Using DSM from air conditioners with cool thermal energy storage to increase the wholesale market value of solar PV electricity -

2040 scenarios for India

Ahmad Murtaza Ershad
Potsdam Institute of Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany
Technical University of Berlin, Berlin, Germany
E-mail: ershad@pik-potsdam.de

Robert Pietzcker
Potsdam Institute of Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany
E-mail: pietzcker@pik-potsdam.de

Gunnar Luderer
Potsdam Institute of Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany
E-mail: luderer@pik-potsdam.de

***Abstract* - We evaluate the degree to which the wholesale market value of solar PV electricity (VOS) increases when a demand-side management (DSM) measure using air conditioners with cool thermal energy storage (CTES) is implemented at different gross solar PV shares. We examine two DSM measures with different maximum DSM durations, efficiencies and costs namely, mechanical precooling of the building thermal mass using programmable thermostats here called in short, Precooling, and chilled water storage (CWS). Using the open-source power sector model DIETER, we first we quantify the decline in the Wholesale VOS with increasing gross solar PV shares in the final electricity demand for a reference scenario. Next, we quantify change in the wholesale VOS due to our DSM measures compared to our reference scenario in a highly-air-conditioned Indian power system in 2040 under a carbon price of 50 USD/tCO2. We show that the Wholesale VOS declines from 89 USD per MWh at 1 % solar share to less than 10 USD per MWh at 60 % solar shares in our reference scenario driven by a decrease in wholesale electricity prices while solar generation is abundant and an increase in solar curtailment. Precooling and CWS increase the wholesale VOS up to 18 USD per MWh and 26 USD per MWh compared to our reference scenario respectively by improving the matching between solar generation and AC demand profiles, which leads to increased solar-coincident wholesale electricity prices and reduced curtailment.**

Keywords - Air conditioning; demand response; solar wholesale market value

I. INTRODUCTION

A future with high shares of solar PV in many power systems is inevitable if global warming is to be limited to well beyond 2 °C and SDGs are to be met [1]. Empirical and modelling evidence suggests that as the share of solar and wind in the electricity generation increase, their wholesale economic value decrease mainly due to the mismatch between solar generation and demand profiles. This drop is mainly attributed to reduced capacity and energy values. The phenomena of solar devaluation at higher shares is well studied for developed power systems such as California [2], Germany [3] or Florida [4]. However, less attention is paid to the developing power systems such as the one in India that will have large shares of solar in their systems driven mainly by climate mitigation and energy access.

This decline in economic value has serious implications for the achievement of high solar shares as it affects the competitiveness of solar investments and total power system costs. For a given solar investment cost, the optimal solar investment occurs when the revenues of solar plants from the electricity market equal their costs. Solar is profitable only when it is below the optimal share. Thus, it is important to implement measures that would mitigate the decline in the VOS and consequently achieve higher optimal solar shares.

The purpose of our paper is to evaluate the degree to which the wholesale VOS increases when a DSM measure using air conditioners with CTES is implemented at different gross solar PV shares in a highly-air-conditioned Indian power system in 2040 under a carbon price of 50 USD/tCO2. We examine two DSM measures with different maximum DSM durations, efficiencies and costs namely, mechanical precooling of the building thermal mass using programmable thermostats here called in short, Precooling, and CWS. CTES enables the shifting in time of the electricity consumption of air conditioners from times of low or no solar generation to times of high solar generation.

Using the open-source power sector model DIETER [5], we first we quantify the decline in the Wholesale VOS with increasing gross solar shares in the final electricity demand for a reference scenario. Next, we quantify change in the wholesale VOS due to our DSM measures compared to our reference scenario using DIETER's DSM module [6] and building on its DSM formulation. We take a "what if" approach meaning we answer questions such as what if all air conditioners in India had a programmable thermostat allowing for precooling. Alternatively, what if all buildings had a CWS. In addition to showing the change in the wholesale VOS in our Precooling and CWS over different gross solar PV shares, we also show how AC demand, prices and curtailment change during a day with DSM. We show results for the day with the highest peak AC demand.

II. MODELLING

A. Electricity supply and demand in 2040

We model the highly air-conditioned Indian hourly total load in 2040, Ref-AC scenario, with 807 TWh of final space cooling electricity demand and 3535 TWh of total final electricity demand as projected by Levesque et al. 1 (2019) [7]. AC load is projected to make up around 22 % of the total annual load. We follow a partial disaggregation approach by which we scale up the disaggregated, modelled 2010 AC and non-AC load curves using their distinct growth rates. We assume that only the share of AC load in the total load grows and the share of other end-uses stay the same as in 2010. This is an improved approach compared to the simple scaling up of 2010 total load, which would not capture the impacts of growth in demand intensity of air conditioners. Details of our load modelling are presented in a companion paper not finalized yet. Table 1 shows details of our projected load curve in the Ref-AC scenario and in another scenario, which we simply scaled up 2010 load to match the same projections in 2040.

Table 1 - Projected 2040 load curves

	Ref-Simple	*Ref-AC*	Unit
Total AC load		807	TWh
Total load	3535	3535	TWh
Load factor (%)	84	67	%
Peak load (GW)	482	606	GW
Average load (GW)	403	403	GW
Minimum load (GW)	305	259	GW
Peak coincident AC load (GW)		350	GW
Peak non-coincident AC load (GW)		350	GW
Time of total peak load	8:00 PM	5:00 PM	
Month of peak load	October	May	

We assume there is a CO2 price of 50 USD per ton of CO2 implemented in India due to climate targets. Our exogenous capacity assumptions include 11 % of wind electricity in final electricity demand, 20 GW of pumped hydro storage with 4 hours of storage capacity and 40 GW of hydro capacity with a constant capacity factor of 35 %. Our wind assumption is consistent with the IEA New Policies Scenario (NPS). We allow for the build-out of hard coal, combined cycle gas turbines and combustion turbines to meet the electricity demand under various DSM scenarios. We assume at least 147 GW of hard coal capacity standing to reflect on one hand the heavy reliance of India on coal and on the other hand the potential coal-phase out by that time. We also constrain nuclear build-out by assuming a maximum capacity limit of 47 GW. Our nuclear limit is driven mainly by our assumption of high investment costs. No biomass is considered in our analysis due to biomass resource constraints. Table 2 shows our technical and cost assumption relating to conventional power plants and Table 3 shows our assumed fuel and CO2 prices in 2040 in India. Hourly solar and wind generation profiles are modelled using open-sources models System Advisor Mode (SAM) and Renewables.ninja, an online simulator of hourly wind power plant output, respectively. Annual solar and wind capacity factors are 20 % and 31 % respectively.

Table 2 - Technical assumptions on conventional

	Nuclear	Hard coal	CCGT	OCGT	Unit
Efficiency	34.3	43	58	45.7	%
Carbon content	0	0.354	0.202	0.202	t/MWh
Overnight investment costs	5,500,000	1,580,000	700,000	400,000	USD/MW
Annual fixed costs	140,000	55,000	25,000	20,000	USD/MW
Variable O&M costs		-	-		USD/MWh
Load change costs up and d	50	30	20	15	USD/MW
Technical lifetime	40	35	25	25	years
Interest rate	7	7	7	7	%
Maximum capacity factor	85	85	85	85	%
Maximum load change for reserves	4	6	8	15	% of capacity per minute

Table 3 - Fuel and CO2 prices

	Value	Unit
Hard coal	14	USD/MWh-th
Gas	34	USD/MWh-th
Nuclear	3	USD/MWh-th
CO2 price	50	USD/tCO2

B. Wholesale electricity price

Wholesale electricity price is calculated using the open-source power sector model, DIETER. DIETER is a partial equilibrium model of the wholesale electricity market focusing both on supply and demand sides. DIETER minimizes total system costs over 8760 hours of a full year ensuring that power generation equals demand at all time. At its simplest formulation, system costs comprise annualized investment costs and fixed costs as well as variable costs of dispatchable generators (e.g. fuel and CO2 costs), variables renewables and demand-side management (DSM) technologies.

Wholesale electricity price is the shadow price of demand estimated by diving the change in total system cost by change in total load (Equation 1). In other words, it is the social cost of generating one more unit of electricity, which includes fuel, CO2, variable O&M and investment costs. DIETER's electricity market is an energy-only market with scarcity pricing, meaning all capacity investments have to be recovered through energy-sales revenues.

$$P_h \equiv \frac{\partial C}{\partial d_h} \qquad \textit{Equation 1}$$

C. Wholesale VOS

We estimate wholesale VOS by dividing the total wholesale revenues of solar plants by the total gross solar generation (generation before curtailment) (Equation 2) Wholesale solar revenues are estimated by summing over all the hours of the year the product of wholesale electricity prices and solar feed-in. Here, we assume all solar plants to be utility-scale and these plants sell their generated electricity at the wholesale electricity price. Our approach captures both the energy value and the capacity value since our wholesale price model includes scarcity price.

$$Solar\ market\ value\ = \frac{\sum_{h=1}^{8760} P_h\, G_{res}}{(\sum_{h=1}^{8760} G_{res} + \sum_{h=1}^{8760} CU_{res})}$$

Equation 2

D. Wholesale VOS

We build on a wholesale DSM model formulation suggested by [6] here called AC-DSM. Main AC-DSM inputs (Table 4) include DSM investment and operation costs, DSM technical lifetime and efficiency, maximum DSM duration, maximum DSM installed capacity, recovery period between two DSM cycles and an hourly AC demand profile. The most important outputs are optimal DSM installed capacity and hourly wholesale load addition and reduction. In the following, the main equations used in the formulation of AC-DSM are explained. Table 5, Table 6 and Table 7 show sets, variables and parameters used in our DSM modelling.

Table 4 - Technical assumptions on DSM

	Precooling	CWS	Unit
Load shifting costs	1	1	USD/MWh
Overnight investment costs	30,000	100,000	USD/MW
Annual fixed costs	-	-	USD/MW
Interest rate	7	7	%
Technical lifetime	10	10	Years
Efficiency	70	90	%
DSM maximum duration	4	8	Hours
DSM recovery time	1	1	Hours
Maximum installable capacity	350,000	350,000	MW

Table 5 - DSM sets

Element	Description
ls	DSM load shifting technologies
h, hh	Hours

Table 6 - DSM variables

Variable	Unit	Description
$DSM_{ls,h}^{UP}$	MW	Load increase taking effect in the wholesale segment shifting technology ls in hour h
$DSM_{ls,h}^{DOWN}$	MW	Load decrease taking effect in the wholesale segment shifting technology ls in hour h
N_{ls}	MW	Installed capacity DSM load shifting

Table 7 - DSM parameters

Parameters	Description
c^m	Marginal operating costs
c^i	Annualized specific investment costs
c^{fix}	Annual fixed costs
t_{ls}^{dur}	maximum DSM duration
φ_{AC}	Hourly AC profile
m_{ls}	Maximum DSM potential

AC-DSM always shifts AC loads to an earlier time. The model reduces load in the subsequent hours to account for loads increased in previous hours corrected for the process inefficiencies (Equation 3). Thus, load decrease in an hour can come from load increase in different hours. Increased load in an hour is balanced no earlier than the hour the load is increased and no later than the maximum DSM duration.

$$DSM_{ls,h}^{UP} \varepsilon_{ls} = \sum_{h \le hh \le h + t_{ls}^{dur}} DSM_{ls,h,hh}^{DOWN} \qquad \textit{Equation 3}$$

Total wholesale load reduction in an hour cannot be larger than the DSM installed capacity times the hourly AC profile (Equation 4). Including a temporal profile for the DSM installed capacity replicates the fact that not all ACs participating in the DSM program are turned on in each hour due to occupancy or temperature constraints.

$$DSM_{ls,h}^{DOWN} \le \varphi_{AC}\, N_{ls} \qquad \textit{Equation 4}$$

In addition, total wholesale load addition in an hour can cannot be larger than the difference between the maximum DSM capacity and total wholesale reduction (Equation 5).

$$DSM_{ls,h}^{UP} \le 1.2\, N_{ls} - \varphi_{AC}\, N_{ls} \qquad \textit{Equation 5}$$

We make two assumption in the above. First, we assume that DSM installed capacity to be 80 % of the Maximum DSM installed capacity. In other words, we assume not all ACs participating in the DSM program are operated at maximum capacity and that their consumption can be increased to the maximum capacity when DSM is economically viable. Second, we assume that all ACs participating in the DSM program are available to be turned on whenever called. This is no problem if buildings are not occupied. However, if buildings are occupied, it might hamper thermal comfort.

Finally, we limit the DSM installed capacity to a fixed exogenous capacity limit, which is the overall peak AC load as seen by the power system (Equation 6). We assume that the electricity consumption of all of the air conditioners turned on in the peak hour is available to be shifted to an earlier time.

$$N_{ls} = m_{ls} \qquad \textit{Equation 6}$$

III. RESULTS

A. Wholesale VOS declines with increasing solar share

We estimate the wholesale VOS to decline from 89 USD per MWh at 1 % solar share to less than 10 USD per MWh at 60 % solar in our Ref-AC scenario as shown in Figure 1. With the deployment of air conditioners in our Ref-AC scenario, VOS improves especially at shares of up to 20 % mainly due to the improvement of the temporal matching of solar generation with demand relative to our Ref-Simple scenario.

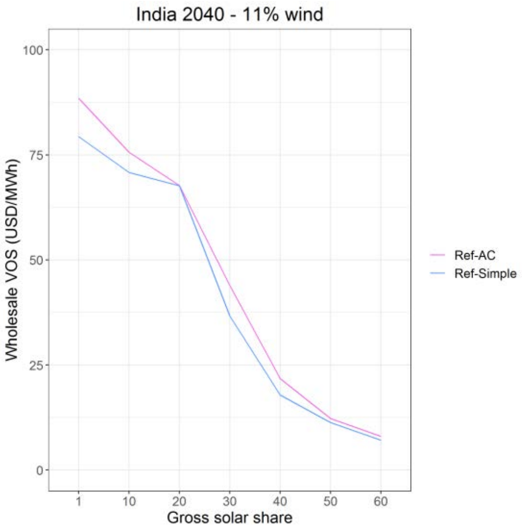

Figure 1 - Wholesale value of solar (VOS) in USD/MWh

One reason for the drop of wholesale VOS with increasing solar share is suppressed solar-coincident electricity prices and the resulting lower average electricity prices as shown in Figure 2. Electricity price during hours where solar produces decrease with increasing solar share, because less residual generation is needed, thus power plants with lower variable costs set the price (merit order effect). Average electricity prices stay flat by 20 % solar share and by 60 % solar share, price drops by about 24 USD per MWh in both of our reference scenarios.

Another reason is that a larger share of solar generation gets no revenues at all because it is curtailed as shown in Figure 3. The power system is flexible enough to accommodate solar shares of up to 20 %. However, at solar shares larger than 20 %, curtailment increases exponentially. The impact of air conditioner deployment on the curtailment is mixed, with a slight increase at shares of 30 % and 40 % and a slight decrease at higher shares.

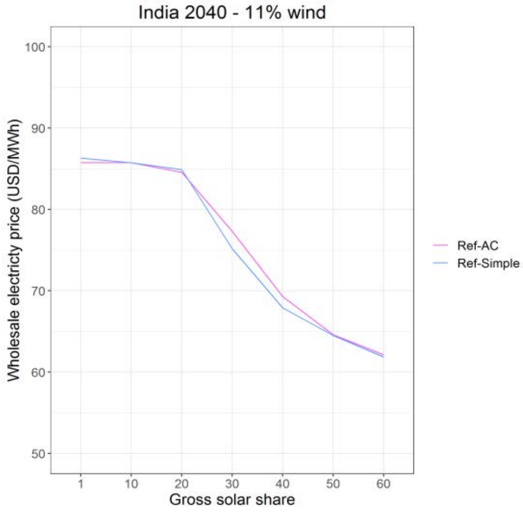

Figure 2 - The decline of average wholesale electricity prices with increasing solar share

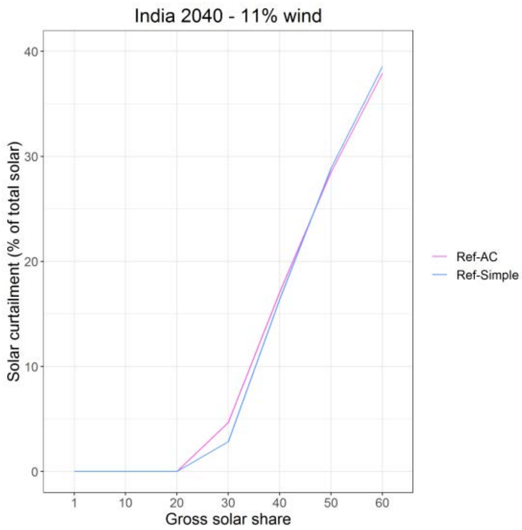

Figure 3 - Solar curtailment as percent of total solar generation

B. Precooling and CWS mitigates decline in wholesale VOS

Precooling and CWS increase the wholesale VOS up to 18 USD per MWh and 26 USD per MWh compared to our Ref-AC scenario respectively as shown in Figure 4. In the Precooling scenario, wholesale VOS starts increasing significantly only after 20 % solar share and peaks at 40 %. In the CWS scenario, however, wholesale VOS starts increasing significantly earlier than the Precooling scenario given its longer DSM duration and higher efficiency. The change in the wholesale VOS compared to the Ref-AC scenario peak at 40 % solar share in both scenarios and the change remains relatively significant at 50 % and 60 % shares in the CWS scenario.

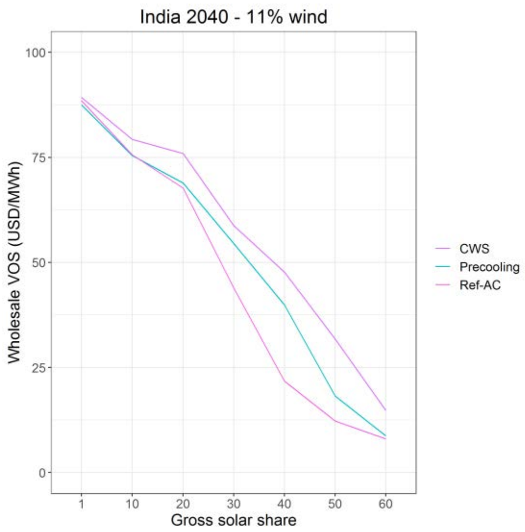

Figure 4 - Change in the wholesale value of solar due to Precooling and CWS

Figure 5 shows the net effect of Precooling and CWS on AC demand. Although total AC demand increase slightly due to inefficiencies of the storage mediums in both cases, peak AC demand actually decreases in the Precooling scenario and substantially increases in the CW scenario. Peak AC demand is shifted from 6 pm to 3 pm due to Precooling and CWS. The reason for change in the wholesale VOS in our Precooling and CWS scenarios is due to improved matching of the solar generation with the total AC demand in the Precooling and CWS scenarios.

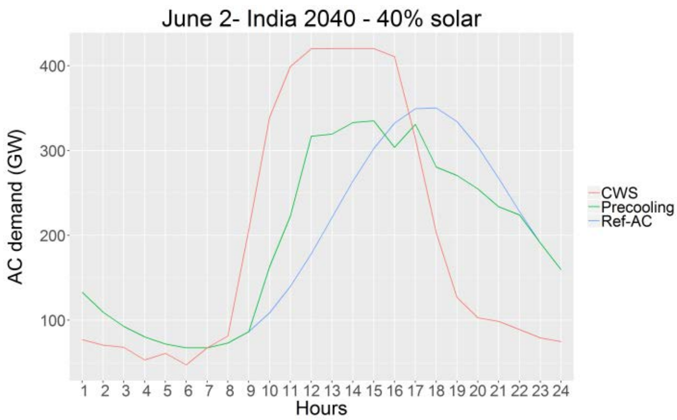

Figure 5 - Hourly AC demand before and after DSM at 40 % solar share on June 2, which is the day with the highest AC demand.

By improving the matching of the hourly solar generation with hourly AC demand, Precooling and CWS increase the average wholesale prices (Figure 6) and reduce curtailment (Figure 7) compared to the Ref-AC scenario. Average daily price in the peak AC day increase from 67 USD/MWh in the Ref-AC scenario to 82 USD/MWh in both the Precooling and CWS scenarios. One interesting finding is that although the increase in average price is the same in both DSM scenarios, solar-coincident price is higher and price is less volatile in the CWS compared to the Precooling scenario.

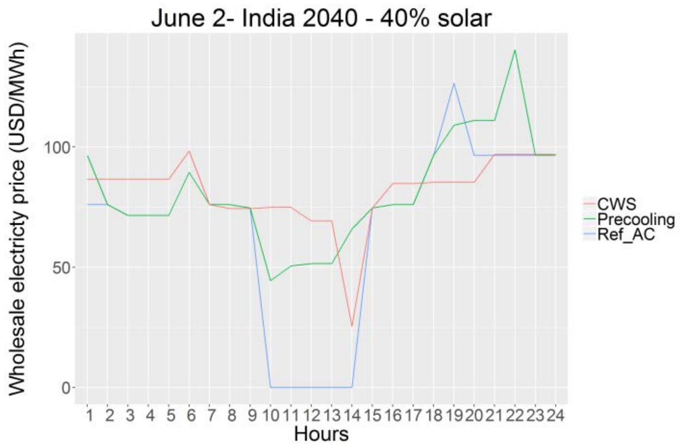

Figure 6 - Hourly wholesale price in USD per MWh on June 2, the peak AC demand day, at 40 % solar share before and after DSM

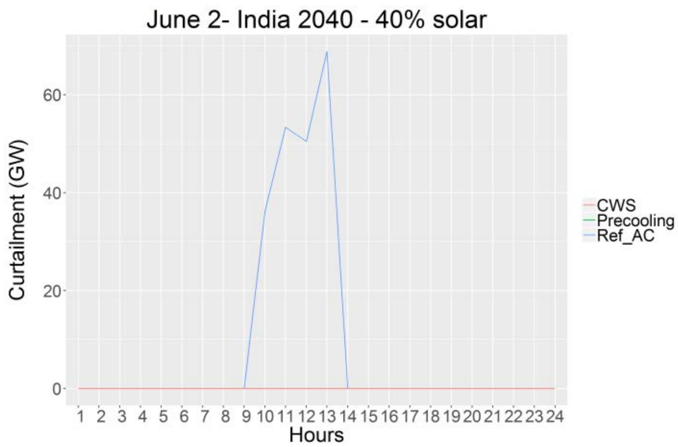

Figure 5 - Hourly solar curtailment in GW on June 2, the peak AC demand day, at 40 % solar share before and after DSM

IV. CONCLUSION AND DISCUSSION

We examined the role of two DSM measures using air conditioners with CTES to mitigate the decline in the wholesale market value of solar by shifting AC demand from hours with low or no solar PV generation to hours with high solar PV generation. Our DSM measures are implemented over different solar shares in a highly air-conditioned Indian power system in 2040 under a CO2 price of 50 USD per ton of CO2. We found that the wholesale VOS declines from 89 USD per MWh at 1 % solar share to less than 10 USD per MWh at 60 % solar in our reference scenario driven by a decrease in wholesale electricity prices while solar generation is abundant and an increase in solar curtailment.

Precooling and CWS increased the wholesale VOS up to 18 USD per MWh and 26 USD per MWh compared to our Ref-AC scenario respectively by improving the matching between solar generation and AC demand profiles, which led to increased solar-coincident wholesale electricity prices and reduced curtailment.

Precooling represents a very low-cost DSM measure that only requires equipping all buildings with a programmable thermostat [8]. Thermostat set points can be lowered when solar generation is abundant. Precooling however has some limitations. First, thermal comfort of building occupants might be hampered if the air-conditioned spaces are over-cooled. Second, storing cold in the building thermal mass is neither very efficient nor very flexible with regard to when and what rate should the stored energy be used. CWS mitigates the above limitations. However, chilled water storage tanks have relatively high investment costs and require space [9], which would be a constraint for residential buildings.

TOU rates with relatively higher peak price to off-peak price ratios that reflect actual solar PV generation are important to modify consumption patterns of residential air conditioning. However, they are not the only policy tools. DSM measures can also be directly dispatched by aggregators through the wholesale market under Demand-side bidding mechanisms (DSB). This might be more interesting for households because customers do not have to worry about varying rates and the burden will be carried by third party aggregators.

DSM measures provided by distributed thermal energy storage could make solar PV investments cost-competitive at larger shares, which is key for the transition to a low-cost and low-carbon energy system. Indian policy makers, utility planners, regulators and system operators ought to consider DSM provided by distributed CTES as a key resource when planning and setting targets for large-scale solar PV deployment and peak load management.

REFERENCES

[1] F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet, and R. C. Pietzcker, "The underestimated potential of solar energy to mitigate climate change," *Nature Energy*, vol. 2, p. 17140, Aug. 2017.

[2] A. D. Mills and R. H. Wiser, "Strategies to mitigate declines in the economic value of wind and solar at high penetration in California," *Applied Energy*, vol. 147, pp. 269–278, Jun. 2015.

[3] L. Hirth, "The market value of variable renewables: The effect of solar wind power variability on their relative price," *Energy Economics*, vol. 38, pp. 218–236, Jul. 2013.

[4] E. T. Hale, B. L. Stoll, and J. E. Novacheck, "Integrating solar into Florida's power system: Potential roles for flexibility," *Solar Energy*, vol. 170, pp. 741–751, Aug. 2018.

[5] A. Zerrahn and W.-P. Schill, "A Greenfield Model to Evaluate Long-Run Power Storage Requirements for High Shares of Renewables," *SSRN Journal*, 2015.

[6] A. Zerrahn and W.-P. Schill, "On the representation of demand-side management in power system models," *Energy*, vol. 84, pp. 840–845, May 2015.

[7] A. Levesque, R. C. Pietzcker, and G. Luderer, "Halving energy demand from buildings: The impact of low consumption practices," *Technological Forecasting and Social Change*, vol. 146, pp. 253–266, Sep. 2019.

[8] W. J. Cole, J. D. Rhodes, W. Gorman, K. X. Perez, M. E. Webber, and T. F. Edgar, "Community-scale residential air conditioning control for effective grid management," *Applied Energy*, vol. 130, pp. 428–436, Oct. 2014.

[9] A. Van Asselt, D. T. Reindl, and G. F. Nellis, "Policy recommendations for using cool thermal energy storage to increase grid penetration of renewable power sources (1607-RP)," *Science and Technology for the Built Environment*, pp. 1–11, Dec. 2017.