

Sound Intensity Mapping of Power Generators in Solar Energy Systems: A Case Study on Inverter Noise Emissions

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ABSTRACT

This study examines the acoustic emissions produced by power generators in solar energy systems, with a particular focus on inverters. Noise emissions from these systems are frequently overlooked, despite their potential environmental and health effects. Sound intensity mapping (SIM) was conducted at two distances (0.3 m and 1.0 m) and at three different times of the day to identify noise hotspots and characterize variations in sound power levels (SWL). The inverter, a crucial component of solar systems, was found to generate substantial noise, with SWLs reaching as high as 89 dB during peak operation. The findings underscore the significance of acoustic analysis in the design of solar systems and propose mitigation strategies to reduce noise exposure in sensitive environments. This research advocates for the incorporation of acoustic considerations into the planning and implementation of sustainable energy systems.

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INTRODUCTION

The global adoption of solar energy systems as sustainable alternatives to fossil fuels has surged in response to concerns about climate change and the depletion of non-renewable resources [1]. However, integrating solar energy systems into urban and semi-urban environments presents new challenges [2], particularly in managing non-electrical side effects such as noise. Auxiliary components, such as inverters, are crucial for converting the direct current (DC) from solar panels into alternating current (AC) [3]. These components can produce significant noise through their cooling systems and internal switching circuits. Acoustic pollution can jeopardize human health and comfort, particularly in residential, institutional, and educational settings. Chronic exposure to elevated noise levels can lead to increased stress, decreased concentration, and long-term

health issues, including hearing impairment and cardiovascular problems [4]. Despite these concerns, noise emissions from solar systems remain an under-researched area. Gaining a better understanding of the sound emission behavior of these components is essential for enhancing solar energy system designs and minimizing their environmental impact.

Numerous noise source identification techniques are available for investigating complex noise environments. Among these techniques are beamforming, which employs arrays of microphones to identify the direction and intensity of noise sources [5]; nearfield acoustic holography (NAH), which reconstructs acoustic fields based on measurements taken close to the noise source [6]; and sound intensity mapping (SIM), which measures sound pressure and particle velocity across a defined spatial grid [7]. SIM is particularly effective for assessing inverter emissions in open or semi-enclosed environments due to its excellent spatial resolution and ability to isolate specific noise sources even amid background sounds.

In solar energy systems, three-phase inverters are widely employed due to their high efficiency, though they can produce noise during faults. El Idrissi et al. [8] investigate fault detection in three-phase asynchronous machines (ASMs) through acoustic analysis, with a particular emphasis on stator unbalance faults (SUF). Their research demonstrates that SUFs generate distinct acoustic signals that can be analyzed without the need for physical sensors, enabling early fault detection. Using statistical tools, the researchers discovered that acoustic signals exhibit greater total harmonic distortion than electrical signals, with parameters such as RMS and standard deviation proving more effective for diagnostics. The study concludes that the acoustic patterns in healthy ASMs typically follow a normal distribution, while deviations from this pattern indicate faults, highlighting the potential of acoustic analysis as a non-invasive and reliable method for monitoring the health of ASMs. In a separate study, Li et al. [9] evaluated the acoustic impact of flexible photovoltaic (FlexPV) panels in emergency shelters, discovering a slight increase in indoor noise levels. During rainfall, the acoustic intensity averaged 61.9 dB(A) under FlexPV panels, compared to 58.0 dB(A) under a textile-only roof, representing a 6.7% increase, yet remaining well below the 82 dB(A) threshold set by Environmental Noise Guidelines. Although the panels lead to a minor degradation of acoustic conditions, this effect is deemed acceptable for temporary shelter use. The study is based on data from only two rainfall events, and the authors suggest further research to assess performance under varying weather conditions.

Recent studies have highlighted the dual benefits of incorporating photovoltaic (PV) technologies into building materials, focusing on both energy generation and acoustic performance. Li et al. [10] note that acoustic analyses of building-integrated PV (BIPV) systems often prioritize the soundproofing of panels over inverter noise. In contrast, Kim et al. [11] developed a soundproof photovoltaic-thermal (PVT) module with an impressive sound insulation level of 32.3 dB below 1000 Hz and an average absorption coefficient of 0.93 across critical frequencies. This innovation incorporates polyester acoustic-absorbent material to enhance noise reduction and thermal insulation. Furthermore, Huang et al. [12] explored the potential of transparent quantum dot glass (TQDG), which boasts exceptional sound insulation—twice that of standard glass—making it particularly effective in filtering both low- and high-frequency sounds. This characteristic positions it as an excellent solution for improving urban acoustic comfort. Complementing this, Li et al. [13] highlighted the benefits of vacuum glazing, which offers superior sound insulation due to its vacuum-layer design and edge sealing with V2O5-TeO2-Bi2O3. This design effectively blocks sound transmission while

maintaining thermal efficiency. Cuce's [14] research on Heat Insulation Solar Glass (HISG) further demonstrates advancements in this field. HISG exhibited a sound absorption rate of 26.6%, significantly higher than the 18.2% rate of conventional glass, leading to improved indoor noise levels. When paired with aerogel glazing, HISG could yield even greater performance benefits. Collectively, these innovative technologies represent promising solutions for creating sustainable and acoustically optimized architecture.

While previous studies have underscored the importance of acoustic evaluation in material analysis, few have extended this approach to mechanical and electrical systems. This study aims to address that gap by characterizing the acoustic emissions of a solar inverter under real-world conditions. Through localized sound intensity mapping at specific distances and time intervals, the research identifies the spatial and temporal characteristics of inverter noise. It also proposes mitigation strategies to enhance the design and implementation of quieter, more community-friendly solar energy systems.

METHODOLOGY

Test Section

The core components of a solar power system include photovoltaic panels, inverters, and electrical distribution elements. Photovoltaic panels generate direct current (DC) electricity from sunlight, which the inverter transforms into alternating current (AC) to ensure compatibility with standard electrical appliances and grid infrastructure. In addition to power conversion, the inverter plays a crucial role in regulating voltage, monitoring system performance, and ensuring safety during operation.

However, inverters can also be significant sources of acoustic emissions within solar power systems. Noise generated by internal cooling fans, high-frequency switching mechanisms, and electromagnetic vibrations can become especially pronounced in noise-sensitive environments, such as pedestrian pathways at educational institutions. In these settings, unmanaged inverter noise may lead to distractions, diminish concentration, and adversely affect the well-being of nearby individuals. Figure 1 shows the solar power inverter plant, while Table 1 presents the inverter utilized in the building-applied photovoltaics (BAPV) solar system installed at the Faculty of Mechanical and Automotive Engineering Technology (FTKMA) of Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Pekan, Pahang.



Figure 1. Solar power inverter.

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Table 1. Solar inverter specifications.

Model	Sungrow SG125CX-P2
Phases	Three
Maximum output (kW)	125
Conversion efficiency (%)	98.8
Features	Maximum power point trackers (MPPT) Superior cooling technology
Scale	Large

Equipment and Setup

Measurements were carried out using a handheld analyzer equipped with data logging and real-time acoustic processing capabilities, along with a sound intensity probe designed to assess the direction and magnitude of acoustic energy. The equipment was set up in compliance with ISO 9614-1 standards, which outline the procedures for measuring sound power levels of noise sources through sound intensity methods. Figure 2 illustrates the field calibration process being done before each measurement.



Figure 2. Field calibration before measurement.

A grid-based analysis framework ensured extensive spatial coverage of the inverter's sound field. As depicted in Figure 3, the grid consisted of 35 measurement points surrounding the inverter, strategically arranged to capture both vertical and horizontal propagation patterns. Sound power level (SPL) data were collected at two distinct distances: 0.3 meters (proximity) and 1.0 meters (standard ISO 3744 reference distance). Measurements were taken at three different times of day: morning (10:00 AM - 12:00 PM), afternoon (12:00 PM - 2:00 PM), and evening (2:00 PM - 4:00 PM), reflecting typical variations in daily operation.

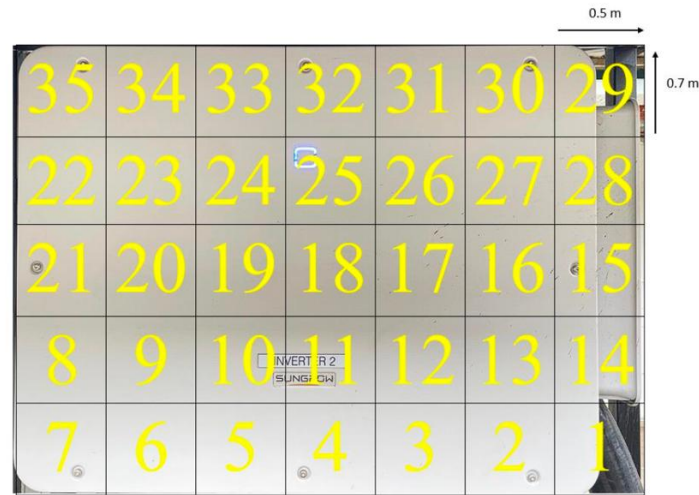


Figure 3. Gridding for the single-unit inverter.

Measurement Procedure

Before the measurements, the sound analyzer and intensity probe were calibrated with a certified acoustic calibrator to ensure accuracy. During each measurement cycle, the overlay grid was carefully aligned with the inverter, and SPL readings were sequentially collected at each grid point. Environmental conditions, including ambient temperature, humidity, and background noise, were monitored to ensure consistency throughout the process.

Each measurement session included real-time data visualization at the instrument interface, enabling the verification of data consistency and the early detection of anomalies. Following the sessions, the collected data were processed with advanced acoustic analysis software, which generated two-dimensional SPL maps. These visual representations were crucial for identifying noise hotspots, aiding in the interpretation of areas with elevated sound emissions.

RESULTS AND DISCUSSION

SIM at 1.0 Meter

The sound intensity mappings conducted at a distance of 1.0 meters from the power generator demonstrate notable variations in acoustic behavior throughout the day. During the morning (10:00 AM – 12:00 PM), the intensity distribution in Figure 4 is relatively moderate and spatially dispersed, indicating lower operational loads and potentially decreased environmental and mechanical activity. According to foundational acoustic propagation theory, sound levels are affected by the source's strength and environmental factors such as temperature, humidity, and air density [15]. Cooler morning temperatures typically result in diminished sound propagation efficiency due to reduced air molecule agitation, likely accounting for the generally subdued noise levels observed during this timeframe.

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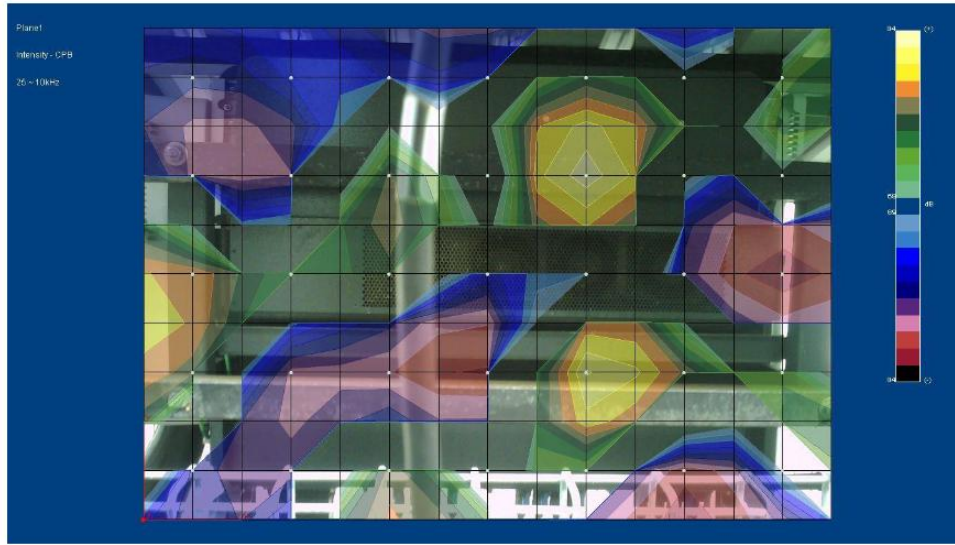


Figure 4. Sound intensity mapping in the morning (10.00 AM – 12.00 PM) at 1.0 m.

In contrast, the afternoon period (12:00 PM – 2:00 PM) reveals a significant increase in sound intensity levels as shown in Figure 5. The mapped area exhibits a more centralized and heightened concentration of sound energy, which can be attributed to the peak operational output of the solar system, its associated inverters, and auxiliary equipment. According to ISO 9614-1:1993, sound intensity measurements are particularly adept at identifying sources of airborne sound near equipment surfaces under load. The elevated readings during this period correspond to intensified system activity, with components such as inverters, transformers, and cooling fans contributing to high-frequency broadband noise. Furthermore, the temperature-induced upward refraction of sound waves in the warmer afternoon air may lead to localized amplification in specific zones [16].

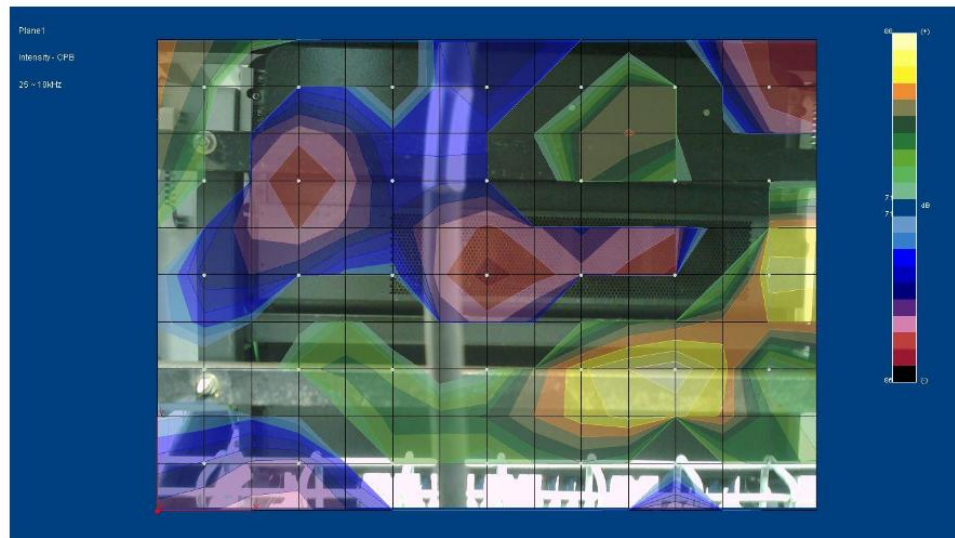


Figure 5. Sound intensity mapping in the afternoon (12.00 PM – 2.00 PM) at 1.0 m.

By the evening (2:00 PM – 4:00 PM), the sound intensity distribution in Figure 6 exhibits elevated values and irregular spatial characteristics. Certain areas maintain high

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sound levels, while others display attenuation, possibly due to changes in equipment cycling, environmental cooling, or partial system shutdowns. This spatial irregularity aligns with findings in environmental acoustics, which highlight fluctuating sound fields in mixed-use mechanical environments, particularly during transitional load conditions [17]. These variations suggest that while some equipment operates at high intensity, others may transition into idle or reduced-load states, contributing to a non-uniform sound field.

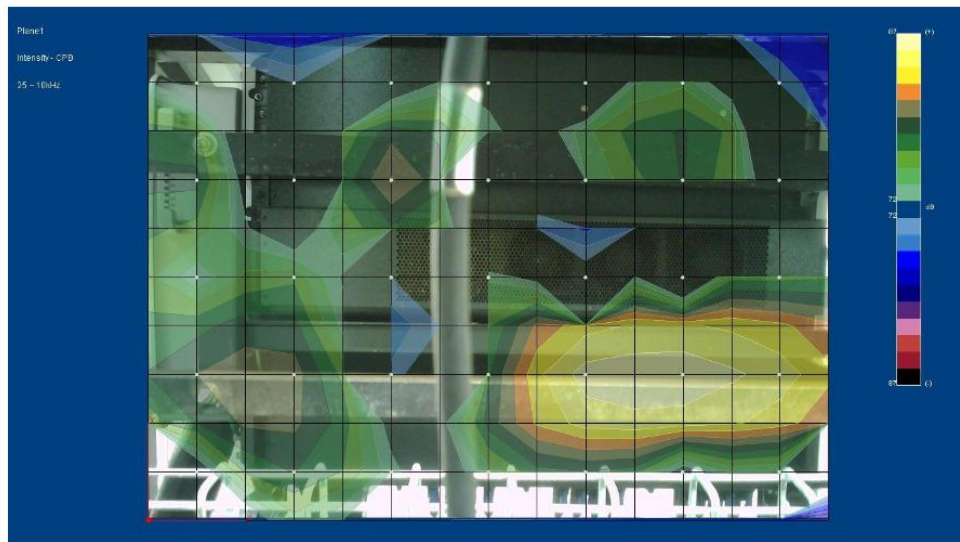


Figure 6. Sound intensity mapping in the evening (2.00 PM – 4.00 PM) at 1.0 m.

These findings underscore the critical importance of time-dependent acoustic analysis in solar power installations. Consistent sound intensity mapping provides valuable insights into occupational noise exposure and system diagnostics. Particular attention is warranted during afternoon periods for the implementation of mitigation strategies, such as acoustic shielding, scheduling maintenance during quieter times, and optimizing layout design to relocate noise-generating components away from occupied areas. Moreover, the utilization of ISO-compliant sound intensity mapping enhances the reliability of these observations and supports adherence to occupational noise regulations, including those specified in ISO 11690-1:1996 and OSHA standards.

SWL at 1.0 Meter

Figure 7 presents the sound power distribution measured across 35 points, which exhibits distinct temporal patterns throughout the day. Notably, sound levels in the afternoon are consistently elevated compared to those recorded in the morning and evening. This trend likely reflects peak operational activity during midday, characterized by increased human presence, heightened equipment usage, and greater energy demand associated with the solar system setup. Acoustic propagation theory indicates that sound pressure levels are directly influenced by machinery's energy output and vibrational characteristics [18]. The stability of these higher sound levels in the afternoon across most measurement points reinforces that this time frame corresponds with the most acoustically active phase of the day.

In contrast, both morning and evening measurements display greater variability. For instance, point 10 registers a notably high morning intensity at 82.65 dB, while Point 4 experiences a significant decrease to only 59.02 dB, suggesting the presence of

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relatively quiet zones or inactive equipment during the early hours. Such observations align with established environmental acoustic models, which propose that lower ambient temperatures and operational ramp-up periods contribute to reduced noise propagation and generation in the morning [19]. Evening measurements similarly fluctuate, with notable spikes observed at points 8 through 10 (exceeding 84 dB), potentially indicating residual mechanical activity or operational routines extending into the later hours. Conversely, point 18 exhibits a dramatic decline in the evening, dropping to 54.76 dB, signifying a quieter region that may be distanced from primary noise sources or shielded by structural elements. This phenomenon could be partially explained by environmental factors, such as cooler evening air that fosters downward refraction of sound, thereby dampening its propagation over distance [20].

Repeated peaks at points 9 and 10 throughout all periods suggest proximity to dominant noise sources, including generators or high-load inverters that emit consistent sound regardless of the time of day. These findings underscore the importance of source localization and sound intensity mapping, as outlined in ISO 9614-1:1993, which details methods for determining sound power through directional intensity measurements near industrial equipment. Incorporating these spatial data enables engineers and facility managers to deploy noise mitigation strategies more effectively, particularly in areas where exposure levels exceed the guidelines defined in ISO 11690-1:1996 and OSHA's permissible exposure limits (29 CFR 1910.95).

In summary, the data underscore the efficacy of sound intensity mapping in identifying high-noise zones and optimal periods for noise-sensitive assessments. Morning hours, which generally have lower and more dispersed intensity levels, present favorable conditions for maintenance or inspection activities. From a noise control perspective, interventions such as acoustic shielding, equipment relocation, or scheduling shifts should prioritize locations and time windows associated with peak sound pressure levels. Furthermore, these acoustic assessments not only support safe occupational practices but also contribute to long-term enhancements in soundscape quality around solar energy systems.

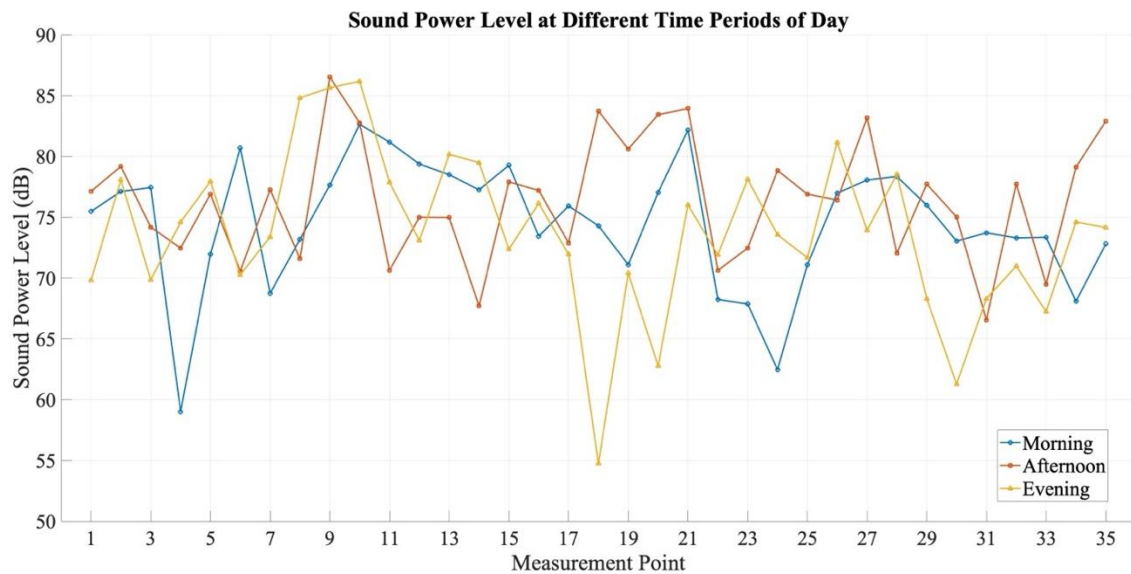


Figure 7. Sound power level (dB) at different measurement points at 1 m away.

SIM at 0.3 Meter

In the morning session displayed in Figure 8, the sound intensity mapping reveals a relatively moderate and evenly distributed sound field, indicative of a quieter environment with fewer abrupt or dominant sound sources. According to acoustic propagation theory, sound disperses uniformly in the absence of strong directional sound sources, due to spherical spreading and limited constructive interference [21]. The uniform intensity observed during the morning indicates ambient noise levels, likely influenced by natural or environmental sounds with minimal anthropogenic input.

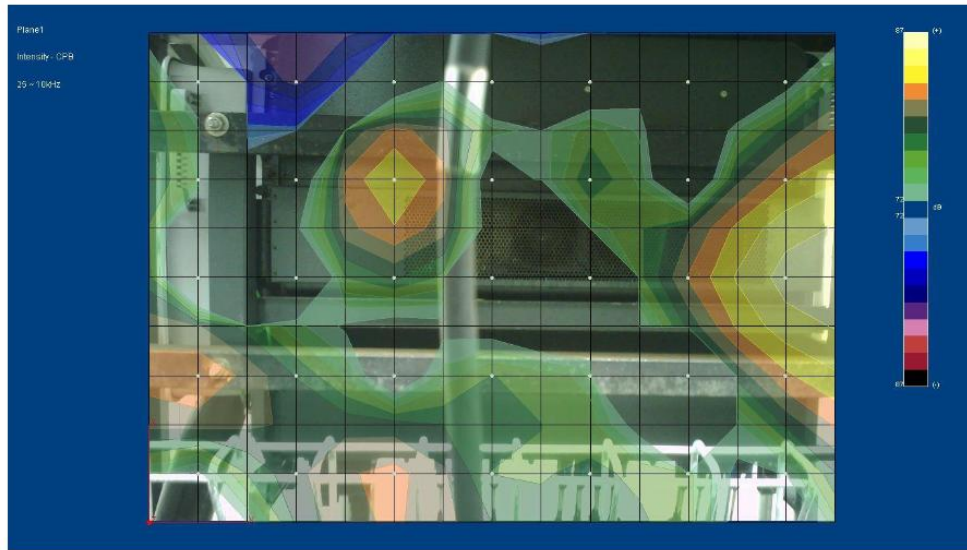


Figure 8. Sound intensity mapping in the morning (10:00 AM – 12:00 PM) at 0.3 m.

In contrast, the afternoon mapping shown in Figure 9 exhibits a marked increase in overall sound intensity levels, highlighting several localized regions with significantly higher intensity values. This change can be attributed to heightened human activity or mechanical operations that introduce new and stronger sound sources. As point-source radiation and sound interference theory describes, multiple coherent sound sources can lead to spatially varying intensity patterns due to constructive and destructive interference [22]. Furthermore, the increase in activity levels may contribute to an uptick in reflections and diffractions, particularly in semi-enclosed environments, thereby altering the distribution of acoustic energy at proximity (0.3 m).

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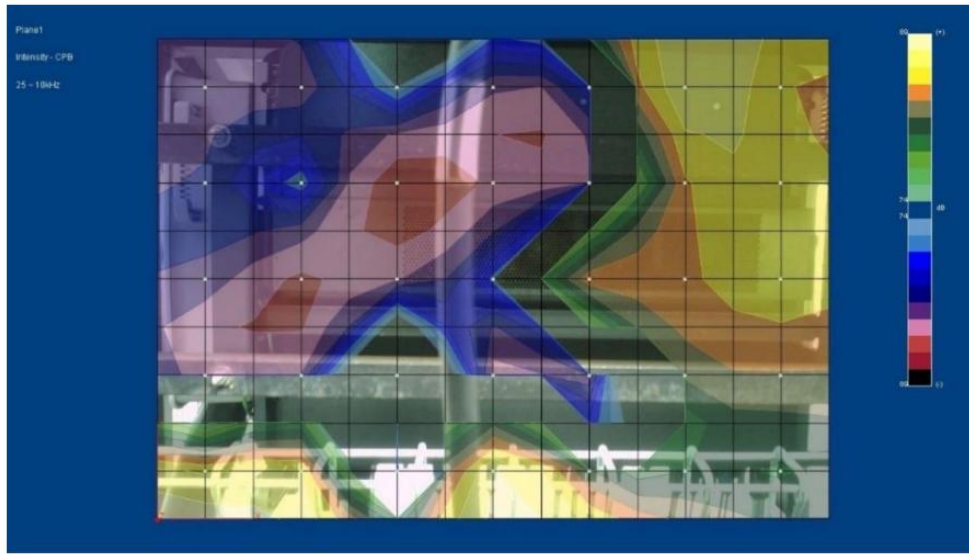


Figure 9. Sound intensity mapping in the afternoon (12.00 PM – 2.00 PM) at 0.3 m.

By the evening period, the intensity distribution in Figure 10 exhibits another shift. While certain regions maintain high-intensity zones, others show signs of dissipation or attenuation. This alteration aligns with the principles of acoustic damping, which stipulate that energy loss due to surface absorption, air attenuation, and diminishing source strength decreases intensity over time [23]. Additionally, the redistribution of sound zones may be influenced by evolving environmental conditions, such as temperature gradients, which can significantly affect sound speed and propagation paths [24].

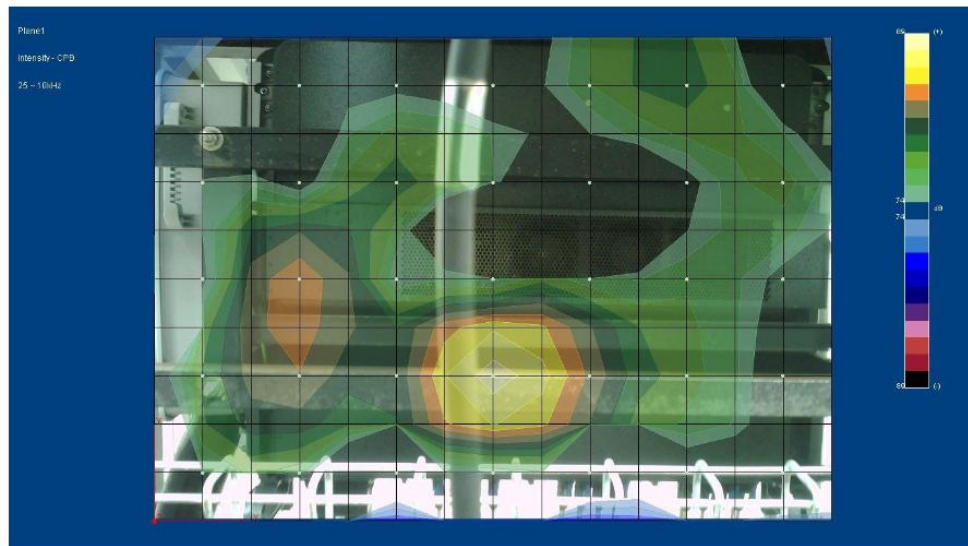


Figure 10. Sound intensity mapping in the evening (2.00 PM – 4.00 PM) at 0.3 m.

Overall, the temporal variations observed in the intensity mappings underscore the dynamic nature of the acoustic environment at a distance of 0.3 meters. These patterns highlight the importance of temporal context in sound field analysis, as both sound propagation and intensity are inherently influenced by environmental variables and source characteristics. The study reinforces fundamental acoustic concepts, including

intensity decay, interference, and absorption, while highlighting practical implications for time-dependent acoustic monitoring.

SWL at 0.3 Meter

The sound power levels obtained at a distance of 0.3 meters across 35 observation points plotted in Figure 11 reveal significant variations during morning, afternoon, and evening periods. Notably, the afternoon readings consistently register the highest sound power, with several points exceeding 85 dB, indicating peak operational noise. This pattern aligns with expectations for midday hours when energy demand and equipment utilization surge, particularly in solar systems where inverters, battery management systems, and cooling fans operate at maximum capacity. Ogunlade et al. [25] affirm that machinery noise during peak operational periods typically results in elevated broadband sound levels, especially in systems characterized by high electrical throughput and dynamic loads.

Conversely, while exhibiting slightly lower intensity, the morning measurements still demonstrate multiple peaks, particularly around Points 3–10 and 20–21, indicative of early startup activities or residual operational hums. This observation is consistent with established acoustic principles that highlight increased tonal noise during the early hours, primarily due to mechanical warm-up phases and reduced ambient noise, which in turn lessen masking effects. Additionally, the propagation of sound during the morning is influenced by cooler air layers that can alter the refraction and absorption of sound waves. Liptai et al. [26] suggest that such atmospheric conditions can diminish dispersion, resulting in localized intensity peaks.

Evening data, while generally lower than afternoon measurements, exhibit notable fluctuations in sound levels. This variability can be attributed to the gradual shutdown of system components or the shifting energy loads typical in hybrid setups. Specifically, points 11, 13, and 15 exhibit evening spikes that approach or exceed 85 dB, likely reflecting transient surges or cooling cycles of the fans. The observed uneven profile during the evening is consistent with transient sound behavior during load shedding or thermal equalization, wherein short bursts of mechanical or electronic noise dominate [27].

These findings underscore the importance of time-resolved acoustic mapping in noise-sensitive environments, such as solar generator enclosures. The afternoon period emerges as the most acoustically intense, necessitating targeted mitigation strategies, including enclosure insulation, repositioning of equipment, or the installation of acoustic baffles. Furthermore, sound mapping conducted at short distances, such as 0.3 meters, provides a high-resolution perspective on source-specific contributions, in accordance with ISO 9614-1:1993 standards for determining localized sound intensity.

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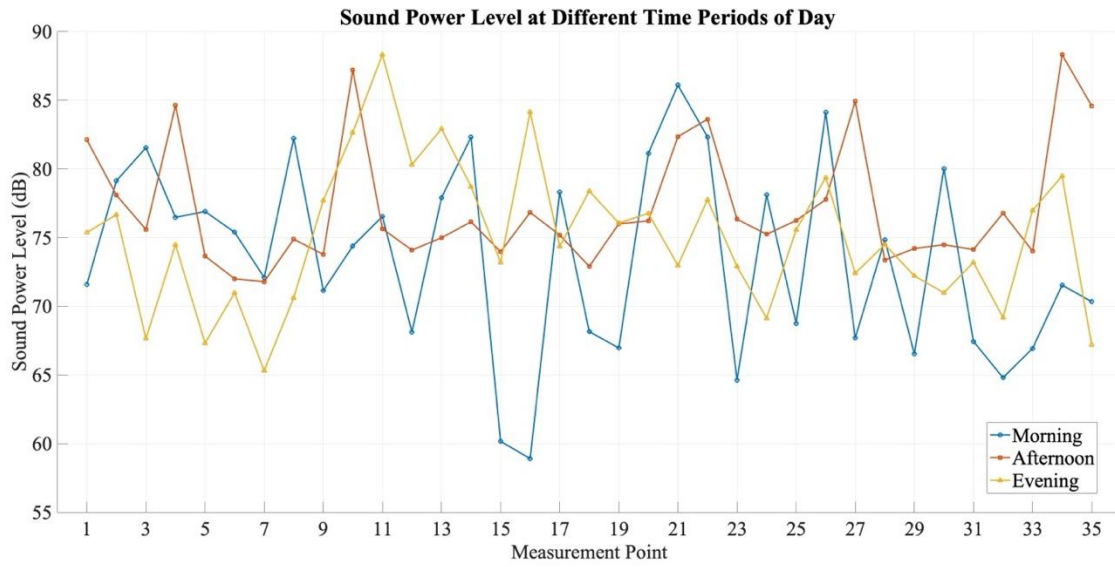


Figure 11. Sound power level (dB) at different measurement points at 0.3 m away.

CONCLUSIONS

This research investigates the effectiveness of sound intensity mapping as a tool for assessing inverter noise in solar energy systems. The findings reveal that noise levels are significantly elevated during periods of high electrical load and localized hotspots near cooling components. These insights are crucial for optimizing system design, particularly in environments where noise sensitivity is paramount, such as schools, hospitals, and residential neighborhoods. The study further establishes that inverter noise can reach levels that necessitate mitigation, primarily when systems are situated near occupied areas. To address these concerns, practical recommendations include implementing acoustic enclosures, using vibration isolation mounts, and strategically placing sound-absorbing materials. Future research should focus on long-term noise monitoring, the impact of inverter age on noise emissions, and a comparative analysis of different inverter models and brands. Integrating these insights into engineering practices enables the significant enhancement of the acoustic performance of renewable energy technologies, promoting broader adoption while minimizing environmental disruption.

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