
- Solar Compatibility: If the community would work effectively (Navajo Nation) or not (Nome)

This allowed for an added layer of diversification for data collected, showing various situations to properly analyze, and strengthen the truth and reliability of my findings. Again, no part of America should be left behind, and this is a generalized but widely applicable solution–it's all about equity.

Method Strengths

By combining the technical feasibility with the modeling, with the social and economic impact given from the case studies, this study views many dimensions of the overall function of the system. The focus on real-world situations helps prevent a greater generalization, by making my data more specific.

Method Limitations

Most of the limitations pertain to my case-study approach, as my findings may not fully represent all rural communities. This is a very small sample of a greater rural America, and the political climate also varies across these communities. Additionally, the model makes the assumption that the cost of the technology will remain stable and decrease as before, and also assumes that political support for the development of nuclear energy remains constant, both of which could drastically change soon.

Ethical Considerations

In terms of the ethics, special attention was given to the date to ensure it didn't misinterpret the needs of rural communities (specifically Navajo Nation). In addition to this, the environmental and social benefits were widely looked at, to not take a one-dimensional technical standpoint, and to ensure a better ethical evaluation.

Findings

This section will explore the data collected, and the findings from the four different case studies. I focus on 3 points; technical, economical, and social factors, which intersect to determine the feasibility of my proposed hybrid SMR-solar energy system for rural US communities.

Rural Energy Demand Table

Sector	Daily Energy Demand (MWh)	% of Total Rural Demand
Agriculture	5,120	10.2%
Residential/Commercial	44,880	89.8%
Total	**50,000**	**100%**

(Source: U.S. Energy Information Administration [EIA], 2023; U.S. Department of Agriculture [USDA], 2016)

- Most of the 5,120 MWh is used up for irrigation, drying grain, and large-scale livestock operations
- The residential and commercial demand breaks down into primarily heating (more significant in areas like Nome), lighting, as well as usage of everyday appliances.

Note that this is a generalization into two greater categories, as a further breakdown is not so important to look at in this study.

Estimate for Proposed Hybrid Energy System Output

Energy Source	Capacity	Daily Production (MWh)	% of Daily Rural Demand
SMR (300 MWe)	300 MW	7,200	14.4%
Solar (1 GW)	1,000 MW	4,800	9.6%
Combined Output	**1,300 MW**	**12,000**	**24%**

(Source: International Atomic Energy Agency [IAEA], 2024; National Renewable Energy Laboratory [NREL], 2024)

According to the data, an SMR-solar hybrid system would cover around 24% of the overall rural electricity demand. By scaling this up, the gap could be closed.

Case-Study Summary and Feasibility

Region	Energy Source	Demand (MWh/day)	Cost ($/kWh)	Grid Access	Solar Suitability	Energy Burden
Nome, AK	Diesel	~15–20	$0.44	Isolated	Moderate	High
Beaver Island, MI	Grid + Diesel Backup	~27	~$0.115	Cable to mainland	Moderate	Moderate
Navajo Nation, AZ	Diesel, Off-grid	~40–50	$0.15–$2.00	Severely Limited	Excellent	Very High
McDowell, WV	Grid (Coal)	~300	~$0.10	Connected	Moderate	Very High

(Source: DOE, EIA, NRDC reports, 2024)

Nome, Alaska

Energy Challenges

Nome suffers from incredibly high energy costs, due to the town relying entirely on imported diesel fuel. There is one fuel barge a year, and if it doesn't arrive, they are left without fuel for a while. The harsh winter conditions make energy less accessible, pushing the energy cost to over $0.4/kWh. The lack of a proper grid connection leaves Nome with no backup supplies, and solar power is only effective during summers.

Why Hybrid Systems Would Help

- The 300 MWe SMR could run all year and provide solid base-load energy for Nome
- Alaska does actually have bright summers, so solar would be highly effective during these summer days, reducing the reliance on diesel.
- The hybrid system would make sure Nome is not vulnerable to a lack of backup power, or spikes in energy cost due to no fuel barge arriving.

Nome Environmental Impact

- There would be a nearly complete cut of diesel use, significantly cutting carbon emissions.
- The Arctic ecosystems surrounding would no longer be affected by the high levels of pollution and diesel spills.
- It would also support the goals Nome has set to transfer to clean energy, and reduce the reliance on outside energy supply.

Nome Economic Impact

- Due to the lower amount of fuel importance, the annual cost of energy would go down by almost 30%
- The energy savings could be reinvested into more local infrastructure and services, specifically for this system
- The system creates opportunities for more jobs, with the SMR operation needing to be watched as well as the solar panels to be maintained.

Nome Social Impact

- There would be much more affordable electricity, making QOL way better throughout Nome.
- Schools, hospitals, and businesses would safely be able to operate.
- Homes would be heated year-round.

Beaver Island, Michigan

Energy Challenges

Beaver Island in Michigan is connected to land by a singular underwater cable, and has diesel generators for backup electricity. There are frequent outages with the bad weather, and that one cable is incredibly expensive to maintain. Solar is already used in the surrounding areas, so implementing it here would be smart.

Why Hybrid Systems Would Help

- An even smaller scale SMR could provide better backup energy and peak-load support.
- Solar energy could allow for stronger support when there is heavy tourism in summer, and decrease the main grid load.
- This would heavily reduce the reliance on the singular cable that supports the island.

Navajo Nation, Arizona

Energy Challenges

The Navajo Nation, specifically the Arizona part, is not connected to any grid. Many of these native households rely on high cost and inefficient diesel generators. It's a shame that Native Americans have been left exempt from America's plan to move towards a greener future.

Why Hybrid Systems Would Help

- The great amount of sunlight would make solar power quite important here.
- SMRs would fill the gaps–cloudy days, rain, etc…–providing for an effective and stable system.
- The system would allow for more education access, healthcare, and other economic opportunities.

McDowell County, West Virginia

Energy Challenges

McDowell has a very old, coal-dependent system, which is unsafe, old, and incredibly unreliable. McDowell has some of the highest poverty rates. Even though the energy cost is pretty low, the actual energy burden is quite high.

Why Hybrid Systems Would Help

- The decaying coal plants could be swapped out with new clean energy from SMRs.
- Solar energy could allow for better summer coverage.
- This would also create many jobs, allowing for management of the plants and the solar farms, and fighting the poverty and lack of job opportunities McDowell suffers from.

Data Analysis

This section of the paper looks at the data collected to figure out the feasibility and true impact of my proposed hybrid SMR-solar energy system, in rural communities. It will have a similar approach to the findings section–technical evaluation, cost consideration, and socioeconomic impact.

Technical Feasibility

The daily estimated rural energy consumption is estimated to be around 50,000 MHw/day (U.S. Energy Information Administration [EIA], 2023; U.S. Department of Agriculture [USDA], 2016).
To recap, the data shows that a singular 300 MWe SMR system will produce around 7,200 MWh of electricity per day, and a 1 GW solar unit would produce around 4,800 MWh daily (International Atomic Energy Agency [IAEA], n.d.; European Commission, n.d.; National Renewable Energy Laboratory [NREL], 2024). If you combine these systems they produce a total of 12,000 MWh per day, covering 24% of the total rural demand (refer to data collection section to see full table and breakdown). This approach, where each system covers the others weaknesses, uses the steady and reliable output of SMRs to counteract the night time unreliability of solar power. Though the current hybrid solution proposed addresses only a portion of total demand, it can easily be scaled up, expanded on, or even coupled with other renewable energy systems to have greater impact.

Cost and Deployment Considerations

The cost and initial investments required play quite the important role in determining the viability of the system. The different options examined for deployment include the three possible configs:

- Single SMR (300 MWe): This has an estimated capital cost of $1.5-2.5 billion, and an LCOE of $60-100 per MWh
- 1 GW Solar + Storage: This has an estimated capital investment of $1.2-2 billion and an LCOE of $45-80 per MWh
- Hybrid (SMR + Solar): Finally and most notably, the combined system has an estimated cost of $2.5-3.5 billion, and an LCOE of $50-90 per MWh.

According to statistics provided by the US Dept. of Energy, and the EIA, while these SMRs require a high upfront investment, the cost it takes to actually maintain them, and their longevity coupled with their consistent energy output makes them a much more compelling option. Solar power, while they have a lower LCOE, requires a storage system in order to continuously power areas. The hybrid system balances all of these pros and cons, allowing for a more stable and reliable energy solution for rural communities.

Socioeconomic Impact

The socioeconomic data shows that all rural households spend on average around 1.25x more on energy than urban ones (DOE, 2022; Natural Resources Defense Council [NRDC], n.d.). This significantly limits the potential for economic growth, and makes energy inequity a much greater deal in these communities. The implementation of a hybrid SMR-solar system could aid in breaking down these barriers, and enabling reliable and relatively inexpensive energy across these communities. In addition to this, many new policies, such as the Inflation Reduction Act and the Bipartisan Infrastructure Law, have been put in place to foster more development of renewable energy as well as nuclear energy tech. The policies could allow for more funding and political support, allowing for the deployment of my proposed hybrid system to be significantly more feasible in rural settings (DOE, 2024).

Environmental and Social Equity Impact

The diesel and coal based system cause lots of pollution in these rural communities, standing as a great threat to the safety of the ecosystems, and harming both public health and biodiversity. The hybrid systems would substantially reduce the emissions produced, irrespective of where the rural community is in America. For example, in Nome, it could eliminate the thousands of tons of diesel/energy related carbon emissions produced annually. In McDowell County, the coal based system would be swapped out with a zero emission hybrid SMR-solar system.

Moreover, the path to energy equity, which includes expanding energy access and reliability, ensures that many of the historically underserved communities are not left behind as the nation moves towards a green future. The hybrid system allows for more than just energy equity, but energy justice:

- It lowers energy cost for many of the marginalized communities.
- It reduces the risk of natural disaster or climate induced incidents.
- It allows for economic prosperity, with more jobs, and cleaner energy.

Scalability and Nationwide Applicability

The modularity of this hybrid module allows for more in-depth customization across regions. For example in the more solar rich areas like Navajo Nation, a larger solar installation would reduce the need for a higher SMR daytime output. In cloudier areas like Nome, a more SMR reliant system would allow for solar to only cover seasonal peaks.
This adaptable system makes my proposed hybrid model not only technically outstanding, but also socially and economically adaptable to the various rural regions across the US.

Conclusion

Further Direction and Synthesis

The technical feasibility review shows that the overall output from the SMR-solar hybrid energy system meets around 24% of rural energy needs. This figure reveals how the system can be scaled easily. With small capacity increases over time, as well as adding in more renewable energy sources, the hybrid model could potentially expand to address a greater portion of rural demand. Additionally, the cost portion of the analysis shows the importance of having a more well-rounded deployment strategy. Although there is a significant amount of initial funding the hybrid system demands, there is much more potential for greater reliability improvements, as well as a reduction to the overall operational costs. There is a clear long-term solution, and method of addressing sustainability goals this way.

Any further research should definitely focus on optimizing the configuration of the system, and going more in-depth on some of the technical aspects, and data that I was unable to obtain. Moreover, one of the most important things is the view of the energy system. Future research should focus on optimizing system configurations, exploring region-specific energy demands, and evaluating the impact of evolving policy frameworks. Such efforts will be critical in developing a comprehensive roadmap for the practical implementation and expansion of hybrid energy systems in underserved rural communities.

Assumptions and Limitations

This study is on the basis of several vital assumptions. Firstly, it assumes that the energy technology will continue to advance at a similar rate to what it currently is, and SMR costs will gradually reduce. Additionally, given how much solar panel costs have dropped in the last 15 years, I am also assuming that trend will persist. It also makes the assumption that there will be a continued political and financial interest in such a project, especially for the various clean energy initiatives. The acceptance of SMRs nationwide is expected to swiftly improve, and this will help speed up deployment in isolated communities.

Limitations also exist. The costs assumed for SMRs are based solely on proposed designs as opposed to a more large-scale operational standpoint, from existing American-based projects. The rural setting is a difficult one, with its own unique challenges–difficult terrain, poor infrastructure, and varying climate. In addition to this, with a continued negative social stigma surrounding nuclear energy, it may be hard to adopt these systems within a reasonable time frame.

Conclusion

In conclusion, my proposed hybrid SMR-solar energy system provides a promising gateway to defeating energy inequity across rural America. Mixing the reliability of Small Modular Reactors, with the daytime power of solar energy, can truly lead to a powerful energy system that would defeat aging infrastructure, high energy costs, and limited grid access.

While there may be setbacks during the initial deployment, there are countless long-term benefits (discussed throughout this paper) in terms of achieving a greener future, plain reliability, and affordability. With more specific and region specific research, as well as stronger support pushing SMR implementation, the potential for this system can be fully realized. With proper investment and continued technological developments, this hybrid energy system, as well as similar configurations, can be what America needs to promote energy equity, and make sure that no community is left behind in our country’s transition to a cleaner, greener, sustainable future.

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