Design and comparison of Solar Energy Solutions for Jamaica

A comparison of a 500 MW_p Photovoltaic Power Station with battery storage and 500 MW_e Concentrated Solar Power Plant with heat storage

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Abstract

Currently the electricity production of Jamaica is heavily dependent on fossil fuels and with the government's goal of 50% renewable energy production by year 2030 it is interesting to investigate the competitiveness solar energy solutions. In this paper a 500 MW_e concentrated solar power plant and a 500 MW_p photovoltaic power system, both with and without storage, was compared in terms of energy production, levelized cost of electricity and levelized power purchase agreement prices. It was found that the cost-optimal PV generation solution was able to achieve a real PPA price of 7.06 c/kWh whereas the cost-optimal CSP generation solution achieved a real PPA price of 16.21 c/kWh given internal rate of return targets of 11%.

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Introduction

Currently Jamaica is heavily dependent on imported fossil energy sources for its electricity generation and at the same time its generation infrastructure is aging resulting in a number of power plants becoming candidates for displacement (Ministry of science and technology, 2018). Furthermore renewable energy generation solutions able to displace the old fossil plants, both reducing the emissions of greenhouse gases and providing Jamaica with domestic generation capabilities, is naturally of interest. Jamaica is a temperate country with plenty of solar irradiance why utilizing that irradiance seems highly relevant. Jamaica has set a goal that 50 % of the produced electricity will come from renewable sources by year 2030 (Solar head of state, 2018). With that in mind, and in the light of the recent developments in photovoltaic and concentrated solar power markets, i.e severe cost reductions, solar energy generation solutions seem a fit candidate for the job.

Purpose

The purpose of the paper is to design and present two different solar energy solutions for the island of Jamaica. The systems will be of the types photovoltaic power station with or without battery storage and concentrated solar power with or without thermal storage and will be dimensioned to 500 MW_p and 500 MW_e respectively. Furthermore the systems will be analyzed with respect to their levelized costs of electricity and levelized power purchase agreement prices for a set internal rate of return in order to determine their competitiveness relative to each other and other generation solutions.

Method

First base cases without storage for both the solar thermal and photovoltaic energy generation solutions will be developed using the SAM software analysis tool. The solar irradiance data was downloaded from the National Renewable Energy Laboratory's National Solar Radiation Database. To find the best orientations for the systems, in terms of their LCOEs, parametric simulations was employed. The basecases was then improved further by altering other parametrics, such as DC/AC ratio and storage capacity. The new improved-upon cases was then presented and compared to each other. The financial power purchase agreement (PPA) model was used since it is suitable for large-scale utility generation projects. A PPA is a legal contract between the seller and buyer defining all the commercial terms for the sale of electricity between the parties.

An internal rate of return target of 11%, a loan term of 25 years and loan rate of 5% was used in the calculation of the PPA price. The inflation rate was set to 2.5%. The income tax for Jamaica was found to be 28%, the sales tax 16.5% and the property tax 1.3%. No incentives were applied.

The yearly load profile was constructed from the typical weekday load profile of Jamaica (Office of Utilities Generation, 2010). In Jamaica the power demand load pattern on weekends is similar to that of weekends (ibid.) and furthermore, since the average temperature is fairly consistent over the whole year, the load profile of all the days of the year was assumed to be the same and is shown in *figure A1 in appendix A.*

The system peak demand was found to be 618 MW in the load profile around 18:00 (Office of Utilities Generation, 2010). To resemble the fluctuation of the electricity price the PPA modelation uses Time of Delivery Factors (TOD). The TODs were estimated from the electric load to be slightly higher during peak hours and slightly lower during non-peak hours. The average electricity rate charge in Jamaica is roughly 0.3 $/kWh (MSET, 2018) and is good to use for reference for determining the economic-feasibility of a project.

Results

Solar Thermal Power Plant

Case #1 Base case

In the base case the default solar multiple of 2 was used yielding a solar field land area of 11.6 Mm^2 and a total land area of 16.2 Mm^2. The default Solargenix SGX-1 solar collector, 2008 Schott PTR70 Vacuum receiver and Dry Cooled SEGS 80 MW_e Turbine were used. In the base case no thermal storage was employed. A degradation rate of 0.5%/yr was found to be reasonable (IRENA, 2012). Default stow angle and deploy angle of 170º and 10º respectively were used.

The default costs were also used, and are presented in *table C1 in appendix C*, yielding a total installed cost per net capacity of 4647 $/kW which is comparable to recent concentrated solar power projects (IRENA, 2017).

Simulation results

Table 1. Base case simulation results

Annual energy (year 1)	974,993,856 kWh
LCOE (nominal)	20.98 ¢/kWh
LCOE (real)	16.59 ¢/kWh

Levelized PPA price (nominal)	22.78 ¢/kWh
Levelized PPA price (real)	18.02 ¢/kWh
Net capital cost	$2,313,775,360

Case #2 Optimized case

In this case the previous base case was improved in terms of reducing the LCOE by adding a heat storage and changing the solar multiple. A heat storage of 5 equivalent full load hours in combination with a solar multiple of 2.7 were found to be the best. Furthermore the optimized stow and deploy angles were found to be 175º and 5º respectively. The total estimated system cost per capacity for this case is 6888 $/kW and is higher than the previous of 4647 $/kW mainly due to increased solar field and storage cost. The changes in solar multiple yielded a solar field land area of 15,6 Mm^2 and a total land area of 21,9 Mm^2.

Simulation result

Table 2. Optimized case with thermal storage simulation results

Annual energy (year 1)	1517 GWh
LCOE (nominal)	18.77 ¢/kWh
LCOE (real)	14.84 ¢/kWh
Levelized PPA price (nominal)	20.50 ¢/kWh
Levelized PPA price (real)	16.21 ¢/kWh
Net capital cost	$3,421,384,704

Solar Photovoltaic Power Station

Case #1 Base case

The base case was modeled as a 500 MW_p power plant with 12 modules per string, 5 374 strings and 22 inverters. The DC/AC ratio was kept to the default value of 1.2, so the total capacity of the inverters was 417 MW_{AC}. By using the parametric simulation in SAM the optimal azimuth and tilt was found to be 155° (with 180° is directly to south) and 20°. The total module area was 2.63 Mm^2 and the total land area was 8.77 Mm^2. The losses and shading were kept as the default value.

The costs of the system are presented in *table C2* in *appendix C* and the results from the base case simulation can be seen in *table 3*.

Simulation results

Table 3. Base case simulation results.

Annual energy (year 1)	836 GWh
LCOE (nominal)	8.31 ¢/kWh
LCOE (real)	6.66 ¢/kWh
Levelized PPA price (nominal)	8.95 ¢/kWh
Levelized PPA price (real)	7.08 ¢/kWh
Net capital cost	531 M$

Case #2 Optimized case

To find the optimal case two parameters were varied; the DC/AC ratio and the battery capacity. The optimal DC/AC ratio was surprisingly 1. Normally in Sweden this value would be around 1.1-1.2. The difference could be because there is a lot more irradiance in Jamaica so the modules are actually able to produces peak power more often. Therefore, it is not worth it to limit the power from the modules just to save some cost by having fewer inverters. The other simulations showed that the LCOE and LPPA increase a lot with increasing battery capacity. Therefore, the optimal case for the PV power plant was a system without batteries and with an DC/AC ratio of 1.0. The system with batteries is shown in *appendix D* and the results from the optimal system are shown in *table 4.*

Simulation results

Table 4. Optimized DC/AC ratio simulation results.

Annual energy (year 1)	838 GWh
LCOE (nominal)	8.41 ¢/kWh
LCOE (real)	6.65 ¢/kWh
Levelized PPA price (nominal)	8.93 ¢/kWh
Levelized PPA price (real)	7.06 ¢/kWh
Net capital cost	531 M$

Comparison of energy production and costs

	Levelized COE (real)	Levelized PPA price (real)
Optimized Thermal Plant	14.99 ¢/kWh	16.37 ¢/kWh
Optimized Photovoltaic Power Station	6.65 ¢/kWh	7.06 ¢/kWh

The yearly electricity demand for Jamaica was approximately 4.56 TWh. The CSP optimized case covered 33.3% of the yearly demand and PV optimized case covered 18.4%, which can be seen in *figure 1.* The reason why it is difficult for the power plants to produce a higher share is because the peak production in the middle of the day cannot be higher than the load at the same time. Having a storage can help leveling out the peak and shift the electricity delivered to the grid some hours. This can be seen in *figure 2*, the CSP plant has storage and therefore covers more hours than the PV power plant.

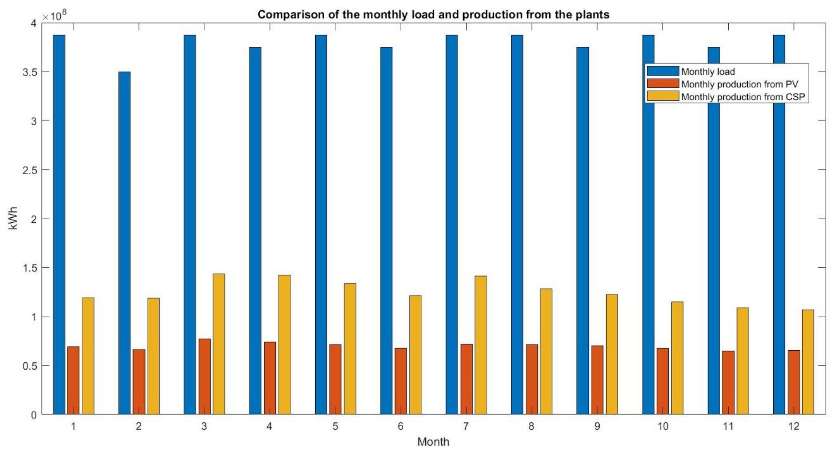

Figure 1: The comparison of the monthly load and production from the plats.

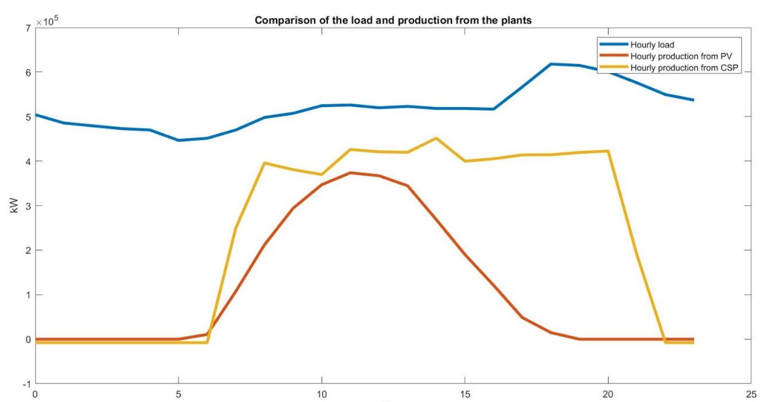

Figure 2: The comparison of the load and production from the plats one day in May.

Discussion

It was found that the PV power station had a much lower PPA price (7.06 ¢/kWh) compared to the CSP plant (16.21 ¢/kWh) which is remarkable and shows the competitiveness of large-scale PV projects. The used cost per total installed capacity of 9.80 ¢/W_{DC} (C. Anderson, 2018) in the simulations matched the cost of Kamuthi Solar Power Station in India where 648 MW solar park was installed in 2016 for 10.5 ¢/W_{DC} (Power Technology, 2018). It is however surprising that the large scale CSP plant was so far off and twice as expensive as the PV power station when recent CSP projects have signed PPA's for as little as 7 ¢/kWh (Lilliestam & Pitz-Paal, 2018). The cheap PPA projects described (ibid.) raises both amazement and questions of how such low costs are achieved. We believe it is due to low capital costs and low system costs since these are main drivers of cost for CSP projects.

Currently the electricity charge rate of Jamaica is roughly 30 ¢/kWh and in the light of this the simulated PV project with a PPA price of 7.06 ¢/kWh seems very attractive. With Jamaica's renewable energy goals in mind we should see an increase in the share of solar power in their electricity mix.

Furthermore it is seen that the optimized CSP project described has a much larger production compared to the optimized PV project,1502 and 838 GWh respectively, which is expected and incorporated in the LCOE metric. The systems with storage however can benefit the electric grid by e.g. responding to peak demand and thus add system value which is then not fairly reflected in the LCOE metric thus the true value of the systems with storage is harder to estimate.

However there is a great trouble and concern with the CSP thermal storage simulation since in theory the PPA price for a system with storage always should be higher than for a system without storage given uniform time of delivery factors. This is inconsistent with our simulation yielding an optimal LCOE and PPA price of a storage size of equivalent five full load hours of production regardless of whether uniform or peak-adjusted time of delivery factors were used. A heat storage should only be, given a uniform TOD scheme, an added cost generating no net cash inflows and then ought to decrease the profitability of the project. We have no explanation for this occurrence.

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Appendix A Electric Load

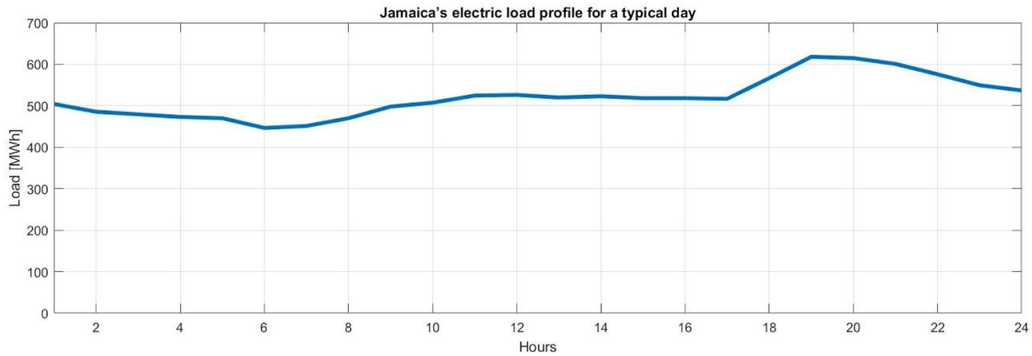

Figure A1. Jamaica's electric load profile for a typical day.

Appendix B Location and Solar Resource

The solar generation facilities should preferably be placed in an fairly unpopulated area with plenty of beam irradiance and in close proximity to the Jamaica JPS 138 kV distribution grid. From consideration such a location could be the area marked with red in *Figure B1* just south of May Pen which receives an average yearly beam irradiance of 5560 kWh/m^2. The simulated results are for the chosen location of latitude 17.88 and longitude -77.19 which receives an average beam irradiance of 5.56 kWh/m^2/yr.

Figure B1. Map over Jamaica’s 138 kV distribution grid (JPS, 2018).

Appendix C System Costs

Table C1. System costs for the parabolic trough.

Site improvements	25 $/m^2$
Solar field	150 $/m^2$
HTF system	60 $/MW
Storage	65 $/MWh$_t$
Power Block	1150 $/MW
Balance of Plant	120 $/MW
O&M Fixed Cost by Capacity	66 $/kW-yr
Variable cost by generation	4 $/MWh
Total installed costs	2.091 G$
Total installed costs per net capacity	4647 $/kW

Table C2. System costs for the photovoltaic power station (Anderson, C. et al, 2018).

Module	390 $/kWdc
Inverter	90 $/kWdc
Battery bank	500 $/kWh dc
Balance of system equipment	130 $/kWdc
Installation labor	110 $/kWdc
Installer margin and overhead	0 $/kWdc
Total direct costs	360 M$
Total indirect costs	129 M$
Total installed costs	489 M$
Total cost per capacity	980 $/kWdc

Appendix D PV System with battery storage

Simulation results

Table D1. PV system with battery simulation results.

Bank capacity	2 MWh
Bank power	100 MW
Actual DC/AC ratio with battery bank	1.21
Annual energy (year 1)	860 GWh
LCOE (nominal)	20.19 ¢/kWh
LCOE (real)	15.97 ¢/kWh
Levelized PPA price (nominal)	21.86 ¢/kWh
Levelized PPA price (real)	17.29 ¢/kWh
Net capital cost	1 780 M$

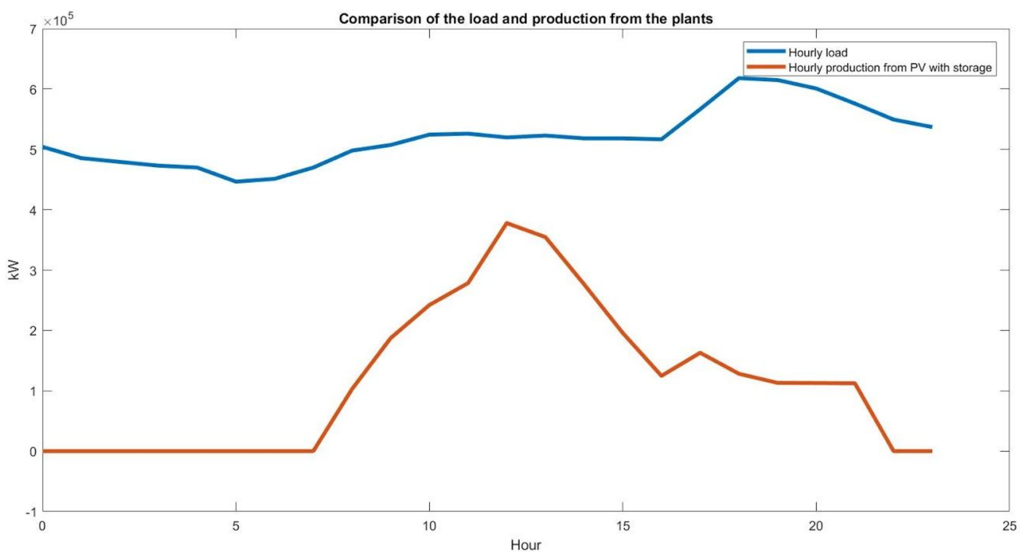

Figure D1. *The comparison of the load and production from PV power plant with battery storage for a day in May.*