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PERSPECTIVE

PROGRESS IN PHOTOVOLTAICS WILEY

What is going on with Middle Eastern solar prices, and what does it mean for the rest of us?

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Abstract

For the third time in a decade, solar energy pricing records are tumbling in the Persian Gulf. As each previous wave of new records was met with incredulity, only for these prices to become the new normal around the world within a few years, it would be unwise to once again dismiss low prices as unrepresentative outliers. In this study, we show how local conditions and global macroeconomic factors have conspired to bring solar energy into a new regime of extreme affordability in the region and argue that the Gulf market, especially the United Arab Emirates and Saudi Arabia, represents the leading edge of the global learning curve and therefore offers a window into the likely near future of large-scale photovoltaics around the world. As this future increasingly appears to be one of previously unimaginably cheap energy, we conclude with a discussion of the ways in which the region and the world can seek to meet the opportunities and challenges of the coming renewable revolution.

KEYWORDS

energy transition, Middle East, solar energy economics, utility-scale photovoltaics

1 | INTRODUCTION

Over the last several years, the oil-rich Persian Gulf region has emerged as a global leader in photovoltaic deployment and pricing. Large utility-scale projects totaling over 7 GW of capacity have been ordered since 2015 in Saudi Arabia,[1] Qatar,[2] Oman,[3] and the United Arab Emirates,[4,5] mostly under long-term power purchase agreements (PPAs) that have consistently broken global pricing records.[6] The region has proven to be a bellwether for global solar trends, with pricing records set in the Gulf being replicated around the world in subsequent years.[7] Hence, it is of global interest to understand the factors leading to solar pricing records in the region, as guidance in developing pro-solar policies elsewhere or simply as a window into possible future trajectories of the global market.

In a previous work,[8] we investigated the factors that allowed record-low prices under 3 ¢/kWh—widely seen as the "tipping point" for solar to be economically favored over coal or gas plants for new generating capacity[9]—to be realized for two GW-scale photovoltaic projects in the UAE, announced in 2016–2017.[4,10] That work was undertaken in response to widespread skepticism regarding the viability of the announced prices and a common suspicion that they were achieved only with large hidden subsidies that could not be replicated globally. Our analysis contradicted that belief, demonstrating that rapidly declining hardware prices, local standard business conditions, and access to generous financing packages on favorable but realistic terms were the major factors contributing to the observed low prices. In the intervening years, the market has validated our assessment as global average prices for utility-scale solar capital expenditures (CapEx) and generation costs in comparable climates have declined to the levels observed in the Gulf at the time of our initial study.[11]

It is therefore of some interest to see the Gulf region (henceforth denoted by the local moniker "GCC," referring to the Gulf Cooperation Council of Kuwait, Bahrain, Qatar, Oman, the Kingdom of Saudi Arabia, and the United Arab Emirates) entering a new pricing regime once again with a new round of mega-projects in several countries. PPAs are now routinely awarded for prices well below 2 ¢/kWh,[12] including most recently the 2-GW Al Dhafra solar project in Abu Dhabi with an awarded PPA price of 1.35 ¢/kWh.[13,14] This pricing represents the crossing of a second and perhaps more consequential tipping point, where solar energy becomes economically favored relative to *existing* fossil fuel capacity.[15,16] That this second barrier is crossed at a time when renewables have only recently been shown to be economically superior to maintaining fossil-fuel capacity with carbon capture[17] demonstrates the speed at which the economics are evolving. If pricing at this level spreads around the world, simple business sense would suggest a rapid decarbonization of electricity generation, where coal and gas plants are retired as quickly as possible and replaced with photovoltaics simply to save money. The target of deep decarbonization by 2030 being held up by many climate scientists and advocates[18] would suddenly enter the realm of feasibility with far less disruptive interventions that were previously believed necessary.

With this in mind, we now undertake an update of our previous study accounting for this new wave of projects to gain a deeper understanding of the factors driving prices in the Gulf and what this may mean for the global market. Reported CapEx, PPA prices, and financing information will be summarized in the context of global market trends, along with a consideration of the different stakeholders in the projects, including developers, utilities, contractors, and financing entities, and how their interests influence the economic decision-making involved in developing them. Consideration of global learning curves for different cost metrics provide a framework for understanding how local trends are likely to manifest themselves in the global market. Synthesizing these different streams of information, we will attempt to peer into the near future of the local and global solar industry and begin to evaluate some of the likely impacts of the coming revolution in the energy sector.

2 | UTILITY-SCALE SOLAR IN THE GULF: RAPID GROWTH AND FALLING PRICES

At the time of our original study on solar energy costs in the GCC region, the largest active utility-scale solar plant was the 200-MW project forming phase 2 of Dubai's Mohammed bin Rashid Al Maktoum solar park (henceforth MBR2). It was the Gulf's first utility-scale photovoltaic plant and the second solar plant using any technology, after Abu Dhabi's 100-MW Shams 1 CSP-gas hybrid plant.[19] The plant sells electricity to the Dubai Electricity and Water Authority (DEWA), the public utility company of Dubai, at 5.84 ¢/kWh, a record at the time it was announced in 2014, under a 25-year PPA. DEWA also holds a 51% ownership stake in the plant, with the remaining ownership shares held by the project developers, Saudi Arabia's ACWA Power, and Spanish contractor TSK Solar, a common feature of the regional solar industry where ownership is often shared between the developer as an independent power producer (IPP) and the utility. The pricing record that inspired the previous analysis was set almost simultaneously by the PPAs signed for the 800-MW phase 3 of the MBR solar park (MBR3) and the 1.17-GW Noor Abu Dhabi project near Sweihan in the Emirate of Abu Dhabi, with PPA prices of 2.99 and 2.94 ¢/kWh, respectively.[20] The Dubai project was developed by a consortium of two state-owned project developers, Abu Dhabi's Masdar and France's EDF,[21] whereas the Abu Dhabi project went to an Asian consortium led by Japanese conglomerate Marubeni and Chinese PV manufacturer JinkoSolar.[22] Both projects received generous financing packages from consortia of local and international banks. A fourth project, Saudi Arabia's inaugural solar plant in Sakaka (300 MW), had received a bid from Masdar for 1.79 ¢/kWh,[23] assumed to be based on bifacial module technology and some extremely aggressive assumptions,[24] but was eventually awarded to ACWA at 2.34 ¢/kWh.[25] We found that the majority of the price reduction relative to the UAE projects could be attributed to the superior solar resource in Sakaka compared with the UAE sites. MBR3 was brought online in stages, with the first 200 MW beginning operation in 2018, and the remainder inaugurated in 2020.[26] Noor Abu Dhabi became operational in June 2019 and the Sakaka plant in November of the same year.[27,28]

The intervening time has seen a continuation of rapid capacity expansions and falling prices, illustrated in Figure 1. Phase 4 of the MBR park, currently under construction, features a 700-MW concentrated solar thermal power plant with thermal energy storage (CSP + TES) providing overnight electricity at 7.3 ¢/kWh, alongside a 250-PV component selling at 2.4 ¢/kWh.[29] A PPA for the 500-MW Ibri-II project in Oman was signed in 2020. Dubai signed a PPA for the 900-MW phase 5 of the MBR project (MBR5), using bifacial PV technology at 1.69 ¢/kWh, whereas Qatar saw a PPA price of 1.57 ¢/kWh for its 800-MW first foray into utility-scale PV, and Saudi Arabia has issued a new round of tenders for which a number of bids in the 1.6–1.7 ¢/kWh range have been received.[30] We note that capacities in the region are typically reported in MWac, although in the case of Qatar's 800-MW Al-Kharsaah project this is not stated explicitly. Some reports from suppliers[31] indicate that the reported capacity may in fact be DC; however, our cost modeling indicates that the reported PPA price is more plausible if the reported capacity is AC, in keeping with the regional standard. Therefore, all capacities given in this study are assumed to be in AC unless stated otherwise. Although less active than their GCC neighbors, Bahrain has ordered a 125-MW PV project on the Al Askar landfill site,[32] and Kuwait has received bids for a 1.5-GW plant.[33] Bids in both countries remain above 3 ¢/kWh, perhaps owing to a comparative lack of investment in solar relative to their neighbors. After some initial difficulties, Kuwait, at least, seems to be aiming for a reset, withdrawing its original tender for the Dibdabah plant,[34] which was reported to be an engineering, procurement, and construction (EPC) contract for a utility-owned plant, and now stating its intention to reissue the tender under the IPP model that has proven successful for its neighbors.[35] Financing has been a crucial component of realizing large projects at low PPA prices, with financing packages characterized by high debt loads and low interest rates typically being provided by consortia dominated by local banks and institutions from the developers' home countries, although other regional and global players have increasingly entered the regional

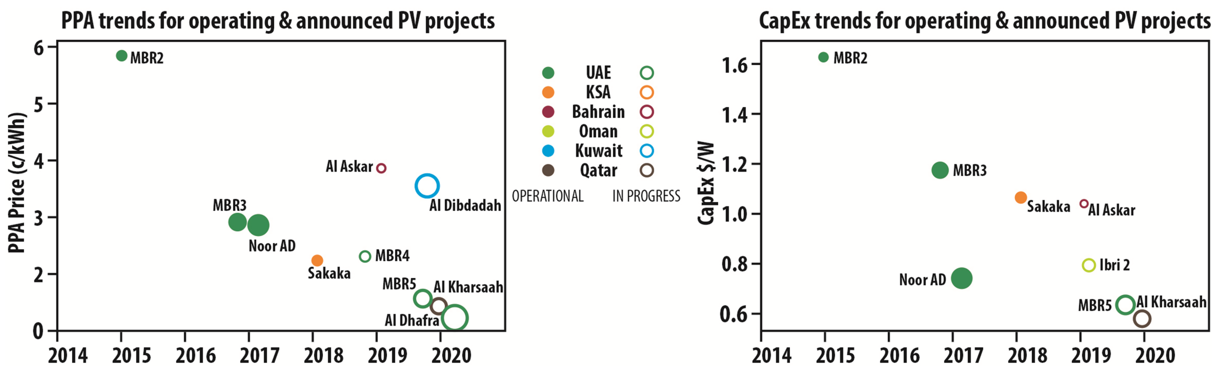

FIGURE 1 Evolution of reported PPA prices (left) and project CapEx (right) for operating and announced/under construction utility PV projects in the GCC region [Colour figure can be viewed at wileyonlinelibrary.com]

market. Chinese banks in particular have become a major source of financing in recent years,[36,37] with GCC solar projects being hailed as success stories is the country's ambitious "Belt and Road" global investment initiative.[38] Japanese banks have played a prominent role in financing Qatar's solar development.[39] The spate of new large-scale projects seems poised to propel the region to global prominence in solar energy, with the UAE seeing particular success. Between Abu Dhabi and Dubai, currently operation or awarded utility-scale PV projects total 5.3 GW (with an additional 800 MW of CSP between Abu Dhabi's Shams 1 and Dubai's MBR4). This exceeds the current installed solar capacity of much larger energy consumers such as Vietnam and Taiwan, and when adjusting for overall energy consumption far exceeds the solar penetration in major economies including China, India, and the United States.[40]

3 | MODELING GENERATION COSTS IN THE GULF—WHERE ARE ULTRA-LOW PRICES COMING FROM?

Key cost metrics including CapEx and PPA price are made public for most projects in the region. These values are tabulated for all utility-connected projects over 100 MW in Table 1, along with additional information on the projects' technical specifications, financing information, and the various stakeholders. Analysis of the factors contributing to generation costs can be done by evaluating the levelized cost of electricity (LCOE) as

$$\mathrm{LCOE} = \frac{C + \sum_{i=0}^{L} \frac{O_i}{(1+r)^i}}{\sum_{i=0}^{L} \frac{E_i}{(1+r)^i}}, \quad (1)$$

where C is CapEx, O_i is operating expenses (OpEx) in year i, E_i is energy generation in year i, L is the plant lifetime in years (or the PPA duration if no residual value is assumed), and r is the discount rate. This r can be taken as the internal rate of return (IRR) of the project at a given price point or as the weighted average cost of capital (WACC) if the financing terms are known and the LCOE represents the minimum sustainable price of electricity.

To understand what has changed over the last few years, we compare the calculated LCOE for MBR3 and MBR5 using cost figures publicized for the two projects and assuming the same plant configuration, but with bifacial modules used in MBR5 as has been reported.[12] Overall CapEx has been announced for both projects in press releases dealing with the financing of the project, totaling \$1175/kW for MBR3 (800 MW at \$940 M)[50] with a dramatic drop to \$633/kW for MBR5 (900 MW at \$570 M).[52] Energy generation claimed by the utility for MBR3 indicates a capacity factor just over 35%,[5] which is consistent with a tracking c-Si array with a DC/AC ratio (or inverter loading ratio ILR) of ∼1.3 under the weather conditions of the MBR solar park site, according to the PV performance model of PVGIS,[51] which we combine with the industry-standard assumption of 0.5% annual reduction in plant output due to module degradation to estimate annual energy yield. This assumption regarding ILR is borne out by the one finished project for which both AC and DC capacity have been publicly reported: Saudi Arabia's 300 MWac/405 MWdc Sakaka project[53] giving ILR = 1.35. The calculations in this study assume IRL = 1.3 except where sufficient data have been publicized to estimate or directly calculate the ILR. The only project that can be shown to deviate significantly from this assumption at this point is Oman's Ibri 2, with a reported ILR of 1.15 (500 MWac/575 MWdc).[54,55] As this project uses a technical configuration that is now becoming standard (tracker-mounted bifacial modules), it will be interesting to see whether ILRs also trend lower in newer projects in the region. OpEx is assumed to average \$10/kW/year based on O&M contracts for smaller projects in the UAE[56] and the global trend toward lower O&M costs for large-scale PV plants.[57] The discount rate (taken as the WACC) is set to the value that yields an LCOE equal to the PPA price of 2.99 ¢/kWh for MBR3, which given our assumptions is 4.25%. Although still somewhat low by global standards, our previous study on PV financing in the region has given some indications of how WACC at this level could be achieved given the economic conditions in the region and the interests of the stakeholders involved.[58] It is also worth noting that, although the current spate of development has taken place during a decade of already-low interest rates, borrowing costs tumbled again in 2020 as central banks seek to prop up investment during the coronavirus pandemic and the associated economic downturn. Some reports from the

TABLE 1 Data on operation, under-construction, and planned utility PV projects in gulf cooperation council (GCC) countries (UAE, Kingdom of Saudi Arabia, Qatar, Bahrain, Kuwait & Oman)

		MBR2[1]	MBR3[5]	Noor AD[22]	Sakaka[41]	MBR4 (PV)[37]	Askar[42]	Al Kharsaah[2,39]	Ibri II[36]	MBR5[12,43]	Al Dhafra[13,14]	Al Dibdibah (BID)[33]	REPDO 2 (multiple projects)[30]
Country		UAE	UAE	UAE	KSA	UAE	Bahrain	Qatar	Oman	UAE	UAE	Kuwait	KSA
Capacity (MWac)		200	800	1177	300	250	125	800	500	900	2000	1500	1500
PPA	Price ($/kWh)	5.84	2.99	2.94	2.34	2.4[5]	3.91	1.57[44]	?	1.69	1.35	3.60 (lowest bid)	1.61 (lowest bid)
	Length (years)	25	25	25	25	35	20	25	15	25?	25?	N/A	N/A
Cost (MUSD)		325[5]	940	872[a]	320	?	130	467[45]	400	564	Pending	1400[34]	
	Awarded/ PPA	01/2015	06/2017	03/2017	02/2018[25]	11/2018	02/2019	01/2020	03/2019	11/2019	07/2020	11/2019 (bid)	04/2020 (bid)
	Fin. close	07/2015[46]	06/2017[47]	05/2017	11/2018	03/2019	?	2020	03/2020	09/2020	2020	CANCELLED[a]	
	Operational	03/2017[5]	05/2018 (200 MW) 2020 (500 MW)	06/2019[27]	11/2019	2020–2021	?	2021–2022	06/2021[3]	2021 (stage 1)	2022		
Developers	Dev 1	ACWA (KSA)	Masdar (UAE)	Marubeni	ACWA	ACWA	ACWA	Total (FR) Marubeni (JP)	ACWA	ACWA	Masdar/ TAQA (UAE)	CN. Metal. Corp.	
	Share (%)	42	24	20	70	24.99%	60	20/20	50	20	60		
	Dev 2	TSK (SP)	EDF (FR)	JinkoSolar (CN)	AlGihaz (KSA)	Silk Road Fund (CN)	Mitsui (JP) Almoyyad (BH)	Qatar Petr./ QEWC	GIC (KW) APEC (KW)	GIC	EDF/Jinko		
	Share (%)	7	16	20	30	24.01%	30/10	24/36	40/10	20	40		
Offtaker		DEWA	DEWA	ADWEA (EWEC)	SPPC	DEWA	EWA Bahrain	QEWC (Kahramaa)	OPWP	DEWA	EWEC		
Share (%)		51	60	60	0	51	0	0	0	60	0		
EPC		TSK	GranSolar (SP) Acciona (SP) Ghella (IT)	Sterling & Wilson[48]	Mahindra Susten (IN) CHINT (CN)	Shanghai Electric	?	?	?	Shanghai Electric[38]	?		
O&M		NOMAC		Sterling & Wilson[48]	NOMAC (KSA)	?	?	?	?	?	?		
Tech		CdTe, Fixed tilt[5]	c-Si all-glass, 1X tracking	c-Si Fixed, E/W alternating tilt[49]	c-Si tracking	c-Si	c-Si?	Bifacial. 1X tracking, automated cleaning	Bifacial, 1X tracking	Bifacial, 1X tracking	Bifacial, 1X tracking		

(Continues)

TABLE 1 (Continued)

	MBR2[1]	MBR3[5]	Noor AD[22]	Sakaka[41]	MBR4 (PV)[37]	Askar[42]	Al Kharsaah[2,39]	Ibri II[36]	MBR5[12,43]	Al Dhafra[13,14]	Al Dibdibah (BID)[33]	REPDO 2 (multiple projects)[30]
Debt: equity	80:20	70:30[50]	75:25	80:20	70:30	?	?	70:30	?	?		
Loan tenor (years)	27	?	26	?	?	?	?	16.5	27	?		
WACC (back-calculated)[b]	6%	4%	5%	3%	I.D.	7%	3%	I.D.	4%	I.D.		
Lending institutions (country)	AE	AE, KW, FR, JP, KR, CA[47]	JP, FR, AE	FR, SA	CN, AE, FR, UK	?	JP	CN, OM, DE, UK	AE, SA (APICorp), CN, SG, KW, FR	Pending		

Note: Green dates are projected, Red indicates cancelled/withdrawn project or bid.
[a]Tender withdrawn, will be reissued as IPP (see Section 2).[35]
[b]Assumptions: 1st-year energy yield from PVGIS[51] for appropriate configuration; yield boost of 5% for bifacial; 0.5% annual degradation ILR = 1.3 except for Sakaka where it has been reported as 1.35; O&M $10,000/MWac/year, escalating by $100/MWac/year.

regions suggest that falling financing costs are already having an impact of auction bid prices.[44] The importance of financing in the global market is gaining increasing attention[59] and presents promising avenues for the design of policies to promote the rapid deployment of solar and other renewables.[60] Although details of financing costs are not available for newer projects, WACC has been back-calculated for all projects where both capital costs and PPA price are reported, assuming a plant lifetime of 25 years, and is reported in Table 1.

Evaluating the LCOE for both sets of assumptions, we see that 90% of the drop in LCOE from MBR3 to MBR5 can be accounted for by the reduction in CapEx (Figure 2). Indeed, both MBR5 and Al Kharsaah fall at the extreme low end of the global range of PV system CapEx as reported in the most recent IEA PV Trends report,[61] projects such as Al Askar that have not achieved notably low PPA prices fall in the middle of the global range. The remaining reduction can be explained by assuming a modest boost in capacity factor of 5% due to the use of bifacial modules, which has been indicated by modeling under local conditions.[62] No further assumptions regarding OpEx or financing costs are required to reconstruct the observed PPA prices, allowing us to focus more detailed attention on explaining how such dramatic reductions in CapEx could be achieved in such a short time.

4 | WHAT IS RESPONSIBLE FOR FALLING CAPITAL COSTS?

In our previous study,[8] we used global market data combined with knowledge of the local environment and business practices to build a bottom-up model for PV system CapEx in the UAE. We found that CapEx below $1000/kW was feasible based on rapidly declining module costs (around 30 ¢/W at the time of that writing), BOS and tracker costs, the low cost of labor in the region, and minimal overhead and "soft" costs. Roughly, cost per watt could be represented by a "30-30-30" breakdown—30¢/W of module, 30¢/W of other hardware, and 30¢/W in labor and overhead. Developers do not appear to be responsible for interconnection costs in any of these projects, with these being borne by the utility. These costs will likely be reduced in the future due to the planned colocation of large amounts of capacity in multi-GW solar parks in multiple countries. International data from IRENA show that this breakdown holds true in many low-cost markets, most notably China, where low module prices are unsurprising due to the country's dominant position in PV manufacturing; in India, the lowest-cost market, modules accounted for nearly 50% of CapEx in 2019 and all other costs were far below the global average.[7]

Explaining the latest round of CapEx reductions from a bottom-up perspective has been somewhat less feasible in this study than the last. Whereas module pricing trends are heavily reported on and indicate a continued strong decline in prices, other system components are less well documented and the data that are available do not clearly support the idea of a similarly strong downward trend in inverter and BOS pricing. In addition, spot prices for bifacial modules, now becoming the preferred module technology in the region, are currently

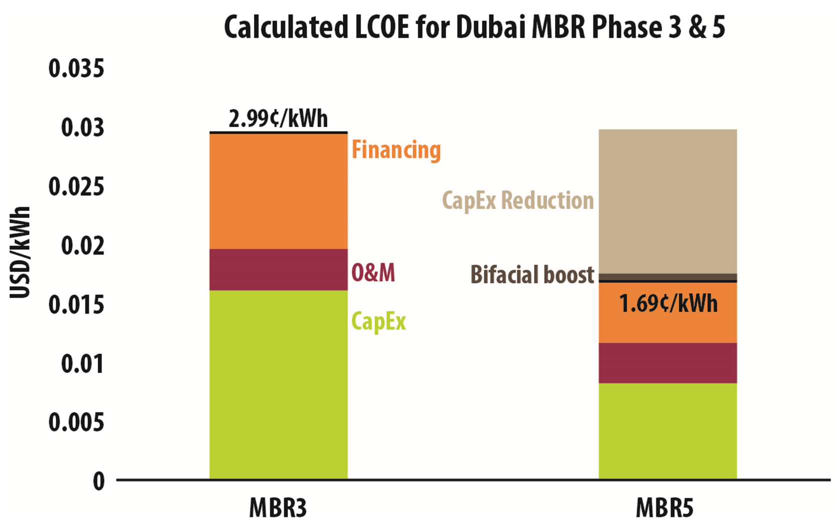

FIGURE 2 LCOE broken down into CapEx, OpEx and financing contributions for cost model of Dubai's Al Maktoum solar park phase 3 (announced 2016) and phase 5 (announced 2019). Reduction in LCOE is fully explained by modest boost in energy yield from the use of bifacial modules, and a large reduction in CapEx [Colour figure can be viewed at wileyonlinelibrary.com]

higher than those of conventional modules, although they are declining more rapidly.[63] However, a number of global trends and observations from previous experience suggest that this granular view is insufficient to capture what is truly driving CapEx for large solar projects in low-cost markets and that a more holistic approach is needed. This mindset has proven valuable in explaining the evolution of global PV manufacturing,[64] and can likewise offer insights into the changing economics of PV project development.

We first consider a number of factors that were first identified in our 2018 study. The first is that auction bids have been characterized by forward-looking cost projections—developers will tend to bid not based on the market price of hardware at the time of bidding, but on the prices, they expect to pay a year or more in the future when hardware is actually being ordered. As strong downward pricing trends continue, this pattern of aggressive forward-bidding can be expected to hold.

A second factor, somewhat controversial, relates to economies of scale. Past studies of U.S. and global utility-scale solar economics have delivered an uncertain verdict on whether large projects achieve lower per-watt costs than mid-sized projects, leading to a widespread impression that economies of scale are a less significant factor than might be expected in utility-scale solar projects.[11] This, however, does not fully align with the experience of the Gulf region. In multiple cases, tenders have been issued for projects of a given size, only to be scaled up in agreement with the developer upon signing the PPA, suggesting that developers may see a benefit to increased capacity that leads them to accept a lower-priced PPA.[48,65–67] Whether this indicates a substantial cost saving for the developer is uncertain. It is also possible that developers accept lower margins in exchange for a benefit that larger projects provide for their overall business model. These benefits can include reputational factors—"bragging rights" associated with developing larger projects and gaining market share—or potentially the benefit of experience—that the developer has its own learning curve, and building larger projects allows it to move faster down this learning curve and reduce its costs for future projects.[6] The recent tender in Saudi Arabia[30] provides a natural experiment, as bids have been received for six projects ranging in size from

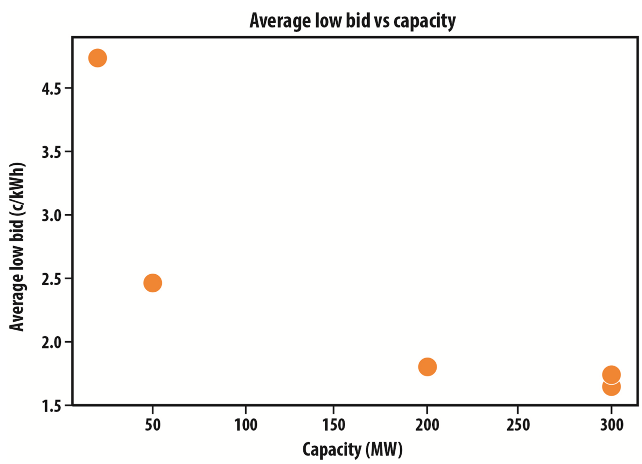

FIGURE 3 Average of two lowest bids for five out of six PV projects tendered in Saudi Arabia's REPDO 2 auction. Evidence of economies of scale for projects below 100 MW is clear, whereas evidence for economies of scale above this level is inconclusive, although a stronger case may be made by the impending announcement of the PPA for the 600-MW Faisaliah project [Colour figure can be viewed at wileyonlinelibrary.com]

20 MW to 600 MW. As of this writing, the two lowest bids have been publicized for each project except the 600-MW Al-Faisaliah project. In Figure 3, the plot of average bid price versus capacity shows a clear trend toward lower bid prices for larger projects, indicating that at some level, economies of scale are indeed realized. Whether this holds as capacity is increased beyond 100 MW has been unclear in studies done in other markets, and here as well the evidence is at present inconclusive. The pending announcement of the sixth and largest project in this tender may shed a bit more light on the question. In June of 2020, the Saudi Minister of Energy indicated that an announcement of a record-low PPA price for a PV project would soon be announced, which is presumably a reference to the forthcoming award of the Al Faisaliah project.[68] Given that the award of Abu Dhabi's Al Dhafrah project for 1.35 ¢/kWh was widely expected at the time, this would be expected to indicate a price around

1.3 ¢/kWh, one of the clearest indications to date of significant economies of scale in 100-MW to 1-GW scale photovoltaic projects.

The prominence of major international players in the Gulf's solar development is undoubtedly a factor in the realization of below-market costs. In addition to the major project developers, large engineering firms with a global footprint, including China's Shanghai Electric[29,38] and India's Sterling & Wilson[48] and Mahindra Susten,[28] have been contracted for EPC on these projects. It can be assumed that large firms with an established presence in the region will have a lower cost of doing business. Furthermore, as major customers in a buyer's market, one would expect that these contractors are able to set their prices for large orders of hardware to a significant degree. Hence, a bottom-up summation of different component costs based on reported market data will likely yield an overestimate of total system CapEx. In Figure 4, we display average CapEx and LCOE/PPA prices for the Gulf, Indian, and Chinese markets, in the context of the global market trends for each metric, based on data from IRENA.[7] Projects are counted in the year that they are commissioned. The Gulf has consistently set records for PPA pricing; however, CapEx has "caught up" to the more established Chinese and Indian markets only in the latest round of projects. This speaks to the importance of generous financing packages, coupled with the strong solar resource, in supporting the Gulf region's early low bids.

5 | LEARNING CURVES FOR UTILITY-SCALE PV

The steady year-on-year declines in CapEx and LCOE suggest learning behavior typical of mass-produced goods. Learning curve analysis has proven effective at projecting the price evolution of photovoltaic module manufacturing in a way that bottom-up analysis has not and is increasingly being extended to system-level analysis. We consider here the learning curves for utility-scale solar CapEx and LCOE for the Gulf and global markets, plotted in Figure 5. The learning curves for the Gulf region alone (A,B) exhibit a robust but not exceptional learning rate for both CapEx (18% reduction per doubling of installed capacity) and PPA price (20%), due to the rapid growth of the sector as large projects come online. However, as has been established by previous observers, considering a country or region's learning curve in a vacuum does not provide a full picture because local developments are strongly influenced by global market trends.[69] When the evolution of electricity price/LCOE and plant CapEx are considered in relation to global PV capacity expansions (C,D), a learning rate is found that roughly matches the global rate (E,F). Although the comparatively small number of projects in the region leads to a somewhat noisy correlation, this does represent an indication that solar energy economics in the Gulf follow the same general patterns as global trends, but substantially advanced. We regard this as evidence that trends in the Gulf are best viewed not as an aberration but as an indicator of how the global market is likely to evolve in the future. This paints an exceptionally promising picture of the future trajectory of the industry, where solar electricity prices approaching 1 ¢/kWh are likely to be seen in many parts of the world in 5 years, with no clear lower bound. This would herald a revolution in not only solar energy but in the energy sector generally, with a new age of ultra-cheap electricity transforming our lives, economies, and environment. We are by no means the first to predict this transition,[70] but the experience of the Gulf may provide a window into how it might play out in the near future. With such dramatic change on the horizon, it makes sense to consider the next steps that should be taken prepare to fully take advantage of the coming energy transformation.

6 | ENERGY, ECONOMY, ENVIRONMENT: PREPARING FOR THE RENEWABLE REVOLUTION

The coming shift to extremely low-cost renewable energy, suggested by recent developments in the Gulf and other low-priced solar markets, will be a generation-defining transformation. There will be opportunities as well as challenges that must be met, not only from a technical perspective but also from that of society more broadly.[71] By way of conclusion, we discuss briefly some of these challenges and how the region's solar energy pioneers are attempting to meet them.

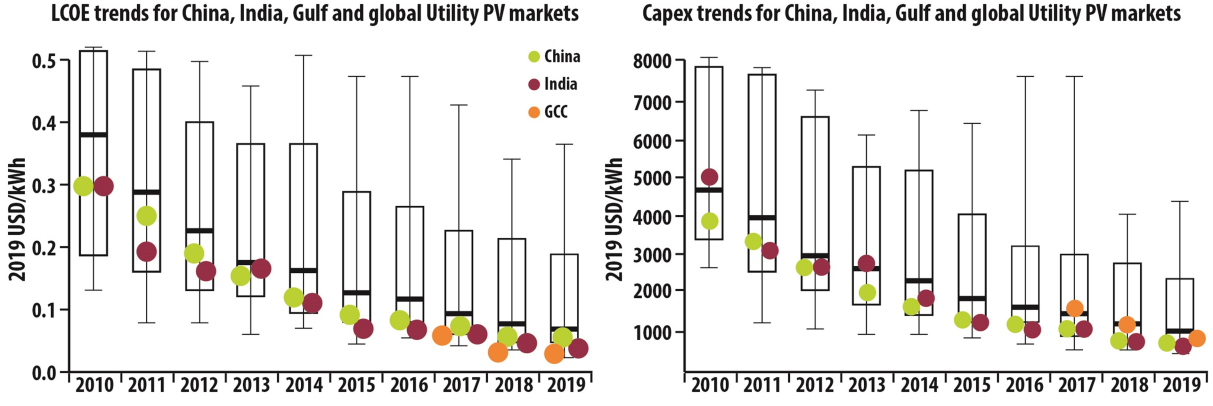

FIGURE 4 Average LCOE (left) and CapEx (right) for Chinese, Indian and gulf utility PV projects by year. Modified box & whisker plots represent global market where boxes encompass the fifth to 95th percentile values [Colour figure can be viewed at wileyonlinelibrary.com]

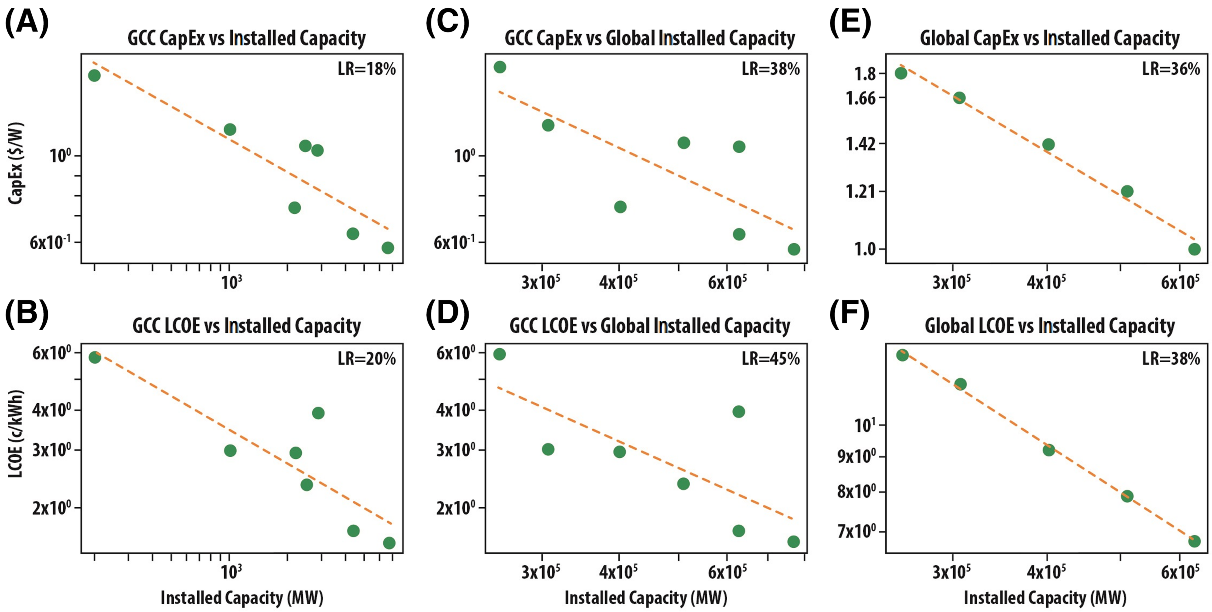

FIGURE 5 Learning curves for CapEx and LCOE for the GCC market (A,B); GCC prices versus global installations (C,D); and the global market (E,F). The learning rate is the percent reduction in cost per doubling of capacity [Colour figure can be viewed at wileyonlinelibrary.com]

The standard first attack on claims of the economic favorability of solar energy is intermittency. It is true that the low-priced solar electricity discussed here is nondispatchable as it is produced by solar parks without storage capacity and therefore is of lower value because it cannot replace load-following or baseload generating capacity. This recognition, however, is not the end but the beginning of a conversation if taken in good faith. There are myriad ways to modify our energy systems to enhance the value of this low-cost solar electricity. The most straightforward is energy storage, which can take many forms beyond batteries. Approaches to energy storage in the Gulf include the CSP + TES facility, which forms the largest component of MBR4[37]; pumped hydropower[72]; and solar fuel generation[73]; in addition to battery storage including a 108-MW/6-h distributed battery storage project in Abu Dhabi,[74] an increasingly viable option as battery prices continue to fall across the globe.[75] This is before considering the potential of demand-side management strategies that aim to shift the energy demand curve to match the solar generation curve, minimizing the need for storage. Expanding the thermal storage capacity of the region's large district cooling plants is already being undertaken as a means of adding flexibility,[76] and the nascent push to deploy electric vehicles presents not only substantial challenges but also great opportunities to shape the demand profile through smart charging strategies.[77]

A host of potential economic pitfalls present themselves as well, as the dominance of a few major players and countries can lead to fears of eroding local industries and creating a situation of dependence on a small number of "titans." Saudi Arabia in particular has enforced local content requirements in its solar projects,[25] with its own ACWA Power taking the lead on both construction and operation of many domestic energy projects while aggressively expanding its footprint throughout the region and beyond. Other regional project developers, including Saudi Arabia's Abdul Latif Jameel and Abu Dhabi's Masdar, have taken on projects around the world. Hence, the Gulf states have made some clear moves not only to protect local companies but to become global players in a vital growth industry whose international nature cannot be denied. In the same vein, several countries in the region have also moved to localize hardware manufacturing, establishing facilities for both PV module[78,79] and battery production,[80] avoiding a situation of absolute dependence of overseas manufacturing while also laying the groundwork to exploit the region's vast energy and material resources to potentially become global players in this area as well. It may also be worthy of note that neither American (after the involvement of First Solar in MBR2) nor German firms have been especially prominent in the region's solar industry in recent years, excluding the two countries perhaps most responsible for the early growth of photovoltaics prior to the entry of China. The center of mass of the photovoltaic industry has shifted decisively eastward.

A final class of challenges relate to the environmental footprint of the photovoltaic industry. Although this has not factored so prominently in the solar economy of the Gulf up to this point, it stands to become an area of some concern for the global industry. A significant amount of research has been put into life-cycle analysis of photovoltaic modules,[57,81] with some studies suggesting that depending on the environmental and energy efficiency standards applied to their production, the overall impact of photovoltaic manufacturing can vary by a significant factor.[82] Environmental impacts include both carbon and energy intensity and a range of issues related to resource extraction, manufacturing, and end-of-life.[83] The establishment of a circular economy for photovoltaic modules will be key to mitigating these and creating a maximally sustainable solar energy industry.[84] Deployment of photovoltaics has some associated environmental impact as well—

even in the inhospitable interior deserts of the UAE, the Noor Abu Dhabi project was reported to have taken precautions to avoid disturbing the habitats of endangered desert lizards.[49] Taking the mindset of minimizing interference with the natural world—a key component of any holistic approach to sustainability—next-generation technologies will likely have a substantial role to play in enabling dual land use (urban, building integrated, and agricultural photovoltaics), and maximizing solar resource utilization through hybridized or "multifunctional" solar collectors.[85]

7 | CONCLUSIONS

In this work, we have surveyed the expansion of photovoltaics in the GCC region and investigated cost trends, in particular focusing on the dramatic reduction in PPA prices from 3 ¢/kWh at the time of our last study, to ∼1.5 ¢/kWh or less in several countries. Noting that the region has seemed to be a bellwether for global pricing trends, we investigate the factors leading to this latest round of cost reductions from a holistic perspective, considering component pricing trends, the interests and business models of the various stakeholders, and the industrial learning rates for photovoltaic system costs in the region compared to global trends. This analysis indicates that the Gulf, rather than being qualitatively different from the global market, rather benefits from a confluence of factors including favorable financing conditions, low costs of doing business, a strong presence of highly experienced project developers, both domestic and foreign, and of course a strong solar resource, that consistently yield prices that are low by global standards, but whose evolution over time is similar to global trends. Hence, the Gulf market can be seen as "advanced" relative to the global market—further down the learning curve but not qualitatively unique—and therefore can offer into a window into the likely future trajectory of photovoltaics globally. In this case, the "crystal ball" of the Gulf market predicts that global solar electricity prices will soon enter a regime that will favor the decommissioning of large numbers of fossil fuel plants and the rapid transition to a renewable-dominated energy system. We have summarized in a cursory way what we believe to be the biggest challenges and opportunities implied by this transition. Further understanding and responding to these opportunities and challenges will be a critical goal of future work in both the technical and policy arenas.

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REFERENCES

1. ACWA. ACWA Power wins 200 megawatts (260MWp) phase II Mohammed bin Rashid Solar Park by Dubai Electricity. *ACWA Power*, 2015.
2. Total. Total to develop Qatar's First Large-Scale (800 MWp) Solar Plant. ed. Paris, 2020.
3. Knott D. Oman Awards 500mw Ibri 2 Solar Project. *MEES*. 2019. https://www.mees.com/2019/3/22/oil-gas/oman-awards-500mw-ibri-2-solar-project/223b9080-4cc1-11e9-92d1-a54b97b26a57
4. Graves L. Abu Dhabi plant to produce region's cheapest electricity from solar. in *The National*, ed. Abu Dhabi, 2017.
5. DEWA. *Mohammed bin Rashid Al Maktoum Solar Park—A Leading Project that Promotes Sustainability in the UAE*. Dubai Electricity and Water Authority (DEWA); 2019.
6. The land of the low tender. 2020. *PV Magazine*. https://www.pv-magazine.com/2020/01/11/the-weekend-read-the-land-of-the-low-tender/
7. IRENA. *Renewable Power Generation Costs in 2019*. Abu Dhabi: International Renewable Energy Agency; 2020.
8. Apostoleris H, Sgouridis S, Stefancich M, Chiesa M. Evaluating the factors that led to low-priced solar electricity projects in the Middle East. *Nat Energy*. 2018;3(12):1109-1114.
9. DOE. The SunShot Initiative's 2030 Goal: 3¢ per kilowatt hour for solar electricity. *US Department of Energy*.
10. DEWA announces selected bidder for 800 MW third phase of the Mohammed bin Rashid Al Maktoum solar park. *Dubi Electricity and Water Authority*, 2016.
11. Bolinger M, Seel J, Robson D. "Utility-scale solar: empirical trends in project technology, cost, performance, and PPA pricing in the United States–2019 Edition," 2019.
12. DEWA. *DEWA Signs Power Purchase Agreement for 900MW 5th Phase of the Mohammed bin Rashid Al Maktoum Solar Park*. Dubai: Dubai Electricity and Water Authority (DEWA); 2020.
13. EWEC. *Abu Dhabi Power Corporation Announces Lowest Tariff for Solar Power in the World*. Abu Dhabi: Emirates Water & Electricity Co.; 2020.
14. Masdar, "EWEC Announces Partners to Develop the World's Largest Solar Power Plant," ed. Abu Dhabi, 2020.
15. Brockway PE, Owen A, Brand-Correa LI, Hardt L. Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nat Energy*. 2019;4(7):612-621. https://doi.org/10.1038/s41560-019-0425-z
16. Powering down coal: Navigating the economic and financial risks in the last years of coal power. *Carbon Tracker, London*, 2018.
17. Sgouridis S, Carbajales-Dale M, Csala D, Chiesa M, Bardi U. Comparative net energy analysis of renewable electricity and carbon capture and storage. *Nat Energy*. 2019;4(6):456-465. https://doi.org/10.1038/s41560-019-0365-7
18. Sgouris S, Denes C, Ugo B. The sower's way: quantifying the narrowing net-energy pathways to a global energy transition. *Environ Res Lett*. 2016;11(9):094009. http://stacks.iop.org/1748-9326/11/i=9/a=094009
19. Alobaidli A, Sanz B, Behnke K, Witt T, Viereck D, Schwarz MA. Shams 1—Design and operational experiences of the 100MW - 540°C CSP plant in Abu Dhabi. *AIP Conf Proc*. 2017;1850(1):020001. https://doi.org/10.1063/1.4984325
20. ADWEA, "Sweihan PV IPP—Bids Opening Summary," 2016. http://www.adwec.ae/Documents/160919%20Sweihan%20PV%20Bids%20Opening%20Summary.pdf
21. Masdar. Shuaa Energy 2: Mohammed Bin Rashid Al Maktoum Solar Park Phase 3. http://www.masdar.ae/en/energy/detail/mohammed-bin-rashid-al-maktoum-solar-park-phase-3
22. Carvalho S. Abu Dhabi closes $872 financing on world's larges solar power plant. *Reuters*, 2017.
23. Dipaola A. Saudi Arabia Gets Cheapest Bids for Solar Power in Auction. in *Bloomberg Markets*, 2017.
24. Parnell J. Bifacial technology was likely reason world's lowest ever solar bid was rejected. *PVTech*. 2018
25. Kenning T. ACWA Power wins 300MW Saudi solar project. *PV Tech*. 2018. https://www.pv-tech.org/news/acwa-power-wins-saudi-300mw-solar-project
26. DEWA. *Mohammed bin Rashid Inaugurates DEWA Innovation Centre and 800MW 3rd Phase of the Mohammed bin Rashid Al Maktoum Solar Park*. Dubai: Dubai Electricity & Water Authority; 2020.

27. EWEC. *EWEC announces full operations of world's largest single solar project in Abu Dhabi*. Abu Dhabi: Emirates Water & Electricity Co.; 2019.
28. ACWA. ACWA Power connects the first renewable energy project in the Kingdom, Sakaka PV IPP, to the national electricity grid, commencing initial production. *ACWA Power*, 2019.
29. Bhatia N. Ground broken on $3.8bn Phase 4 of Dubai's MBR Solar Park. 2018. *Construction Week Online*. http://www.constructionweekonline.com/article-48668-ground-broken-on-38bn-phase-4-of-dubais-mbr-solar-park/
30. Bellini E. Lowest shortlisted bid in Saudi 1.47 GW tender was $0.0161/kWh. 2020. *PV Magazie*. https://www.pv-magazine.com/2020/04/03/lowest-shortlisted-bid-in-saudi-1-47-gw-tender-was-0-0161-kwh/
31. Ideematec, "Ideematec Announces World's Largest Single-Axis Tracker Solar Project," 2020.
32. Bellini E. ACWA wins Bahrain's 100 MW PV tender with bid of $0.039/kWh. 2019. *PV Magazine*. https://www.pv-magazine.com/2019/02/25/acwa-wins-bahrains-100-mw-pv-tender-with-bid-of-0-039-kwh/
33. Bidders await decision on 1.5GW Kuwait solar project. *Power Technology*. 2019. https://www.power-technology.com/comment/bidders-await-decision-on-kuwait-solar-project/
34. Staff. Kuwait cancels Al-Dabdaba solar plant project due to coronavirus, in *Reuters*, 2020.
35. Kuwait to procure 1.5GW Dibdibah solar scheme as IPP project. *Energy & Utilities*. 2020
36. Asaba B. Financial close achieved for the largest solar photovoltaic power plant in Oman. 2020. https://www.arabianindustry.com/utilities/news/2020/mar/24/financial-close-achieved-for-the-largest-solar-photovoltaic-power-plant-in-oman-6354920/
37. DEWA. *DEWA, ACWA Power, and Silk Road Fund Reach Financial Closing on 950MW 4th Phase of Mohammed bin Rashid Al Maktoum Solar Park*. Dubai: Dubai Electricity and Water Authority (DEWA); 2019.
38. ACWA, "ACWA Power partners with Shanghai Electric as EPC contractor for delivery of the 5th phase of the Mohammed Bin Rashid Solar Park," Dubai: ACWA Power.
39. Bellini E. Japanese banks back world's second cheapest solar project. *PV Magazine*. 2020
40. Jäger-Waldau A. Snapshot of Photovoltaics—February 2020. *Energies*. 2020;13(4):930.
41. ACWA. ACWA Power and AlGihaz achieve financial closure for Sakaka PV IPP, *ACWA Power*, 2018.
42. ACWA. Projects: Al Askar PV IPP. https://www.acwapower.com/en/projects/al-askar-pv-ipp/
43. ACWA. ACWA Power announces the successful signing of financing agreements for the 900MW Solar PV fifth phase of MBR Solar Park, *ACWA Power*, 2020.
44. Bellini E. 2020. Qatar's 800 MW tender draws world record solar power price of $0.01567/kWh. *PV Magazine*. https://www.pv-magazine.com/2020/01/23/qatars-800-mw-pv-tender-saw-world-record-final-price-0-01567-kwh/
45. Qatar solar project reaches financial close. *Energy & Utilities*. 2020
46. DEWA. *DEWA Announces Financial Close for 200MW IPP Phase II of the Mohammed bin Rashid Al Maktoum Solar Park*. Dubai Electricity and Water Authority (DEWA); 2015.
47. DEWA. *800MW Third Phase of Mohammed bin Rashid Al Maktoum Solar Park Reaches Financial Close*. Dubai: Dubai Electricity & Water Authority; 2017.
48. Sweihan Photovoltaic Independent Power Project, Abu Dhabi. *Power Technology*. https://www.power-technology.com/projects/sweihan-photovoltaic-independent-power-project-abu-dhabi/
49. Sanderson D. How a remote patch of Abu Dhabi desert became a world leading solar plant, *The National*, 2019.
50. Bintcliffe J. Dubai attracts lowest solar tariff, again. *IJ Global Project Finance & Infrastructure Journal*. 2016
51. PVGIS. *EU Science Hub*. https://ec.europa.eu/jrc/en/pvgis (accessed 26 November, 2020).
52. ACWA. Dubai achieves world-record, lowest ever PV tariff for 900 MW solar project, *ACWA Power*, 2020.
53. Rogers M. Blog: Solar Tracker O&M Considerations for the Middle East and North Africa, *Nextracker*, 2020.
54. Jolywood To Supply 458 MW NTOPCon Bifacial Solar Modules For Oman Ibri II Solar Project—'Largest' N-Type Solar Park In Middle East To Date. *Taiyang News*. 2020
55. ACWA. *500 MW Ibri 2 Solar PV Project achieves a new milestone*. Oman: ACWA Power; 2020.
56. Tuomiranta A, Abdul Aziz M, Ghedira H, Zoning Study for Deployment of Photovoltaic Power Stations in the UAE. 2017.
57. Wiser RH, Bolinger M, Seel J. *Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results From a Survey of US Solar Industry Professionals*. Berkeley, CA (United States): Lawrence Berkeley National Lab.(LBNL); 2020.
58. Apostoleris H, Chiesa M. The role of financing in realizing ultra-low solar electricity prices in the Middle East. In: *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, 16–21 June 2019; 2019:595–600. https://doi.org/10.1109/PVSC40753.2019.8980633
59. Vartiainen E, Masson G, Breyer C, Moser D, Román Medina E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Prog Photovolt: Res Appl*. 2020;28(6):439-453. https://doi.org/10.1002/pip.3189
60. Apostoleris H, Sgouridis S, Stefancich M, Chiesa M. Utility solar prices will continue to drop all over the world even without subsidies. *Nat Energy*. 2019;4(10):833-834.
61. Masson G, Kaizuka I. *IEA PVPS Report—Trends in Photovoltaic Applications 2019*. Paris: IEA; 2019.
62. Tuomiranta A, Cattin J, Levrat J, et al. Comparative field performance assessment of bifacial solar modules. In: *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*. IEEE; 2020:1033-1034.
63. Schashinger M. PV Module Price Index June 2020: Is Size All That Matters? *PV Magazine*. 2020. https://www.pv-magazine.com/module-price-index/
64. Green MA. How did solar cells get so cheap? *Joule*. 2019;3(3):631-633.
65. DEWA. *DEWA selects Saudi ACWA and Spain's TSK for the project with the world's lowest LCOE*. Dubai: Dubai Electricity and Water Authority (DEWA); 2015.
66. DEWA. *DEWA Receives Lowest International Bid for 4th Phase of the Mohammed bin Rashid Al Maktoum Solar Park*. Dubai: Dubai Electricity and Water Authority (DEWA); 2017.
67. DEWA. *DEWA Awards AED14.2 Billion Largest CSP Project in the World With a Record Bid of USD 7.3 Cents per kW/h to Generate 700MW*. Dubai Electricity and Water Authority (DEWA); 2017.
68. Saudi Arabia prepares to announce world record solar tariff project. *Energy & Utilities*. 2020
69. Naam R. Solar's Future is Insanely Cheap; 2020.
70. Green MA. Photovoltaic technology and visions for the future. *Prog Energy*. 2019;1(1):013001.
71. Carley S, Konisky DM. The justice and equity implications of the clean energy transition. *Nat Energy*. 2020;5(8):569-577. https://doi.org/10.1038/s41560-020-0641-6
72. Bellini E. 2019. DEWA to use solar to power new pumped-storage project. *PV Magazine*. https://www.pv-magazine.com/2019/08/19/dewa-to-use-solar-to-power-new-pumped-storage-project/
73. Dubai home to first solar-powered hydrogen facility in Mena, *The National*, 2019.
74. Abu Dhabi launches world's largest virtual battery plant. *Utilities Middle East*. 2019. https://www.utilities-me.com/news/12329-abu-dhabi-launches-worlds-largest-virtual-battery-plant

75. B. N. E. Finance. Battery Pack Prices Fall as Market Ramps up with Market Average at $156/kWh in 2019, 2019.
76. Zawya. Dubai's Empower starts full-fledged operations at world's first unmanned district cooling plant; 2019.
77. Elgqvist EM, Pohl J. *Evaluating Utility Costs Savings for EV Charging Infrastructure*. Golden, CO (United States: National Renewable Energy Lab.(NREL); 2019.
78. Gouras E. 2019. Pioneering PV in Saudi Arabia. *PV Magazine*. https://www.pv-magazine.com/magazine-archive/pioneering-pv-in-saudi-arabia/
79. Bellini E. A new module factory in Bahrain. *PV Magazine*. 2020. https://www.pv-magazine.com/2020/03/12/a-new-module-factory-in-bahrain/
80. Bellini E. A 3 GWh redox flow battery factory in Saudi Arabia. *PV Magazine*. 2020. https://www.pv-magazine.com/2020/05/11/a-3-gwh-redox-flow-battery-factory-in-saudi-arabia/
81. Fthenakis V, Kim HC. Photovoltaics: life-cycle analyses. *Solar Energy*. 2011;85(8):1609-1628.
82. Yue D, You F, Darling SB. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy*. 2014;105:669-678. https://doi.org/10.1016/j.solener.2014.04.008
83. Weckend S, Wade A, Heath GA. *End of Life Management: Solar Photovoltaic Panels*. Golden, CO (United States: National Renewable Energy Lab.(NREL); 2016.
84. Tsanakas JA, van der Heide A, Radavičius T, et al. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. *Prog Photovolt: Res Appl*. 2020;28(6):454-464. https://doi.org/10.1002/pip.3193
85. Apostoleris H, Chiesa M. High-concentration photovoltaics for dual-use with agriculture. In: *AIP Conference Proceedings*. Vol. 2149. AIP Publishing LLC; 2019:50002.

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