A Framework to Reduce Dust Problems on PV Modules in the US Climatic Zones

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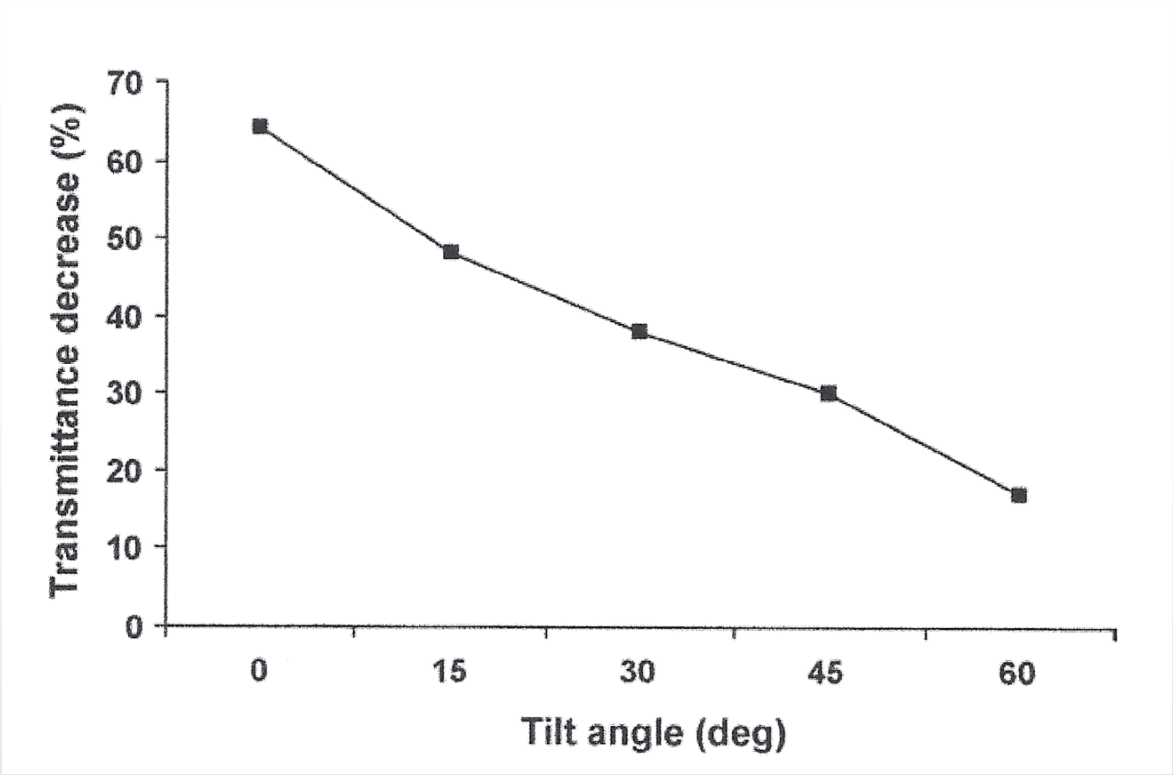
STUDY OBJECTIVES

- PROVIDES AN OVERVIEW OF THE RESEARCH OF PV SOILING PROBLEMS; ESPECIALLY DUST OR/OR SAND AND COMBINED DUST-MOISTURE CONDITIONS IN ASHRAE CLIMATIIC ZONES IN THE UNITED STATES.
- REVIEWS THE IMPACT OF DUST DEPOSITION ON THE PERFORMANCE OF SOLAR PV AND IDENTIFIES CHALLENGES TO FURTHER RESEARCH IN THIS AREA.
- PRESENTS RECOMMENDATIONS TO GUIDE IN IDENTIFYING THE APPROPRIATE CLEANING/MAINTENANCE CYCLE FOR PV SYSTEMS IN RESPONSE TO THE PREVALENT CLIMATIC AND ENVIRONMENTAL CONDITIONS IN THE UNITED STATES' CLIMATIC ZONES.

ONGOING RESEARCH

- RESEARCH HAS AIMED TO STUDY THE DUST DEPOSITION PRIMARILY IN THE CONTEXT OF PV INSTALLATIONS.
- RESEARCH CAN BE CATEGORIZED INTO THE 2 MAIN TOPICS.
  - FIRST, THE WIND EFFECTS/DIRECTIONS AND EXPOSURE TIME STUDIES, PRIMARILY LOOKED INTO SYSTEM CHARACTERISTICS SUCH AS TILT ANGLE, GLAZING, AND ITS IMPACT OF DUST ACCUMULATION.
  - SECOND, ARE THE MORE COMPREHENSIVE STUDIES ON DUST PARTICLES PHYSICS AND CHEMISTRY WITH GREATER ACCURACY IN EXPERIMENTAL INVESTIGATIONS.

DUST IMPACT ON PV PERFORMANCE: WIND EFFECTS-EXPOSURE TIME-TILT ANGLE

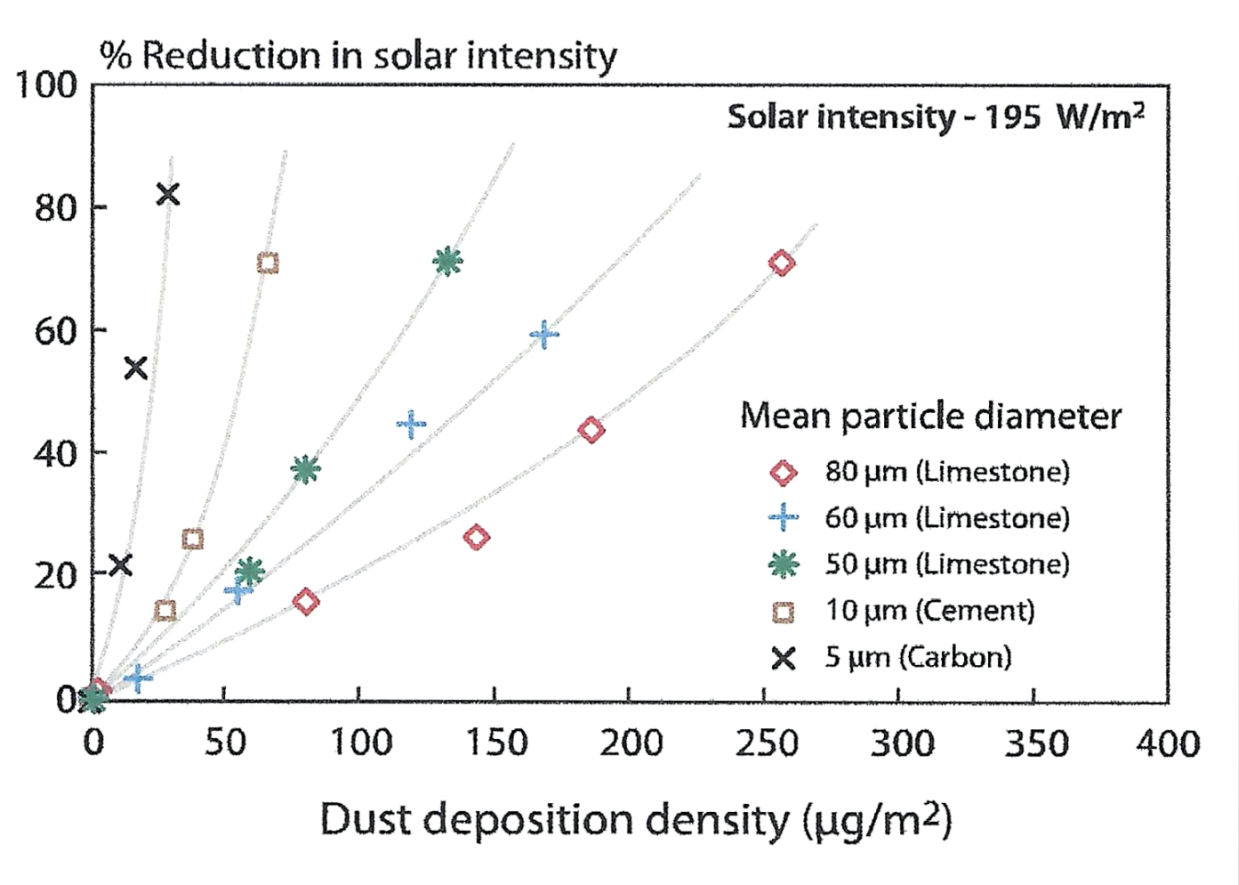


REDUCTION IN SOLAR INTENSITY FOR VARIOUS PARTICLE SIZE DUE TO DUST DEPOSITION

DUST IMPACT ON PV PERFORMANCE: WIND EFFECTS-EXPOSURE TIME-TILT ANGLE

- STUDY EXAMINED THE REDUCTION IN TRANSMITTANCE VS. TILT ANGLE IN THE ARABIAN DESERT.
- IT FOUND A REDUCTION IN PLATE-TRANSMITTANCE BY AN AMOUNT RANGING FROM 64% TO 17% FOR TILT ANGLES RANGING FROM 0° TO 60°, RESPECTIVELY AFTER 38 DAYS OF EXPOSURE.
- IN ADDITION, A REDUCTION OF 30% IN USEFUL ENERGY GAIN WAS OBSERVED BY THE HORIZONTAL COLLECTOR AFTER 3 DAYS OF DUST ACCUMULATION.

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE



REDUCTION IN SOLAR INTENSITY FOR VARIOUS PARTICLE SIZE DUE TO DUST DEPOSITION

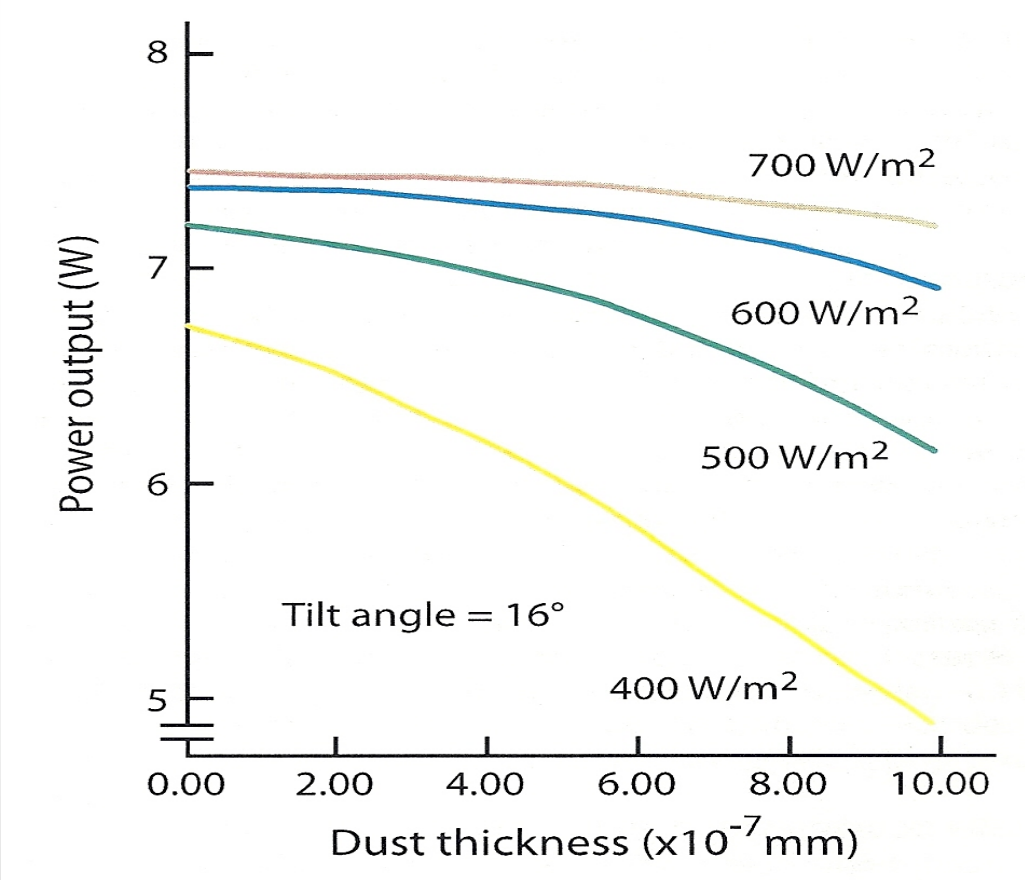
DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

- STUDY INVESTIGATED THE PHYSICAL PROPERTIES OF THE DUST ACCUMULATION AND DEPOSITION DENSITY ON THEIR IMPACT ON DEGRADING PV EFFICIENCY.
- STUDY WAS SIMULATED WITH ARTIFICIAL DUST (INCLUDING LIMESTONE, CEMENT AND CARBON PARTICULATES) AND HALOGEN LAMPS. WHILE KEEPING THE SOLAR (LIGHT) INTENSITY CONSTANT AND VARYING THE DIFFERENT DENSITIES OF DUST.

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

- THE STUDY REVEALED THE IMPACT OF CEMENT PARTICLES TO BE THE MOST SIGNIFICANT, WITH A 73 G/M2 DEPOSITION OF CEMENT DUST RESULTING IN AN 80% DROP IN PV SHORT-CIRCUIT VOLTAGE; ATMOSPHERIC DUST WITH MEAN DIAMETER 80 MM AT 250 G/M2 WAS FOUND TO REDUCE THE SHORT-CIRCUIT CURRENT BY 82%.
- FINE CARBON PARTICULATES (5 MM) WERE FOUND TO HAVE THE MOST DETERIORATING EFFECT ON THE PV EFFICIENCY.
- THE STUDY ALSO FOUND THE IMPACT OF FINER PARTICLES TO HAVE A GREATER IMPACT THAN COARSER PARTICLES ON PV PERFORMANCE. (EL-SHOBOKSHY ET AL., 1993)

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

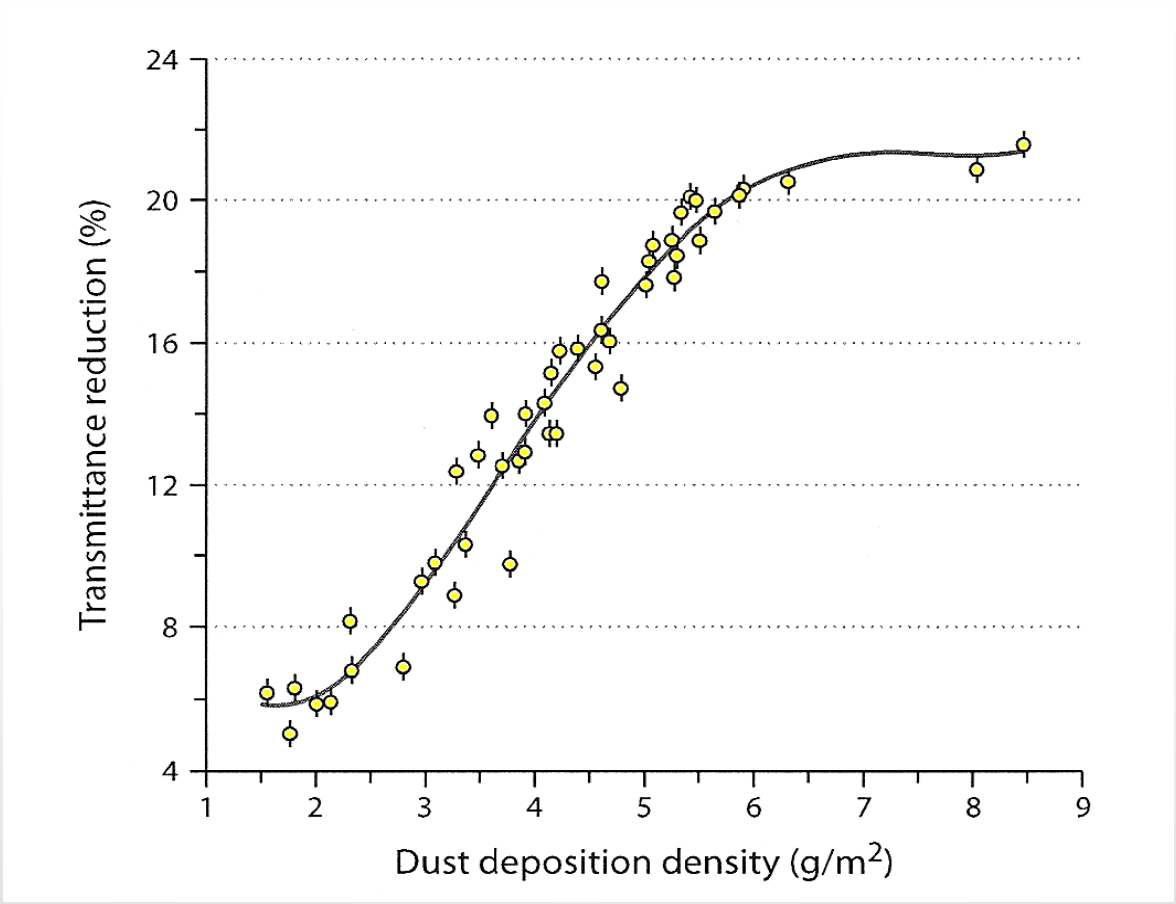


POWER DEGRADATION OF A PV MODULE FOR VARIOUS INTENSITIES AS A FUNCTION OF DUST THICKNESS

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

- STUDY CONDUCTED AN EVALUATION ON SOLAR ENERGY USE IN KENYA. THE PV MODULE-BASED STUDY FOCUSED ON THE IMPACT OF DUST LAYER DENSITY, TILT ANGLE, AND SOLAR INTENSITY.
- IT CONCLUDED THAT AS SOLAR INTENSITY INCREASED, PV PERFORMANCE DUE TO DUST ACCUMULATION DECREASED.
- AT 700 W/M2, THE REDUCTION IN OUTPUT WAS ALMOST NEGLIGIBLE. HOWEVER, WHEN SOLAR INTENSITY DROPPED TO 400 W/M2, THE LOSS WAS NEAR 25% OF INITIAL POWER OUTPUT. (MAILUHA ET AL., 1994)

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

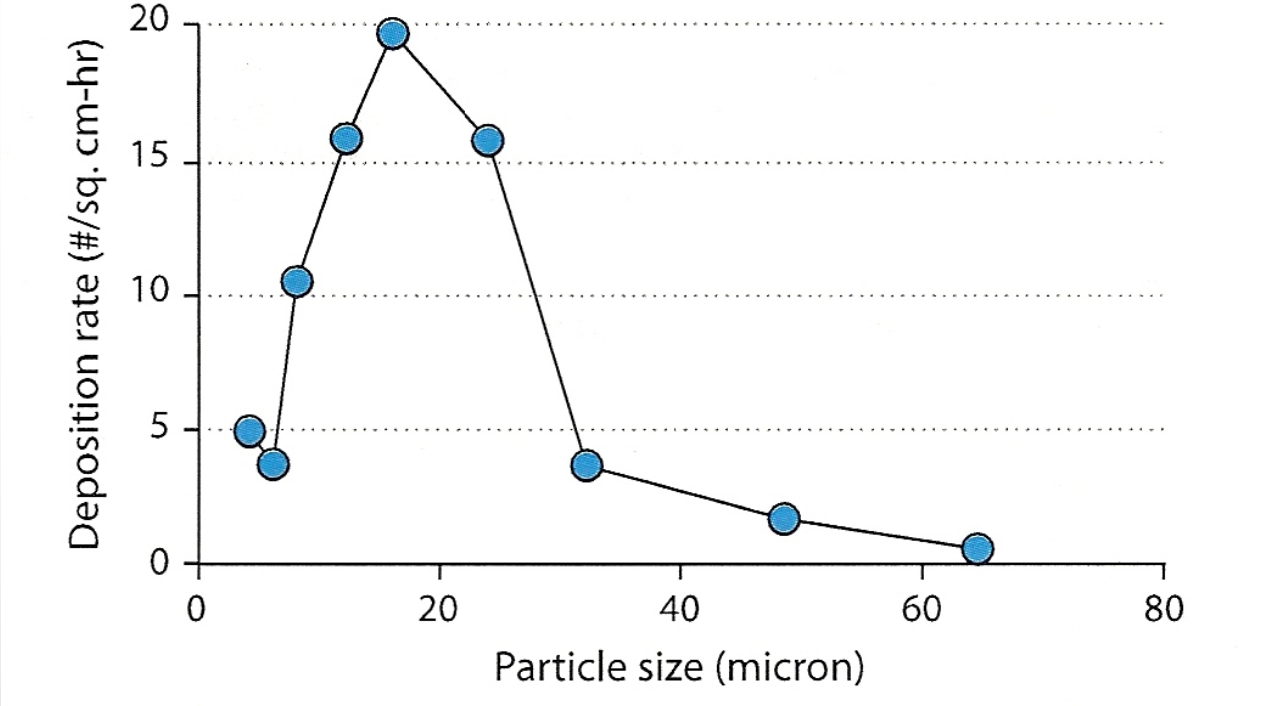


SOLAR TRANSMITTANCE REDUCTION AS A FUNCTION OF DUST DEPOSITION DENSITY

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

- THE STUDY EXPERIMENTED 100 GLASS PLATES WITH DIFFERENT TILT AND AZIMUTH ANGLES.
- THE GLASS TRANSMITTANCE WAS EVALUATED AT REGULAR INTERVALS OVER A 7 MONTHS PERIOD FOR THE PREVALENT WIND CONDITIONS, INCLUDING THUNDERSTORMS.
- THE STUDY REVEALED A REDUCTION IN DUST DEPOSITION FROM 15.84 G/M2 (FOR A 0° TILT) TO 4.48 G/M2 (FOR A 90° TILT) AND A CORRESPONDING INCREASE IN TRANSMITTANCE FROM 12.33% TO 52.54%.
- A CRITICAL OBSERVATION REVEALED THAT DIFFERENCES IN HUMIDITY LED TO THE FORMATION OF DEW ON THE PV SURFACE WHICH COAGULATED DUST.
- WEEKLY CLEANING CYCLE WAS RECOMMENDED FOR MODERATELY DUSTY PLACES. (ELMINIR ET AL., 2006)

DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE



PARTICLE SIZE AS A FUNCTION OF DEPOSITION RATE OF A SOLAR COLLECTOR IN THE DESERT AREA

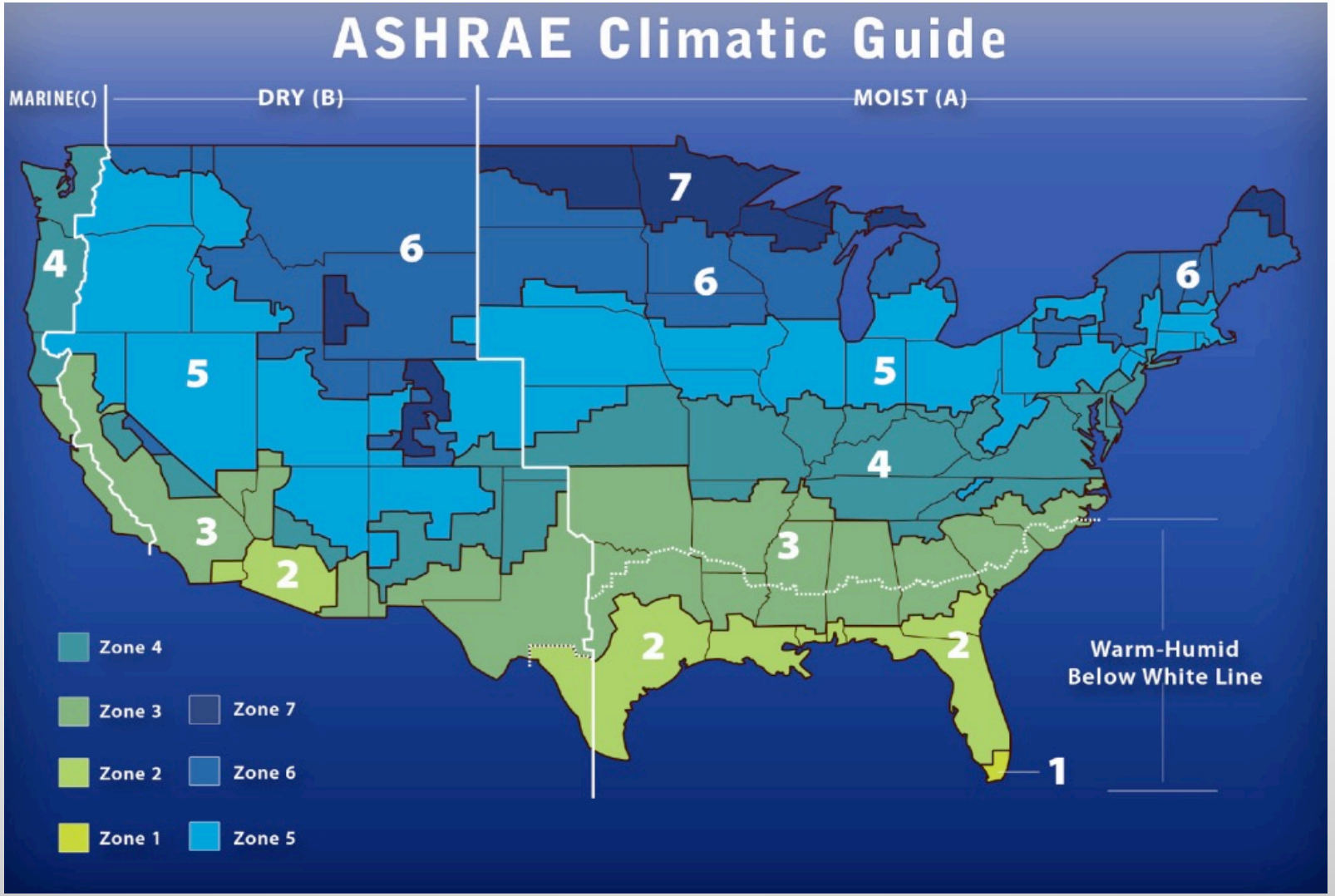
DUST PHYSICAL & CHEMICAL PROPERTIES IMPACT ON PV PERFORMANCE

- STUDY IS CONDUCTED IN THE NEGEV DESERT.
- IT EVALUATES PARTICLE SIZE DISTRIBUTION USING VARIOUS MICROSCOPIC TECHNIQUES.
- A RELATIONSHIP WAS FOUND BETWEEN DEPOSITION RATE, TILT ANGLE, PV PERFORMANCE, AND PARTICLE SIZE.
- THE STUDY FOUND THAT 90% OF DUST PARTICLE DIAMETER RANGES BETWEEN 5 AND 60 MICRON. THE HIGHEST DEPOSITION RATE PER SQUARE CENTIMETER PER HOUR IS FOUND IN PARTICLES THAT RANGE BETWEEN 15 AND 25 MICRON.
- THIS SUPPORTS THE BIGGER THE SIZE, THE SLOWER THE DEPOSITION RATES IN DESERT AREAS. (BIRYUKOV, 1996)

U.S. CLIMATIC ZONES: ASHRAE CLIMATE CLASSIFICATION

- ASHRAE CLIMATE ZONES FOR THE UNITED STATES USES NUMBERS (0-8) AND 3 LETTER SYSTEM (A,B,C) TO DEFINE CLIMATE ZONES.
- THE FIRST NUMBER REPRESENTS A LOCATION'S MAIN CLIMATE TYPE (TEMP DATA): 1: VERY HOT, 2: HOT, 3: WARM, 4: MIXED, 5: COOL, 6: COLD, 7: VERY COLD, 8: SUBARCTIC/ARCTIC.
- A SECOND LETTER ASSIGNED BASED ON PRECIPITATION: A: HUMID, B: DRY, C: MARINE
- THE UNITED STATES HAS 8 OF THE 9 DEFINED ASHRAE CLIMATE ZONES.
- ZONE 0 DOES NOT EXIST IN THE U.S.

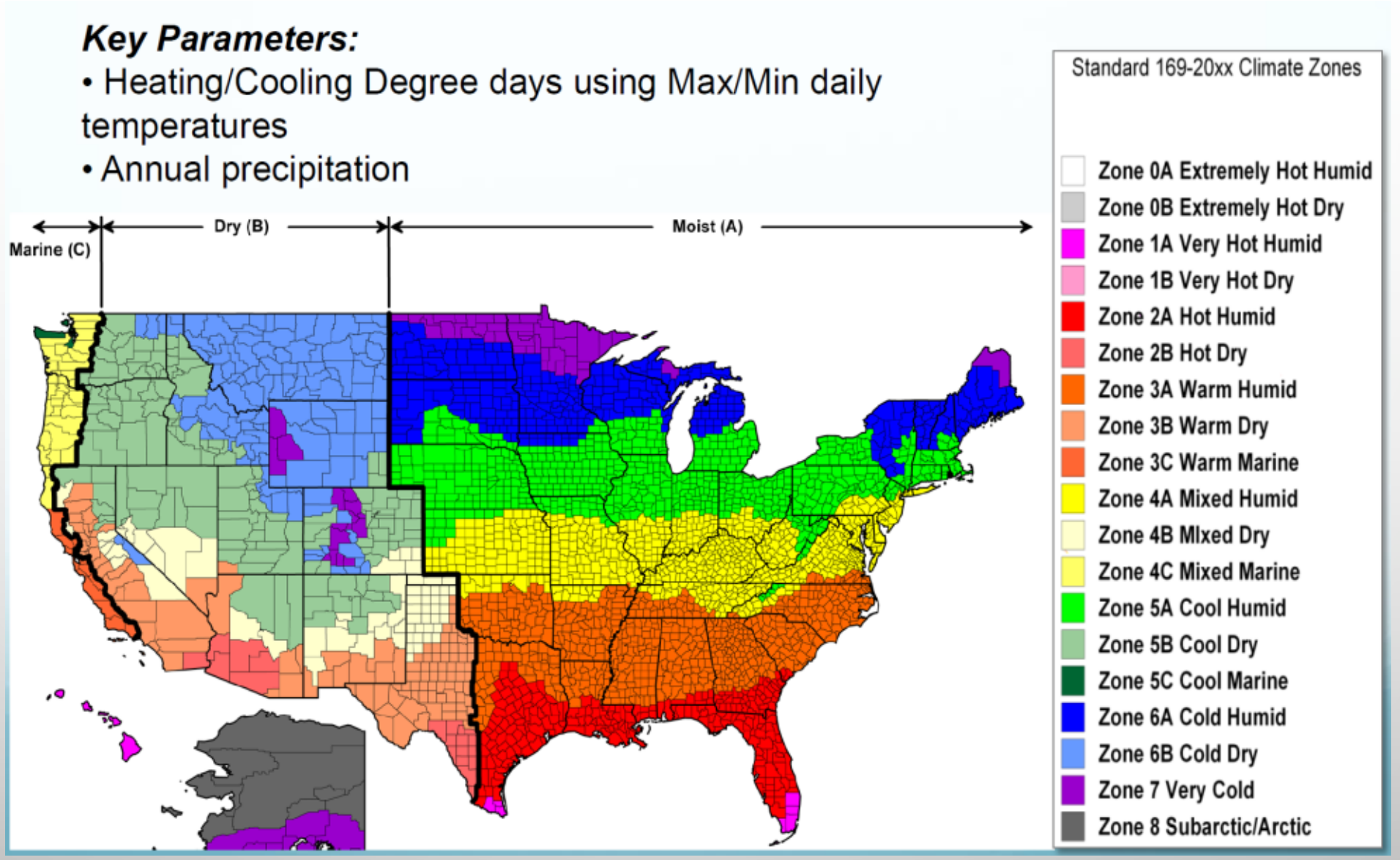
CLIMATIC ZONES OF CONTINENTAL UNITED STATES



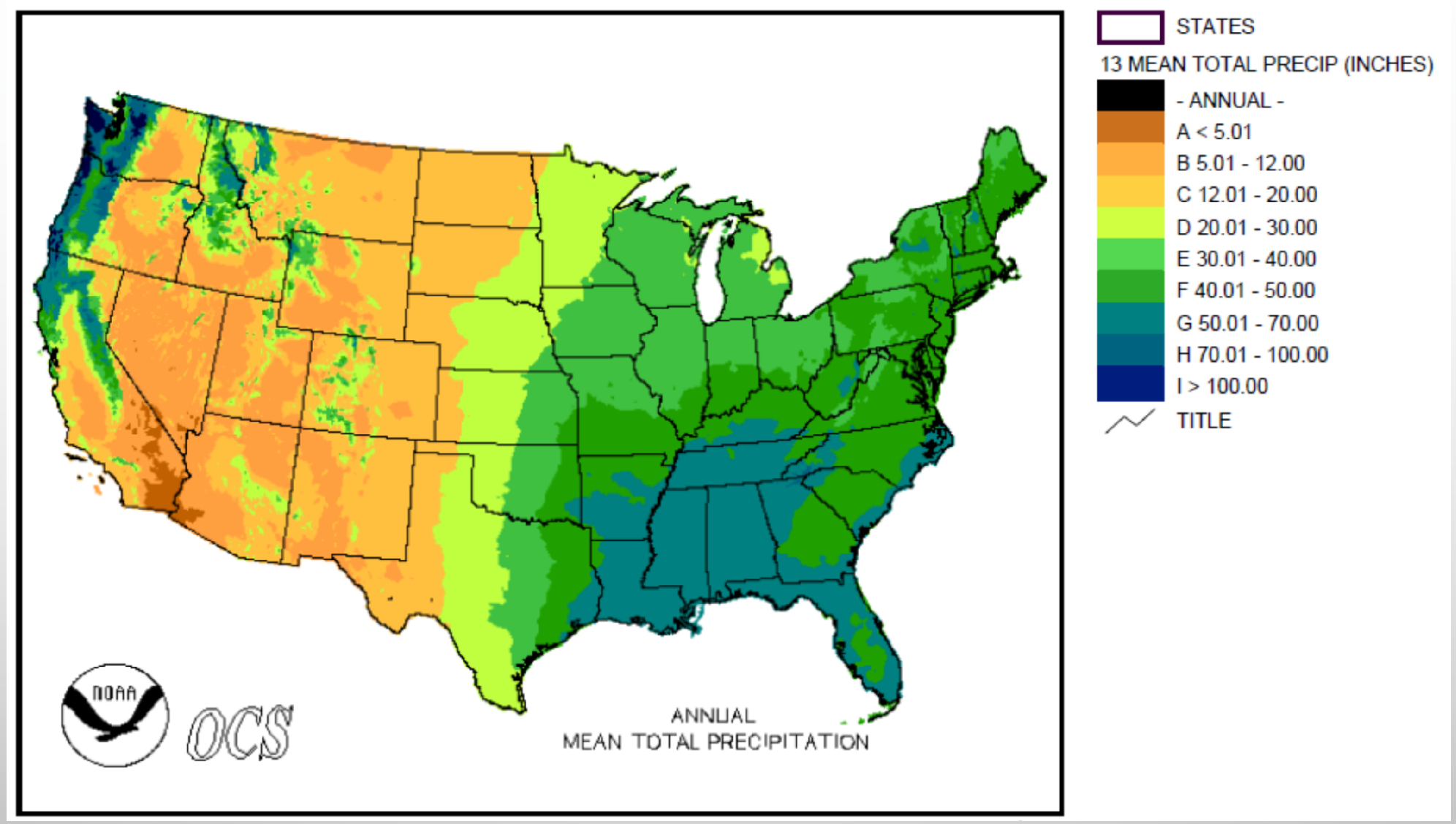
MORE BREAKDOWN OF CLIMATIC ZONES OF UNITED STATES

Key Parameters:

- Heating/Cooling Degree days using Max/Min daily temperatures
- Annual precipitation



ANNUAL PRECIPITATION – U.S , SELF CLEAN PV



DUST MITIGATION RECOMMENDATIONS FOR U.S. CLIMATIC ZONES

Climate Zone	Characteristics Location within the U.S.	Conditions affecting PV performance and dust deposition.	Cleaning Frequency & Recommendations
1-A **VERY HOT HUMID** (TROPICAL)	Tropical climate: without frost, coolest month is warmer than 65ºF (18ºC) e.g. Extreme Southern FL, FL Keys, West Palm Beach area, Miami	Mostly low latitudes and require low tilt in PV systems to maximize energy Lower tilt angles tend to accumulate more dust deposition, therefore, tilt PV modules higher than latitude is recommended to reduce dust accumulation High annual rainfall minimizes dust accumulation	Periodic washing by continuous annual precipitation reduces dust accumulation Cleaning is recommended of a weekly/biweekly basis during dry season Frequency depends on intensity of dust accumulation

DUST MITIGATION RECOMMENDATIONS FOR U.S. CLIMATIC ZONES

Climate Zone	Characteristics Location within the U.S.	Conditions affecting PV performance and dust deposition.	Cleaning Frequency & Recommendations
2-A **HOT HUMID** Warm winter	Wet- tropical: without frost, coolest month is warmer than 65ºF (18ºC) e.g. FL, Southern of GA, AL, MS, LA, SE of TX	Mostly low latitudes and require low tilt in PV systems to maximize solar energy PV systems with higher tilt angle are recommended in subtropical areas to reduce dust accumulation Utilize wind during the dry season to blow dust from the panels.	Periodic washing by continuous annual precipitation reduces dust accumulation Cleaning is recommended weekly for moderate dust accumulation in the dry season.
2-B **HOT-DRY** (ARID) Desert Mild/warm winter	Arid climate: evaporation exceeds precipitation Arid (desert): minimal annual rainfall Many regions: SW of TX, Southern AZ	Dusty desert environments and frequent dust storms reduces PV efficiency Low humidity and rainfall contribute to the problem High temperature reduces PV performance Has the max available, and intense solar radiation than any other regions	Cleaning to respond to intensity of dust accumulation-at least a weekly cleaning is recommended Immediate cleaning following dust storms is required Application of dust-repelling coatings is highly recommended as preventative approach

DUST MITIGATION RECOMMENDATIONS FOR U.S. CLIMATIC ZONES

Climate Zone	Characteristics Location within the U.S.	Conditions affecting PV performance and dust deposition.	Cleaning Frequency & Recommendations
3-A WARM-HUMID Mild/warm winter	Wet- semi-tropical: without frost, coolest month is warmer than 50ºF (10ºC) e.g. NC, SC, GA, AL, MS, LA, AR, OK	Mostly low latitudes and require low tilt in PV systems to maximize solar energy PV systems with higher tilt angle are recommended in subtropical areas to reduce dust accumulation Utilize wind during the dry season to blow dust from the panels.	Periodic washing by continuous annual precipitation reduces dust accumulation Cleaning is recommended weekly for moderate dust accumulation in the dry season.
3-B WARM-DRY Tundra (Savannah) Semi Desert Cool winter	Arid climate: evaporation exceeds precipitation Semi-arid (steppe): low annual rainfall Many regions: West TX, Parts of AZ, Southern and middle CA (away from ocean)	High latitudes require high tilt angle in PV system; a lower fixed tilt angle is recommended to optimize year-round solar gain Dust generally tends to fall off with an increased tilt angle Areas with higher rainfall would aid in cleaning the PV panels	With low rainfall and high tilt angle, a moderate frequency cleaning cycle (weekly) is recommended More frequent cleaning cycle is recommended with lower tilt angle (to maximize solar gain) A less intense (weekly or biweekly) cleaning cycle is adequate for above 40º N

DUST MITIGATION RECOMMENDATIONS FOR U.S. CLIMATIC ZONES

Climate Zone	Characteristics Location within the U.S.	Conditions affecting PV performance and dust deposition.	Cleaning Frequency & Recommendations
4-A MIXED-HUMID (TEMPERATE-HUMID) humid, no dry season warm summer cool winter	Temperate, subtropical climate: 8 months or more of average warmer than 50ºF(10ºC), rainfall all year MD, DE, VA, WV, KY, MO, KS.	A lower fixed tilt angle is recommended to optimize year-round solar gain in temperate areas. High latitudes require high tilt angle Dust generally not a problem unless combined with heavy moisture Heavy rainfall aids in cleaning the PV panels	The least intense cleaning required- a monthly or bi-weekly cleaning cycle is adequate Intense rainfall washes off the dust from the panels and maximize benefits of nature
4-B MIXED-DRY (TEMPERATE-DRY) tundra/dry warm summer cool winter	Temperate, subtropical climate: 8 months or more of average warmer than 50ºF(10ºC), Dry summer (Mediterranean) Northern TX, NM	High latitudes require high tilt in PV system; a lower fixed tilt angle is recommended to optimize year-round solar gain Dust generally tends to fall off with the increase in the tilt angle	Recommended cleaning weekly or bi-weekly depending upon the rate of dust accumulation on the surface. Regions with higher dust accumulation may need a daily cleaning

DUST MITIGATION RECOMMENDATIONS FOR U.S. CLIMATIC ZONES

Climate Zone	Characteristics Location within the U.S.	Conditions affecting PV performance and dust deposition.	Cleaning Frequency & Recommendations
5-A **COOL-HUMID** **6-A** **COLD-HUMID** humid, no dry season mild summer cool summer	Cool to Cold, temperate, moist, and forest: 4-8 months of average warmer than 50ºF (10ºC), rainfall all year **5-A**: PA, OH, MI,, IL, IA, NE **6-A**: ME, NH, VT, WI, MN, ND, SD	Dust is less critical factor in comparison to maximizing solar gain in these regions Sun movable tracking may be needed to harness solar energy Colder temperature improves PV performance Dust generally tends to fall off at near-vertical tilt angles	Weekly cleaning cycle is adequate A less intense biweekly cleaning cycle is adequate for above 40º N Intense rainfall washes off the dust from the panels and maximize benefits of nature Removing snow accumulation needs to be frequent and immediate after snow storms
5-B **COOL-DRY** **6-B** **COLD-DRY** mild summer cool summer	Cool to cold, mountain climate, changes rapidly, has same seasons of wet and dry periods of the immediate surrounding climate. e.g. Higher latitudes. 5-B: CO, UT, ID 6-B: MT, WY	High latitudes require high tilt angle closer to vertical Sun movable tracking may be needed to harness solar energy Colder temperature reduces PV cells heat and improves performance Dust generally tends to fall off at near-vertical tilt angle	Weekly cleaning frequency is adequate Removing snow accumulation needs to be frequent and immediate after snow storms

HOW TO REMOVE AND PREVENT DUST

- IN AREAS OF LOW-SOILING CONDITIONS AND/OR PERIODIC RAIN (E.G. NW U.S), DUST REPRESENTS NO MAJOR PROBLEM. NATURALLY, RAIN, OR SNOW, WOULD CLEAN THE SURFACES PERIODICALLY. THIS IS VALID IN MOST OF THE UNITED STATES
- IN AREAS OF HIGH MOISTURE AND HEAVY MORNING DEWS, PERFORMANCE IS AFFECTED BY COMPOUNDING OF DUST PROBLEM. LIGHT RAIN CAN COLLECT PARTICLES AND FORM A RESIDUE THAT STICK TO THE COLLECTOR UNLESS IT IS CONTINUOUS AND WASH OFF THE SURFACE.
- IN DESERT AREAS (E.G. SW U.S), PV HAVE TO BE CLEANED REGULARLY BY WIPING, CLEANING ROBOTS, OR PROTECTIVE GLASS COATINGS. THESE AREAS ARE THE MOST PROBLEMATIC IN THE U.S. BECAUSE OF ITS DESERT NATURE.

MANUAL WASH

MACHINE AND ROBOTS

MACHINE AND ROBOTS

CONCLUSION

- PAPER REVIEWS THE RESEARCH DEVELOPMENT, CHALLENGES RELATING TO THE DUST DEPOSITION ON PV INSTALLATIONS.
- IT PROVIDES ANALYSIS ON THE ENVIRONMENTAL EFFECTS (WIND, EXPOSURE) ON DUST DEPOSITION, AND THE DUST PARTICLE ANALYSIS (PHYSICAL AND CHEMICAL PROPERTIES) AND HOW IT AFFECTS PV PERFORMANCE.
- IT ANALYZES UNITED STATES CLIMATIC ZONES AND PROVIDES DUST MITIGATION RECOMMENDATIONS BASED ON THE VARIATION IN WEATHER CONDITIONS FOR EACH ZONE.
- IT HIGHLIGHTS THE PROBLEMS ASSOCIATED WITH DESERT CLIMATE IN REGIONS LIKE THE SOUTHWEST OF THE U.S. THESE AREAS HAVE THE GROWING AND HIGHEST POTENTIAL IN INTEREST AND INVESTMENT BUT NEED TO MITIGATE THE DUST ACCUMULATION PROBLEMS ASSOCIATED WITH IT.

THANK YOU FOR YOUR ATTENTION