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Powering Third World Countries for the Same Cost as Building the Border Wall

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Abstract

The border wall between Mexico and the United States has an estimated cost of $30 billion. This same budget could be used as foreign aid to build solar farms in Third World countries. For example, three solar PV farms could be built in Kenya, three in Ethiopia, and one in Zimbabwe around the capital of Harare. The three solar PV farms in Kenya would have a combined power of 4 GW, the solar PV farms of Ethiopia would have a combined power of 4 GW as well, and the Zimbabwe plant would have a power 3.75 GW. Ethiopia would produce 9.49 billion kWh in the first year, Kenya would generate 9.1 billion kWh in the first year, and Zimbabwe would generate 8.05 billion kWh in the first year. This would give clean energy to 167 million people. The cost of building these farms would be about $23.65 billion, leaving $6.35 billion for additional infrastructure. These various solar PV systems were simulated and designed using the NREL SAM software suite. The presentation will summarize the results of this study including economic analysis via LCOE and hardware /system performance trade studies

Keywords: *PV farm, simulation, economics, modeling, third-world*

1. Introduction

Many immigrants leave their homes in search of a better future for themselves and their families. In 2016, 1.49 million people immigrated to the USA, and roughly 44 million immigrants currently live in this country per Zong et al. (2018). America is currently the wealthiest nation on Earth with an annual GDP of $18.6 trillion (data.worldbank.org, 2018a). Even though this is the wealthiest nation on earth, it is not economically feasible for America to open its doors to the billions of people currently living in poverty. America cannot become home to everyone, but it can seek to improve the welfare of foreign nations, so their people will not feel the need to leave their homes to find a better one. For countries to compete and thrive in a global market, they need to have a constant and stable source of electricity. Building large solar PV farms in developing nations can help to build the economies of Third World nations and the standard of living for their citizens. To properly size the necessary solar PV farms, the simulated farms were compared to actual solar farms that exist in China and India. China constructed the Tengger Desert Solar Park in 2015, which has a power capacity of 1.55 GW, and India constructed the park spans across 43 km², while India's solar

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park spans across an area of 24 km² (Weaver, 2018 , Kumar, 2018). A 1.55 GW solar farm was simulated in Ethiopia to see the energy yield that a farm of this size would produce in Ethiopia.The SunPower SPR-X22-475-COM modules were chosen because they have a power rating of 476.5W and a nominal efficiency of 22.04%. Each of the systems have 2-axis tracking because Ethiopia is located between the Tropic of Cancer and the Equator, Kenya lies on the Equator, and Zimbabwe lies between the Tropic of Capricorn and the Equator. If the systems were using single-axis tracking or a fixed orientation, they would not be able to capture as much of the Sun's energy as the seasons change. Each system was simulated with a performance degradation of 0.5% per year to account for slow degradation of the panels over time. All solar panels will degrade over time, regardless of maintenance, but this can be minimalized if proper maintenance is conducted on the system. Each solar farm was connected to 10,000 kWh battery bank, which is about 2,900 kWh less than what the average American uses in a year (data.worldbank.org, 2018b). This would provide enough electricity for the panels to rotate back to their original East-facing position after the sun sets. This will ensure that the panels will collect as much direct sunlight as possible when the sun begins to rise the next morning, and it will provide power to the main facility and monitoring stations after sunset. The simulations also accounted for potential losses that would likely occur in a real system: 5% annual soiling losses, 4.44% DC power losses, and 1% AC wiring losses. These small details are important for providing accurate results for the systems in the selected countries. Ethiopia, Kenya, and Zimbabwe were selected based on certain characteristics: geographical areas that can contain large scale solar farms, a low per capita GDP, population, energy consumption of the nation, regional stability, preexisting infrastructure, and necessary weather data for running the simulations. Geography of the area was important for several reasons: the PV farms need to be constructed in areas that are accessible, won't flood during the monsoon season, and away from wildlife reserves. The per capita GDP was taken into consideration, because these solar farms are meant for countries that would not be able to afford purchasing these systems without foreign aid. Ethiopia was the first country to undergo the simulations. To offer some perspective on the comparison between electricity consumption of other nations versus the USA, Table 1 shows some important economic details.

Tab. 1: United States of America population and economic analysis

Population	325.7 million
GDP per capita	$57,466.79 (USD)
Annual Electricity consumption	4.2 trillion kWh
Annual Electricity consumption per capita	12,986.74 kWh
Cost of electricity	$0.13/kWh

The USA has a population of 325.7 million people, and it consumes over 4.2 trillion kWh of electricity every year. Ethiopia has a population of 102.4 million people, yet it only consumes 8.14 billion kWh per year, which is roughly 80 kWh per capita (www.worlddata.info, 2018). In comparison, the USA consumes 12,987 kWh per capita (data.worldbank.org 2018b). This means that in three days, the average American consumes more electricity than the average Ethiopian consumes in a year. Since the per capita GDP of Ethiopia is $706.76 (USD), this means that the average person in Ethiopia lives on less than $2 a day. The energy yield of the 1.55 GW solar farm was not large enough to completely power the nation, so it was resized and simulated until the proper size was found. Through-trial-and error, it was discovered that a 4.0 GW system is necessary to completely power the nation. The system has been oversized to account for degradation of the panels over time and potential energy loss of transporting the electricity throughout the nation. The first simulation was completed in Addis Ababa, the capital of Ethiopia, because this city lies in the center of the country (ww.nationsonline.org, 2018a). Simulations were also done in other areas of the country to find the best location for the solar PV farms. PV farms in Gondar and Dire Dawa produced the greatest annual energy yield, so the 4.0 GW system was split up into three systems: a 500 MW system in Dire Dawa, a 500 MW system in Gondar, and a 3.0 GW system in Addis Ababa. Even though the PV farm at the capital did not have the highest energy yield, the largest PV farm was placed here because electricity could easily be distributed from here. These PV farms will require thousands of people for construction, so having large cities next to these solar farms will be ideal for providing a necessary work force. Table 2 shows the populations of these cities, and Figure 1 shows the location of the solar farms on the map of Ethiopia.

Tab. 2: Ethiopia population and economic analysis

Population	102.4 million
GDP per capita	$706.76 (USD)
Annual Electricity consumption	8.14 billion kWh
Annual Electricity consumption per capita	80 kWh
Cost of electricity	$0.09/kWh
Addis Ababa Population	3,385,000
Gondar Population	207,044
Dire Dawa Population	607,231
Percent of Population with Access to Electricity	42%

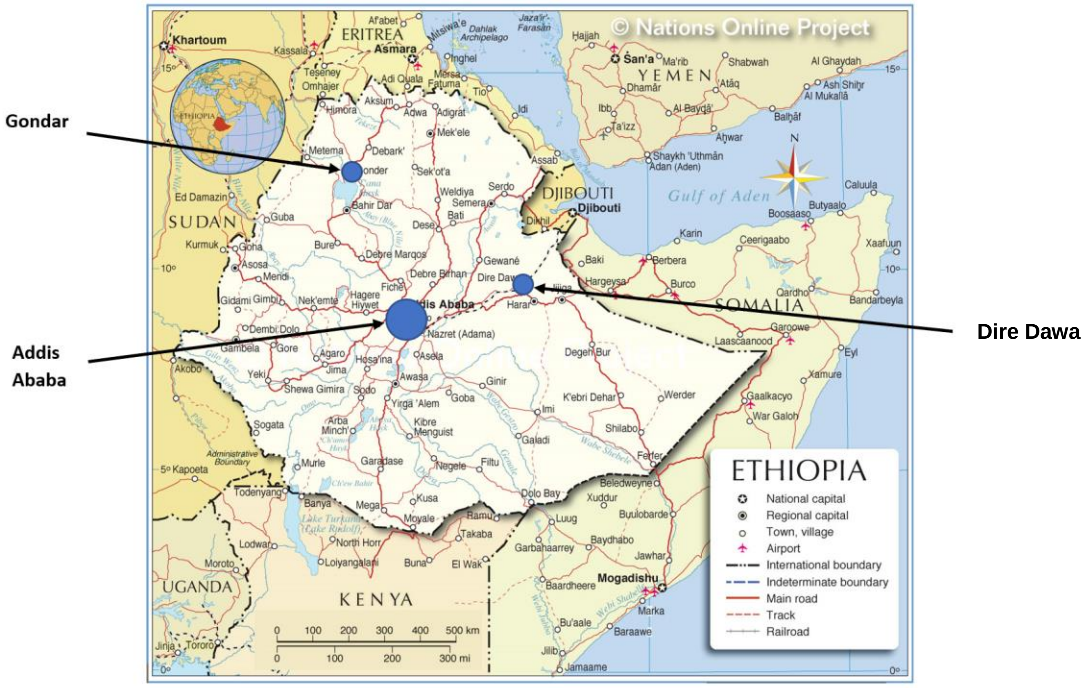


Fig. 1: Map of Ethiopia with location of proposed solar farms, map from www.nationsonline.org (2018a)

Table 3 shows the population of Kenya, its economics, and the electricity consumption and rates of the country. Figure 2 shows the proposed locations of the proposed PV farms in Kenya.

Tab. 3: Kenya population and economic analysis

Population	48.46 million
GDP per capita	$1,455.36 (USD)
Annual Electricity consumption	7.67 billion kWh
Annual Electricity consumption per capita	158 kWh
Cost of Electricity	$0.23/kWh
Lodwar Population	48,316
Marsabit Population	291,166
Eldoret Population	289,380
Percent of Population with Access to Electricity	56%

Kenya has the highest GDP per capita out of the three simulated nations, but it is still only 2.5% of the per capita GDP of the USA. It also has the highest electricity rate out of these three nations at $0.23/kWh (stima.regulusweb.com/historic, 2018). The process for designing and simulating the PV farms in Kenya was similar to the process used for Ethiopia. Locations with the best solar insolation were selected for testing. Lodwar and Eldoret are not located on or near wildlife reservations, so they will not impose upon those restricted areas, but the PV plant in Marsabit needs to be constructed about 10 miles northeast of the city to avoid interfering with the boundaries of the Marsabit National Reserve (www.nationsonline.org, 2018a). The population density is much greater in the southern part of Kenya than in the northern regions. Eldoret is located in the southwest region of Kenya and is much closer to the densely populated zones, so it was chosen as the location with the largest PV farm in Kenya to limit losses across the power lines. It is only 200 miles from the Kenya's largest city and capital, Nairobi. Marsabit is 325 miles away north of the capital, while Lodwar is 370 miles north (www.nationsonline.org, 2018a). All three locations are less than 100 miles from the Kenyan border, so excess electricity could be sold to neighboring countries if connecting power lines were constructed, which would benefit the economy of Kenya. The systems at Lodwar and Marsabit each have a 500 MW power capacity, while the system at Eldoret has a 3.0 GW capacity.

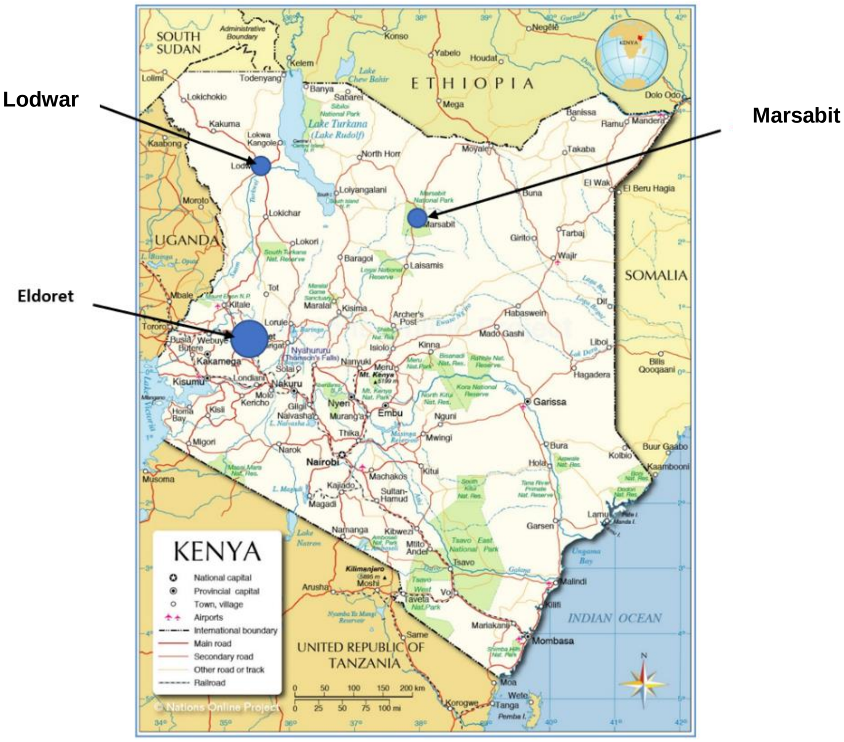


Fig. 2: Map of Kenya with location of proposed solar farms, map from www.nationsonline.org (2018b)

Table 4 shows the population of Zimbabwe, its economics, and the electricity consumption and rates of the country while Figure 3 shows the location of the proposed PV farm in Zimbabwe.

Tab. 4: Zimbabwe population and economic analysis

Population	16.15 million
GDP per capita	$1,008.60 (USD)
Annual Electricity consumption	7.63 billion kWh
Annual Electricity consumption per capita	472 kWh
Cost of Electricity	$0.10/kWh
Harare Population	1,560,000
Percent of Population with Access to Electricity	38%

Zimbabwe has the smallest population of the three nations selected for this research, yet it consumes more electricity per capita than Kenya and Ethiopia combined. A 3.75 GW system was simulated near the capital of Harare to power the entire nation. Harare is close enough to the other large cities to avoid significant line losses that will come from transmitting power from the PV farm (www.nationsonline.org, 2018b). It is also close to the border of Mozambique and Zambia, countries that Zimbabwe could sell excess electricity. According to the World Bank, only 38% of the population of Zimbabwe has access to electricity (data.worldbank.org, 2018c). The excess electricity could also be used for disconnected villages once the infrastructure is built to connect them to the grid.

Fig. 3 Map of Zimbabwe with location of proposed solar farms, map from www.nationsonline.org (2018c)

Even though Zimbabwe uses almost the same amount of electricity as Kenya, the power capacity of the solar farm in Zimbabwe was designed to be a little smaller than the power capacity of the farms in Kenya because it has a smaller population. Since Kenya's population is 3 times larger than Zimbabwe's, it has the potential to grow larger and faster than Zimbabwe, which means that Kenya needs a larger power capacity for its solar farms as the growing population will require more electricity. Nevertheless, Zimbabwe needs a solar farm that is large enough to provide for the entire country's power needs and provide enough electricity for potential growth of the nation. The system costs were simulated using wages and expenses that would be common in America. Using a more expensive cost analysis was necessary to avoid underestimating the total cost of the system. The system costs are listed below in Table 5. In the event that the cost of labor, system balancing, and installer margin and overhead can be reduced, the extra money can be used for building a larger system or for improving each nation's infrastructure.

Tab. 5: System expenses

Component	$/WDC
Module	0.64
Inverter	0.13
Balancing System Equipment	0.33
Installation labor	0.19
Installer Margin and Overhead	0.72

2. Simulation Results

The simulaton tool NREL SAM was used to perfrom modeling of the proposed PV farms. The software tool NREL SAM has a proven track record as a turn-key tool for aid in designing and simulating renewable energy systems (Blair et al. 2012, Blair et al. 2014, Freeman et al. 2013, Freeman et al. 2014)). Each location chosen within Ethiopia, Kenya, and Zimbabwe was selected because solar farms in these areas yielded the greatest annual energy. Table 6 shows the results for the PV farms in Ethiopia.

Tab. 6: Cost and energy yield of proposed PV plants in Ethiopia

Plant Location in Ethiopia	Proposed PV Plant Number	Facility Power Capacity (GW)	Energy Yield (kWh/kW)	Annual Energy Yield (TWh) (1st year)	Cost of Facility (Billion USD)	LCOE (real) (¢/kWh)
Addis Ababa	Plant 1	3.0	2,386	7.158	6.035	3.14
Dire Dawa	Plant 2	0.5	2,386	1.193	1.01	3.23
Gondar	Plant 3	0.5	2,283	1.141	1.01	3.10
Total	n/a	4.0	n/a	9.492	8.055	n/a

The plant in Addis Ababa is six times larger than the plants in Dire Dawa and Gondar, and it has the greatest annual energy yield at 7.158 TWh. Gondar has a slightly smaller annual energy yield than Dire Dawa even though they have the same power capacity. This difference is due to weather losses and does not have a significant impact on the overall yield of the system. In total, all three solar farms will produce 9.492 TWh for a country that only consumes 8.14 TWh annually. This means that the country's energy requirement will be completely fulfilled by the solar plants, and they will be able to sell the additional 1.35 TWh of energy to neighboring countries, or the people of Ethiopia will be able to enjoy using more electricity in their homes and businesses. The levelized cost of electricity ranges from 3.10 ₵/kWh to 3.23 ¢/kWh, while the current cost of electricity in Ethiopia is 9 ¢/kWh (ww.worlddata.info, 2018a). This means the cost of electricity will be decreased by around 60%. For a country whose people live on $2 a day, this would provide significant savings on electricity. Table 7 shows the results for the PV plants in Kenya.

Tab. 7: Cost and energy yield of proposed PV plants in Kenya

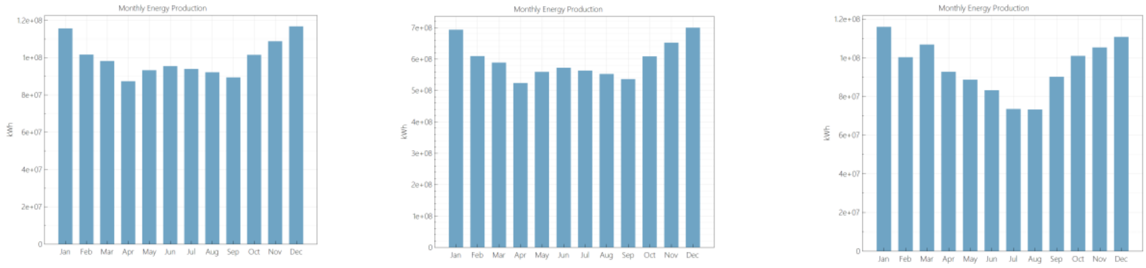
Plant Location in Kenya	Proposed PV Plant Number	Facility Power Capacity (GW)	Energy Yield (kWh/kW)	Annual Energy Yield (TWh) (1st year)	Cost of Facility (Billion USD)	LCOE (real) (¢/kWh)
Lodwar	Plant 1	0.5	2341	1.171	1.01	2.46
Marsabit	Plant 2	0.5	2,282	1.141	1.01	2.50
Eldoret	Plant 3	3.0	2,264	6.792	6.035	3.26
Total	n/a	4.0	n/a	9.194	8.055	n/a

Lodwar and Marsabit were selected as the locations for the 500 MW farms because they had the highest solar insolation and energy yield in Kenya, but they are farther away from Kenya's largest cities than Eldoret. Lodwar has the highest energy yield of the 3 sites at 2341 kWh/kW, and the LCOE at this location is only 2.46 ¢/kWh. The highest LCOE comes from Eldoret at 3.26 ¢/kWh, but this is only 14% of Kenya's current cost of electricity at 23 ¢/kWh (stima.regulusweb.com, 2018. This would also provide the people of Kenya with significant savings, and this may be necessary since most Kenyans live on $4 per day. The Annual Energy yield of these PV farms is 9.104 TWh, compared to their current consumption of 7.67 TWh (recall, 1TWh = 1e9 kWh). This means Kenya would have an additional 1.434 TWh of electricity they could sell to neighboring countries or consume in their own homes and businesses at a significantly cheaper rate than their current electricity cost. Table 8 shows the results for the proposed PV plant in Zimbabwe.

Tab. 8: Cost and energy yield of proposed PV plant in Zimbabwe

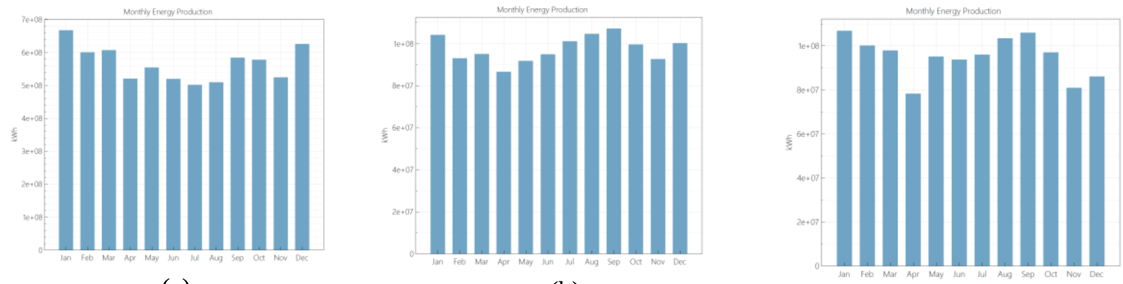
Plant Location in Zimbabwe	Proposed PV Plant Number	Facility Power Capacity (GW)	Energy Yield (kWh/kW)	Annual Energy Yield (TWh) (1st year)	Cost of Facility (Billion USD)	LCOE (real) (¢/kWh)
Harare	Plant 1	3.75	2146	8.047	7.542	3.44

The 3.75 GW power plant produces an annual yield of 8.047 TWh. Their current annual electricity consumption is 7.63TWh, so they will have an additional 4 GWh of electricity to use for whatever purposes they choose. Their LCOE is 3.44 ¢/kWh, which is 34.4% of their current electricity cost at 10 ¢/kWh. The cost of this system would be about $7.542 billion (USD), and for a country whose annual GDP is $16.62 billion, this would cost them 45.4% of their annual GDP. It would be necessary for America to purchase this system for Zimbabwe to improve their standard of living without putting crippling financial strain on the nation. Figures 4, 5, and 6 show the monthly energy production of the proposed PV plants in Ethiopia, Kenya, and Zimbabwe, respectively. Even though Zimbabwe is in the Southern Hemisphere and should have a higher energy yield during the fall and winter months, the energy production of the PV plants decreases between November to March because this is the Wet (Monsoon) Season (www.safaribookings.com, 2018). The Dry Season occurs between April to October, which is reflected in Figure 6 as the energy production is at its peak during these months.



(a) (b) (c)

Fig. 4: NREL SAM simulation results of monthly energy production of proposed PV plant in Ethiopia (a) 500 MW proposed PV farm in Dire Dawa, (b) 3.0 GW proposed PV farm in Addis Ababa, (c) 500 MW proposed PV farm in Gondar



(a) (b) (c)

Fig. 5: NREL SAM simulation results of monthly energy production of proposed PV plant in Kenya

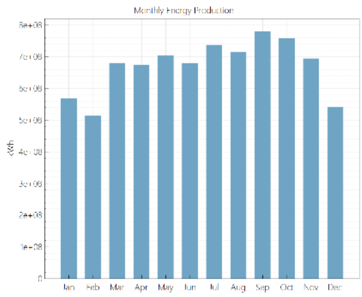


Fig. 6: NREL SAM simulation results of monthly energy production of proposed PV plant in Zimbabwe

Table 9 shows the amount of land required for building PV farms of this scale.

Tab. 9: Amount of land required for each proposed PV farm

Proposed PV farm location	Area (sq. miles)	Area (acres)
Addis Ababa, Ethiopia	17.518	11,212
Dire Dawa, Ethiopia	2.919	1,868
Gondar, Ethiopia	2.919	1,868
Lodwar, Kenya	2.919	1,868
Marsabit, Kenya	2.919	1,868
Eldoret, Kenya	17.518	11,211
Harare, Zimbabwe	21.898	14,014

The 500 MW PV farms would require almost 3 mi² of land for all the solar panels, while the 3.0 GW farms would require around 17.5 mi². This comes to a total of 23.356 mi² of land required for the solar farms in Kenya and Ethiopia. This area is almost as large as the city of Boulder, Colorado, which occupies roughly 25 mi² of land (United States Census Bureau, 2017). Zimbabwe requires 21.898 mi² of land for their 3.75 GW solar farm. The Topaz Solar Farm is a 550 MW solar farm that was constructed in San Luis Obispo, CA (www.power-technology.com, 2018). The PV farms in Kenya and Ethiopia have a capacity 7 times larger than the Topaz Solar Farm, meaning that these solar farms have the potential to create thousands of good-

paying jobs.Maintenance costs on the solar farms are also necessary for evaluation. The 500 MW solar farms will cost at least $10 million for the first year of maintenance, while the 3 GW plants will cost roughly $60 million (USD) a year to maintain. This means that Kenya and Ethiopia will have to spend $80 million a year to maintain their facilities, with costs varying according to their inflation rates. The 3.75 GW plant in Zimbabwe will cost $75 million to maintain for the first year. If Kenya sells its electricity at $0.04/kWh, and it produces 9.104 billion kWh in the first year, they would make $364.2 million in the first year. If Ethiopia and Zimbabwe sold their electricity for the same rate, the plants would make $380 million and $322 million, respectively. This would be more than enough money to continue operating the facilities, and the additional funds could go towards improving their infrastructure.

3. Discussion and Conclusions

The construction of these solar farms could have a tremendous impact on the lives of the 167 million people living in Ethiopia, Kenya, and Zimbabwe. The total cost of these seven systems was calculated using labor costs that would be similar to building PV systems in America. Labor costs in Africa are much cheaper than in America. Kenya has the highest per capita GDP of the three selected nations, and the highest minimum wage in Kenya is $2.60 per hour, or $288 per month (USD). To put this into perspective: if 10,000 Kenyans were payed $600 a month to construct these sites for 2 years, the labor would only cost $144 million, while the current labor cost of the 3 systems is estimated to be $760 million. The remaining $616 million could be used to improve the infrastructure of Kenya's electrical grid, providing power to millions of people without access to electricity. Additionally, the installer margin and overhead costs a total of $2.88 billion for all three solar farms. This accounts for transportation of the modules and other potential expenses. Lodwar and Marsabit are not connected to railroads, so the transportation of all materials will have to be conducted via trucks on dirt roads. If this cost could be reduced as well, Kenya would have even more money to build up its infrastructure. These same cost reductions could be used for the solar farms in Ethiopia and Zimbabwe. Paying workers $600 dollars a month means they would earn $7,200 a year. This means the income of the solar farm workers in Zimbabwe would be 600% higher than the average per capita GDP, and the income for the Ethiopian workers would be 900% higher than the average per capita GDP. The saved expenses could be used to build up the infrastructure of these nations as well. Fifty-eight percent of the people in Ethiopia and 62% of the people in Zimbabwe do not have access to electricity (data.worldbank.org, 2018c) The additional money would be vital to providing electricity to the entire nation and connecting communities who do not have any access to electricity. The current power plants in each country should remain operational to provide electricity to the people at night. Massive battery banks could be installed to store some of the electricity that is gathered during the day, but this may not be a practical solution for an entire nation. Lithium-ion batteries are very expensive, recycling them is difficult, and if the batteries burst and spill into the environment, cleaning up the spilled contaminants would be very difficult (waste-management-world.com, 2018). Africa also experiences very intense rains during the Wet Season, would could damage large battery banks if they are not stored correctly. The most practical use for large battery banks would be storing electricity for the main cities to use at night. Limiting the batteries to large cities may help to avoid potential environmental hazards, and it would reduce the CO2 emissions that are created to power the most populated cities, but keeping the current power plants active may be the best solution for powering the nations at night. The current power plants may also become necessary once more communities gain access to the electrical grid. Additional transmission lines will be necessary for transporting the PV generated electricity throughout each nation. The cost of transmission lines varies depending on the voltage capacity of the lines. High-voltage 230kV power lines cost $1 million per mile, while 139kV power lines cost $390,000 per mile (www.xcelenergy.com, 2018, www.elp.com, 2018). Using the current left-over funds of $6.35 billion, 16,282 miles of 139 kV power lines could be used throughout each of these countries, providing power to unreached areas or providing additional power to areas that have a higher electricity demand. If the 230kV power lines are used, the nations would be able to construct 6,350 miles of high-voltage lines. The billions of dollars saved during the construction of the PV farms could also be used to purchase thousands of miles of power lines. Millions of people would no longer have to live without electricity. Farms could power irrigation pumps for their fields, children could do their homework under luminescent bulbs instead of lanterns, communities could have consistent electricity, and economies could grow as nations are provided with constant, stable sources of power.

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