University of California, Irvine

Resource Dynamics and Techno-Economic Assessment of Renewable Power Solutions for Data Centers as a Solution to Reduce Energy Inequities in the Least Developed Countries

Thesis

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MASTER OF SCIENCE

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by

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Dedication

To all the teachers and professors who have taught me everything I know.

"Unless someone like you cares a whole awful lot, nothing is going to get better. It's not."

-Dr Seuss, *The Lorax*

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Acknowledgments

I would like to thank my advisor, Professor Brouwer, for his constant support.

I would also like to thank my colleague Melina for allowing me to use her data center model in my research.

Lastly, thank you to my parents for supporting me and believing in me during every step of my academic journey.

Abstract

This thesis investigates the feasibility of using carbon offsets to incentivize corporate investments in renewable infrastructure in developing nations. Corporations have historically been substantial greenhouse gas producers and possess the opportunity to offset their emissions while increasing energy equity. The methodology encompasses several key components: identification of countries that exhibit the greatest need and ability to be supported by renewable infrastructure, emissions modeling to provide context for potential greenhouse gas mitigation, technoeconomic modeling of a renewable data center, and additional renewable infrastructure for residential communities as a means for technology companies to contribute to regional progress. A comprehensive analysis delves into the specific contexts of the Central African Republic, Chad, Niger, and South Sudan, highlighting their potential for sustainable development. Djibouti is considered as an alternative location within the region. Among these, Niamey, Niger emerges as a cost-effective location for a data center, with a levelized cost of electricity at $182.58/MWh for hydrogen storage. However, Djibouti City, Djibouti is a viable alternative location at $183.54/MWh with the added benefits of political stability and strong ties to the United States. For regions where alternative solutions are necessary, options such as efficiency improvements and renewable fuels are considered. The collaborative efforts of nations and more affluent entities are essential to drive the changes needed to combat climate change and address energy inequity.

1 Introduction

The least developed countries in the world face a variety of economic, environmental, and health-related challenges. This research assesses a potential solution to address the energy-related problems faced by these nations. Corporations contribute substantially to climate change, but increasingly are also investing in projects to reduce their greenhouse gas emissions as well as to offset their emissions. This research outlines the prospect of carbon offset projects as a tool to address energy inequity in the least developed countries in the world.

The first step is identifying the countries with the greatest need for renewable energy adoption and evaluating their suitability for renewable energy installations based on land usage and topography. ArcGIS allows for a more detailed land analysis of a few selected countries to locate and visualize suitable regions for renewable energy infrastructure, as well as the size requirements for complete reliance on renewable energy. Solar power is selected as the primary renewable energy source due to its availability in virtually every part of the world and its increasingly low cost. An analysis of projected future emissions contextualizes the potential mitigation of greenhouse gas (GHG) emissions in these countries as their development continues.

The modeling of a renewable data center near the capitals of these countries aims to encourage tech companies to establish data centers in these regions, fostering technological opportunities. Increasing solar capacity to reduce storage requirements is explored as an option to potentially cut costs and provide excess energy to the surrounding area. Investing in additional solar and storage for the surrounding communities allows for more consistent delivery of renewable energy. The storage methods considered will be batteries and hydrogen produced from electrolysis. A comprehensive feasibility analysis will consider the levelized cost of electricity, the potential for carbon offsets, and the availability of resources to determine the preferred location for a renewable data center aligned with corporate needs. Alternative solutions for regions where the proposed model may not be viable will be explored.

2 Background

Scientists have warned that greenhouse gas emissions must be reduced to prevent irreversible climate change. Many of these emissions result from fossil fuel usage, harming the climate and human health. Moreover, fossil fuel reserves are concentrated in specific regions, with nearly half of the world's oil reserves in the Middle East and three-quarters of gas reserves in Eastern Europe and the Middle East as of 2022 [1]. The long-distance transportation of fossil fuels to areas lacking these resources can pose challenges, particularly during times of conflict.

Renewable energy offers a path to minimal end-use emissions. However, the accessibility of renewable energy varies worldwide. Many countries that primarily depend on renewable energy, such as Iceland and Norway, benefit from their proximity to hydroelectric and geothermal energy sources [2]. Solar energy offers a promising solution due to its widespread availability. Using locally produced solar power can reduce the need for regions to import energy from other countries, reducing emissions associated with energy imports and end-use.

A current barrier to reliance on solar power is its large spatial, daily, and annual variabilities. Solar energy production peaks at midday, which often corresponds to a period of low demand, while energy demand surges in the evening when solar energy availability diminishes. This creates a gap in energy supply and demand, referred to as the duck curve [3], resulting in insufficient renewable energy when it's most needed. In addition, the seasonal variability of solar can produce the need for large size and long-duration storage [4].

Some solutions to address intermittent solar energy include installing higher-capacity renewable electricity systems and storing excess renewable electricity for use during off-peak hours. Two methods of storing excess renewable energy include charging batteries or producing hydrogen gas through electrolysis. While electrolysis requires access to fresh water, it presents fewer spatial limitations than fossil fuels. Current research efforts are underway to develop hydrogen production from seawater.

2.1 Inaccessibility of Sustainable Solutions

The adoption of energy storage solutions has been lagging in comparison to solar adoption. While costs have decreased over time, affordability is still a concern, especially for those struggling to pay their electric bills. For example, in California, the mass installation of rooftop solar without concurrent energy storage solutions has resulted in California paying other states to consume its excess electricity [5]. California also utilizes net energy metering (NEM) where residents are paid by utility companies for their excess solar to be used elsewhere on the grid. The newest version of California's net energy metering, NEM 3.0, majorly reduces the amount residents are compensated for their solar and instead offers incentives for battery storage [6]. While incentivizing battery storage is a partial solution, it increases the initial cost to consumers.

Overbuilding solar capacity and curtailing excess electricity produces challenges as well. While this approach can address higher energy demand, it poses economic challenges due to the large initial investment. In addition to upfront costs, installation of rooftop solar is more challenging for renters [7], who are disproportionately minority groups [8]. Additionally, photovoltaic (PV) systems are less likely to be in communities of color, regardless of income level and home ownership [7], highlighting systemic issues in solar deployment in the United States.

Other sustainable solutions face similar accessibility issues. Replacing appliances and mechanical systems with more efficient models has a large upfront cost with a long payback time. Electric cars have recently gained popularity but are often marketed as luxury cars with higher upfront costs that prevent adoption [9]. Additionally, many do not have access to a garage or a reliable electric grid to charge their vehicle, and income and racial disparities exist where community charging stations are located [10]. Public transportation can majorly increase commute time, decreasing the time an individual can work and care for their health or family. Many consumers are unable to afford lifestyle changes to mitigate their environmental impact. Consumers are always told to be mindful of their actions to care for the environment, even though their impact is much less than that of massive corporations. Since the industrial revolution, 100 fossil fuel producers have been responsible for half of the global greenhouse gas emissions [11].

The ability to adapt to issues caused by climate change is also an issue. On a global scale, the countries most vulnerable to climate change are the ones who contribute to climate change the least and often lack the resources to adapt effectively. This has been illustrated by the Notre Dame Global Initiative (ND-GAIN) matrix, which shows a negative correlation between vulnerability and readiness [12], [13].

2.2 Offsets and Renewable Energy Credits

Corporations have large financial resources to alter their practices or invest in mitigating climate change. Investment in renewable technologies is rising, including from corporations that are historically prominent fossil fuel producers [14]. In recent years, clean energy investment has surpassed fossil fuel investment [15].

Many companies have pledged to become net zero by “canceling out” their carbon emissions [16]. Offsets and Renewable Energy Credits (RECs) are two strategies to do this.

Offsets result from projects that enable entities to claim reductions in or avoidance of greenhouse gas emissions across various scopes. RECs verify the purchase of renewable electricity, allowing entities to claim using it to cancel out their scope two emissions, which are indirect emissions from the generation of purchased energy.

Offsets require testing for additionality, which confirms that the project would not have occurred without the incentive of carbon offsets. RECs do not require testing for additionality [17]. This theoretically allows corporations to purchase the rights to existing renewable electricity instead of investing in new renewable electricity infrastructure.

Investment in renewable infrastructure near the source of the emissions (such as factories) can maximize the direct impact of offsets on air quality, human health, and climate change. However, geospatial limitations, such as land availability and topography, may prevent this. To promote energy equity through offsets, corporations can invest in renewable infrastructure in areas highly susceptible to climate change and unable to access renewable energy otherwise, particularly in underdeveloped countries.

Many technology and software companies have pledged to be carbon-neutral or carbon-negative. Data centers are large energy users that are rapidly expanding and great potential candidates for carbon offset projects and promoting development. Constructing an excess of solar infrastructure enables large reductions in energy storage and associated expenses. Excess electricity is typically curtailed or “thrown away,” but it could be sent to the adjacent communities in this scenario. Investing in additional infrastructure beyond the needs of the data center could help provide reliable, clean energy to the surrounding population and allow for additionality and larger claims for carbon offsets.

2.3 Least Developed Countries

Countries that could benefit the most from carbon offset projects are the least developed countries (LDCs), which the UN has designated to receive additional assistance based on income per capita, health and education levels, and economic and environmental vulnerability. The list of LDCs is reviewed every three years. Of the 46 countries currently classified as LDCs, 33 are in Africa [18]. Africa has previously been explored as a candidate for large-scale solar installation, especially in North Africa, where the Sahara Desert is located [19]. Past and ongoing projects or studies suggest installing solar in the Sahara Desert and exporting a large portion of it elsewhere to meet regional or global energy needs. These studies often focus on the current energy usage of the world [19], [20]. This perspective neglects to account for the future projected energy usage of the world. More importantly, it overlooks the necessity for currently underdeveloped regions to gain greater access to energy, fostering their economic, social, and technological development.

This research aims to determine the theoretical land requirements necessary to provide renewable energy to data centers and provide entire countries with energy levels per capita comparable to those in middle-income and high-income countries while ensuring that all of this energy is from and remains within their borders.

2.4 Potential for Increased Access to Clean Water

More than 600 million people in the least developed countries cannot access safe drinking water [21]. Sub-Saharan Africa is one of the regions that is particularly struggling when water resources such as rivers and lakes are present but are subject to pollution [22]. Wastewater has been considered to produce hydrogen, often using biological processes to consume the waste, resulting in hydrogen gas [23], [24]. Others have considered novel methods of electrolysis as a means to remove pollutants from industrial wastewater [25]. This analysis will consider conventional wastewater treatment as a means to achieve the clean water standards needed for electrolysis. While not directly considered a carbon offsets project, a corporation could oversize the water treatment plant to supply clean water for electrolysis and clean water to the surrounding communities.

3 Goals and Objectives

The goal of this research is to evaluate the technoeconomic viability of corporate-funded renewable energy infrastructure serving as carbon offsets in the least developed countries with the most pressing need for energy equity.

The objectives of this research are as follows:

a. Identify the least developed countries with sufficient available land and the greatest need for renewable energy infrastructure.

b. Conduct an in-depth analysis of land suitability, energy, and pollution modeling for the entire population of the chosen countries, using energy consumption patterns of middle- and high-income nations.

c. Perform a technoeconomic analysis for a renewable data center powered by solar energy, incorporating storage options such as batteries or hydrogen, situated in the capitals of the selected countries.

d. Perform a technoeconomic analysis for additional community-based renewable infrastructure to support residential communities.

e. Explore alternative solutions for improving energy access in these regions.

4 Analysis of the Least Developed Countries

4.1 Methods

4.1.1 World Development Indicators

Our World in Data is a resource with various collections of data regarding energy worldwide displayed visually and graphically [26]. The collection of 157 energy-related graphs was narrowed down to 58 related to the scope of this research. A noteworthy observation was that the percentage of the population with access to electricity in each country [27] was incredibly low in some regions, especially landlocked African countries. This region included South Sudan, the country with the lowest proportional access to electricity worldwide. Upon further investigation, South Sudan was not included in many graphs and maps as no data was available for the year being analyzed. The raw data used for these maps and graphs is available through the World Bank and goes back to 1960 [28]. South Sudan may not have had data available in recent years, but there was data available for many energy-related world development indicators in 2015. Data is available for individual countries and various aggregate classifications regarding location and income. To identify possible reasons for South Sudan's low electricity access, such as income or regional conflict, the following aggregates were selected to be analyzed alongside South Sudan:

- High income
- Upper middle-income
- Middle income
- Low and middle income
- Lower middle income
- Low income
- Fragile and conflict-affected situations
- Least developed countries
- World

Figure 1 shows the 2021 gross national income (GNI) per capita for the different income-related aggregates that will be used throughout the rest of this analysis.

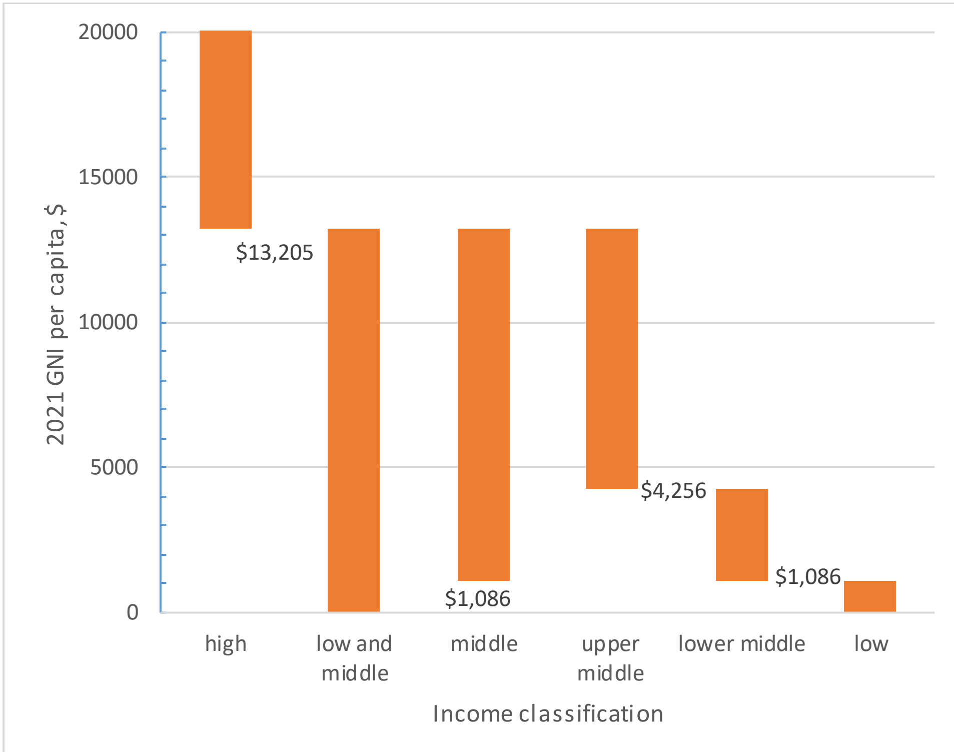


Figure 1. Distribution of 2021 GNI per capita for each income aggregate. Data from [28].

2014 was the most recent year that South Sudan and all of the aggregates mentioned had data available and was the year selected for further analysis.

To compare South Sudan's electricity access to the rest of the world, proportional electricity access vs. gross domestic product (GDP) for the mentioned aggregates and South Sudan was graphed in Excel. The logarithmic trend line was selected as it had the highest correlation of any trend line. The fit of the trend line to the data was assessed by removing outliers from the graph. When choosing the best fit, the R and R^2 values were noted and considered.

To analyze overall energy use, the energy consumed per capita vs. GDP for the aggregates and South Sudan was graphed. The same process was taken to remove outliers and analyze the R and R^2 values to assess the best fit. Using the equation for the best fit logarithmic trend line, the predicted energy use was calculated to compare it to the actual energy use for the outliers, high-income countries, and South Sudan.

This same energy use vs. GDP analysis could not be expanded to all LDCs, as the data was only available for 18/46 countries. A similar plot was made to interpolate the missing data points, but too many points were missing, and there was not a strong enough correlation between the data and any trend line.

4.1.2 Assessing Land Availability in LDCs

This theoretical energy consumption is how much energy each country would use if their energy consumption matched that of middle and high–income countries. The theoretical energy consumption of each LDC was calculated using population data and the values in Table 1.

Aggregate	Energy Use (kWh/Capita)
High-income countries	54,436
Middle-income countries	16,096

Table 1. Energy use per capita assumption for middle-income and high-income countries. 2014 data [28]. *Values used to calculate theoretical energy use of LDCs.*

These theoretical energy consumption values were used to calculate the size of a PV system needed to supply the proposed energy amounts. The average specific photovoltaic power output (in units of kWh/kWp, where kWp is the kilowatt peak power output of the photovoltaic system) from Global Solar Atlas [29] for each country was used to calculate the kWp of solar panels needed in both the middle-income and high-income energy usage scenarios. The PV system size for the calculations is assumed to be 5 m^2/kW. The PV land requirements were divided by the total area for each country and scenario.

To evaluate which countries might have the land availability needed for large-scale PV installation without cutting down trees or crops, the land available was calculated as: Available land area = total land area– agricultural land area – forested land area.

The need for renewable energy was assessed quantitatively to determine which countries to analyze. The following world development indicators were selected to narrow down the countries:

- Access to clean cooking, % of pop
- Access to electricity % of pop
- CO_2 emissions per capita from total fuel consumption
- Individuals using the internet %
- Mortality rate attributed to household ambient air pollution
- Time required to get electricity

The ten countries struggling the most in each category were recorded, and the number of times a country appeared was tallied. This analysis was combined with the land availability mentioned previously to decide which countries to model.

4.2 Results

4.2.1 World Development indicators

Figure 2 shows the proportional access to electricity on the y-axis vs. the GDP per capita on the x-axis for the analyzed aggregates. The x-axis is a logarithmic scale. A logarithmic trendline is displayed, which is the best fit of any trendline. The equation of the trendline and corresponding coefficient of determination is also shown. The high-income and South Sudan data points, highlighted in red, fell far away from the trendline, shifting it away from the other data points. Figure 3 is almost equivalent to Figure 2, with the high-income and South Sudan data points removed.

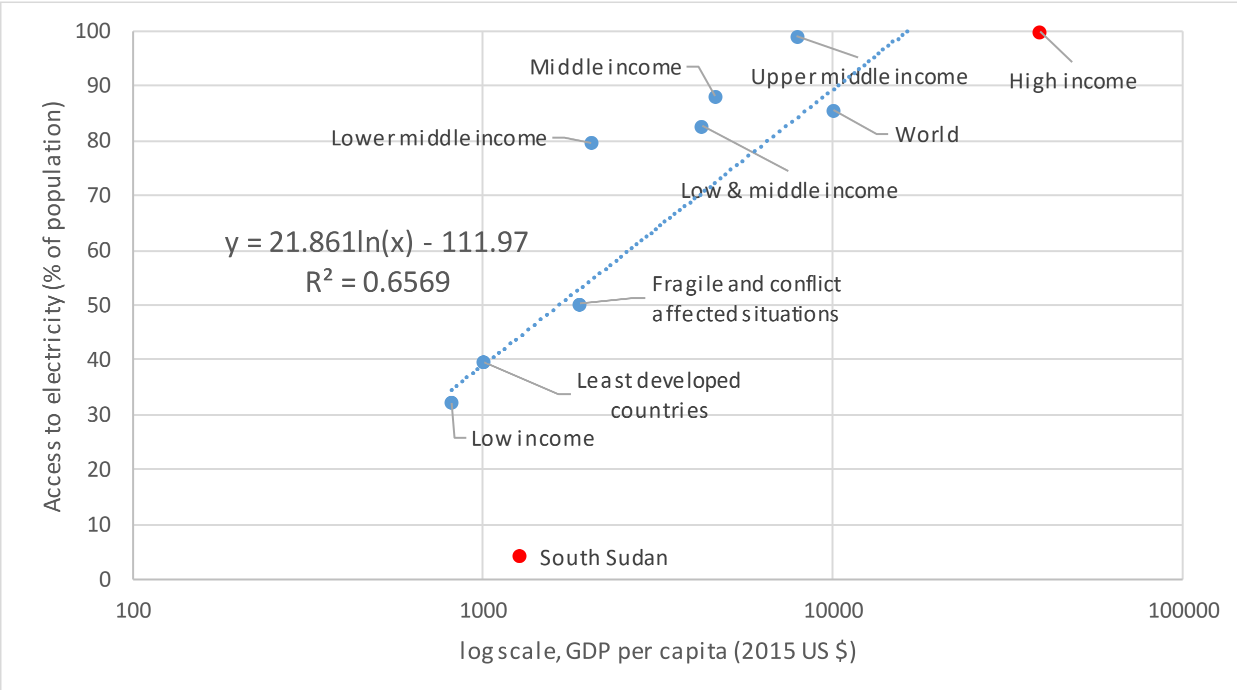


Figure 2. Electricity Access vs. GDP per capita. 2014 data from [28], *with all data points.*

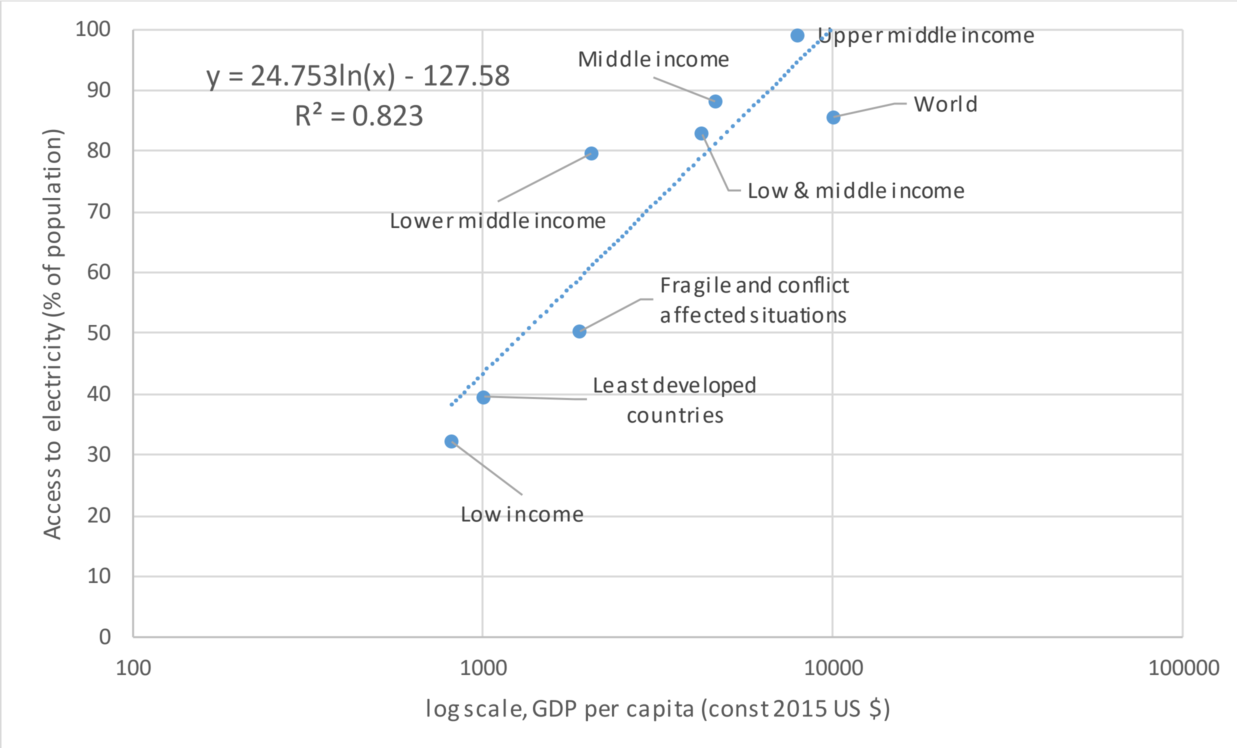


Figure 3. Electricity Access vs. GDP per capita. 2014 data from [28], *without the high-income and South Sudan data points.*

The correlation coefficient, R, is interpreted as the strength between the two variables, and the squared correlation coefficient becomes the coefficient of determination, R^2, which can be interpreted as how well the model fits the data. R and R^2 increased after removing the high-income data point, from 0.811 to 0.839 and 0.657 to 0.704, respectively. They increased even further upon removing the South Sudan data point, from 0.811 to 0.907 and 0.657 to 0.823, respectively. The correlation coefficient and coefficient of determination values before and after removing each outlier are summarized in Table 2.

	R-value	R^2 value
All values	0.811	0.657
Without high-income data point	0.839	0.704
Without high-income or South Sudan data points	0.907	0.823

Table 2. R and R^2 values for electricity access vs. GDP with and without various outliers.

Figure 4 shows the energy consumption per capita on the y-axis vs. the GDP per capita on the x-axis. The x-axis is a logarithmic scale again, as a logarithmic correlation was present.

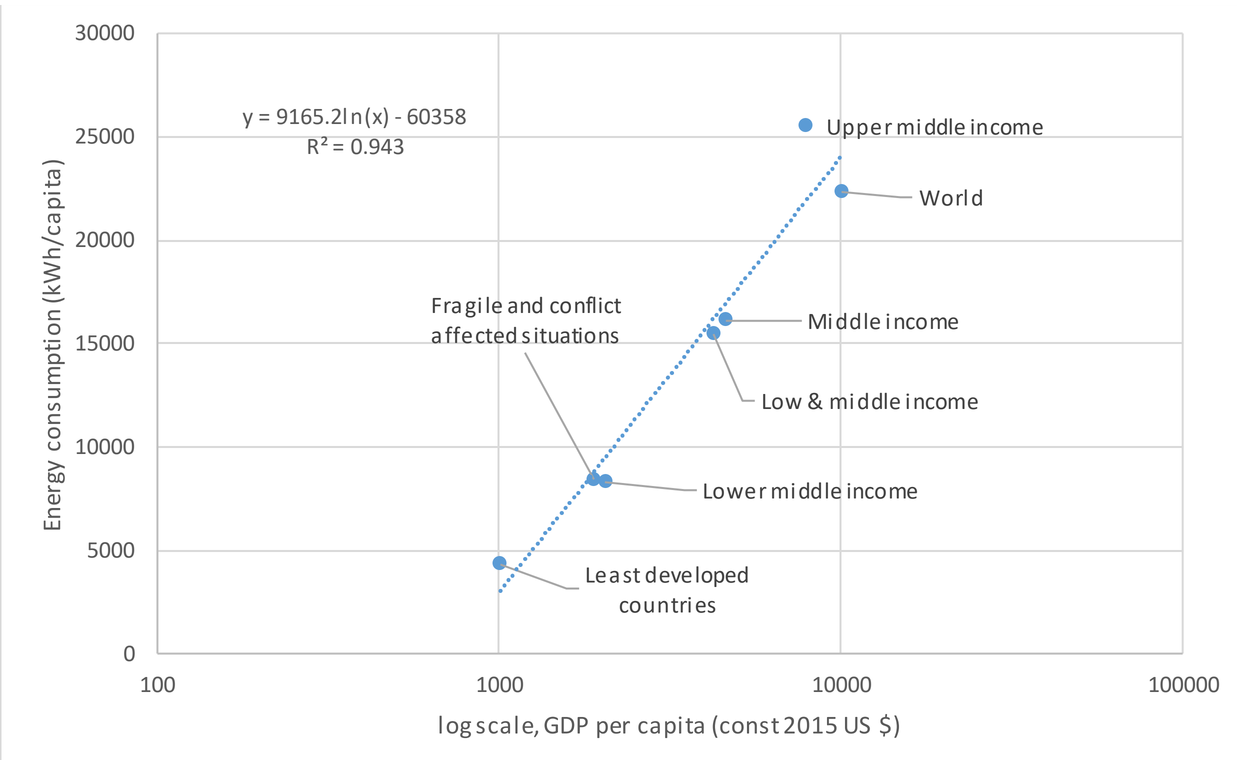


Figure 4. Energy consumed per capita vs. GDP per capita. 2014 data from [28], *without high-income or South Sudan data points. Energy use in kg oil equivalent/capita converted to kWh/capita by multiplying by 11.63* [30]. *Low-income aggregate had no data available for 2014.*

The logarithmic correlation between energy consumption per capita and GDP per capita was much stronger than the correlation between proportional electricity access and GDP per capita, as reflected by the higher values of R and R^2. Table 3 shows all values of the correlation coefficient and coefficient of determination values, all larger than 0.9. The R and R^2 values demonstrated a similar trend to the proportional electricity access vs. GDP upon removing the high-income data point, increasing from 0.9643 to 0.9664 and 0.9298 to 0.9339, respectively, and increased further after removing the South Sudan data point to 0.971 and 0.943, respectively.

	R-value	R^2 value
All values	0.9643	0.9298
Without high-income data point	0.9664	0.9339
Without high-income or South Sudan data points	0.971	0.943

Table 3. R and R^2 values for Energy use vs. GDP with and without various outliers.

The predicted energy use for the high-income and South Sudan data points calculated from the trend line from Figure 4 differed greatly from the actual energy use. These results are shown in Table 4. High-income countries use almost 50% more energy per capita than the logarithmic model predicted from GDP per capita, while South Sudan uses 85% less energy per capita than predicted from GDP per capita.

	2014 GDP/capita (const. 2015 US $)	Predicted energy use (kWh/capita)	Actual energy use (kWh/capita)	Difference % $(\frac{actual - predicted}{predicted})$
High-income Countries	$39,148	36,565	54,436	+49%
South Sudan	$1,274	5,172	772	-85%

Table 4. GDP and predicted vs. actual energy use. 2014 data from [28].

Figure 5 shows the energy use per capita on the y-axis vs. the GDP per capita on the x-axis for all of the LDCs that had the data available for 2014, which was only 18 out of the 46 countries. There is no clear relationship between the variables to interpolate the values for the countries with missing data confidently.

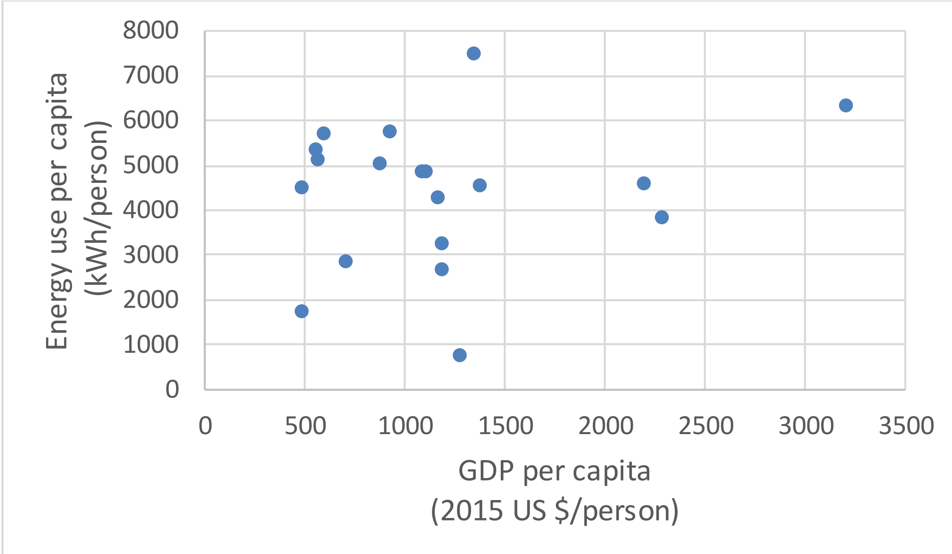


Figure 5. Energy Use vs. GDP for the LDCs. 2014 data from [28].

4.2.2 Assessing Land Availability in LDCs

The percentage of land needed to support the entire population with as much energy per person as middle-income and high-income countries with just solar panels for each of the 46 LDCs is displayed in box and whisker plots in Figure 6 and Figure 7, respectively. A box and whisker plot shows the range of values, mean, median, and outliers.

The box represents the middle 50% of the data points, and the box size is known as the interquartile range (IQR). The bottom edge of the box is the median of the data points below the median and is known as the first quartile, Q_1. The top edge of the box is the median of the data points above the median and is known as the third quartile, Q_3. The distance between these two values and the box size is known as the interquartile range, IQR, which spans the middle 50% of the data points. The line in the box represents the median value (sometimes called the second quartile, Q_2), and the “x” in the box represents the mean value. The whiskers represent the top and bottom 25% of non-outlier data points. The outliers are denoted as the dots outside the whiskers and are designated as such if they fall outside the following range: $\{Q_1 - 1.5IQR, 1.5IQR + Q_3\}$

Figure 6 is a box and whisker plot of the proportional land requirements for PV for the middle-income equivalent energy usage (16,096 kWh/capital) for all of the LDCs. The plot shows that more than 75% of the LDCs need less than 1% of their land area to be covered in solar panels to provide their population with as much energy per capita as middle-income countries with a mean value of 0.66% and a median of 0.28%. Bangladesh is the only LDC that needs more than 2.5% of its land and has a value of 6.73%.

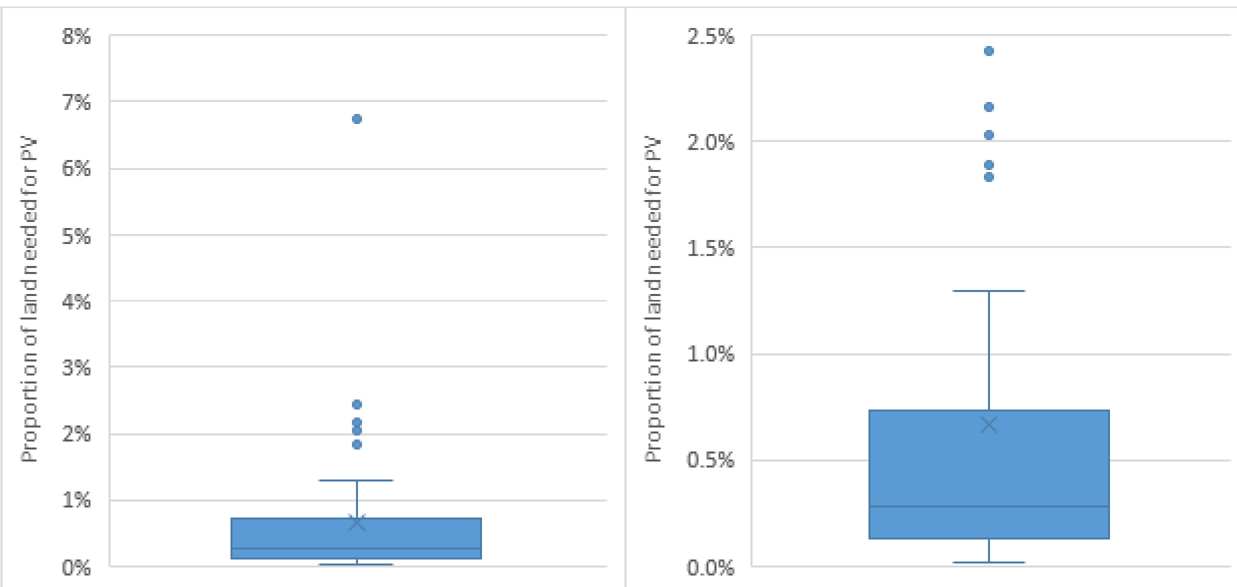


Figure 6. Box and whisker plots of the proportion of land needed in LDCs to supply the middle-income equivalent energy usage. The left plot shows the entire range of the box and whisker plot. The right plot shows a zoomed in version to better analyze the spread of the data.

Figure 7 is a box and whisker plot of the proportional land requirements for PV for the high-income equivalent energy usage (54,436 kWh/capital) for all of the LDCs. The plot shows that more than 75% of the LDCs need less than 3% of their land area to be covered in solar panels to provide their population with as much energy per capita as high-income countries with a mean value of 2.25% and a median of 0.96%. Bangladesh is the only LDC that needs more than 10% of its land and has a value of 22.76%.

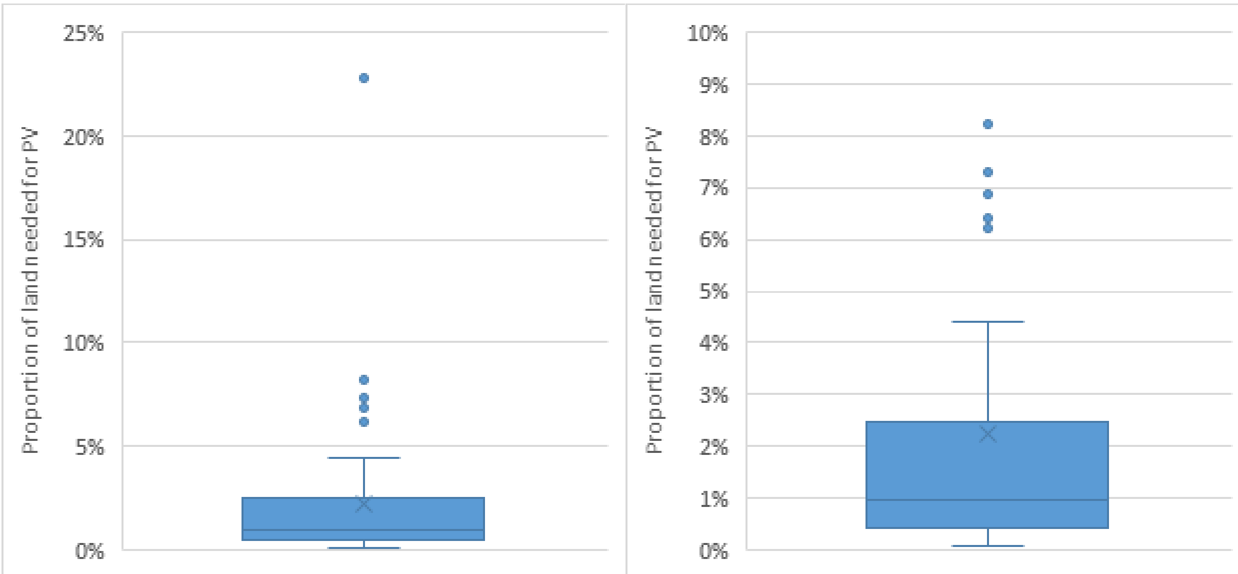


Figure 7. Box and whisker plots of the proportion of land needed in LDCs to supply the high-income equivalent energy usage. The left plot shows the entire range of the box and whisker plot. The right plot shows a zoomed in version to better analyze the spread of the data.

Figure 8 is a box and whisker plot of the proportion of forested or agricultural land of all of the LDCs, and Figure 9 is a histogram displaying the same data. Both figures show that more than a quarter of the LDCs have 90% or more of their land covered by forest or agriculture. While there is likely some overlap in the agricultural and forested lands, it is not expected to majorly increase the land availability for solar. Both figures also show that more than half of the countries have 80% or more of their land covered by forest or agriculture.

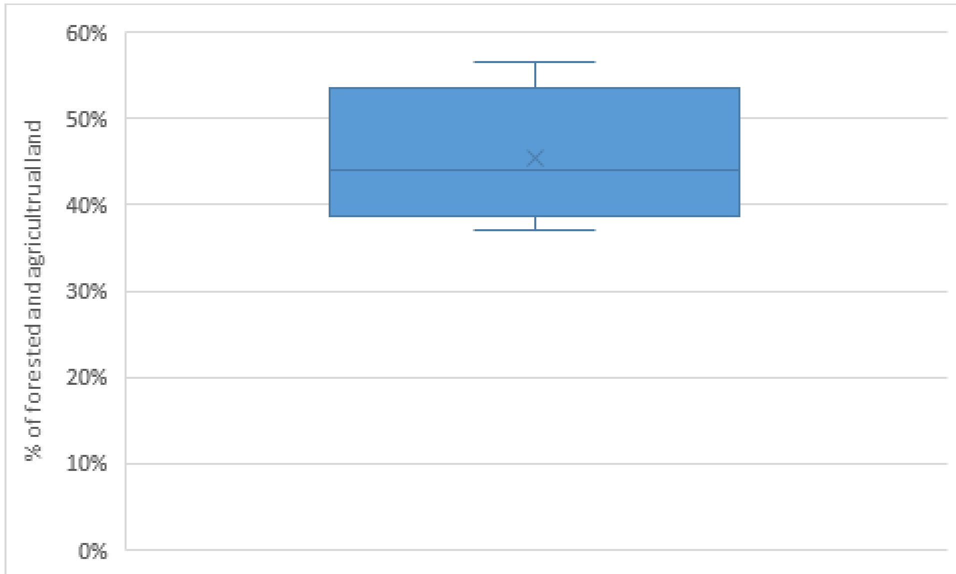


Figure 8. Box and Whisker plot of Agricultural and Forested land in the 46 least develop countries.

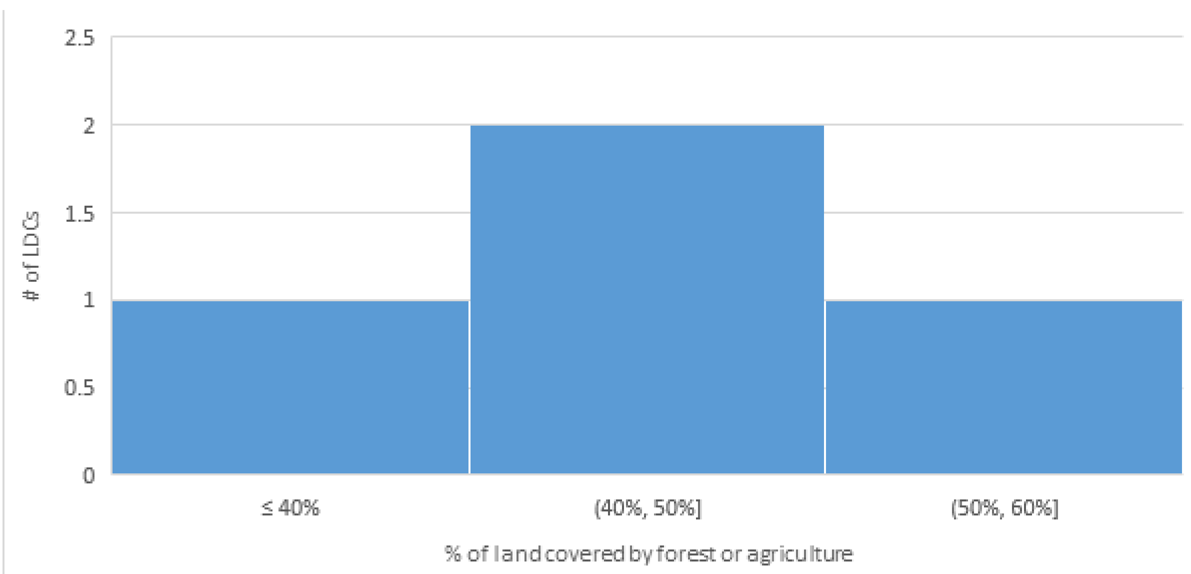


Figure 9. Histogram of Agricultural and Forested land in the 46 least developed countries

The ten LDCs struggling the most in various energy-related categories are shown in Table 5. The frequency that each country appeared in these categories is summarized in Table 6. Seventeen countries were mentioned once, six countries were mentioned twice, five countries were mentioned three times, and four countries were mentioned four times.

% access to clean cooking	% access to electricity	CO_2 emissions/capita from fuel consumption
South Sudan	South Sudan	Tuvalu
Burundi	Burundi	Timor-Leste
Liberia	Chad	Lesotho
Sierra Leone	Liberia	Angola
Rwanda	Malawi	Bhutan
Central African Republic	Central African Republic	Yemen, Rep.
Uganda	Congo, Dem. Rep.	Mauritania
Madagascar	Niger	Djibouti
Guinea	Guinea-Bissau	São Tomé and Príncipe
Mali	Sierra Leone	Lao PDR

% of individuals using the internet	Mortality rate attributed to household and ambient air pollution	Time required to get electricity
Eritrea	Sierra Leone	Liberia
Niger	Chad	South Sudan
Burundi	Niger	Madagascar
Somalia	Timor-Leste	Bangladesh
South Sudan	Guinea	Guinea-Bissau
Central African Republic	Gambia, The	Cambodia
Chad	Guinea-Bissau	Malawi
Congo, Dem. Rep.	Somalia	Burkina Faso
Guinea-Bissau	Central African Republic	Burundi
Madagascar	Afghanistan	Angola

Table 5. 10 countries struggling the most in various energy-related categories.

1x	2x	3x	4x
Afghanistan	Angola	Liberia	Guinea-Bissau
Bangladesh	Congo, Dem. Rep.	Sierra Leone	Burundi
Bhutan	Guinea	Madagascar	South Sudan
Burkina Faso	Malawi	Chad	Central African Republic
Cambodia	Somalia	Niger	
Djibouti	Timor-Leste		
Eritrea			
Gambia, The			
Lao PDR			
Lesotho			
Mali			
Mauritania			
Rwanda			
São Tomé and Príncipe			
Tuvalu			
Uganda			
Yemen, Rep.			

Table 6. Number of times various countries were listed in one of the categories in Table 5. 10 countries struggling the most in various energy-related categories.

After assessing the land availability in the nine countries that appeared three or more times, two had negative land availability, three had less than ten percent availability, and four had more than forty percent land availability. These results are shown in Table 7.

Country	Total land – agricultural or forested land – land needed for solar	
	Middle-income scenario	High-income scenario
Guinea-Bissau	-0.30%	-1.01%
Liberia	-0.26%	-0.87%
Burundi	8.58%	3.74%
Sierra Leone	8.01%	6.76%
Madagascar	8.02%	7.57%
South Sudan	**43.44%**	**43.24%**
Central African Republic	**55.72%**	**55.64%**
Chad	**56.07%**	**55.96%**
Niger	**62.96%**	**62.80%**

Table 7. Total land – forested land – agricultural land – PV size needed for middle-income and high-income energy scenarios.

The four LDCs selected for further analysis with the biggest need for renewable energy and have the most land availability are South Sudan, Central African Republic, Chad, and Niger, all located in Central Africa. A map of these four countries is shown in Figure 10.

Figure 10. Map of selected countries.

4.3 Discussion

South Sudan's electricity access and energy usage fell far below the trend line that predicted proportional access to electricity based on GDP per capita in Figure 2. This indicates that factors other than economics contribute to their energy usage. At first, it is expected that the conflict in the region might have something to do with this. While this is likely true, the proportional electricity access of the data point for fragile and conflict-affected countries was accurately predicted from the GDP per capita. This suggests that conflict has disproportionately impacted South Sudan more than other countries. This would make sense since South Sudan was established in 2011, making it the youngest country in the world, and it has experienced conflict for its entire existence thus far. Without any period devoid of conflict, it would be challenging for a country to develop its energy infrastructure. However, it is also possible that the fragile and conflict-affected countries may not accurately represent all countries experiencing conflict. South Sudan has missing data for many years between 2011 and the present day, and it would not be unlikely that other countries experiencing conflict also lack data availability. This was confirmed when analyzing the energy usage vs. GDP for the LDCs when only eighteen out of forty-six countries had the data available for the selected year. This lack of data makes it difficult to understand what is happening in these countries and highlights the struggle they are experiencing.

When assessing the land needed to support each LDC with the energy amounts reported in Table 1, most countries required a very small portion of their land to be covered in solar panels. The majority of countries need less than 1% of their land to be covered by solar panels in the middle-income scenario, with 16,096 kWh per person, and less than 5% of their land to be covered by solar panels in the high-income energy scenario, with 54,436 kWh per person.

Bangladesh had the highest proportion of land needed to support these energy amounts at 6.73% for the middle-income and almost 25% to support the high-income energy scenario. This is due to its high population density of about 1,200 people per square kilometer [25], the highest out of all forty-six LDCs. This is more than twice the population density of the second most densely populated LDC, Rwanda, which has a population density of about 450 people per square kilometer [28]. Countries with high population densities are not the ideal candidates for complete reliance on solar and will need other options for increasing their usage of renewable energy, especially if that large population density is coupled with a large amount of agricultural or forested land.

For all of the other LDCs, the land requirements for large-scale solar installation were much lower. However, when assessing the amount of land these countries had available, many had a high proportion of forested and agricultural land. Since other land use data (such as urban areas) was not readily available for all countries, large-scale PV installation is likely less feasible for countries with high proportions of agriculture and forests. Bangladesh specifically had 84% of its land covered in forests or agriculture, and it will need more spatially dense renewable energy solutions, to be discussed in a later section.

After assessing the countries with the greatest need for renewable energy, only four of the nine countries had more than 10% of their land available and were selected to analyze further. These four countries are Niger, Chad, Central African Republic, and South Sudan, which happen to all be next to each other. It makes sense that these countries would have similar levels of land availability due to their proximity but also have a large need for renewable infrastructure. They are all landlocked, limiting the availability of resources and trade. All four countries have also experienced major conflict, as have the countries surrounding them, making it challenging to develop any energy infrastructure, especially renewable.

5 LDC Modeling

5.1 Methods

5.1.1 Projected Emissions

From 2021 raw data, the TWh consumed by varying energy sources for high-income, lower-middle-income, and upper-middle-income countries [26], [31] was converted to percent usage for each entity. Without dedicated data for middle-income countries, the values for lower-middle income and upper-middle income were averaged for the middle-income scenario. The percentages of each fuel type were multiplied by the total energy consumption values for middle-income and high-income scenarios in Table 1 to find the projected energy usage per person in kWh of each fuel source.

There were many variations of each fuel type, so the following variations and corresponding emissions factors were selected:

- Oil: values for “Crude Oil” and “Other Petroleum Products”
- Coal: values for “Other Bituminous Coal” and “Coking Coal”
- Gas: values for “Natural Gas”
- Biomass: values for “Other Primary Solid Biomass”

The emission factors for each greenhouse-gas-producing energy source (oil, coal, biomass, and gas) are listed in Table 8.

Emission Factor (kg/TJ)	Biomass	Gas	Coal	Oil
CO_2	100000	56100	94600	73300
CH_4	30	1	10	3
N_2O	4	0.1	1.5	0.6

Table 8. Emission factors used to calculate theoretical emissions. Values from the IPCC [32].

After converting from TJ to kWh, the emission factors for each fuel type were multiplied by the theoretical fuel consumption for both income scenarios to find the theoretical amount of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emitted per capita. Each of these greenhouse gases has a different impact on the climate over a period of time, quantified by its global warming potential (GWP), which is listed in Table 9. The GWP_{100}, the warming effect of a kg of greenhouse gas released over 100 years, was used. For example, the warming effect over 100 years of releasing 1 kg of N_2O is equivalent to releasing 265 kg of CO_2.

GHG	GWP_{100} (kg CO_{2eq})
CO_2	1
CH_4	28
N_2O	265

Table 9. GWP values used, from IPCC 5th assessment [33].

The theoretical amount of each greenhouse gas produced was multiplied by its appropriate GWP_{100} value and added to get the total theoretical kg CO_{2eq} per capita for the middle-income and high-income scenarios.

Data for total greenhouse gas emissions from various sectors was available across many years for the four LDCs from Climate Watch [34]. The source reports using GWP_{100} values from the IPCC 4th assessment report. These values differ slightly from the values reported in Table 9. In the 4th assessment report, the GWP_{100} value is 25 for methane and 298 for nitrous oxide [35]. Since biomass, gas, coal, and oil emit much more carbon dioxide than other greenhouse gases (as shown in Table 8), this minor change in GWP values is assumed to be negligible.

The value for total greenhouse gas emissions (excluding land-use change and forestry) is the sum of emissions from agriculture, energy, industrial processes, and waste. The percentage contribution of emissions for each of these sectors for Central African Republic, Chad, Niger, South Sudan, and the United States was calculated and displayed in a stacked bar chart to compare the breakdown of emissions for each country. Greenhouse gas emissions from the energy sector are used in the following analysis, as opposed to total greenhouse gas emissions.

The greenhouse gas emissions from the energy sector of Central African Republic, Chad, Niger, South Sudan, and the United States were divided by the population [28] for the years 2011-2020. All units were converted to metric tons of CO_{2eq}/capita. These values were graphed for the four LDCs to visualize any changes in energy-related greenhouse gas emissions over time. The 2020 values for each LDC were graphed alongside the middle-income scenario, high-income scenario, and the United States for comparison.

The carbon intensity for the middle-income and high-income scenarios was calculated by dividing the emissions by energy use to get the mass of CO_{2eq} emitted per kWh in each scenario. The carbon intensity could only be calculated for Niger and South Sudan in select years due to limited data availability. The energy usage per capita in the Central African Republic and Chad has not been available from 2011 to the present. The carbon intensity of Niger and South Sudan was calculated by dividing the energy greenhouse gas emissions of the country by its population to get kg CO_{2eq}/capita, then dividing that by the energy usage per capita for each year that all the data was available. The values for population and energy usage per person are from the World Bank [28], and those for energy-related greenhouse gas emissions are from Climate Watch [34]. As mentioned in the previous section in Figure 4, the energy usage per person in kg oil equivalent/capita is converted to kWh/capita by multiplying by 11.63 [30]. The same process was done for the United States.

5.1.2 Land Analysis

The land availability was assessed in more detail for the four countries using ArcGIS Pro. Central African Republic, Chad, Niger, and South Sudan were selected from a layer with the world countries [36] and moved to their own layer. In a copy of this layer, the border between the four countries was dissolved to create an outline for clipping. A raster file of the world land cover [37] was added and clipped with the outline geometry to assess the coverage of forested, agricultural, urban, and other types of areas. The land types considered suitable for PV installation were Barren/minimal vegetation or Shrub/Scrub. Barren or Minimal Vegetation is described as "Land with minimal vegetation (<10%) including rock, sand, clay, beaches, quarries, strip mines, and gravel pits. Salt flats, playas, and non-tidal mud flats are also included when not inundated with water" [38]. Shrub or Scrub is described as "Woody vegetation <3 meters in height, > 10% ground cover. Only collect >30% ground cover" [38]. Large-scale solar installations in these two land areas would avoid cutting down forests or trees. These two land types were selected and isolated from the rest of the land types.

A raster file of the African land surface forms [38] was added and clipped with the outline geometry to assess where the land would be flat enough for a large-scale solar installation. The smooth plains were selected and isolated. The overlap between smooth and available land was found using the raster calculator tool. The overlap within each country was clipped with each country's border. The overlap area within each country was calculated using the number of pixels, pixel size, and pixel units. Circles representing the theoretical solar panel area needed to match middle and high-income energy usage were added for each country by inputting the radius corresponding to the appropriate area ($radius = \sqrt{\frac{area}{\pi}}$).

5.2 Results

5.2.1 Projected Emissions

The percent usage of each energy source for middle and high-income countries is displayed in Figure 11, with the numerical values listed in Table 10. The single energy source used the most by middle-income countries is coal, at 38% of their total energy use. High-income countries use much less coal, at only 12%. The single energy source used the most by high-income countries is oil, at 39% of their total energy use. Middle-income countries use a smaller proportion of oil at 25%. High-income countries use a higher proportion of carbon-free (solar, wind, hydro, nuclear) sources at 18% than middle-income countries at 12%. High-income countries use more nuclear energy (7%) than middle-income countries (2%).

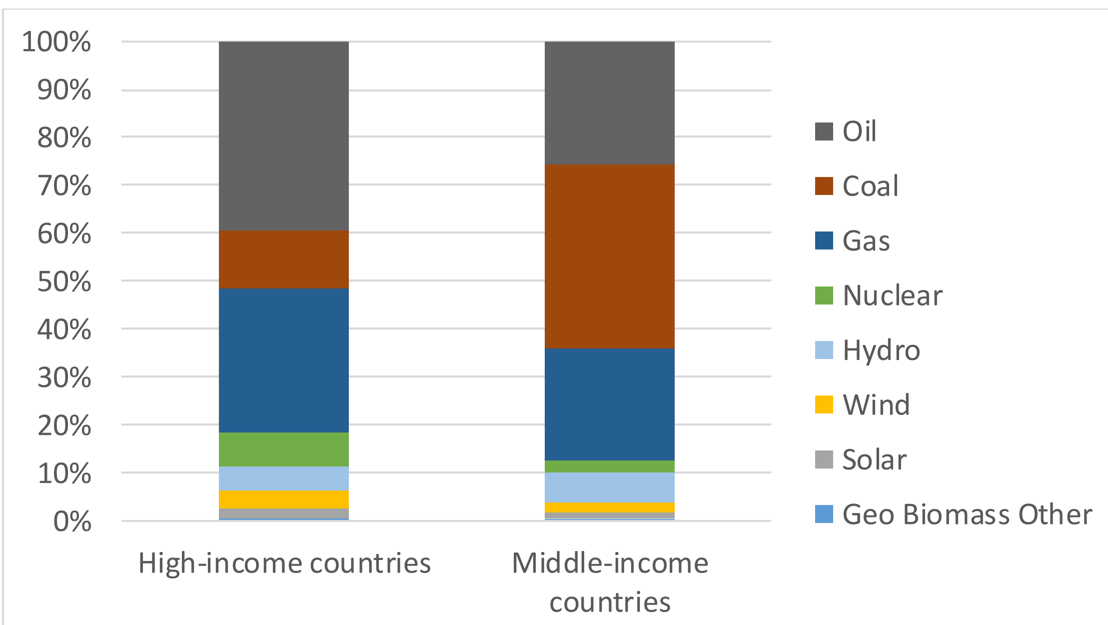


Figure 11. Energy source consumption breakdown for middle-income and high-income countries.

Entity	Biomass	Solar	Wind	Hydro	Nuclear	Gas	Coal	Oil
High-income countries	0.58%	2.02%	3.65%	5.11%	7.30%	29.74%	12.32%	39.30%
Middle-income countries	0.38%	1.42%	2.14%	6.35%	2.17%	23.43%	38.43%	25.68%

Table 10. Energy source consumption breakdown. The values for middle-income countries are an average between the upper-middle-income countries and lower-middle-income countries.

The theoretical greenhouse gas emissions per capita for each fuel type are shown in Table 11 for the high-income scenario and Table 12 for the middle-income scenario. The high-income scenario emits more of each greenhouse gas than the middle-income scenario. The emissions for coal are the most similar between the two groups (2300 kg CO_{2eq}/capita for the high-income scenario and 2122 kg CO_{2eq}/capita for the middle-income scenario).

The total theoretical kg CO_{2eq} emitted per capita was 11.4 metric tons CO_{2eq}/capita for the high-income scenario and four metric tons CO_{2eq}/capita for the middle-income scenario.

GHG	Biomass emissions (kg/capita)	Gas emissions (kg/capita)	Coal emissions (kg/capita)	Oil emissions (kg/capita)	Total emissions (kg/capita)
CO_2	113.4335	3269.0263	2283.8975	5644.9122	11311.2695
CH_4	0.0340	0.0583	0.2414	0.2310	0.5648
N_2O	0.0045	0.0058	0.0362	0.0462	0.0928
Total CO_{2eq}	115.5887	3272.2021	2300.2542	5663.6259	11351.6709

Table 11. Theoretical GHG emissions per capita, by fuel type for the high-income energy usage scenario.

GHG	Biomass emissions (kg/capita)	Gas emissions (kg/capita)	Coal emissions (kg/capita)	Oil emissions (kg/capita)	Total emissions (kg/capita)
CO_2	22.0897	761.7762	2106.8950	1090.7505	3981.5114
CH_4	0.0066	0.0136	0.2227	0.0446	0.2876
N_2O	0.0009	0.0014	0.0334	0.0089	0.0446
Total CO_{2eq}	22.5094	762.5163	2121.9840	1094.3665	4001.3762

Table 12. Theoretical GHG emissions per capita, by fuel type for the middle-income energy usage scenario.

The relative contribution of greenhouse gas emissions in 2020 for the Central African Republic, Chad, Niger, South Sudan, and the United States from each sector is summarized in a stacked bar chart in Figure 12, with the percentages for each sector listed in Table 13. The vast majority of greenhouse gas emissions in Central African Republic, Chad, Niger, and South Sudan are from the agricultural sector in 2020. Less than 10% of the greenhouse gas emissions in these countries are from the energy sector. In contrast, 86% of greenhouse gas emissions in the United States were from the energy sector in 2020. Due to the large differences between sectors, energy-related greenhouse gas emissions were used for further analysis instead of total greenhouse gas emissions.

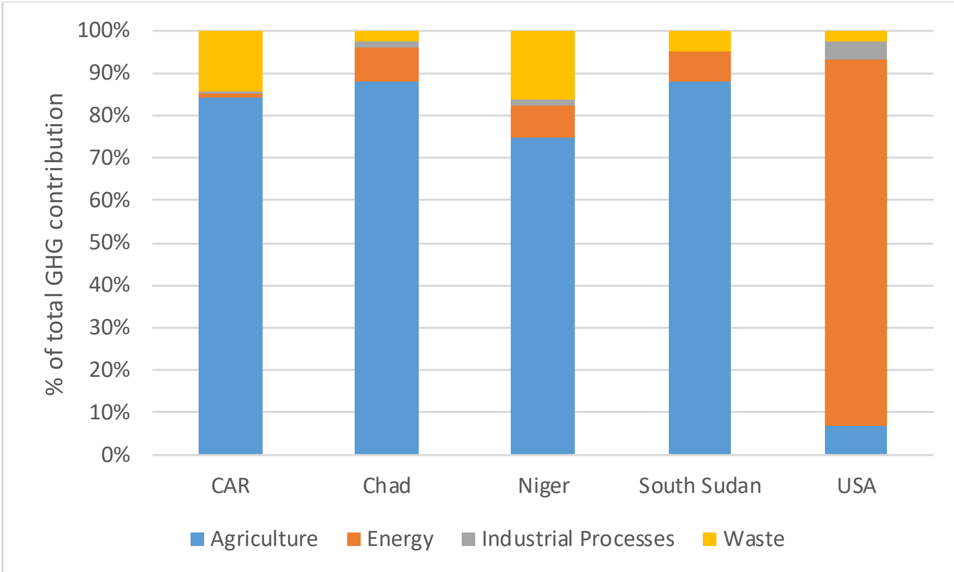


Figure 12. Relative contribution of greenhouse gas emissions from agriculture, energy, industrial processes, and waste.

	Agriculture	Energy	Industrial Processes	Waste
Central African Republic	**84.15%**	1.14%	0.19%	14.52%
Chad	**87.97%**	8.27%	1.07%	2.68%
Niger	**74.72%**	7.46%	1.79%	16.03%
South Sudan	**88.24%**	6.76%	0.18%	4.82%
United States of America	6.94%	**86.18%**	4.42%	2.46%

Table 13. Relative contribution of greenhouse gas emissions from agriculture, energy, industrial processes, and waste. Values corresponding to the percentages in Figure 12.

The change in greenhouse gas emissions over time for the four countries is displayed in Figure 13, with metric tons of carbon dioxide equivalent per person per year on the y-axis and years from 2011 to 2020 on the x-axis. Central African Republic, Chad, and Niger have historical energy greenhouse gas emissions per capita that appear relatively stable over time. South Sudan had a large drop in emissions after 2011 and has had slight ups and downs since then. Central African Republic has the lowest value of 0.0144 metric tons CO_{2eq}/capita in 2020. Chad had the highest value of 1.39 metric tons CO_{2eq}/capita in 2020, almost one hundred times the value of the Central African Republic.

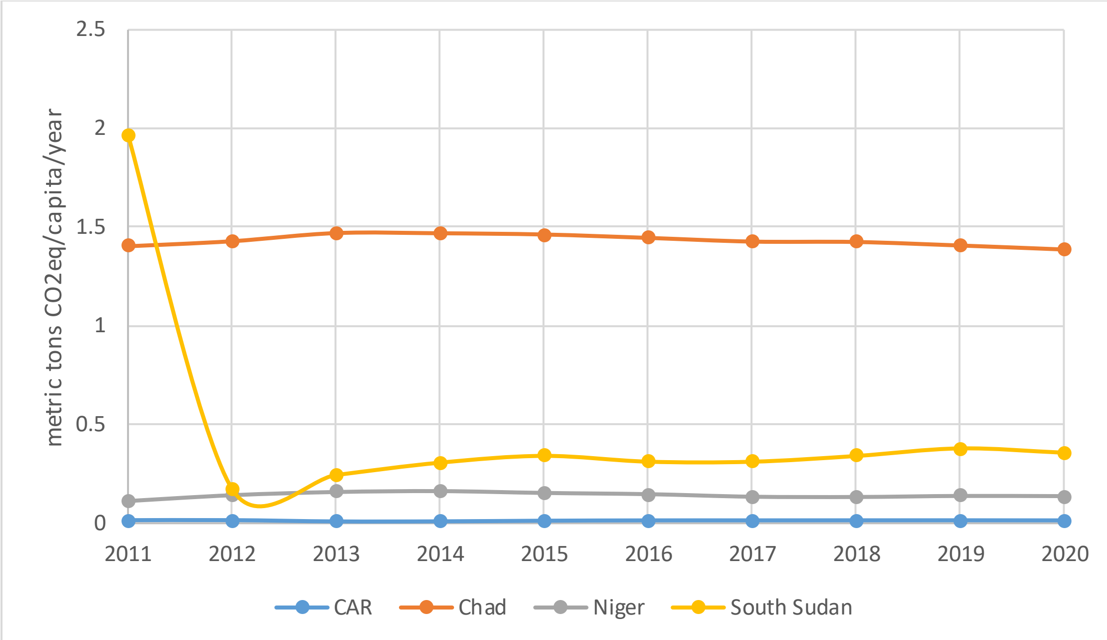


Figure 13. Energy greenhouse gas emissions per capita over time in the Central African Republic, Chad, Niger, and South Sudan.

The 2020 greenhouse gas emissions per capita of the four LDCs are compared to the theoretical emissions of the middle-income and high-income scenarios and the United States in Figure 14. If the Central African Republic, Chad, Niger, and South Sudan could increase their energy usage per capita to match that of middle-income countries while also using the same types of fuels as middle-income countries, all of them would see a dramatic increase in CO_{2eq} emissions per capita to 4 tons CO_{2eq}/capita. Central African Republic would see an increase by an order of magnitude of one hundred. Niger and South Sudan would see an increase by an order of magnitude of 10. Chad would see the smallest relative increase of about 285%. If they were to match the energy and fuel usage of high-income countries, the CO_{2eq} emissions per capita would increase even more drastically, almost three times the amount per capita as the middle-income scenario. However, they would still emit less per person than the United States in 2020.

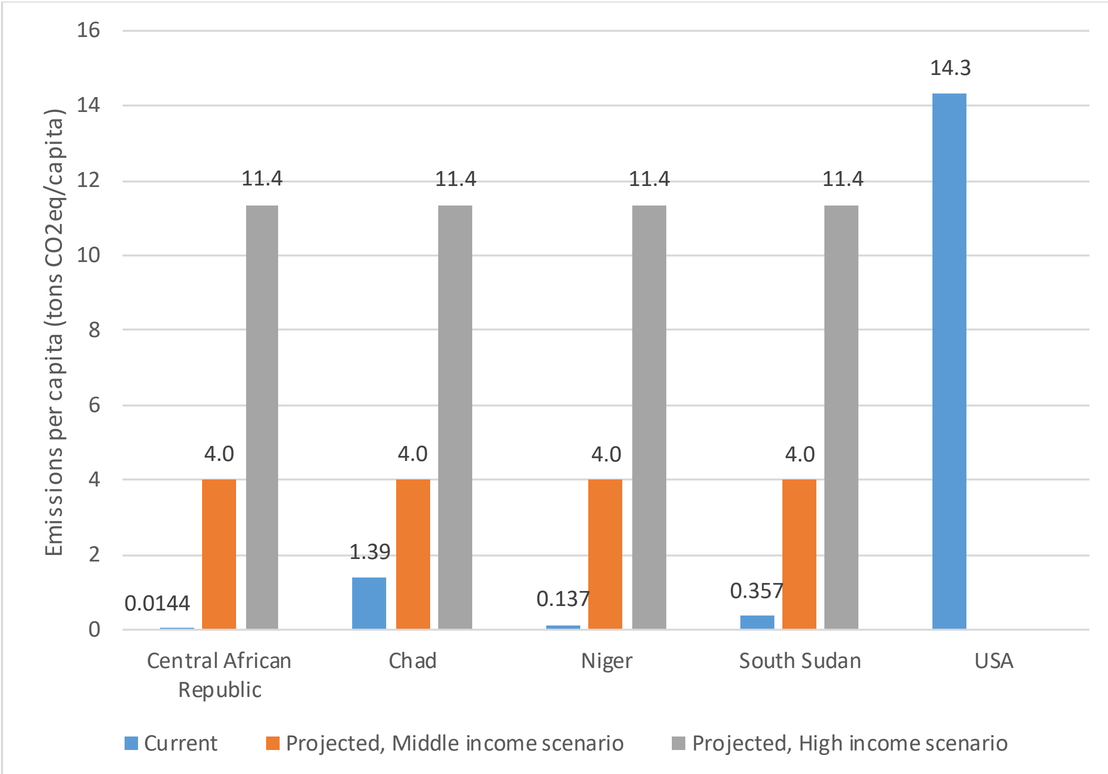


Figure 14. Per Capita Annual Energy Greenhouse Gas Emissions, Current (2020) and Projected emissions.

Carbon intensity is a measure of the greenhouse gas emissions (in units of carbon dioxide equivalent) released per unit of energy. The carbon intensity of the middle-income energy usage and projected emissions is about 0.25 kg CO_{2eq}/kWh. The high-income scenario has a carbon intensity that is ~20% less than the middle-income scenario of about 0.21 kg CO_{2eq}/kWh.

Carbon intensity (kg CO_{2eq}/kWh)	
Middle-income	0.2486
High-income	0.2085

Table 14. Projected carbon intensity of the middle-income and high-income scenario energy usage.

The carbon intensity for the countries with the available data is shown in Table 15. Niger's carbon intensity was lower than the carbon intensity of South Sudan and Niger, ranging from 0.086 to 0.096 kg CO_{2eq}/kWh. South Sudan's carbon intensity was more than double Niger's carbon intensity and ranged from 0.248 to 0.422 kg CO_{2eq}/kWh. It is also noteworthy that South Sudan has a higher carbon intensity than the United States in all years that data was available for both countries, with the largest difference in 2014, where nearly twice as much CO_{2eq} was emitted per kWh in South Sudan than the United States.

Carbon intensity (kg CO_{2eq}/kWh)					
Year	**2011**	**2012**	**2013**	**2014**	**2015**
Niger	0.086	0.096	0.088	0.094	-
South Sudan	-	0.248	0.344	0.422	-
United States	0.217	0.212	0.215	0.213	0.212

Table 15. Carbon intensity of energy in the LDCs with data available from 2011 present + the United States for comparison.

5.2.2 Land Analysis

The different types of land throughout Central African Republic, Chad, Niger, and South Sudan are shown in Figure 15. The types of land considered suitable for large-scale PV installation are barren, displayed as beige, and shrub/scrub, displayed as a light yellow-green. Niger and Chad both appear to have a large portion of barren land in the north, which happens to be the Sahara Desert. A good amount of the remaining land in the south is shrubs. Niger has a good amount of agricultural land in the southern portion of the country, which is the largest amount of agriculture in any of the four countries. Central African Republic and South Sudan have a substantial portion of shrub land. Central African Republic appears to be the most forested of the four countries, with both deciduous and evergreen forests present. Small areas of wetlands exist throughout the region. There are no visibly significant clusters of urban areas.

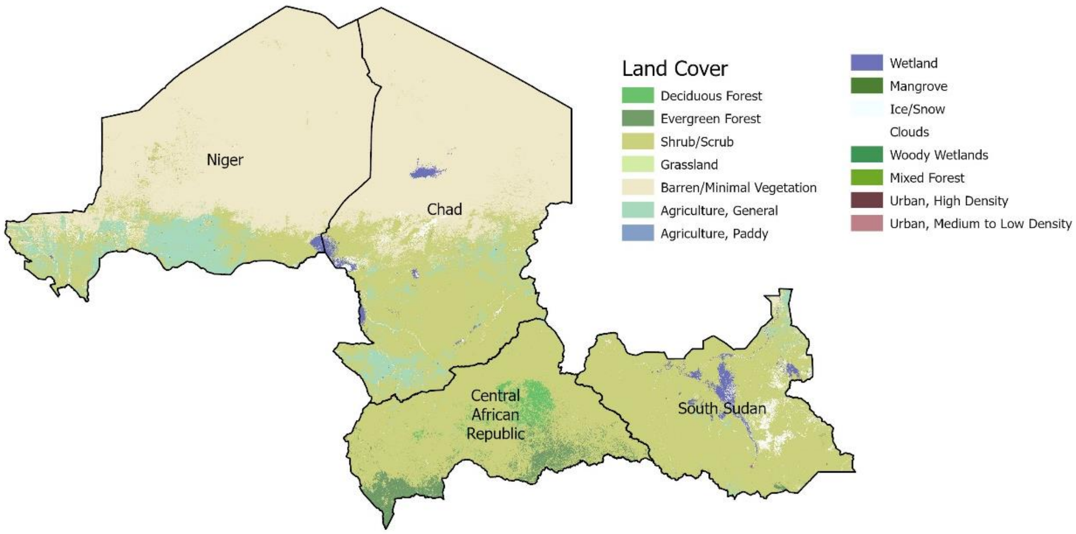


Figure 15. Land Coverage classification for the selected countries.

The land surface forms in the four countries are shown in Figure 16. Smooth plains is the land surface considered suitable for large-scale solar installation, shown in blue. Niger and Chad have a few mountainous ranges and some irregular plains but have mostly smooth plains. South Sudan has overwhelmingly smooth plains, while the Central African Republic has primarily irregular plains.

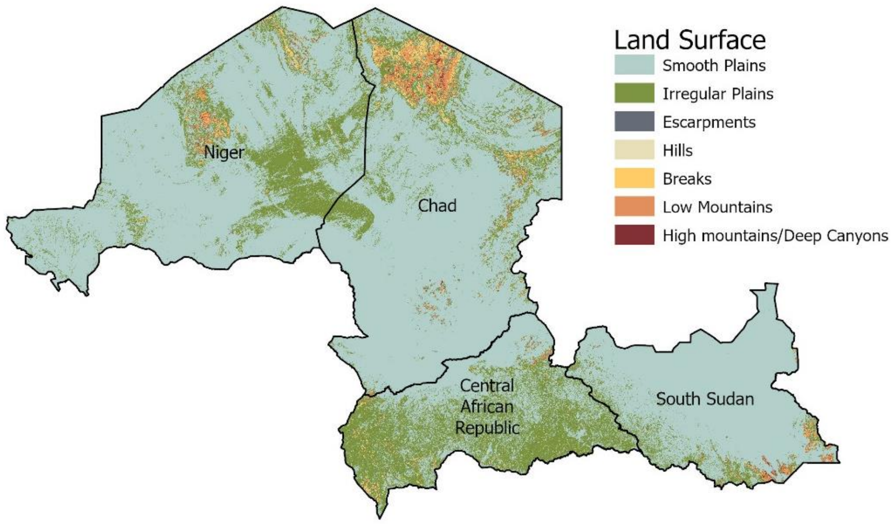


Figure 16. Land surface forms for the selected countries.

The overlap between smooth and available land is displayed in pink in Figure 17. The numerical values for the amount of smooth and available land within each country and the percentages are listed in Table 16. Chad has the largest amount of land and the largest proportion of its land area (77%) suitable for PV installation. The land is available all over the country, with limitations in the northern portion. Niger has the second highest amount of suitable land, which is 68% of its land area. Some clusters throughout the country are not suitable for solar energy, but there are plenty of decent-sized clusters of suitable land in all corners of the region. South Sudan has the third highest amount of suitable land, which is 70% of its land area. Central African Republic has the least amount of suitable land, which makes up 39% of its total area. Central African Republic's suitable land is mainly clustered in the northern portion of the country, with smaller areas spread out throughout the rest of the country.

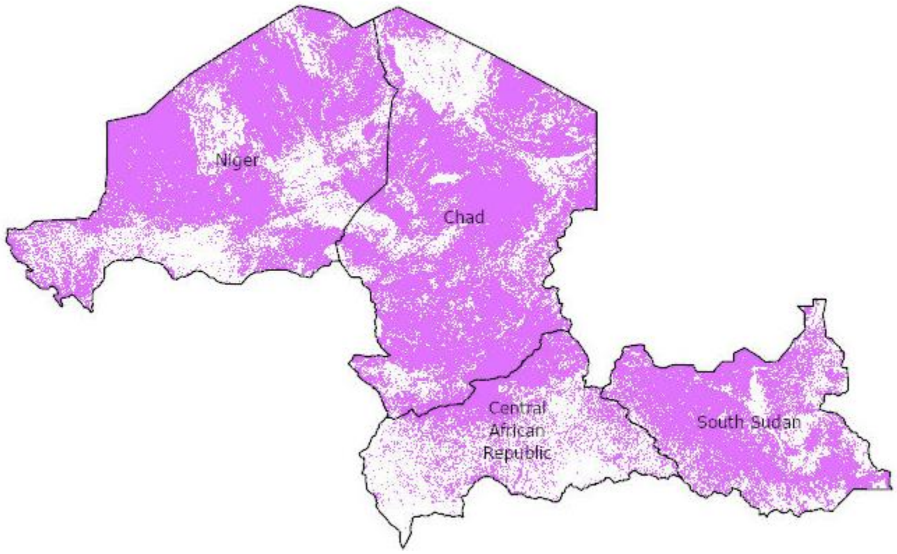


Figure 17. Overlap between flat and available land.

Country	Total land area (km^2)	Flat + available land (km^2)	Percent of flat + available land
Central African Republic	622,980	242,987.7036	39%
Chad	1,259,200	974,816.7352	77%
Niger	1,266,700	866,340.8447	68%
South Sudan	631,957	442,358.1237	70%

Table 16. Total and flat + available land for PV systems.

Figure 18 shows the spread of suitable land in addition to red and green circles representing the size of the theoretical solar panel coverage needed to supply their populations with as much energy per person as middle-income and high-income countries. The red circle represents the size required for the high-income energy scenario, and the green circle represents the size needed for the middle-income energy scenario. All four countries appear to have plenty of land to support both of these large-scale solar installations simultaneously. Table 17 has the numbers associated with the area coverage needed for each energy usage scenario. Niger needs the largest area of solar panels, at over 800 km^2, which is almost four times the area that the Central African Republic needs.

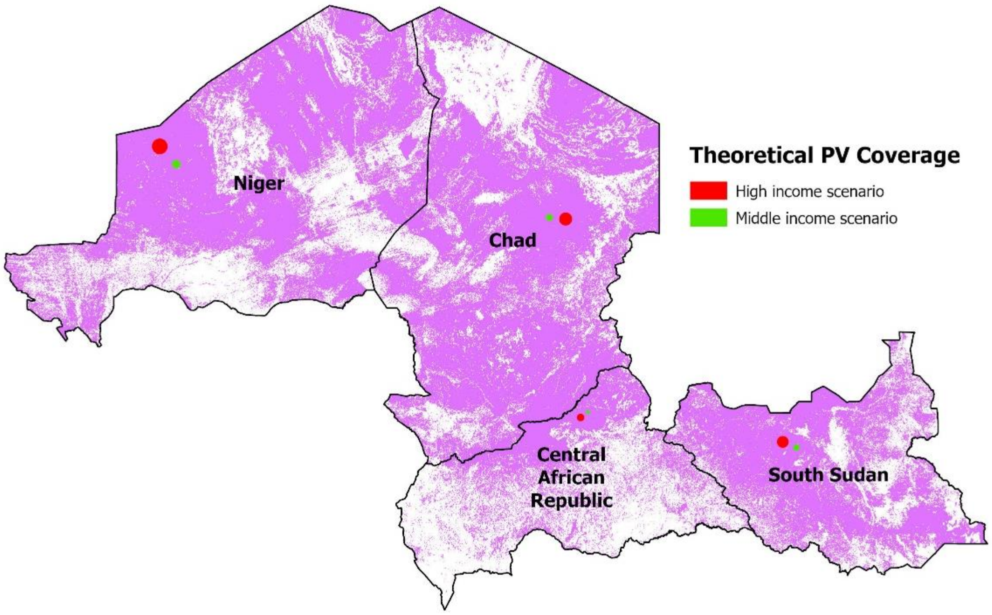


Figure 18. Theoretical PV coverage for the high-income equivalent energy usage (54,436 kWh/capita) and middle-income equivalent energy usage (16,096 kWh/capita).

Country	PV coverage needed, MI (km^2)	PV coverage, HI (km^2)
Central African Republic	219	741
Chad	601	2034
Niger	843	2852
South Sudan	523	1768

Table 17. PV coverage for the middle-income (MI) and high-income (HI) energy equivalent scenario.

5.3 Discussion

5.3.1 Projected Emissions

It is inevitable for countries to develop at different rates and pass through similar stages of development at different points in their history. Coal was the largest contributor to worldwide primary energy consumption in the early 1900s before oil, then natural gas, and later renewables, increased in popularity [39]. Countries further in their development (specifically high-income countries) would be more likely to have the monetary resources to invest in new energy resources and their development early on. Therefore, it makes sense that the high-income countries would have higher proportions of "newer" energy resources, such as oil, natural gas, and various renewable energy resources, than the middle-income countries, as reflected in Figure 11.

The current greenhouse gas emissions per capita and per kWh for the four LDCs were initially calculated using the total greenhouse gas emissions from all sectors. These numbers (especially the GHG per kWh) were far too large, which made more sense after analyzing the breakdown of greenhouse gas emissions by sector. The LDCs use so little energy that their overall energy greenhouse gas emissions make up less than 10% of their greenhouse gas emissions. In contrast, their agricultural emissions are a far bigger contributor. Analyzing energy-related greenhouse gas emissions made more sense numerically to compare emissions to the United States, whose greenhouse gas emissions are primarily from the energy sector.

Even though the world around them is vastly different than when the middle- and high-income countries were developing, the least developed countries may still go through similar stages of energy infrastructure development. If they follow closely in the footsteps of middle-income countries regarding energy usage and energy sources, the LDCs could end up emitting 4 tons of carbon dioxide equivalent greenhouse gases per person or 11.4 metric tons of carbon dioxide equivalent greenhouse gases per person in the energy sector if they follow in the footsteps of high-income countries. That is a massive increase in emissions per capita from what the Central African Republic, Chad, Niger, and South Sudan are currently emitting today. Even if these countries used the same energy and fuel breakdown as high-income countries, they would still emit much fewer greenhouse gases per capita than the United States, as shown in Figure 14. This is slightly expected considering the exceedingly high energy usage of the United States. This highlights how the United States substantially contributes to climate change and must reduce its greenhouse gas emissions while potentially supporting other countries on their path to renewable development.

As these countries increase their energy usage, their population will grow, increasing greenhouse gas emissions further. Large-scale renewable energy infrastructure investment has the potential to avoid these emissions altogether and allow these countries to accelerate their development while skipping the stage of considerable greenhouse gas emissions that many countries have gone through.

Additionally, when looking at the carbon intensity of energy produced in the four LDCs when the data was available, South Sudan was producing more emissions per kWh in 2014 (0.422 kg CO_{2eq}/kWh) than the projected middle (0.2486 kg CO_{2eq}/kWh) and high income (0.2085 kg CO_{2eq}/kWh) scenarios. This reflects South Sudan’s usage of carbon-intensive energy sources. While criteria pollutants are more challenging to find data on, it can be inferred that the high GHG-intensity fuels currently being used in South Sudan also release a substantial number of criteria pollutants. Therefore, an increase in renewable electricity is also predicted to considerably benefit people's health. Data for current and historical energy usage of Chad and the Central African Republic is completely unavailable from 2011 to 2022, and South Sudan and Niger have this data available only as recently as 2014 [28]. Therefore, the other three countries may use very emission-intensive energy sources.

5.3.2 Land Analysis

After a detailed assessment of land types and surfaces, all four countries have a surplus of land suitable for supporting large-scale solar installation without removing trees or interfering with existing development or agricultural activities.

The theoretical PV coverage was calculated as the minimum land requirement to meet the suggested energy consumption; therefore, these calculations do not factor in the inherent inefficiencies associated with energy storage. The amount of storage needed depends on each country's solar dynamics and load profile. These will vary between and within countries; therefore, calculating the amount of storage for the entire country is intricate and beyond the scope of this analysis. Nonetheless, the land deemed suitable for solar installation largely exceeds the minimum land requirements, affording ample room for expanding solar coverage to compensate for these inefficiencies. Additionally, there is plenty of space for increasing the solar capacity to curtail the excess electricity produced, which can help reduce the storage size.

The land analysis further reveals that there are viable plots of land scattered throughout each nation that could accommodate multiple, smaller-scale solar farms. A decentralized approach is more practical than a single massive installation. By dispersing solar farms strategically, the distance electricity needs to traverse can be minimized. Furthermore, the presence of multiple solar farm locations acts as a safeguard against nationwide outages. In contrast, relying solely on a single large solar farm would entail the risk of a total blackout in the event of a localized outage.

The energy consumption amounts used to calculate the land requirements for solar displayed in Figure 18 are a major increase from the current energy consumption in these countries. While data for several countries is completely unavailable, the most recent data from 2014 shows South Sudan consumed 727 kWh/capita, while Niger used 1,733 kWh/capita [28]. To reach the 2014 energy consumption values of middle-income countries (16,096 kWh/capita), these nations would need to increase their energy usage by more than tenfold and by more than thirtyfold to match the energy consumption of high-income countries (54,426 kWh/capita). Such a substantial increase is not required for an increased quality of life. Therefore, the scenarios presented may be considered “overkill,” as solar installations at half the proposed size would still substantially benefit these countries and their populations. Smaller-scale solar projects that support a lower energy usage than the proposed values can still lead to meaningful improvements in energy accessibility at a smaller cost.

6 Data Center Modeling

6.1 Methods

6.1.1 Solar Data Collection and Validation

PVWatts can provide a year's worth of hourly solar output information for a specific location based on a typical meteorological year (TMY). PVWatts did not have this data available in any of the selected countries. Figure 19 shows the PVWatts stations within 2,000 miles of the capital of South Sudan. The closest of the stations is 302 miles away. Figure 20 shows the only PVWatts station within 2,000 miles of the capital of Niger, which is 569 miles away. No data was available within 2,000 miles of the capitals of the Central African Republic or Chad.

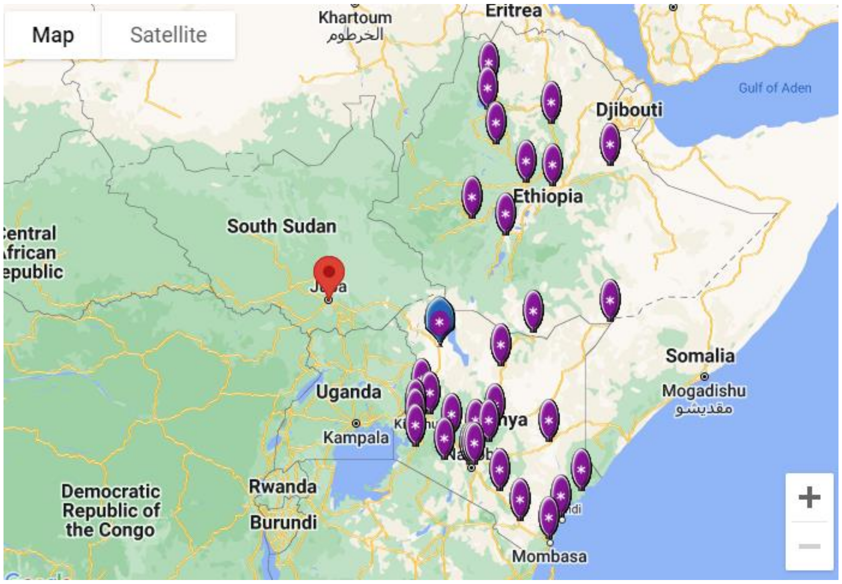


Figure 19. Locations closest to the capital of South Sudan, Juba, with hourly solar data in PVWatts [40].

Figure 20. Locations closest to the capital of Niger, Niamey, with hourly solar data in PVWatts [40].

Fortunately, the Global Solar Atlas has data available that gives the average solar output each hour of the day for each month. These averages do not account for days or weeks without sun and, therefore, are insufficient for estimating dynamics and battery size but can help compare two locations.

Since Juba, South Sudan, had the most stations within 2,000 miles, the monthly hourly profiles of several "representative" locations could be compared to Juba. Three selected locations with latitude are shown in Figure 21, and their details are listed in Table 18.

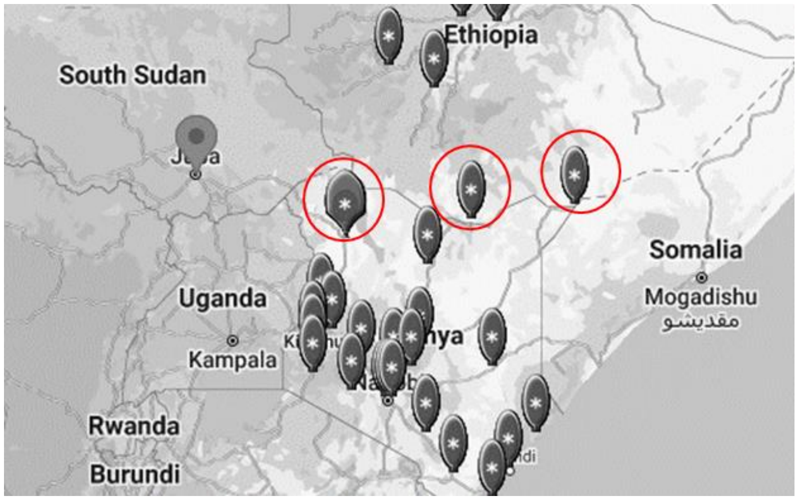


Figure 21. PVWatts map [40] *with selected locations circled in red.*

PVWatts Location	Distance from Juba	Coordinates	Location name in Global Solar Atlas*
Lodwar, Kenya	302 miles	3.120, 35.620	Nakwalele, Kenya
Moyale, Kenya/Ethiopia	521 miles	3.530, 39.050	Moyale, Kenya/Ethiopia
Mandera, Kenya	710 miles	3.930, 41.870	Beled Hawa, Somalia

Table 18. Selected locations and their distance to Juba, South Sudan. Data from [40] *Location name differences between PVWatts and Global Solar Atlas due to specificity differences.*

The coordinates for each location were entered into Global Solar Atlas (GSA), and the PV details are listed in Table 19. The outputted data was the average amount of solar electricity produced by this system for each hour for each month.

System type	Ground mounted large-scale
Azimuth	180 (default)
Tilt	9 (default)
System size	One kWp

Table 19. PV system details entered into GSA.

To decide which representative location was the closest match to Juba, the average solar output for each hour of the day was graphed by month for Juba and the three representative locations. To numerically confirm which location was the closest match, the percentage difference between the curves at each hour of the day was calculated for each representative location. The differences for all twelve months were combined in a single column and displayed in a box and whisker plot.

Yearly data for 2017, 2018, and 2019 in 15, 30, and 60-min increments is available for these locations through the National Solar Radiation Database (NSRDB). This data will allow for energy modeling of all four countries, instead of just South Sudan, and allow for comparing Juba's representative TMY data and actual data for Juba. The weather files for each location were downloaded within NREL's System Advisor Model software and plugged into the PVWatts model to simulate the same data output from the PVWatts website. The inputs for the model are summarized in Table 20.

System nameplate capacity	1000 kWdc
Module type	Standard
DC to AC ratio	1.15
Inverter Efficiency	96%
Array type	Fixed open rack
Tilt	20°
Azimuth	180°
Total system losses	14.08%

Table 20. System Design inputs for System Advisor Model PVWatts - Commercial Owner.

6.1.2 Energy Modeling

The PVWatts model outputs were converted to MW to be normalized to MW output/MW solar installed. These normalized values were put into the data center model to find the exact size of the PV system and battery needed without curtailment.

2018 was the year selected to be further analyzed for the other capitals and curtailment optimization. To decrease the energy storage requirements, the model was optimized from 5% to 95% curtailment in increments of 5%.

Utilized a simplified version of a colleague's existing data center energy model [41] for battery and hydrogen scenarios. The mathematical model for charging the energy storage systems is the following:

The objective function is the following:

$$O.F. \quad \sum_{0}^{8760} Electricity_{Data\,Center\,demand} = \sum_{0}^{8760} P_{RES-DC} + P_{SS-DC}$$

The constraints for the objective function are the following:

$$E_{SS}(0) = E_{SS}(8760)$$

$$\min \; E_{SS}(t) = E_{SS_C} \times (1 - DOD)$$

P_{RES-DC}	Power supplied to DC directly from Renewable Energy
P_{SS-DC}	Power supplied to DC from storage energy system
E_{SS}	Energy stored at time t
E_{SS_C}	Energy storage capacity
DOD	Storage depth of discharge

Table 21. Variables included in the objective function and its constraints [41].

The detailed equations and constraints used in the model that describe the energy delivery directly from the solar power to the data center, when the storage is charged, and when the storage is discharged, are listed in the appendix

6.1.2.1 Power to Batteries

Using the battery storage version of the described model, the PV and battery system was appropriately sized to supply a constant 49 MW load, with about one day of backup power in various locations. The battery system parameters are summarized in Table 22.

Charge/Discharge Efficiency	85%
Depth of Discharge	20%
Self-discharge rate	0.73%/year
Degradation	1.7%/year
Operation Life	15 years

Table 22. Battery System Parameters in data center model [41], [42].

6.1.2.2 Power to Hydrogen

Using a simplified power-to-hydrogen version of a colleague's existing data center energy model [41], the PV and hydrogen systems were sized to supply a constant 49 MW load, with about one day of backup power in various locations. The hydrogen system comprises an electrolyzer, liquefier, hydrogen tank, and fuel cell. The hydrogen system parameters are listed in Table 23 and Table 24. Additionally, liquefaction is assumed to require 15% of hydrogen's energy content [41].

	Efficiency	Degradation
Electrolyzer	75%	1.7%/year
Fuel Cell	60%	1.7%/year

Table 23. Electrolyzer and fuel cell parameters [41].

Energy capacity	9,632 MWh
Diameter	10 m
Boil off	1%/day

Table 24. Hydrogen tank parameters [41].

6.1.3 Preferred Data Center Location

Several factors are considered for finding the preferred location for a data center. These include proximity to existing infrastructure and fiber optic cables, cost, and land availability. The proximity to existing infrastructure is taken into account by considering the capitals of each country, assuming that they will have higher levels of infrastructure than other cities. The other factors are looked at through GIS and economic modeling.

The levelized cost of energy (LCOE) for each location was calculated at varying curtailment amounts and cost projection scenarios using the data center energy model results. The base year for the costs is 2030, and the period is 30 years. The lifespan of the batteries is assumed to be 15 years [42], and the PV system is assumed to last the entire 30-year period. The PV and battery system values are listed in Table 25 and Table 26, respectively. The capital cost metric used was the overnight capital cost (OCC) because this was the only capital cost metric available for both utility-scale PV and utility-scale batteries from the same source. The low, middle, and high-cost values are based on varying possibilities of future research, development, and investment.

	Low	Middle	High
OCC ($/MW)	885,390	1,002,240	1,163,023
O&M ($/MW-yr)	19,932		

Table 25. Utility Scale PV Costs, 2030. O&M costs assumed to be fixed used mid-range value [43].

	Year	Low	Medium	High
OCC ($/MWh)	2030	226,435.5	300,961.25	373,227.75
	2045	166,875.75	231,353	334,896.75
O&M ($/MW-yr)	7,500			

Table 26. Utility Scale Battery Storage Costs. O&M costs assumed to be fixed at 2030 values, used mid-range values. Costs listed in the source as $/kW for a 4-hour battery [44].

More factors must be considered to calculate the LCOE of the hydrogen scenarios. The technologies needed for the hydrogen scenarios, especially the electrolyzer and fuel cell, are not as commercially available today as technologies like solar and batteries. Therefore, there is less analysis of the future cost projections of these technologies. Hopefully, these future costs will be much less as the research in this area has very recently received considerable research funding and attention.

Water treatment, on the other hand, is very technologically mature. A comprehensive economic analysis of water treatment in the United States reports the cost of treatment at around $20 per gallon for capacities between 0.1 and 1 MGD, including both capital, operational, and maintenance costs [45], which is the appropriate range for the data center water requirements for electrolysis. This price also includes the price of oil as the energy source. The energy costs were reported to be 18% of water treatment costs in Europe [46]. Hence, the value used for water treatment costs in this analysis was $16.4/gallon (18% of $20 per gallon) since this analysis considers solar as the only energy source, and that cost is already considered. The inputs for the LCOE of the hydrogen scenarios are summarized in Table 27. Additionally, the energy requirements for water treatment are assumed to be 2 kWh/m^{3}, which is on the higher end of energy needed to treat wastewater [47], [48]. The maximum amount of water required for any location results in around 3,000 MWh of energy necessary to treat water, less than 1% of the energy needed for the data center, and could be supplied very easily with 1% curtailment. Therefore, the size of the energy infrastructure is assumed to be the same as without providing the energy for water treatment.

			Reference
Electrolyzer	Capital cost ($/MW)	500,000	[49]
	O&M ($/MW/year)	47,900	[50]
	Lifetime	10 years	[41]
Fuel Cell	Capital cost ($/MW)	100,000	[50]
	O&M($/MW/year)	37,600	[50]
	Lifetime	10 years	[41]
Hydrogen tanks	Cost ($/tank)	13,310,000	[41]
Hydrogen liquefaction	Cost ($/kg)	1.33	[51]
Water treatment	$/gallon	16.40	[45]

Table 27. 2030 costs of the various hydrogen infrastructure needed.

Another critical factor in deciding the preferred location for a data center is the presence of fiber optic cables. Information and GIS-compatible files regarding fiber optic cables in Africa were available from AfTerFibre [52]. AfTerFibre is a crowdsource project that is updated by the public and is not guaranteed to be up to date. The shapefile from AfterFibre of existing and planned fiber optic cables was added and clipped to the existing GIS map of the selected countries. While there was no indication of fiber optic cables in all of Central African Republic, efforts are underway to install fiber optic cables in the region [53].

The capitals of each country were also added and clipped to the map from a world capitals dataset [54]. Following the suggested procedure for contribution to AfterFibre, a map of these cables was traced in Google Earth and exported as a .kml file. This file and supporting information were submitted to the creator of AfterFibre to hopefully be added to their current website. The .kml file was added into GIS, converted to a layer, and formatted to match the rest of the map.

Several size assumptions were made to estimate the size of the data center and its renewable infrastructure. The size was estimated for the level of curtailment with the lowest LCOE for each location. The solar panel size used throughout this analysis is 5 m^2/kW. This was multiplied by the capacity of the PV system for the lowest LCOE. The battery size is assumed to be 1000 ft^2/MWh [55]. This was multiplied by the battery capacity for the lowest LCOE. The data center size was calculated with the power density assumption of 160 W/ft^2[56]. The size of the data center (49 MW) was divided by this power density to calculate the square footage. All values were converted to square kilometers, and the space requirements for the solar panels, battery system, and data center were added together.

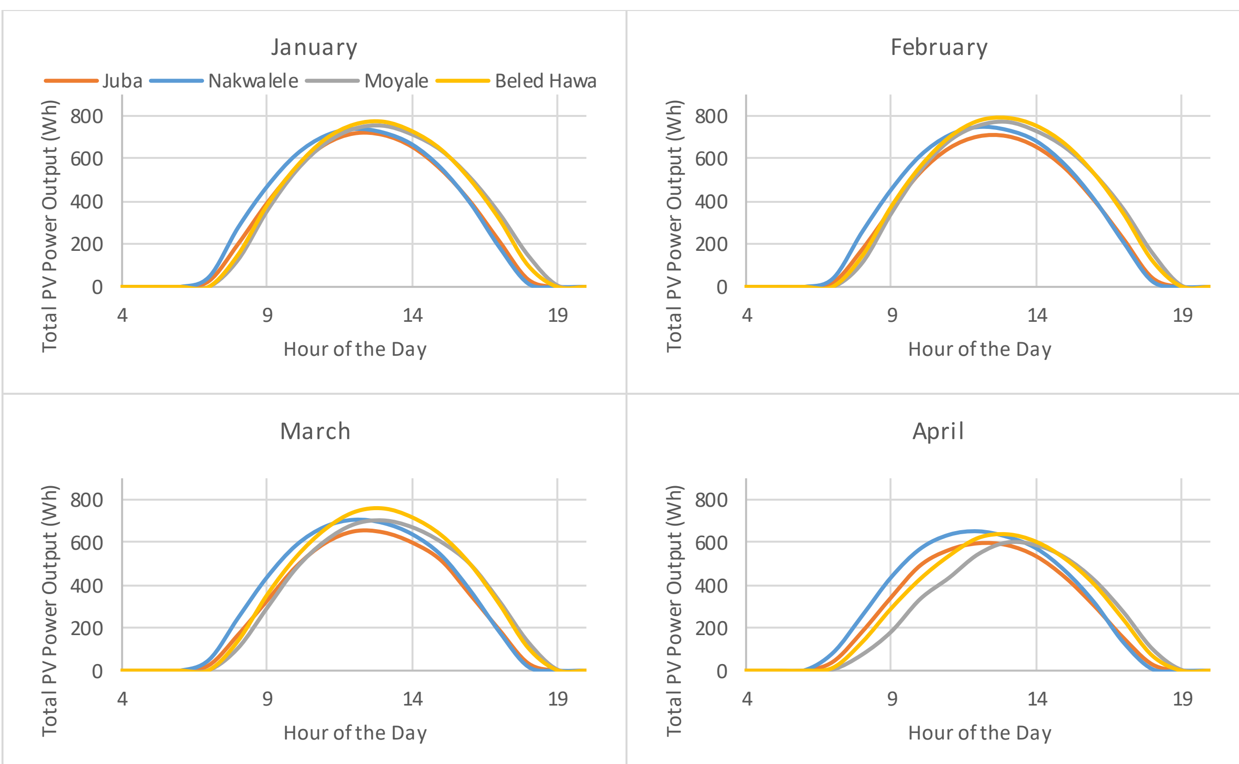
The size estimations for the hydrogen-specific infrastructure include the electrolyzer size of 6 m^2/MW for the electrolyzer itself [57]–[59], and the size requirements for the BOP were expected to be equal. The fuel cell is assumed to take up 1 acre/10 MW [60]. The hydrogen tanks have a 10 m diameter [41], and the hydrogen liquefaction plant is assumed to take up 30,000 m^2, modeled after an existing project with similar capacity [61]. The land required for a wastewater treatment plant is considered negligible compared to the rest of the energy infrastructure, particularly the solar panels. A modern wastewater treatment plant in Texas with a capacity of 35 MGD (more than 350x the capacity needed for the data center) takes up less than 0.01 square kilometers [62].

The land availability for a potential renewable data center site was considered for each capital within a 25 km radius. In ArcGIS Pro, a 25 km buffer was created and clipped around each capital. The resulting values were calculated from the number of pixels and the cell size.

6.2 Results

6.2.1 Solar Data Collection and Validation

The average PV power output for each hour of the day for each month is displayed in Figure 22. The x-axis represents the time of day, and the y-axis is the amount of power produced during that hour interval for a 1000 kW system, with the y-value for hour 1 being the amount of power produced between midnight and 1 am, and so on. From inspecting the various graphs, it appears that the average hourly profiles for Nakwalele most closely match those of Juba.



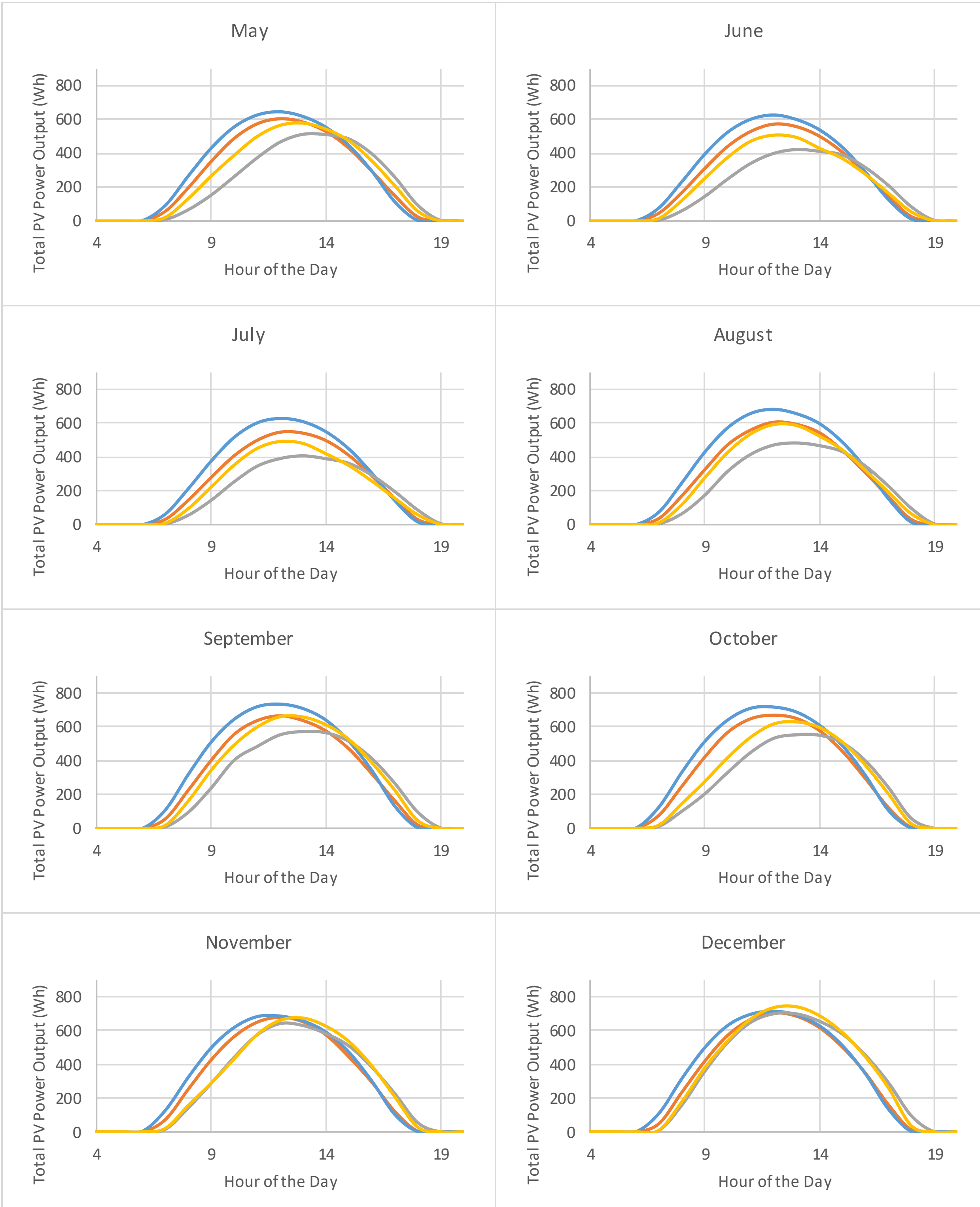


Figure 22. Average Hourly Profiles, Total PV Power Output of Juba vs. 3 Various "Representative" Locations. Data from [29].

The distribution of percentage differences for the power output for each hour of the day between each curve for the representative location and Juba is shown in Figure 23. Note that the y-axis of this figure goes from -100% to +100% to show the differences more clearly. The large outliers outside this range almost exclusively result from differences in sunrise or sunset times when one location produces one Wh and the other produces two to ten Wh.

The relevant box and whisker plot values are in Table 28. As mentioned previously, the IQR represents the middle 50% of data points, where Q_1 and Q_3 are the lower and upper bounds of the IQR, respectively. For Nakwalele, the middle 50% of the points on the Nakwalele curve were between 2% and 21% higher than the solar output in Juba, which results in an IQR of 19%. For Moyale, the middle 50% of the points on the Nakwalele curve were between 33% lower and 17% higher than the solar output in Juba, which results in an IQR of 50%. For Beld Hawo, the middle 50% of the points on the Nakwalele curve were between 15% lower and 17% higher than the solar output in Juba, which resulted in an IQR of 32%. The difference between Nakwalele and Juba has the smallest IQR, meaning that the middle 50% of data points have the smallest range of differences. This confirms the earlier visual assumption that Nakwalele is the closest numerical match for average PV output.

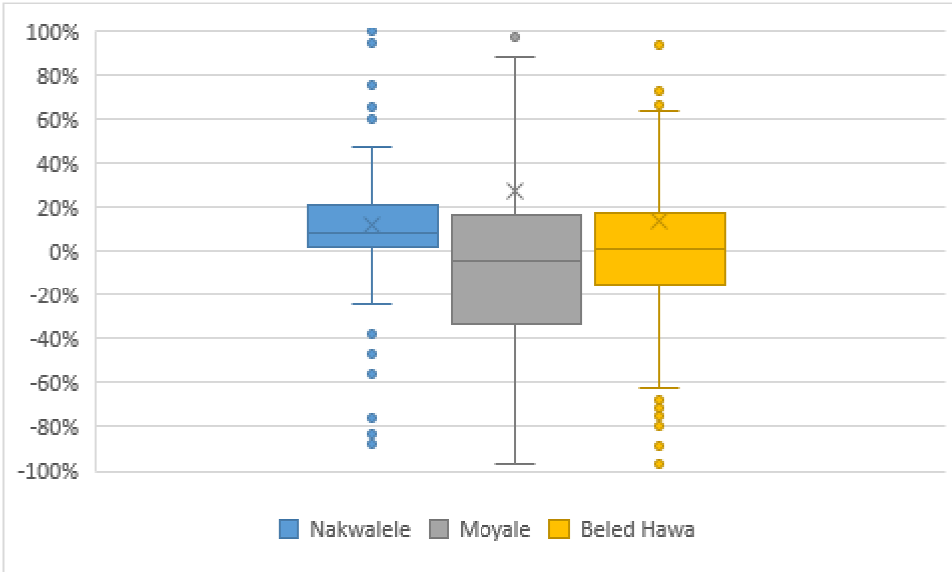


Figure 23. Box and Whisker Plot of Percent Differences between each representative location and Juba.

	Nakwalele	Moyale	Beled Hawa
Min	-88%	-96%	-96%
Max	200%	1250%	575%
Average	12%	28%	14%
Median	9%	-4%	1%
Q_1	2%	-33%	-15%
Q_3	21%	17%	17%
IQR	19%	50%	32%

Table 28. Summary of values relevant to box and whisker plot data for Figure 23.

6.2.2 Power to Batteries

The solar and battery capacities for a 49 MW data center with no curtailment for various years in Juba, South Sudan, are summarized in Table 29. The solar dynamics in 2017 needed the largest battery size of any of the years, while 2019 required the largest amount of solar panels. 2018 needed the smallest amount of solar panels and a much smaller battery than the other two years (around 10% smaller).

Year	Solar Capacity Installed (MW)	Battery Nominal Capacity (MWh)
2017	379.53	81,374
2018	378.50	72,851
2019	392.75	79,784

Table 29. Juba, South Sudan data center model results.

The solar and battery capacities for a 49 MW data center with varying levels of curtailment (shown as percentages associated with each data point) in Juba, South Sudan, using 2018 NSRDB data, and the PVWatts "representative" location in Nakwalele/Lodwar, Kenya in Figure 24. The data for 2018 in Juba results in the need for a larger battery and a larger number of solar panels installed than the PVWatts data for Lodwar/Nakwalele at every level of curtailment.

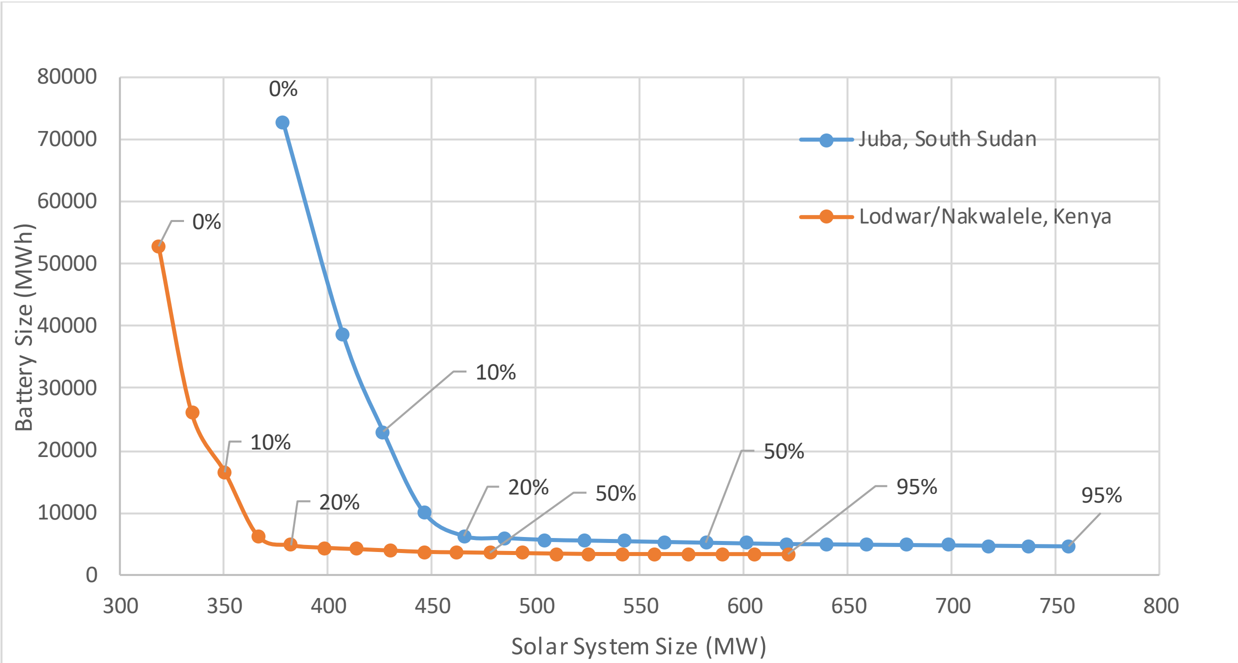


Figure 24. Battery size vs. solar system size: 2018 PVWatts Lodwar/Nakwalele, Kenya results from TMY data and 2018 SAM/PVWatts Juba, South Sudan results.

The solar and battery capacity for varying curtailment levels for all four capitals are combined and displayed in Figure 25. Figure 26 offers a zoomed-in perspective of the same results to analyze better what occurs at moderate to high curtailment levels. Niamey, Niger, requires the smallest battery and solar capacity for the same level of curtailment as the other locations. The only overlap between any lines occurs at high curtailment levels when the CAR line crosses the South Sudan line. Juba, South Sudan, and Niamey, Niger, see a dramatic drop in battery size that levels out of battery size after about 20% curtailment. Bangui, Central African Republic, and N'Djamena Chad see a more gradual, curved decline in battery size.

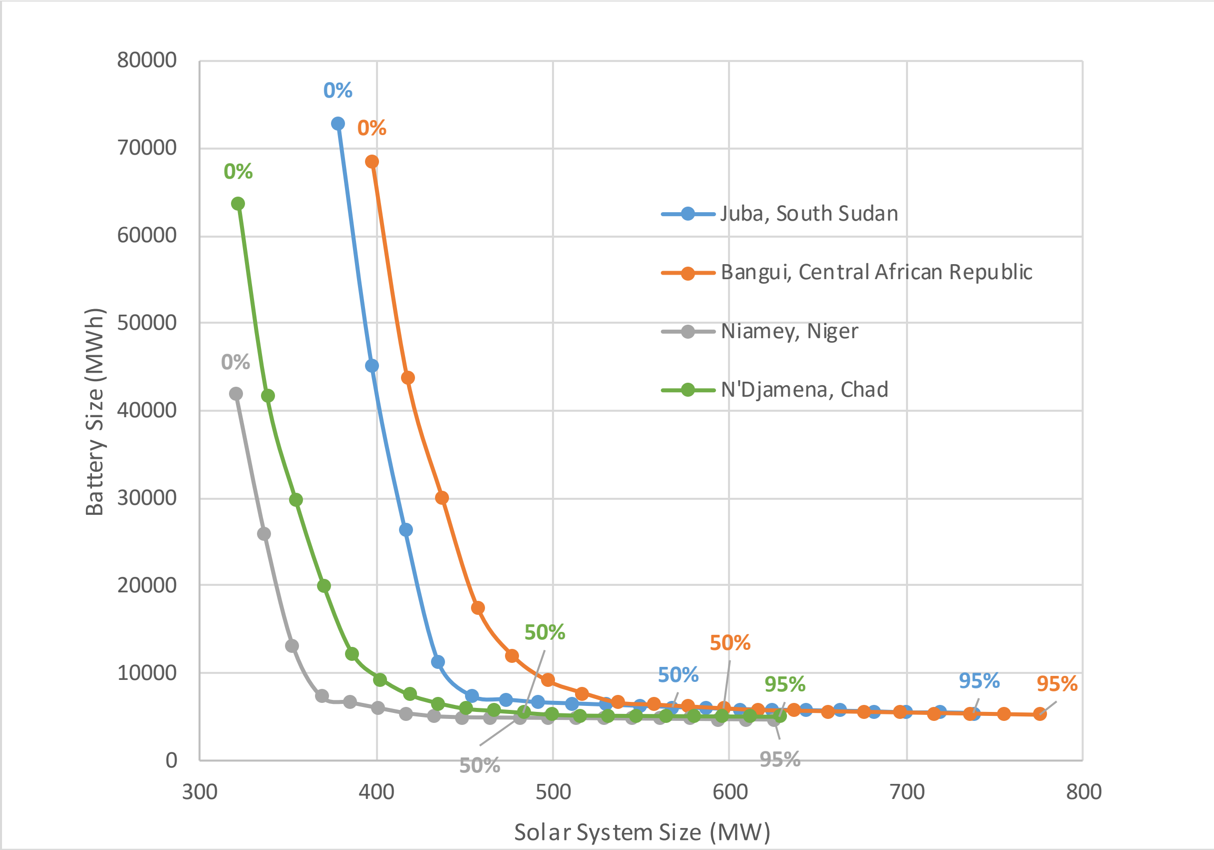


Figure 25. Battery size vs. solar system size for varying levels of curtailment for a 49 MW data center for all four countries.

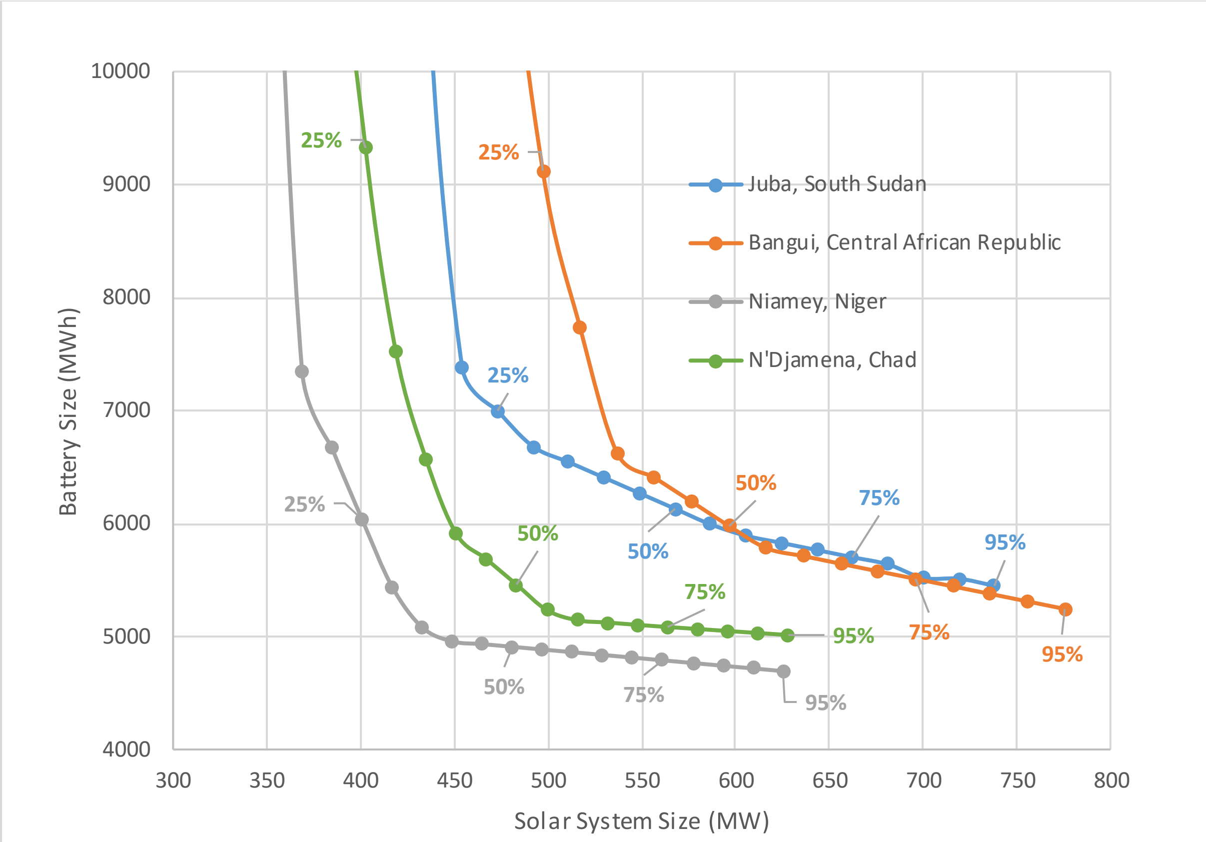


Figure 26. Zoomed in version of Figure 25. Battery size vs. solar system size for varying levels of curtailment for a 49 MW data center for all four countries.

6.2.3 Power to Hydrogen

The solar and hydrogen storage requirements for varying levels of curtailment for all four capitals are combined and displayed in Figure 27. Niamey, Niger, requires the smallest storage and solar capacity for the same level of curtailment as the other locations. The only overlap between any lines occurs as Bangui, Central African Republic, increases from 5% to 10% curtailment. After 10% curtailment, Bangui, Central African Republic, requires less storage than Juba, South Sudan.

Dashed lines are added to display the tank capacity for storing hydrogen, as the hydrogen storage requirements consider only the energy of the hydrogen stored. For example, the number of storage tanks required for N'Djamena, Chad, at 95% will be equivalent to the number of storage tanks needed for Niamey, Niger, at 95% curtailment, even though Niamey, Niger, requires less hydrogen overall.

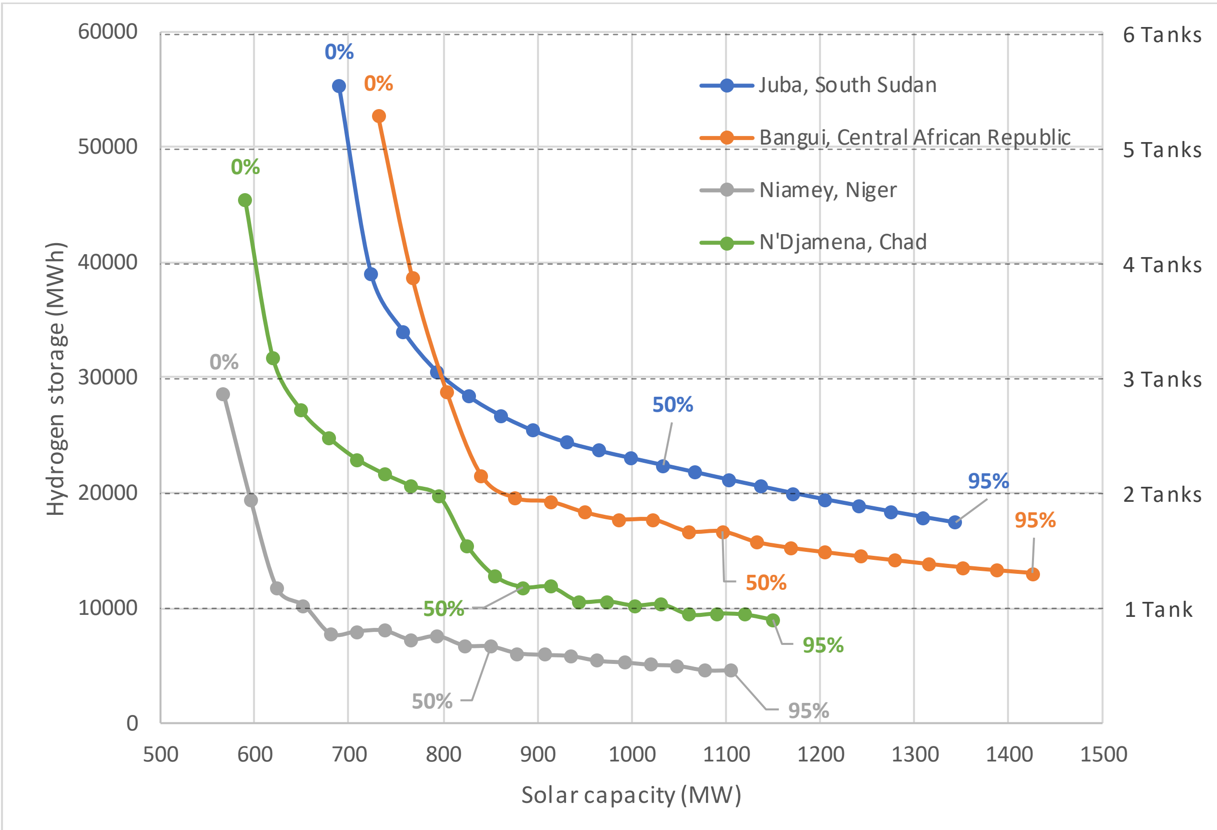


Figure 27. Hydrogen storage requirements vs. solar system size for varying levels of curtailment for a 49 MW data center for all four countries.

The electrolyzer size requirements and the solar capacity state for varying curtailment levels for all four capitals are combined and displayed in Figure 28. Niamey, Niger, requires the smallest electrolyzer for the same level of curtailment as the other locations, while Bangui, Central African Republic, requires the largest.

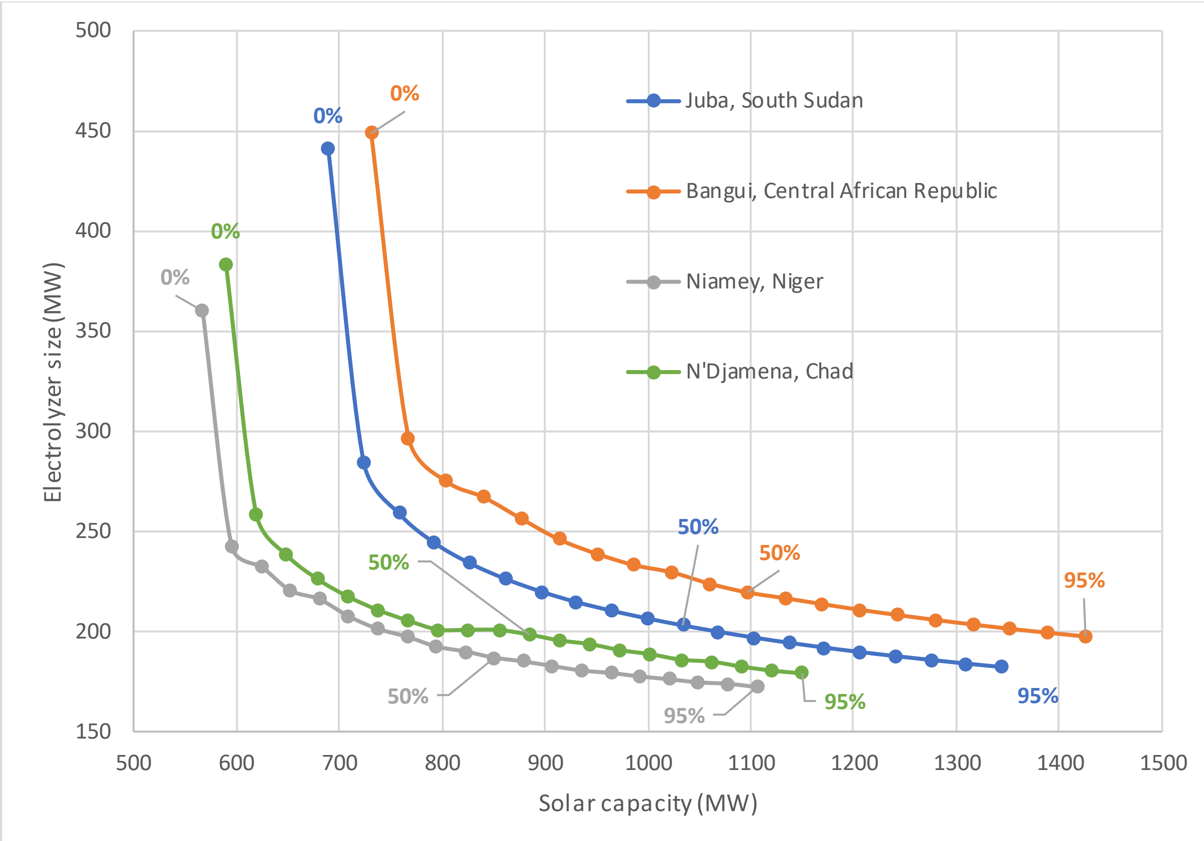


Figure 28. Electrolyzer size requirements vs. solar system size for varying levels of curtailment for a 49 MW data center for all four countries.

6.2.4 Batteries vs. Hydrogen Storage Requirements

Figure 29, Figure 30,Figure 31, and Figure 32 compare the storage requirements vs. solar capacity at varying curtailment levels for hydrogen storage vs. battery storage. Due to the lower efficiency of power-to-hydrogen storage, the battery storage case requires less solar capacity than the hydrogen case in all locations. The storage requirements for batteries are higher than hydrogen at low levels of curtailment, but the battery case requires less overall energy storage than the hydrogen case at moderate to high levels of curtailment. The hydrogen storage cases decrease more gradually with curtailment than the battery cases and continue to decline more steadily at high curtailment levels.

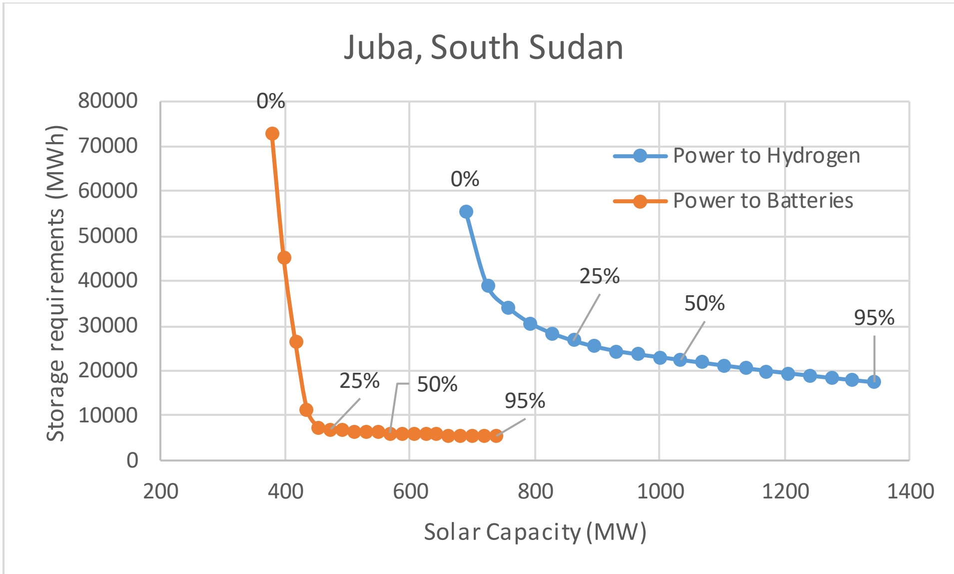


Figure 29. Comparison between hydrogen and battery energy storage for a 49 MW data center in Juba, South Sudan.

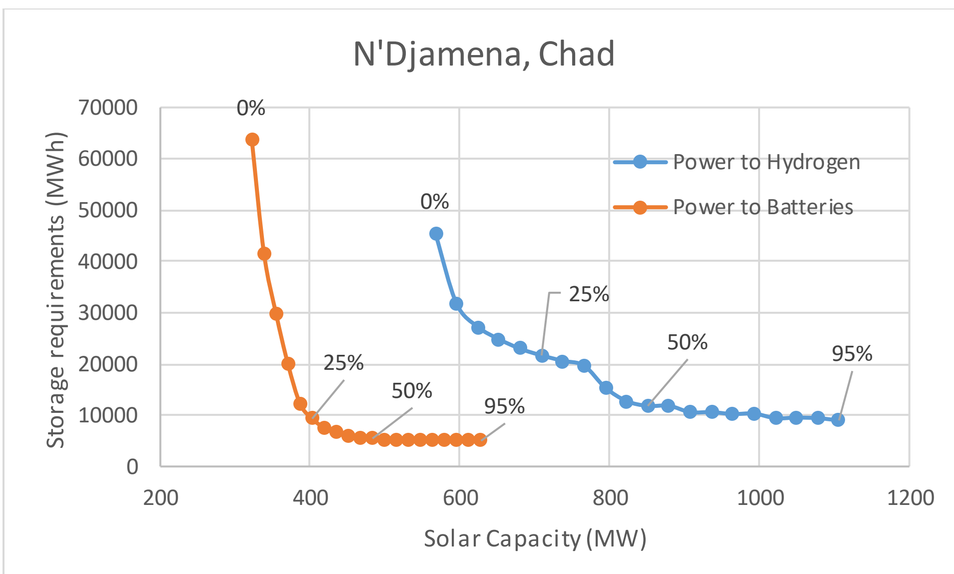


Figure 30. Comparison between hydrogen and battery energy storage for a 49 MW data center in N'Djamena, Chad.

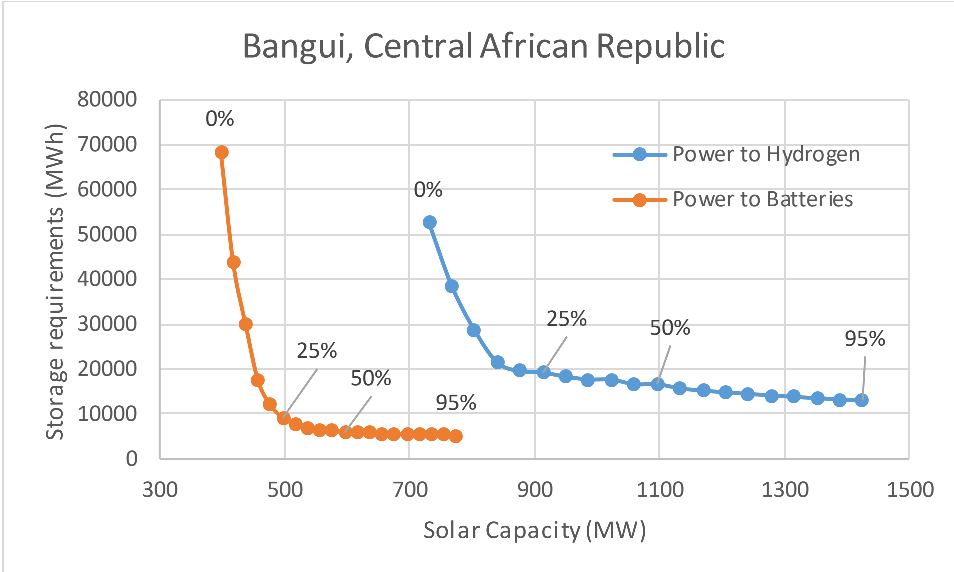


Figure 31. Comparison between hydrogen and battery energy storage for a 49 MW data center in Bangui, Central African Republic.

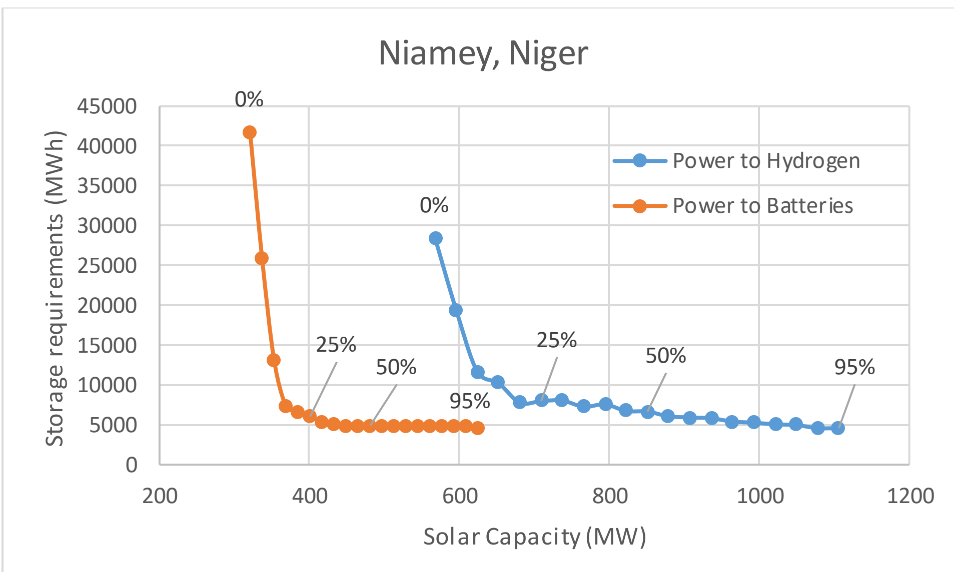


Figure 32. Comparison between hydrogen and battery energy storage for a 49 MW data center in Niamey, Niger.

6.2.5 Preferred Data Center Location

The numerical results for the economic modeling of a data center using battery storage in various locations are displayed in Table 30. The table includes the lowest LCOE for each location at the low, middle, and high-cost projections, as well as the corresponding level of curtailment, size of the PV system, and battery size.

The lowest LCOE across all three cost projections happened at the same level of curtailment for each location. Niamey, Niger, had the overall lowest LCOE of $279.60/MWh for the lowest cost projection at a 40% level of curtailment. Juba, South Sudan, had the highest overall LCOE of $333.54/MWh for the lowest cost projection at an 85% level of curtailment. Central African Republic has its lowest LCOE at the maximum curtailment value of 95%. All four locations had a battery size of around 5,000 MWh.

Location	LCOE ($/MWh)			% curtailment	PV Size (MW)	Battery Size (MWh)
	Low	Middle	High			
Juba, South Sudan	333.54	397.16	478.30	85	700	5,518
Bangui, Central African Republic	329.23	390.65	469.09	95	776	5,244
Niamey, Niger	279.60	335.17	405.89	40	449	4,956
N'Djamena, Chad	295.70	353.80	427.80	60	515	5,144

Table 30. Data center battery storage case: minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario.

Figure 33 shows the relationship between the levelized cost of electricity for the battery case on the y-axis and the level of curtailment on the x-axis for all four capitals for various cost projections. The figure shows that the cost reduction between data points is highest at lower curtailment levels. However, there are still marginal changes between data points that could lead to major cost savings, as shown in Figure 34, which offers a closer look at the change in LCOE with curtailment at moderate and high curtailment levels.

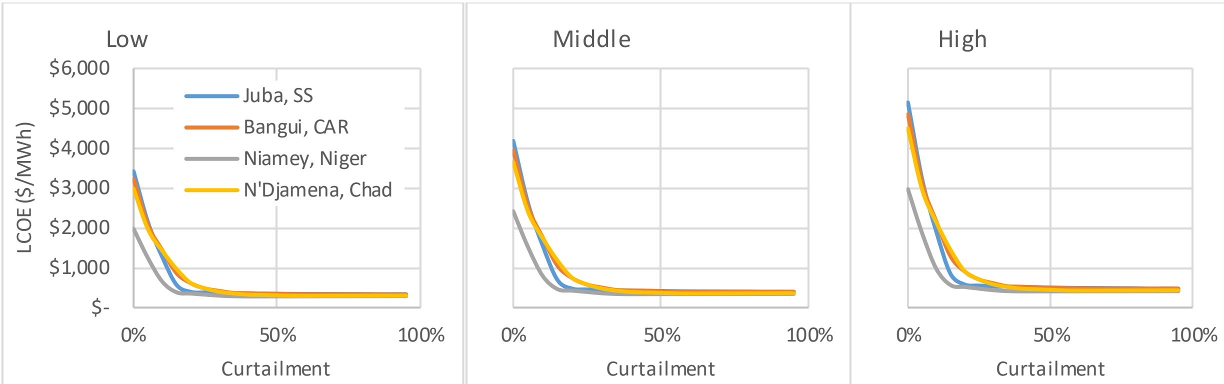


Figure 33. LCOE vs. Curtailment for low, middle, and high-cost projections for the data center battery scenarios.

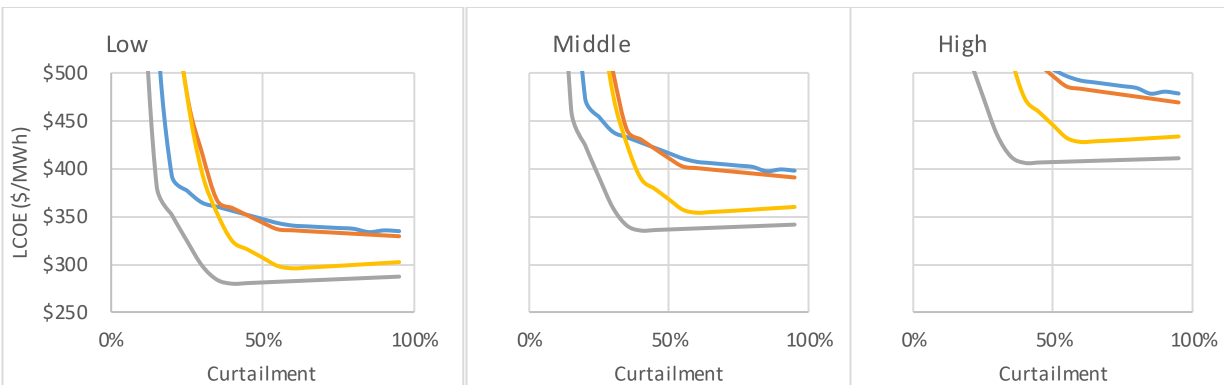


Figure 34. Zoomed in LCOE vs. Curtailment for low, middle, and high-cost projections for the data center battery scenarios.

Table 31, Table 32, andTable 33 show the results for the hydrogen storage scenarios for the 49 MW data center across the low, medium, and high-cost solar projections. Unlike the battery scenarios, the curtailment at which the lowest LCOE occurred was not constant across the three different cost projections. The hydrogen case also differed considerably from the battery case by the LCOE occurring at relatively low curtailment levels. However, the hydrogen scenarios did mimic the battery scenarios by having Niamey, Niger, consistently with the lowest LCOE. The costs for the hydrogen scenarios are consistently lower than those for the battery scenarios across all locations and cost projections.

Location	LCOE ($/MWh)	% curtailment	PV size (MW)	Hydrogen storage (MWh)	Electrolyzer size (MW)	Fuel cell size (MW)
Juba, South Sudan	209.14	20	827	18959	239	52
Bangui, Central African Republic	217.50	15	841	31202	257	52
Niamey, Niger	182.58	15	652	9570	222	52
N'Djamena, Chad	193.35	20	708	16597	228	52

Table 31. Data center hydrogen storage case: minimum LCOE and corresponding curtailment, and the size of the PV system, hydrogen storage, electrolyzer, and fuel cell for the lowest projected cost of solar.

Location	LCOE ($/MWh)	% curtailment	PV size (MW)	Hydrogen storage (MWh)	Electrolyzer size (MW)	Fuel cell size (MW)
Juba, South Sudan	216.20	15	793	21007	250	52
Bangui, Central African Republic	224.77	10	804	33893	271	52
Niamey, Niger	188.30	15	652	9570	222	52
N'Djamena, Chad	199.53	15	678	16595	241	52

Table 32. Data center hydrogen storage case: minimum LCOE and corresponding curtailment, and the size of the PV system, hydrogen storage, electrolyzer, and fuel cell for the moderate projected cost of solar.

Location	LCOE ($/MWh)	% curtailment	PV size (MW)	Hydrogen storage (MWh)	Electrolyzer size (MW)	Fuel cell size (MW)
Juba, South Sudan	225.75	15	793	21007	250	52
Bangui, Central African Republic	234.46	10	804	33893	271	52
Niamey, Niger	196.16	15	652	9570	222	52
N'Djamena, Chad	207.42	5	619	31663	258	52

Table 33. Data center hydrogen storage case: minimum LCOE and corresponding curtailment, and the size of the PV system, hydrogen storage, electrolyzer, and fuel cell for the highest projected cost of solar.

Figure 35 shows the change in LCOE vs. curtailment for the hydrogen data center scenarios. There is an initial sharp decline in costs as the storage and electrolyzer sizes decrease, but as the solar capacity increases with more curtailment, the costs begin to go back up at relatively low curtailment levels. This is another deviation from the battery scenarios that sees consistent marginal cost reductions at moderate to high curtailment levels.

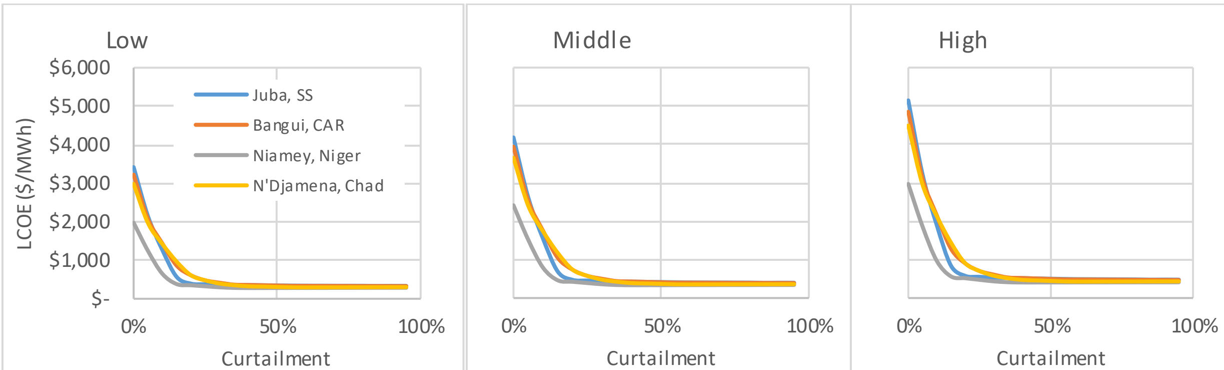


Figure 35. LCOE vs. Curtailment for low, middle, and high-cost projections for the data center hydrogen scenarios.

Figure 36 shows the land suitable for solar as well as the capitals and fiber optic cables that currently exist or are under construction. Fortunately, all of the capitals are located near existing or planned fiber optic cables.

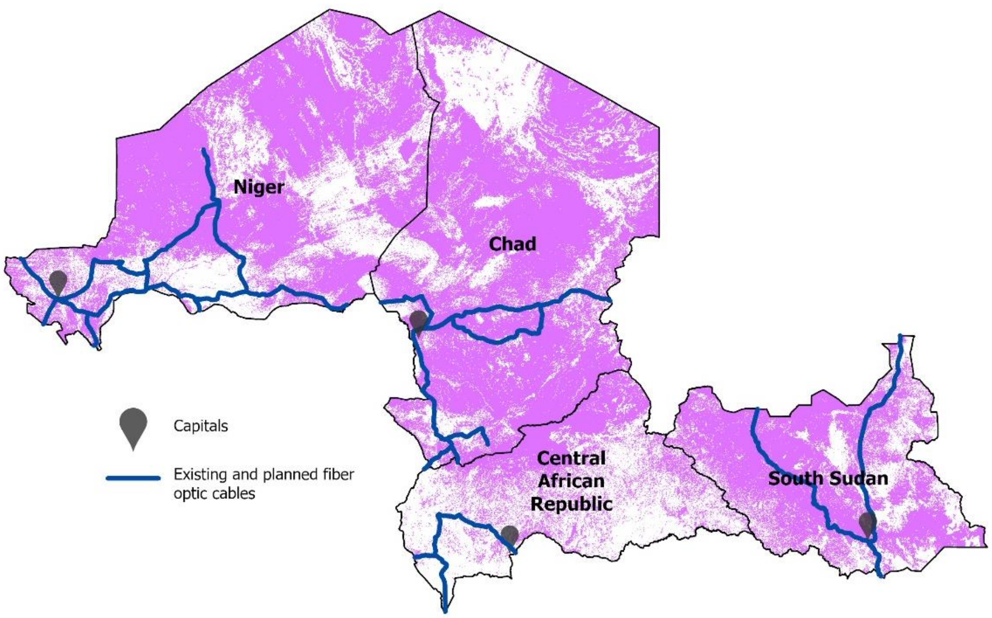


Figure 36. Map of fiber optic cables in Africa from AfTerFibre [52] *and the Central African Republic portion of the Central African Backbone Project* [53] *with the capitals of each country* [54].

The size of land needed for each data center in the capitals of the Central African Republic, Chad, Niger, and South Sudan is listed in Table 34 for the battery scenarios and in Table 35 for the hydrogen scenarios. For all locations, the land needed for PV is larger than the amount required for the energy infrastructure data center. The data center only takes up 0.0285 square kilometers, which is only around 1% of the land needed for solar panels. Niamey, Niger, had the smallest land requirements to support the renewable data center at about 2.7 square kilometers for the battery scenario and 3.3 km^2 for the hydrogen scenario. Bangui, Central African Republic, requires the most land to support the renewable data center at around 4.4 square kilometers for the battery scenario and 4.3 km^2 for the hydrogen scenario.

Location	PV (km²)	Battery (km²)	Data center (km²)	Total space (km²)
Juba, South Sudan	3.5	0.513	0.0285	4.0413
Bangui, Central African Republic	3.88	0.487		4.3958
Niamey, Niger	2.245	0.461		2.7340
N'Djamena, Chad	2.575	0.478		3.0815

Table 34. Battery scenarios: Space requirements for the 49 MW data center and its renewable energy infrastructure. The PV, and battery sizes were calculated from the values corresponding to the lowest LCOE in Table 30.

	PV (km²)	Tanks (km²)	Electrolyzer (km²)	Fuel cell (km²)	Data center (km²)	Liquefaction plant (km²)	Total space (km²)
Juba, South Sudan	4.14	0.0000628	0.00292	0.0210	0.0285	0.03	4.22
Bangui, Central African Republic	4.21	0.0001257	0.00314	0.0210			4.29
Niamey, Niger	3.26	0.0000314	0.00271	0.0210			3.34
N'Djamena, Chad	3.54	0.0000628	0.00279	0.0210			3.62

Table 35. Hydrogen scenarios: Space requirements for the 49 MW data center and its renewable energy infrastructure. The PV, and battery sizes were calculated from the values corresponding to the minimum LCOE for the lowest cost projection in Table 31.

Figure 37 shows the land suitable for solar within a 25-mile radius of each capital (within the country's borders) in maroon. The circle represents the 25-km radius. The numerical results are listed in Table 36. N'Djamena, Chad, and Juba, South Sudan, had the largest availability, followed by Niamey, Niger, and then Bangui, Central African Republic. The smallest amount of land available (in Bangui) was 266 km^2.

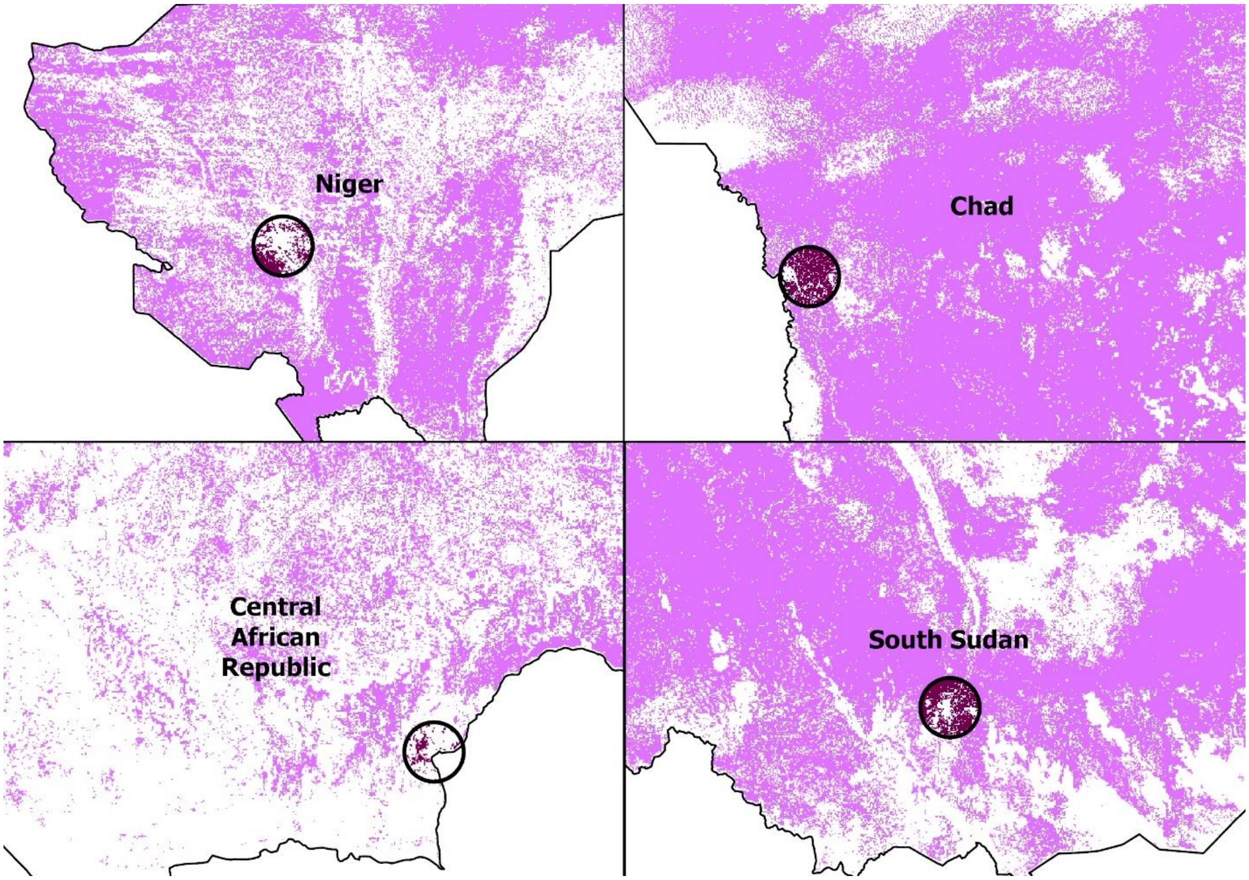


Figure 37. Land suitable for solar within a 25 km radius of each capital.

	Area around capital for solar (km^2)	Area around capital for solar (%)
Niamey, Niger	733.994	37%
Ndjamena, Chad	1325.193	67%
Bangui, Central African Republic	266.086	14%
Juba, South Sudan	1330.451	68%

Table 36. Land suitable for solar within a 25 km radius of each capital.

6.3 Discussion

6.3.1 Solar Data Collection and Validation

A barrier to the most accurate modeling of a data center is the lack of solar data for a typical meteorological year. Among the capitals of the four countries considered, only Juba, South Sudan had multiple PVWatts sites with TMY data within a reasonable proximity to facilitate modeling the solar dynamics. The compilation and analysis of TMY data requires years of effort, and the unavailability of such data severely restricts the ability to accurately model a PV system in the capitals of Niger, Chad, South Sudan, and Central African Republic. This data scarcity further underscores the challenges faced by these countries as LDCs.

Comparing the monthly averages of hourly solar output proved to be the most viable option to gauge the solar potential of representative locations in relation to Juba, despite its limitation in accounting for cloudy days and weeks, which are critical for accurately sizing an energy storage system. The curves in Figure 22 show discernable disparities in the average solar outputs over a year between Juba and the other locations. Notably, the smallest gap between the curves was observed for Nakwalele, suggesting that it offers the most suitable TMY data for modeling Juba. This intuitively aligns with the fact that Nakwalele is the closest of the three locations, lying “only” 302 miles from Juba.

However, the gap between the curves was smaller for Beled Hawa than for Moyale, despite Beled Hawa being farther from Juba (710 miles) than Moyale (521 miles). This discrepancy could be attributed to the fact that Beled Hawa is slightly closer in latitude to Juba than Moyale, which could have a substantial impact at a distance of over 500 miles. Nevertheless, other factors such as topography, climate, or other regional differences could also contribute to this variation. This reaffirms the importance of obtaining accurate and comprehensive data specific to each location for precise modeling.

6.3.2 Energy Modeling

The solar and battery capacities for a 49 MW data center in Juba, South Sudan, are subject to variation based on the year of data input. This variability is expected due to the influence of different weather events in various years, which may deviate from typical conditions. When comparing the 2018 data for Juba with its most representative location, Nakwalele, using TMY data, there are noticeable disparities in the sizing of the systems across varying levels of curtailment. Juba required a larger PV and battery system compared to Nakwalele at all points of curtailment. This suggests that Nakwalele’s TMY data has a higher solar output than Juba’s 2018 data. This difference in PV and battery sizes could be attributed to differences in solar dynamics between the two locations, or it may result from a difference in 2018 solar dynamics that deviate from a typical meteorological year. It is not possible to decide the exact reason or which location is more accurate. However, less accurate data could lead to over- or under-sizing the required systems, resulting in unnecessary cost increases or insufficient power supply. This underscores the critical need for accurate data in these locations.

For the data center scenarios, the difference in storage sizing between the locations can be attributed to the varied solar dynamics and overall solar output. In a comparison of the 2018 data for all capital cities, Niamey, Niger, consistently required the smallest PV system and storage size at all levels of curtailment, followed most closely by Chad. This aligns with expectations as these two locations are situated within the Sahara Desert, where solar output is abundant. Niger's capital is located in the far southwest corner of the country, one of the most distant points from the central Sahara. This suggests that the system size needed to support a 49 MW data center farther northeast in the country would require an even smaller system size.

Curtailment is typically viewed negatively as it entails wasting energy. However, it offers the advantage of drastically reducing storage requirements. All of the capitals (as well as Nakwalele) experience a considerable reduction in battery size with low levels of curtailment. Moreover, curtailed electricity can be redirected to surrounding communities, providing them with clean energy they currently do not have.

If hydrogen is selected as the storage method, water treatment will be necessary to prepare it for electrolysis. The water treatment facility could easily be oversized to treat water for electrolysis and provide clean water to the surrounding community.

6.3.3 Preferred Data Center Location

As mentioned previously, curtailment allows for major reductions in storage size. This notably impacts the cost of the data center. Implementing more solar panels than necessary and curtailing excess energy decreases battery, hydrogen tank, and electrolyzer size, leading to major cost reductions. The levelized cost of electricity tells us how much curtailment is ideal for maximum cost reduction. Each location has different solar dynamics that impact the sizing of its energy infrastructure.

For the battery storage scenarios, the curtailment of electricity by 20% reduced the battery sizes by nearly 90% and continued to decrease marginally after that. The lowest LCOE occurred for all locations at a higher curtailment than 20%, demonstrating that the marginal reductions in battery size are still cost-effective. These marginal decreases in battery size are still cost-effective in Bangui, Central African Republic, where the lowest LCOE occurs at the maximum curtailment value of 95%. Juba, South Sudan, also experiences cost benefits at very high curtailment levels, with the lowest LCOE at 85% curtailment. This indicates that the cost of battery systems is a major limiting factor of affordable renewable energy reliance. Not only are the batteries needed to be completely reliant on solar very large (~5,000 MWh), but they also need to be replaced more frequently than solar panels, further increasing the LCOE over time. When not accounting for the cost-benefit of curtailed electricity, Niamey, Niger, had the lowest LCOE out of the four capitals, with only 40% curtailment needed to reach that cost. All of the other capitals required more curtailment to reach their lowest cost, and all of them were higher than that of Niamey, Niger, thanks to its high solar output and favorable dynamics.

For the hydrogen case, the lowest LCOE occurred at much smaller curtailment levels and had lower overall costs, even though batteries are more efficient. This suggests that hydrogen may be a better solution for the demand of the data center, especially regarding cost. Niamey, Niger, once again had the lowest overall LCOE, confirming that its solar output and dynamics are very suitable for a renewable data center for overall cost reduction.

It is important to note that many cost assumptions used in the LCOE analysis are specific to the United States, and actual energy infrastructure costs in other locations will vary. As these countries are provided with more energy to support their development, it is hoped that it will bring them closer to the economic levels of middle- and high-income countries. This analysis is aimed at projecting costs under these circumstances. The United States has an extensive research network in this field, making it a suitable reference for these values. Additionally, it's worth acknowledging that cost projections are subject to change, especially as new research and development occurs.

It is also important to note that the LCOE does not account for selling curtailed electricity. Therefore, this LCOE could be viewed as a ‘maximum’ cost that is expected to decrease if power purchase agreements were considered. The aspiration is that the data center could supply the surplus electricity to the surrounding population at no cost.

To further analyze the preferred location for a data center beyond cost, we needed to consider the feasibility of establishing one in each location. Two critical factors for implementing a renewable data center are the presence of fiber optic cables and sufficient land suitable for large-scale solar installation.

Fortunately, all the capital cities are near fiber optic cables that currently exist or will exist in the near future. Additionally, all of the locations possess the land needed to support the renewable data center at the lowest levelized cost of energy. This is true even considering the extensive solar installations with 95% curtailment in Bangui, Central African Republic.

Bangui, Central African Republic, requires the largest amount of land needed for a renewable data center for either the battery or hydrogen case, which was 4.3-4.4 km^2 for solar panels, data center, and storage infrastructure. Bangui also has the least available land suitable for large-scale renewable infrastructure within a 25-kilometer radius, with 266 km^2 available. Fortunately, this area is sufficient to accommodate the renewable data center.

The other locations also possess sufficient land for this purpose, as they have more land available and a smaller land requirement for the renewable data center. It’s important to note that the estimates for calculating the land requirements may vary. However, plenty of land in all locations is available if the land requirements are much larger.

Given that none of the locations have land constraints, the LCOE becomes the most logical factor for a corporation to consider when selecting a renewable data center site. Hydrogen emerges as the most cost-effective option overall, and Niger's low LCOE makes it the most cost-effective location. Its 15% curtailment for the hydrogen scenario enables the data center to supply excess clean electricity to the neighboring population.

However, establishing a battery-reliant data center in Bangui, Central African Republic, with a 95% curtailment rate, allows for a much larger delivery of clean electricity to the surrounding communities. Furthermore, the increased solar installation capacity enables the corporation to invest in additional solar power generation assets to offset their emissions. Alternatively, a battery-reliant data center in Niamey, Niger, at 40% curtailment, strikes a balance between cost and carbon offset potential with a lower LCOE than the other locations for the battery scenarios. The choice ultimately depends on the corporation's priorities and objectives.

7 Additional Community Energy Infrastructure

7.1 Importance of Reliable, Renewable Energy Delivery

A practical solution for harnessing the potential of carbon offsets is to build supplementary renewable infrastructure in nearby communities. This strategy not only increases the energy supply for these communities but also substantially improves the reliability of their energy supply. Ensuring a dependable and consistent energy supply to communities is paramount, particularly during high demand. Consequently, the local population surrounding data centers should be provided with a reliable electricity supply and should not be subjected to only the intermittent delivery of otherwise curtailed electricity. Installing additional solar and storage facilities becomes imperative to meet the energy needs of these communities. Simultaneously, the curtailment of energy will contribute to a reduction in storage size requirements.

Residential energy usage will be considered for the additional community infrastructure. The load profile of residential housing is expected to be very different from that of the data center. The data center is assumed to have a relatively constant load profile throughout all hours and seasons. The continuous load requirements, including at night when no solar energy is available to harness, result in the very high storage requirements analyzed previously. The load profile of a house is much more dynamic and will have very low energy demands in the middle of the night, altering the storage requirements compared to those of a data center.

7.2 Methods

7.2.1 Developing a Residential Load Profile

The United States has ample data and analysis in modeling residential load profiles and serves as a model for the potential future of residential energy usage in the LDCs. A modified Koppen-Geiger climate classification map was used to compare the climates of regions in the United States and the countries analyzed. Chad and Niger mostly fall under the BWh classification (Arid hot desert) with a small region of BSh (Arid hot steppe). The capitals of Niger and Chad appear to border the BWh and BSh regions. South Sudan and the Central African Republic are almost entirely classified as Aw (Tropical Savannah). Southern Chad has a portion of Aw as well. The areas in the United States that also fall under these climate zones are Western Arizona (BWh), Southern Texas (BSh), and South Florida (Aw) [63]. The climate zones used in the following analysis will be BWh (Arid hot desert) for Niamey, Niger, and N'Djamena, Chad, and Aw (Tropical Savannah) for Bangui Central African Republic and Juba, South Sudan.

Data regarding residential energy usage in 15-minute increments from NREL's ResStock Analysis tool was available by region, state, or country [64]. The region selected for arid hot steppe is Mohave and La Paz Counties in western Arizona. The annual time series data for residential energy usage in 2018 from all fuel types for this region was downloaded from [65]. The region selected for Aw (Tropical savannah) is Charlotte County in Southern Florida. The annual time series data for residential energy usage in 2018 from all fuel types for this region was downloaded from [66].

The 15-minute increments of total residential energy usage were added together for every hour of the year. To account for the difference in seasonal variation between the northern and southern hemispheres, the residential energy usage from January through June was shifted to after July through December. That way, the residential energy usage profile reflects the year starting with summer, winter in the middle, and ending with summer.

The total amount of energy, in kWh used per hour was divided by the population from the 2020 US Census of the county or counties to get kWh/hour/capita. The populations are listed in Table 37. The kWh/hour/capita was converted to MWh/hour/10,000 people to be entered into the energy model.

County	Population from 2020 Census
Mohave, Arizona	213,267
La Paz, Arizona	16,557
Charlotte, Florida	186,847

Table 37. Population values used to normalize the energy usage in each county. Data from [67]–[69].

7.2.2 Energy model

The same energy model and methods used to model the data centers will be used to model the additional community energy with the appropriate theoretical load profile input. The effects of curtailment will be analyzed in increments of 10%.

7.3 Results

7.3.1 Theoretical Load Profiles of 10,000 Residents

The resulting load profile for the arid, hot, steppe climates in Niger and Chad is shown in Figure 38. The y-axis is the amount of residential energy used by 10,000 people within a given hour, and the x-axis is the hour of the year that that energy usage occurs. The peaks and valleys show large weekly, monthly, and seasonal variations as the heating and cooling needs vary. The peak energy usage occurs in the middle of the year at almost 120 MWh per hour per 10,000 residents.

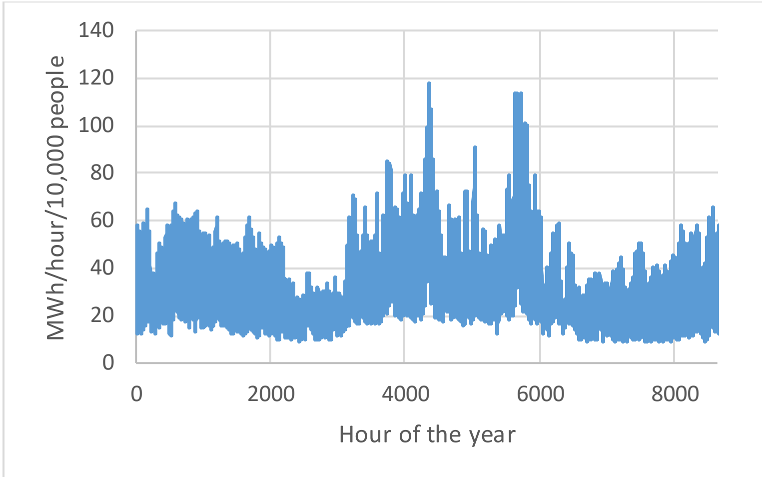


Figure 38. Theoretical Residential load profile for an entire year, for Niamey, Niger and N'Djamena, Chad. Based on data from [65].

A single day from the arid, hot, steppe year-long energy load profile is shown in Figure 39 for June 1st. The y-axis is the same as previously, with the x-axis as the hour of the day. The energy usage on this particular day peaks in the morning at around 9 am, decreases until 4 pm, and steadily increases throughout the evening and night.

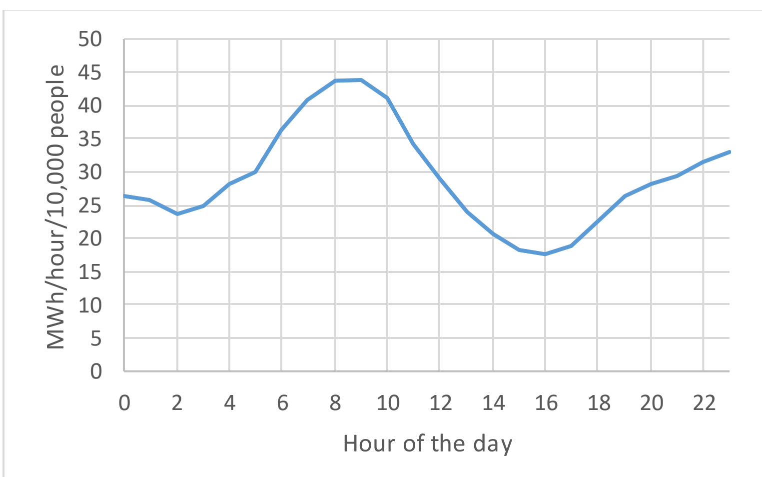


Figure 39. Theoretical Residential load profile for June 1st, for Niamey, Niger and N'Djamena, Chad. Based on data from [65].

The resulting load profile for the tropical savannah climate in South Sudan and the Central African Republic is shown in Figure 40. The peak energy usage occurs in the middle of the year at about 80 MWh per hour per 10,000 residents.

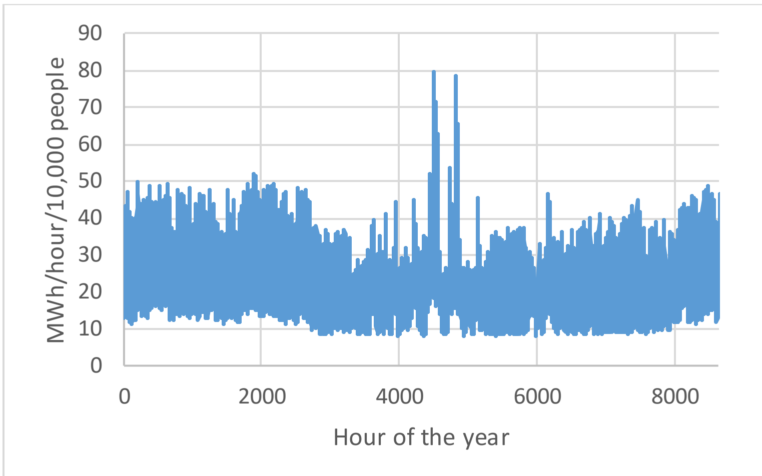


Figure 40. Theoretical Residential load profile for an entire year, for Bangui, Central African Republic and Juba, South Sudan. Based on data from [66].

The tropical savannah energy load profile for June 1st is shown in Figure 41 for June 1st. The energy usage follows a similar pattern, with the energy usage peaking in the morning at around 7 am, decreasing until 2 pm, and slightly increasing throughout the evening and night.

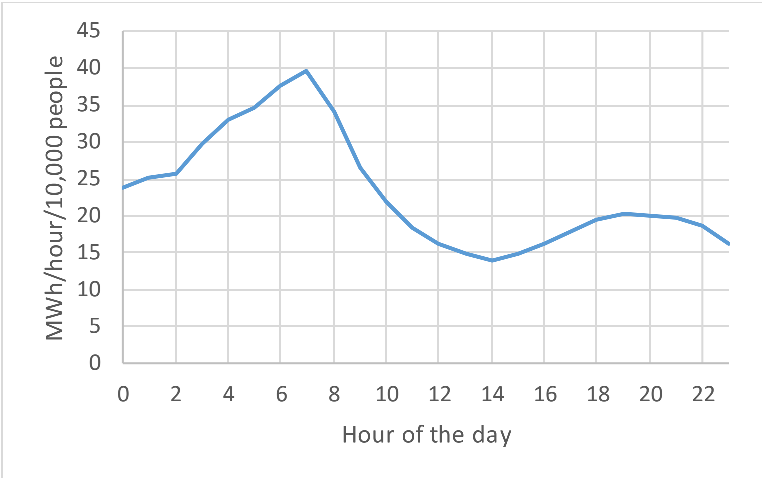


Figure 41. Theoretical Residential load profile for June 1st, for Bangui, Central African Republic and Juba, South Sudan. Based on data from [66].

7.3.2 Energy Model

7.3.2.1 Power to Batteries

The solar and battery capacity for varying levels of curtailment for the theoretical residential load profile of 10,000 residents for all four capitals are combined and displayed in Figure 42 and Figure 43. Juba, South Sudan, requires the smallest solar capacity of all four locations at all levels of curtailment and the smallest battery capacity above 10% curtailment. Bangui, Central African Republic, has similar results to Juba, South Sudan. N'Djamena, Chad, consistently requires the most solar and battery capacity to meet the energy demand.

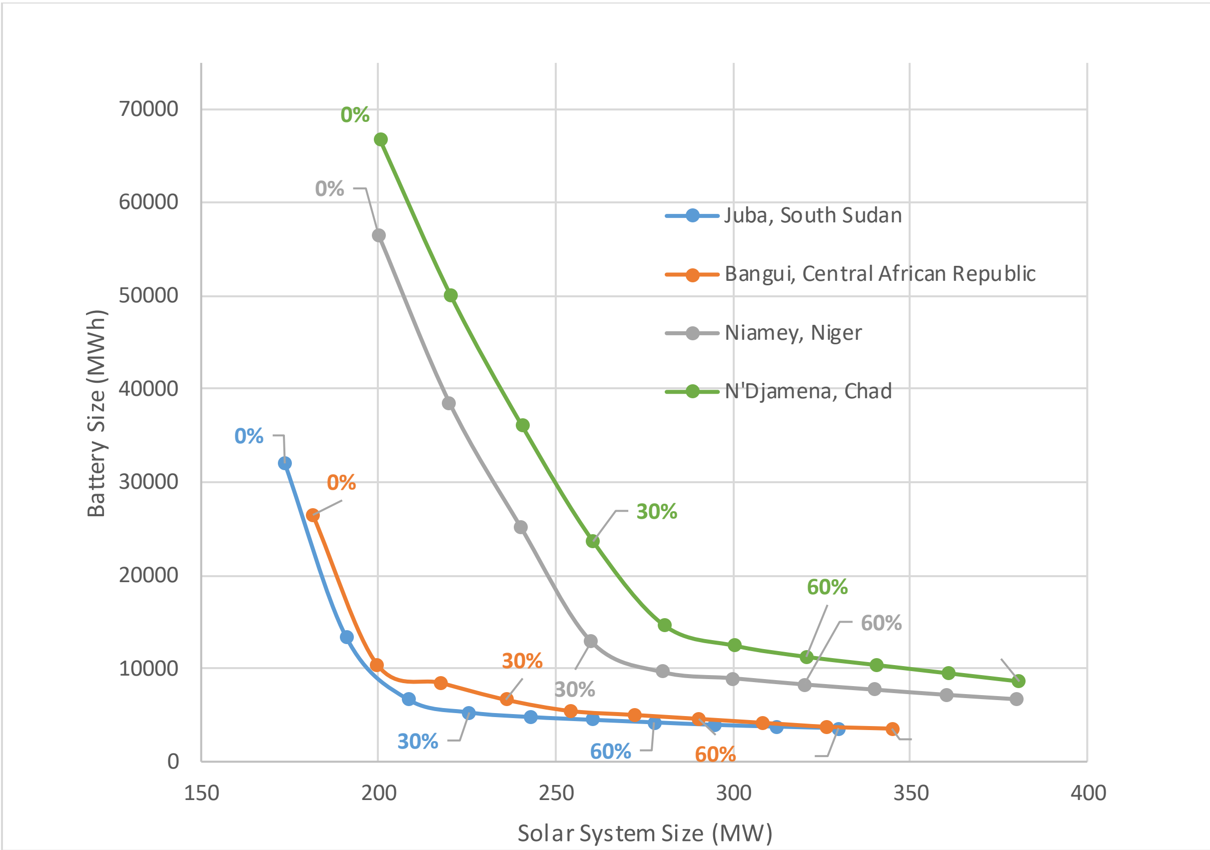


Figure 42. Battery size vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents in all four countries.

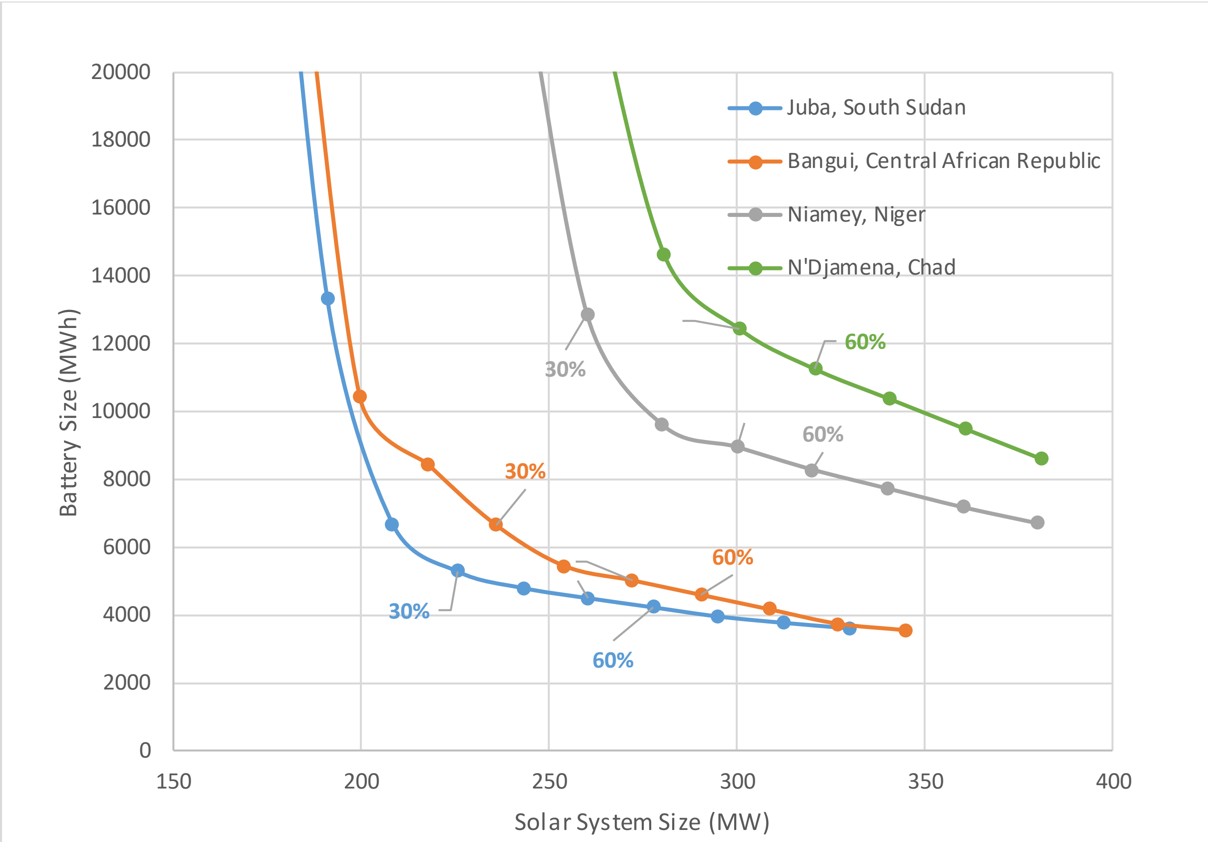


Figure 43. Zoomed in version of Figure 42. Battery size vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents in all four countries.

7.3.2.2 Power to Hydrogen

The solar and hydrogen storage requirements for varying levels of curtailment for the theoretical residential load profile of 10,000 residents for all four capitals are combined and displayed in Figure 44. Like the battery case, Juba, South Sudan, requires the smallest solar capacity for the same level of curtailment as the other locations and the smallest battery at 10% curtailment and higher. N'Djamena, Chad, requires the most storage overall, with a very slight overlap with Niamey, Niger at high levels of curtailment.

The dashed lines are added as before to display the tank capacity for storing hydrogen. These storage requirements are for 10,000 residents, and the number of tanks will scale with larger populations according to the fraction of the hydrogen tank.

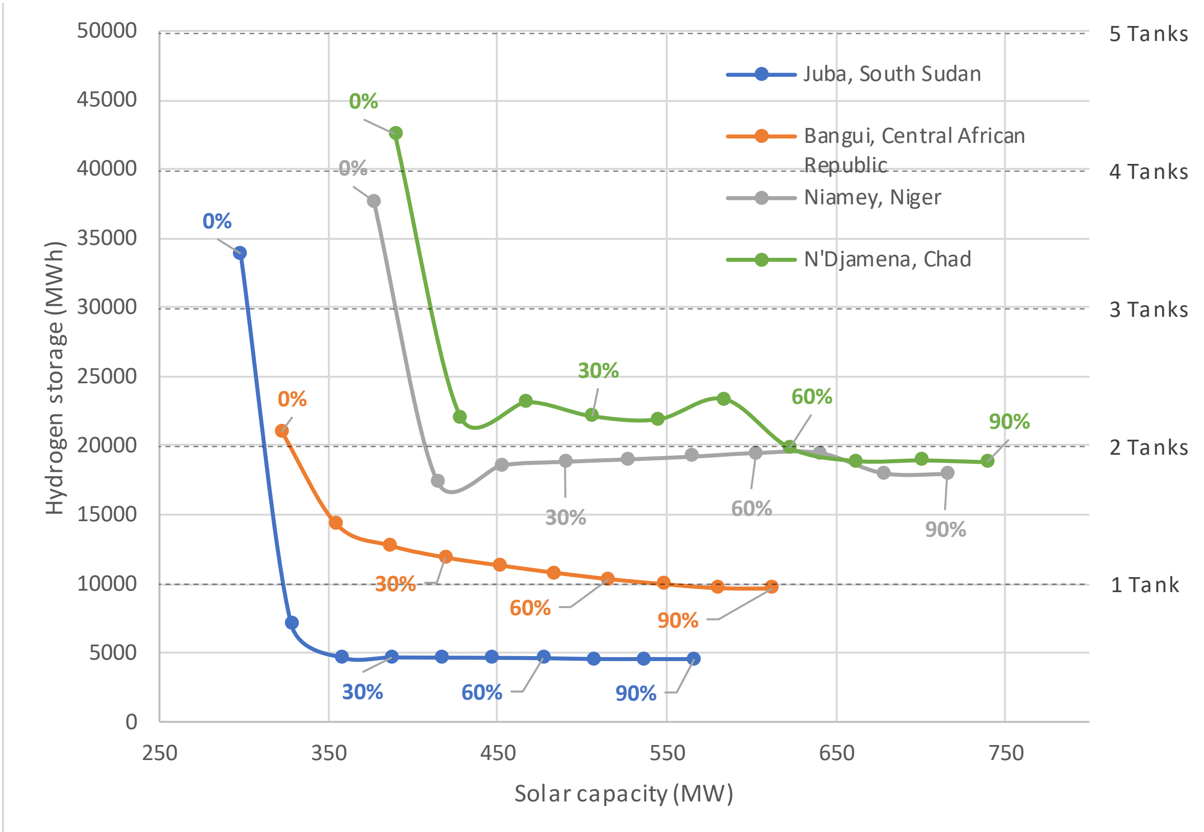


Figure 44. Hydrogen storage requirements vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents in all four countries.

The electrolyzer size requirements and the solar capacity state for varying curtailment levels for all four capitals are combined and displayed in Figure 45. Bangui, Central African Republic, requires the smallest electrolyzer of any location at and above 10% curtailment. This deviates from the previous trend of Juba requiring the smallest infrastructure. N’Djamena, Chad requires the largest electrolyzer for most levels of curtailment, with Niamey, Niger needing a larger electrolyzer at only 10% curtailment.

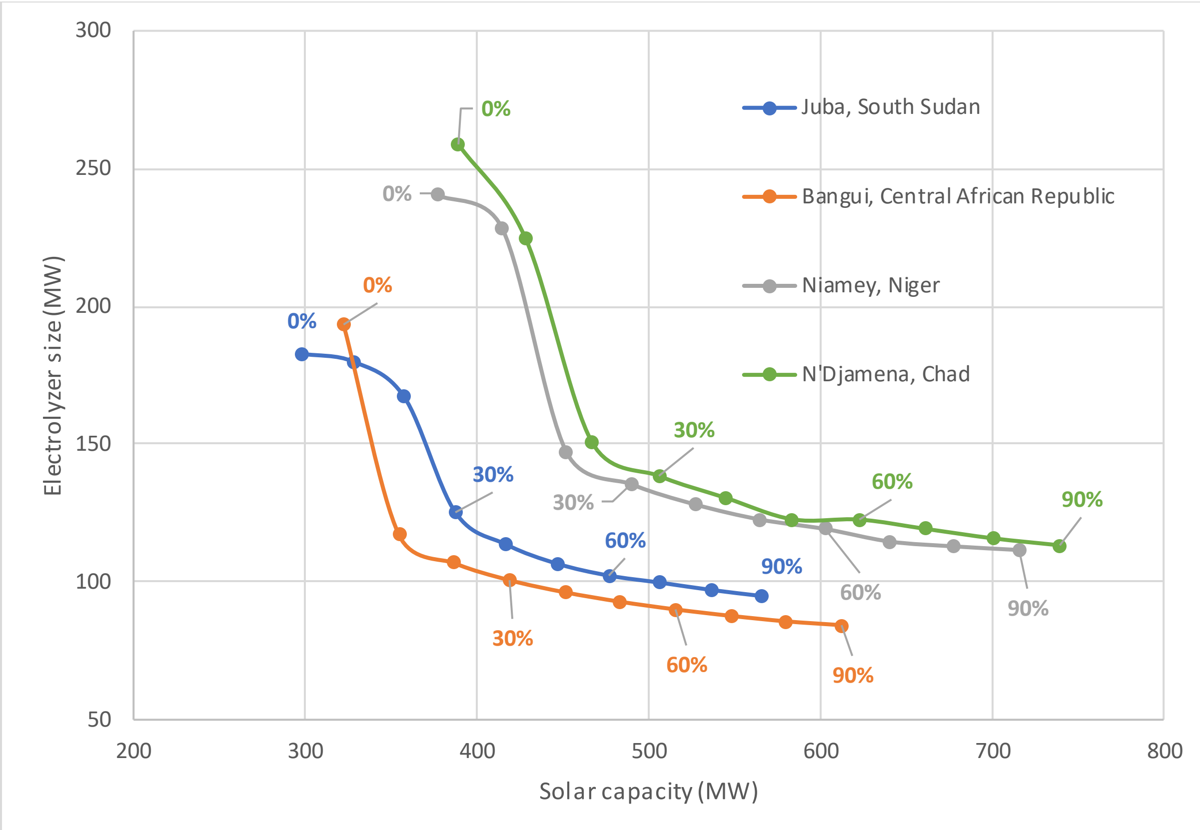


Figure 45. Electrolyzer size requirements vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents in all four countries.

7.3.2.3 Batteries vs. Hydrogen

Figure 46, Figure 47, Figure 48, and Figure 49 compare the storage requirements vs. solar capacity at varying curtailment levels for hydrogen storage vs. battery storage. Like the data center scenarios, the battery storage case requires less solar capacity than the hydrogen case in all locations due to differences in efficiencies. In most of the locations, the storage requirements for batteries are higher than hydrogen at low levels of curtailment. However, the battery case requires less overall storage than the hydrogen case at moderate to high curtailment levels. Juba, South Sudan has a slightly different story, requiring virtually the same amount of storage in hydrogen as batteries, but still needs a higher solar capacity. Additionally, the storage requirements drop quicker with curtailment for the hydrogen case than the battery case, which is more of a gradual decline.

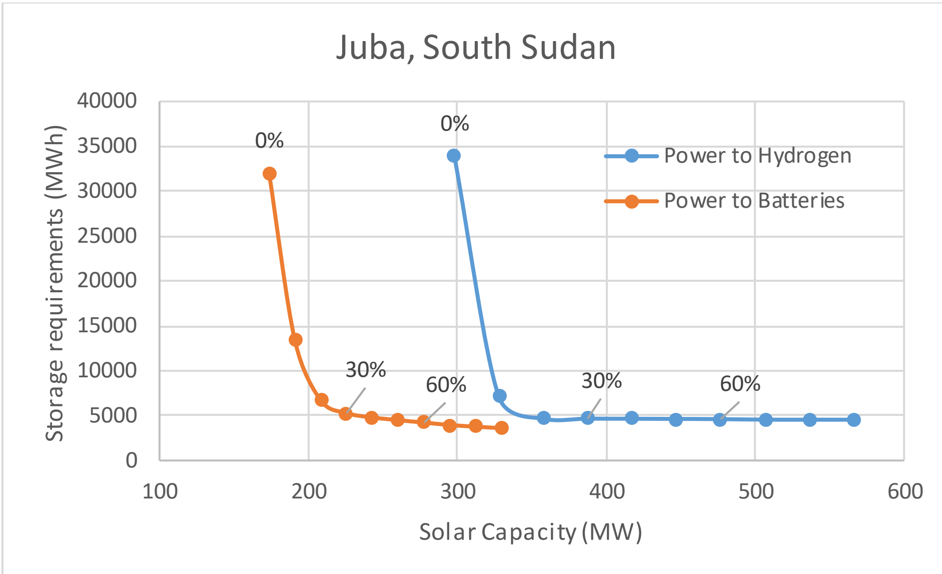


Figure 46. Comparison between hydrogen and energy storage for a theoretical load profile of 10,000 residents in Juba, South Sudan.

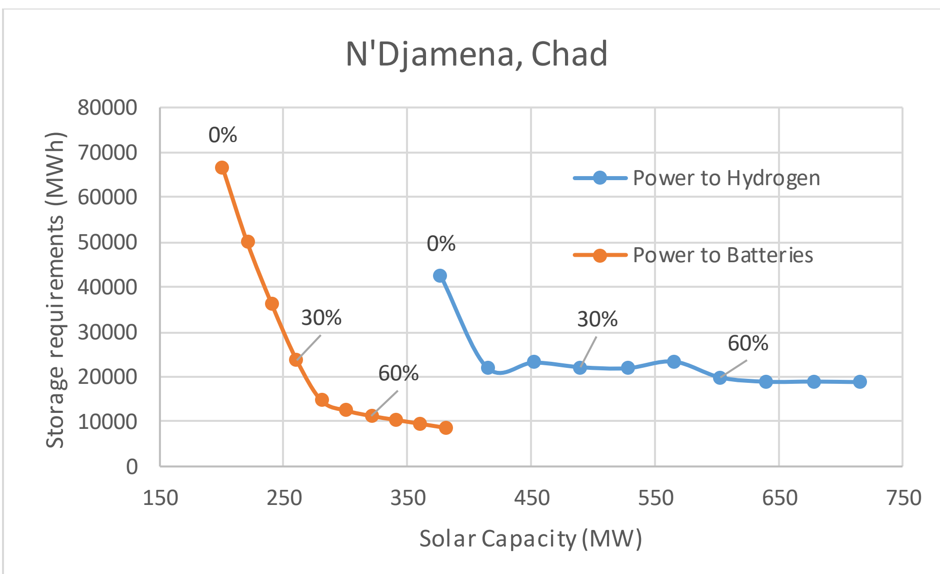


Figure 47. Comparison between hydrogen and energy storage for a theoretical load profile of 10,000 residents N'Djamena, Chad.

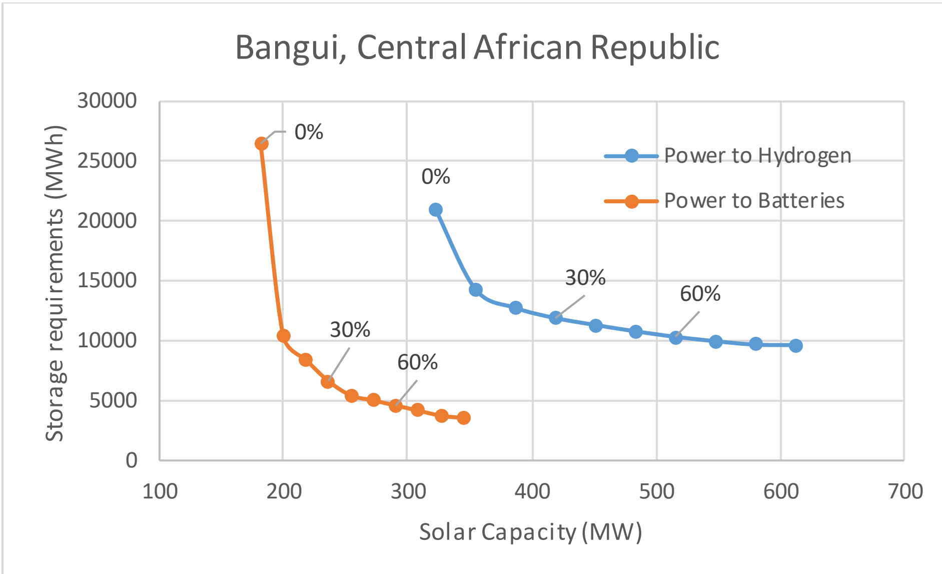


Figure 48. Comparison between hydrogen and energy storage for a theoretical load profile of 10,000 residents Bangui, Central African Republic.

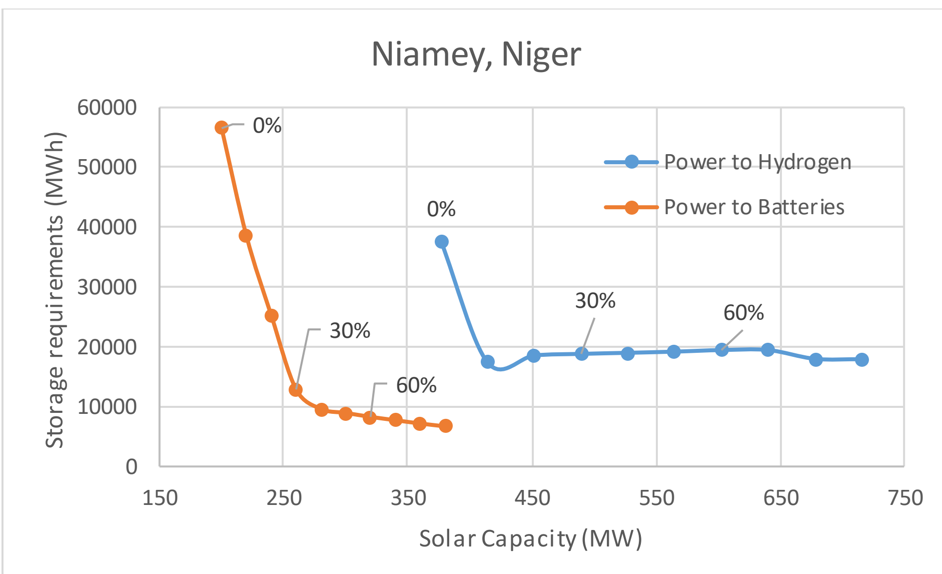


Figure 49. Comparison between hydrogen and energy storage for a theoretical load profile of 10,000 residents Niamey, Niger.

7.3.3 Residential Levelized Cost of Electricity

The minimum LCOE across all three cost projections for the battery residential scenarios is observed at a level of 90% curtailment for all of the locations analyzed. For the best-case scenario, Bangui, Central African Republic, exhibits the lowest cost at $202.83 per MWh, closely trailed by Juba, South Sudan at $203.71 per MWh. N'Djamena, Chad, has the highest cost among all locations, at more than double the energy cost in Bangui. The findings for the LCOE, curtailment, and sizing are summarized in Table 38.

Location	LCOE ($/MWh)			% Curtailment	PV Size (MW)	Battery Size (MWh)
	Low	Middle	High			
Juba, South Sudan	203.71	244.15	295.62	90	330	3605
Bangui, Central African Republic	202.83	242.82	293.75	90	345	3549
Niamey, Niger	352.84	426.00	518.89	90	380	6702
N'Djamena, Chad	441.38	534.42	652.47	90	381	8611

Table 38. Residential battery storage case: minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario.

The change in levelized cost of electricity with curtailment is shown in Figure 40 for the residential battery scenarios. All locations experience the sharpest decline in LCOE at low curtailment levels, with much smaller decreases at moderate to high curtailment levels. The minimal LCOE occurring at maximum curtailment reflects that the marginal cost reductions at high curtailment levels are still impactful.

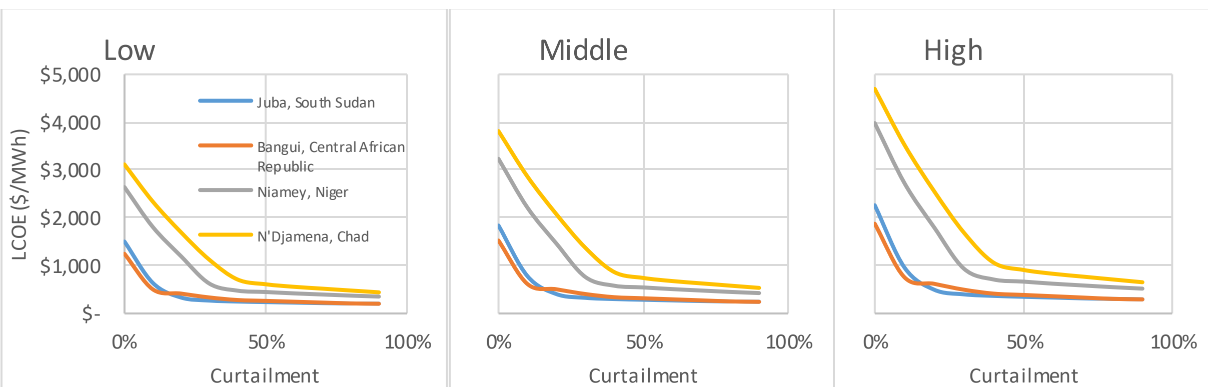


Figure 50. LCOE vs. Curtailment for low, middle, and high-cost projections for the residential battery scenarios.

The results for the LCOE, curtailment, and sizing for the hydrogen scenarios are summarized and listed in Table 39. Unlike the hydrogen results for the data center, the minimum LCOE for the residential scenarios occurred at the same level of curtailment across low, medium, and high-cost projections for each location. Similar to the battery residential case, Bangui, Central African Republic, has the minimum levelized cost of electricity of $226.61 per MWh for the lowest cost projection, simultaneously requiring the lowest level of curtailment needed to meet that cost. Niamey, Niger, and Juba, South Sudan, have a LCOE only 2-3% higher than Bangui. N'Djamena, Chad has the highest cost among all locations, but at a much smaller scale than previously, at barely 10% more than Bangui for this case. The LCOE for Juba and Bangui hydrogen scenarios is larger than the battery scenarios, but the opposite is true for Niamey and N'Djamena.

Location	LCOE ($/MWh)			% Curtailment	PV Size (MW)	Hydrogen Storage (MWh)	Electrolyzer Size (MW)	Fuel Cell Size (MW)
	Low	Middle	High					
Juba, South Sudan	233.97	241.29	251.34	30	387	4662	125	76
Bangui, Central African Republic	226.61	233.3	242.51	10	355	14321	117	69
Niamey, Niger	231.63	238.25	247.36	20	452	18556	147	100
N'Djamena, Chad	240.11	246.95	256.36	20	467	23145	151	100

Table 39. Residential hydrogen storage case: minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario.

The LCOE vs. curtailment for the residential hydrogen case is shown in Figure 51 for the low-, medium-, and high-cost projections. All locations see an initial decline in cost with slight curtailment that then increases, making higher curtailment less cost-effective.

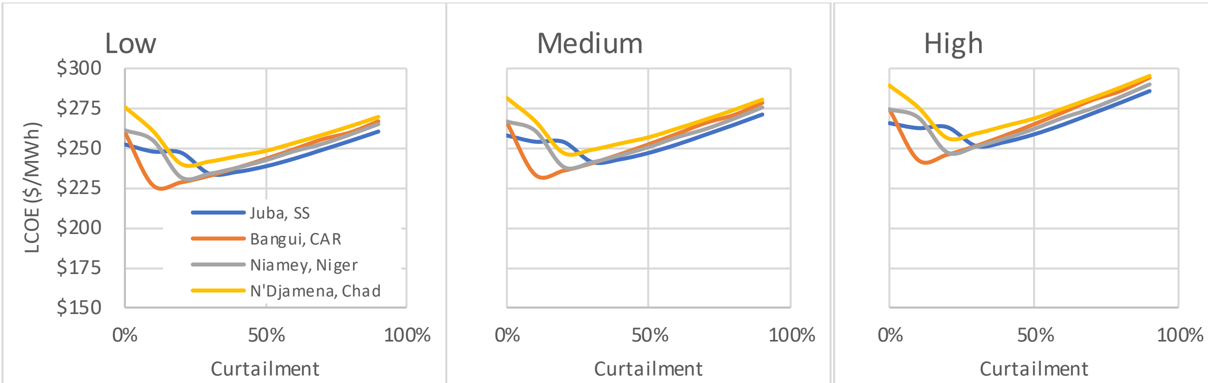


Figure 51. LCOE vs. Curtailment for low, middle, and high-cost projections for the residential hydrogen scenarios.

7.4 Discussion

7.4.1 Load profile considerations

The load profiles downloaded from the United States may be in the same climate zone as the countries considered, but it is acknowledged that there will still be differences present between the climates. For example, the prominent peaks in the middle of the year for the modified arid, hot, steppe theoretical load profile used for Niger and Chad are a result of large amounts of heating in Mohave and La Paz Arizona in the winter time [65]. The annual average temperatures in Mohave Valley, Arizona, fall between 46°F and 110°F [70]. For Niamey, Niger, the average temperatures are between 63°F and 106°F [71], and the averages for N'Djamena, Chad are between 59°F and 106°F [72]. These temperature differences would likely result in less heating used in Niamey, Niger, and N'Djamena, Chad, and an overall lower energy use.

For the tropical savannah load profile, Port Charlotte, Florida, exhibits average temperatures between 52°F and 90°F [73], which is a relatively close match to the climate in Bangui, Central African Republic, which experiences temperatures between 65°F and 94°F [74]. However, Juba, South Sudan, has temperatures between 71°F and 102°F [75] and would require less heating and more cooling than in Florida.

Additionally, the residential energy load profile considers all types of energy usage and appliances and systems, including those powered by natural gas, propane, or electricity. If all residential energy usage were electrified, the actual resulting energy usage would undoubtedly change due to differences in efficiencies between gas and electric appliances and systems. However, estimating these differences is not a simple task.

It is also worth noting that residents in the United States could make significant changes to their habits to reduce energy consumption. Setting the thermostat a few degrees higher in the summer, and a few degrees lower in the winter could lead to major reductions in energy usage.

7.4.2 Energy Model

For residential energy usage, Juba, South Sudan, and Bangui, Central African Republic, exhibit lower solar and storage needs compared to Niamey, Niger, and N'Djamena, Chad, in both the battery and hydrogen storage scenarios. However, this trend differs from the previously analyzed data center scenarios, where Niamey and N'Djamena had the minimum storage requirements, suggesting that their solar dynamics are better suited for the energy requirements of the data center. This divergence can likely be attributed to the distinct load profiles between the locations. Juba and Bangui consume less energy overall than the load profiles in Niamey and N'Djamena. Despite the favorable solar dynamics of Niamey and N'Djamena, they were insufficient to bridge the energy usage gap.

7.4.3 Levelized Cost of Electricity

The lowest levelized cost of electricity for the residential scenarios was observed in Bangui, Central African Republic, and Juba, South Sudan, using battery storage. There was a large gap in cost between Juba/Bangui and Niamey/N'Djamena in the battery scenarios, likely due to the varied energy requirements mentioned previously. In the hydrogen case, Bangui and Juba exhibited the lowest costs again, but the gap with Niamey and N'Djamena was considerably smaller. Hydrogen storage proved to be a much more cost-effective option than battery storage in Niamey and N'Djamena.

It is important to note that the theoretical energy usage used to size the renewable infrastructure was based on a population of 10,000 residents, and these results may not be directly applicable to different populations. The battery case is anticipated to scale linearly with the population, but the hydrogen case is expected to scale differently. If this analysis were conducted for a population of 50,000 people using the same energy usage per capita, the number of hydrogen tanks would likely increase by less than a factor of five, as the tanks are typically not full. Therefore, hydrogen is expected to become more cost-effective than batteries at higher energy usage, which was the trend observed in the data center analysis.

8 Other solutions

8.1 Djibouti

8.1.1 Methods

Due to its political stability and strong diplomatic ties with the United States, Djibouti was chosen as an alternative location to analyze for the data center. The location on the ocean makes the country more accessible to foreign shipments, and there is no need to pass through other countries, possibly experiencing conflict, when delivering supplies. These factors make the implementation of a data center in the near future more feasible than the other countries analyzed. The same methods used previously for analyzing the land availability throughout the country and near the capital and modeling a data center were applied to Djibouti. For modeling the additional infrastructure for the theoretical residential load, the climate of Djibouti City most closely matched that of Western Arizona, and that was the modified load profile selected for use.

8.1.2 Land Analysis Results

Figure 52 shows the various types of land that are present in Djibouti. The majority of the country appears to be barren, with large amounts of shrub. Some wetlands spread throughout the country as well, and a small visible urban center where the capital, Djibouti City, is located.

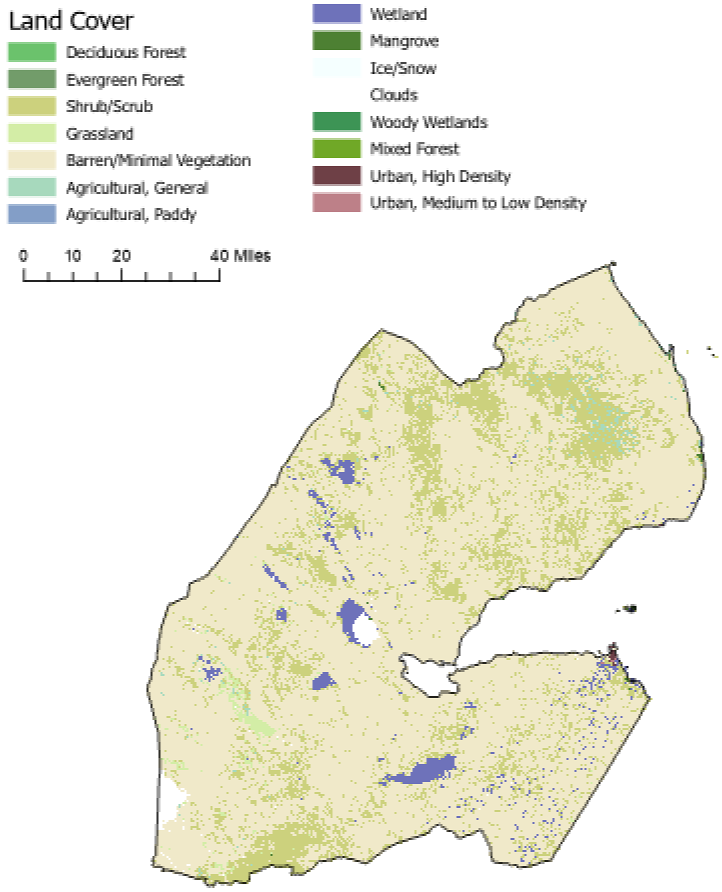


Figure 52. Land coverage classification for Djibouti.

The surface of Djibouti, shown in Figure 53, appears to have relatively few smooth plains. Most of the land appears to comprise other land surface forms, such as irregular plains, hills, and mountains.

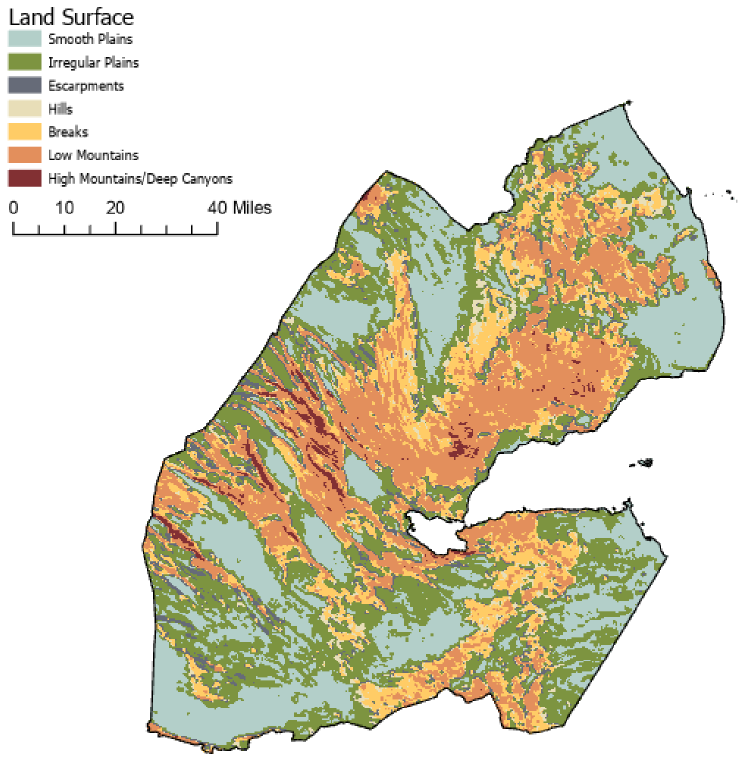


Figure 53. Land surface forms in Djibouti.

The overlap between the smooth plains and barren or shrub land in Djibouti is displayed in Figure 54. These regions are most appropriate for PV installation and are spread throughout the country, with large, uninterrupted clusters in the northeastern part of the county.

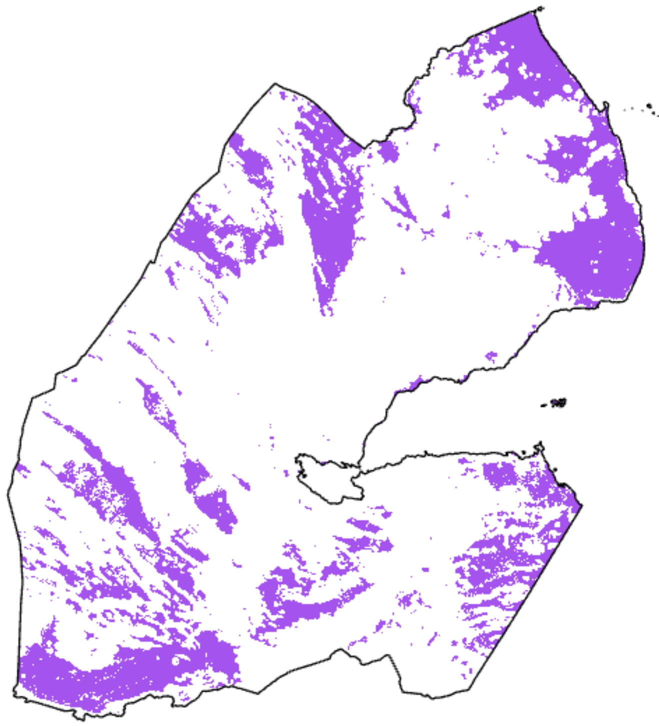


Figure 54. Overlap between flat and available land in Djibouti.

Djibouti is a much smaller country than the others mentioned previously, at just over 23,000 km^2. About 5,000 km^2 of Djibouti's land area is suitable for large scale solar installation, which is 22% of its land area. This is a smaller proportion of land available than the other countries mentioned previously. Djibouti's land area is summarized alongside the other countries in Table 40, with Djibouti's values bolded.

Country	Total land area (km^2)	Flat + available land (km^2)	Percent of flat + available land
Central African Republic	622,980	242,987.70	39%
Chad	1,259,200	974,816.74	77%
Niger	1,266,700	866,340.84	68%
South Sudan	631,957	442,358.12	70%
Djibouti	**23,180**	**4,991.74**	**22%**

Table 40. Total and flat + available land for PV in Central African Republic, Chad, Niger, South Sudan, and Djibouti. Same information from Table 16 with Djibouti added.

The amount of land needed to support middle-income and high-income energy usage by just solar is displayed as green and red circles in Figure 55. The middle-income energy usage is shown in green, and the high-income energy usage is displayed in red. Djibouti has adequate land availability to support both of these energy usage scenarios.

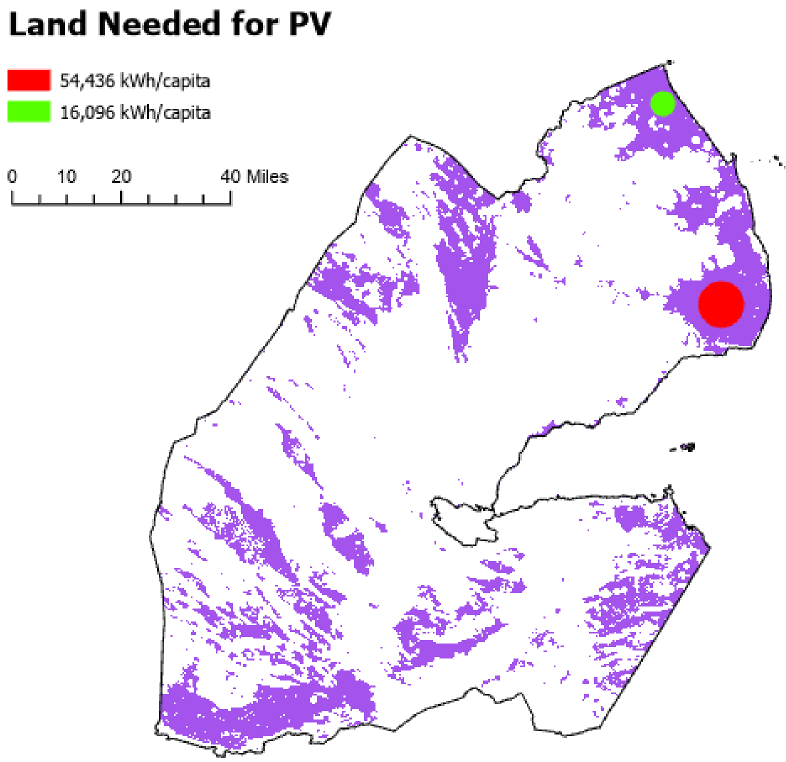


Figure 55. Theoretical solar panel coverage in Djibouti needed to supply the population with as much energy as middle-income and high-income countries.

8.1.3 Data Center Modeling Results

8.1.3.1 Solar Data Collection

Similar to the other countries analyzed, there were no PVWatts sites within the entire country of Djibouti. A map of the PVWatts sites closest to Djibouti's capital is shown in Figure 56. The closest PVWatts site is 162 miles away in Ethiopia. Therefore, 2018 Global Solar Atlas data will be used instead to compare Djibouti to the other four countries.

Figure 56. Closest PVWatts locations to Djibouti City [40].

8.1.3.2 Power to Batteries

The solar and battery capacities of a 49 MW data center for 0% to 95% curtailment for the four countries analyzed previously are compared to Djibouti City, Djibouti, in Figure 57. Djibouti City has the smallest battery needed at 0% curtailment, and as curtailment increases, it most closely follows the line for Niamey, Niger. Djibouti City requires the smallest battery size for the specified level of curtailment, up to 20% curtailment. Niamey, Niger, has the smallest battery size for each level of curtailment after 25%, as shown in Figure 58.

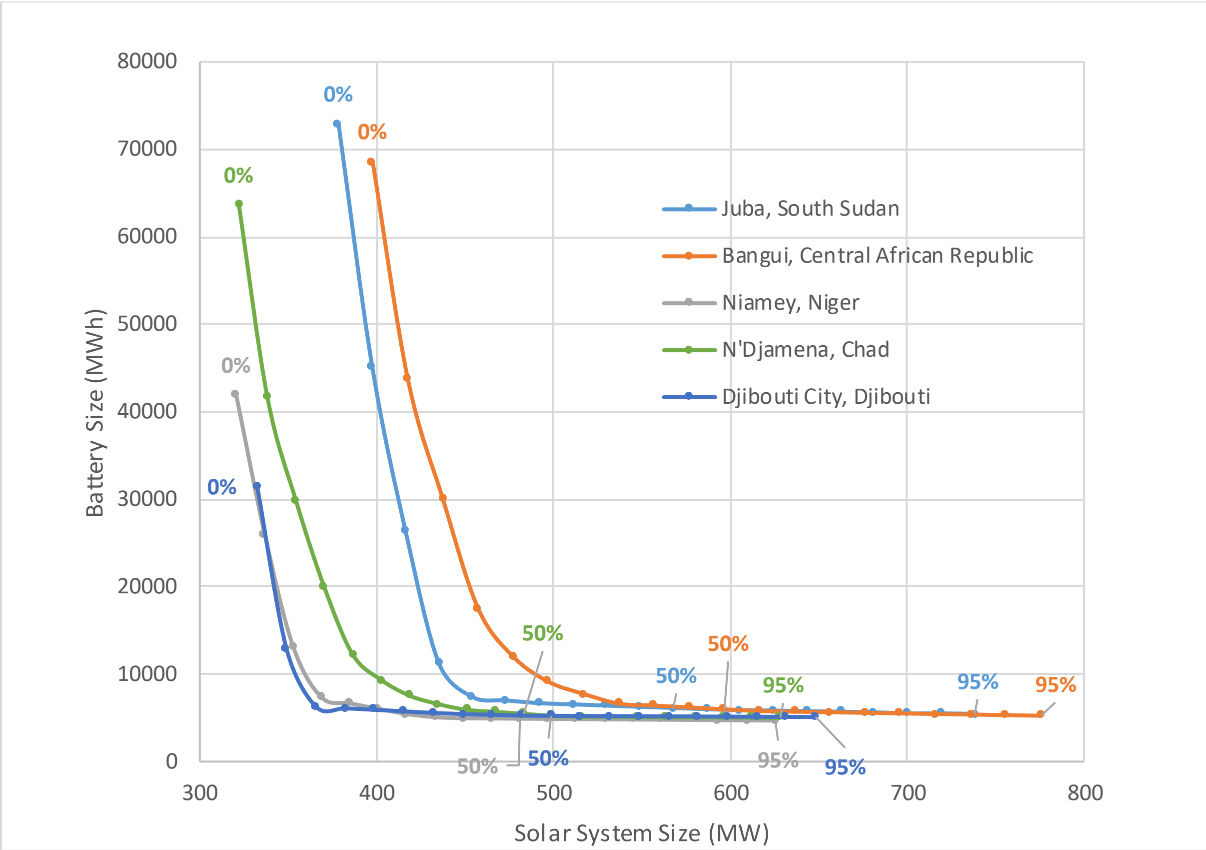


Figure 57. Battery size vs. solar system size for varying levels of curtailment for a 49 MW data center for all four selected LDCs plus Djibouti City.

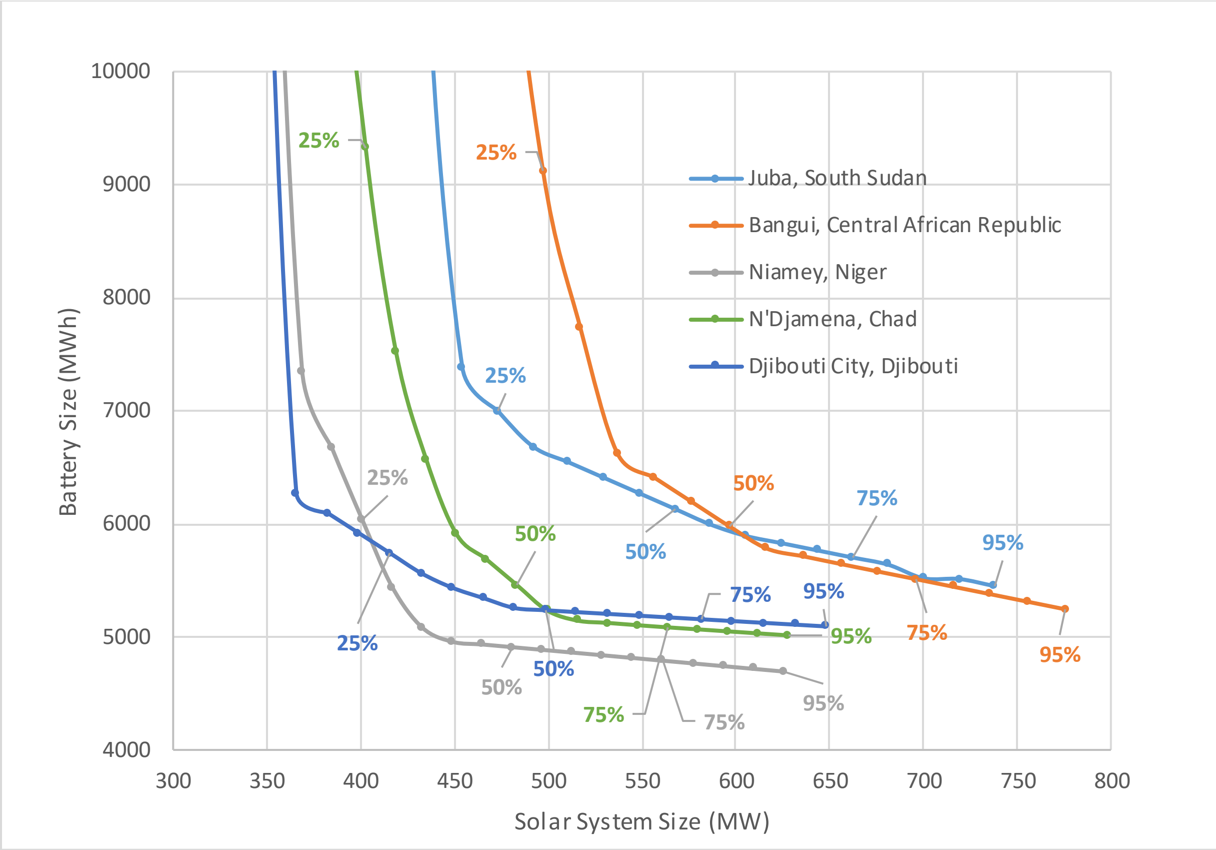


Figure 58. Zoomed in version of Figure 57.

8.1.3.3 Power to Hydrogen

Figure 59 shows the hydrogen storage requirements vs. the solar capacity at varying curtailment levels for a 49 MW data center in all the countries analyzed, plus Djibouti. Djibouti City requires the smallest amount of storage at 0% curtailment, the second lowest amount of storage for moderate curtailment, and the third lowest amount of storage above 50% curtailment. The hydrogen storage requirements for Djibouti City reach an apparent asymptote much quicker than the other locations, with minimal decreases in storage above 20% curtailment.

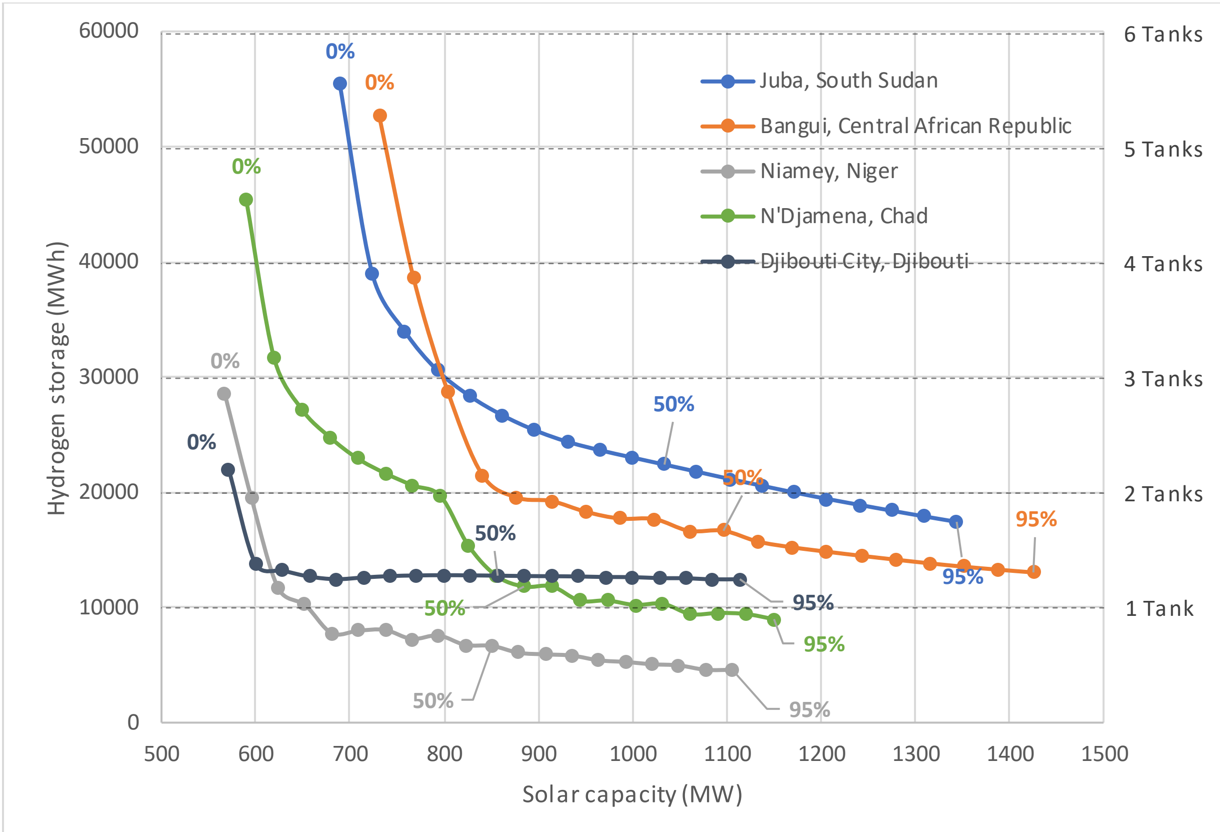


Figure 59. Hydrogen storage requirements vs. solar system size for varying levels of curtailment for a 49 MW data center for all four selected LDCs plus Djibouti City.

Figure 60 shows the electrolyzer size needed for the 49 MW data center in Djibouti City compared to the other locations. Djibouti City requires an electrolyzer of very similar size to Niamey at very low curtailment, and very similar to N'Djamena at moderate to high curtailment levels.

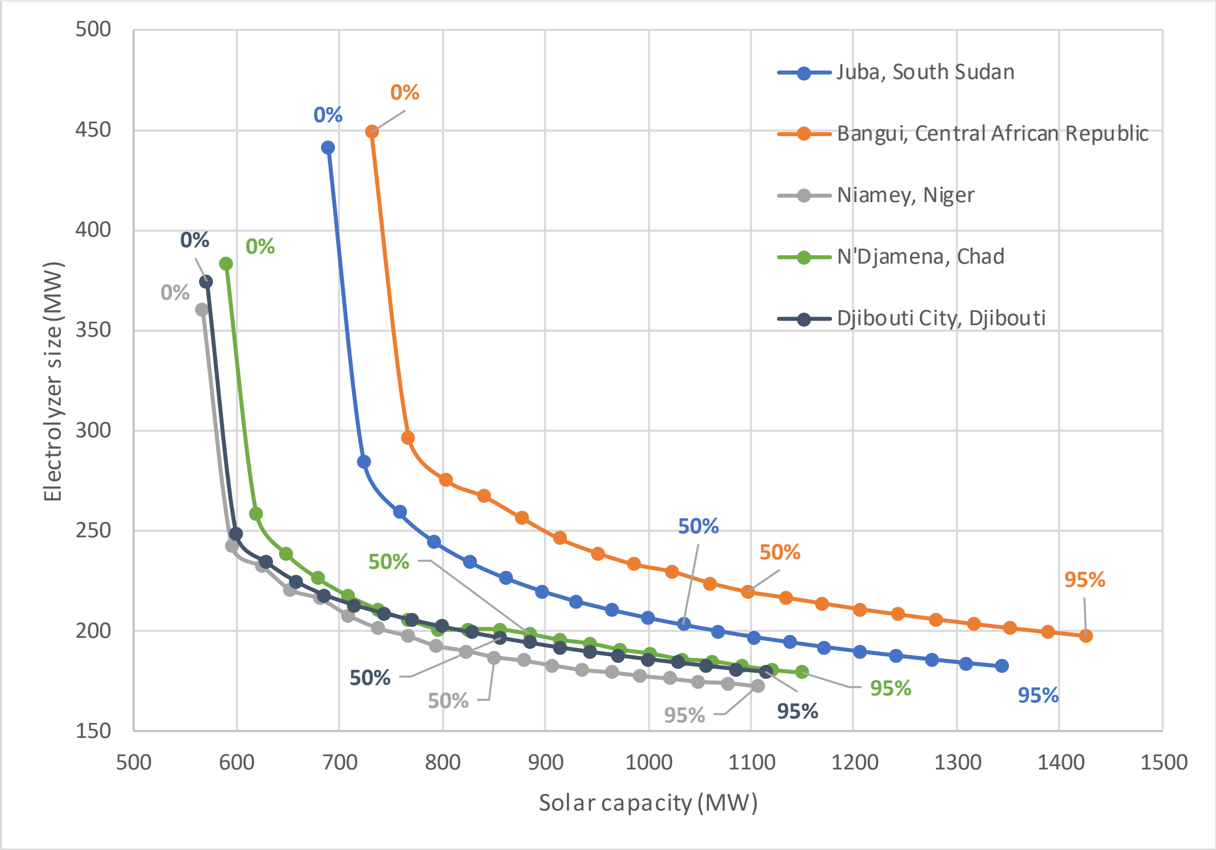


Figure 60. Electrolyzer size vs. solar system size for varying levels of curtailment for a 49 MW data center for all four selected LDCs plus Djibouti City.

8.1.3.4 Batteries vs. Hydrogen

Figure 61 compares storage requirements for the battery and hydrogen case data center in Djibouti City. Like the other locations, Djibouti City requires more storage capacity for the hydrogen case compared to the battery case beyond 0% curtailment due to the higher efficiency of batteries.

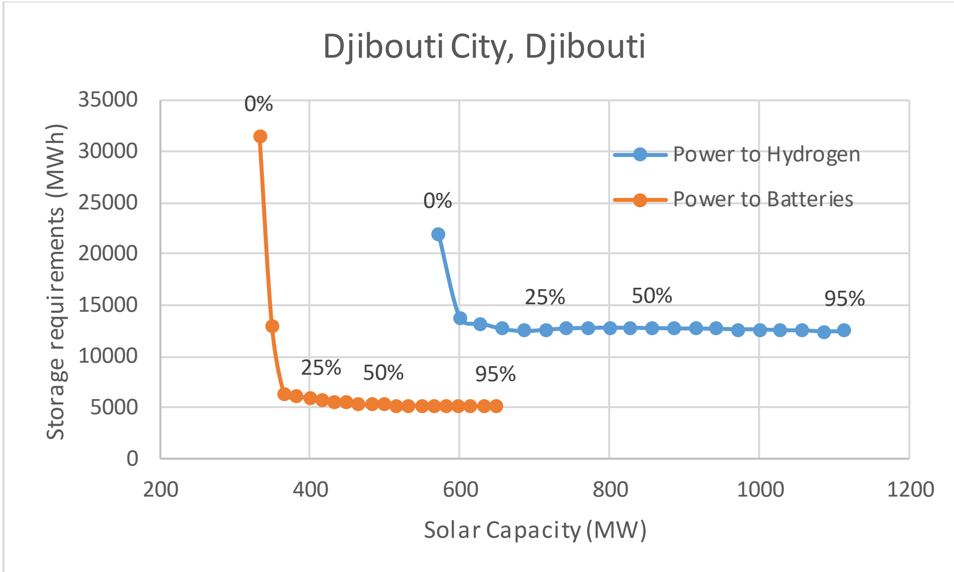


Figure 61. Comparison between hydrogen and energy storage for a 49 MW data center in Djibouti City, Djibouti.

8.1.3.5 Preferred Data Center Location

The economic modeling results for a 49 MW data center in Djibouti City are compared to those previously shown, with the values for Djibouti City in bold in Table 41. The lowest LCOE for Djibouti City, Djibouti, occurs at 45% curtailment with a PV system size of 482 MW and a battery size of 5,255 MWh. The LCOE for Djibouti City is similar to N'Djamena, Chad, but at a slightly higher curtailment level.

Location	LCOE ($/MWh)			Curtailment (%)	PV Size (MW)	Battery Size (MWh)
	Low	Middle	High			
Juba, South Sudan	333.54	397.16	478.30	85%	700	5,518
Bangui, CAR	329.23	390.65	469.09	95%	776	5,244
Niamey, Niger	279.60	335.17	405.89	40%	449	4,956
N'Djamena, Chad	295.70	353.80	427.80	60%	515	5,144
Djibouti City, Djibouti	**297.11**	**356.08**	**431.13**	**45%**	**482**	**5,255**

Table 41. Data center minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario. Equivalent to Table 30 with Djibouti City added.

The LCOE vs. curtailment for the battery storage scenarios in Djibouti City is displayed alongside the other capitals in Figures 62 and 63. Djibouti City follows a similar pattern of cost reduction to the other capitals, with the highest cost reduction at low levels of curtailment and marginal reductions at slightly higher levels of curtailment.

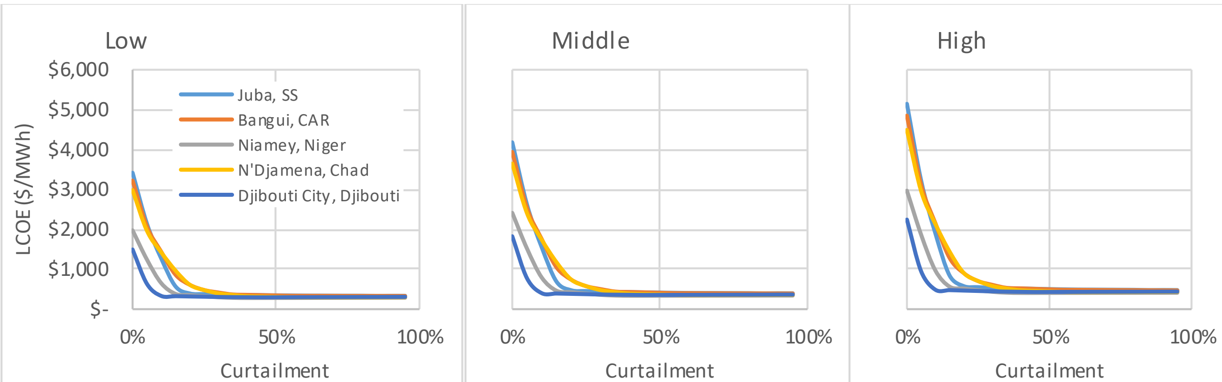


Figure 62. Data center LCOE vs. Curtailment for low, middle, and high-cost projections for the data center battery scenarios. Equivalent to Figure 33 with Djibouti City added.

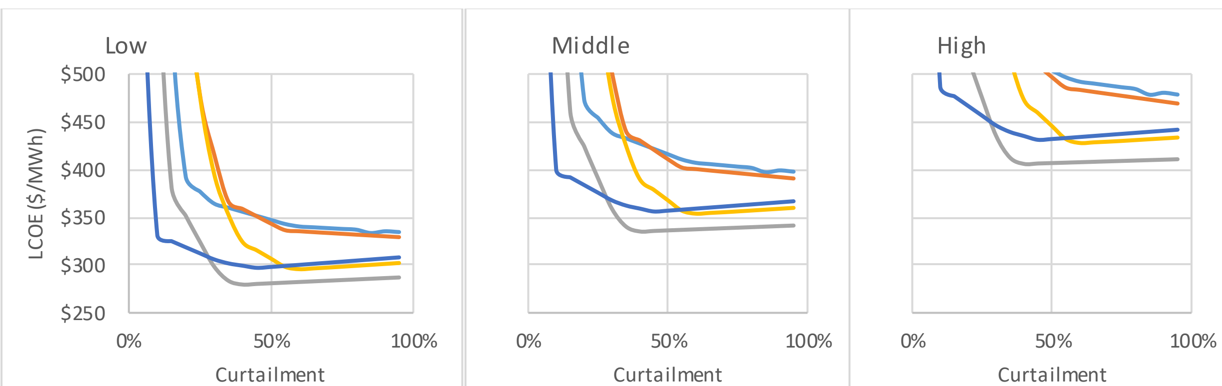


Figure 63. Zoomed in data center LCOE vs. Curtailment for low, middle, and high-cost projections for the data center battery scenarios. Equivalent to Figure 34 with Djibouti City added.

For the hydrogen scenarios, Djibouti City has the second lowest LCOE and is only less than $1 higher than the LCOE for Niamey, Niger. Across all three cost projections, Djibouti City only needed 5% curtailment to achieve its lowest LCOE. The cost, curtailment, and infrastructure sizing for Djibouti City are compared to the other capitals in Table 42, Table 43, and Table 44.

Location	LCOE ($/MWh)	Curtailment	PV size (MW)	Hydrogen storage (MWh)	Electrolyzer size (MW)	Fuel cell size (MW)
Juba, South Sudan	209.14	20%	827	18959	239	52
Bangui, Central African Republic	217.50	15%	841	31202	257	52
Niamey, Niger	182.58	15%	652	9570	222	52
N'Djamena, Chad	193.35	20%	708	16597	228	52
Djibouti City, Djibouti	**183.54**	**5%**	**600**	**13770**	**248**	**52**

Table 42. Data center hydrogen storage case: minimum LCOE and corresponding curtailment, and the size of the PV system, hydrogen storage, electrolyzer, and fuel cell for the lowest projected cost of solar. Equivalent to Table 31 with Djibouti City added.

Location	LCOE ($/MWh)	Curtailment	PV size (MW)	Hydrogen storage (MWh)	Electrolyzer size (MW)	Fuel cell size (MW)
Juba, South Sudan	216.20	15%	793	21007	250	52
Bangui, Central African Republic	224.77	10%	804	33893	271	52
Niamey, Niger	188.30	15%	652	9570	222	52
N'Djamena, Chad	199.53	15%	678	16595	241	52
Djibouti City, Djibouti	**188.80**	**5%**	**600**	**13770**	**248**	**52**

Table 43. Data center hydrogen storage case: minimum LCOE and corresponding curtailment, and the size of the PV system, hydrogen storage, electrolyzer, and fuel cell for the moderate projected cost of solar. Equivalent to Table 32 with Djibouti City added.

Location	LCOE ($/MWh)	Curtailment	PV size (MW)	Hydrogen storage (MWh)	Electrolyzer size (MW)	Fuel cell size (MW)
Juba, South Sudan	225.75	15%	793	21007	250	52
Bangui, Central African Republic	234.46	10%	804	33893	271	52
Niamey, Niger	196.16	15%	652	9570	222	52
N'Djamena, Chad	207.42	5%	619	31663	258	52
Djibouti City, Djibouti	**196.02**	**5%**	**600**	**13770**	**248**	**52**

Table 44. Data center hydrogen storage case: minimum LCOE and corresponding curtailment, and the size of the PV system, hydrogen storage, electrolyzer, and fuel cell for the highest projected cost of solar. Equivalent to Table 33 with Djibouti City added.

The LCOE vs. curtailment for the hydrogen storage scenarios in Djibouti City is displayed alongside the other capitals in Figure 64. Djibouti City follows a similar pattern of cost reduction to the other capitals, with an initial sharp decline with low levels of curtailment and a sharp increase after the minimum LCOE is reached.

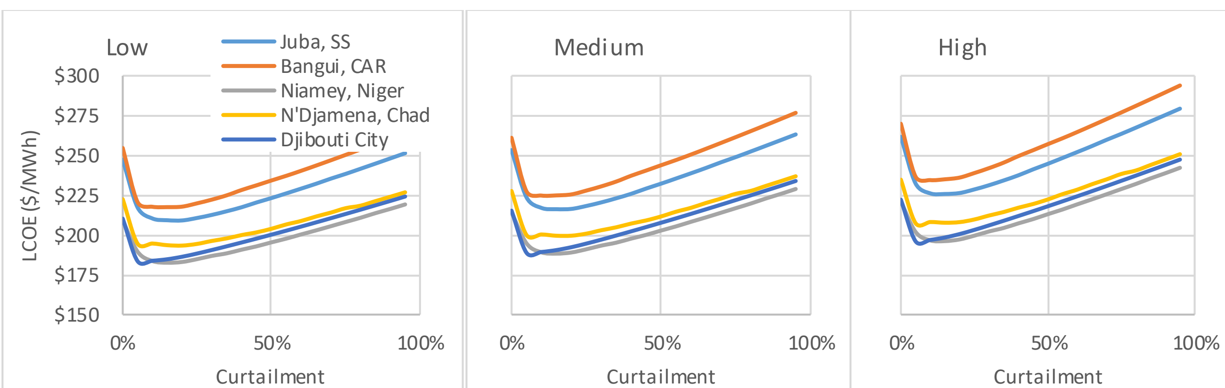


Figure 64. Data center LCOE vs. Curtailment for low, middle, and high-cost projections for the data center hydrogen scenarios. Equivalent to Figure 35 with Djibouti City added.

Like the Central African Republic, AfterFibre did not include terrestrial fiber optic cables in Djibouti. Fortunately, Djibouti is on the coast, and the capital, Djibouti City, is connected to an extensive network of undersea fiber optic cables. Terrestrial cables exist as well that link other parts of Africa to this network [76]. The undersea and terrestrial cables connecting to or within Djibouti are shown in Figure 65.

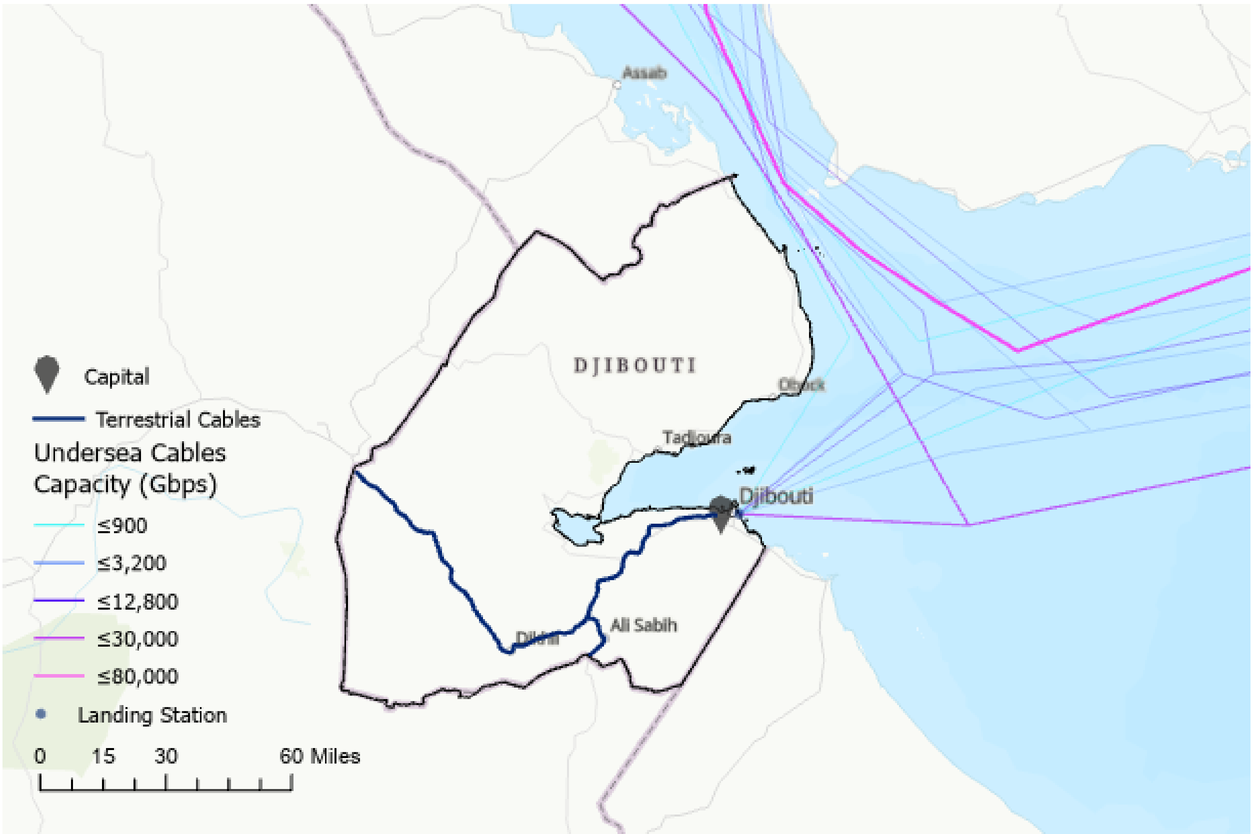


Figure 65. Undersea submarine cables [77] *and terrestrial cables. Terrestrial cables traced in google earth.*

The size of land needed for each data center in the capitals of Central African Republic, Chad, Niger, South Sudan, and Djibouti is listed in Table 45, with the values for Djibouti City bolded. The renewable data center in Djibouti City would require the second smallest amount of land of the locations analyzed, at only 2.9 km^2. This value is very close to the amount of land needed in N'Djamena, Chad, at 3.1 km^2.

Location	PV space (km^2)	Battery space (km^2)	Data center space (km^2)	Total space (km^2)
Juba, South Sudan	3.5	0.513	0.0285	4.0413
Bangui, Central African Republic	3.88	0.487		4.3958
Niamey, Niger	2.245	0.461		2.7340
N'Djamena, Chad	2.575	0.478		3.0815
Djibouti City, Djibouti	**2.41**	**0.488**		**2.9268**

Table 45. Space requirements for the 49 MW data center and its renewable energy infrastructure. The PV, and battery sizes were calculated from the values corresponding to the lowest LCOE in Table 41, equivalent to Table 34 with Djibouti added.

The land suitable for solar within a 25 km radius of Djibouti City is displayed in Figure 66. The circle represents the 25 km radius around the city center, and the purple within represents the land suitable for solar within that radius. Djibouti City has 377 km^2 of land suitable for solar, 19% of the total area within 25 km of the city. As shown in Table 46, this is a smaller proportion of land than in N'Djamena, Juba, and Niamey, but it is more land than in Bangui.

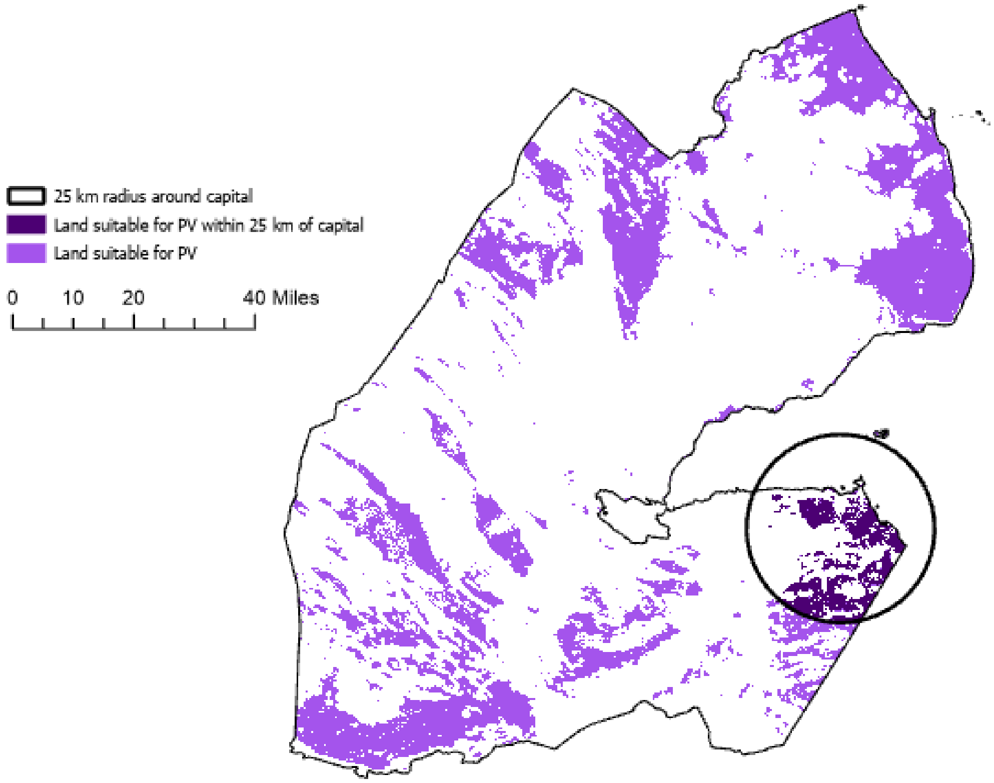


Figure 66. Land suitable for solar within a 25 km radius of Djibouti City.

	Area (km^2)	% available
Niamey, Niger	733.994	37%
Ndjamena, Chad	1325.193	67%
Bangui, Central African Republic	266.086	14%
Juba, South Sudan	1330.451	68%
Djibouti City, Djibouti	**377.311**	**19%**

Table 46. Same as Table 36. Land suitable for solar within a 25 km radius of each capital, with Djibouti added.

8.1.4 Additional Community Energy Infrastructure

8.1.4.1 Power to Batteries

Figure 67 and Figure 68 show the battery storage vs. solar capacity requirements for the theoretical residential load profile for 10,000 residents in the previously analyzed locations and Djibouti City. Djibouti City has very similar battery and solar size requirements to Niamey, Niger. Each dot represents a different level of curtailment that increases in increments of 10% for 0 to 90%.

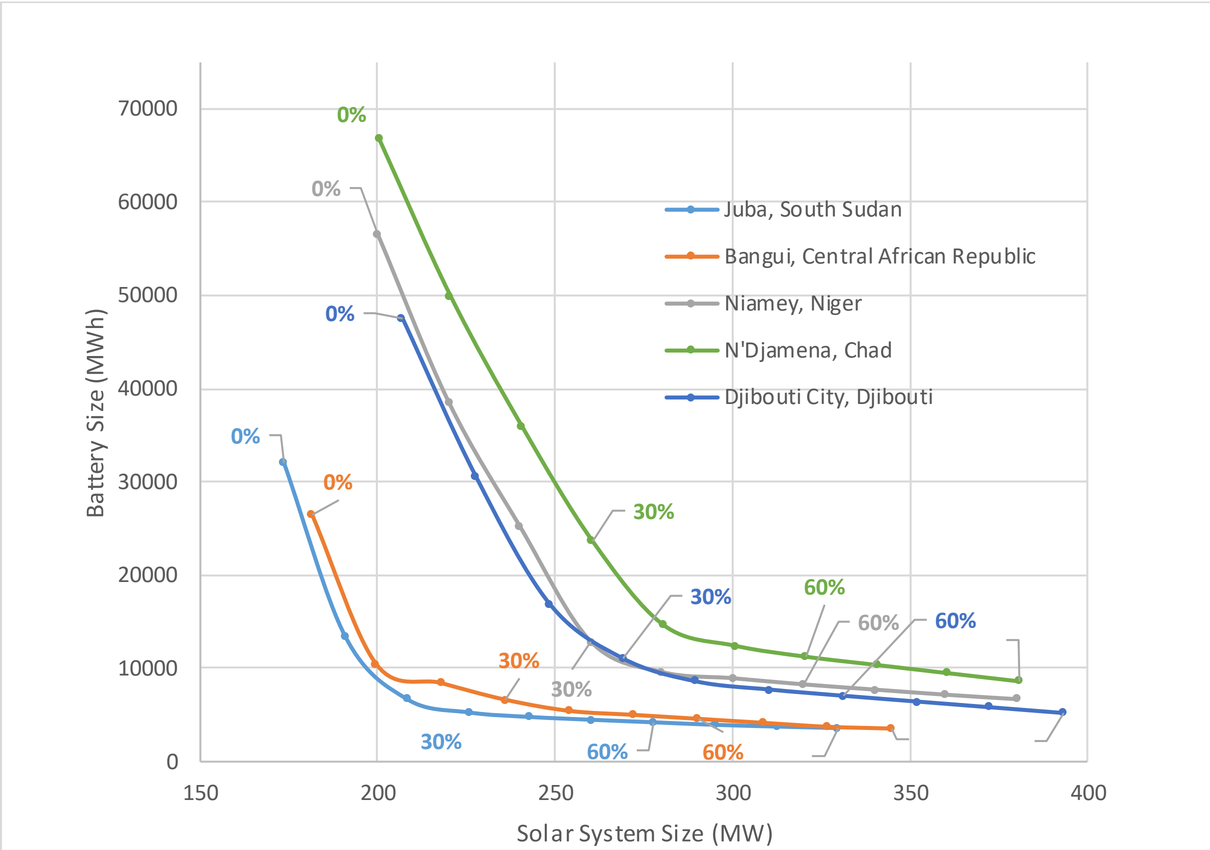


Figure 67. Battery storage requirements vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents for all four selected LDCs plus Djibouti City.

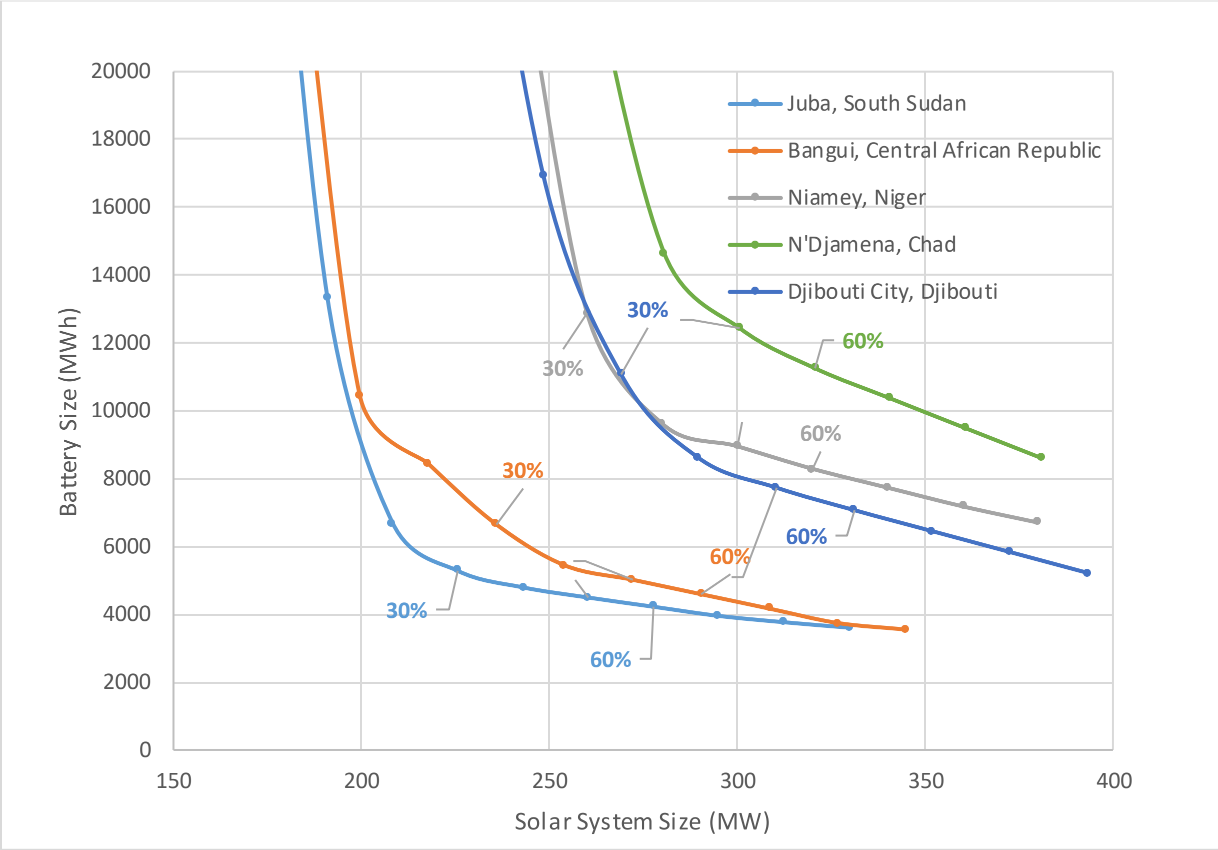


Figure 68. Zoomed in version of Figure 67. Battery storage requirements vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents for all four selected LDCs plus Djibouti City.

8.1.4.2 Power to Hydrogen

The residential hydrogen storage requirements vs. solar capacity for different curtailment levels in Djibouti City are displayed next to the results for the other capitals in Figure 69. Dashed lines represent the number of hydrogen tanks needed to store each amount of energy. Djibouti City has one of the smallest hydrogen storage requirements as curtailment increases. While it requires more solar capacity than Juba, South Sudan, its hydrogen storage requirements are similar and fill up about half of a single tank at moderate to high curtailment levels.

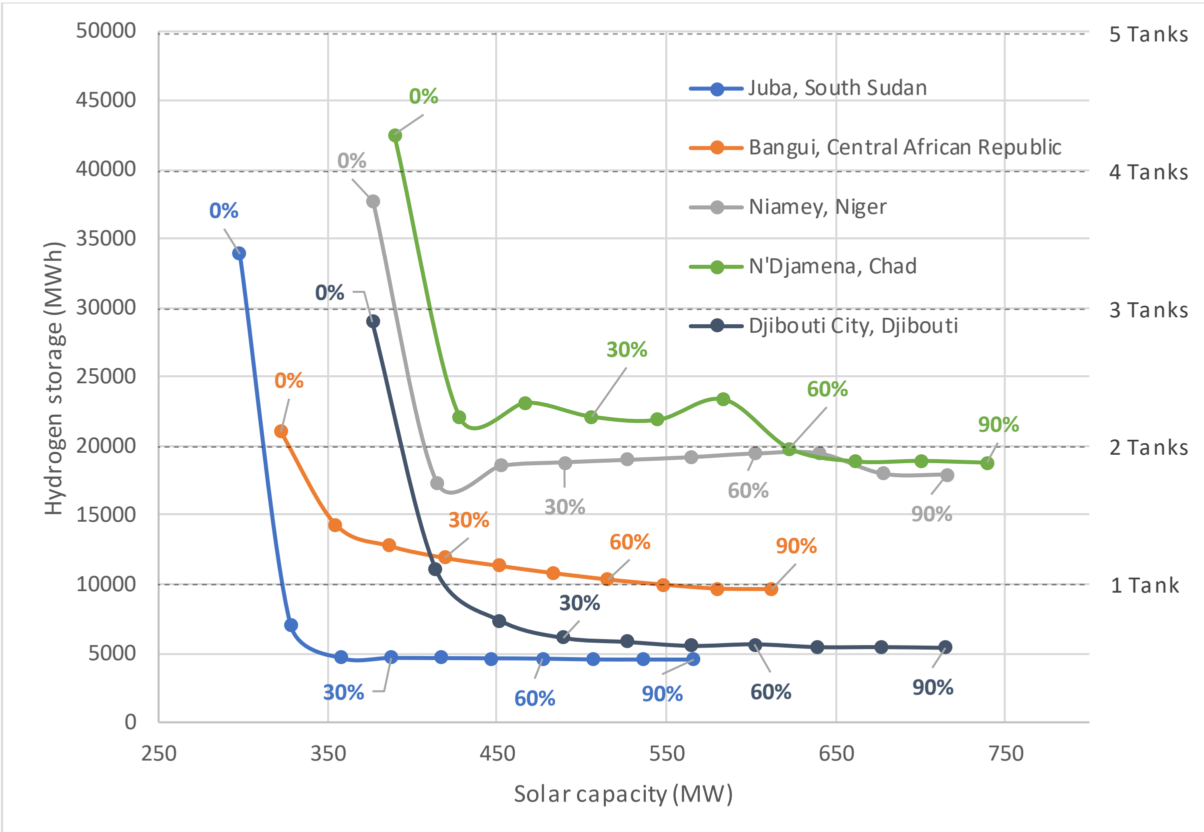


Figure 69. Hydrogen storage requirements vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents in all four selected LDCs plus Djibouti City.

The electrolyzer size vs. solar capacity for different curtailment levels in Djibouti City is shown among the other locations in Figure 70. Djibouti City requires a much larger electrolyzer than Juba, South Sudan, and Bangui, Central African Republic, for all levels of curtailment and a slightly larger electrolyzer than N'Djamena, Chad, and Niamey, Niger, above 30% curtailment.

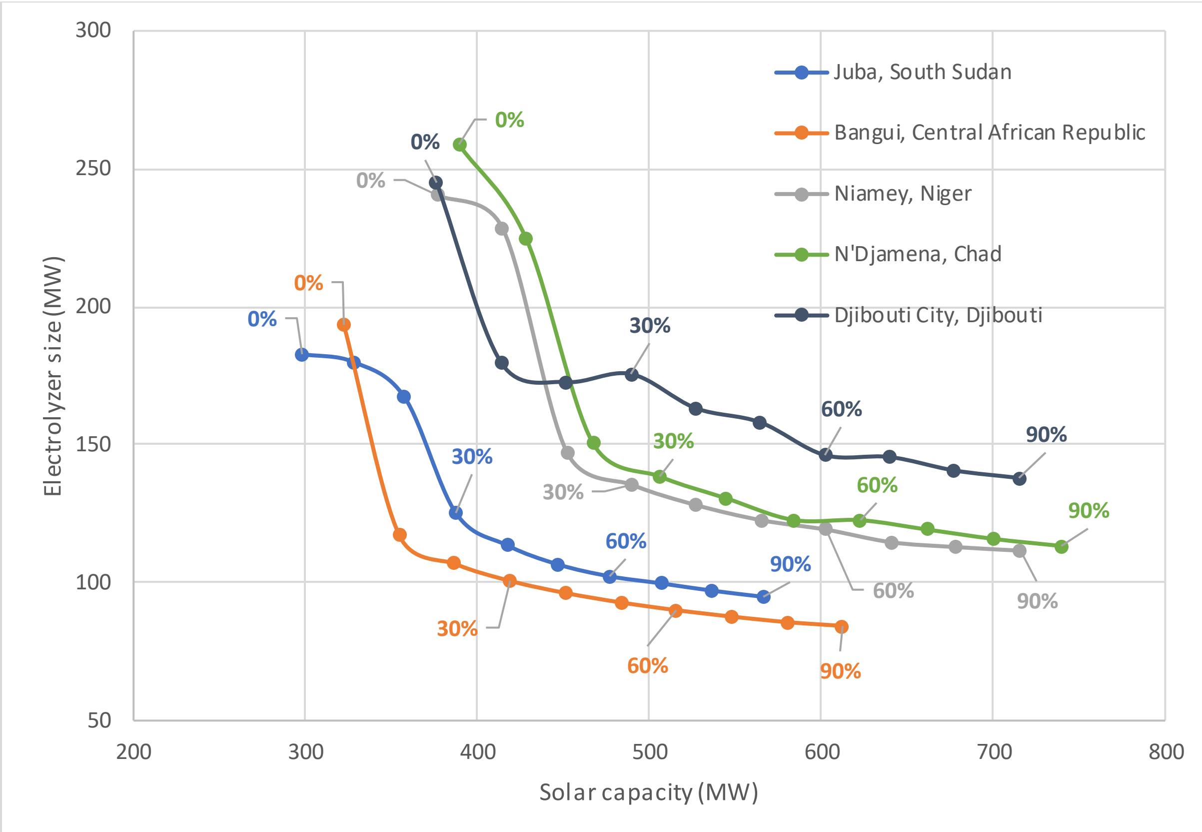


Figure 70. Electrolyzer size vs. solar system size for varying levels of curtailment for a theoretical load profile of 10,000 residents in all four selected LDCs plus Djibouti City.

Figure 71 shows the difference in storage vs. solar requirements for residential energy usage in Djibouti City. Similar to Juba, South Sudan (Figure 46. Comparison between hydrogen and energy storage for a theoretical load profile of 10,000 residents in Juba, South Sudan), there is an initially large decline in storage with low levels of curtailment that approaches an asymptote for the hydrogen case. The battery storage case has a more gradual decrease in storage size as curtailment increases and ends up approaching a similar energy storage level to the hydrogen case at maximum curtailment.

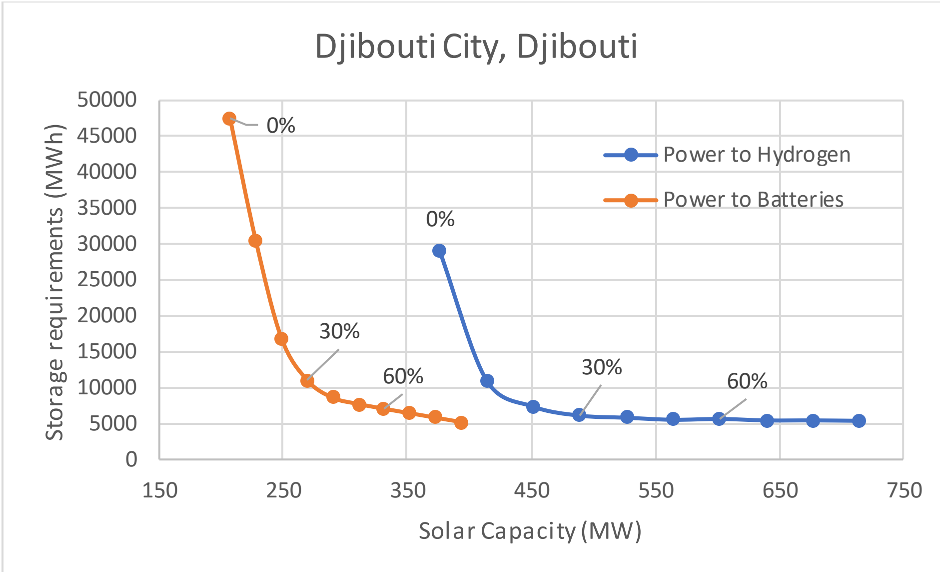


Figure 71. Comparison between hydrogen and energy storage for a theoretical load profile of 10,000 residents in Djibouti City, Djibouti.

8.1.4.3 Residential Levelized Cost of Electricity

The levelized cost of electricity results for the residential battery case in Djibouti City are summarized in Table 47. Residential battery storage case: minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario. Equivalent to Table 38 with Djibouti City added.. Djibouti City has a higher battery LCOE than Juba and Bangui, but it is much smaller than the costs in Niamey and N'Djamena.

Location	LCOE ($/MWh)			% Curtailment	PV Size (MW)	Battery Size (MWh)
	Low	Middle	High			
Juba, South Sudan	203.71	244.15	295.62	90	330	3605
Bangui, Central African Republic	202.83	242.82	293.75	90	345	3549
Niamey, Niger	352.84	426.00	518.89	90	380	6702
N'Djamena, Chad	441.38	534.42	652.47	90	381	8611
Djibouti City, Djibouti	**285.50**	**343.29**	**416.78**	**90**	**393**	**5217**

Table 47. Residential battery storage case: minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario. Equivalent to Table 38 with Djibouti City added.

The LCOE for Djibouti City follows a similar trend to the other locations as curtailment increases and falls in the middle of the other four locations. The change in battery residential LCOE vs. curtailment is displayed in Figure 72.

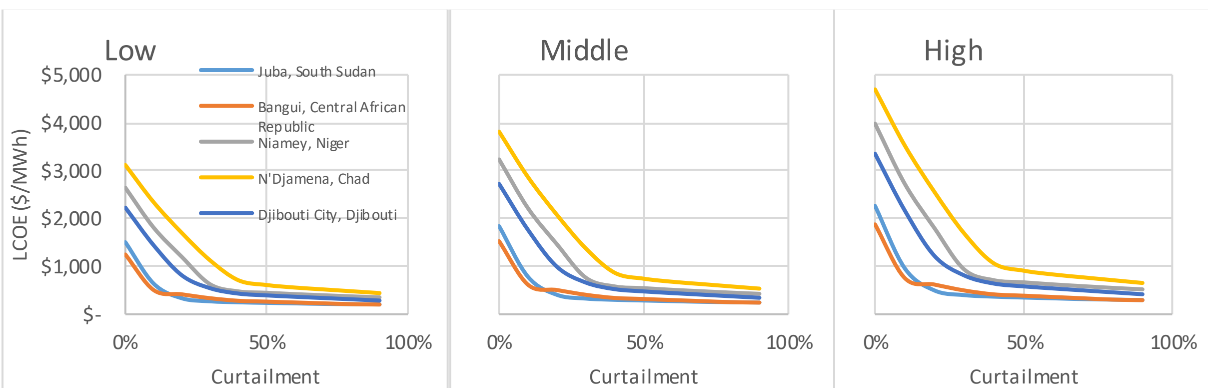


Figure 72. LCOE vs. Curtailment for low, middle, and high-cost projections for the residential battery scenarios. Equivalent to Figure 50 with Djibouti City added.

The levelized cost of electricity results for the residential hydrogen case in Djibouti City are summarized in Table 48. Djibouti City has the second lowest cost of any location, at only $4 per MWh more than Bangui.

Location	LCOE ($/MWh)			% Curtailment	PV Size (MW)	Hydrogen Storage (MWh)	Electrolyzer Size (MW)	Fuel Cell Size (MW)
	Low	Middle	High					
Juba, South Sudan	233.97	241.29	251.34	30	387	4662	125	76
Bangui, Central African Republic	226.61	233.3	242.51	10	355	14321	117	69
Niamey, Niger	231.63	238.25	247.36	20	452	18556	147	100
N'Djamena, Chad	240.11	246.95	256.36	20	467	23145	151	100
Djibouti City, Djibouti	**230.65**	**236.71**	**245.05**	**10**	**414**	**11035**	**180**	**92**

Table 48. Residential hydrogen storage case: minimum LCOE and corresponding curtailment, PV system size, and battery size for each cost projection scenario. Equivalent to Table 39 with Djibouti City added.

Figure 73 shows the change in the LCOE vs. curtailment for the residential hydrogen scenarios. Djibouti City closely follows the same trend as Bangui at all curtailment levels.

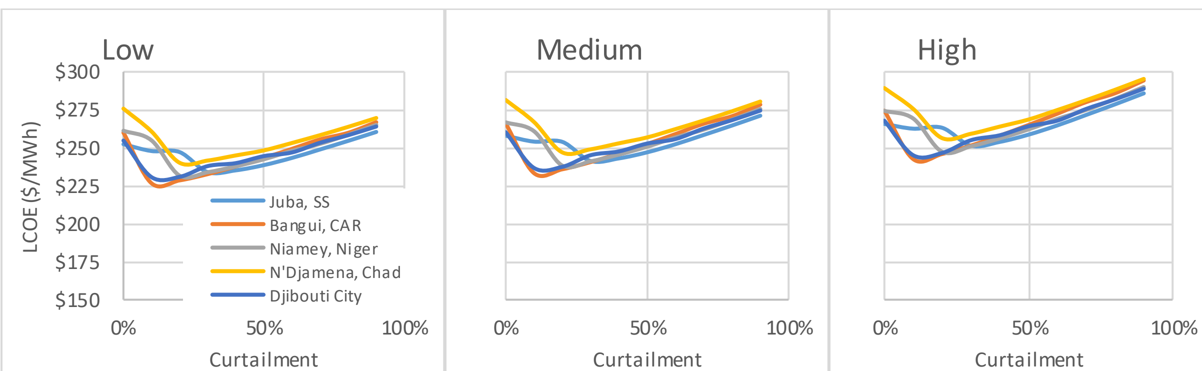


Figure 73. LCOE for the hydrogen case in all previous locations plus Djibouti City. Equivalent to Figure 51 with Djibouti City added.

8.1.5 Discussion

Compared to the Central African Republic, Chad, Niger, and South Sudan, Djibouti has a much smaller portion of land suitable for large-scale solar installation. The region has an abundance of scrub, but its mountainous topography poses challenges for large-scale solar projects across much of the country. Fortunately, the land requirements for PV installations are still manageable within the available land.

When examining the need for renewable energy in the LDCs earlier in Table 5 and Table 6, Djibouti only appeared one time as one of the countries struggling the most with various energy related categories. In contrast, Central African Republic, Chad, Niger, and South Sudan appeared at least three timed. While these methods suggest that Djibouti fares relatively better than the other analyzed countries regarding energy, it is classified as an LDC by the United Nations and its population would benefit from increased renewable infrastructure. Similar to the other four countries analyzed, it lacks TMY data for the analysis of solar dynamics. This lack of data, which amplifies its status as an LDC.

The data center's renewable infrastructure in Djibouti City is consistently smaller in scale compared to those in Bangui and Juba. For the battery storage scenarios, Djibouti has a smaller battery capacity than N'Djamena at curtailment levels below 50% and a smaller battery capacity than Niamey at curtailment levels below 25%. Djibouti City similarly displays consistently smaller storage and electrolyzer size requirements for the hydrogen storage scenarios than Juba and Bangui.

Djibouti City is near the necessary terrestrial fiber optic cables required for a data center. It is strategically located on the coast, allowing easy access to overseas trade networks, and also serves as a vital point of connection for several major undersea fiber optic cables. These attributes make Djibouti City an appealing choice for hosting a data center. The city also offers ample space within a 25 km radius, requiring less than 1% of the suitable land for the renewable data center. Djibouti City also has the second lowest overall LCOE for the data center, with its hydrogen storage costing less than $1/MWh more than a hydrogen storage data center in Niamey, Niger.

For investing in additional residential renewable infrastructure, Djibouti City's hydrogen storage case is about $30/MWh higher than the most cost-effective location and storage. This difference in cost could make it less favorable than other locations for additional community infrastructure, especially if the renewable energy infrastructure were designed to meet the energy needs of an even larger community. However, it is possible that at larger scales the residential hydrogen LCOE would fall and make Djibouti City more economically favorable.

The primary attraction for companies considering a data center investment in Djibouti over other nations lies in its history of political stability and robust ties with the United States. In contrast, all the other countries have experienced more recent and ongoing political instability. Niger, which presents the most economically favorable option for a data center, is currently facing challenges. Therefore, if a corporation intends to commence the construction of a renewable data center in the near future, Djibouti emerges as the preferred choice. Djibouti will likely remain the most stable location for at least a brief period.

8.2 Efficiency Improvements

Not every region, state, or community can entirely rely on solar and will need other options. Land availability may be limited due to forests, agricultural land, or existing urban development. Energy-efficient buildings are an effective way to reduce energy demands and also minimize the space required to generate power. Several solutions can be employed in constructing new buildings, including compact designs, adequate insulation, and airtight construction. A large portion of building energy consumption is devoted to heating and cooling spaces. Smaller buildings necessitate less energy for climate control, while proper insulation and airtight construction mitigate energy loss through the walls, roofs, windows, and gaps. Considering the location of the sun or surrounding shade in the design of the building can also help. Inadequate housing design can force residents to forego temperature regulation due to financial constraints.

Energy recovery ventilators (ERVs) and heat recovery ventilators (HRVs) offer ventilation without opening windows, thereby minimizing the demand for heating or cooling. Innovative solutions such as phase change materials can help absorb heat from the sun without altering the temperature, reducing the need for air conditioning. These have been very helpful in large office buildings. Efficient appliances and water heaters also contribute to energy conservation. Making these upgrades to existing buildings can be challenging, especially when the financial responsibility falls on the shoulders of individual owners or renters. Architects, designers, landlords, and corporations can incorporate these solutions into their new construction projects. Government regulations can be crucial in elevating standards for minimum insulation values and appliance efficiencies. Such regulations compel third parties involved in design and construction to make environmentally friendly choices that benefit future building occupants by lowering energy costs.

Self-sufficient microgrids and nanogrids may better allow for the delivery of clean energy where it may be challenging to do so otherwise, whether in densely populated urban areas or remote islands. Fully electric buildings and communities eliminate the need for natural gas infrastructure and reduce direct greenhouse gas emissions. This also enables them to fully rely on renewable electricity sources such as solar, wind, geothermal, or whatever is prominent in the area. Combining energy-efficient solutions makes self-sufficiency possible in more locations with space restrictions.

8.3 Hydrogen Derivative Fuels

Hard-to-decarbonize sectors such as heavy transportation and industry will likely always rely on energy-dense liquid fuels. Specific sectors and industries face limitations in relying solely on electrification and will need solutions beyond batteries. Batteries are best for small-scale and short-term energy storage [78], which is ideal in the light transport and residential sectors. Using pure hydrogen as energy storage is not always feasible due to hydrogen's low volumetric density. Hydrogen can be combined with other compounds (such as captured carbon dioxide) to produce various fuels with different physical and chemical properties that may overcome the challenges of using pure hydrogen and prevent emissions from disproportionately impacting disadvantaged communities.

8.3.1 Hard to Decarbonize Sectors

Heavy transport has been challenging to decarbonize due to its need for quick refueling, light payload, and long-distance travel, which batteries have been unable to provide [78]. That means that hydrogen must play a role in decarbonizing these areas of the transportation sector.

The most challenging areas of transportation to decarbonize include long-distance road transport, aviation, and shipping [79]. Hydrogen and battery systems have lower volumetric density compared to internal combustion engines, limiting the capacity of vehicles, airplanes, and ships to carry goods and passengers [79], [80]. Due to their high energy density, liquid fuels will be the best solution for these areas of transportation [79], [81]. The energy-dense liquid fuels can be carbon-free (such as liquid hydrogen or ammonia) or carbon-neutral hydrocarbon fuels (such as synthetic natural gas dimethyl ether) if produced from captured carbon dioxide from the atmosphere.

Both light and heavy transportation particulate matter emissions disproportionately affect people of color [82]. Fossil fuels are only available in certain parts of the world, requiring extensive extraction and transportation, increasing the associated costs and emissions. Wider access to energy resources could reduce energy transportation distances, decreasing the overall energy consumption of heavy transport and emissions before transitioning to zero-emission alternative fuels in the future.

The steel and cement industries are challenging to decarbonize due to their carbon-intensive processes and high heat requirements [79], [83]. Energy emissions could be reduced heavily by using alternative fuels, and process emissions could be limited with carbon capture techniques, providing the carbon necessary to make those alternative fuels [79].

Industrial emissions accounted for almost a quarter of the 2019 greenhouse gas emissions in the United States [84] and nearly a third of global greenhouse gas emissions in 2010 [85]. These emissions result from industrial energy usage, produced onsite through fuel combustion or offsite, and industrial processes like steel and cement production [83]. In the United States, nearly three-quarters of the energy used by the industrial sector in 2020 was supplied by natural gas and petroleum [86]. While these fuel sources produce fewer emissions than coal, the primary industrial energy source in the 1950s [86], the emissions are still considerable.

Natural gas is often marketed as a clean form of energy but is still responsible for emitting greenhouse gases and criteria pollutants. The combustion of natural gas emits carbon dioxide, methane, nitrous oxides, carbon monoxide, sulfur dioxide, particulate matter, plus volatile organic compounds that contribute to the formation of ground-level ozone, a criteria pollutant [87], [88], not to mention the externalities associated with retrieving the natural gas.

Petroleum supplies a third of the energy to the industrial sector in the United States [86]. Petroleum is broadly defined as crude oil and products from processing crude oil such as gasoline, diesel, and jet fuel, among others [89], [90], which means that their emissions vary but include both greenhouse gases and criteria pollutants [91].

8.3.2 Alternative Fuels

Producing alternative fuels from captured carbon and hydrogen from electrolysis extends the benefits of renewable energy sources like solar, wind, hydropower, and geothermal power to more areas. These renewable electricity sources are more widely available globally than fossil fuels, especially solar and wind energy.

Synthetic natural gas (SNG) can be produced from hydrogen and captured carbon dioxide. This can directly substitute for natural gas by using existing infrastructure and knowledge while being produced closer to the end-use site. This transition to SNG could eliminate upstream impacts from extraction and production, including methane emissions, among other externalities associated with obtaining and transporting natural gas. If the SNG were produced from captured carbon, it would be a carbon-neutral fuel. There are still complications regarding the use of SNG, such as leakage (which is already a concern with natural gas usage) and the need for carbon capture technology, which must be addressed. The use of dimethyl ether and ammonia, while less common than natural gas, is under extensive research to make them feasible alternative fuels in the future [92]–[94].

9 Summary and Conclusions

9.1 Summary

The pressing need to reduce global greenhouse gas emissions must be balanced with the imperative to support the development of countries with limited access to energy resources. As these countries continue to further their development, an increase in emissions is inevitable, especially if they follow a similar route of energy usage as other countries unless they are provided with a sustainable energy solution. We must avoid hindering their access to energy and their ability to develop. This is where renewable energy infrastructure plays a pivotal role, offering a pathway to increased resilience without compromising global greenhouse gas emission reduction goals.

The incentive of investments that can be counted towards emissions reduction presents a unique opportunity for corporations to contribute to energy equity by investing in renewable infrastructure in the least developed countries. Simultaneously, these corporations can offset their emissions, making it a win-win situation for environmental sustainability and global development.

While most countries rely on importing energy resources from beyond their borders, combining solar power and battery or hydrogen storage is the most widely promising solution for increased energy independence for even the most resource-depleted regions. The need for renewable energy is widespread, though the availability of land varies greatly. Central Africa stands out as a region with the necessity and the resources for renewable energy infrastructure.

Investing in a renewable data center is an option for technology companies looking to offset their emissions and foster development in this region. One innovative approach to reducing costs and fostering community benefit is overbuilding solar power infrastructure and allowing curtailment (or other power use), which substantially reduces energy storage size. This not only lowers the overall cost of the system but also enables surplus energy to be shared with neighboring communities.

Investing in additional renewable energy infrastructure beyond the data center to support the residential community provides an opportunity for more carbon offsets and supports increased energy availability and reliability in areas that need it.

9.2 Conclusions

Among the capitals explored, Niamey, Niger, offers the lowest levelized cost of electricity, making it a viable location for a renewable data center. The hydrogen storage case was the most cost-effective option at $182.58/MWh for the lowest cost projection. However, the levelized cost of electricity for additional renewable infrastructure to support a residential community in Niamey, Niger, was a minimum of $231.63/MWh for the hydrogen storage case, but this cost could decrease if it were scaled up.

Alternatively, Djibouti City, Djibouti, also exhibits a need for renewable infrastructure, with a very similar levelized cost of electricity for a data center using hydrogen storage at $183.54/MWh. The minimum cost of additional renewable infrastructure for a residential community in Djibouti City was also very close to Niamey, at $230.65/MWh for hydrogen storage—the added advantage of political stability and diplomatic ties that make Djibouti a feasible option.

Hydrogen, as the most cost-effective option for a data center, offers the opportunity for water treatment that could provide clean water for electrolysis to produce hydrogen and safe drinking water for those in Niamey or Djibouti City.

For regions where reliance on solar and batteries is not feasible, other sustainable solutions must be considered, including efficiency improvements and renewable fuels. The fight against climate change requires diverse tools and substantial financial investments, which can also increase energy equity throughout the globe. Entities with considerable wealth are well-positioned to play a crucial role in this global endeavor.

In summary, the journey to combat climate change while promoting global development necessitates a balance between reducing emissions and fostering equitable access to energy resources. Renewable energy infrastructure and the support of corporations and innovative approaches offer promising solutions to address these intertwined challenges. The collective effort of nations and wealthier entities is pivotal in driving the sustainable transformation needed to secure a brighter and more resilient future for all.

10 Sources

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Appendix

List of the Least Developed Countries in alphabetical order [18]:

1. Afghanistan
2. Angola
3. Bangladesh
4. Benin
5. Bhutan
6. Burkina Faso
7. Burundi
8. Cambodia
9. Central African Republic
10. Chad
11. Comoros
12. Congo, Dem. Rep.
13. Djibouti
14. Eritrea
15. Ethiopia
16. Gambia, The
17. Guinea
18. Guinea-Bissau
19. Haiti
20. Kiribati
21. Lao PDR
22. Lesotho
23. Liberia
24. Madagascar
25. Malawi
26. Mali
27. Mauritania
28. Mozambique
29. Myanmar
30. Nepal
31. Niger
32. Rwanda
33. Sao Tome and Principe
34. Senegal
35. Sierra Leone
36. Solomon Islands
37. Somalia
38. South Sudan
39. Sudan

40. Tanzania
41. Timor-Leste
42. Togo
43. Tuvalu
44. Uganda
45. Yemen, Rep.
46. Zambia

Detailed equations used in data center model

If $[E_{RES-SS} \times \eta_{SS+} + E_{SS}(t-1)] < E_{SS_C}$

$$P_{SS+}(t) \cdot dt = \begin{cases} E_{RES-SS}, & \frac{E_{RES-SS}}{dt} < P_{SS_C} \\ P_{SS_C} \cdot dt, & \frac{E_{RES-SS}}{dt} > P_{SS_C} \end{cases}$$

Else

$$P_{SS+}(t) \cdot dt = \begin{cases} \frac{E_{SS_C} - E_{SS}(t-1)}{\eta_{SS+}}, & \frac{E_{SS_C} - E_{SS}(t-1)}{\eta_{SS+}} \frac{1}{dt} < P_{SS_C} \\ P_{SS_C} \cdot dt, & \frac{E_{SS_C} - E_{SS}(t-1)}{\eta_{SS+}} \frac{1}{dt} > P_{SS_C} \end{cases}$$

end

The mathematical model for discharging the energy storage systems is the following:

If $[\mathrm{E_{SS}}(\mathrm{t}-1) \times (1 - \sigma) - \mathrm{E_{SS-DL}}] > \frac{\mathrm{E_{L\prime}(t)}}{\eta_{\mathrm{SS-}}}$

$$P_{SS-}(t) \cdot dt = \frac{E_{L}\prime(t)}{\eta_{SS-}}$$

else

$$P_{SS-}(t) = max(0, [E_{SS_C}(t-1) \times (1 - \sigma) - E_{SS-DL}])$$

end

The constraints for charging and discharge are the following:

$$E_{SS}(0) = I_{ES}$$
$$E_{SS}(t) = \left[E_{SS}(t-1) + \eta_{SS+} P_{SS+}(t) \cdot dt - \frac{P_{SS-}(t) \cdot dt}{\eta_{SS-}}\right] \times (1-\sigma),$$
$$E_{SS}(t) \geq E_{SS_C} \times (1 - DOD),$$
$$E_{SS}(t) \leq E_{SS_C}$$
$$P_{SS+} \leq P_{SS_C}$$
$$P_{SS-} \leq P_{SS_C}$$

For hydrogen storage systems:

$$E_{RES-SS} = \frac{E_{RES-SS}'}{1 + \eta_{EZ} + L}$$

E_{RES-SS}	Renewable energy feed to storage system
η_{SS+}	Charging efficiency of storage system
E_{SS}	Energy stored at time t
E_{SS_C}	Energy storage capacity
P_{SS+}	Power feed to storage system/ energy conversion system
E_{SS-DL}	Energy storage discharge limit
P_{SS_C}	Storage system / energy conversion capacity
η_{SS-}	Discharging efficiency of storage system
E_L'	Load energy requirements
σ	Self – discharge / Boiled off rate
P_{SS-}	Power discharge from storage system
E_{RES-SS}	Renewable energy available to storage
η_{SS+}	Charging efficiency of storage system
I_{ES}	Initial state of storage
L	Energy % required for liquefaction

Table 49. Variables included for charging and discharging the energy storage, and the associated constraints [41]