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TECHNO-ECONOMIC COMPARISON OF BIFACIAL VS MONOFACIAL SOLAR PANELS

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Abstract. A techno-economic analysis is performed for a solar farm with a 35 MWe installed capacity using bifacial solar panels and compared with standard monofacial solar panels at the same installed capacity level. The bifacial panel usage gain from total panel efficiency is identified from 4-year measurements to be within a range of 7.9–16.8% depending on monthly yield. A Monte Carlo simulation is carried out to forecast electricity prices under uncertainty. In terms of Net Present Value, it is found that the bifacial farm yields 12.6% higher values than the monofacial options under reference assumptions. An incremental internal rate of return (IRR) analysis is carried out yielding an IRR for the bifacial panels of 44% under various scenarios. The sensitivity analysis reveals that results are highly sensitive to discount rate and lifetime, and less sensitive to electricity prices. SWOT analysis performed to compare the bifacial with the monofacial panel and evaluate panels according to internal and external factors. The study was concluded with a summary of the technical specifications based on the test results. The results were used to identify that 12.2% added net present value corresponding to \$186.7 – \$214.5 per unit MW (under various electricity price trajectories) can be used as a reference for assessing the benefit for usage of bifacial PV for 35 MW type medium-size projects. In summary, it is suggested that bifacial solar PV with its outstanding techno-economic results can be the driving force of the growing solar PV market.

Keywords: bifacial solar PV, monofacial solar PV, techno-economic analysis, SWOT, Monte Carlo simulation.

Introduction

The International Technology Roadmap for Photovoltaics [ITRPV] (VDMA, 2020) predicts a global market share of 70% for bifacial photovoltaic (PV) modules by 2030. The scientific literature includes vast research on the performance of bifacial solar panel arrays based on analyses conducted at various sites worldwide. Findings, however, are highly location specific as climate parameters significantly affect the efficiency of solar power generation. While climate conditions in Turkey vary significantly from one region to another, areas located in southern Turkey have solar irradiation >1600 kWh/m^2-year. To the best of our knowledge, there is no study analyzing the techno-economic implications of bifacial solar PV installations in comparion to monofacial ones.

A techno-economic analysis was performed for a solar farm with a 35 MWe installed capacity using bifacial double glass Mono-PERC solar panels and compared with standard monofacial Mono-PERC solar panels at the same installed capacity level. The usage of bifacial PV is relatively new in Turkey however with having the prospect of being a promising market player. Also, studies involving the techno-analysis comparison of bifacial PV versus monofacial Mono-PERC has been very limited in the Turkish market setting. The study aimed to identify the sensitivity of the incremental internal rate of return (IRR) for bifacial PV to discount rates, lifetime, and electricity prices. The assessment was conducted by reviewing the technical properties based on test results and a SWOT analysis to finalize the study. The findings can be used to further the techno-economic usage knowledge base for bifacial double glass Mono-PERC solar panels at a regional scale as well as for the analyses conducted at various sites worldwide.

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1. Literature review

Within the scope of this study, a literature review was conducted before comparing bifacial and monofacial solar panels. During the research, it was focused on the comparison of bifacial and monofacial, and then the articles focused on bifacial efficiency. For example, Tillman and his friends calculate the energy yield and levelized cost of electricity generation (LCOE) for bifacial solar panel arrays at four locations with different climates (Tillmann et al., 2020). One of these locations is Seattle, Washington (WA), having a warm-temperate Mediterranean climate with relatively dry summers and cool wet winters, classified as Koppen–Geiger Csb. For this location, the LCOE reduction for bifacial modules with optimized tilt is found to reach 23.7% when compared with monofacial ones. The bifacial energy yield gain is found to reach 13.6%.

Rodríguez present a worldwide analysis on the yield potential and cost-effectiveness of solar PV farms composed of monofacial fixed-tilt and single/dual (1T/2T) tracker installations, as well as their bifacial counterparts, focusing on 10 locations across all continents (Rodríguez-Gallegos et al., 2020). Their results reveal that bifacial-1T installations increase energy yield by 35% and reach the lowest LCOE levels for the majority of the world (93.1% of the land area).

Shoukry have developed a simulation tool capable of modelling the annual energy yield of both stand-alone bifacial module installations with vertical and tracked systems for stand-alone and in-field installations in different geographical locations (Shoukry et al., 2016). It is found that a fixed bifacial module has a higher yield than a tracked monofacial module. Results show that bifaciality is more advantageous than simple tracking systems in sunbelt regions, with the benefits of bifaciality more prominent for higher ground albedo coefficients. Simulations show, that vertically mounted bifacial modules can achieve a higher annual energy yield than south-facing monofacial modules in locations at higher latitudes. One of the simulation results shows that, while a stand-alone module with an optimum configuration yields a 33.9% bifacial gain, the bifacial gain of the same module is decreased to 31.4% in a field installation for the best and 27.7% for the worst performing modules. Furthermore, simulations show, that vertically mounted bifacial modules can achieve a higher annual energy yield than south-facing monofacial modules in locations at higher latitudes.

The prediction accuracy of simulation results for bifacial technology is studied by Nussbaumer comparing the results of various simulation tools with measured data under varying irradiation conditions and tilt angles (Nussbaumer et al., 2020). The deviations are found to be smaller than ±2% for 30° to 45° tilt angles and mostly well below ±1%. It is concluded that the observed trends in bifacial gains and the measured total electrical output are well predicted by all models, showing that bifacial yield modeling is reaching a stage of maturity.

Park evaluates the outdoor performance of bifacial PV modules and string systems under different ground reflection conditions. The monthly average bifacial gain is found to vary from 6.1% (December) to 13.8% (June) under 21% ground reflection (Park et al., 2019). For the module with 79% ground reflection, the gain is found to vary from 26.0% (February) to 45.1% (August). The tracker gain is found to change significantly from −12.7% (January) to 31.5% (May and June).

Libal claims that just like solar trackers a few years back, bifaciality will enter the PV market with a high impact when the financing sector will have gained more confidence (Libal & Kopecek, 2019). For different system configurations and ground reflection conditions, the bifacial energy gain is observed. The smallest value observed is above 10% except of an outlier and reaches 25–30% under different bifaciality values. Their cost computations, assuming a system lifetime of 25 years, a 6% discount rate and 16% tracking gain, show that the LCOE of bifacial systems are around 20% lower than for standard monofacial fixed tilt.

Moehlecke analyzed with a white reflective reflector for 18 months to improve solar radiation reaching the back surface of double-sided solar cells. They observed that the output power of bifacial modules increased by 29% thanks to the white reflector (Moehlecke et al., 2013).

Kılci provided an evaluation of the performance of the tracker system bifacial and monofacial panels of 1123.2 kWp PV plant based on radiation values in Karaman. Energy production, specific efficiency, performance ratio (PR) values of 2 different systems were analyzed. The data measured from the established systems were compared in terms of global horizontal irradiation, global incident Irradiation, energy at the output of the array, energy injected into grid, specific energy yield, and performance ratio which are intended to be established at the same power. Using PVsyst (PC software package used globally for the study, sizing, simulation and data analysis of complete solar PV System), the two simulations were done under the same conditions and for the same geographic region. The energy generated by both systems. It is revealed that the bifacial system is more advantageous in production than monofacial system (Kılci & Koklu, 2020).

Raina carried out simulation to determine the capability of c-SiPERC bifacial solar cells to derive power compared to its monofacial counterparts. Bifacial modules have the capability of absorbing irradiation from its front as well as its rear side. The results show that bifacial solar cell produces more Jsc (rear side short circuit current density) and power relative to monofacial cell (Raina & Sinha, 2020).

In the light of literature research, many studies show that bifacial solar panels are more effective than single-surface panels in terms of performance. In this study, it is aimed to support this past work with projected financial analysis with real time data of the bifacial panels.

2. Economic analysis

The economic analysis is based on projected data for a solar farm with 35 MWe installed capacity using bifacial double glass Mono-PERC solar panels. A comparison has been performed with monofacial Mono-PERC solar panels at the same installed capacity level for three system options including two alternatives for monofacial panels as follows:

- *Option 1:* locally made standard 390 W Mono Perc panels at the cheapest price available yielding 1.16 cent per kwh incentive from the government.
- *Option 2:* Multibusbar Half-Cut 445 W Mono Perc panels.
- *Option 3:* bifacial 390W (front side) panels which are also locally made, hence yielding 1.16 cent per kwh incentive from the government.

2.1. Assumptions

Assumptions employed in the economic analysis are depicted in Table 1. The first part includes general assumptions on panel area and quantities, capacities, acquisition cost items, discount rates and lifetimes. The installed capacity level is taken as 35 MWe, common for all three options, and other assumptions of the configurations are identified accordingly based on the technical specifications of the considered options.

The total investment cost covers all costs to deliver the turnkey facility including engineering, procurement and construction. Assumptions on generation amount and degradation percentage are based on the technical specifications of the considered PV systems, inferred from plants in operation and test results. Employee requirements and salary payments are assumed to be the same for all three options. The only difference in operational cost items is the maintenance and repair cost, which is slightly lower for the bifacial system option. Naturally, electricity price assumptions are the same for all options. Details on the simulation of electricity prices are provided in the following section. All of the remaining assumptions (TEIAS contribution margin, distribution fee, exchange rate, tax) is system-independent, i.e. same for all options. The TEIAS contribution margin refers to the payment to the electricity transmission corporation TEIAS.

2.2. Electricity prices – Monte Carlo simulation

The feed-in-tariff for solar power under the Turkish Renewable Energy Support Scheme (YEKDEM) is used in the calculations for the first 10 years of operation. YEKDEM was set up in 2013 to incentivize renewable energy generation with a feed-in tariff. The scheme offers guaranteed purchase for renewable energy generation at a technology-specific fixed feed-in tariff for a period of ten

Table 1. General and economic assumptions

Summary of Assumptions	Option 1	Option 2	Option 3
	Monofacial Frame	Multibusbar Half-Cut Perc	Bifacial Frame
Panel Capacity (W)	390 W	445 W	385 W
Panel Capacity (kWp)	50,007 kWp	50,000 kWp	50,000 kWp
Electric Capacity (kWp)	35,000 kWe		
Panel Unit Cost ($/Wp)	$0.250	0.29	$0.295
Total Investment Cost ($)	$24,392,649	$25,000,000	$26,489,979
Real Discount Rate (%/Year)	5%		
Project Life (Years)	25		
Annual Generation (kWh/kWp/year)	1,962	2,106	2,105
First Year generation (kWh)	98,113,675	100,075,949	105,249,895
Degradation (% /year)	0.70%	0.70%	0.40%
Maintenance Costs ($/Year)	$315,000	$300,000	$245,000
Annual Overhead Cost (10% incr. p.a.)	31,815 TRY		
Insurance Costs ($/MW/Year)	$3,000		
Contingency (1% of Revenue)	1.00%		
Electricity Sale Price ($/MWh) Year 1–5	$0.1446		
Electricity Sale Price ($/MWh) Year 6–10	$0.1330		
Electricity Sale Price ($/MWh) Year 11–25	Monte Carlo Simulation		
TEIAS Margin (TL Total; equally distributed over initial 3 years)	30,301,440 TRY		
Distribution Fee (TL/kWh)	0.0146 TRY		
Price Increase (%/Year)	10%		
USD/TL FX Rate	6.75		
Devaluation of TL (%/Year)	10%		
Corporate Tax Rate	22%		

years. There is an additional support for the first five years of operation if the mechanical and/or electro-mechanical components of the plant are manufactured domestically. The tariff for solar PV stands at \$0.1330 per kWh, with a surplus for domestic manufacturing in the first 5 years. Accordingly, the electricity price for the first 10 years of operation is taken as follows:

Year 1–5 : \$0.1446 per kWh

Year 6–10 : \$0.1330 per kWh

Beyond year 10, the produced electricity will have to be sold in the marketplace as per the Turkish Regulatory framework. A Monte Carlo simulation has been performed to estimate prices from the 11th year on. The following procedure is employed to estimate the simulation parameters:

– Daily market clearing prices for the last 10 year (Dec. 1, 2011 – July 1, 2020) are retrieved.
– Annual and monthly average prices are computed.
– The minimum extreme distribution and logarithmic distribution are identified as the best fits for annual and monthly prices respectively.
– 10,000 Monte Carlo simulation runs are done.

Results of the Monte Carlo simulation are depicted in Figure 1 together with historical data.

The average annual prices as a result of the 10,000 simulations for a 25-year period are shown in Table 2. for the two scenarios based on (i) annual average prices with best fit minimum extreme distribution yielding a decreasing price trend and (ii) monthly average prices with best fit logarithmic distribution yielding an increasing price trend. The forecast for year 11, which corresponds to the first year after the end of the guaranteed feed-in tariff, is \$0.0179 per kWh under the decreasing price trend scenario and \$0.0834 per kWh under the increasing price trend scenario. The long-term average growth rate of prices from the simulation result corresponds to roughly 6.4% per annum while the long-term decline rate corresponds to 8.2%. It should be noted that the prices are all nominal values. The real discount rate is taken as 5% (see Table 1) in the reference run implying that the real price change margin is about 2%. This margin is taken as a basis in the sensitivity analysis when evaluating the impact of price

Table 2. Electricity price forecast – Monte Carlo simulation results

Year	Decreasing Price Trend (\$/MWh)	Increasing Price Trend (\$/MWh)
1	0.0418	0.0394
2	0.0406	0.0487
3	0.0355	0.0516
4	0.0318	0.0547
5	0.0264	0.0577
6	0.0223	0.0613
7	0.0202	0.0650
8	0.0175	0.0691
9	0.0174	0.0732
10	0.0180	0.0786
11	0.0179	0.0834
12	0.0160	0.0906
13	0.0133	0.0987
14	0.0117	0.1090
15	0.0107	0.1111
16	0.0094	0.1390
17	0.0094	0.1382
18	0.0090	0.1477
19	0.0085	0.1542
20	0.0075	0.1528
21	0.0069	0.1522
22	0.0064	0.1586
23	0.0060	0.1646
24	0.0054	0.1839
25	0.0049	0.2023

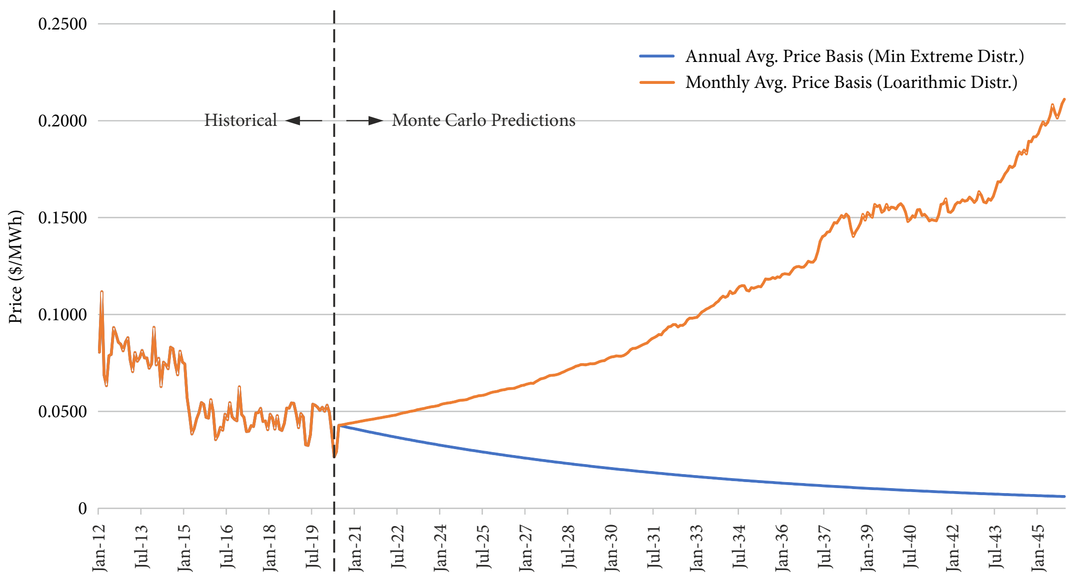

Figure 1. Electricity price: Monte Carlo simulations based on monthly and annual average prices

changes on the economic analysis. The wide spectrum provided by the two scenarios and the added sensitivity analysis provides a solid understanding of the impact of prices on the economic analysis. Nevertheless, a third scenario assuming electricity prices to remain constant (at $0.0428 per kWh) is also included in the analysis.

2.3. Results

The payback period, IRR and NPV values computed for the options obtained under the presented assumptions are shown in Table 3.

A techno-economic analysis is performed in this study for a solar farm with a 35 MWe installed capacity using bifacial double glass Mono-PERC solar panels and compared with standard monofacial Mono-PERC solar panels at the same installed capacity level. The bifacial solar panel usage gain from total panel efficiency is identified from 4-year measurements to be within a range of 7.9–16.8% depending on monthly yield. It is found that, in terms of NPV, the bifacial panels yield $6.9 million – $12.30 million additional NPV under different scenarios. The additional NPV of bifacial modules corresponds to an increase in NPV of around 11.6% which is $186.7 – $214.5 per unit MW under various electricity price trajectories.

In all scenarios, the NPV of option 3 is highest when compared with options 1 & 2 under the same assumptions, indicating the added value of the bifacial modules. In terms of NPV, the bifacial panels yield $83.2 million whereas $74.3–78.8 million is attained by monofacial systems under increasing electricity prices. Under decreasing prices, the bifacial panels yield $63.2 million whereas $56.7–59.9 million is attained by mono facial systems. When the electricity price is fixed, the bifacial panels yield $71.5 million whereas $63.9–67.8 million is attained by monofacial systems. It is observed from the NPV values that an additional investment expenditure of $3.5 million generates $6.5 million, $8. million and $7.5 million additional net profit under the decreasing, increasing and constant price scenarios respectively. It is observed that the additional NPV of bifacial modules corresponds to a 11.6% increase in NPV which is $214.5 per unit MW additional income in the constant price scenario.

The payback period does not change for the different price scenarios because the investment pays back in less than 3 years in all scenarios when the electricity produced is still sold under fixed prices determined by the Renewable Energy Support Scheme.

In terms of IRR, the values of the different options are not directly comparable. It should be noted that attempting to rank options similarly based on their IRR values would be a major mistake. Only incremental analysis is possible for project comparison of mutually exclusive investment alternatives based on rate of return methods. This is due to the assumption inherent in the IRR methodology where funds generated throughout the project are reinvested at the calculated rates of return rather than market rates. Therefore, the IRR values of mutually exclusive investment alternatives cannot be compared directly to identify the best option: an incremental rate of return analysis is needed. Incremental internal rate of return is the discount rate at which the present value of periodic differential cash flows of two projects equals the difference between the initial investments needed for each project. Hence, the incremental analysis starts with the least cost investment project and evaluates if the additional investment in a more expensive project is justified.

Table 3. Economic analysis results

a) Decreasing Price Trend

	Option 1	Option 2	Option 3
Simple Payback Period (years)	2.37	2.37	2.36
Discounted Payback Period (years)	2.42	2.39	2.40
IRR	40.80%	41.01%	41.11%
NPV	$56,661,023	$59,950,920	$63,196,750

(b) Increasing Price Trend

	Option 1	Option 2	Option 3
Simple Payback Period (years)	2.37	2.37	2.36
Discounted Payback Period (years)	2.42	2.39	2.40
IRR	40.97%	41.18%	41.28%
NPV	$74,260,537	$78,839,508	$83,186,634

(c) Constant Price

	Option 1	Option 2	Option 3
Simple Payback Period (years)	2.37	2.37	2.36
Discounted Payback Period (years)	2.42	2.39	2.40
IRR	40.88%	41.09%	41.19%
NPV	$63,963,289	$67,788,039	$71,475,006

Results of the incremental rate of return analysis for the three price scenarios are as follows:

a) Decreasing Price Trend Scenario (Table 3).

Table 3. Option 1 vs Option 2: incremental cash flow

Year	Cash Flow	Year	Cash Flow
0	(607,351)	13	170,915
1	234,004	14	150,978
2	230,328	15	122,762
3	226,862	16	101,426
4	223,589	17	90,301
5	220,493	18	76,372
6	701,910	19	75,349
7	696,997	20	77,735
8	692,118	21	76,708
9	687,273	22	67,074
10	682,462	23	53,767
11	205,922	24	45,836
12	198,316	25	40,827

The resulting *incremental rate of return is 47.11%*. Since the incremental rate of return is higher than the minimum attractive rate of return, the incremental investment into Option 2 is justified. Hence, we compare Option 3 to Option 2 (Table 4).

Table 4. Option 2 vs Option 3: incremental cash flow

Year	Cash Flow	Year	Cash Flow
0	(1,489,979)	13	145,682
1	690,069	14	141,984
2	715,379	15	131,302
3	740,827	16	122,652
4	766,371	17	119,369
5	791,975	18	112,925
6	205,935	19	115,652
7	236,185	20	121,217
8	266,097	21	123,932
9	295,676	22	118,376
10	324,923	23	108,258
11	145,528	24	102,511
12	151,213	25	99,211

The resulting *incremental rate of return is 43.00%*. In other words, the incremental investment on the bifacial panels brings an incremental return of 43% in addition to the Multibusbar Half-Cut 445 W Mono Perc panels.

b) Constant Price Trend Scenario (Table 5).

Table 5. Option 1 vs Option 2: incremental cash flow

Year	Cash Flow	Year	Cash Flow
0	(607,351)	13	208,150
1	234,004	14	206,692
2	230,328	15	205,246
3	226,862	16	203,809
4	223,589	17	202,382
5	220,493	18	200,966
6	701,910	19	199,559
7	696,997	20	198,162
8	692,118	21	196,775
9	687,273	22	195,397
10	682,462	23	194,030
11	211,094	24	192,671
12	209,617	25	191,323

The resulting *incremental rate of return is 47.21%*. Since the incremental rate of return is higher than the minimum attractive rate of return, the incremental investment into Option 2 is justified. Hence, we compare Option 3 to Option 2 (Table 6).

Table 6. Option 2 vs Option 3: incremental cash flow

Year	Cash Flow	Year	Cash Flow
0	(1,489,979)	13	165,524
1	690,069	14	174,231
2	715,379	15	182,838
3	740,827	16	191,347
4	766,371	17	199,760
5	791,975	18	208,075
6	205,935	19	216,296
7	236,185	20	224,421
8	266,097	21	232,453
9	295,676	22	240,391
10	324,923	23	248,237
11	147,812	24	255,992
12	156,718	25	263,656

The resulting *incremental rate of return is 43.06%*. In other words, the incremental investment on the bifacial panels brings an incremental return of 43.06% in addition to the Multibusbar Half-Cut 445 W Mono Perc panels.

c) Increasing Price Trend Scenario (Table 7).

Table 7. Option 1 vs Option 2: incremental cash flow

Year	Cash Flow	Year	Cash Flow
0	(607,351)	13	253,035
1	234,004	14	266,966
2	230,328	15	280,185
3	226,862	16	296,204
4	223,589	17	312,480
5	220,493	18	330,483
6	701,910	19	348,220
7	696,997	20	372,004
8	692,118	21	392,545
9	687,273	22	424,273
10	682,462	23	459,815
11	193,507	24	505,227
12	239,923	25	511,536

The resulting *incremental rate of return is 47.31%.* Since the incremental rate of return is higher than the minimum attractive rate of return, the incremental investment into Option 2 is justified. Hence we compare Option 3 to Option 2. (Table 8).

Table 8. Option 2 vs Option 3: incremental cash flow

Year	Cash Flow	Year	Cash Flow
0	(1,489,979)	13	189,444
1	690,069	14	209,116
2	715,379	15	229,661
3	740,827	16	253,340
4	766,371	17	278,727
5	791,975	18	306,987
6	205,935	19	336,750
7	236,185	20	373,401
8	266,097	21	409,398
9	295,676	22	458,014
10	324,923	23	513,486
11	140,046	24	582,695
12	171,483	25	613,549

The resulting *incremental rate of return is 43.13%.* In other words, the incremental investment on the bifacial panels brings an incremental return of 43.13% in addition to the Multibusbar Half-Cut 445 W Mono Perc panels.

As can be seen from the results of the IRR analysis, the additional investment of the bifacial panel yields significant additional income throughout the project lifetime in all of the price scenarios such that the incremental rate of return is at least 43%.

3. Sensitivity analysis

A sensitivity analysis is carried out under different assumptions for the discount rate, electricity prices, and economic lifetime. The following ranges were used:

Discount Rate	: Base 5%; Sensitivity 3% and 7%
Electricity Prices	: Base Monte Carlo (MC); Sensitivity MC–2% and MC+2%
Economic Life	: Base 25 year; Sensitivity 30 years and 35 years

The sensitivity analysis is performed for the increasing price scenario only as findings will be the same for the constant and decreasing price scenarios. Results of the sensitivity analysis are summarized in Tables 4–6 where extraordinarily high and low values are color-coded with NPV < \$70,000 highlighted in red and NPV > \$100,000 highlighted in green. The color-coding is done for ease of visual analysis to have a better understanding at first glance. The values \$70k and \$100k have no special meaning attached, are chosen at the occurrence of larger gaps to highlight the difference between the scenarios (Tables 9–11).

It can be seen from the above tables that results are highly sensitive to the discount rate and lifetime, and less sensitive to prices. At the same discount rate and lifetime, bifacial panels yield NPVs that are around 10% higher than others, which is even true when the electricity produced from bifacial panels are sold at the lower price level (MC–2%) and others are sold at the higher one (MC+2%). From all the analyzed cases, the possibility of a relatively high NPV (>\$100,000) is 6/27 for monofacial option 1 and 10/27 for monofacial option 2 whereas it is 12/27 for bifacial ones. The possibility of a relatively low NPV (<\$70,000) is 7/27 and 5/27 for monofacial options 1 and 2 respectively, whereas it is 3/27 for bifacial ones.

Table 9. Sensitivity analysis results for Option 1: NPV (\$)

	3% discount rate			5% discount rate			7% discount rate		
Electricity Prices	25 yrs	30 yrs	35 yrs	25 yrs	30 yrs	35 yrs	25 yrs	30 yrs	35 yrs
MC–2%	93,234,559	111,248,356	128,982,323	73,702,935	84,022,056	93,233,876	59,154,949	65,132,961	69,981,047
MC	94,044,399	112,447,174	130,561,312	74,260,537	84,802,494	94,211,818	59,544,183	65,651,294	70,603,338
MC+2%	94,854,240	113,645,991	132,140,302	74,818,139	85,582,932	95,189,759	59,933,418	66,169,627	71,225,629

Note: Green: NPV > \$100,000; Red: NPV < \$70,000.

Table 10. Sensitivity analysis results for Option 2: NPV ($)

	3% discount rate			5% discount rate			7% discount rate		
Electricity Prices	25 yrs	30 yrs	35 yrs	25 yrs	30 yrs	35 yrs	25 yrs	30 yrs	35 yrs
MC–2%	99,132,707	118,523,117	137,605,342	78,241,065	89,348,802	99,261,036	62,706,121	69,141,007	74,357,749
MC	100,001,865	119,809,742	139,299,984	78,839,508	90,186,403	100,310,607	63,123,865	69,697,306	75,025,620
MC+2%	100,871,022	121,096,367	140,994,627	79,437,952	91,024,004	101,360,178	63,541,609	70,253,605	75,693,491

Note: Green: NPV > $100,000; Red: NPV < $70,000.

Table 11. Sensitivity analysis results for Option 3: NPV ($)

	3% discount rate			5% discount rate			7% discount rate		
Electricity Prices	25 yrs	30 yrs	35 yrs	25 yrs	30 yrs	35 yrs	25 yrs	30 yrs	35 yrs
MC–2%	104,697,357	125,904,345	147,083,365	82,556,516	94,703,524	105,703,830	66,121,522	73,157,706	78,946,522
MC	105,613,502	127,273,153	148,901,427	83,186,634	95,592,932	106,826,603	66,560,910	73,747,296	79,658,932
MC+2%	106,529,647	128,641,961	150,719,490	83,816,752	96,482,339	107,949,377	67,000,298	74,336,885	80,371,341

Note: Green: NPV > $100,000; Red: NPV < $70,000.

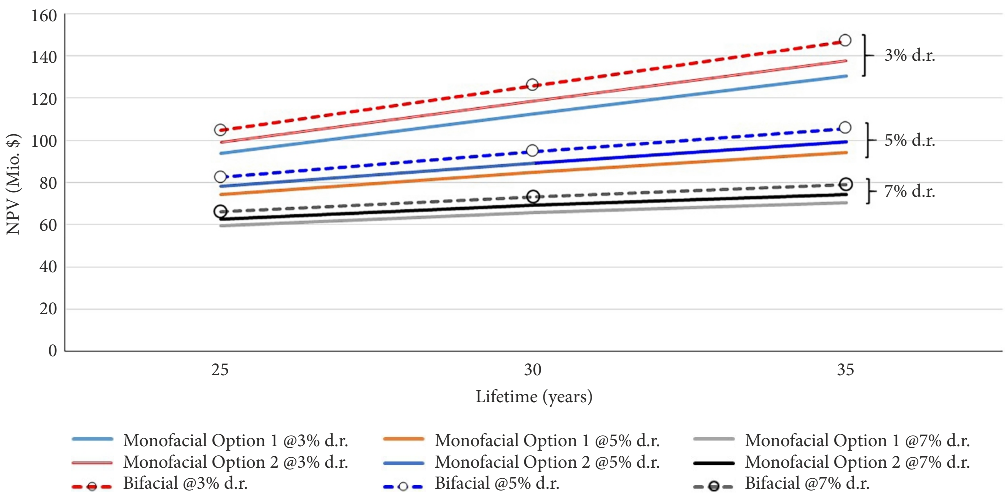

Figure 2. Sensitivity of NPV on lifetime and discount rate

Having identified the sensitivity to discount rate and lifetime, the sensitivity graph in Figure 2. is constructed focusing on the most sensitive two factors. The impact of bifacial panels, compared to monofacial ones at a given discount rate and lifetime assumptions is evident. It can be observed that the bifacial panel makes the difference. It is further observed that sensitivity increases further as the discount rate lowers, which can be identified from the steeper slope at lower discount rates.

4. Technical properties and SWOT analysis for bifacial solar PV

Recent Solar industry developments indicate that bifacial technology is one of the more advanced ways to further improve the energy production efficiency and further lower the cost of energy production. Unlike photovoltaic (PV) systems using conventional monofacial modules, bifacial modules allow radiation to enter both from the front and back sides of a solar panel. By converting both direct and reflected sun light into electricity, bifacial PV systems can generate up to 30% more electricity compared to a similar size monofacial system, depending on the location of the system as well as how it is installed (angle, elevation, tracker system applications etc.).

The rear side efficiency of the bifacial cell, which is the main component of higher production efficiency, can vary significantly by the effects of differences in solar cell technologies. p-PERC and n-PERT cell technologies are the two most prominent technology concepts.

p-PERC technology: Only minor changes in manufacturing processes are required to achieve a bifacial p-PERC solar cell. However, a thin aluminum (Al) grid must be pressed against the back of the cell to ensure impurity capture where Al is in contact with the p-type Silicon (Si) wafer. These Al “fingers” cause some shades to evolve behind the solar cell and limit the bifacial production coefficient 70–80% for p-PERC based solar cells.

n-PERT technology N-type wafers have some conceptual advantages over p-type wafers, such as a longer lifespan of the carrier and the absence of boron in the material of the bulk wafer that prevents degradation caused by radiation. This is why solar cells of n-type usually achieve greater conversion efficiencies than of p-type. On the rear side of the solar cell, which by default bifacializes all n-type solar cells, no Al is needed. However, n-type solar cells are sold at a premium price because n-type wafers are more costly, and the cell production processes are less widely applied. The bifacial production coefficient is around 90% for most n-type solar cells, which is 10 to 20% higher than p-PERC type cells.

4.1. Design options for bifacial PV modules

The majority of bifacial modules are designed with a double-glass configuration. As the double-glass lamination itself is very robust mechanically, double-glass modules do not need to be fitted with a supporting aluminum frame. Removing the frame may be a cost benefit for the manufacturer over the conventional module design with a frame, but extra caution is needed when packing, storing, racking and installing the module to prevent damage and cracking of the glass edges. On the front side, tempered safety glass is usually applied to prevent minimize the effects of mechanical collisions, but usually the edges are prone to disastrous glass fractures. This is why some manufacturers of bifacial modules have followed the more traditional design approach with a single front glass and a (transparent) backsheet al.ng with an aluminum frame.

The manufacturing process of bifacial PV modules is identical to of traditional mono-facial modules. However, when sourcing bifacial PV modules, there are a number of particular production quality risks that should be considered:

- The cell's bifacial coefficient depends on the consistency and quality of the method of producing cells. Therefore, an independent audit of the cell production process is generally needed.
- Bifacial modules are double glass modules, in most situations. Compared to traditional single glass module manufacturing, production of double-glass modules involves certain changes, including extra care in the lamination processes. For long-term durability, lamination is a critical operation. To ensure that it is adequately equipped to handle double glass components, the production line should be tested.
- Under standard test conditions, special care must be taken to assess the front-side strength (STC). During front side power testing, any light approaching or flowing through from the rear side of the module can lead to an extra current and over-estimated power. The production line's flash testing section needs careful attention to precisely how the module's front and rear-side power is measured and balanced.
- Packaging is a more sensitive factor for frameless modules than for standard framed modules. It is important to check and test the packaging method according to appropriate transportation standards.

Either monocrystalline or polycrystalline wafers may be used to manufacture Bifacial modules. Each solar cell is comprised of a single silicon crystal in a monocrystalline bifacial panel. These panels are more efficient than polycrystalline bifacial panels, which are made of silicon fragments that have been melted together, by giving more space for movement to the electrons that produce electricity flow. On polycrystalline sheets, however, manufacturing costs are usually lower than their monocrystalline counterparts.

Bifacial modules, like all solar panels, receive a power rating that reflects their projected capacity under optimal sunlight/radiation and temperature conditions, usually 250 to 400 watts. Since this power rating only takes into consideration the front side of the solar panel, a second rating is often applied to bifacial panels for the electrical output of the rear side of the cell. Known as bifaciality, this ratio contrasts, as determined under standard test conditions (STC), the power generated by the rear side of the module to the power generated by the front:

$$B = Pmpp, rear/Pmpp, front.$$

While a bifacial ratio has meaning, it is not inherently a reasonable predictor of the field efficiency of a bifacial PV system, which relies heavily on everything from its geographic position to the time of day or year. Bifacial arrays may be mounted above light-colored surfaces that reflect as much sunlight as possible to maximize bifacial energy production. In ways to gather more reflective light and discourage shading in the rear sides, they may even be elevated and angled. Through moving solar panels to match the sun during the day, solar monitoring systems will also help optimize energy generation, maximizing the angle at which panels absorb solar radiation. In addition, the standard tracking systems can be modified by tracker manufacturers to accommodate for bifacial units, such as minimizing backtracking or changing mid-day locations. According to SolarPro, studies performed by PV module manufacturers have shown energy yield improvements of up to 11 percent for fixed tilt systems and 27 percent for with tracker systems, relative to conventional modules rated similarly.

Compared to regular monofacial systems, more variables influence the production of energy for bifacial PV systems. While it sounds straightforward – considering the light falling on the rear side of the module, the actual measurements are much more complicated in practice. The following are the most important parameters which decide the actual energy production gain from the rear side of the module:

- Bifacial Coefficient: The additional gain is strictly proportional to the bifacial coefficient.
- Ground Reflectivity.
- Height of the module above ground: Experiments show that additional gain is strictly proportional to installation height as well as albedo.
- Module row spacing: As the gap between modules (spacing) increases, more light can reach the back of the module.

4.2. Bifacial module construction options

There are two primary ways to building bifacial cells.

1. Encapsulate the cells on both sides in a solar glass sheet. On the front, most use glass and on the back a translucent polymer-backsheet material.
2. More manufacturers today are opting for the dual glass solution, which is a more robust structure.

Dual-glass solutions are more stable and less water-permeable, which helps to secure and protect from wind, rain, snow and other environmental factors during handling and installation. Historically, such panels have survived longer and had lower failure rates. Therefore, many vendors offer longer warranties on dual-glass modules. According to Solar Power World, this durability results in a lower annual degradation rate (0.4–0.5% per year for dual glass vs ~0.7% per year for polymer back sheets).

A PV module's degradation rate, also known as quantification of power decay over time, is critical to all stakeholders, companies, investors, and integrators. These rates are important economically because higher degradation rates implies that the system is producing less output power which eventually reduces future cash inflow. Generally accepted degradation test results yield that double glass bifacial solar panels' yearly degradation rate is ~0.4% while mono facial solar panels' test results are around ~0.7%.

4.3. SWOT matrix

SWOT analysis was performed to compare the bifacial panels with the monofacial panel and to evaluate the two panels according to internal and external factors. While making the analysis in Table 12, the comments, literature research and analyzes in the previous sections were used.

Table 12. SWOT analysis of bifacial solar panels vs monofacial

STRENGTHS	WEAKNESSES
• High efficiency electricity generation • Bifacial panel does not weigh more than standard monofacial panels • Electricity generation amount higher than monofacial Mono-PERC for equal front side DC load • High resistance levels in compliance with IEC standards • Long lifetime • Low maintenance cost due to glass-glass frameless design • Class A burning brand and Class A spread of flame extremely strong durability against fire • Provides an insulation sheet against electrical fires • High durability (low ageing) results under IEC 61215 TC1200, HF60, DH6000 extended tests • Lower LCOE compared to monofacial standard panels under all conditions • Excellent electricity production boost when used with trackers • Generates equal electricity on fixed mount as monofacial standard panels on trackers • Minimum 6% gain on white rooftop installations • Low carbon footprint	• Initial cumulative investment costs greater than monofacial standard panels for same front side DC • Higher price per watt based on only front power • Lesser front side DC load meaning less total markup for EPC's in bifacial solar plants • Requires skilled EPC installation crews to comply with higher quality requirements of handling glass-glass modules • New technology with relatively rare execution, unknown with a low profile, low customer support and recognition
OPPORTUNITIES	**THREATS**
• More electricity production on same square area of Panels/Roofs/Fields • 60 cell Panels including mounting apparatus on a rooftop weigh less than standard panels • Lower LCOE may be even lower with R&D induced gains in technology • Big opportunity in BIPV markets as glass thicknesses and sizes can be adjusted in production for custom tailoring • Solar may develop into a long-term investment strategy like all other energy investments requiring longer lifetimes for solar panels • Equal investment cost per electricity produced 1st year in solar plants where the plants are designed to have less DC load than standard plants resulting in equal electricity output- all succeeding years LCOE cost per electricity produced becomes lower as bifacial panels age slower comparatively producing more electricity across time	• Loss of price incentives for future investments • Removal of barriers for imported state subsidized far eastern solar panels • Non-analytical Investors & Consumers who feel comfortable copying and following the status quo • Market Misinformation • Complacent Solar Consultants • Believers of Fate • Lack of education regarding international guarantees • Trade advantages within Turkey given to Free Trade Zone international producers by the Turkish government • Government disregard and lack of a comprehensive support program for Turkish made technology and innovation in local industrial production

In strength aspect, according to several studies conducted by Tillman, Rodríguez-Gallegos, and Shoukry, modules were tested at different locations with different climates, and it was proved that bifacial module has lower LCOE compared to monofacial standard panels under all conditions. Shoukry also proved that a fixed bifacial module has a higher yield than a tracked monofacial module. Bifacial modules not only provide long lifetime and low carbon footprint, but also an insulation sheet against electrical fires. Having high durability under several tests and high resistance levels in compliance with IEC standards are also ones of the critical strengths of bifacial modules.

The most obvious weakness of bifacial modules is that initial cumulative investment costs greater than monofacial standard panels for same front side DC. It also requires skilled EPC installation crews to comply with higher quality requirements of handling glass-glass modules, causing higher operational expenditures. In addition to that, adaptation of bifacial modules might sometimes challenge for customers since lack of awareness of the system, low customer recognition, and rare execution compared to traditional ones are always issue for new technologies.

As internal factors play important role on comparing these modules, external factors also essential indicators for the appliance of each aspect of the business. In energy market, sustainable systems have gained importance more than ever all over the world, showing that solar may develop into a long-term investment strategy like all other energy investments requiring longer lifetimes for solar panels. It is also proven that lower LCOE lower with R&D induced gains in technology and long lifetime may make investor see BIPV markets big opportunity to invest in.

In threat aspect, lack of governmental support programs in Turkey for technology and innovation in local industrial production is the one of the main challenges for bifacial modules. Moreover, market misinformation, complacent solar consultants, and removal of barriers for imported state subsidized far eastern solar panels can be counted as notable threats for the business.

Conclusions

The World Energy Outlook's (International Energy Agency [IEA], 2020) Stated Policies Scenario, which reflects all of today's announced policy intentions and targets, estimates that renewables meet 80% of the growth in global electricity demand to 2030 with solar being the main driver of growth setting new records for deployment each year after 2022. It is because of technological advancement that solar becomes the new king of electricity, which highlights the need for techno-economic reviews in solar power generation.

A techno-economic analysis is performed in this study for a solar farm with a 35 MW installed capacity using bifacial double glass Mono-PERC solar panels and compared with standard monofacial Mono-PERC solar panels at the same installed capacity level. The bifacial solar panel usage gain from total panel efficiency is identified from 4-year measurements to be within a range of 7.9–16.8% depending on monthly yield. It is found that, in terms of NPV, the bifacial panels yield $6.9 million – $12.30 million additional NPV under different scenarios although the initial investment costs are substantially higher in the Bifacial options. The additional NPV of bifacial modules corresponds to a 12.2% increase in NPV which is $223,020 per unit MW under various electricity price trajectories.

The uncertainty in electricity prices that prevail in the competitive market for the next 25 years is captured via various scenarios within a Monte Carlo simulation. An incremental IRR is performed yielding an IRR for the bifacial panels of at least 44% under various scenarios. The sensitivity analysis reveals that results are highly sensitive to discount rate and lifetime, and less sensitive to prices. A summary of technical properties based on test results and a SWOT analysis finalize the study. According to the SWOT analysis of the bifacial panel, the panel's greatest strength is that it has a lower LCOE compared to standard monofacial panels. However, the initial cumulative investment cost is a weakness of the panel. Although the lack of government support programs delays the scalability of production in the current market, ultimately in line with the long-term investment strategy, customers will prefer bifacial panels due to longer lifespan.

In summary, it can be concluded that bifacial solar PV, with its superior techno-economic results, may become the driving force of the rapidly growing solar PV market.

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Author contributions

Gürkan S. Kumbaroğlu, Dr. Emre Çamlıbel and Cem Avcı conceived the study and was responsible for the design and development of the data analysis. Gürkan S. Kumbaroğlu, and Cem Avcı were responsible for data collection and analysis. Dr. Emre Çamlıbel and Gürkan S. Kumbaroğlu were responsible for data interpretation.

Disclosure statement

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References

International Energy Agency. (2020). *World energy outlook*.

Kılci, O., & Koklu, M. (2020). Bifacial and monofacial photovoltaic module with tracker system analysis. *Journal of Amasya University the Institute of Sciences and Technology*, *1*(2), 101–105.

Libal, J., & Kopecek, R. (2019). *Bifacial photovoltaics: Technology, applications and economics*. The Institution of Engineering and Technology. https://doi.org/10.1049/PBPO107E

Moehlecke, A., Febras, F. S., & Zanesco, I. (2013). Electrical performance analysis of PV modules with bifacial silicon solar cells and white diffuse reflector. *Solar Energy*, *96*, 253–262 https://doi.org/10.1016/j.solener.2013.07.028.

Nussbaumer, H., Janssen, G., Berrian, D., Wittmer, B., Klenk, M., Baumann, T., Baumgartner, F., Morf, M., Burgers, A., Libal, J., & Mermoud, A. (2020). Accuracy of simulated data for bifacial systems with varying tilt angles and share of diffuse radiation. *Solar Energy*, *197*, 6–21. https://doi.org/10.1016/j.solener.2019.12.071

Park, H., Chang, S., Park, S., & Kim, W. K. (2019). Outdoor performance test of bifacial n-type silicon photovoltaic modules. *Sustainability*, *11*, 6234. https://doi.org/10.3390/su11226234

Raina, G., & Sinha, S. (2020). A simulation study to evaluate and compare monofacial vs bifacial PERC PV Cells and the effect of albedo on bifacial performance. In *Materials today*: Proceedings (Vol. 46, Part 11, pp. 5242–5247). Elsevier. https://doi.org/10.1016/j.matpr.2020.08.632

Rodríguez-Gallegos, C. D., Liu, H., Gandhi, O., Singh, J. P., Krishnamurthy, V., Kumar, A., Stein, J. S., Wang, S., Li, L., Reindl, T., & Peters, I. M. (2020). Global techno-economic performance of bifacial and tracking photovoltaic systems. *Joule*, *4*(7), 1514–1541. https://doi.org/10.1016/j.joule.2020.05.005

Shoukry, I., Libal, J., Kopecek, R., Wefringhaus, E., & Werner, J. (2016). Modelling of bifacial gain for stand-alone and in-field installed bifacial PV modules. *Energy Procedia*, *92*, 600–608. https://doi.org/10.1016/j.egypro.2016.07.025

Tillmann, P., Jäger, K., & Becker, C. (2020). Minimizing the levelized cost of electricity for bifacial solar panel arrays using Bayesian optimization. *Sustainable Energy and Fuels*, *4*, 254–264. https://doi.org/10.1039/C9SE00750D

VDMA. (2020). *International Technology Roadmap for Photovoltaic* (11th ed.).