Comparison of Middle-Sized PTC and PV Power Plants for METU NCC

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Abstract

Since usage of fossil fuels for producing electricity causes climate change, renewable energy options have become one of the best substitution for fossil fuels. Solar energy promises high amount of resources for producing electricity. Among solar energy alternatives, Photovoltaic (PV) and Parabolic Trough Collectors (PTC) are dominant in the market. This paper compares middle size of PV and PTC power plant for the electricity need of Middle East Technical University Northern Cyprus Campus. Based on the maximum hourly demand of METU NCC, both PV and PTC are sized to 3 MWe. The simulations were performed via SAM software using the hourly values from typical meteorological data, which include solar irradiation, wind speed, dry and wet bulb temperatures, relative humidity and pressure. For the PTC and PV plants, commercially available components are used. The scenario assumes METU NCC to be a grid-connected micro-grid with one-way tariff, so that any deficit energy can be met by the utility and any excess energy produced by the suggested renewable energy systems will be given to the grid for free. The results indicate that 3 MW PV plant would generate annual energy of about 4.95 GWh with a capacity factor of 18.9%. These numbers would yield to a LCOE value of 2.60 ¢/kWh. On the other hand, the suggested 3 MW PTC plant with 2 solar multiple would supply about annual energy of 6.3 GWh at a capacity factor of 24.0%. The LCOE of the energy from PTC plant was estimated to be 8.47 ¢/kWh due to high capital and operation cost of PTC plants compared to PV plants. However, over years the cost of PTC power plants has been decreasing. Additionally, both PTC plant and PV plant would consume water only for cleaning purposes that makes them suitable for Cyprus water scarcity conditions. Overall, this study shows pros and cons of middle-sized PV and PTC plants with the case study of METU NCC.

Keywords: economic comparison, levelized cost of energy, parabolic trough, photovoltaic, renewable energy, solar energy

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1. Introduction

Energy consumption globally increased 1% in 2014, 0.9% in 2015 and 1% in 2016. Statistics claim that in 10 years the average increase of consumption for a year will be 1.8%. The fact that conventional energy resources are depleting rapidly, the depletion rate is much higher than the rates, which can be met with the current demand. In addition, Energy Information Administration (EIA) claims that energy consumption will increase 48% by 2040 (BP Global). At this point, renewable energy resources come to the picture. They have become more attractive not only for being infinite resources but also for being environmental friendly. Solar energy is one of the most promising renewable energy type. In general there are four ways to utilize solar energy; photovoltaics, solar thermal, biofuels and artificial photosynthesis. Concentrated Solar Power (CSP) plants are categorized as solar thermal way of utilizing solar energy, as they convert solar energy into thermal energy by producing steam generally. This steam is fed to a turbine to generate electricity. Worldwide, there are 9945 MW CSP projects, which are operational, under construction or under development currently. Spain and USA lead the market with 2304 MW and 1745 MW installed capacity. However, China and MENA countries have started 1089 MW and 1020 MW plant projects, respectively. In near future, China is expected to lead the market with coming CSP projects Solar Pages (2018). Additionally, CSP technologies have promising future in countries with high direct normal irradiance (DNI) since it operates only with DNI (Zhang, Baeyens, Degrève & Cacères, 2013).

CSP technologies are divided into four, which are (i) Parabolic Trough Collectors (PTC), (ii) Linear Fresnel Reflector (LFR), (iii) Solar Power Tower (SPT), and (iv) Parabolic Dish (PDS) (Barlev, Vidu & Stroeve, 2011). As well as CSP systems, PTC power plants have gained attention all over the world. Like other solar energy technologies, the main problem with CSP is drawbacks due to lack of solar radiation. However, low cost thermal energy storage (TES) option eliminates this problem for CSP systems. Although TES increases levelized cost of energy (LCOE), it increases capacity factor, which makes TES advantages for electricity generation investors IRENA.

Parabolic trough collectors are mainly used in two areas, which are Concentrated Solar Power (CSP) and Industrial Process Heat (IPH). In CSP applications, temperature may go up to 400°C while in IPH, it may go up to 250°C. Majority of parabolic trough collectors in both CSP and IPH are located in United States and Spain (Pytilinski, 1978).

According to NREL, capacity of PTC power plants that are operational varies between 50 MW and 350 MW and located mostly in USA, Spain, India and recently China (NREL, 2018). There are few small-scale PTC power plants either operational or under- development.

Pikra et al. (2013) designed linear parabolic trough, which provides 214 kW heat to run 10 kW Organic Rankine Cycle turbine for the isolated area of Indonesia (Pikra, Salim, Prawara, Purwanto, Admono & Eddy, 2013).. In addition, Willwerth et al. (2017) commissioned 65 kW$_e$ PTC test plant at the University of ENIT for the purpose of education with the technology of direct steam generation and organic Rankine cycle. The aim of this study is optimization of hybridized PTC with biomass. Furthermore, they designed thermal and material storage facilities for the plant [9]. Moreover, Ktistis et al. (2018) designed pilot small size PTC plant that produces 1125 kW$_{th}$ for the thermal energy need of soft drink factory in Cyprus. Then, they scaled it up for the dairy factory with 394 tons of CO_2 emission saving. Furthermore, Dickes et al. (2018) designed experimental small-scale PTC plant at the University of Liege in Belgium. Plant has eight collectors that make 66 m^2, single tank for thermal storage, organic Rankine cycle unit. System produces 2000 kW$_e$ with maximum 150^{0}C operation temperature. The plant is for experimental purposes especially to see whether losses are mostly coming from optical issues or heat losses. They found out that most of the losses because of tracking errors which belong to optical issues. Additionally, Orosz et al. (2009) claims that distributed small-scale CSP are economically preferable option for rural areas with lack of electric infrastructure. In large-scale CSP plants, LCOE is between $0.15 and $0.20 per kWh while it is $0.30-$0.50 per kWh for PV and diesel generator power plants. Finally, they achieved to build test plant with 3 kW$_e$ capacity, 70 m^2 collector area, installed cost of $6 per Watt in southern Africa (Orosz, 2009). This study proves the feasibility of kilowatt-scale CSP power plant can be economically feasible when compared to large-scale commercial plants.

Photovoltaics (PV) are more popular around the globe than PTC. The energy production share of PV plants is about 1.9% of all the renewables by the end of 2017. Total world installed capacity reached

402 GW. There are some studies, which involve PV systems for METU NCC. Sajed et al. studied the sizing of a PV power plant with storage using technical and economic analyses (Sadati, Jahani & Taylan, 2015, November). They found that 4.5 MW PV system with 15 MWh storage would yield to LCOE of $0.25 per kWh. In another study, Sajed et al. (Sadati, Jahani, Taylan & Baker 2018) added 3 MW of wind turbines to 2 MW PV power plant and LCOE reduced to $0.15 per kWh. Later in 2018, Al-Ghussain and Taylan (2018) suggested another method for the sizing of a hybrid PV/wind system for METU NCC. They kept the LCOE value at the grid tariff, which was $0.175 per kWh, and found that a 2 MW turbine and 760 kW PV plant can meet about 53% of the annual energy demand of the campus.

Northern Cyprus has three middle-scale PV Plants 1.27 MW in Serhatköy, 1.3 MW in Cyprus International University and 1 MW in Middle East Technical University NCC as renewable energy resources. Island also has small-scale PV installations in hotels and households. The only PTC plant is built in Middle East Technical University NCC in 2010 with 216-m^2 collector area (Electra-Therm, 2015).

Large scale PTC or CSP studies include techno-economic analyses; however, no study has been found which investigates the economy of small-scale PTC. In the literature, only technical analyses of small scale PTCs can be found. This study not only looks into the economic aspects of small-scale PTCs, but also compares them with PV power plants to meet the same demand.

2. System Descriptions and Methodology

System Advisor Model (SAM) software with Version 2017.9.5 is used for the simulation of Concentrated Solar Power Plant and PV power plant. For all the simulations in this study, weather data including solar radiation values of Kalkanlı/N. Cyprus are obtained in Typical Meteorological Year (TMY) format from Meteonorm software and uploaded to software to be used in location and resource section.

The plant sizes are chosen to match the maximum hourly energy of METU NCC. The maximum hourly energy consumption is obtained from the local electricity company, Kıb-Tek to be about 2725 kWh. To illustrate the future improvements of the campus, the plant sizes are chosen to be 3000 kW.

2.1. PTC System Description

Parabolic trough collectors have mirror collectors (receivers) in parabolic shape to reflect sun arrays and absorbers where HTF absorbed the energy from focused sun arrays. Different coating materials can be used for collectors in order to capture as much sunlight as possible. Usually, one single axis tracking system is used for collectors to maximize captured energy from the sun. In the center of collectors, long absorber tubes are located. Heat transfer fluid, which is mostly synthetic oil, flows inside the tube and is heated up with absorbed solar energy. Usually, absorber tube is also coated with materials in order to reduce heat loss as much as possible. Minimizing heat losses is important in terms of efficiency of conversion of thermal energy to electricity. Then, HTF is gone through heat exchangers to generate steam, which is going to be used in turbine to produce electricity in a Rankine cycle.

For the CSP plant, within the scope of parameters, the software has location and resources, collectors, receivers, power cycle, thermal storage, parasitic and financial parameters. In solar field part, default inputs, which are coming by choosing solar multiple 2 option and configuration of 8 collector assemblies are chosen. Then, Therminol VP-1 is chosen as heat transfer fluid from library of heat transfer fluid, which contains 10 different HTFs. It is also allowed to add new HTF by user, but the software has the most commercially available HTFs in its library. After choosing all necessary inputs in solar field part, collector type preference is next step to complete simulation. The software has nine different collector type and EuroTrough ET150 is chosen as a collector for the plant. With choosing collector type, parameters related with collector are added to the simulation by default. Receiver type selection is next step after choosing appropriate collector. Eight different receiver types are available in software library and Royal Tech CSP RTUVR 70M4 is chosen as a receiver for the plant. After the receiver type is set, power cycle part is ready to select inputs. In this part, capacity is chosen as 3 MW$_e$. In addition, air-cooled cooling option is chosen in order to decrease water consumption. Finally, in financial part, capital and operating cost are chosen with financial assumptions. At the end of selection of parameters, simulations are performed.

Table 1: Parameters Used in PTC Plant Simulation

Parameter	Value	Parameter	Value
Solar Multiple	2	Design Gross Output	3 MW
HTF	Therminol VP-1	Cycle Conversion Efficiency	0.4
Solar Field Area	0.11 km^2	Condenser Type	Air-cooled
Number of collectors	8	Rankine Cycle Type	Steam
Collector Type	Euro-trough ET150	Thermal Storage	None
Receiver Type	Royal Tech CSP RTUVR 70M4		

2.2. PV System Description

A photovoltaic (PV) based solar power plant consists of PV modules that convert incident solar energy into DC electricity, inverters that convert DC electricity into single-phase AC electricity and a transformer substation that converts single-phase AC into three-phase AC electricity. The substation is connected to the grid. In this study, the installed PV modules and inverters at METU NCC are selected in the analysis, as all the specifications are available and it was possible to validate the results with the actual energy production. Table 2 shows the specifications of the selected PV module and inverter. These specifications are input to the simulations.

Table 2. Technical specifications of the PV modules and inverters *(Axitec AXIpower AC250P/156-60S)*.

PV module (Axitec AXIpower AC250P/156-60S)		Inverter (SMA Sunny Tripower 25000TL-30)	
Parameter	Value	Parameter	Value
Rated Power (W)	250	Max. Power (kW)	25
Rated Efficiency (%)	15.37	Max. Efficiency (%)	98.3
Max. MPPT Voltage (V)	30.7	Nominal AC Voltage (V)	220
Max. MPPT Current (A)	8.18	Max. DC Voltage (V)	1000
Open Circuit Voltage (OCV) (V)	37.8	Min. DC Current (A)	33
Short Circuit Current (SCC) (A)	8.71	Max. MPPT DC Voltage (V)	150
Temperature Coefficient of OCV (%/°C)	-0.3	Nominal DC Voltage (V)	390
Temp. Coeff. of SCC (%/°C)	0.04	Max. MPPT DC Voltage (V)	800
Temp. Coeff. of MPPT (%/°C)	-0.42		
Air Temp. at STC (°C)	25		
NOCT (°C)	45		
Reference Temp. for NOCT (°C)	20		
Reference Solar Radiation (W/m^2)	800		
Number of Cells in Series	60		
Module Area (m^2)	1.6		

2.3. Financial Model

The financial parameters are summarized in Table 3. Using these parameters, levelized cost of electricity (LCOE) is calculated as,

$$LCOE = \frac{C + \sum_{t=1}^{n}\frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E}{(1+r)^t}} + \sum_{t=1}^{n}\frac{V}{(1+r)^t}$$

(1)

where C, M and V are the capital, fixed and variable costs, respectively, E is the annual energy production, r is the annual discount rate that accounts for the inflation and interest rates, and n is the lifetime of the plant.

Table 3: Financial Parameters Used in the Simulations

Parameter	Value for PTC	Value for PV
Capital Cost ($/kW)	6065	1745
Fixed Operating Cost ($/kW)	66	14
Variable Operating Cost ($/kWh)	0.0040	0
Analysis Period (years)	25	25

Inflation Rate (%/year)	15	15
Interest Rate (%/year)	8	8

3. Results and Discussion

With TMY data for the campus location, SAM is used for power plant simulation. Table 4 summarizes the simulation results for 3 MW PTC and PV power plants. The results show that the annual energy production by PTC plant is about 6.3 GWh with a capacity factor of 24% and a net conversion of 89.5%. The resultant LCOE value is 14.7 cents/kWh. Due to dry cooling tower, the annual water usage was low, 1.8 m^3. Table 4 also shows that the annual energy production by PV plant is about 4.95 GWh with a capacity factor of 18.9% and a performance ratio of 81%. The resultant LCOE value is 4.94 cents/kWh.

Table 4: Results of 3 MW PTC and PV power plants

Parameter	PTC Plant	PV Plant
Annual Energy	6.30 GWh	4.95 GWh
Gross-to-net conversion	89.5%	81%
Capacity Factor	24.0%	18.9%
Annual Water Usage	1.8 m^3	-
Levelized COE	14.7 cent/kWh	4.94 cent/kWh

Figure 1 shows the monthly energy production from 3 MW PTC power plant. The energy production follows the trend of the solar insolation incident on the collectors. However, the energy produced in July is lower than May and June, which is unexpected. The power produced in the months of May, June and July are 986, 1024 and 953 MWh, respectively. The reason of this decrease in July is due to higher dumped energy in this month when compared to May and June. The lowest monthly energy produced is 231 MWh, which is observed in January, whereas the highest value is 1135 MWh that is observed in August. These results are due to the incident direct normal insolation incident on receiver tubes.

Figure 1 also shows the monthly energy production from 3 MW PV power plant for each month of the year. The results show that the month of May has slightly higher production than June and July, which is due to the ambient temperature differences between these months. The average temperature is about 22°C in May, whereas it is about 30°C in July. Therefore, even though the solar insolation is about 4.5% higher in July than May, the energy production is about 1% higher in May. The month of August has the highest energy production with about 174 MWh, whereas the month of January has the lowest one with about 102 MWh. Therefore, August has 41% higher energy production than January and about 9% higher energy production than May. This is due to the difference in incoming solar radiation onto the solar modules as well as the angle of incidence.
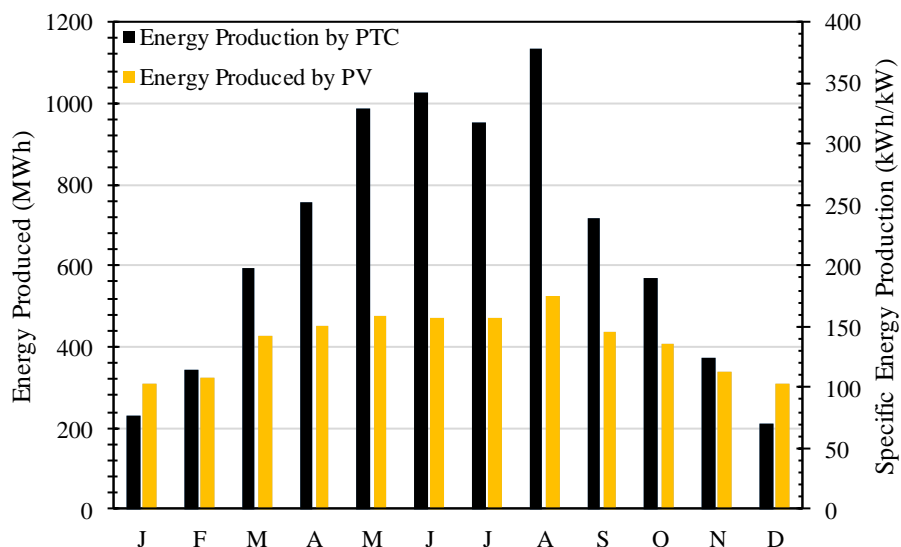

Figure 1. Monthly Energy Production from 3 MW PTC Power Plant

Figure 2 shows the daily distribution of average power production from 3 MW PTC power plant annually and in some selected months. The selected months are January, April, July and October to represent four different seasons. This figure clearly exhibits the advantage of CSP as the power production continues for several hours after the sun sets. Otherwise, more symmetrical power production would be expected. The production flattens around noontime for 7-9 hours due to the heat losses when the heat transfer fluid gets hot as well as heat capacitance of the heat transfer fluid. As expected, the highest production is observed during summer and the lowest one occurs in winter, whereas the fall and spring production values are close to the yearly average value. When the peak power production in January and July are compared, it is revealed that the peak power is about 75% higher in July than January. Additionally, the annual average peak value is about 16% lower than the peak in July.

Figure 2 also shows the daily average power production from the 3 MW PV power plant for the entire year as well as for the months of January, April, July and October to represent four different seasons. The figure reveals that yearly production follows the pattern of the month of October with a peak power of about 1845 kW. The lowest production is in the month of January due to lower insolation in winter. The peak production in January is about 1533 kW, nearly 17% lower than the yearly average. July has the highest insolation, however due to high ambient temperatures, the power production is lower than April. The values of peak power production are 1988 kW and 1927 kW in the months of April and July, respectively. These values correspond to 8% and 4% higher than the yearly average value.
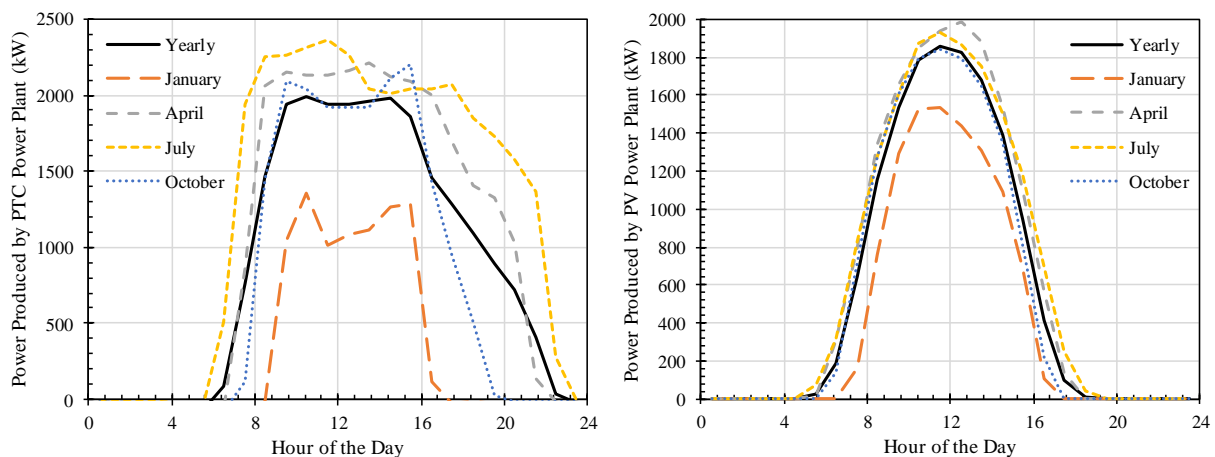

Figure 2. Daily Average Power Production for the Gıven Months from 3 MW PV Power Plant

Social cost of carbons (SCC) means "economic damage of carbon dioxide emission". According to EPA (2015), the social cost of carbon is 42\$ per metric tons (Marten, Kopits, Griffiths, Newbold & Wolverton, 2015). PTC power plant saves 4687 tons of carbon dioxide emission while PV power plant saves 3683 tons. As it is seen, PTC plant reduces more CO_2 emission than PV plant. Because of that when social cost of carbon takes into account, PTC plant is 27% more advantageous. Although, LCOE of PTC plant is more expensive than PV, economic damage of CO_2 emission is lower. Table 5 shows the details of the social cost of carbon of two power plants

Table 5: Carbon Emission and Cost Calculations

	PTC Power Plant	PV Power Plant
Avoided carbon dioxide emission (tons)	4687.2	3682.8
Equivalent Social cost of carbon (\$)	196862	154678

4. Conclusions

As a conclusion, this paper compares middle size of PV and PTC power plant for the electricity need of Middle East Technical University Northern Cyprus Campus, based on the maximum hourly demand of METU NCC, both PV and PTC are sized to 3 MWe. For the same gross design output that is 3 MW, PTC power plant produces 28% more energy than PV power plant. The advantage of PTC at that point is mainly because power production continues for several hours after the sunset. Capital cost of PTC

power plant is 3.5 times more expensive than PV power plant, which also one of the reason why LCOE value of PTC plant is almost three times higher than PV plant. However, when social cost of carbon take into account, PTC plant saves $42,000 more than PV plant. Although the PV system has an economic advantage over PTC these days, the investment cost of CSP plants are expected to decrease up to 40% in near future. This could give economic advantage to CSP plants over PV. As a future work, thermal energy storage (TES) unit may be added to PTC plant, in order to be economically more advantageous than PV plant.

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