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Concentrated Photovoltaics and its techno-economic comparison with the Photovoltaics

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Abstract

Solar energy technologies have achieved unprecedented level of deployment in recent years. RAK Research and Innovation Center (RAKRIC) has deployed 59kWp PV-Diesel-Battery Hybrid plant at its facility [1, 2]. Many factors have mainly driven utility-scale solar projects, including the sharply declining prices of solar modules, growing demand of renewable energy due to the increasing energy consumption, financial incentives from governments [3]. Until now, the utility-scale projects are generally categorized in two groups: concentrated solar power (CSP) and photovoltaic (PV). However, another new technology, concentrating photovoltaic (CPV), has begun to share the cake of utility-scale solar market [3]. This paper, serves as a primer on CPV investigation at RAK Research and Innovation Center (RAKRIC), focused to summarize the current state of CPV technology, economically compare CPV and other kinds of PV systems, and propose the possible integration of CPV technology.

Keywords—techno-economic;CPV;PV;PVsyst;Polysun; simulation

INTRODUCTION

Concentrated photovoltaic (CPV) system use optics such as lenses or mirrors to focus a great quantity of sunlight onto a small area of high-efficient solar cells, as shown in Fig.1. On one hand, CPV systems can save the cost of solar cells due to the much smaller requirement of photovoltaic materials compared with traditional PV panels. On the other hand, extra money has to be invested into other components of CPV systems, such as concentration optics, cooling system for the solar cell and single- or dual-axis solar trackers to follow the sun all the time.

CPV systems are usually categorized according to the number of concentration, measured in "suns". Current concentrations are distinguished as low, medium and high integrated with different types of solar cells as shown in Table.1. For economic reasons, conventional silicon solar cells are employed in low concentration photovoltaic (LCPV) system, while multi-junction solar cells, which is initially designed for satellites with outstanding efficiency and temperature tolerance, are favored over single junction cells for high concentration photovoltaic (HCPV) [3,8].

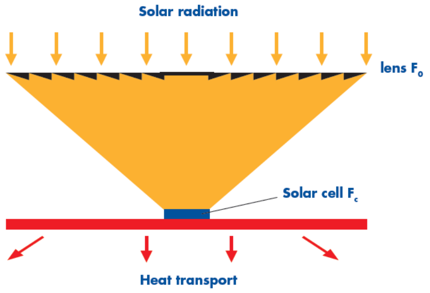


Figure 1. Principle sketch of CPV module with lenses concentrator or mirror concentrator

CPV has lower land deployment requirement than any other PV technology due to the high power density. Furthermore, a big part of CPV cost from solar trackers and concentrating optics which can competitive at the industry scale. These highly increase the potential of CPV systems on future PV market.

TABLE I. CLASSES OF CONCENTRATED PHOTOVOLTAIC

Class of CPV	Concentration Ratio	Type of Converter
High-concentration	>300	Multi-junction
Medium-concentration	100-300	Silicon or others
Low-concentration	<100	Silicon

A. *Market overview*

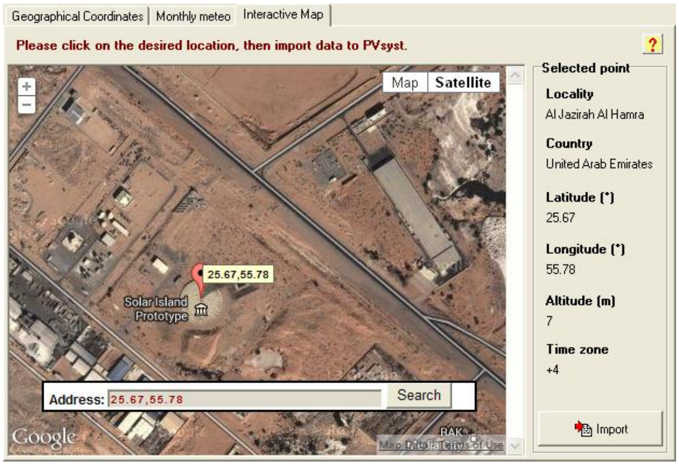
CPV is one of the latest commercially implemented PV technologies. Although attention are often focused on its high efficiency, for example reaching 35.9 % in Aug. 2013 in Amonix [9], commercial success of CPV to date is still limited due to the cheap price of silicon PV panel. HCPV, thin-film PV and LCPV are estimated to have similar costs by Richard Swanson in CPV6 conference. The growing market scale will be the most critical factor to have competitive cost in the market with traditional PV and fossil fuels. Until now leading manufacturers like Amonix in US, Soitec in Germany and Suncore in China have completed MW-scale installations and hundreds-MW/y manufacturing lines. Fig.2 shows a utility-scale CPV project installed by Amonix in River Mountains in US. It is predicted that the learning curve for CPV costs will be steeper than for flat-plate costs [10].

Figure 2. CPV project installed by Amonix in River Mountains WTF USA

TECHNICAL COMPARISON OF CPV AND PV SYSTEMS

To better understand the performance and economic feasibility of CPV compared with PV systems, simulation is conducted by PVsyst software. The specification of simulation is set according to the real situation of RAKRIC. Economic feasibility is then investigated according to the latest component prices from market research.

The geographical location of RAKRIC's solar island prototype considered in PVsyst simulation is 25.67N, 55.78E, as shown in Fig.3.



Please click on the desired location, then import data to PVsyst.

Address: 25.67,55.78

Selected point

Locality: Al Jazirah Al Hamra

Country: United Arab Emirates

Latitude (°): 25.67

Longitude (°): 55.78

Altitude (m): 7

Time zone: +4

Figure 3. Geographical location of RAKRIC site in PVsyst simulation

1) *Specification of CPV module and PV panels used in simulation analysis*

Table II shows the specification of CPV module and PV panels analyzed in this work. The mono-crystalline silicon PV panel has been recently installed at RAKRIC site. The poly-crystalline silicon PV panel was selected and simulated in Polysun in the previous installation at RAKRIC, which can be used for validation for PVsyst [7].

TABLE II. SPECIFICATION OF CPV MODULE AND PV PANELS IN ANALYSIS

Type		CPV	Poly-crystalline Silicon	Mono-crystalline Silicon
Manufacturer		Soitec	Sharp	Jinko Solar
Model No.		Concentrix Gen II	ND-220R1J	JKM260M-96
Maximum Power	Pmax(W)	85.7	220	260
Max-Power Voltage	Vmp(V)	134.2	29.2	50.5
Max-Power Current	Imp(A)	0.64	7.54	5.15
Open-Circuit Voltage	Voc(V)	153.5	36.5	61.1
Short-Circuit Current	Isc(A)	0.69	8.2	5.72
Module Efficiency (%)		26.78	13.41	15.26
Pm Temperature Coefficients (%/°C)			-0.44	-0.43
Isc Temperature Coefficients (%/°C)			0.038	0.04
Voc Temperature Coefficients (%/°C)			-0.329	-0.33
Length (mm)		800	1652	1575
Width (mm)		400	994	1082
Thickness (mm)		102	46	45
Weight (kg)		9.4	19	20

The area of CPV or PV systems installation is considered the same 600 m2 in simulation, which roughly corresponds to the area available for the installation at RAKRIC site. The electrical capacity of different systems are compared based on the same area.

2) *PV system with fixed tilt and azimuth angle*

Traditional poly-crystalline silicon PV modules Sharp ND-220R1J with permanently fixed tilt and azimuth angle are considered as the basic case in the simulation. Fig. 4 shows the comparison of monthly electricity generation from PV panels with different tilt angles, where the azimuth remain 0° to the south. The monthly electricity is strongly affected by tilt angle. In summer, when solar elevation is high, small tilt angles lead to high electricity generation. On the contrary, in winter when solar altitude angle is small, the inclined PV panels with 50° tilt angle generate more electricity. Overall, Table. III shows PV panel with 25° tilt angle can generate most electricity in a whole year at RAKRIC, which matches the conclusion of Pranav's previous work [14].

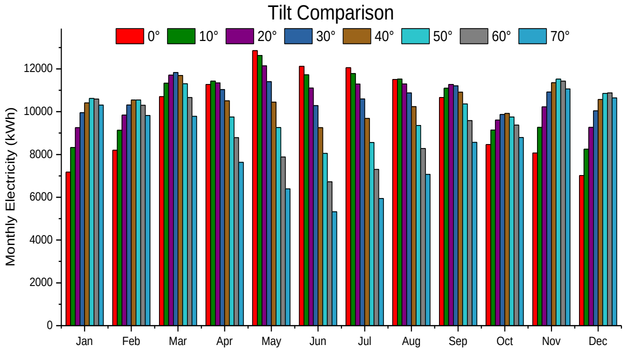


Figure 4. Comparison of monthly electricity generations by fixed PV systems with different tilt angles when azimuth angle angle remain 0°

TABLE III. YEARLY ELECTRICITY GENERATION BY FIXED PV SYSTEMS WITH DIFFERENT TILT ANGLES

Tilt	Yearly Electricity (kWh)	Tilt	Yearly Electricity (kWh)	Tilt	Yearly Electricity (kWh)
0°	120092	25°	128681	50°	119975
10°	125627	30°	128341	60°	111799
20°	128377	40°	125543	70°	101363

Keeping tilt angle at 25°, the performances of PV system with different azimuth angles are compared. As shown in Fig. 5, the azimuths between -20° and 20° have little impact on electricity generation. To sum up, permanently fixed PV panels with 25° tilt and 0° have best performance on the site of RAKRIC, which is regarded as the standard case of fixed PV.

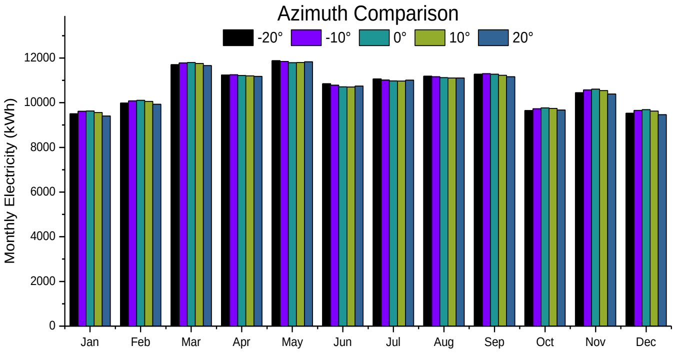


Figure 5. Comparison of monthly electricity generations by fixed PV systems with different azimuth angles when tilt angle is 25°

3) PV system with seasonal changed angles

As discussed above, solar elevation angle moves periodically through the year, and therefore seasonal electricity generation can be enhanced with different tilt angles. In Fig.6, electricity of half year is compared with different angle. Here, the half year of summer is defined from April to September, while the half year of winter is defined from October to March. For summer, the optimal tilt angle is 0°, while for winter it is 50°.

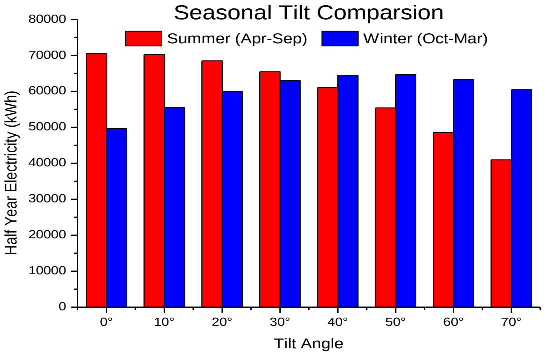
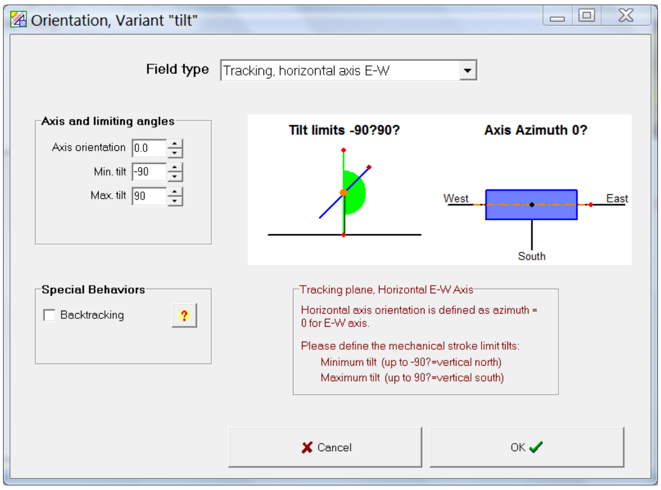


Figure 6. Comparison of half year electricity generations by PV systems with seasonally changed tilt angles

4) PV systems with single-axis solar trackers

Solar trackers are devices that orient PV panels toward the sun. Solar trackers are more and more implemented in commercial installations nowadays. PV panels installed with different single-axis trackers, having one degree of freedom that acts as an axis of rotation, are compared. Several common kinds of single trackers on the market are considered in simulation. As shown in Fig.7 (a), single-axis trackers with horizontal axis from East to West are able to tune the tilt angle, also known as single-axis EW frame. As shown in Fig. 7 (b), the axis can also be vertical to track azimuth. Fig. 7 (c) shows another kind of tracker with inclined axis from north to south. The tracker angle is often defined and orients sun in east-west direction, which is known as single-axis NS frame.


Orientation, Variant "tilt"

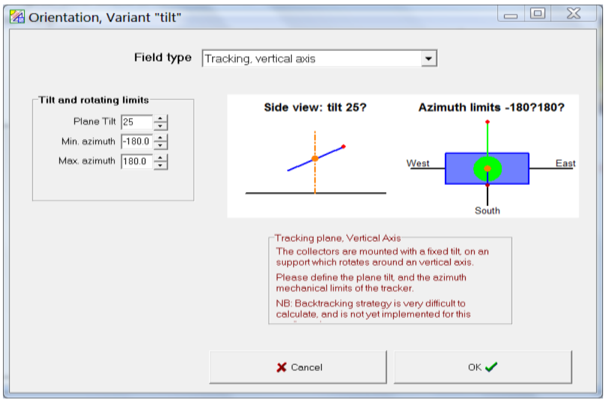
Field type: Tracking, horizontal axis E-W

Axis and limiting angles
Axis orientation: 0.0
Min. tilt: -90
Max. tilt: 90

Special Behaviors
☐ Backtracking

Tracking plane, Horizontal E-W Axis
Horizontal axis orientation is defined as azimuth = 0 for E-W axis.
Please define the mechanical stroke limit tilts:
Minimum tilt (up to -90?=vertical north)
Maximum tilt (up to 90?=vertical south)

(a)



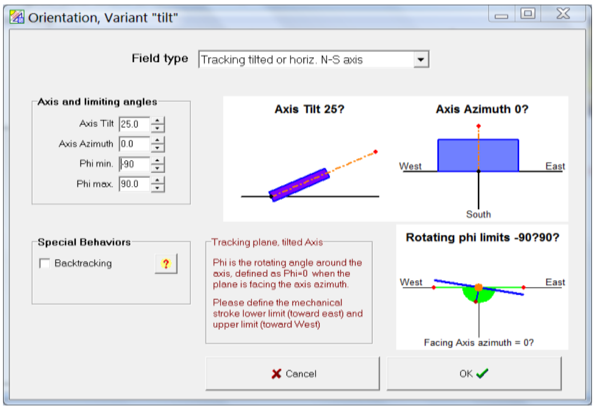
Orientation, Variant "tilt"

Field type: Tracking, vertical axis

Tilt and rotating limits
Plane Tilt: 25
Min. azimuth: -180.0
Max. azimuth: 180.0

Tracking plane, Vertical Axis
The collectors are mounted with a fixed tilt, on an support which rotates around an vertical axis.
Please define the plane tilt, and the azimuth mechanical limits of the tracker.
NB: Backtracking strategy is very difficult to calculate, and is not yet implemented for this

(b)



Orientation, Variant "tilt"

Field type: Tracking tilted or horiz. N-S axis

Axis and limiting angles
Axis Tilt: 25.0
Axis Azimuth: 0.0
Phi min.: -90
Phi max.: 90.0

Special Behaviors
☐ Backtracking

Tracking plane, tilted Axis
Phi is the rotating angle around the axis, defined as Phi=0 when the plane is facing the axis azimuth.
Please define the mechanical stroke lower limit (toward east) and upper limit (toward West)

(c)

Figure 7. Specifications of single-axis solar trackers with (a) EW axis frame (b) vertical azimuth frame (c) NS axis frame in PVsyst simulation

Fig. 8 shows that PV panels on single NS frame solar tracker generates more electricity than the other two kinds of system significantly due to the more daily change of sun elevation from east to south direction than north to south direction. The NS frame solar tracker should be the first choice when integrating PV panel single-axis tracking system.

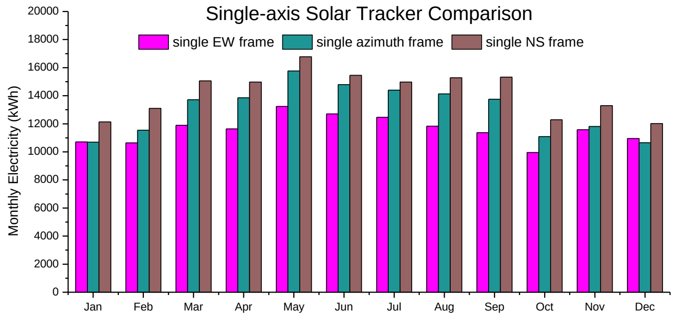
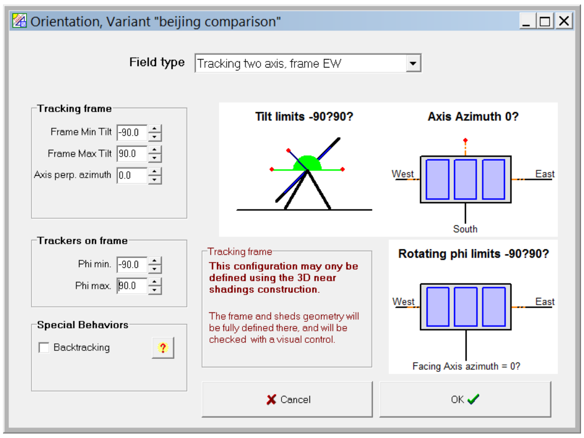


Figure 8. Comparison of monthly electricity generations by PV systems with different single-axis solar trackers

5) PV system with dual-axis solar tracker

Dual axis solar trackers have two degrees of freedom that act as axes of rotation. Several common implementations of dual axis trackers are shown in Fig. 9. Similar to single-axis trackers, EW frame, azimuth frame and NS frame dual-axis trackers are considered in the simulation. We can see in Fig. 10, the electricity generations from PV systems with different dual-axis solar trackers have little difference, as the dual-axis trackers can always orients the sun directly.



Orientation, Variant "beijing comparison"

Field type: Tracking two axis, frame EW

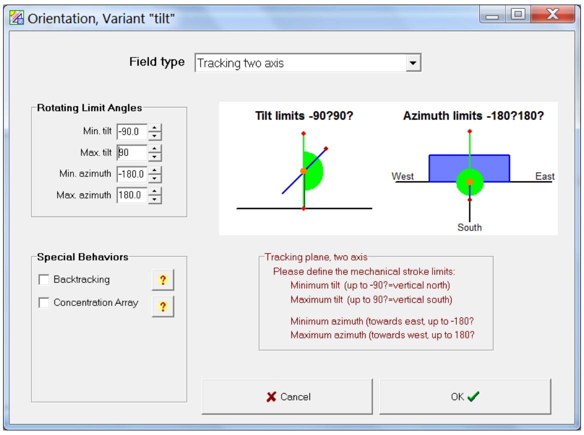
Tracking frame
Frame Min Tilt: -90.0
Frame Max Tilt: 90.0
Axis perp. azimuth: 0.0

Trackers on frame
Phi min.: -90.0
Phi max.: 90.0

Special Behaviors
☐ Backtracking

Tracking frame
This configuration may ony be defined using the 3D near shadings construction.
The frame and sheds geometry will be fully defined there, and will be checked with a visual control.

(a)



Orientation, Variant "tilt"

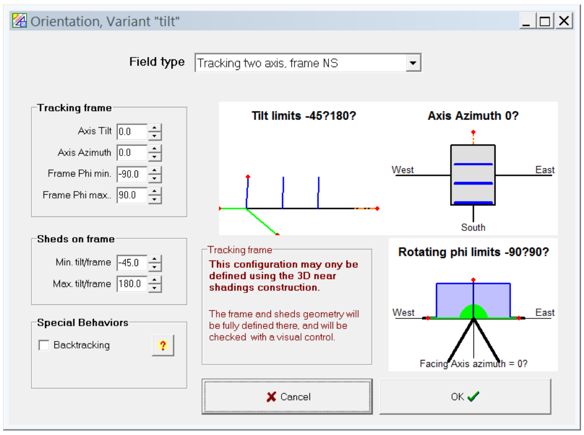
Field type: Tracking two axis

Rotating Limit Angles
Min. tilt: -90.0
Max. tilt: 90
Min. azimuth: -180.0
Max. azimuth: 180.0

Special Behaviors
☐ Backtracking
☐ Concentration Array

Tracking plane, two axis
Please define the mechanical stroke limits:
Minimum tilt (up to -90?=vertical north)
Maximum tilt (up to 90?=vertical south)
Minimum azimuth (towards east, up to -180?
Maximum azimuth (towards west, up to 180?

(b)



Orientation, Variant "tilt"

Field type: Tracking two axis, frame NS

Tracking frame
Axis Tilt: 0.0
Axis Azimuth: 0.0
Frame Phi min.: -90.0
Frame Phi max..: 90.0

Sheds on frame
Min. tilt/frame: -45.0
Max. tilt/frame: 180.0

Special Behaviors
☐ Backtracking

Tracking frame
This configuration may ony be defined using the 3D near shadings construction.
The frame and sheds geometry will be fully defined there, and will be checked with a visual control.

(c)

Figure 9. Specifications of dual-axis solar trackers with (a) EW frame (b) azimuth frame (c) NS frame in PVsyst simulation

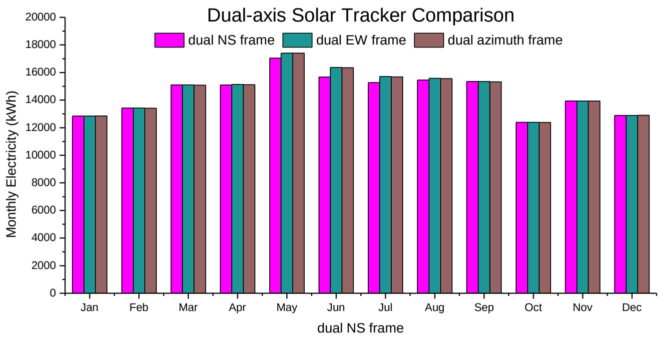


Figure 10. Comparison of monthly electricity generations by PV systems with different dual-axis solar trackers

6) *CPV system with dual-axis solar tracker*

Dual-axis solar trackers are necessary for CPV modules. The same three kinds of dual-axis trackers are considered for CPV simulation. **Error! Reference source not found.**. 11 shows that the monthly electricity generation in the cases of azimuth frame tracker and EW frame tracker are almost the same, while in the case of NS frame electricity in summer are lower obviously due to the imperfect tilt range from -45° to 180°. It also illustrates how sensitive the performance of CPV module is to the solar orientation compared with PV panel.

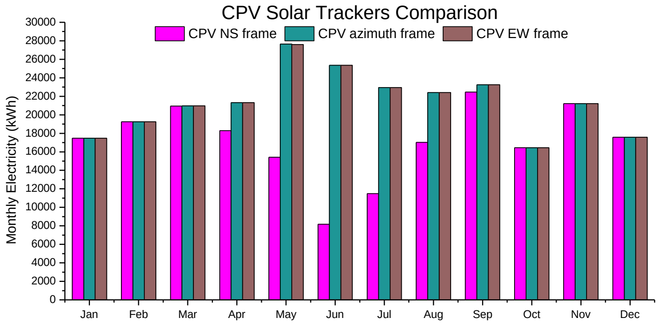


Figure 11. Comparison of monthly electricity generations by CPV systems with different dual-axis solar trackers

B. *Comparison based on Performance*

Fig. 12 shows the comparison of electricity generated by all kinds of PV systems and CPV systems discussed above. The poly-crystalline PV panels here are Sharp ND-220R1J, mono-crystalline PV panels are Jinko 260M-96 and CPV modules are from Soitec. The colors of columns in figure correspond to the scale of electricity. In general, electricity generation goes up in the order of poly-crystalline, mono-crystalline and concentrated multi-junction photovoltaic. The integration of solar trackers with PV panels improves the power performance significantly. Looking into details, we can find that the yearly electricity from seasonal tilt changed PV systems is very close to that from PV panel with single-axis EW frame solar tracker that orients tile angle to the sun. In addition, among three cases of single-axis solar trackers, the electricity in the case of NS frame tracker is much higher that is very close to the case of dual-axis tracking system.

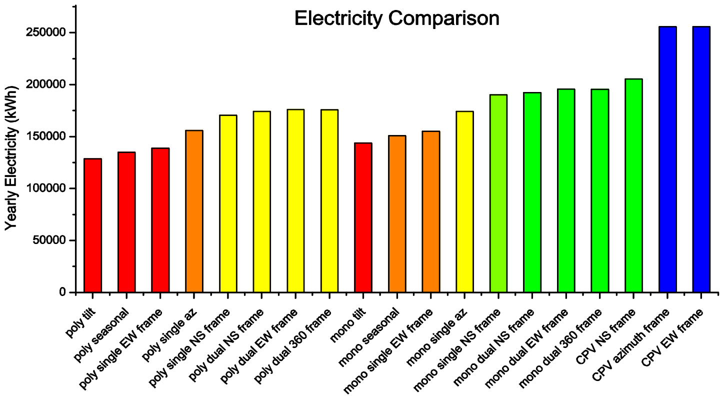


Figure 12. Comparison of electricity generations by different PV systems and CPV systems

Error! Reference source not found. 13 shows the normalized improvement of different PV systems and CPV systems compared with the basic case, fixed poly-crystalline PV panels. Without any solar trackers, the mono-crystalline PV panel Jinko 260M-96 generates 11.8% more electricity compared with Sharp ND-220R1J. With seasonal changed mounting base, PV panels can generate around 5% more. And different single-axis or dual axis solar trackers can offer 8% up to 37% improvement to the PV capacity. Having almost doubled efficiency 26.78% compared with 13.41%, CPV systems generate 98.8% more electricity.

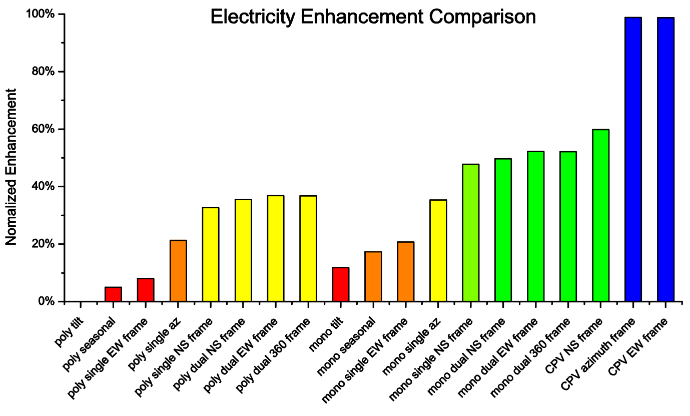


Figure 13. Comparison of normalized electricity enhancement by different PV systems and CPV systems

ECONOMIC COMPARISON OF CPV AND PV SYSTEMS

The electricity capacities of PV and CPV systems are compared above. Tilt adjustable mountings, solar trackers or concentrating collectors, on one hand, improve the performances of system. On the other hand, they also cost more than simple PV systems. To find the best photovoltaic solutions for RAKRIC, the economic analysis between different PV and CPV systems are investigated. The cost of photovoltaic systems consists of three main parts – photovoltaic modules, mounting or tracking systems and accessories such as cables, inverters, installation fees. The following analysis about systems are based on the summary of real cost in a fixed PV system at RAKRIC. The prices of solar trackers are researched from the market. For utility-scale photovoltaic projects, expense of land is also considerable, which is roughly assumed at 30 AED/Square-feet according to the land on sale in Ras al Khaimah [16]. Table. IV and Table. V list the cost of mounting/tracking systems and all the components of projects. The symbol of one * stands for approximate number based on the market valuation, while ** stands for assumptions by author.

TABLE IV. COSTS OF MOUNTING OR TRACKING SYSTEMS IN 600M2 PHOTOVOLTAIC PROJECT

Mounting/Tracking	Unit	AC-coupled 600 m^2
Fixed Mounting	$	38000
Seasonal Tilt Mounting	$	48000**
Single-axis solar tracker	$	57085*
Dual-axis solar tracker	$	81550*

TABLE V. COSTS OF COMPONENTS IN 600M2 PHOTOVOLTAIC PROJECT

	Poly-Si	Mono-Si	CPV
Nominal Power (kW)	80.3	91.5	163.1
Unit Module ($/kWp)	500*	600*	2000*
Module Cost ($)	40150	54900	326200
Accessories ($)	50000*	52000	65000*
Land ($)	50000*	50000*	50000*
SUM ($)	140150	156900	441200
Mounting or Tracking	fixed	fixed	Dual-axis
Maintenance/Year	3%*	3%*	3%*

The lifetime of photovoltaic modules are 25 years. To calculate the electricity capacity throughout the whole module lifetime, the efficient drop of 1% every year is assumed in calculation. To measure the investment of photovoltaic project, the operational cost is also taken into consideration. Here the electricity generations every year are converted to the initial date of invested by a yearly interest of 5%*. Thus the present value of electricity generation in year N is shown in (1).

$$E\,(N) = 1\times(1-E.D.R)\,N\times(1+I.R)\,-N \quad (1)$$

where;

E is the Electricity generation

E.D.R is efficiency dropt rate

I.R is interest rate

N is no of years

As shown in Table. VI, taking the yearly electricity generation ideally from the PVsyst simulation as 1 unit, the electricity generation whole life is 12.84 units.

TABLE VI. AMOUNT OF ELECTRICITY GENERATION THROUGHOUT THE WHOLE LIFE OF PROJECT CONSIDERING EFFICIENCY DROP AND OPPORTUNITY COST

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Electricity	1.00	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.90	0.89
After interest	0.95	0.90	0.85	0.80	0.75	0.71	0.67	0.63	0.59	0.56	0.53	0.50	0.47
Year	14	15	16	17	18	19	20	21	22	23	24	25	SUM
Electricity	0.88	0.87	0.86	0.85	0.84	0.83	0.83	0.82	0.81	0.80	0.79	0.79	
After interest	0.44	0.42	0.39	0.37	0.35	0.33	0.31	0.29	0.28	0.26	0.25	0.23	12.84

Table. VII and Fig. 14 shows the economic comparison of photovoltaic projects with different PV and CPV systems. On the land of 600 m^2, the nominal power of CPV systems is much higher than PV systems due to the module efficiency. However, costs of module and tracker for CPV are also high. As a result, for a scale of hundred-kWp project, electricity generation cost from CPV is around 60% higher than that from PV. Among all kinds of systems, mono-crystalline PV panel integrated with NS frame single-axis solar trackers is the optimal choice on the site of RAKRIC.

TABLE VII. ECONOMIC COMPARISON BETWEEN PV AND CPV SYSTEMS

	Nominal Power (kWp)	Type	Yearly Power	Total Electricity in 25 years(kWh)	Total Cost($)	Electricity Cost($/kWh)
Sharp Poly-Si	**80.3**	**fixed**	**128681**	**1652065**	**183495**	**0.111**
		seasonal changed	**135083**	**1734257**	**193795**	**0.112**
		single-axis NS frame	**170682**	**2191293**	**203152**	**0.093**
		dual-axis EW frame	**176108**	**2260954**	**228351**	**0.101**
Jinko Mono-Si	**91.5**	**fixed**	**143927**	**1847800**	**200747**	**0.109**
		seasonal changed	**151025**	**1938927**	**211047**	**0.109**
		single-axis NS frame	**190185**	**2441681**	**220405**	**0.090**
		dual-axis EW frame	**195854**	**2514462**	**245604**	**0.098**
Soitec CPV	**163.1**	**dual-axis azimuth frame**	**255805**	**3284141**	**538433**	**0.164**

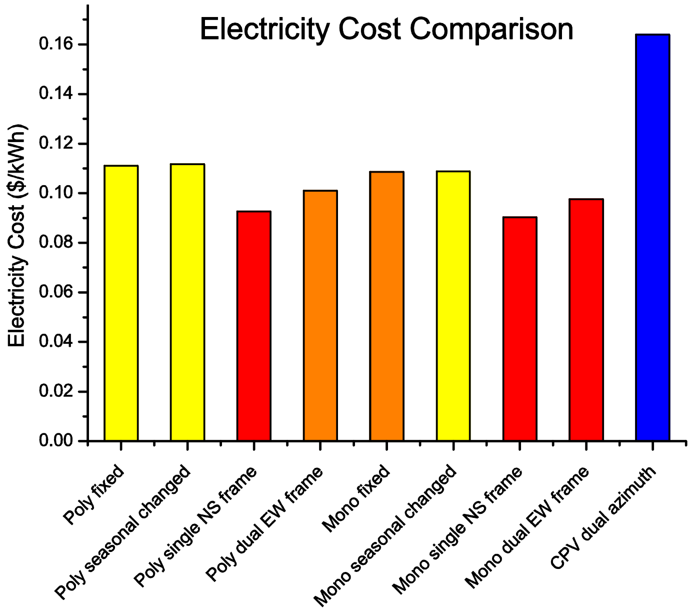


Figure 14. Economic comparison between PV and CPV systems

The economic analysis above that is conducted based on the normal prices of components on market gives a roughly insight of electricity cost from photovoltaic power plants and the feasibility of CPV projects at RAKRIC. In fact, the unit electricity cost is also considerably influenced by the scale of project. Since the prices of different mounting/tracking systems and CPV modules are expected to reduce faster than traditional PV panels and the price of land continue to soar up, these new technologies seasonally changed mounting, solar trackers and concentrating collectors integrated with photovoltaic deserve to be followed and investigated for future.

CONCLUSION

Market research about concentrated photovoltaic (CPV) is conducted and suppliers of both CPV modules and multi-junction solar cells are contacted and summarized for the future purchase and experiments. The performances and costs of different PV systems and CPV systems are compared from simulation by PVsyst. Simulation result shows that the optimal fixed system is tilt 25° and azimuth 0° to the south, which matches the conclusion of previous Pranav's simulation work with Polysun [14]. To increase the electricity generation, the seasonal changed mounting, single-axis NS frame solar trackers and dual-axis solar trackers are recommended to install with PV panels from the performance comparison of systems. For the same area of land $600m^2$ at RAKRIC, CPV systems generate almost double electricity as traditional fixed PV systems. To capture the economic behavior of different systems, the unit costs of electricity generation are then roughly estimated and compared. Mono-crystalline PV panels integrated with NS frame single-axis solar trackers produces cheapest electricity, as the analysis of this study. Due to the extra costs of concentrators and other accessories, the price of electricity generated from CPV is about 60% higher than PV systems. Hence to conclude although technically the CPV can produce higher electricity for the same area of PV, however economically the cost of electricity is higher than the PV.

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