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OPTIMISATION OF THERMAL LOAD OF PHC UNIT, KARACHI-PAKISTAN, BY OPTIMIZATION USING ORIENTATION, ENERGY SIMULATION IN AUTODESK ECOTECT & PVSYST SOFTWARE

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Abstract

In hot areas, buildings consume significant amounts of electricity on cooling, which puts additional strain on the power system in Pakistan. This study investigates if the building orientation alone has a cooling load reducing effect. A primary health care unit of the area of 500 m² was modelled in Autodesk Ecotect for Karachi (24.86° N, 66.99° E). The model was then rotated around from 0 degree to 360 degree in 10 degree increments and the cooling requirement was noted for each angle. Load increased from 38.20 tons of refrigeration (TR) for the building oriented North (0°/360°) to 38.62 TR at 230°. The alignment with the north thus reduced the heat gain by approximately 5,070 BTU/h or a saving of 561.9 kWh per month (PKR 33,713 at PKR 60 per kWh) compared to the baseline of 34,765.9 kWh. The optimised load is 38.2 TR (approx. 133 kW) and PVSyst was used to design a solar supply system of 532 modules of 400 W and an inverter of 150-200 kW and 98.2% efficiency, for the daytime operation. The orientation gain is relatively small (e.g., 1.1% of the peak cooling load), but it is free at design time and can be used in conjunction with other envelope measures like reflective roofs, insulation and thermal mass. The outcomes provide an easy, inexpensive design guideline for new health facilities and housing scheme in Karachi and other hot coastal cities.

1. Introduction

Buildings are one of the biggest consumers of energy in today's society. According to a widely cited review, buildings in developed countries consume approximately 20–40% of the total final energy use, with heating, ventilation and air conditioning (HVAC) representing the largest single contribution to the total use [1]. The global energy demand is still on the rise and fossil fuels lead to the depletion of resources, pollution and climate impacts at local levels [2, 3]. Thus, numerous studies have called for the acceleration of the transition to renewable energy and to reduce energy consumption in buildings [4, 5]. This is a very acute issue in Pakistan. The country suffers from power shortage for many years and policy review calls the power shortage as a long-standing issue, which is interrupting daily life, and economic growth [6–8]. Meanwhile, Pakistan is in the global solar belt. The measured and modelled data confirmed that the annual global radiation within the country is in the range of approximately 1800–2200 kWh/m², indicating that solar photovoltaic (PV) and solar thermal systems are viable [9-11]. Yet bad building design does not compensate for a bad solar building. The more heat a building absorbs, the larger a cooling plant will have to be, and the larger the cooling plant the larger a power source will be needed.

Karachi is the largest city of Pakistan and one of the fastest-growing cities of South Asia [12]. Its climate is hot and humid, and dense concrete and asphalt surfaces strengthen the urban heat island effect. Studies of low-income communities in the city show high levels of thermal discomfort and a strong need for better building design [13]. More widely, heat extremes in Pakistan have become more frequent, and climate models project that heat waves will become more intense and longer worldwide [14–16].

For public buildings such as health care units, a failure of cooling is not only a matter of comfort. It can affect patient care, so these buildings need a reliable and low-energy way to stay cool.

Passive design is one of the oldest ways to reduce cooling demand. Bioclimatic design guides have long stressed that the shape, the position and the orientation of a building should respond to the local sun and wind [17, 18]. Reviews of passive cooling list shading, natural ventilation, insulation, thermal mass and good window design among the main measures [19, 20]. Orientation is attractive because it is free: it needs no extra material and no extra equipment, only a decision at the site-planning stage. Field and simulation work in other climates has shown that orientation can change energy demand in a noticeable way [21, 22]. However, the effect depends on latitude, on climate and on the building form, so results from other regions cannot be copied directly to Karachi.

This study therefore asks a focused question: **how much cooling load can be avoided in a typical primary health care unit in Karachi by choosing its orientation with care, and what size of solar PV system is needed to meet the remaining daytime load?** The work has three aims: (i) to model the building and the solar geometry of the site in Autodesk Ecotect; (ii) to find the orientation with the lowest cooling load by rotating the building through a full circle; and (iii) to convert the saving into energy and cost terms and to size a PV array and an inverter in PVsyst. The main contribution is a complete, site-specific and easy-to-repeat workflow that links building-side load reduction with supply-side solar sizing for a hot, coastal, low-latitude city.

2. Background

2.1 Solar energy and cooling in Pakistan

Solar electricity is regarded as a sustainable option for developing economies [23]. Pakistan receives high and fairly uniform solar radiation, with long sunshine hours in most regions [9, 10]. Reviews of national progress describe the growth of PV and the policy and technical barriers that remain [11, 24]. Solar energy has also been proposed for cooling, either through PV-driven electric chillers or through heat-driven thermal systems [25]. Both routes are sensitive to the size of the load: the smaller the cooling demand, the smaller and cheaper the solar plant. For this reason, load reduction should come first and supply sizing second. General solar design methods and PV system sizing follow standard references [26, 27].

2.2 Climate and Thermal Comfort

The factors that influence thermal comfort are: air temperature, radiant temperature, humidity, air velocity, and clothing and activity. Classic comfort standards are conditions where the majority of the occupants are comfortable and they apply the predicted mean vote (PMV) model [28, 29]. A typical comfort temperature range for occupied spaces is approximately 21–27 °C [30]. Additionally, people in naturally ventilated buildings will tolerate a broader range of adaptive models, as they adapt their clothing, behavior and expectations [31, 32]. In hot and humid environments, the interaction between heat and moisture is known as apparent temperature or heat index and according to the study conducted in Pakistan, Sindh and parts of Punjab are highly vulnerable to extreme heat [14, 33]. Reliability of comfort is important in health care buildings since staff and patients may not be able to adapt as well.

2.3 Passive Cooling and Building Orientation

Passive cooling involves bringing down heat gain and unwanted heat by using a powerless mechanism. The main techniques are solar shading, natural ventilation, high-albedo (reflective) surfaces, insulation, thermal mass and controlled glazing [5, 19, 20]. In addition to determining which walls and windows receive direct sunlight during the hottest part of each day, orientation determines the amount of heat received. Research work carried out in the design of envelopes indicates that both the percentage of glazing and the properties of the envelope have significant impact on the energy consumption of a building in hot climates [22, 34]. In addition, guidance on adaptation of buildings to a warming climate emphasises that it is difficult to

change the location and shape of structures later in their lives [35].

2.4 Building simulation tools

Whole-building simulation provides designers with the ability to evaluate numerous options in a short time. Reviews of simulation programs emphasize that the programs vary in strengths, in the level of detail in their solar models, and in how easy they are to use [36]. The software Autodesk Ecotect Analysis, which integrates a simple 3D modelling environment with solar, shading, daylight and thermal calculations, has been widely used in the teaching and early stages of design [37]. PVsyst is a program designed for the design of PV systems. It uses site weather data to simulate the PV energy production and array and inverter losses. Since the computer program Ecotect has a weather file of Karachi, then it is practical for this location. It is only a few studies that have applied it in the context of an orientation sweep of a health care building in Karachi and a PV sizing step. This is what this gap is resolved in this.

3. Materials and Methods

The study followed the eight-step workflow in Figure 1. Steps 1–3 define the site and the building, step 4 studies the sun, steps 5–6 find the best orientation, and steps 7–8 convert the result into energy, cost and PV size.

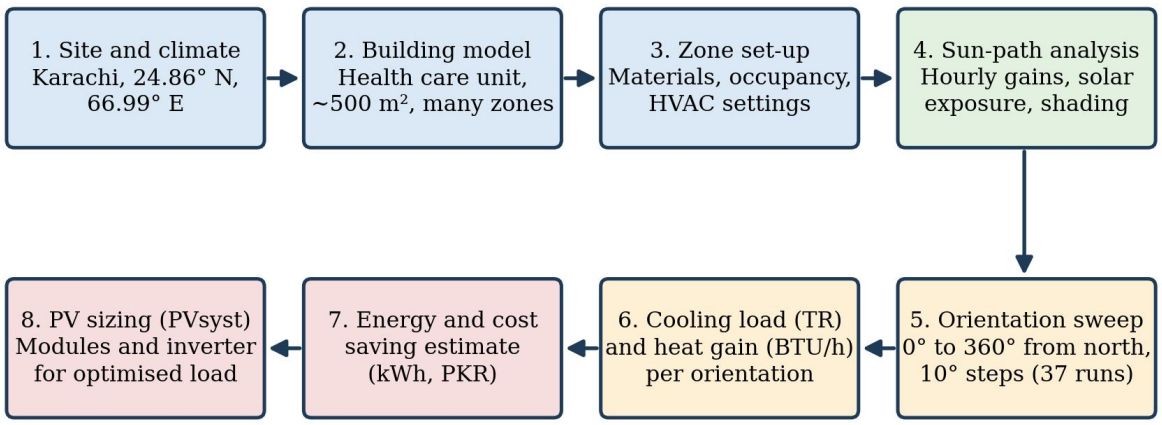


Figure 1. Workflow of the study, from site selection and modelling to orientation analysis, saving estimation and PV sizing.

3.1 Study site

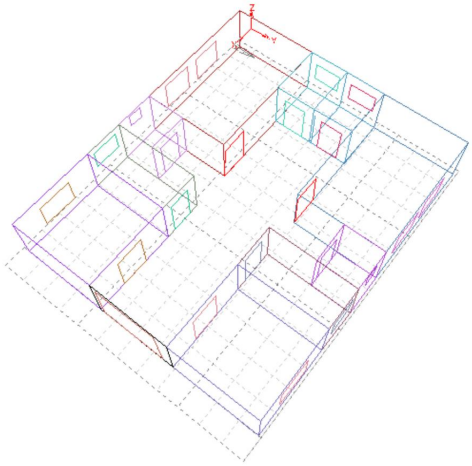
Karachi (24.86° N, 66.99° E) was chosen for two reasons. The first is that the city is one of the hottest and densest urban areas in Pakistan and its inhabitants are at high risk of exposure to strong urban heat [12, 13]. Secondly, Karachi is the only place available for weather data in the Ecotect library that have weather data for Pakistan, and the simulation may benefit from a consistent built in weather file. The city lies on the Arabian Sea coast, at sea level, and has a hot season from March to October with the highest temperatures in May, June and July. It is said to have approximately 300 sunny days annually and hence is suitable for solar energy.

3.2 Building Model

A single-storey primary health care unit with a total plan area of about 500 m² was drawn in Ecotect, first as a 2D plan and then as a 3D model with an open central courtyard (Figure 2). The unit contains two wards (male and female), male and female doctor rooms, male and female nurse rooms, male and female washrooms, an inspection (dressing) room, a clerical room and an entrance. Each room was defined as a separate thermal zone, and walls, doors and windows were attached to the zones in the Zone Management panel. The model geometry was checked to be fully enclosed before any calculation was run, because open zones give wrong thermal

results. A summary of the model and the settings is given in Table 1.

(a) Zone wire-frame (2D/3D view)



(b) Massing model used in simulation

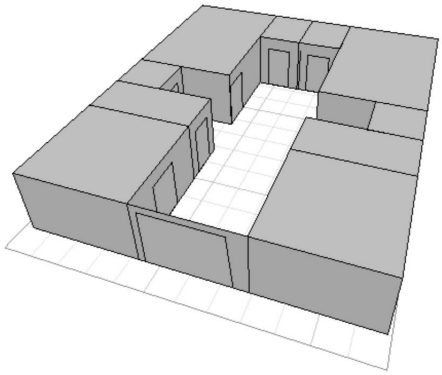


Figure 2. Ecotect model of the primary health care unit: (a) zone wire-frame showing rooms, doors and windows; (b) 3D massing model with the central courtyard. Source: model developed for this study.

Table 1. *Summary of the building model and simulation set-up.*

Item	Description
Building type	Primary health care unit, single storey
Plan area	About 500 m²
Thermal zones	Two wards, two doctor rooms, two nurse rooms, two washrooms, inspection room, clerical room, entrance
Location and coordinates	Karachi, Pakistan; 24.86° N, 66.99° E; sea level
Weather data	Karachi file in the Ecotect library; reference hot day 27 July
Variable tested	Orientation of the building from north, 0° to 360° in 10° steps (37 cases)
Response variables	Cooling load (TR), heat gain (BTU/h), direct solar gain
PV sizing tool	PVsyst; 400 W modules; inverter efficiency 98.2%

3.3 Solar analysis

After the geometry was complete, the sun path for Karachi was generated with the legal time of Pakistan. Four outputs were used: (i) the hourly heat gains of all visible thermal zones on the reference hot day; (ii) the sun height for the main seasons; (iii) polar and stereographic sun-path diagrams that show the sun position through the year; and (iv) the monthly direct solar gain on the building surfaces. These outputs show when and from where the sun heats the building, and they guide the choice of orientation. The solar geometry follows standard relations for sun position and incidence [26].

3.4 Orientation sweep and load calculation

The building was rotated about the vertical axis from 0° to 360° in steps of 10°, where 0° means that the main axis points to true north. For each of the 37 positions, Ecotect calculated the hourly thermal balance of all zones and reported the peak cooling requirement in tons of refrigeration (TR) and the total heat gain in BTU/h. The two units are linked by Equation (1). The reduction in heat gain obtained by moving from the worst to the best orientation is given by Equation (2).

$$Q = 12{,}000 \times TR \quad [BTU/h] \tag{1}$$

$$\Delta Q = Q_{max} - Q_{min} \quad [BTU/h] \tag{2}$$

where Q is the heat gain, TR is the cooling load in tons of refrigeration, and Q_{max} and Q_{min} are the heat gains at the worst and best orientations, respectively. One ton of refrigeration equals 12,000 BTU/h.

3.5 Energy and cost estimate

The monthly electricity use of the building was estimated in the software for the conventional case (without orientation optimisation) and for the optimised case. The saving in energy and in cost was then calculated with Equations (3) and (4).

$$E_{saved} = E_{base} - E_{opt} \quad [kWh/month] \quad (3)$$

$$C_{saved} = E_{saved} \times t \quad [PKR/month] \quad (4)$$

where E_{base} and E_{opt} are the monthly electricity use before and after optimisation, and t is the electricity price, taken as PKR 60 per kWh at the time of the calculation. Because tariffs change, the cost figure should be read as indicative.

3.6 PV system sizing

The optimised cooling load of 38.2 TR corresponds to an electrical demand of about 133 kW. The PV system was sized to supply this demand during an eight-hour daytime period. The number of modules was calculated with Equation (5), where P is the load, h is the operating time per day and e_m is the daily energy delivered by one module. A 400 W module was assumed to deliver 2 kWh per day (equal to about five full-sun hours). The inverter was selected in PVsyst so that its rating covers the peak load. PV output also depends on module temperature, which is high in Karachi [38], so the sizing here is a first estimate and not a final design.

$$N = (P \times h) / e_m \quad (5)$$

4. Results and Discussion

4.1 Solar geometry and heat gain at the site

Figure 3 is the solar altitude and the sun-path diagram for Karachi. The maximum elevation of the Sun is approximately 88° around 21 June and the minimum is approximately 43° around 21 December. June has the longest day, December has the shortest. The longer the sun path the longer there are hours of direct radiation, so the building gets more heat during the long summer days than in winter. This software had identified 27th July as the hottest day in the file of Karachi's weather so the day was taken as the reference for the hourly analysis.

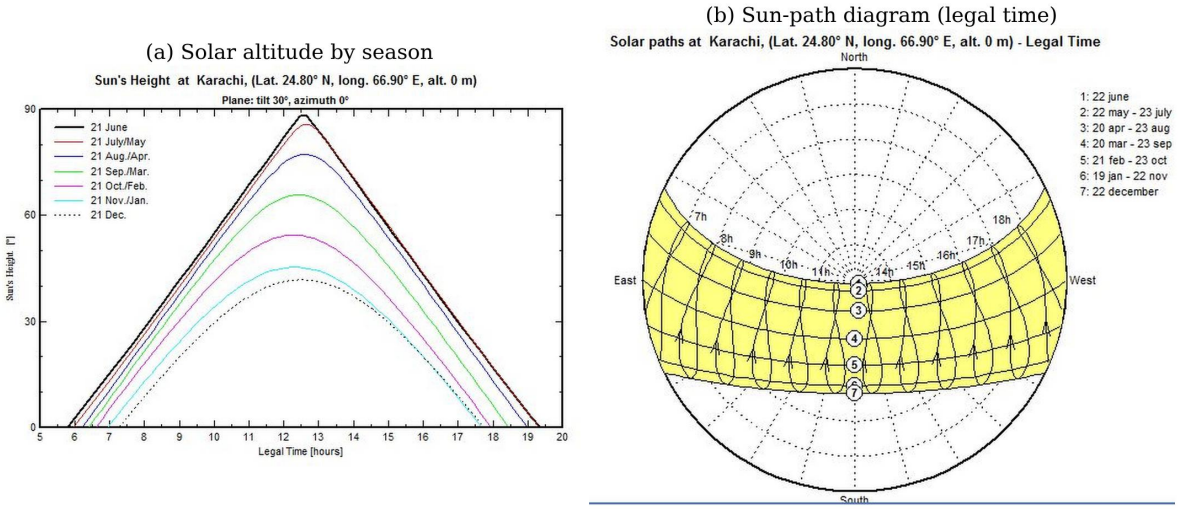


Figure 3. Solar geometry of Karachi (24.80° N, 66.90° E): (a) sun height against legal time for the main dates of the year; (b) polar sun-path diagram. Source: Ecotect output.

Figure 4 gives the hourly heat gains of all thermal zones on the reference day. The direct solar gain is small during the night and the early morning, grows from about 9:00 and is highest in the afternoon and early evening. The HVAC load follows the same pattern. This delay is common in buildings with thermal mass: heat absorbed by the envelope during the day is released into the rooms several hours later. The result also shows that the hot period of the day is long, so any reduction in direct solar exposure acts over many hours.

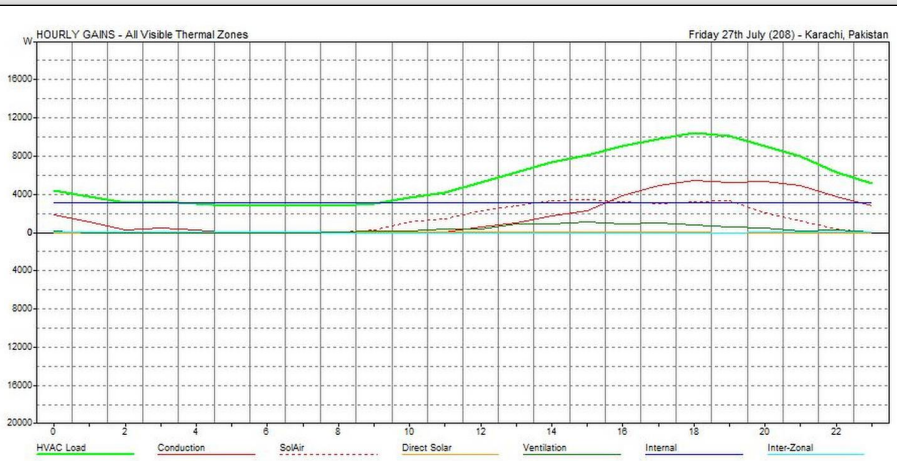
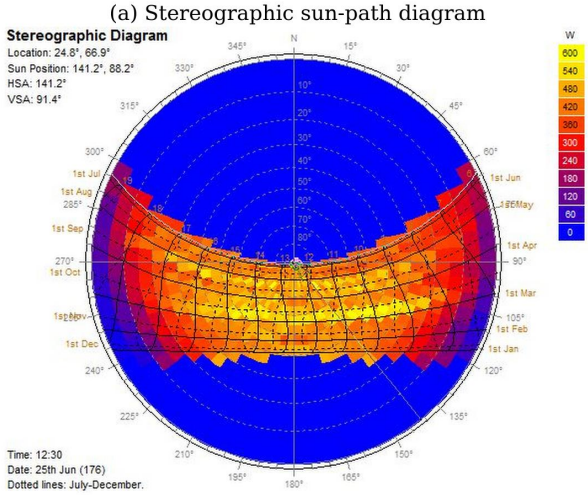


Figure 4. Hourly heat gains of all visible thermal zones on the reference hot day (27 July): HVAC load, conduction, solar, direct solar, ventilation, internal and inter-zonal gains. Source: Ecotect output.

4.2 Annual solar exposure

The exposure is summarised for the whole year in the stereographic diagram and the gain map displayed in figure 5. The best direct gains are in the middle part of the day. As illustrated by the map in Figure 5(b), there is a similar daily variation in solar loading for all months of the year, meaning that there is no month without a solar load. This implies that cooling is required in most seasons in Karachi and solar control is a design activity which should be addressed year round and not just during the summer season.

(a) Stereographic sun-path diagram



(b) Monthly direct solar gain by hour

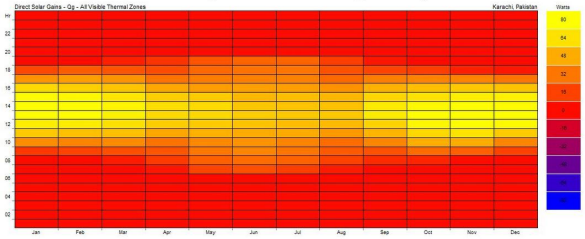


Figure 5. Annual solar exposure at the site: (a) stereographic sun-path diagram with direct solar gain in W; (b) direct solar gain on the building for each hour and month. Source: Ecotect output.

4.3 Effect of building orientation on cooling load

The main result of the study is the response of the cooling load to orientation (Figure 6 and Table 2). The range of load was 38.20 TR to 38.62TR, with the mean load being 38.46TR and the standard deviation 0.13TR across the 37 positions. The minimum load was obtained when the building was oriented towards the north (angles of 0°, 360°), while the maximum load was obtained at 230°. The curve is not smooth, exactly, as there are several peaks and dips, especially near 80°, 160° and 230°; and near 100° and 290°; these most likely are due to the interaction of the sun path with the courtyard geometry of the plan. Note that all orientations within about 20° of north (340°-20°) had a load of 38.34 TR or less, which means that the best results are not severely constrained to an exact angle. This practice is helpful as it's rarely possible to align the site boundaries

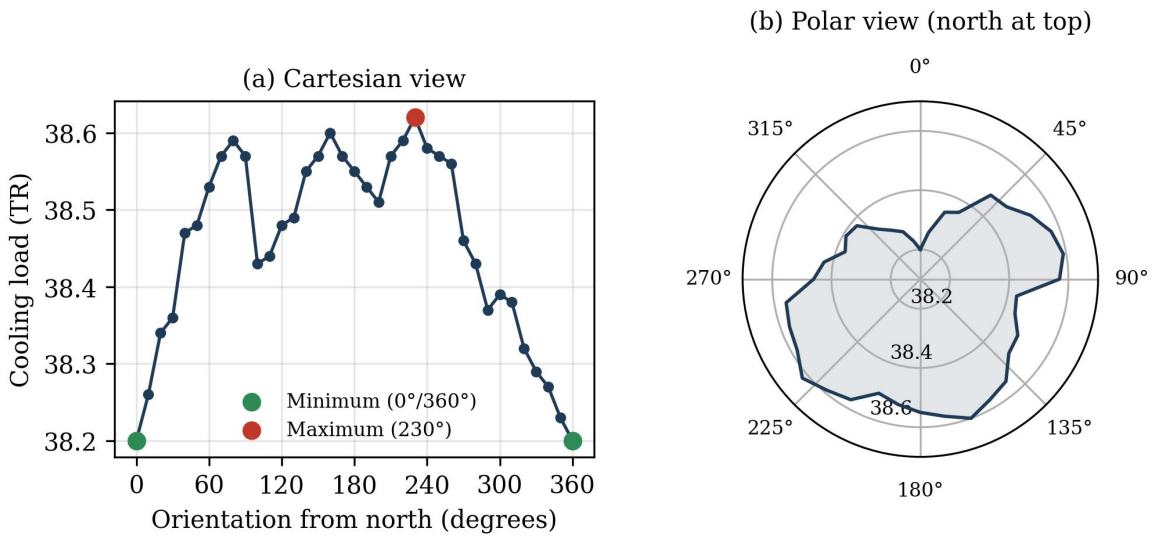


Figure 6. Cooling load of the health care unit against its orientation from north: (a) Cartesian plot with the minimum (0°/360°) and maximum (230°) marked; (b) the same data in polar form, with north at the top. Data: Ecotect simulations, 37 orientations.

Table 2: *Cooling load at selected orientations and summary statistics of all 37 cases.*

Orientation from north	Cooling load (TR)	Increase over minimum (TR)	Increase over minimum (%)
0° / 360° (minimum)	38.20	0.00	0.0
10°	38.26	0.06	0.2
90°	38.57	0.37	1.0
160°	38.60	0.40	1.0
180°	38.55	0.35	0.9
230° (maximum)	38.62	0.42	1.1
270°	38.46	0.26	0.7
350°	38.23	0.03	0.1
Mean of 37 cases	38.46	0.26	0.7
Standard deviation	0.13	–	–

Values are taken from the 10° simulation series. The heat-gain difference between the best and the worst case, calculated from unrounded model output, is 5,070.65 BTU/h.

Figure 7 shows the two extreme cases in the sun-path view. At 230°, more of the facade is exposed to the sun in the afternoon so the direct radiation on the surfaces is greater. If the exposure area is reduced and the heat gain reduced at 0° then that is what you will find here. The difference in the two cases is 0.42 TR (approximately 5,070 BTU/h) (Equations 1 and 2). In comparison, this is approximately 1.1% of the design cooling load. This is a not insignificant number, but it needs to be viewed in its context. First, it comes with no additional materials, equipment or expense. Second, it is used for all the hours of cooling plant operation. Third, it is additional to any saving from shading, insulation or reflective surfaces, which act on different heat paths.

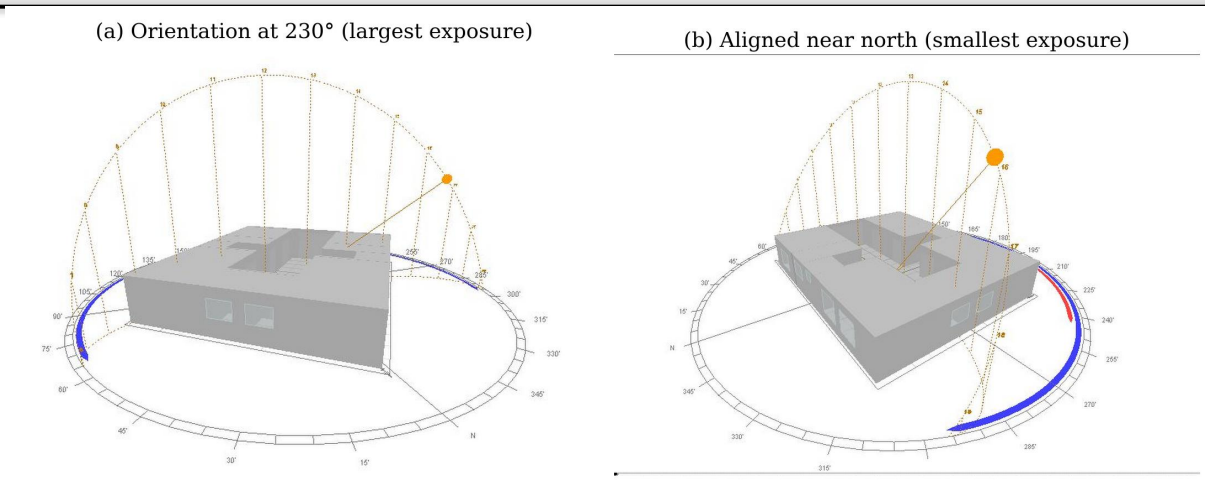


Figure 7. Sun paths over the building at the two extreme orientations: (a) 230 degrees, with the largest area exposed to direct radiation; (b) building aligned near north (0°–10°), with the smallest exposed area. Source: Ecotect output.

The size of the effect is modest. This may be realistic in a small courtyard with little rotation of the wall area that needs to be glazed. The magnitude of orientation effects is known to depend on the building form and the glazed area [22, 34] and hence a larger effect might be observed for buildings with long glazed facades, but this was not investigated here. This is a minimum estimate for similar health care units.

4.4 Energy and cost savings

Table 3 and Figure 8 convert the load reduction to electricity and money. Consumption estimated was 34,765.9 kWh per month in the conventional design, and 34,204 kWh per month in the north aligned design. This represents a monthly savings of 561.9 kWh or 1.6% of baseline. At PKR 60 per kWh the monthly saving is PKR 33,713. If the same saving is assumed for every month (a simple extrapolation, since the real value will change with season and tariff), it amounts to about 6,740 kWh and PKR 404,500 per year. This is an excellent amount of savings for a public health facility on a restricted budget, especially as a permanent savings which requires no maintenance.

Table 3: ***Estimated electricity and cost savings from north alignment of the building.***

Quantity	Value	Unit
Heat gain removed (ΔQ)	5,070.65	BTU/h
Electricity use, conventional design	34,765.9	kWh/month
Electricity use, optimised design	34,204.0	kWh/month
Electricity saved (E_{saved})	561.9	kWh/month
Relative saving	1.6	%
Cost saved at PKR 60/kWh	33,713	PKR/month
Extrapolated annual saving (indicative)	6,742 kWh; 404,557 PKR	per year

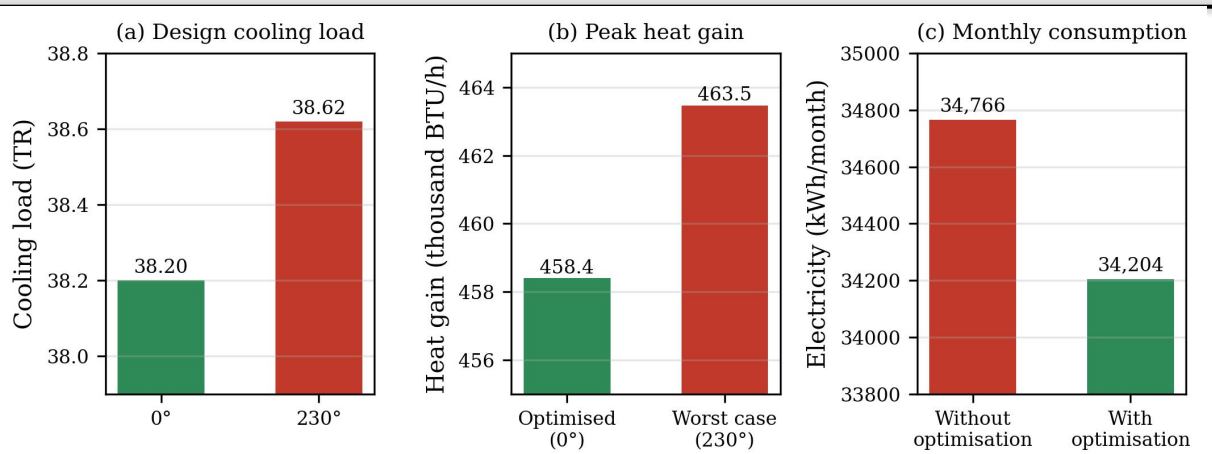


Figure 8. Effect of north alignment: (a) design cooling load at 0° and 230°; (b) peak heat gain at the two orientations (the y-axes of panels (a) and (b) do not start at zero, to make the differences visible); (c) estimated monthly electricity use with and without optimisation.

4.5 Solar PV and inverter sizing

This optimised cooling load is equivalent to approximately 133 kW of electrical load. With an 8 hour operating time, the daily energy requirement is approximately 1064 kWh using solar energy. An array of approximately 213 kWp is calculated from Equation (5) for the module providing 2 kWh per day (Figure 9 and Table 4). The SMA inverters of the class 150-200 kW (Sunny Highpower and Tripower models) recommended by PVsyst are 98.2% efficient and cover the peak load. The efficiency of the inverter is high, so that there are still few losses in the modules from high temperature and dust.

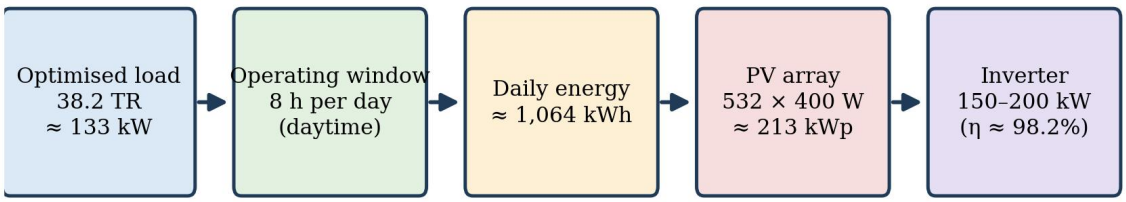


Figure 9. Sizing chain for the solar supply: from the optimised cooling load to the PV array and the inverter.

Table 4. ***PV system sizing for the optimised cooling load.***

Parameter	Value	Note
Optimised cooling load	38.2 TR	North-aligned building
Equivalent electrical load	≈ 133 kW	As reported in the study
Operating period	8 h/day	Daytime supply
Energy per 400 W module	2 kWh/day	≈ 5 full-sun hours
Number of modules	532	Equation (5)
Array size	≈ 213 kWp	532 × 400 W
Inverter rating	150–200 kW	Efficiency 98.2%

An interesting point to note here is the location of the PV array. In the PVsyst stage, the maximum solar capture was obtained for the module azimuth of 230° from north (south-west) which is also the worst azimuth for the building envelope. The result indicated that the building and PV array should be

oriented separately, i.e. the PV array may be mounted separately on the frames or alternatively, the PV array should be mounted on a different roof mount with a different orientation to the building to capture more solar gain. A 230° azimuth differs from the south-facing azimuth commonly recommended in the northern hemisphere, so the PVsyst result must be re-evaluated using a complete loss diagram prior to construction of the system.

4.6 Further passive measures

Orientation is just the beginning. The small orientation gain should be integrated with envelope measures dealing with other heat paths. For a health care unit in Karachi 4 measures are most relevant. High-albedo roofing materials (roofing materials with white coating or reflective roofing) can reduce the heat absorption of the roof surface, the most exposed surface in a low-rise building [39]. Second, above the occupied spaces an insulated double roof or a vegetated roof will provide an additional thermal barrier [19]. Third, thermal mass in the walls including rammed earth, adobe or dense concrete slows down the transfer of heat into rooms, and is most effective when paired with night ventilation [40]. Fourth, cool facade finishes, like lime wash, ceramic coatings or ventilated facades, reduce wall surface temperature [5, 20]. These can be combined with the north alignment to reduce the size of the cooling plant and PV array from the values listed above.

4.7 Limitations

There are a number of restrictions to consider. The numerical values obtained in the study were only for this configuration of building form, city and weather file and should be re-tested for other forms and sites. The results are based on simulation only and there was no in situ measurement of the indoor temperature or electricity use for the model to be compared with. Ecotect is not being developed any longer and newer tools may employ more sophisticated solar and airflow models, but it is very useful for initial comparisons. The electricity price and the PV assumptions (daily yield per module, operating hours and module temperature effects) are simple and will be changed in a detailed design. Lastly, the research focused only cooling and did not consider daylight, glare or natural ventilation aspects nor the influence of orientation on wind.

5. Conclusions

In this study, the cooling load of a primary health care unit in Karachi has been investigated when the building orientation is taken into consideration and the rest of cooling load is fulfilled by solar photovoltaic (PV). The following are the key findings.

- The cooling load changed with orientation from 38.20 TR (0°/360°) to 38.62 TR (230°). The building was oriented to the north, which reduced the heat gain by approximately 5070 BTU/h or approximately 1.1% of the peak load.
- A deviation of ±20° from 'True North' made no difference to the load as all orientations within this range showed a load of 38.34 TR or less and so a small deviation from the true course of 'North' does not negate the benefit.
- The estimated saving was 561.9 KWh/month (or 1.6% of the baseline use) which equated to PKR 33,713/month at a price of PKR 60 per kWh. This saving can be achieved without additional material or equipment.
- The optimal load, estimated to be around 133 kW, yielded a figure for the PV size of 532 modules of 400 W (around 213 kWp) and a 150–200 kW inverter with a 98.2% efficiency, as shown by PVsyst.
- The most optimal orientation is different for the building (north) and the PV array (230° in this study), so the two should be independently designed.

The bottom line to planners and designers is: Decide at the site-planning stage because it's free, and it is not possible to change it later. Future work should

(i) Validate the model using the measured indoor temperature and electricity data,

(ii) Include insulation, reflective roofs, shading and thermal mass in the model and test the combined effect of these,

(iii) Repeat the PV sweep for other building forms and other cities of Pakistan, and

(iv) Extend the PV analysis to a full hourly simulation with storage and grid interaction.

Author Contributions, Funding and Data Availability

S.K.: Conceptualisation, methodology, simulation and writing; R.: supervision and review. This research is not funded. The simulation data that supports the findings (the 37-case orientation series) are provided in Table 2 and Figure 6 and can be obtained on reasonable request from the corresponding author. The authors do not have any conflicts of interest.

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