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An overview of sound from commercial photovoltaic facilities

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ABSTRACT

Do solar photovoltaic power projects generate sound? The quick answer is that while solar panels themselves are largely silent, the infrastructure around larger commercial photovoltaic projects do generate sound. This paper discusses the components of solar projects from a sound perspective - transformers, inverters, storage devices, and tracking motors. The paper will give ranges of component sound emissions and provides sound propagation modeling guidance for use in project permitting.

1 INTRODUCTION

Since 2013, the amount of electricity generated by solar in the U.S. has increased by over 800 percent. The U.S. Energy Information Administration (EIA) expects this increase to continue, with another nine-fold increase in the next 30 years (Figure 1). By 2050, the EIA forecasts renewable energy sources will exceed natural gas in U.S. electricity generation.

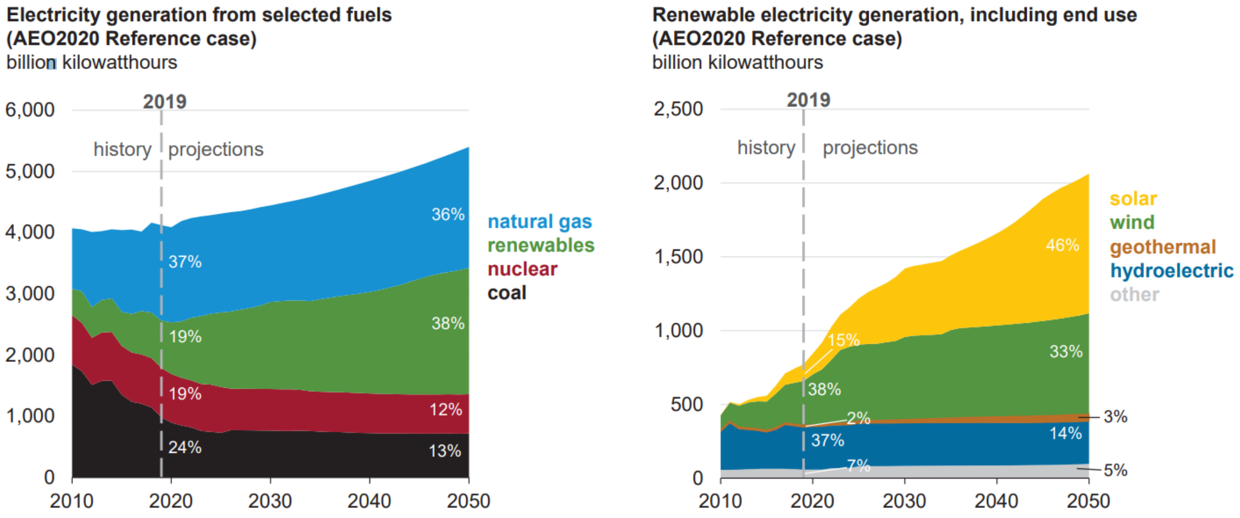

Figure 1*: U.S. electricity generation by source [1]*

Much of this rapid growth has been in relatively large photovoltaic facilities. The projects are often located in tracts of former agricultural land, desert lands, pasture, and even abandoned mines. These projects contain hundreds or thousands of photovoltaic panels with the larger projects generating more than 100,000 kW of AC power.

In a typical solar project, a photovoltaic panel converts sunlight into DC power. The panels may be mounted on motorized single axis or dual axis trackers, that tilt the panels to optimize power generation. This power is collected and converted from DC to AC by power inverters. These inverters are often co-located with power transformers that increase the AC power to a medium voltage. In some cases, the inverters and power transformers are combined in a single unit. The power can then be stored in batteries or other devices. For transmission to the utility grid, the power is stepped up to higher voltage by a substation transformer. This entire process is shown in Figure 2.

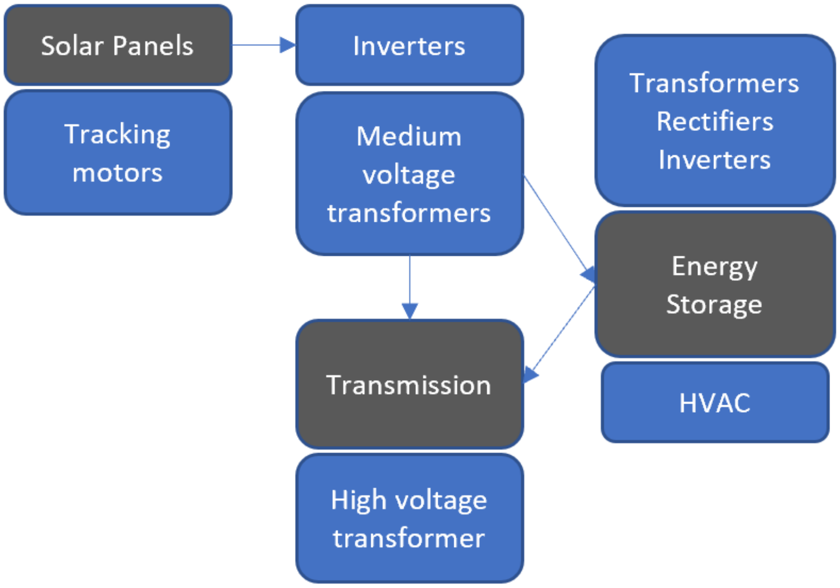

Figure 2: *Generic solar energy power flow (arrows) and sound sources (blue boxes)*

Do these processes generate sound? The quick answer is, “yes”. While the photovoltaic panels convert sunlight to DC power silently, the other equipment, including tracking motors, inverters, medium and high voltage transformer, and energy storage generate sound. As a result, these sounds should be considered when designing larger solar projects to assess noise impacts to neighboring properties.

This paper first discusses the equipment used in larger solar projects and their associated sound emissions, and then discusses modeling to assess sound levels at neighboring properties.

2 SOLAR EQUIPMENT AND SOUND EMISSIONS

2.1 Solar panels

Solar panels in and of themselves do not generate sound. However, they do affect the overall acoustics of a solar power project. The panels, particularly when blocking the line of sight between source and receiver, will act as a sound barrier. However, this effect has not yet been thoroughly quantified and it is beyond the scope of the most common sound propagation modeling algorithms (i.e. ISO 9613-2, Harmonoise, etc.,) to directly model them.

At the present time, we, ignore the barrier attenuation from solar panels. In doing so, sound propagation models will tend to overstate the actual sound levels from sources surrounded by solar panels (e.g. inverters and medium voltage transformers) at distant receptors.

2.2 Tracking motors

Tracking motors are small motors that rotate the panels so they "track" the sun's location in the sky. Not all solar power projects use tracking motors, though when they are used, their acoustical contribution to a project should be taken into account.

The overall sound emissions of the trackers vary depending on the overall size and type of the tracker. Figure 3 shows a range of tracker sound emissions, though this data is dominated by the products of a single manufacturer (most manufacturers do not publish tracker sound emissions data).

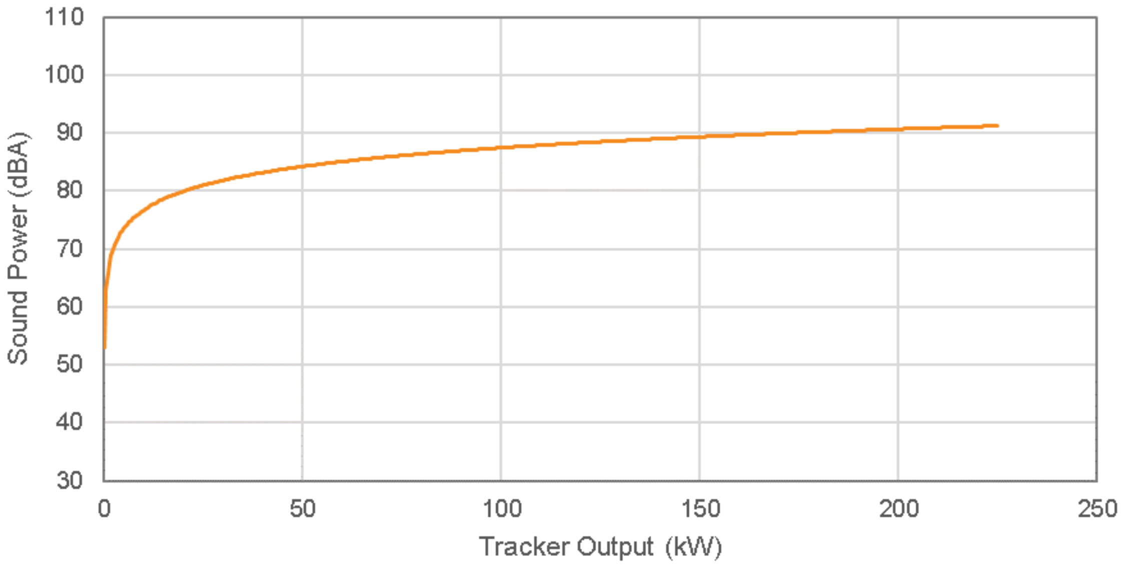

***Figure 3**: Tracker Sound Emissions*

2.3 Inverters

Inverters convert the DC power generated by the solar panels to AC power. They can also be used for VAR support. Inverters generally come in three types: micro, string, and central. Micro-inverters are small and generally associated with single panels. However, these are almost never used in commercial installations. String inverters service the power from a series of solar panel rows. Central inverters convert power from a large portion or the entire project at once.

The sound power levels for string and central inverters are shown in Figure 4. This figure is based on a library of 27 string inverters and 30 central inverters. Most of the data is from manufacturer literature. The logarithmic regression line for the string inverters has an R^2 of 0.81. The linear regression lines for the central inverters has an R^2 of 0.55. Both are significant with p values <0.001. As shown, the fans of the central inverters increase sound levels by about 7.5 dB.

Figure 5 shows the measured spectra of several inverters ranging from 3 to 3,000 kW. The results do not show much consistency, except that most spectra have some peaks somewhere in the spectrum though where this peak occurs varies from unit to unit.[1]

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[1] Some of this data comes from [5].

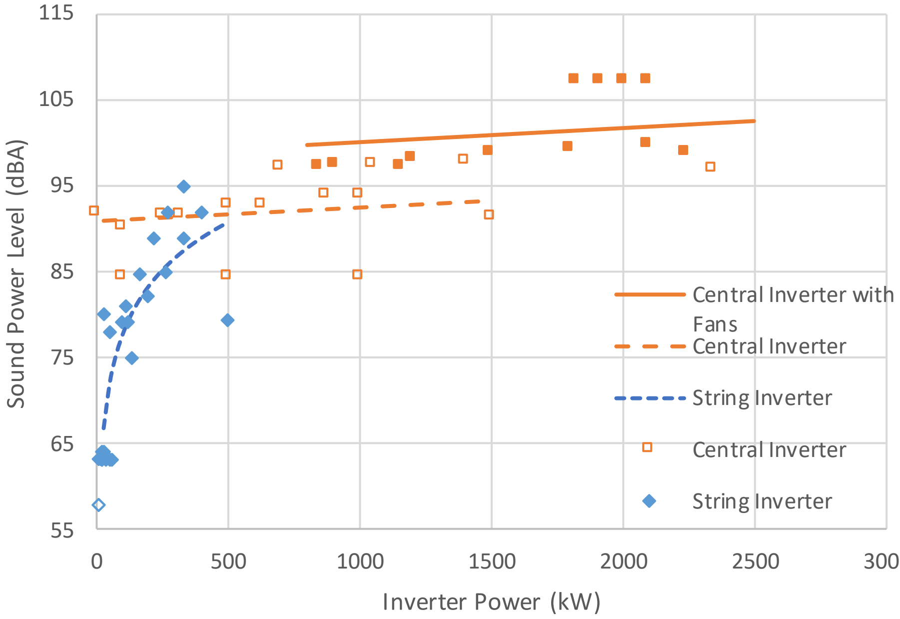

Figure 4*: Average sound power for string and central inverters as a function of inverter power. Solid markers are with fans, hollow markers are without fans*

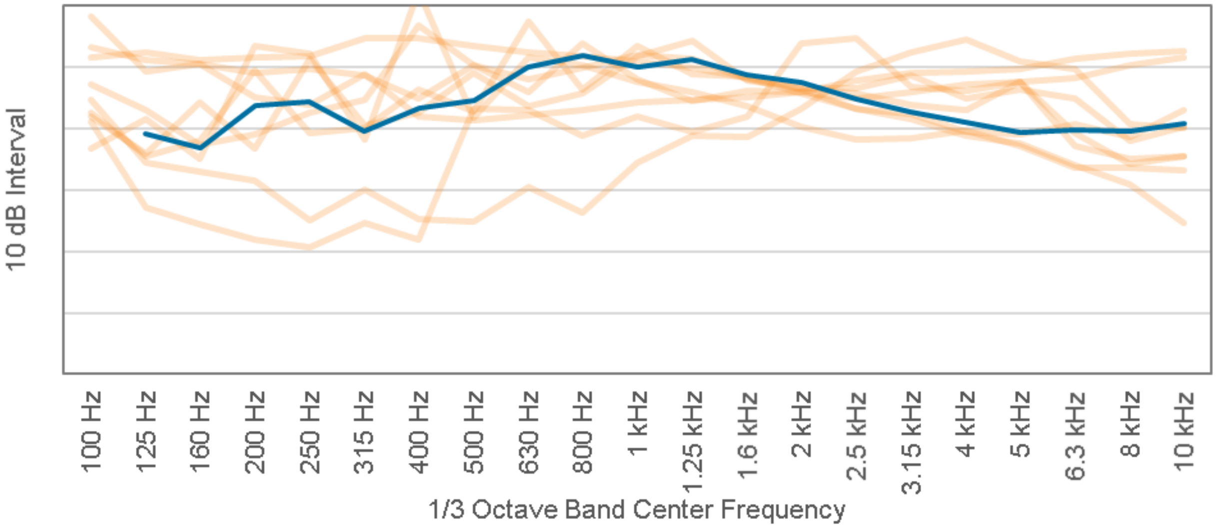

Figure 5*: Inverter spectra – The blue line is a moving average and orange lines are individual spectra*

2.4 Medium and high voltage transformers

A larger solar photovoltaic facility usually has two types of transformers. The first are medium voltage transformers that are often co-located with the inverters. These transformers are usually passively cooled. In some cases, the inverters and medium-voltage transformers are integrated within the same cabinet.

The second type are high voltage transformers. These connect the entire project to the utility distribution grid by stepping up the power from the medium voltage to the voltage of the power line. There is usually one high voltage transformer in a project, but larger projects may have more. These transformers often have two or three stage cooling, including the use of cooling fans.

By default, the sound pressure level of transformers is given in standard NEMA TR-1 [2] and is a function of the transformers' basic insulation level (BIL), two-winding rating (in kVA), and cooling stage. To convert sound pressure level to sound power level, standard IEC 60076-10 is used which requires knowledge of the transformer dimensions.

While NEMA TR-1 represents the maximum sound pressure level, transformer noise can be mitigated at the source. This is especially true with "low-loss" transformers, which are often about 10 dB below the NEMA TR-1 levels. For other abatement techniques, see IEEE Standard C57.136-2000. [3]

2.5 Energy Storage

Solar projects have the disadvantage in that they only generate power when the sun shines. However, often the highest electrical demand of consumers is in the evening. As a result, many solar projects are being constructed with energy storage devices, such as batteries. In this system, the power generated during the day is used to charge the batteries, which release the power in the evening. The charging and discharging of the batteries generate heat, which must be dissipated using fans or chillers. These cooling units generally represent the major source of sound from the energy storage systems.

The sound from energy storage systems is highly varied, as the systems can range from integrated exterior units, like the Tesla PowerWall, containerized systems, or building systems. Given the variability of equipment and components, Ther.

2.6 Construction and Vehicle Traffic

Construction noise is a short-duration part of the overall noise impact from solar power projects. The extent of the impact over that time will be dependent on the distance between equipment and the closest residences and the type of equipment required. Some construction equipment will not be necessary at all project sites. For example, wooded sites will require tree-clearing equipment and more mountainous sites may require limited blasting or rock drilling. The particular method of setting the posts for mounting the panels may also vary. Table 1 shows of list of construction sources that have been listed in noise assessments from recently proposed projects in New York, with the sound level at 50 feet (15 meters) that was listed in the assessment. Many of the sound levels listed were obtained from the FHWA's Roadway Construction Noise Manual (RCNM) [4].

3 SOUND PROPAGATION MODELING FOR SOLAR PROJECTS

Sound propagation modeling for solar projects is complicated by several factors inherent to solar facilities:

- Sound generation is time-of-day dependent
    - Inverters generate the highest sound during sunny days. While they typically do not produce sound at night, they can be used for VAR control (Voltage-Ampere Reactive) at night; in which case, they will generate sound at night on occasion.
    - Transformers are energized day and night, but cooling fans will likely only operate during the day.
    - Energy storage generates sound during the day and evening, typically with none at night.
- Sound propagates least efficiently during sunny days
- Solar panels may act as sound barriers, but the effect is difficult to quantify.

These issues are discussed further below.

Table 1: Solar Project Construction Noise Sources (from [5] [6] [7])

Sound Source	Sound Pressure Level at 50 feet (15 meters) (dBA)
Auger Drill Rig	85
Backhoe	80
Bar Trencher	89
Dozer	85
Drill Rig Truck	84
Excavator	85
Flatbed Truck	84
Forklift	85
Generator Set	81
Grader	85
Large Crane	83
Loader	85
Pickup Truck/ATV	55
Pile Driver	84
Scraper	89
Small Crane	83
Trencher	83
Water Truck	80

3.1 Meteorological effects

The ISO 9613-2 methodology for sound propagation outdoor assumes a standard condition of a moderate nighttime inversion, or equivalently, moderate winds from the source to the receiver. These conditions result in the downward refraction of sound in the atmosphere. However, during peak solar generation, the sun is high in the sky with no clouds. This sets up an ideal situation for upward refraction of sound (Figure 6).

To test this condition and its effect on sound propagation, we ran the NORD2000 [8] sound model under upward refracting conditions, as implemented in Datakustik's Cadna/A software. The NORD2000 model differs from ISO 9613-2 [9], with which most sound modeling is done in the U.S., in that it can model the curvature of sound rays under different meteorological conditions. The results of the modeling, depicting the difference between the NORD2000 results and ISO 9613-2, are shown in Figure 7, below.

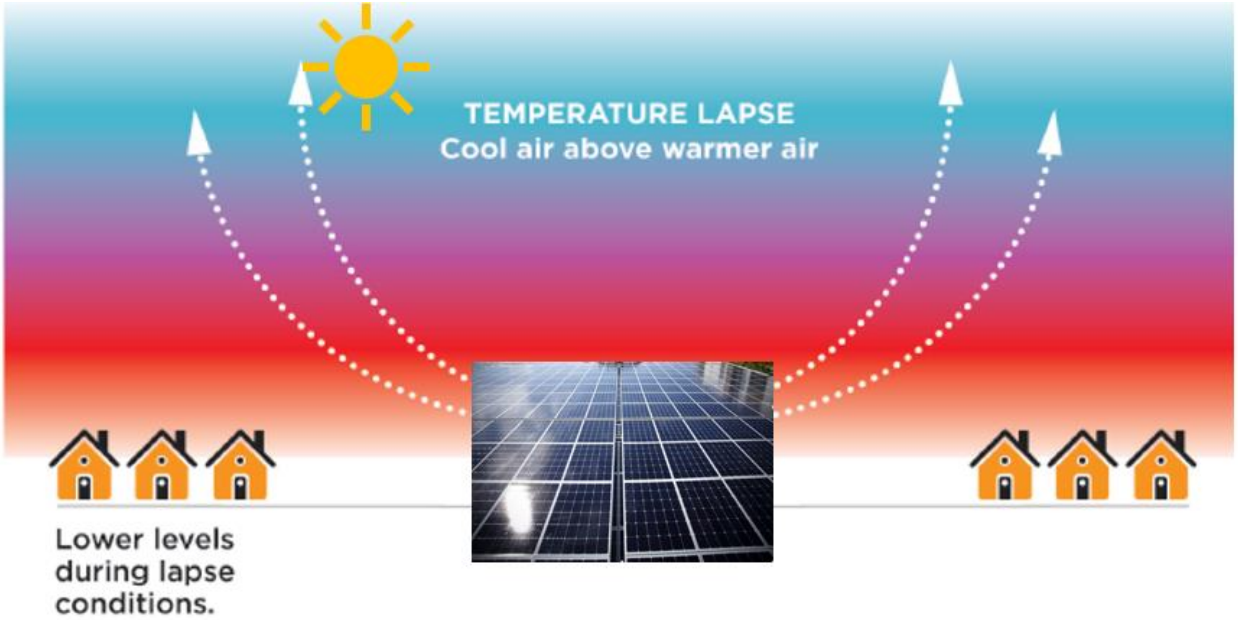

Figure 6: *Schematic of the upward refraction of sound during a sunny day*

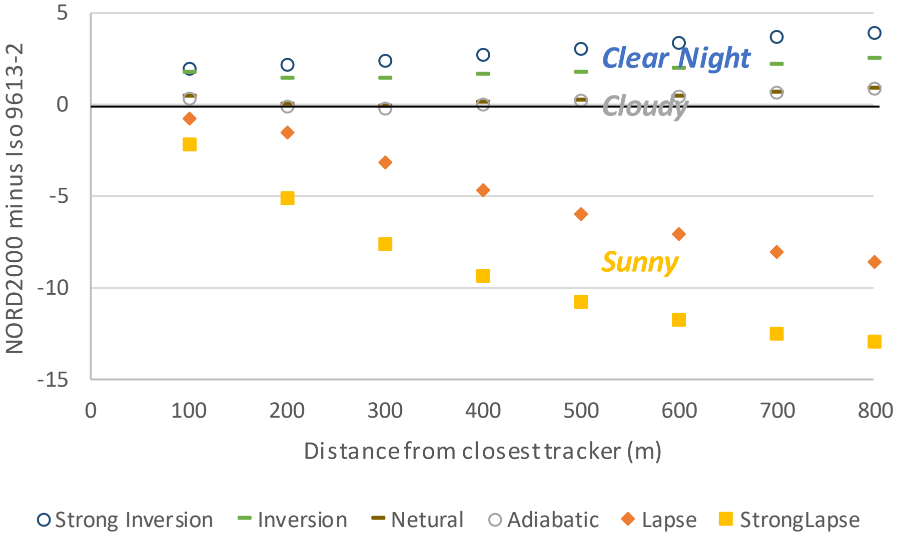

Figure 7: *Difference between NORD2000 under different temperature profiles and ISO 9613-2 (G=1) for a sample solar project.*

Under acoustically neutral (no change in sound speed with height) and normal adiabatic conditions the results of NORD2000 and ISO 9613-2 are similar, differing by less than 1 dB at 800 meters from the nearest tracking motor of the sample array. Under moderate and strong inversion conditions, the NORD2000 sound levels are higher by 1.7 to 3.9 dB. However, under lapse and strong lapse conditions (temperatures decreasing in height faster than adiabatic), which is typical of sunny days, the NORD2000 sound levels drop off substantively faster than the ISO 9613-2 model with distance. Under lapse conditions, the range is -1 to -10 dB and under strong lapse conditions, the range is -2 to -13 dB, from 100 meters to 1,000 meters from the closest tracker.

These results suggest that the ISO 9613-2 modeling of daytime sources, including trackers, medium voltage transformers, and inverters is likely to overestimate the actual sound level at distant receivers.

Note that at night, the project transformers are typically unloaded but energized. As a result, they still generate sound, albeit typically without sound from cooling fans and load harmonics. In addition, energy storage can discharge during the evening, creating sound from their cooling systems. Nighttime temperature profiles generally range from adiabatic to strong inversion. Thus, when modeling nighttime noise from the project substation, one could consider a more conservative approach than during the day. Alternatively, one could apply the same factors, which would be appropriate for the night and conservative for the day.

3.2 Ground

The ground absorption parameters should reflect the actual ground porosity surrounding the project during most of the year. For most projects in the U.S., which are situated in rural landscapes, this means using G=1, for ground that is suitable for the growth of vegetation.

For the transformer and inverter pads, as well as small bodies of water, hard ground, or G=0, is appropriate. Ground factors of either G=0.5 or 0.6 are appropriate for substations, assuming that the ground is gravel. Substations with concrete yards should use G=0.

3.3 Barrier effects

One interesting aspect about solar power projects that has not been well studied is the effect of the solar panels themselves on propagation of sound through the array. This is particularly interesting since sound generating components in the arrays (typically smaller transformers and inverters) are often surrounded by solar panels. Looking at it simplistically, it is almost as if these sources are surrounding by suspended or floating barriers. This should provide some sound attenuation, but it has not been well studied. While it is possible to model a floating barrier with some sound propagation models, current sound propagation standards do not account for diffraction on the underside of an open barrier because engineered simplification of the model scenario assumes that any barrier would be flush to the ground or horizontal surface. If one were to model solar panels as floating barriers with the existing sound propagation standards, it would likely result in an overestimation of attenuation since the diffraction on the underside of the barrier would not be taken into account [10]. This remains a topic in need of full study. To date, we have not tried to capture this effect in modeling.

3.4 Suggested modeling parameters

Unlike wind power projects, photovoltaic projects do not have the same elevated source height issue, which necessitates use of highly conservative modeling parameters (for example, G=0.5 with 2 dB added or G=0.0 with 0 dB added [11]). As a result, we have found that the addition of uncertainty factors to modeled sound levels of nearby receptors is not needed under most circumstances. With the exception of surfaces with low porosity (concrete pads, substations, water, pavement, etc.,) we have found the use of a ground factor of G=1 appropriate for the porous ground around projects.

3.5 Tonality

The project transformers are likely to be the largest source of tonal sound. Transformers operating without fans are always tonal, as the sound generated by them is created by, among other things, magneto-restriction. As a result, the sound has a fundamental frequency of 120 Hz, with 120 Hz harmonics up to at least the fourth harmonic, where harmonics start running together in 1/3 octave band spectra. Often harmonics are still visible beyond the fourth harmonic in narrowband spectra. If the transformer has fans, their broadband sound can mask this tonal sound to an extent.

To account for the tonal nature of transformers, we often apply a 5 dB tonal penalty to the modeled sound if the transformer is close enough to the receiver that there would be negligible background sound masking.

The inverters can be tonal, but in our experience, in most inverters, the broadband fan sound is dominant (Figure 5).

5 CONCLUSIONS

The authors' experience in conducting noise assessments of solar projects has resulted in the following best practices:

- Assess noise impacts for both daytime and nighttime periods, even though it is likely that the only notable nighttime source is the project transformers.
- Include in the assessment:
    - Solar array sources: inverters (string or central type), medium voltage transformers, and tracking motors (if any).
    - Substation sources: high voltage transformers
    - Energy storage sources: inverters/rectifiers, medium voltage transformers, cooling fans and/or other HVAC equipment
- Use manufacturer-specific sound emissions data when available. When manufacturer-specific data is not available, NEMA TR-1 levels can be used for transformers and data from similarly sized units can be used for inverters and tracking motors.
- Sound propagation modeling should be conducted in accordance with ISO 9613-2. A ground factor of G=1 for porous ground is appropriate in most circumstances for nearby receptors, except for ground surfaces with low porosity (concrete pads, substations, etc.).
- While there may be a screening effect from solar panels, no attenuation should be taken into account for this effect until the impact of underside edge diffraction has been studied further.

Future research is needed in several areas.

1) Sound levels – In 2012, the Massachusetts Clean Energy Center sponsored a study of the measured sound levels from installed solar equipment [12]. This study, based on photovoltaic arrays from 1,000 to 3,500 kW DC, concluded that "any sound from the PV array and equipment was inaudible at setback distances of 50 to 150 ft from the boundary." While that may be true at the time, modern solar projects can be 100 times larger than the arrays monitored in 2012. Equipment is now larger, and energy storage is added to the mix. We recommend revisiting that the MassCEC study and updating measured sound levels of all facility components based on a monitoring campaign at modern solar photovoltaic facilities.
2) Barrier effects of solar panels – As noted above, the acoustics of a solar facility is unique, in part, due to the effect of the solar panels acting as floating barriers. We believe research is needed as to how effective solar panels are in blocking sound from tracking motors, inverters and medium voltage transformers. With this information, solar panels can be strategically placed to improve noise mitigation.

6 REFERENCES

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