

An Approach to the Design of Photovoltaic Noise Barriers and a Case Study From Istanbul, Turkey

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Abstract

Solar energy solutions that do not require additional space are critical. Noise barriers, which are built in low-value lands next to noise sources, provide effective areas for PV modules. There are many studies on using noise barriers as a sub-structure for photovoltaic systems, providing electricity generation besides noise reduction targets. Photovoltaic Noise Barrier (PVNB) technology combines noise control measures with renewable energy generation. In this study, it is aimed to develop an integrated design method that embeds solar energy technology in noise protection structures. The method is exemplified in an existing settlement located on the side of the road with heavy traffic. According to local climate and solar data, optimum tilt angles have been determined for annual, semi-annual, seasonal, and monthly periods. Noise barrier alternatives are derived with combinations of different diffraction edge sizes of barrier top and determined optimum inclination angles. The performance of the criteria that affect the PVNB effectiveness for alternatives was calculated through software tools. The energy generation potential of PVNB and its shading in adjacent blocks were calculated with PVsyst 6.7.7. The noise control efficiency of the structure was computed via SoundPLAN 7.2. TOPSIS method one of the most common multi-criteria decision-making technique (MCDM) was used in the evaluation. As a result of TOPSIS, the best PVNB solution in the case study is the alternative that has 3m and 2m wide edges; 58 ° and 31 ° tilted edges. Comparison with the current situation, the selected alternative will decrease %44 the number of receiving points affected by noise and provide 524804 kWh annual electricity generation.

1. Introduction

The significant positive impact on carbon dioxide emissions has been supported by empirical studies that shape the energy matrix of the world with renewable energy sources. (Acheampong, Adams, and Boateng 2019; Al-Mulali, Saboori, and Ozturk 2015; Apergis et al. 2010; Inglesi-Lotz and Dogan 2018; Khoshnevis Yazdi and Ghorchi Beygi 2018). Among the renewable resources encouraged by greenhouse gas reduction policies, solar energy has a resource potential that technically exceeds all global energy demand (Ueda et al. 2008).

Power density is the maximum amount of power that can be generated in a land area. Solar energy is low efficient relative to fossil fuels, due to its low energy density (Topcu and Ulengin 2004). Therefore, the need for large areas of land in the supply of solar energy creates a disadvantage for this technology (Calvert and Mabee 2015; Dijkman and Benders 2010; Graebig, Bringezu, and Fenner 2010; Nonhebel 2005; Rathmann, Szklo, and Schaeffer 2010). Solar energy solutions that do not require more land are important when considering that world population growth puts pressure on food and energy. As an example of these solutions; hybrid systems where photovoltaic systems are applied with different renewable energy technologies on mutual land (Calvert and Mabee 2015; Li, Stadler, and Ramakumar 2011; Nema, Nema, and Rangnekar 2009; Shafiullah et al. 2012), building integrated photovoltaic systems (Biyik et al. 2017; Jelle, Breivik, and Drolsum Røkenes 2012; Peng, Huang, and Wu 2011), agrovoltaic systems (Dupraz et al. 2011), PV systems on low-value lands like brownfields (Denholm and Margolis 2008). Besides, photovoltaic system solutions that don't require additional space by integrating noise barriers ensure the double use of land resources (Nordmann and Clavadetscher 2004).

Noise barriers can be the best solution when no noise control measures are taken neither at the noise source nor at the receiver (Garg, Kumar, and Maji 2013). Noise barriers are critical in providing acoustic comfort between major thoroughfares and settlements along roads. Because physical environmental factors, which have negative effects on human health and comfort, can cause serious disturbances in urban areas (Zorer Gedik et al. 2017)(Amoatey et al. 2020). Paschalidou et al. emphasizes that mitigation measures is especially important during the night due to excessive night-time exposure to noise has the biggest harmful effect on public health (Paschalidou et al. 2019).

In the presence of a barrier, noise from a source reaches the receiver through two paths: diffracted waves at the top edge of a barrier and the transmitted pathway through the barrier. Transmitted sound is negligible as barriers are constructed of solid materials. As a result, the barrier performance is limited by the diffracted sound (Fard et al. 2013). Many studies have conducted on the height and width of the noise barriers, since the diffraction path between noise source and receiver is related to height (Maekawa 1968). Calculation of Road Traffic Noise (CRTN), the method used in predicting road traffic noise, assumes that a barrier has an insignificant thickness, but diffraction over the top edge of a barrier is affected by its cross-section. Providing a substantial reduction in noise level in the shadow zone without increasing the height of the barrier, is the focus of the studies. It is impractical to build barriers of extensive height due to aesthetic, economic, and safety reasons (Grubeša, Jambrošić, and Domitrović 2012). The issue of designing multiple edges on a barrier top has been the focus of many researches. It has been observed that adding profiles to the top edge of the vertical barrier increases the insertion loss without a higher noise barrier and absorber surfaces (Crombie and Hothersall 1994; Watts 1996). Many authors researched for the determination of noise barrier tops such as Y, T, arrow, and cylinder, using experimental and numerical methods (Baulac, Defrance, and Jean 2008; Greiner et al. 2010; Hothersall, Chandler-Wilde, and Hajmirzae 1991; Hothersall, Crombie, and Chandler-Wilde 1991; Monazzam and Lam 2008). T shaped barrier designs are effective in noise reduction as the diffraction surface is close to the noise source (Hothersall, Crombie, and Chandler-Wilde 1991; May and Osman 1980). It was also determined that when the slope of the arms of the T-shaped barriers is 120 °; it is the most effective solution in reducing low-frequency sound (Venckus, Grubliauskas, and Venslovas 2012). Ho et al. and Shao et al. have determined that noise barriers with random edge profiles offer more insertion loss than flat ones, especially at high frequencies (Ho, Busch-Vishniac, and Blackstock 1997; Shao, Lee, and Lim 2001).

Crombie et al. found a better attenuation for barriers with two or more diffraction edges by numeric methods (Crombie, Hothersall, and Chandler-Wilde 1995). Another examination has shown that when multiple diffraction edges are used, the surfaces are effective when they are rigid rather than absorbent (Ishizuka and Fujiwara 2004).

In hybrid solutions, where solar energy and noise control are handled together, photovoltaic panels are integrated into the noise barrier with an inclination angle to get maximum power. The inclination of the PV arrays should be determined according to data such as climate data, shading condition, energy consumption profile, structural constraints, and acoustic performance of barrier. The amount of solar radiation reaching the solar modules affects the energy generated in the photovoltaic systems (Huld et al. 2011). The radiation intensity of the module is predominantly determined by the panel orientation and panel tilt. The panel inclination should be deliberated at the design stage, since the orientation of the road that determines the azimuth angle of PVNB systems is fixed and unchangeable. The optimal tilt angle of a solar collector is related to the local climatic condition, the geographic latitude, and the period of its use (Bakirci 2012). On the other hand, Wadhawan and Pearce highlight that non-optimal configurations also offer the potential for large fractions of electricity generation, when soiling losses and structural costs of PVNB systems are analysed together with other system parameters (Wadhawan and Pearce 2017). When the annual energy output data of the PVNB installations in Germany are examined, it has been observed that near-vertical inclined panels with airflow and less shading loss can perform better than panels with optimum tilt (Nordmann and Clavadetscher 2004). Both approaches were used in the PVNB design, on the side of the A22 Brennero motorway in Italy. It comprises two edges with different tilts, one of the diffraction edges of the structure has an optimum angle of inclination (35°), while the other has a steeper angle (60°) (Costa and Duiella 2010). The tilt angles should also be chosen high enough to hinder soil accumulation. Jaszczur et al. stated that dust accumulation on panel surfaces is a complex phenomenon that depends on a large number of different environmental and technical factors. Also, in the experimental study conducted in urban area on panels with 15 and 35 degrees inclination, the maximum dust density was recorded for panels with 15° inclination (Jaszczur et al. 2020). Lu ve Zhao were observed the maximum dust deposition rates for the tilted PV panel angles of 25°, 40°, 140° and 155°, respectively (Lu and Zhao 2018). Vallati et al. concluded that when the average height of the roadside buildings is low (3-6m), T shaped barriers will be best. When the average height of the building is higher (6-15m), it has obtained the best result in terms of noise control and solar energy performance in PVNB with a diffraction edge inclined to 60° (Vallati et al. 2015).

Environmental impact assessments (EIA) play an important role in newly planned public projects, as well as the technical performance of the design (Tamura, Fujita, and Koi 1994). A sound barrier, as part of the surrounding landscape, could be a cause of impact for both drivers and residents along the barriers. Noise barriers also create some disadvantages, in addition to providing acoustic comfort for residents living behind obstacles. For example, there is a study which has negative views of residents such as landscape obstruction, a feeling of being trapped, loss of air circulation, loss of sunlight, and inadequate maintenance of the barrier (Tamura, Fujita, and Koi 1994).

In this study, a novel design method in which it integrates solar energy technology into noise barrier solutions has been developed. The method was exemplified in Istanbul. Within the study, an existing residential settlement exposed to the noise level above the limit value, along a highway with heavy traffic, was considered. The flow chart showing the steps of the case study is shown in Figure 1. Noise maps of the current environment were generated by using SoundPLAN 7.2 simulation software, and the accuracy of the maps were validated by comparing them with actual noise measurements. Barrier design and design variables were determined with literature review and site-specific needs. In compliance with local climate and solar data; monthly, seasonal, semi-annual, and annual optimum tilt angles have been determined. Combinations of determined optimum tilt angles with diffraction edges in different sizes have been grouped as alternatives. The energy generation potential of barrier alternatives and light loss in neighboring blocks were calculated with PVsyst 6.7.7. The acoustic performance of the noise barriers was tested with the SoundPLAN 7.2 software. The best alternative for the site was determined by analysing the barrier alternatives with TOPSIS, which is a multi-criteria decision method.

2. Methodology

The following steps outline the case study:

- Gathering data and making assumptions.
- Environmental noise modelling and validation.
- Simulation of solar physical models and determination of optimum tilt angles.
- Generating PVNB alternatives.
- Specifying criteria and criteria weights.
- Selection of optimum PVNB with the MCDA method.

2.1. Gathering Data and Making Assumptions

The *study* is based on the assumptions shown in the Table 1 and listed below;

- As stated in the literature review, multiple edge barriers are effective when the surfaces are rigid. Due to the rigidity of the photovoltaic panel surfaces, the barrier type with 2 diffraction edges was determined as the optimum form.
- To show the effectiveness of the PVNB alternatives, some parameters have been kept constant, including traffic characteristics, atmospheric conditions, road-barrier distance, and topographic conditions.
- It is assumed that the PVNB will be built uninterruptedly between two secondary roads included in the actual maps of the study field.
- It is envisaged that the PVNB installation will be used as an electric vehicle charging station for residents. Due to the location of the PVNB in the area designed for a parking lot, the barrier top has been 5m wide in line with parking lot length.
- At the analysis step of PVNB alternatives in terms of noise control, the situation in which the PVNB is positioned instead of the garden wall is accepted as the basic case to make the assessment more apparent.
- While determining the number of people affected by noise, it is accepted that the apartments are used at full capacity and there are no vacant flats

2.2. Environmental Noise Modelling and Validation

2.2.1. Modelling

The noise maps, showing the acoustic climate of the 450.000m² area where the case study was carried out, were generated in SoundPLAN 7.2 (Braunstein + Berndt GmbH) software (SoundPLAN n.d.). The base maps of the site and the environmental properties were transferred to SoundPLAN 7.2. Population data and properties of noise sources were assigned in the software. The number of residents was calculated according to the room numbers of the flats and defined in the software as given in Table 2. The distances of the blocks in the first row most affected by the noise from the highway vary between 20 and 70m. Figure 2 appears the site plan of the case study plot.

Annual data on the traffic volume of the highway was got from the Istanbul Department of Transportation. Under data collected from the closest sensor (sensor no: 551), the total number of vehicles passing the highway between 31.05.2018 and 31.05.2019 is 34.946.809. Traffic flow characteristics of the highway is given in Table 3 according to the daytime, evening, and nighttime intervals. The traffic volume on the highway does not differ significantly on a monthly and daily basis. These counts are converted to Annual Average Daily Traffic (ADDT) and a daily traffic volume of 95.744 vehicles/day. The road is one of the highways with the highest density in the traffic volume scale of the General Directorate of Highways. Traffic data of other secondary roads in the district were also taken into account in noise mapping.

The climate data of Istanbul were defined in SoundPLAN 7.2 software. Prevailing and secondary wind direction was defined to be NNE and SSW, respectively; the mean annual temperature was defined to be 13,9° and average relative humidity was defined to be % 71,5 (Climate consultant 6.0 n.d.).

The dual carriageway is defined into software as 3,5m lane width and % 0 inclination. Smooth asphalt pavement was selected as the road surface in the software. In pursuance of the European Union Environmental Noise Directive, noise maps should present the sound level distribution at 4m above ground (European Parliament and Council of the European Union 2002). However, the ANNEX 1 of the same directive states that other heights may be chosen for design local measures, provided that the minimum height above ground should be 1.5m. Since this study evaluates the acoustic attenuation in open areas, assessment point height was accepted as 1,5m, the average height of the ear level (standing) (Akdağ et al. 2017).

The grid spacing in noise mapping should be no more than 10 meters, even 5m spacing may be desirable in urban areas (WG-AEN 2007). In this study, the grid space was selected as 5 x 5m as stated in the guide since the case study was conducted in an urban zone. The daytime noise indicator L_{day} time interval (07:00-19:00) were taken into consideration to evaluate the noise mitigation simultaneously with the solar potential of PVNB alternatives. Since solar panels do not produce energy in the evening and at night, the evening (Le- 19:00-23:00) and night (Ln- 23:00-07:00) noise maps have not been generated.

2.2.2. Validation

In the case study, actual noise measurements and acoustic simulations of the existing area were performed. Grid noise map, facade noise map, and cross-section map were generated for L_{day} noise indicator by SoundPLAN 7.2. Environmental parameters (site topography, forms, and dimensions of the buildings, types of ground surfaces) and traffic data (vehicle volume, vehicle speed, heavy vehicle rate, etc) should be defined in the simulation software most accurately to represent real data in the noise maps. As proved by various studies in the literature, when the inputs are detailed and accurate, SoundPLAN 7.2 software performs consistently with a higher accuracy (Akdağ et al. 2017; Guedes, Bertoli, and Zannin 2011; King and Rice 2009). Figure 3 reveals the current noise climate of the case study area.

Traffic noise modelling and traffic noise measurements are complex tasks, due to the stochastic features of traffic. The measured noise level was got by adding the noise generated by independent noise sources (industry, inhabitants, animals, etc.) to the traffic noise (Prezelj and Murovec 2017). Therefore, the validation step is critical to ensure that the noise model is an accurate representation of the real acoustic environment. The most appropriate way of the validation process is based on the comparison between actual noise measurements and simulated model outputs with their respective point receivers (İlgürel, Yüğrük Akdağ, and Akdağ 2016). The difference between the measurement data and simulation outputs and the standard deviation values of the data series is called uncertainty indicators.

The validation process that takes into account the uncertainty of a noise measurement ensures the most accurate representation of the model (Murillo Gómez, Jaramillo, and Ochoa 2020). The uncertainty range or the validation threshold, defined as a quantity of reliability of the calculated values, has been specified in some experimental studies. In their study, Maruyama et al. observed that, if the number of vehicles passing during the measurement time interval exceeds 170, uncertainty indicator (ΔLA_{eqT}) must be within the range of ± 1 dBA (Maruyama, Kuno, and Sone 2013). In some studies, when the measured and calculated data are compared, depending on the noise estimation model used in the study, the validation threshold should be between ± 3 dBA and ± 5 dBA. (Bastián-Monarca, Suárez, and Arenas 2016; Lee, Chang, and Park 2008; Vukadin, Bublić, and Tudor 2008). According to Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure, the difference between actual and calculated results should not exceed 1 dBA in a distance of 300m from the source, 3 dBA in a distance of 600m from the source and 10 dBA in a distance of 2,000–3,000m from the source (WG-AEN 2007).

The noise level measurements made in the case study area were performed as per ISO 1996-1 standard (ISO 1996-1:2003. Acoustics – Description, of environmental noise – part 1: basic quantities and, and Procedures. n.d.). Measurements were carried out on a weekday between 11:00-13:30 in the frequency range A by use of Bruel&Kajer Type 2236 sound level meter. Measurements were made 1.5m above ground level with a microphone windscreen, at least 2m away from buildings to prevent any surface reflection. A-weighted equivalent continuous sound pressure level (LA_{eq}) measurements were made at 13 measurement points shown in Figure 2. The results of 5-min measurements and simulation outputs for each point were given in Table 4.

Four of the measurement points; points 1, 2, 3, and 7; do not have another building block between them and the highway, and their distance to the highway is relatively less than the others. It can be seen from Table 4 that the difference between measurement and model results is within the acceptable range at these 4 measurement points where traffic noise is dominant. However, some points are above the limit range due to the noise sources that cannot be intervened and affect the background noise such as water elements, children's playground, and construction activities.

2.2.3. Evaluation

In Turkey, The Regulation on Environmental Noise Assessment and Management which was prepared as per the European Directive became effective as of 04.06.2010 upon proclaiming on Official Gazette (European Parliament and Council of the European Union 2002), (RENAM 2010). As stated in the regulation, the case study plot is within "Areas with high residential density in zones where commercial buildings and noise-sensitive uses coexist". The noise level should not exceed 63 dBA during the daytime period regarding the regulation.

Figure 4 shows the noise levels on the facades in the daytime. Facade noise maps are generated by making calculations for a center receiver points on each floor of the building blocks. 580 calculation points have been defined for the facade noise map in the case study site. There are 240 calculation points in the 12 blocks of the first row, where there is no other building block between it and the road. The following inferences have been made by evaluating the calculation outputs of the facade noise map;

- 24% of all facades in the settlement; 55% of the facades in the initial row blocks are exposed to noise level above the limit value.
- Considering the Southeast facades facing the highway, 39% of all fronts; 88% of the first row facades are exposed to noise levels above the guideline. Since the sleeping units are on the southeastern facade of the blocks, noise control is critical, for the most part of front facades.
- When the noise levels are evaluated according to the population distribution in the settlement; 14% of whole residents and 31% of the residents in the first row blocks are exposed to noise level above the limit value.
- The noise level that should not be exceeded according to the regulation is 55 Leq dBA in open areas that are generally used during daylight hours. Accordingly, 44% of the open area was exposed to noise above the threshold value.
- When the noise level is evaluated based on floors, 12% of the first floors and 73% of the 5th floors of the building blocks are exposed to the noise level above the limit value.

2.3. Simulation of Solar Physical Models and Determination of Optimum Tilt Angles

PVsyst was used for the solar part of the study, which includes determining radiation data, energy generation potential and optimum tilt angles. Calculation of incident radiation in an inclined plane from horizontal light intensity data is defined as the transposition model. PVsyst 6.7.7 offers two transposition models, Hay and Perez (PVsyst Photovoltaic Software n.d.). Perez model was preferred because it gives better results in terms of root mean deviation (RMSD) in calculations, even with synthetic data (Ineichen 2011).

This study aims to determine the highest performing noise barrier configuration by investigating the effect of the tilt angles and dimensions of the edges on solar energy and noise control performance. The latitude and the longitude of the case study area are 41°47' North Latitude and 29°22' East Longitude respectively, and its height above mean sea level is 110 m. Since the photovoltaic panels will be integrated into the noise barrier, the area assigns the azimuth of the photovoltaic system. The barrier has been designed between the highway and the settlement, which azimuth is measured 30 in degrees counter clockwise from the south.

Panels with the same properties were used in all alternatives analysed in the study. The panel selection allows working with different sizes of the top edge. As a result of market research, a 90 Wp monocrystalline photovoltaic panel was used. The technical details of the panel are given in Table 5.

As seen in Figure 5, global horizontal irradiation, diffuse horizontal irradiation, and clearness index values; between 56.6-259,9 W/m², 34.4-120.3 W/m², and 0.34-0.54 respectively. Optimum tilt angles for monthly, seasonal, semi-annual, and annual periods were calculated via the "Optimisation Tool" module of PVsyst 6.7.7 software. Table 6 reveals the determined angles for the area according to certain periods.

2.4. Generating PVNB Alternatives

In the step of determining the inclination of the double barrier tops, combinations of the annual and other periodic optimum tilt angles are derived. It does not include tilt values below 25° in the calculations as they increase soiling on the PV panels (Lu and Zhao 2018). The annual optimum tilt angle is simulated at the first edge of the barrier top, then at the second edge. Figure 6 shows the flowchart followed during the determination of PVNB alternatives. PVNB alternatives analysed in the study can be seen in Table 7.

2.5. Specifying Criteria and Criteria Weights

The study aims to select the barrier alternative that shows ideal performance in terms of noise control and solar energy. 60 barrier alternatives with various cross-sections were derived with different diffraction edge widths and periodic optimum inclination angles.

The hybrid system design of solar energy and noise barrier technologies, has 2 key criteria. One criterion is the amount of electrical energy generated, which is the performance indicator of the photovoltaic system. The second is the number of receiver points exposed to the noise level above the limit value, which is the noise control performance indicator of the PVNB. As an additional supplementary criterion to the key criteria, the daylight loss caused by the PVNB in the first row buildings is also included in the calculations as environmental impact criteria. Criteria considered in the evaluation are quantitative factors. Criteria weights were determined by the direct rating method.

Alternatives analysed with TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution), the multi-criteria decision method widely used in construction projects.

The way followed in weighting the criteria is as below;

1. The main criteria; the number of affected receiver points and electrical energy generation are assumed to have equal weight.
2. Determination of the criteria weight of daylight loss is based on a study in the literature. Besides the physical and biological effects of the noise barriers, Tamura et al. provide a disutility function for an assessment of the preferences of the inhabitants living near the noise barrier and therefore environmentally affected by the project. In the study's scope, the effect of constructing a 3m-high barrier was evaluated. The three-attribute disutility function created by taking into account the trade-offs between the reduction of environmental effects (noise reduction and reduction in NO_x) and the impact of barrier landscape is shown in Figure 7. Situations represented by different line types in the chart; (solid line) there is no countermeasure, (the dotted line) decrease of environmental impacts and the landscape obstruction are taken into account, (broken line) besides dotted line group, the countermeasures required to mitigate the effect of landscape obstruction (Tamura, Fujita, and Koi 1994). In the case study area, the distance of the first row blocks to the highway varies between 20 and 70m. The disutility function of each building block is determined according to the graph in Figure 7, and then the calculated mean value was added to the column I in Table 8.
3. Relative weights sum rescaled to 1 and calculated values have shown in column III in Table 8.

2.6. Selection of optimum PVNB with the MCDA method

Although there are many noise control measures for transport noise, determining the measure is the most critical phase. Because traffic noise is a typical conflict issue between individual mobility needs and a quieter lifestyle (European Union Road Federation, 2004).

There are different decision methods used in determining the noise reduction measure such as cost minimisation, cost-effectiveness analysis, cost-benefit analysis, and multi-criteria decision analysis.

Multi-criteria decision making (MCDM) techniques are presented as a powerful tool to help decision-makers select the most sustainable alternative for various construction problems. MCDM methods enable the selection of the optimal one among the alternatives by considering different criteria of a product, problem, or service. They have the advantage of a method that cannot be done in cost-benefit analysis, such as weighting each criterion (Ir Bert Peeters Gijssjan van Blokland 2018). One of the most widely used methods among MCDM methods is the TOPSIS method. It was preferred because of its ease of use, being programmable, and its ability to measure the relative performance of alternatives in a simple mathematical form (Tansel 2012). In the TOPSIS method, the most preferred alternative should be the closest to the positive ideal solution and the furthest from the negative ideal solution (Deng, Yeh, and Willis 2000).

As a result of the TOPSIS method, number 20 is determined as the best alternative among the A3 analysis group. The first diffraction edge of the final optimal solution 3m wide and has an angle of 58 °. The second diffraction edge is 2m wide and has an angle of 31°. Figure 8 shows the cross-sectional noise map of the ideal PVNB solution and the current situation.

3. Results

Figure 9 shows the outputs of the analysed alternatives according to the criteria. In the graph, the performance of the A-type barrier is visualised on the left, and the outputs of the B-type barrier is visualised on the right. The horizontal axis represents alternative numbers, vertical axes represent criteria. 'Daylight loss' criterion expresses the radiation loss per unit area on the front facade of the ground floor of the first row blocks, and the low loss is remarkable for the choice of the most appropriate PVNB. 'Electricity generation' criterion expresses the amount of annual energy production from the photovoltaic system and high production increase the performance of the barrier. 'Decrease in the number of receiving points exposed to the noise level above 63 dBA' criterion refers to the number of receiver points positively affected by the noise barrier and it is aimed to be maximum at making a decision.

For example, with the number 10 alternative, more receiver points are positively affected by noise reduction, while they show negative performance in terms of energy generation and daylight loss.

When the results of the study are examined, the following results are obtained;

The first alternative from the A3-analysis group shows the best performance in terms of energy generation. The first larger edge of the barrier top has an annual optimum inclination angle (31 °) and the other edge has an angle of 27 °. In the second alternative of the same analysis group, although both edges have the optimum tilt angle, the energy production potential is lower. This is due to the shading loss caused by the buildings on the opposite side of the road. In urban photovoltaic installations, near-horizontal panel inclination angles that are lower than the optimum tilt may increase electricity generation as they reduce shading loss.

- In the comparison of A-type and B-type alternatives in terms of energy generation criteria, B-type alternatives showed higher performance than A-type alternatives for the same angles. This is related to the fact that a higher position of the edge with the annual optimum inclination angle reduces shading loss in urban applications.
- When A-type alternatives are analysed in terms of energy production, the performance indicator of the A3-analysis group is higher than other analysis groups. Because in the A3-analysis group, the annual optimum tilt angle (31°) is defined to the wider one edge. When B-type alternatives are examined, the same circumstance is observed in the A2-analysis group.
- In terms of noise control, the 10th alternative in the A2-analysis group and the 20th alternative in the A3-analysis group show the highest performance. The height of both PVNB types is equal. Planning the wider edge near-vertical angle increased noise control efficiency.
- TOPSIS results are shown in Figure 10. Alternatives with high TOPSIS results are close to the ideal solution. As the planned angle of inclination in PVNB increases, the result values are approaching to the ideal solution.
- According to Figure 10, A2-analysis group A-type barriers and A3-analysis group B-type barriers perform well. These are alternatives where the wide edge is planned with angles close to vertical.
- The best alternative determined by TOPSIS also has the best performance in terms of noise control. This shows that noise control is more decisive, although the weights of noise control and solar criteria are equal. This can be explained by the higher variance coefficient of the noise control criterion. Since the change in electricity generation is in a smaller range, the effect on the results is less than the noise control.
- Since the edge closer to the road will be more exposed to soiling loss, steeper inclination angle of the panels will positively affect the performance of the system.

- The inclination angle of the edges has a negative correlation with solar energy and daylight potential in houses and a positive correlation with noise control. The increasing panel tilt decreases the performance rate of the photovoltaic system, while the energy production is high in panels with the annual optimum tilt angle. A similar situation was observed in the daylight loss on the ground floor of the houses. The high tilt angles reduce the solar radiation on the facade. The PVNB form, which causes minimal daylight loss in buildings, is the 1st alternative in the A2-analysis group. The lower angle of the longer edge reduced the amount of shading on the facade.

4. Conclusion

The inspiration for the study is the use of noise barriers that protect road adjacent settlements from traffic noise, as a sub-structure for photovoltaic modules. Dysfunctional areas along the roadside can create social and environmental benefits, given the conflict between the need for renewable energy and land scarcity.

In this study, it is aimed to make a reasonable selection among PVNB alternatives developed for the reduction of traffic noise and energy generation. In the study, the best alternative was selected using the TOPSIS method according to various criteria. Criteria are determined as performance indicators expressing the efficiency of the systems and environmental impact on the settlement. Although different indicators are representing the performance of the photovoltaic system, alternatives were evaluated according to the amount of energy production in the study. Noise barrier effectiveness was assessed according to the number of receiving points exposed to unacceptable noise levels specified in the regulation. Besides, daylight loss due to shadows on the ground floors of the front facades of the first row houses was also considered as a criterion.

Among the steps of the study, the most important two steps are creating PVNB variations with determining optimum tilt angles and specifying the criterion weights.

As a result of the literature review, the double-edge noise barrier, which proved to increase the effectiveness of the sound wall, was studied. In line with the solar radiation data of the region; optimum tilt angles were determined in annual, semi-annual, seasonal, and monthly periods. The height, the total barrier top area, and the annual optimum inclination angle of one edge (31 °) remained constant for each barrier, while generating alternatives. 60 alternatives were derived by changing the positions and widths of the diffraction edges, and also the inclination angle of one edge.

The derived 60 barrier types were tested in three criteria. The direct rating method was used while assigning the weights of the criteria. It is accepted that the criteria determining solar energy and noise control effectiveness have equal weights. In first row buildings, there are tradeoffs between maximum noise reduction and loss of landscape view and daylight. An indirect approach has been followed in weighing the environmental impact criterion that takes into account the loss of daylight in buildings. For this, the disutility function developed depending on the distance of the barrier from the buildings was used. The disutility function developed by Tamura et al. is a graphical method that models the mutual concessions of two conflicting factors (Tamura, Fujita, and Koi 1994). Criteria weights determined by direct rating and indirect approach were normalised and used in the TOPSIS method.

When the alternative selected as a result of the TOPSIS method is compared with the current situation, it is predicted that the number of receiving points affected by noise will decrease by 44% and annual electricity generation will be 524804 kWh.

The study provides a useful framework for planning photovoltaic noise barrier installations. The results show that the edges of the roads that adversely affect residential areas are suitable for solar energy gain and photovoltaic noise barriers offer a wide market potential.

In the projection of the expanding transportation network and increasing population density of cities, more studies are needed to take advantage of the production and comfort potential of PVNB technology. Design guidelines that deal with both photovoltaic systems and noise barriers should be prepared. The impact of design variables on cost and barrier effectiveness should also be investigated. The accurate estimation of PVNB's lifetime costs and payback periods will facilitate the future implementation of the system.

Declarations

Authors' contributions [Ferhan Hasmaden](#); Conceptualization, resources, data, investigation, noise level measurements, noise modelling, writing-original draft. [Gülay Zorer Gedik](#); Curation, formal analysis, validation, writing-review & editing, data curation, validation, supervision. [Neşe Yüğrük Akdağ](#); Curation, formal analysis, validation, writing-review & editing, data curation, validation, supervision.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Competing Interests The authors declare that they have no conflicts of interest.

Ethical approval Not applicable.

Consent to participate Yes

Consent to publish Yes

References

1. Acheampong, Alex O., Samuel Adams, and Elliot Boateng. 2019. "Do Globalization and Renewable Energy Contribute to Carbon Emissions Mitigation in Sub-Saharan Africa?" *Science of the Total Environment* 677: 436–46. <https://doi.org/10.1016/j.scitotenv.2019.04.353>.
2. Akdağ, Neşe Yüğrük, Gülay Zorer Gedik, Fatih Kiraz, and Bekir Şener. 2017. "Effect of Mass Housing Settlement Type on the Comfortable Open Areas in Terms of Noise." *Environmental Monitoring and Assessment* 189(10): 1–12.
3. Al-Mulali, Usama, Behnaz Saboori, and Ilhan Ozturk. 2015. "Investigating the Environmental Kuznets Curve Hypothesis in Vietnam." *Energy Policy* 76: 123–31. <http://dx.doi.org/10.1016/j.enpol.2014.11.019>.
4. Amoatey, Patrick et al. 2020. "Exposure Assessment to Road Traffic Noise Levels and Health Effects in an Arid Urban Area." *Environmental Science and Pollution Research* 27(28): 35051–64.
5. Apergis, Nicholas, James E. Payne, Kojo Menyah, and Yemane Wolde-Rufael. 2010. "On the Causal Dynamics between Emissions, Nuclear Energy, Renewable Energy, and Economic Growth." *Ecological Economics* 69(11): 2255–60. <http://dx.doi.org/10.1016/j.ecolecon.2010.06.014>.
6. Bakirci, Kadir. 2012. "General Models for Optimum Tilt Angles of Solar Panels: Turkey Case Study." *Renewable and Sustainable Energy Reviews* 16(8): 6149–59. <http://dx.doi.org/10.1016/j.rser.2012.07.009>.
7. Bastián-Monarca, Nicolás A., Enrique Suárez, and Jorge P. Arenas. 2016. "Assessment of Methods for Simplified Traffic Noise Mapping of Small Cities: Casework of the City of Valdivia, Chile." *Science of the Total Environment* 550: 439–48. <http://dx.doi.org/10.1016/j.scitotenv.2016.01.139>.
8. Baulac, Marine, Jérôme Defrance, and Philippe Jean. 2008. "Optimisation with Genetic Algorithm of the Acoustic Performance of T-Shaped Noise Barriers with a Reactive Top Surface." *Applied Acoustics* 69(4): 332–42.
9. Biyik, Emrah et al. 2017. "A Key Review of Building Integrated Photovoltaic (BIPV) Systems." *Engineering Science and Technology, an International Journal* 20(3): 833–58. <http://dx.doi.org/10.1016/j.jestch.2017.01.009>.
10. Calvert, K., and W. Mabee. 2015. "More Solar Farms or More Bioenergy Crops? Mapping and Assessing Potential Land-Use Conflicts among Renewable Energy Technologies in Eastern Ontario, Canada." *Applied Geography* 56: 209–21. <http://dx.doi.org/10.1016/j.apgeog.2014.11.028>.
11. Climate consultant 6.0. "Climate Consultant Software." <http://www.energy-design-tools.aud.ucla.edu/>.
12. Costa, C., and P. Duiella. 2010. "La A22 Viaggia Verso Il Sole." <https://www.stradeeautostrade.it/strade-e-autostrade/la-a22-viaggia-verso-il-sole/>.
13. Crombie, D. H., and D. C. Hothersall. 1994. "The Performance of Multiple Noise Barriers." *Journal of Sound and Vibration* 176(4): 459–73.
14. Crombie, D. H., D. C. Hothersall, and S. N. Chandler-Wilde. 1995. "Multiple-Edge Noise Barriers." *Applied Acoustics* 44(4): 353–67.
15. Deng, Hepu, Chung Hsing Yeh, and Robert J. Willis. 2000. "Inter-Company Comparison Using Modified TOPSIS with Objective Weights." *Computers and Operations Research* 27(10): 963–73.
16. Denholm, Paul, and Robert M. Margolis. 2008. "Land-Use Requirements and the per-Capita Solar Footprint for Photovoltaic Generation in the United States." *Energy Policy* 36(9): 3531–43.
17. Dijkman, T. J., and R. M. J. Benders. 2010. "Comparison of Renewable Fuels Based on Their Land Use Using Energy Densities." *Renewable and Sustainable Energy Reviews* 14(9): 3148–55. <http://dx.doi.org/10.1016/j.rser.2010.07.029>.
18. Dupraz, C. et al. 2011. "Combining Solar Photovoltaic Panels and Food Crops for Optimising Land Use: Towards New Agrivoltaic Schemes." *Renewable Energy* 36(10): 2725–32. <http://dx.doi.org/10.1016/j.renene.2011.03.005>.
19. European Parliament and Council of the European Union. 2002. Official Journal of the European Communities *Assessment and Management of Environmental Noise (EU Directive)*. <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0049&from=EN%5Cnhttp://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32002L0049>.
20. Fard, Samaneh M., Nicole Kessissoglou, Stephen Samuels, and Marion Burgess. 2013. "A Review of Road Traffic Barriers for Low Frequency Noise." *Proceedings of Meetings on Acoustics* 19: 1–6.

21. Garg, Naveen, Anil Kumar, and Sagar Maji. 2013. "Significance and Implications of Airborne Sound Insulation Criteria in Building Elements for Traffic Noise Abatement." *Applied Acoustics* 74(12): 1429–35. <http://dx.doi.org/10.1016/j.apacoust.2013.05.012>.
22. Graebig, Markus, Stefan Bringezu, and Richard Fenner. 2010. "Comparative Analysis of Environmental Impacts of Maize-Biogas and Photovoltaics on a Land Use Basis." *Solar Energy* 84(7): 1255–63. <http://dx.doi.org/10.1016/j.solener.2010.04.002>.
23. Greiner, David, Juan J. Aznárez, Orlando Maeso, and Gabriel Winter. 2010. "Single- and Multi-Objective Shape Design of Y-Noise Barriers Using Evolutionary Computation and Boundary Elements." *Advances in Engineering Software* 41(2): 368–78. <http://dx.doi.org/10.1016/j.advengsoft.2009.06.007>.
24. Grubeša, Sanja, Kristian Jambrošić, and Hrvoje Domitrović. 2012. "Noise Barriers with Varying Cross-Section Optimized by Genetic Algorithms." *Applied Acoustics* 73(11): 1129–37.
25. Guedes, Italo C. Montalvão, Stelamaris R. Bertoli, and Paulo H.T. Zannin. 2011. "Influence of Urban Shapes on Environmental Noise: A Case Study in Aracaju - Brazil." *Science of the Total Environment* 412–413: 66–76. <http://dx.doi.org/10.1016/j.scitotenv.2011.10.018>.
26. Ho, Steve S. T., Ilene J. Busch-Vishniac, and David T. Blackstock. 1997. "Noise Reduction by a Barrier Having a Random Edge Profile." *The Journal of the Acoustical Society of America* 101(5): 2669–76.
27. Hothersall, D. C., S. N. Chandler-Wilde, and M. N. Hajmirzae. 1991. "Efficiency of Single Noise Barriers." *Journal of Sound and Vibration* 146(2): 303–22.
28. Hothersall, D. C., D. H. Crombie, and S. N. Chandler-Wilde. 1991. "The Performance of T-Profile and Associated Noise Barriers." *Applied Acoustics* 32(4): 269–87.
29. Huld, Thomas et al. 2011. "A Power-Rating Model for Crystalline Silicon PV Modules." *Solar Energy Materials and Solar Cells* 95(12): 3359–69. <http://dx.doi.org/10.1016/j.solmat.2011.07.026>.
30. İlgürel, Nuri, Neşe Yüğrük Akdağ, and Ali Akdağ. 2016. "Evaluation of Noise Exposure before and after Noise Barriers, a Simulation Study in Istanbul." *Journal of Environmental Engineering and Landscape Management* 24(4): 293–302.
31. Ineichen, Pierre. 2011. "Global Irradiance on Tilted and Oriented Planes: Model Validations." *University of Geneva* (February).
32. Inglesi-Lotz, Roula, and Eyup Dogan. 2018. "The Role of Renewable versus Non-Renewable Energy to the Level of CO2 Emissions a Panel Analysis of Sub-Saharan Africa's Big 10 Electricity Generators." *Renewable Energy* 123: 36–43. <https://doi.org/10.1016/j.renene.2018.02.041>.
33. Ir Bert Peeters Gijssan van Blokland, Authors. 2018. "Colophon Dr. Hans Bögli (Swiss Federal Office for the Environment) Title Decision and Cost/Benefit Methods for Noise Abatement Measures in Europe." (February): 1–70.
34. Ishizuka, Takashi, and Kyoji Fujiwara. 2004. "Performance of Noise Barriers with Various Edge Shapes and Acoustical Conditions." *Applied Acoustics* 65(2): 125–41.
35. ISO 1996-1:2003. Acoustics – Description, measurement and assessment, of environmental noise – part 1: basic quantities and, and Assessment Procedures. "International Standard International Standard." *international organization for standardization*.
36. Jaszczur, Marek, Ambalika Koshti, Weronika Nawrot, and Patrycja Sędor. 2020. "An Investigation of the Dust Accumulation on Photovoltaic Panels." *Environmental Science and Pollution Research* 27(2): 2001–14.
37. Jelle, Bjørn Petter, Christer Breivik, and Hilde Drolsum Røkenes. 2012. "Building Integrated Photovoltaic Products: A State-of-the-Art Review and Future Research Opportunities." *Solar Energy Materials and Solar Cells* 100(7465): 69–96. <http://dx.doi.org/10.1016/j.solmat.2011.12.016>.
38. Khoshnevis Yazdi, Soheila, and Ehsan Ghorchi Beygi. 2018. "The Dynamic Impact of Renewable Energy Consumption and Financial Development on CO2 Emissions: For Selected African Countries." *Energy Sources, Part B: Economics, Planning and Policy* 13(1): 13–20. <https://doi.org/10.1080/15567249.2017.1377319>.
39. King, E. A., and H. J. Rice. 2009. "The Development of a Practical Framework for Strategic Noise Mapping." *Applied Acoustics* 70(8): 1116–27. <http://dx.doi.org/10.1016/j.apacoust.2009.01.005>.
40. Lee, Shi Won, Seo Il Chang, and Young Min Park. 2008. "Utilizing Noise Mapping for Environmental Impact Assessment in a Downtown Redevelopment Area of Seoul, Korea." *Applied Acoustics* 69(8): 704–14.
41. Li, Weiping, Steve Stadler, and Rama Ramakumar. 2011. "Modeling and Assessment of Wind and Insolation Resources with a Focus on Their Complementary Nature: A Case Study of Oklahoma." *Annals of the Association of American Geographers* 101(4): 717–29.
42. Lu, Hao, and Wenjun Zhao. 2018. "Effects of Particle Sizes and Tilt Angles on Dust Deposition Characteristics of a Ground-Mounted Solar Photovoltaic System." *Applied Energy* 220(October 2017): 514–26. <https://doi.org/10.1016/j.apenergy.2018.03.095>.
43. Maekawa, Z. 1968. "Noise reduction by Screens*." *Applied Acoustics* 1(3): 157–73.
44. Maruyama, Mitsunobu, Kazuhiro Kuno, and Toshio Sone. 2013. "The Minimum Measurement Time for Estimating LAeqT of Road Traffic Noise from the Number of Vehicle Pass-Bys." *Applied Acoustics* 74(3): 317–24. <http://dx.doi.org/10.1016/j.apacoust.2012.08.005>.

45. May, D. N., and N. M. Osman. 1980. "Highway Noise Barriers: New Shapes." *Journal of Sound and Vibration* 71(1): 73–101.
46. Monazzam, M. R., and Y. W. Lam. 2008. "Performance of T-Shape Barriers with Top Surface Covered with Absorptive Quadratic Residue Diffusers." *Applied Acoustics* 69(2): 93–109.
47. Murillo Gómez, D. M., A. Molina Jaramillo, and J. Ochoa. 2020. "Analysis of the Measurement Uncertainty and Its Effects on Noise Mapping Validations." *Journal of Environmental Management* 266(April): 110606. <https://doi.org/10.1016/j.jenvman.2020.110606>.
48. Nema, Pragya, R. K. Nema, and Saroj Rangnekar. 2009. "A Current and Future State of Art Development of Hybrid Energy System Using Wind and PV-Solar: A Review." *Renewable and Sustainable Energy Reviews* 13(8): 2096–2103.
49. Nonhebel, Sanderine. 2005. "Renewable Energy and Food Supply: Will There Be Enough Land?" *Renewable and Sustainable Energy Reviews* 9(2): 191–201.
50. Nordmann, Thomas, and Luzi Clavadetscher. 2004. "PV on Noise Barriers." *Progress in Photovoltaics: Research and Applications* 12(6): 485–95.
51. Paschalidou, Anastasia K., Pavlos Kassomenos, Fotini Chonianiaki, and Thalia Valkouma. 2019. "3-Year Noise Monitoring and Strategic Noise Mapping in an Extended Motorway." *Environmental Science and Pollution Research*: 15608–16.
52. Peng, Changhai, Ying Huang, and Zhishen Wu. 2011. "Building-Integrated Photovoltaics (BIPV) in Architectural Design in China." *Energy and Buildings* 43(12): 3592–98. <http://dx.doi.org/10.1016/j.enbuild.2011.09.032>.
53. Prezelj, Jurij, and Jure Murovec. 2017. "Traffic Noise Modelling and Measurement: Inter-Laboratory Comparison." *Applied Acoustics* 127(December 2017): 160–68.
54. "PVsyst Photovoltaic Software." <https://www.pvsyst.com/> (November 11, 2020).
55. Rathmann, Régis, Alexandre Szklo, and Roberto Schaeffer. 2010. "Land Use Competition for Production of Food and Liquid Biofuels: An Analysis of the Arguments in the Current Debate." *Renewable Energy* 35(1): 14–22.
56. RENAM. 2010. No. 25862. The Official Gazette *Regulation of Environmental Noise Assessment and Management*. <https://www.mevzuat.gov.tr/File/GeneratePdf?mevzuatNo=14012&mevzuatTur=KurumVeKurulusYonetmeligi&mevzuatTertip=5>.
57. Shafiullah, G. M. et al. 2012. "Prospects of Renewable Energy - a Feasibility Study in the Australian Context." *Renewable Energy* 39(1): 183–97.
58. Shao, W., H. P. Lee, and S. P. Lim. 2001. "Performance of Noise Barriers with Random Edge Profiles." *Applied Acoustics* 62(10): 1157–70.
59. SoundPLAN, GMBH. "SoundPLAN Manual V7.2. Backnang." http://www.soundplan.com/soundplan_en-master.pdf.
60. Tamura, Hiroyuki, Shin ichi Fujita, and Hiroshi Koi. 1994. "Decision Analysis for Environmental Impact Assessment and Consensus Formation among Conflicting Multiple Agents - Including Case Studies for Road Traffic." *Science of the Total Environment, The* 153(3): 203–10.
61. Tansel, Yusuf. 2012. "Robotics and Computer-Integrated Manufacturing An Experimental Design Approach Using TOPSIS Method for the Selection of Computer-Integrated Manufacturing Technologies." *Robotics and Computer Integrated Manufacturing* 28(2): 245–56. <http://dx.doi.org/10.1016/j.rcim.2011.09.005>.
62. Topcu, Y. I., and F. Ulengin. 2004. "Energy for the Future: An Integrated Decision Aid for the Case of Turkey." *Energy* 29(1): 137–54.
63. Ueda, Yuzuru et al. 2008. "Advanced Analysis of Grid-Connected PV System's Performance and Effect of Batteries." *Electrical Engineering in Japan (English translation of Denki Gakkai Ronbunshi)* 164(1): 21–33.
64. Vallati, A., R. De Lieto Vollaro, A. Tallini, and L. Cedola. 2015. "Photovoltaics Noise Barrier: Acoustic and Energetic Study." *Energy Procedia* 82: 716–23.
65. Venckus, Žilvinas, Raimondas Grubliauskas, and Albertas Venslovas. 2012. "The Research on the Effectiveness of the Inclined Top Type of a Noise Barrier." *Journal of Environmental Engineering and Landscape Management* 20(2): 155–62.
66. Vukadin, Predrag, Ivan Bubić, and Ivan Tudor. 2008. "Urban Noise Mapping - an Approach to the Establishment of Standard Making Procedure." *The Journal of the Acoustical Society of America* 123: 3031.
67. Wadhawan, Siddharth R., and Joshua M. Pearce. 2017. "Power and Energy Potential of Mass-Scale Photovoltaic Noise Barrier Deployment: A Case Study for the U.S." *Renewable and Sustainable Energy Reviews* 80(May): 125–32. <http://dx.doi.org/10.1016/j.rser.2017.05.223>.
68. Watts, G. R. 1996. "Acoustic Performance of a Multiple Edge Noise Barrier Profile at Motorway Sites." *Applied Acoustics* 47(1): 47–66.
69. WG-AEN. 2007. *Position Paper: Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure*.
70. Zorer Gedik, Gülay et al. 2017. "Evaluation of Mass Housing Settlements in Terms of Wind and Noise Control: Istanbul and Diyarbakir as a Case." *Journal of Environmental Engineering and Landscape Management* 25(4): 389–401.

Tables

Table 1 Assumptions made in the study	
Meteorological and Radiation Data	Meteonorm 7.2 (synthetic hourly data)
Settlement Area	72.000m ²
Total Construction Area	10.000m ²
Barrier Azimuth Angle	-30°
Storey Height of buildings	3m
Noise exposure assessments	Daytime Period (07:00-19:00)
Total width of barrier top	5m
Length of barrier	590m
Highway	41m wide, 8 lanes

Table 2 Block properties and population distribution in blocks				
Block Type	A	B	C	
Number of Blocks	6	15	4	
Number of Floors	5	5	9	
Number of Rooms	4+1	3+1	2+1	1+1
Number of Residents	6	5	3	2
Number of households each floor	2	2	2	2
Number of Resident in a Block	60	50	90	
Total Number of Residents in the Settlement	1470			

Table 3 Traffic data of the highway						
	Day		Evening		Night	
	<i>07:00-19:00</i>		<i>19:00-23:00</i>		<i>23:00-07:00</i>	
Total Vehicle (annual)	23.852.818		6.823.254		4.270.737	
Heavy Vehicle (annual)	3.031.978		670.207		491.535	
Hourly Traffic Volume (vehicle/hour)	5446		4673		1462	
The proportion of Heavy Vehicles (%)	% 12,7		% 9,8		% 11,5	
Light Vehicle (Vehicle/hour)	4754		4215		1294	
Heavy Vehicle (vehicle/hour)	692		458		168	
Vehicle Speeds (km/hr)	Heavy	72	Heavy	70	Heavy	84
	Light	75	Light	78	Light	81

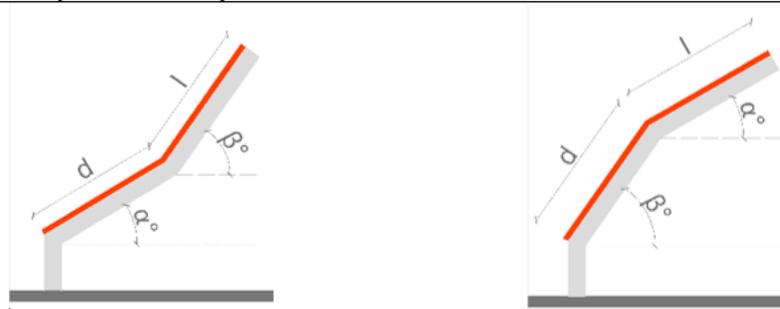
Statistical Evaluations	Measured and calculated levels												STD. DEV
Measurement points	1	2	3	4	5	6	7	8	9	10	11	12	
Distance to the highway	35	20	40	95	110	98	70	115	200	134	77	2	
Measured LAeq	64,7	67,2	61,8	55,1	55,9	56,7	57,8	56	49,7	51,7	57,5	78,4	7,77
Calculated Laeq	64,8	67,1	61,3	54,1	52,1	55,6	58,7	51,1	46	49,4	56	77,8	8,82
Difference	+0,1	-0,1	-0,5	-1,0	-3,8	-1,1	+0,9	-4,9	-3,7	-2,3	-1,5	-0,6	1,60

Module type	90W (1000 W/m ² , 25°C)
Maximum power, Pmax	90 W
Maximum power point voltage, Vmpp	17.7 V
Maximum power point current, Impp	5.15 A
Open circuit voltage, Voc	22.3 V
Short circuit voltage, Isc	5.48 A
Efficiency	% 14.13
Width x length	50,4 cm x 119,6 cm

Months	March	April	May	June	July	August	September	October	November	December	January	February
Monthly Opt. Tilt (°)	34	27	14	8	15	21	33	45	55	58	53	45
Seasonally Opt. Tilt (°)	25			15			43			51		
Semi-Annual Opt. Tilt (°)	19						45					
Annual Opt. Tilt (°)	31°											

Table 7 PVNB alternatives analysed in the study

Schematic Section



Barrier Type	A										B										
Alternative no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Tilt Angles of	α	31										31									
Diffraction Edges	β	27	31	33	34	43	45	51	53	55	58	27	31	33	34	43	45	51	53	55	58
	Analysis	d										2,5									
Widths of	Group A1	l										2,5									
Diffraction	Analysis	d										2									
n Edges	Group A2	l										3									
	Analysis	d										3									
	Group A3	l										2									

Table 8 Calculating criteria weights

	I	II	III
	Direct Rating Weights		Normalised Weights
Electricity Production (kWh)	1	1 / 2,28	0,44
Reduction in the number of receiver points exposed to noise level > 63 dBA	1	1 / 2,28	0,44
Daylight Loss (W/m ²)	0,28	0,28/2,28	0,12
Sum	2,28		

Figures

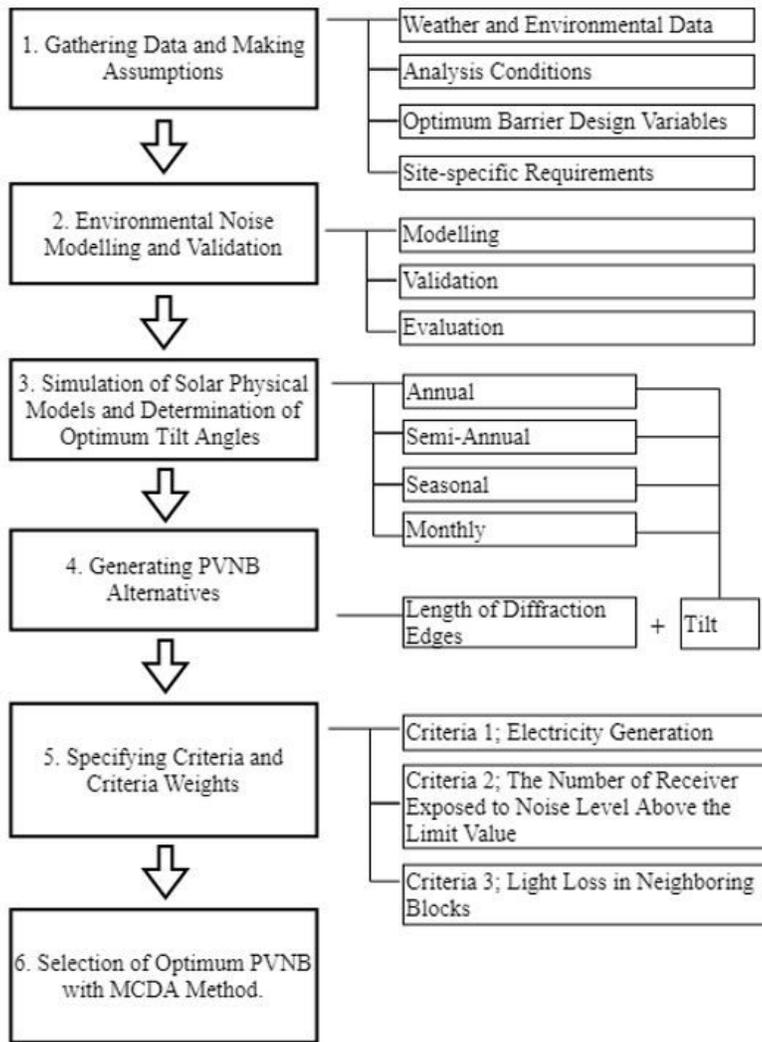


Figure 1

Flowchart of the integrated design method developed in the study



Figure 2

Google Earth view of the residential area where the case study was conducted (2020) and measurement points

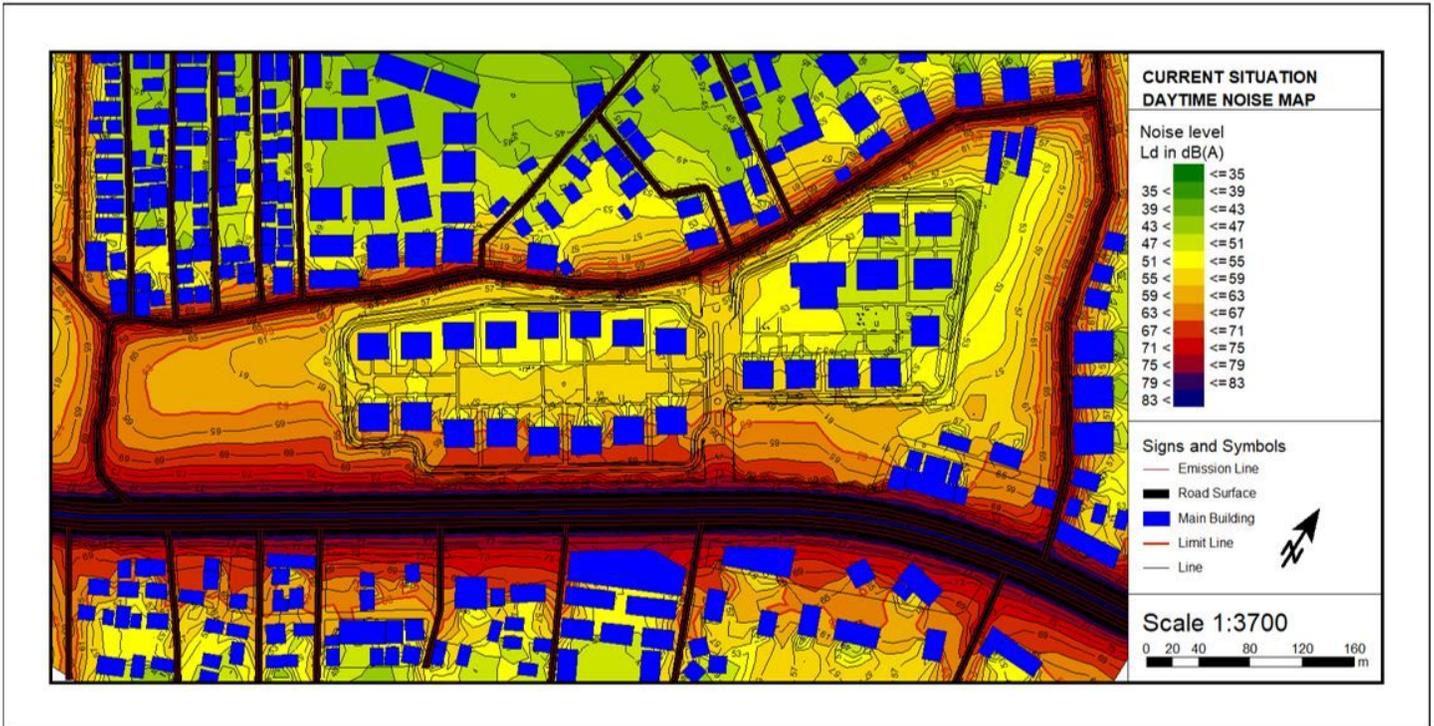


Figure 3

Current situation grid noise map for daytime interval

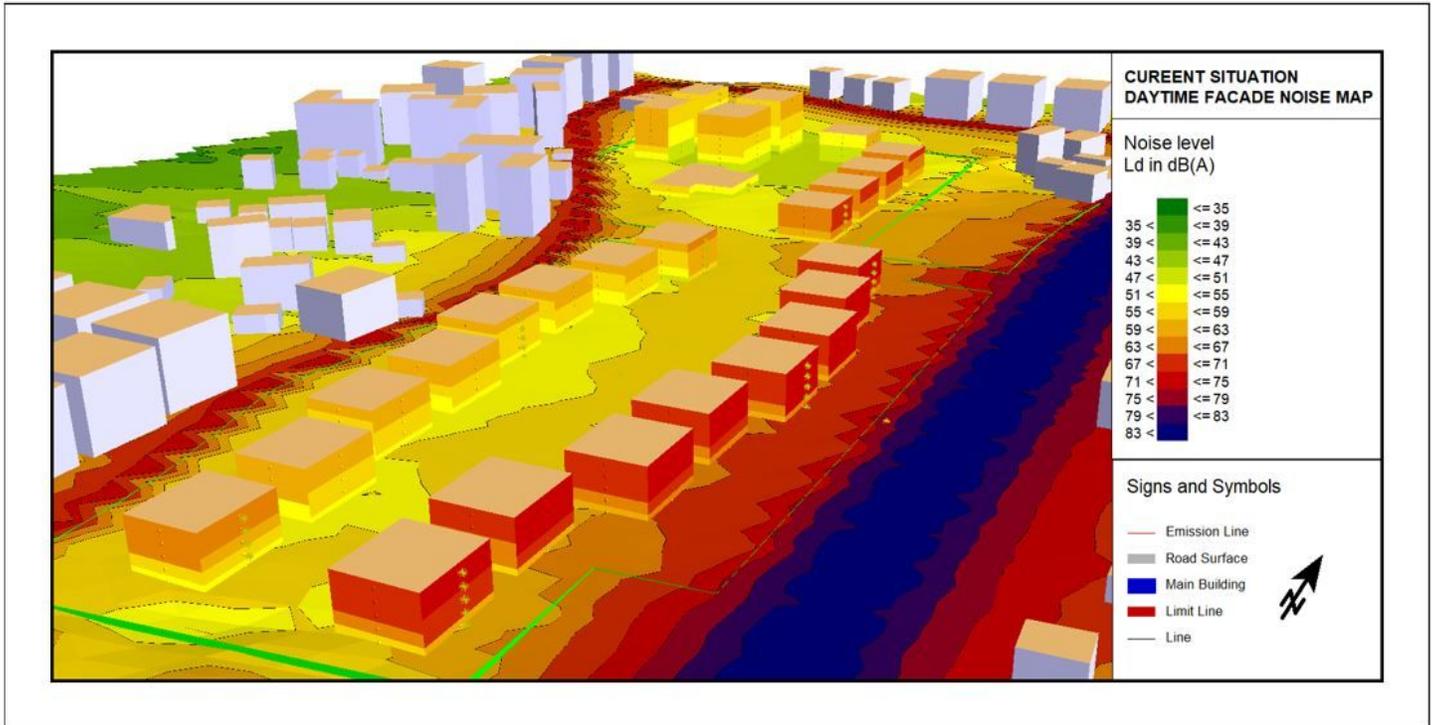


Figure 4

Current situation façade noise map for daytime interval



Figure 5

Monthly average daily global horizontal irradiation, diffuse horizontal irradiation, and clearness index values for the case study area

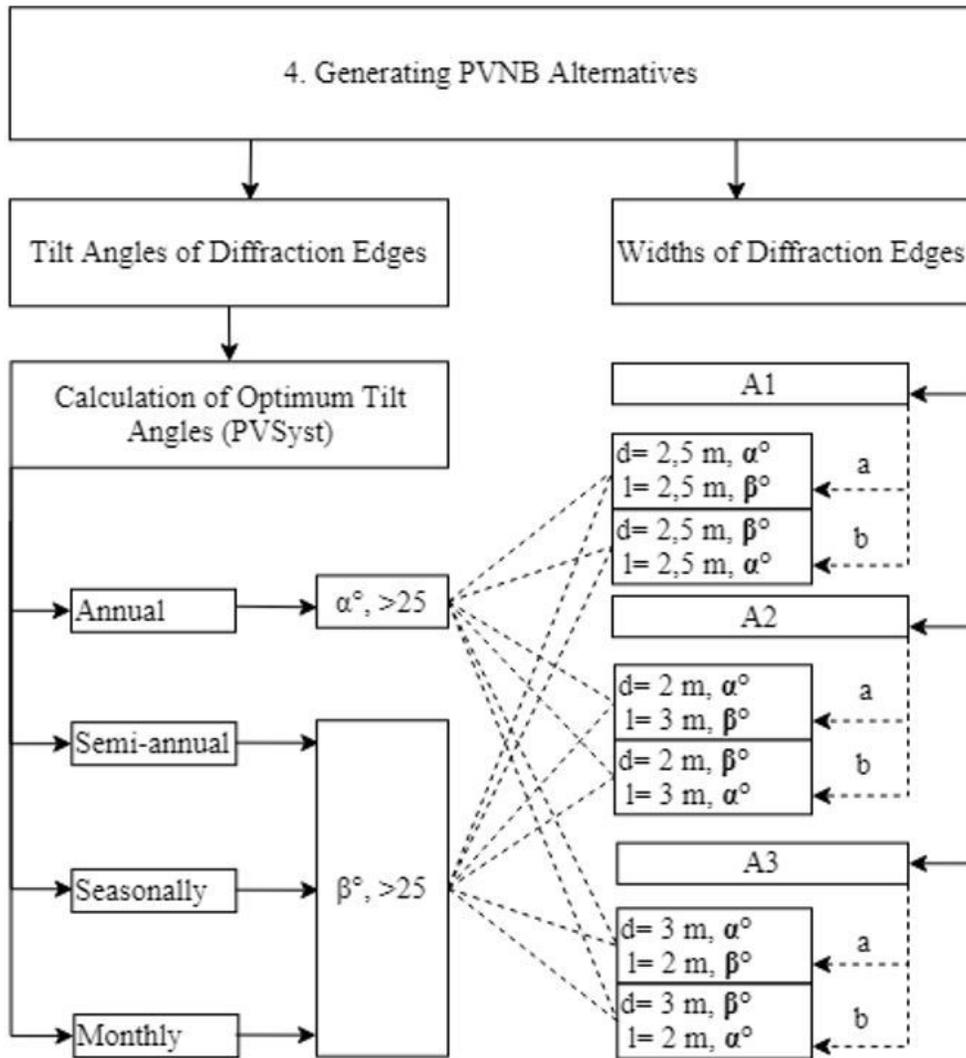


Figure 6

Steps of generating PVNB alternatives

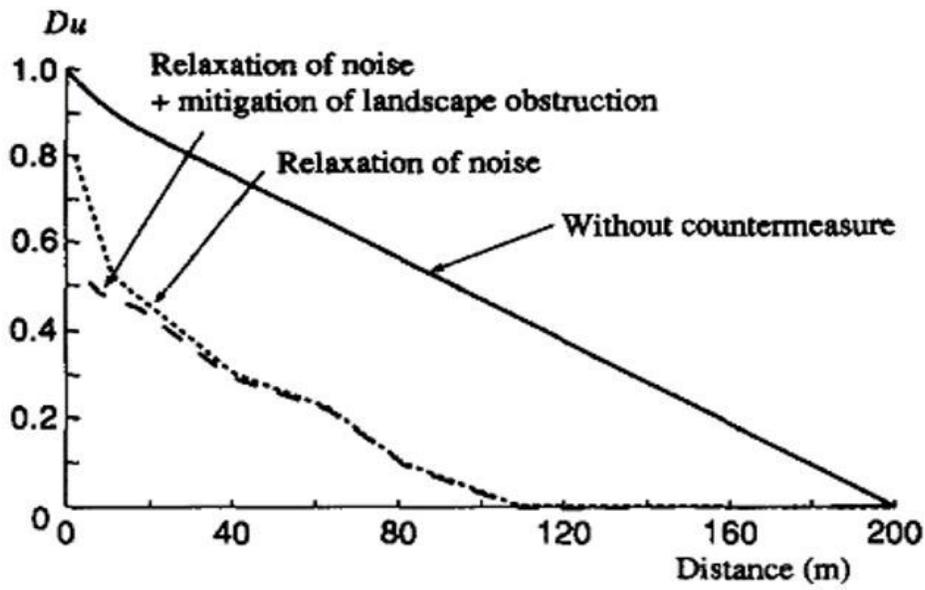


Figure 7

Disutility functions of noise barrier effect for evaluating its environmental impact (Tamura, Fujita, and Koi 1994)

(a)



(b)

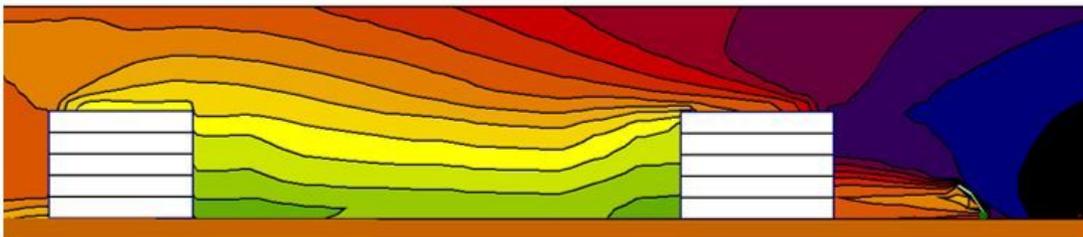


Figure 8

(a) Current situation cross-section map, (b) Cross-section map with optimum PVNB selection

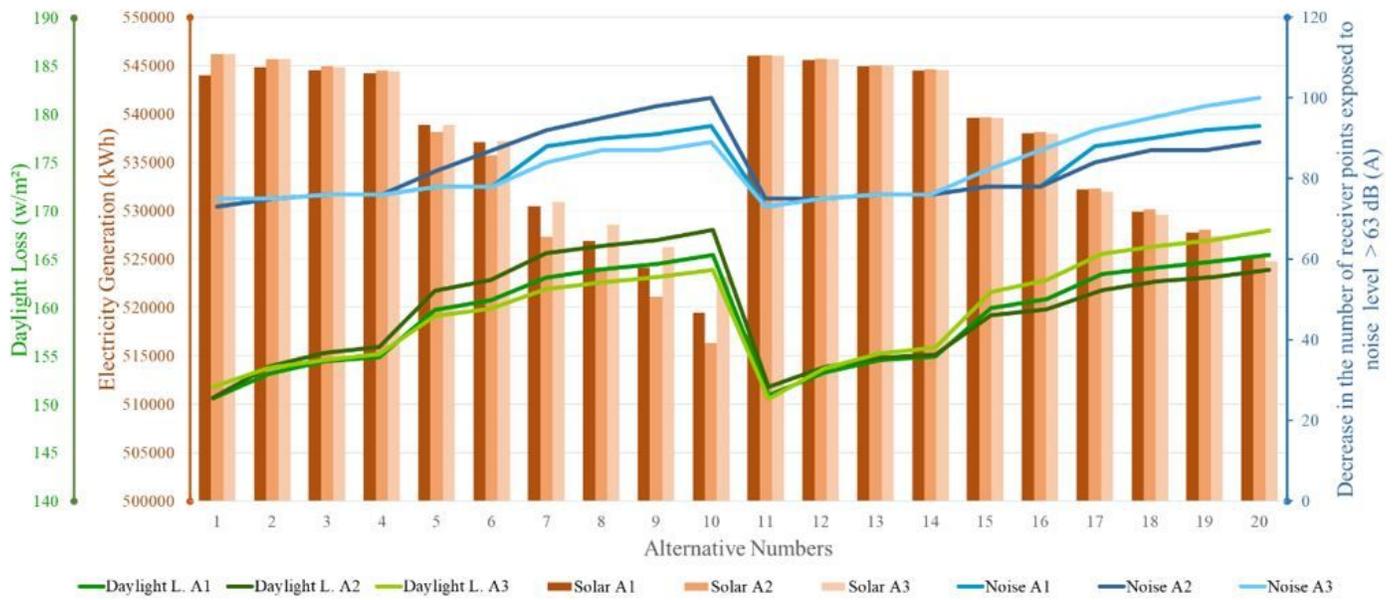


Figure 9

Performance indicators of alternatives based on criteria

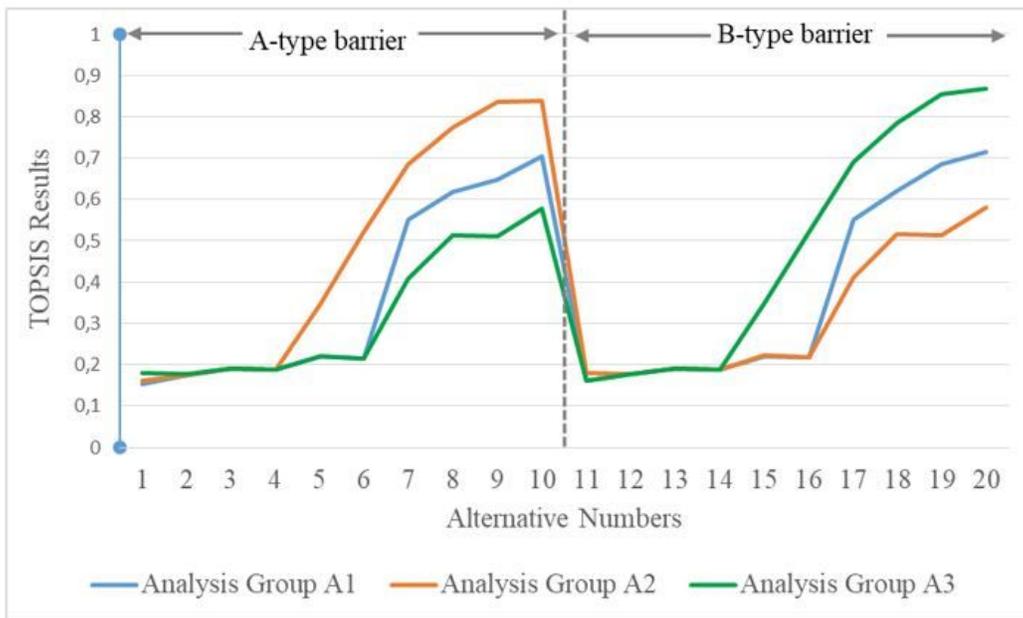


Figure 10

Comparison of alternatives according to TOPSIS results