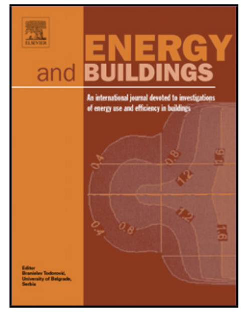
Accepted Manuscript



Title: Will cool roofs improve the thermal performance of our built environment? A study assessing roof systems in Bahrain

Author: Hassan Radhi Stephen Sharples Hanan Taleb Mohammad Fahmy

PII:	S0378-7788(16)31603-6
DOI:	http://dx.doi.org/doi:10.1016/j.enbuild.2016.11.048
Reference:	ENB 7163
To appear in:	*ENB*
Received date:	20-5-2016
Revised date:	31-10-2016
Accepted date:	18-11-2016

Please cite this article as: Hassan Radhi, Stephen Sharples, Hanan Taleb, Mohammad Fahmy, Will cool roofs improve the thermal performance of our built environment? A study assessing roof systems in Bahrain, Energy and Buildings http://dx.doi.org/10.1016/j.enbuild.2016.11.048

Will cool roofs improve the thermal performance of our built environment? A study assessing roof systems in Bahrain

Hassan Radhi [a]*, Stephen Sharples[b], Hanan Taleb[c], Mohammad Fahmy[d],

[a]Tasmeem Engineering, Kingdom of Bahrain
[b]School of Architecture, University of Liverpool, United Kingdom
[c]Faculty of Engineering, British University in Dubai, UAE
[d]Architecture Engineering Department, Military Technical Collage, Cairo, Egypt

*Corresponding author: Hassan Radhi,
Tasmeem Engineering, Kingdom of Bahrain
E-mail address: H.radhi@tasmeemeng.com
Tel.: +973 17002172

'Research highlights'

- The potential of cool roof strategy for Bahrain with its long cooloing season
- The light tile roof and metal decking are relatively cooler and more comfortable than others
- The light tile roof achieves the maximum reduction in cooling energy among roofs systems
- The differance in heat gain for light tile roof with and without thermal insulation is minor.
- The differance in heat gain for other roofs with and without thermal insulation is major.

Abstract

A number of international campaigns have recently proposed the use of cool roofs worldwide in order to cope with the summer urban heat island (UHI) effect. This work investigates cool roof strategy and examines the potential of such a strategy for Bahrain. Full-scale measurement, meteorological modelling and thermal simulation of five standard roofs was performed during particular summer days due to the high intensity levels of solar irradiation. This work shows that the light tile roof and metal decking are relatively cooler and more comfortable than others and that the maximum reduction in heat gain occurs for a light tile roof with thermal insulation materials. Nevertheless, without insulation the cooling load is increased by only 1.3%. This percentage seems not to be cost-effective where economics and building construction are concerned. In contrast, the reduction percentage due to the use of thermal insulation in the case of dark tile roof, felt bitumen roof and screed roof increases to 5-7%, which is more cost effective. This work concludes that the cool roof strategy is the most cost-effective for the hot climate of Bahrain, which has a long cooling season. With the current levels of urban development in Bahrain, cool roofs can reduce UHI intensity and building cooling loads, lowering demand for electricity and greenhouse gas emissions from power plants. To avoid any negative consequences from using this strategy, however, trade-offs between urban mitigation and adoptation strategies and complementary technologies should be accounted for in future urban development plans.

Keywords: cool roof, urban heat island, thermal performance, Bahrain

1. Introduction

The urban heat island (UHI) phenomena has been of growing concern in recent years. The reasons for these phenomena are complex and there are some agreements in the scientific community about the causes. A recent publication by the US Environmental Protection Agency [1] states that increases in temperatures are due to natural factors such as weather and location, in addition to certain human activities such as reduction of vegetation and water bodies and the use of artificial urban surfaces. Many scientists believe that UHI is mainly caused by urbanisation as it can lead to the changing of the landscape from vegetation, sand and water to hard surfaces and building blocks [2-4]. Some scientific research has shown that properties with urban surfaces have a significant effect on the thermal performance of the built environment. Exposing such surfaces to direct sunlight increases their temperature and consequently has an effect on regional weather, energy consumption and thermal comfort through the modification of climatic variables. A recent experimental study [5] shows an increase of up to ten per cent in electricity consumption for air-conditioning in some urban regions of Bahrain. Another study [6] indicates a significant variation in the level of thermal comfort due to an increase in urban temperature in the new Bahraini built environment.

Many urban mitigation and adaptation strategies are proposed to cope with the summer UHI. Some suggest more resilient urban planning [7, 8], while others propose vegetated systems and green roofs [9-12]. Stil more recommend making use of reflective and cool surfaces [13-17]. In addition to these strategies, some complementary technologies exist, such as those for storing energy, utilisation of anthropogenic heat, photovoltaics and canopies. From an engineering perspective the cool surface strategy is seen as viable in that it can provide significant temperature reduction when compared to other strategies.

In terms of a sustainability framework, however, applying a limited strategy and producing a quick urban solution may lead to a deleterious impact on many aspects of our environment. Focusing exclusively on the surface and surface air temperatures and ignoring the impact on parameters such as moisture availability, clouds, rainfall and energy demand may lead to inaccurate results with regard to the benefits of a cool roof strategy. A study by Stanford University [18], found increased reflected sunlight from the cool roof can increase absorbed heat by dark pollutants such as black carbon and consequently increase the temperature of the atmosphere. Another study shows that wide-scale development of cool roofs might alter precipitation levels and moisture content [19]. It has also been indicated that the choice of urban strategies influences not only urban expansion itself, but also future global warming over a large scale [20]. Assessing such consequences shows the need for a multi-disciplinary approach and the importance of trade-offs between urban mitigation and adoptation strategies and complementary technologies that are often unaccounted for [21]. In Bahrain, as a developing country, much work is needed to promote such an approach. This work, therefore, represents a step towards multi-disciplinary thinking to improve the thermal performance of our built environment. It investigates the cool roof strategy to show the potential for such a strategy for Bahrain.

2. Research background

A recent international campaign [22] has proposed the use of cool surfaces in urban regions worldwide and much effort has been spent to develop different types of cool surfaces in many locations. It has been discovered that bright light surfaces remain cooler than traditional materials during peak summer conditions [23, 24]. They are effective in improving the thermal performance of buildings, reducing energy consumption and providing higher savings and environmental benefits than highly insulated standard roofs [25-27]. This is not, however, necessarily when the heating load is dominant or where the application of traditional insulation is the most effective technology in reducing the annual energy use [28]. A comprehensive review of the development and advantages of cool surfaces can be found [29]. A recent study [30] suggests the use of a new family of cool roofs, particularly with retro-reflective surfaces where a significant reduction of the energy available within urban canyons occurs, compared with conventional white and beige surfaces. Such materials can reflect incident radiation backwards to the same direction of incidence [31].

Various criteria and indices are used to assess the effectiveness of cool surfaces [32], including solar reflectance index (SRI) and variation in air temperatures. In terms of SRI, this comprises solar reflectance (Albedo) and thermal emittance and can be calculated by using the equation in ASTM E1980 [33]. This is because the performance of surface materials under direct solar heat and light is strongly correlated to their reflectance and infrared emittance [34-37]. They represent the ability of any material to reflect solar irradiation and to release absorbed heat [38]. Materials with high values of reflectance and emittance would typically be considered cool and vice versa. As a rule of thumb, darker colour materials offer lower solar reflectance. At present, some dark coloured materials are developed with higher reflectivity values through the use of cool coatings and in some cases thermophysical treatments. These materials consequently will have a high SRI and the coolest will be coloured materials with high solar reflectance [39]. The US Environmental Protection Agency [1] mentions that cool light coloured surfaces have a high solar reflectance of more than 65%, absorbing and transferring to the building 35% or less of the solar irradiation that reaches them. These surfaces can reflect almost 80% of the sunlight. In contrast dark coloured, particularly black, roofs reflects only five per cent of the sunlight that heats the buildings.

Different techniques have been utilised to measure the coolness of surface materials such as laboratory analysis. A study in Brazil found that same coloured metals and ceramic surfaces have different ranges of temperature which correspond to their radiative properties [40]. Similar analysis alos discusses which material characteristics affect such properties and shows quantitative figures for some types of material [41], with simulation and mathematical models representing another technique. Some results obtained by using simulation modelling shows that temperatures throughout the summer period depend on their orientation and colour [42]. A recent study in the United States makes a comparison of models for energy saving from cool roofs and supports the use of a web-based Roof Savings Calculator (RSC) [43].

Simulation and models can give good results, however, to show the intersection between urban surfaces and construction elements full scale measurements are needed. Such a technique has been utilised in Turkey to assess the radiative properties of some roof materials [44]. The same technique was applied in Athens in a field study where a great number of cool pavements were examined [45]. Full scale experiments have also been undertaken in Germany to observe surface and air temperatures as well as dewfall dynamics and amounts on an urban green and co-located bitumen roof [46].

An important point to note is that what works in America and Europe does not necessarily provide the same benefits to countries with tropical and hot climates, such as Bahrain and the Gulf States. A recent study focused on developing five suggested parameters, based on the ASHRAE model in the UAE. The strategies included a sunshade, exterior wall design, cool roof, green roof and glazing. The base case was analysed in terms of thermal performance and then used as a reference to compare to these five parameters. The study concluded that the cool roof has a minimal effect compared to the green roof, which worked best in terms of heat gain reduction [47]

Many biophysical and socio-economic complexities exist in western countries which are very different from those in Bahrain, so a spectrum of spatial scales is needed [48].This work assesses the performance of five standard roofs in Bahrain, where the thermal insulation code is applied and without any consideration to the types and properties of surface involved. It is important to mention that the difference in thermal properties of surfaces can lead to variation in the thermal mass and inertia, which control the amount and time that the temperature of the roof approaches that of its surroundings. Adding or removing an insulation layer influences both thermal mass and inertia. Insulation layers mostly decrease thermal transmittance or increase thermal resistance of the roofs due to an increase of thickness. This can be achieved by adding construction layers such as screed. Increasing the mass may lead to an increase in the internal heat capacity of the roof and consequently accumulate heat which can be returned later. This technique is very effective, especially during the summer period summer when passive cooling is essential. In Bahrain, however, passive cooling in the summer months is not effective. Increasing the internal heat capacity of roofs may lead to an increase in the amount of heat transferred through roof layers into air-conditioned spaces and consequently increase the cooling load. A study looking to optimise thermal building design in Bahrain [49], found that a lightweight roof will perform better than a mass roofs. Most roofs in Bahrain are heavyweight and have almost the same composition and thermal properties. The difference can be seen only in the surfacing material and in which different radiative properties are applied. Such properties can significantly control the performance of the roof as a whole.

3. Methodology

Study site and climatic conditions are presented here, the case study roofs are introduced, techniques of data collection and analysis are highlighted and assessment methods are explained. The flowchart in Figure 1 illustrates the methods used in this work, which passed through three main stages, firstly, full-scale measurement, secondely, meteorological modelling and thermal simulation and finally the assessment of the outcome.

3.1. Study site and climatic conditions

Figure 2 shows the location of Bahrain and the study site. It is a 0.25 km² residential and industrial area in the middle of the island of Sitra, itself approximately 10 km². A brief analysis of weather conditions in Sitra [50] offers the following observations. Overall annual average temperature is 26.5 °C meaning a hot climate coupled with occasional high humidity. Mean daily maximum and minimum temperatures for the months from May to October are in excess of 41 °C and 30 °C, respectively. The cooling season is long and extends over six months of the year, with air-conditioning required on a twenty four-hour basis for most of the summer season. Monthly average relative humidity is 65%, with a maximum monthly average of 88% in January and a minimum monthly average of 39% in June. Annual rainfall is 135.0 mm and on average, it can reach 52.0 mm in January. The rainy season is broken up by the six summer months and the Bahrain islands, including Sitra, experience a high solar irradiation level. Statistics show that 1000 W/m^2 is the maximum hourly value at noon in June [51]. Figure 3 shows the monthly average air temperature, relative humidity, wind speed, rainfall and solar irradiation.

3.2. Case study roofs and data collection

Five standard roofs are examined to assess the effect of the roof system on the thermal performance of the built environment in Bahrain. Table 1 shows the examined roofs and their materials and composition. This is lightweight concrete screed, bituminous roofing felt, light and dark coloured ceramic tiles and metal decking. Data and information on these roofs was obtained from working drawings and reports provided by building owners and construction companies. Performance data for the studied roofs was collected using three techniques; full-scale measurements, meteorological modelling, the cooling degree-days method and thermal simulation.

3.2.1 Full-scale measurements and weather conditions

Figure 4 shows the roofs under study and measurements carried out during the summer month of June the 21st to 27th . The month of June was chosen because it is one of the warmest, with the highest level of solar irradiation. The examined days were characterised by predominantly clear skies, raised air temperatures and high levels of solar irradiation. Simple temperature data loggers (HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger) were used to measure air temperature close to a range of surfaces. Basic accuracy for the loggers is ±0. 21 °C. During the duration of the experiment, these loggers were positioned parallel to horizontal surfaces of the roofs - at a 1.2 m distance - from 00:00 AM to 24:00 at two-hour intervals. Surface temperatures for the roofs were measured using an infrared thermometer (IR - Thermotrace Combo Infrared Termocouple Thermometer Model 15038) with accuracy of ±3.0 °C. Readings were taken at different parts of the roofs to ensure that the recorded temperatures were representative. The time series of temperatures taken by loggers and IR was then averaged to construct a temperature profile. Solar irradiation was not measured by the authors, sos readings from another field study [51] were used. Readings for these solar values were reported at a distance of fewer than ten kilometres from the island of Sitra.

3.2.2 Error and uncertainty in measurements

A degree of error and uncertainty always occurs in measurements which are, at best, reduced only to an acceptable level. Errors in measurements can be classified into random and systematic errors. Random errors are due to the accuracy of the instrument used and this type of error leads to constant absolute values and relative percentage errors. Systematic errors occur due to measuring skills and the use of more accurate instruments can lead to lower levels of error and uncertainty. Given the accuracy of data loggers and the IR used in this work, it can be assumed that the actual values are either slightly below or slightly above the recorded values. The range represents the uncertainty of the recorded values and the following formulas were used to calculate the standard error of readings, means and of the estimates:

$$SER = \mathrm{SD}\sqrt{1 - r_{xx}} \qquad (1)$$

$$Sm = \frac{SD}{\sqrt{n}} \qquad (2)$$

$$SEE = \mathrm{Sy}\sqrt{1 - r_{yx}{}^2} \tag{3}$$

Where *SER* = standard errors of readings, *Sm* = standard error of the mean, SEE = standard errors of estimates, *SD* = standard deviation, *rxx* = reliability of the experiment (Cronbach alpha reliability estimate), *n* = number of observations, Sy = standard deviation of the *Y* values in the regression analysis, ryx^2 = correlation squared of *Y* and *X* values in the regression analysis.

Table 2 shows errors and uncertainties in the readings of surface temperatures and surface air temperatures and some observations can be highlighted. First it can be seen that standard error of readings (*SER*) in both types of temperature for all roofs are less than 3.0 °C. Standard errors of means (*Sm*) are within the range of 1.5 and 2.5 °C and the largest difference in standard deviations (*SD*) is 4 °C. These values can be considered as low bias and other observation is that the values of error are almost the same in all cases. Nevertheless, the highest error range in readings is in the surface temperature of the dark tile roof. The regression of surface temperatures and surface air temperatures shows a standard uncertainty in the intercept cases ranging from 1.0 to 2.4 °C.

Probability and cumulative probability are also calculated. It is useful to mention that probability represents an indication of the chance that a given event will happen; while cumulative probability reflects the chance that two or more events will occur. Figure 5/a illustrates the distribution of the probability and cumulative probability of recorded surface temepratures for the monitored roofs, whereas Figure 5/b shows those of the recorded air temepratures for the same roofs. The ranges in error is similar in all cases for either surface temperatures or surface air temperatures; in spite of it being the case that the error bias is slightly larger in the case of surface temperatures than for surface air temperatures.

3.3. Meteorological modelling and thermal comfort assessment

The outcome of field measurements was used as an input for a meteorological modelling application to examine variation in climatic variables at the study site. Envi-met-V4 [52] is a three-dimensional non-hydrostatic model and was used because of its capacity to simulate interactions between the surface, plant and air on a micro-scale level. This model evaluates future areas of optimal outdoor comfort and simulates various UHI phenomena. The type of roof, material and property such as emittance and reflectance can be specified through the configuration stage of modelling. The main prognostic variables, calculated by ENVI-met, are wind speed and direction, air temperature and humidity, turbulence and radiative fluxes. More details about ENVI-met can be found [53] and four receptors at the height of two metres above the largest rooftops of the model were used to record the thermal conditions (Figure 2). A great number of runs were performed to calibrate and validate the geometrical model with the study site. A sensitivity analysis was then performed where the effect of the roof on outside thermal conditions was tested by altering the roof type without changing the construction and properties of the model.

ENVI-met is able to assess thermal comfort based on simple inputs like outdoor air temperature, mean radiant temperature, relative humidity, air velocity and solar gains, all represented by the Predicted Mean Vote (PMV). It is important to mention that the PMV of outdoor spaces is considered a comparative index [54], despite there being many physiological and psychological parameters such as age, gender, race, individual attributes and behaviour in regards to heat exposure [55]. These all need to be considered when assessing thermal comfort at an individual level. PMV is used because it can effectively assess thermal conditions for different outdoor climates [56].

3.4. Cooling degree days and thermal simulation

Two techniques are used to estimate urban cooling loads, the cooling degree days (CDD) method and thermal simulation. The CDD is a key indicator of the severity of the mean ambient temperature when related to cooling energy consumption. This method is applied to show the magnitude and duration of time when the outside air temperature is above or below a specified base temperature. If the outdoor air temperature is above a specified base temperature then space cooling is needed. A heating and cooling base temperature of 18-24 °C was used in the generation of CDD profiles from Eq (4).

$$CDDt = Tm - Tb \tag{4}$$

Where CDD, t is the cooling degree-days at a particular time (t), Tb is the base temperature and Tm is the average outdoor air temperature. From this, CDD profiles were generated and daily amoumts and total CDDs were calculated for the study site and for each roof type.

Cooling loads at individual levels were estimated using two modules of the detailed building simulation software Visual DOE [57]. The first is ‘Conduction Transfer Function’ to calculate conduction through walls and the second is ‘Weighting Factor’, calculating thermal loads and space air temperatures. Variation in cooling energy demands of a two story building were predicted to illustrate the consequences of using each type of roof. Detailed architectural, functional and operational data for the building was obtained from working drawings, utility bills and reports provided by the owner. Details of the physical characteristics of the building are illustrated in Table 3. Utilising the collected weather and solar data, a statistically-based weather data file was generated using MeteoNorm software [58] to reflect the current climate of the study site. A sensitivity analysis was performed by varying the roof systems and keeping other construction elements fixed.

4. Result and discussion

This work uses various criteria to assess the performance of roofs in Bahrain. It compares the SRI of the studied roofs and then studies varied conditions in terms of air temperature and humidity. The study then moves on to evaluate the direct and indirect effect of roofs on the built environment through the use of CDD, PMV and cooling load indicators.

4.1. Assessment of physical properties and field measurements

All the examined roofs, with the exception of metal decking, have almost the same composition and thermal properties. The only difference is the surfacing material, to which different radiative properties are applied. Returning to Table 1 and based on the SRI, we can see that the coolest roof is that with the light tile, followed by metal decking, with SRIs of 0.88 and 0.68 respectively. The dark tile roof, concrete screed roof and bituminous roofing felt have high emittance values but low reflectance values. The SRIs of these roofs ranges from 0.21 to 0.45, which may lead to a lower thermal and environmental performance.

It is expected that variation in the SRIs of roofs will have a significant effect on thermal conditions in the local environment. Several parameters are of importance, particularly the surface temperature and the surface air temperature. Table 4 contains the mean, minimum and maximum surface temperatures, surface air temperatures and time of recording. It is useful to note that surface temperature is affected mainly by properties of the surfaces and levels of solar irradiation and additionally by wind speed. The higher the wind speed, the larger the reduction in surface temperatures. In the current case all the studied roofs experience the same weather and solar conditions. The main effect is therefore the radiative and thermal properties of surface materials. The tabled data shows a variation in surface temperature and surface air temperature. For the purposes of comparison, mean air temperature at the boundaries of the study site (37.5 °C) is taken as a base case and compared with the mean surface air temperatures. The lowest increase is seen in the case of the light tile roof at only 1 °C, followed by metal decking at almost 2 °C. The increase reaches almost 7 °C in the case of the dark tile roof. With respect to other roofs, including the concrete screed roof and the bituminous roofing felt, the increase reaches between 3.7-4.0 °C.

The difference between surface temperature and surface air temperature, within the study site highlights another effect. The maximum difference between means is seen in the case of the concrete screed roof at almost 11°C, followed by the bituminous roofing felt at 8 °C. Difference for the metal decking reaches almost 4 °C. The light and dark tile roofs show the same effect, with a difference range between 5-6 °C, despite the differences between maximum surface temperature and surface air temperature in the two cases reaching over 10 °C. Comparison between the thermal behaviour of the studied roofs leads to the following observations:

1. The concrete screed roof shows a high surface temperature, but less impact on surface air temperature when compared to the bituminous roofing felt. Low solar reflectivity (0.21) and high mass and heat storage capacity are clear evidence of increment in the surrounding area. This is because the stored heat within its mass flows out into the surrounding air and warms up the ambient air temperature close to the surface throughout the day.
2. Bituminous roofing felt has almost the same heat storage capacity as the concrete screed roof, but less effect on the air temperature due to a relatively higher solar reflectance level (0.45).
3. Metal decking shows a significant reduction in air temperature due to its high solar reflectance (0.87) and low storage capacity when compared to the other roofs.
4. Although the dark tile roof is not at the highest maximum and mean surface temperature, it has the highest impact on air temperature. The dark and light

ceramic roofs have similar heat storage capacity, but the lighter shows the lowest maximum and mean surface temperatures and the lowest effect on the air temperature due to differences in SRI values. This means that the amount of absorbed heat from the sun at a particular time is lower in the case of lighter roof.

Replacing conventional roof surfaces such as concrete screed layers with cooler surfaces such as light tiles can cool the air from 2 to 5 °C and the top surface of the building from 6 to 8 °C. It is expected that changes in surface and surface air temperatures due to different surface materials will have a significant effect on both outdoor and indoor thermal conditions.

4.2. Effect of roof type on the built environment

Compositions and properties of roofs have both indirect and direct effects on the thermal environment [59, 60]. The indirect effect represents variation in the surface and near surface air temperatures which correspond to outdoor environmental performance. The direct effect reflects the heat gain through roof layers and corresponds to indoor environmental performance.Variation in surface and near surface air temperatures affects urban budget, cooling potential and consequently outdoor climatic conditions and thermal comfort. Changes in heat gain influence the cooling energy consumption of buildings and indoor thermal conditions.

4.2.1 Outdoor environment performance

The indirect effect is assessed through the use of the CDD method. Figure 6 shows the results of varying the roof type in terms of the number of daily CDD. There is significant variation in the number of CDD due to each roof type and a sharp reduction in CDD when the light tile roof and metal decking are used. The use of these two roofs can reduce CDD between 14.6% and 12% when compared to a standard dark tile roof. This reduction can reach between 10% and 7% in the case of the concrete screed roof and bituminous roofing felt. Variation in CDD implies that air temperature is negatively affected in areas where dark tile, concrete screed and conventional bituminous roofing felt are installed as roof systems.

From a sustainability perspective, assessment should extend beyond air temperatures to include elements such as moisture availability, clouds, rainfall and energy demand. The latter is assessed as a direct effect of using cool roofs. The following section briefly assesses moisture availability despite such assessment ideally needing more comprehensive investigation. In simple terms, the moisture content of air can be measured by several parameters including relative humidity, specific humidity, dew-point, vapour pressure, water vapour mixing ratio and water vapour density. In this work relative humidity is investigated as slice maps alongside a dew point calculated from meterological outputs. Figure 7 draws patterns in air temperatures and contours of relative humidity at a height of two metres above the studied roofs. It can be seen that there is interesting variation in the air temperatures at rooftop level due to different roof types. The maximum average difference is found to be 5.5 °C between the light and the dark tile roof. This difference is reduced to 3.0 °C when the dark tile roof is replaced with the concrete screed roof or bituminous roofing felt. The minimum was found to be 0.5 °C, between the light tile roof system and metal decking.

Furthermore, significant indirect effects can be noted for both light tile roof and metal decking; low-level advection of atmospheric moisture is enhanced when these two types are applied, increasing humidity at the study site. This result confirms the effect of a cool roof on moisture content as reported by [61] and is clearly seen in Figure (8/a). The increase in relative humidity can reach to almost 5% after the use of light tile roof and metal decking. The opposite is applied for dew point temperature in Figure (8/b).

PMV is calculated using the ENVI-met model in order to assess the effect of roof type on outdoor thermal comfort. Figure 9 shows PMV patterns and contours of mean radiant temperatures for each roof effect. PMV patterns, under direct sun, show similar distributions with some differences in each case. The differences are more obvious in the centre of the study site where the studied roofs are applied. In general, outside conditions are uncomfortable, especially at the borders of the study site, due to the existence of asphalt material at street level. The patterns show a reduction in PMV on the rooftop when the light tile roof is applied as well as a reduction in areas with metal decking when compared with the concrete screed and bituminous felt covering. The distribution of light tile roofs and metal decking shows almost the same effect, with a relatively lower PMV when compared to the other roofs. These reductions, however, are not experienced across all areas of the study site or to pedestrians at street level, due to the fact that only the roofs are provided with cool surfaces. Reduction in the PMV values of the light tile roof comes with higher values than that of the metal decking. The outcome of PMV analysis reveals that the lowest minimum, maximum and average PMV values are due to the availability of light and metal decking roofs. In contrast, the dark tile, screed roof and bituminous roofing felt all have higher PMV values. As a result, light tiles and metal decking roofs are cooler, more comfortable and functional for areas such as Sitra.

4.2.2 Indoor environment performance

Roof composition and insulation parameters are components that can increase or decrease the thermal efficiency of roofs. This work sets out to reflect real roof composition in Bahrain. Thermal insulation is added in some cases in order to assess the impact of a cool roof with and without insulation. Figure 10 (a/b) illustrates the variation in hourly electricity use for cooling the studied building with each roof type and with and without insualtion. As expected, there is a variation in the performance of the roofs during different times of the day due to the availabilty of solar irradiation. Without insulation, the light tile roof and metal decking perform better than others during the day and at night. With insulation, the concrete screed roof, bituminous roofing felt and dark tile roofs perfom better and at night the opposite is true. This is because of stored heat within the mass of the first three roofs which transfers into internal air conditioned spaces. In terms of the daily cooling load, the use of a light tile roof leads to the maximum reduction, followed by metal decking, then the concrete screed roof, dark tile roof and finally bituminous roofing felt. The maximum reduction in heat gain occurs with a light tile roof with thermal insulation materials. Without insulation, however, the cooling load increases by only 1.3%. This percentage seems not to be cost-effective when economics and building construction costs are considered. In contrast, the reductions in the case of dark tile roof, bituminous roofing felt and concrete screed roof increased to 5-7%, which seems cost effective. The reduction in light and metal decking cases can be related to a number of factors including:

- Almost 80% of sunlight can be reflected by the surface and only 20% of the sunlight heats the building.
- Mass roofs such as the light tile roof systems benefit from the added value of thermal mass and thermal resistivity of roof layers.

In brief, conductive heat gain through the roofs is reduced when the light tiles are used, both with and without thermal insulation. This reduction represents a clear indication that the use of a light tile roof will lead to a positive effect on the building cooling load. Applying the cool roof strategy has reduced electricity demand and therefore additional total energy can be saved. If we reduce electricity demand then CO_2 emissions due to energy use in buildings will decline by the same percentage and the national net CO_2 emissions will also drop.

5. Conclusion

Many urban mitigation and adoptation strategies have been proposed to cope with summer UHI. The use of a cool roof represents a promising, reliable and environmentally friendly passive strategy, one which has the potential to contribute significantly to mitigating UHI. From a sustainability perspective, applying a cool roof without fully comprehending the outcome is not appropriate. To assess its effectiveness a multi-disciplinary approach is needed. This work represents a step towards multi-disciplinary thinking to improve the thermal performance of the Bahraini built environment. It investigates the cool roof strategy in order to show the potential of such a strategy for Bahrain. Five roof systems were examined; lightweight concrete screed, bituminous roofing felt, light and dark colour ceramic tiles and metal decking. Analysis of the thermal and radiative properties of roof performance showed a significant reduction in the surface and air temperature due to the use of roof systems with high SRI, such as light tile roof and metal decking. In contrast, a significant increase in the surface and air temperature occurred due to the use of roof systems with low SRI and high heat storage capacity such as the dark tile and screed roof and the bituminous roofing felt.

This work has assessed the direct and indirect effects of roofs on the outdoor and indoor thermal environment. It showed a reduction in CDD when a light tile roof and metal decking roof systems were used. This reduction can reach 14.6% and 12% when compared to common roof construction practice in Bahrain. The effect of roof type on air temperature and relative humidity was also investigated. There was a significant reduction in air temperatures at rooftop level due to the use of light tile roof and metal decking when compared with other roof types. A consequence of using these two types of roofs was that an enhancement in atmospheric moisture was noted, thus increasing humidity at the study site. This can influence summer comfort levels in Bahrain where the humidity level reaches above 75% on some days.

Thermal comfort was examined through the use of meteorological modelling. Outside conditions were uncomfortable, especially at the borders of the study site, due to the existence of asphalt materials at street level. A reduction in PMV on the rooftop was seen when the light tile roof and metal decking were applied. Distribution of the light tile roof and metal decking show almost the same effect with relatively lower PMV compared to the othjer roofs. These reductions, however, were not experienced by all area of the study site, particularly pedestrians at street level, due to the fact that only roofs were provided with cool surfaces.

The direct effect, represented by variations in heat gain and the cooling energy of buildings, was measured through the use of thermal simulation software. Although the major effect was related to the surface materials of roof systems, appropriate levels of insulation were found to be an important part of reducing the cooling load. Roof compositions, insulation parameters and surfacing materials were all components that can increase or decrease the efficiency of roofs. It was shown that the light tile roof system lead to the maximum reduction level, followed by metal decking and then the concrete screed roof, dark tile roof and finally bitumen roof felt. Furthermore, the maximum reduction in heat gain occurred for a light tile roof with thermal insulation material. Without insulation, however, the cooling load increased by only 1.3%. This percentage seems not to be cost-effective when the costs of building and construction are concerned. In contrast, the reduction percentage in the case of dark tile roof, felt bitumen roof and screed roof increased to 5-7%, which does seem to be cost effective.

At present, therefore, a cool roof strategy is likely to be cost-effective in the hot climate of Bahrain, which has a long cool season. With the levels of current urban development in Bahrain, it can reduce UHI intensity and building cooling loads, diminishing demand for electricity ande lowering greenhouse gas emissions from power plants. For future development and to avoid the negative consequences of the cool roof strategy, trade-offs between urban mitigation and adoptation strategies and complementary technologies must be accounted for.

References

[1] U.S. Environmental Protection Agency, 2012. Reducing urban heat islands: compendium of strategies-urban heat island basics. <http://www.epa.gov/hiri/resources/pdf/BasicsCompendium.pdf>.

[2] Santamouris, M., Papanikolaou, N., &Livada, I. On the impact of urban climate on the energy consumption of buildings. Solar Energy 2001, 70 (3), 201–216.

[3] Santamouris M. On the energy impact of urban heat island and global warming on buildings. Energy and Buildings 2014, 82:100-113.

[4] Santamouris M., Cartalis C., Synnefa A., Kolokotsa D. On the impact of urban heat island and electricity consumption of buildings – a review. Energy and Buildings 2015, 98:119-124.

[5] Radhi H, Sharples S. Quantifying the domestic electricity consumption for air-conditioning due to urban heat islands in hot arid regions. Applied Energy 2013, 112 (4-6): 371-380.

[6] Radhi H., Fikry F., Sharples S. Impacts of urbanisation on the thermal behaviour of new built up environments – a scoping study of the urban heat island in Bahrain. Landscape and Urban Planning 2013, 113: 47– 61.

[7] Wang Y, Berardi U, Akbari H, The Urban Heat Island Effect in the City of Toronto, Procedia Engineering 2015, 118:137–144.

[8] Fahmy M, Sharples S. Passive design for urban thermal comfort: a comparison between different forms in Cairo, Egypt, in PLEA 2008- 25th conference on Passive and Low Energy Architecture. 2008: University collage of Dublin, Dublin. 22nd -24th October 2008. Dublin, UK, October 22-24.

[9] Cheng CY, Cheung KKS, Chu LM. Thermal performance of a vegetated cladding system on facade walls. Building and Environment 2010, 45: 1779-1787.

[10] Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment 2008, 43: 480 – 493.

[11] Sheweka SM, Mohamed NM. Green facades as a new sustainable approach towards climate change. Energy Procedia 2012, 18: 507–520.

[12] Zhao M, Tabares-Velasco PC, Srebric J, Komarneni S, Berghage R. Effects of plant and substrate selection on thermal performance of green roofs during the summer. Building and Environment 2014, 78: 199-211.

[13] Santamouris M, Gaitani N, Spanou A, Saliari M, Giannopoulou K, Vasilakopoulou K, Kardomateas T. Using cool paving materials to improve microclimate of urban areas e Design realization and results of the flisvos project. Building and Environment 2012, 53: 128-136.

[14] SantamourisM, Synnefa A, Karlessi T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. Solar Energy 2011, 85(12): 3085–3102.

[15] Santamouris M. Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. Renewable and Sustainable Energy Reviews 2013, 26: 224–240.

[16] Santamouris M. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy 2014, 103: 682–703.

[17] Akbari H, Perdahl P, Levinson R, Wiel S. Cool color roofing materials. CA: Lawrence Berkeley National Laboratory Berkeley; 2006. Report no: 94720.

[18] Jacobson M, John E, Hoeve T, 2011: Effects of urban surfaces and white roofs on global and regional climate. J. Clim., In press. http://dx.doi.org/10.1175/JCLI-D-11-00032.1

[19] Wilcox K. Research examines effects of cool roofs. The Magazine of the American Society of Civil Engineers 2014. http://www.asce.org/magazine/20140311-research-examines-effects-of-cool-roofs/

[20] Georgescu M, Morefield PE, Bierwagen BG, Weaver CP. Urban adaptation can roll back warming of emerging megapolitan regions. Proceedings of the National Academy of Sciences 2014, 111(8), 2909-2914.

[21] Georgescu M, Chow WTL, Wang ZH, Brazel A, Trapido-Lurie B, Roth M, Benson-Lira V. Prioritizing urban sustainability solutions: coordinated approaches must incorporate scale-dependent built environment induced effects. Environmental Research Letters 2015, 10 (6), 061001

[22] Akbari H, Matthews HD. Global cooling updates: Reflective roofs and pavements. Energy and Buildings 2012, 55:2-6.

[23] Synnefa A, Santamouris M, Apostolakis K. On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Sol. Energy 2007, 81: 488–497

[24] Synnefa A, Santamouris M, Livada I. A study of the thermal performance and of reflective coatings for the urban environment. Solar Energy 2006, 80: 968–981.

[25]Xu T, Sathaye J, Akbari H, Garg V, Tetali S. Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions.nBuilding and Environment 2012, 48:1-6, (1).

[26] Bevilacqua P, Coma J, Perez G, Chocarro C, Juarez A, Sole C, De Simone M, Cabeza LF. Plant cover and floristic composition effect on thermal behaviour of extensive green roofs. Building and Environment 2015, 92: 305-316.

[27] Gagliano A, Detommaso M, Nocera F, Evola G. A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. Building and Environment 2015, 90: 71-81.

[28] Virk G, Jansz A, Mavrogianni A, Mylona A, Stocker J, Davies M. The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London: Direct and indirect effects in current and future climates. SEGA Journals: Indoor and Built Environment 2014. doi: 10.1177/1420326X14527976.

[29]Qin Y. A review on the development of cool pavements to mitigate urban heat island effect. Renewable and Sustainable Energy Reviews 2015, 52: 445–459.

[30] Rossi F, Castellani B, Presciutti A, Morini E, Anderini E, Filipponi M, Nicolini A. Experimental evaluation of urban heat island mitigation potential of retro-reflective pavement in urban canyons. Energy and Buildings 2016, 126: 340-352.

[31] Rossi F, Morini E, Castellani B, Nicolini A, Bonamente E, Anderini E, Cotana F. Beneficial effects of retroreflective materials in urban canyons: Results from seasonal monitoring campaign (2015) Journal of Physics: Conference Series, 655 (1), art. no. 012012

[32] Saneinejad S, Moonen P, Carmeliet J. Comparative assessment of various heat island mitigation measures. Building and Environment 2014, 73: 162-170.

[33] Akbari H, Levinson R, Berdahl P. ASTM standards for measuring solar reflectance and infrared emittance of construction materials and comparing their steady-state surface temperatures. Energy and Environment Division, Ernest Orlando Lawrence Berkeley National Laboratory; August 1996 [Presented at the American Council for Energy Efficient Economy Summer Study].

[34] Taha H. Modeling the impact of large-scale albedo changes on ozone air quality in the south coast air basin. Atmos Environ 1997,31(11):1667-76.

[35] Taha H. Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. Energy Build 1997,25:99-103.

[36] Taha H, Douglas S, Haney J. Mesoscale meteorological and air quality impactsof increased urban albedo and vegetation. Energy Build 1997,25:169-77.

[37] Akbari H, Konopacki SJ. The impact of reflectivity and emissivity of roofs onbuilding cooling and heating energy use. In: Proceedings of the thermalperformance of the exterior envelopes of building VII December 6e10, 1998. Clearwater Beach, FL.

[38] Marceau ML, VanGeem MG. Solar reflectance of concretes for LEED sustainablesites credit: heat island effect. Research & Development Information.Portland Cement Association; 2007. http://www.concretethinker.com/Content/Upload%5C446.pdf.

[39] Akbari H, Perdahl P, Levinson R, Wiel S. Cool color roofing materials. CA: Lawrence Berkeley National Laboratory Berkeley; 2006. Report no: 94720.(12-13-14)

[40] Prado R, Ferreira F. Measurement of albedo and analysis of its influence the temperature of building roof materials. Energy and Buildings 2005, 37: 295-300.

[41] Berdahl P, Bretz SE. Preliminary survey of the solar reflectance of cool roofing materials. Energy and Buildings 1997, 25(2): 149–158.

[42] Assem EO. Correlating thermal transmittance limits of walls and roofs to orientation and solar absorption. Energy and Buildings 2011, 43: 3173–3180.

[43] Newa J, Millera WA, Huangb Y, Levinsonc R. Comparison of software models for energy savings from cool roofs. Energy and Buildings 2016, 114: 130-135

[44] Din MF, Dzinun H, Mohanadoss P, Chelliapan S, Noor ZZ, Ossen DR, Iwao K, Investigation of heat impact behavior on exterior wall of building material at urban city area. Civil Environment Eng 2012, 2(2):1-6.

[45] Bougiatioti F, Evangelinos E, Poulakos G, Zacharopoulos E. The summer thermal behaviour of ‘‘skin” materials for vertical s in Athens, Greece as a decisive parameter for their selection. Solar Energy 2009, 83: 582–598.

[46] Heusinger J, Weber S. Comparative microclimate and dewfall measurements at an urban green roof versus bitumen roof. Building and Environment 2015, 92: 713-723.

[47] Taleb H. Enhancing the skin performance of hospital buildings in the UAE. Journal of Building Engineering 2016, 7: 300-311.

[48] Mills G, Cleugh H, Emmanuel R, Endlicher W, Erell E, McGranahan G, Ng E, Nickson A, Rosenthal J and Steemer K. 2010 Climate information for improved planning and management of mega cities (needs perspective) Procedia Environ. Sci. 1 228–46

[49] Radhi H. Can envelope codes reduce electricity and CO2 emissions in different types of buildings in the hot climate of Bahrain. Energy 2009, 34: 205-215.

[50] Meteorological Directorate. A digital copy of weather data for the year 2015.CivilAviation Affairs, Bahrain.

[51] Alnaser WE, Al-Attar R. Simple models for estimating the total\ diffuse\direct and normal solar irradiation in Bahrain. Technical note. Renewable Energy 1999, 18: 417-434.

[52] Bruse M, Fleer H. Simulating Surface- Plant-Air Interactions Inside Urban Environments with a Three Dimensional Numerical Model, Environmental Software and Modelling 1998, 13: 373–384

[53] Bruse M. 2004. ENVI-met 3.0: Updated Model Overview.www.envi-met.com

[54] ISO (1994) ISO 7730 – Moderate thermal environments – deter- mination of the PMV and PPD indices and specification of the conditions for thermal comfort. International Organization for Standardization.

[55] Kuras ER, Hondula DM, Brown-Saracino J. Heterogeneity in individually experienced temperatures (IETs) within an urban neighborhood: insights from a new approach to measuring heat exposure. International journal of biometeorology 2015, 59(10), 1363-1372.

[56] Matzarakis A, Mayer H. Heat stress in Greece. Internatinal Journal of Biometerolgy 1997, 41:34-39.

[57] Visual DOE User Manual, Architectural energy Corporation, USA, 2004.

[58] Remund R, Lang S, Kunz S. MeteoNorm V.5.1 Software and Handbook on CD-ROM. Meteotest, Fabrikstrasse 14, 3012 Bern, Switzerland; 2003.

[59] Akbari H, Konopacki S, "Calculating energy-saving potentials of heat-island reduction strategies," Energy Policy 2005, 33: 721-756.

[60] Xu T, Sathaye J, Akbari H, Garg V, Tetali S. Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions. Building and Environment 2012, 48: 1-6.

[61] Li D, Bou-Zeid E, Oppenheimer M.The effectiveness of cool and green roof as urban heat island mitigation strategies. Environ. Res. Lett 9 (2014) 055002 (16pp)

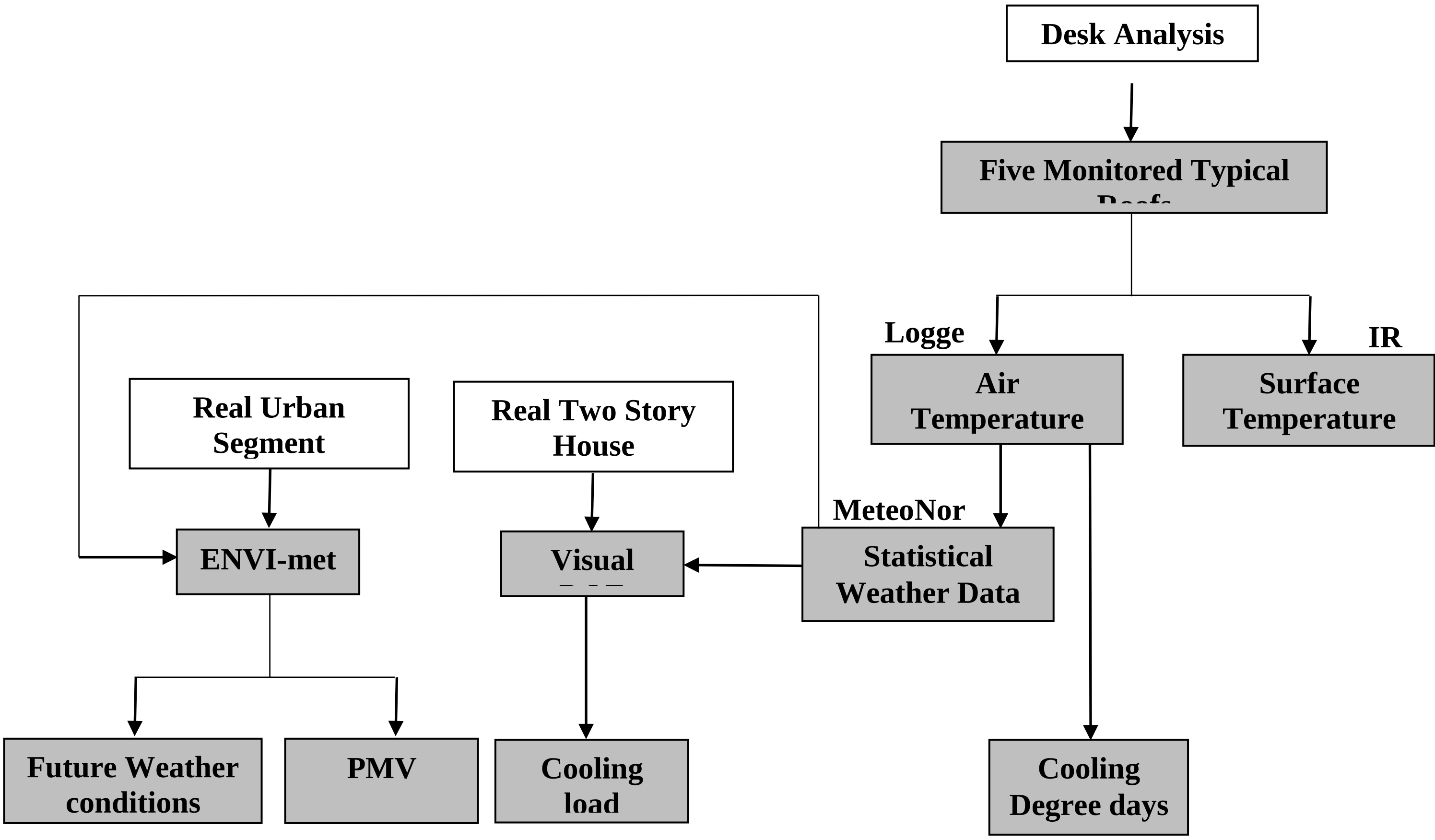


Figure 1: Flowchart illustrates stages and scientific methods used at each stage of research.

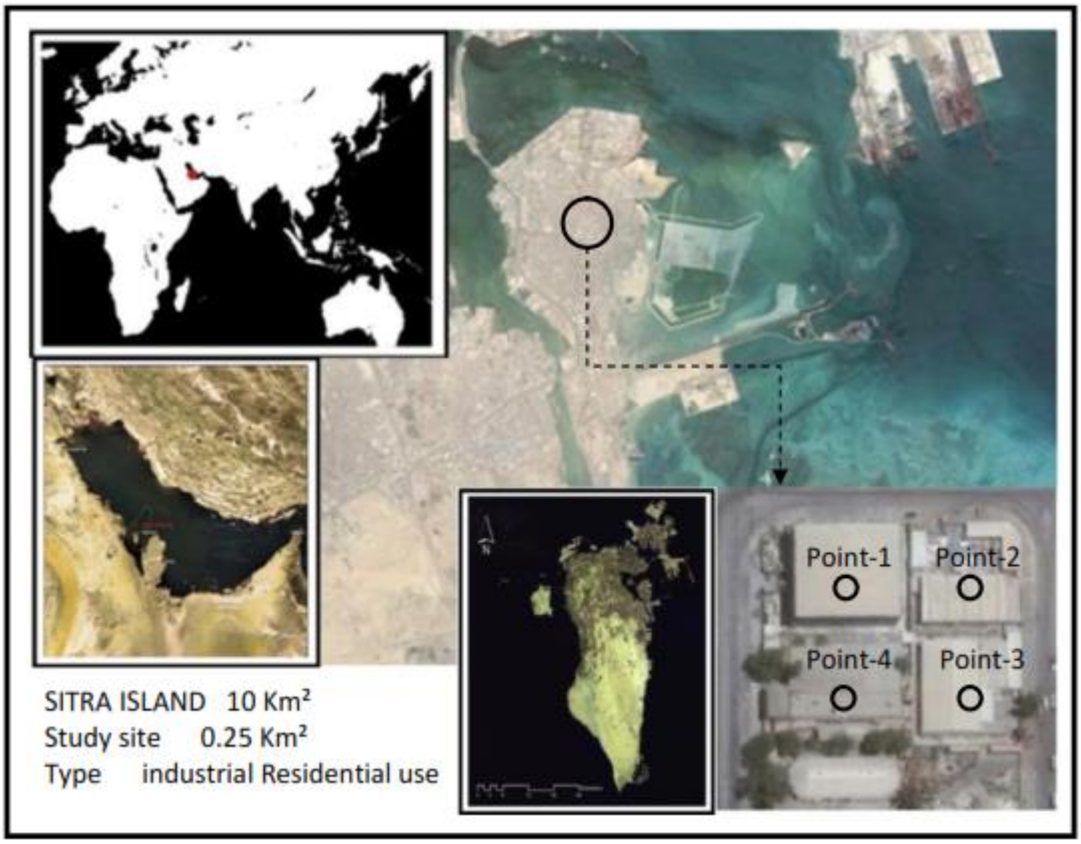


Figure 2: Location of Bahrain and the study site for field measurements and meteorological modelling.

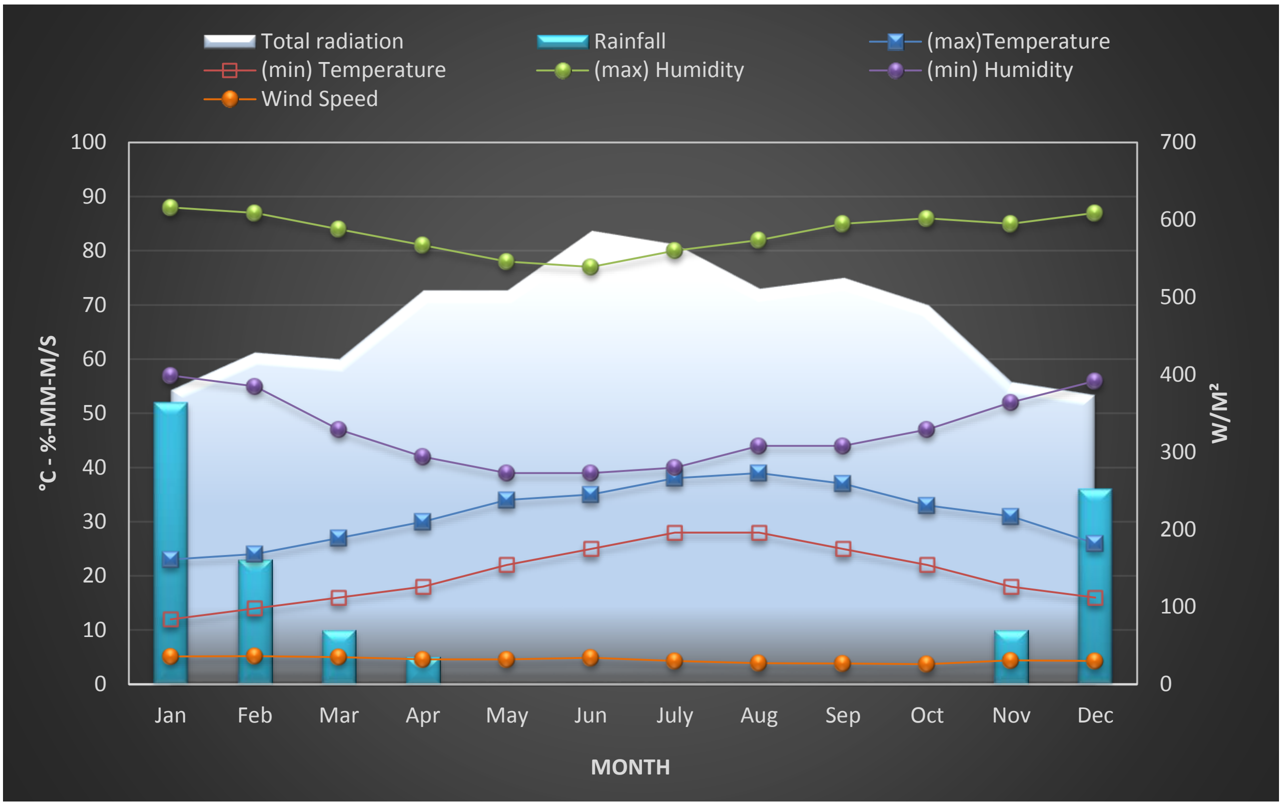


Figure 3: Monthly averages of weather conditions in SITRA

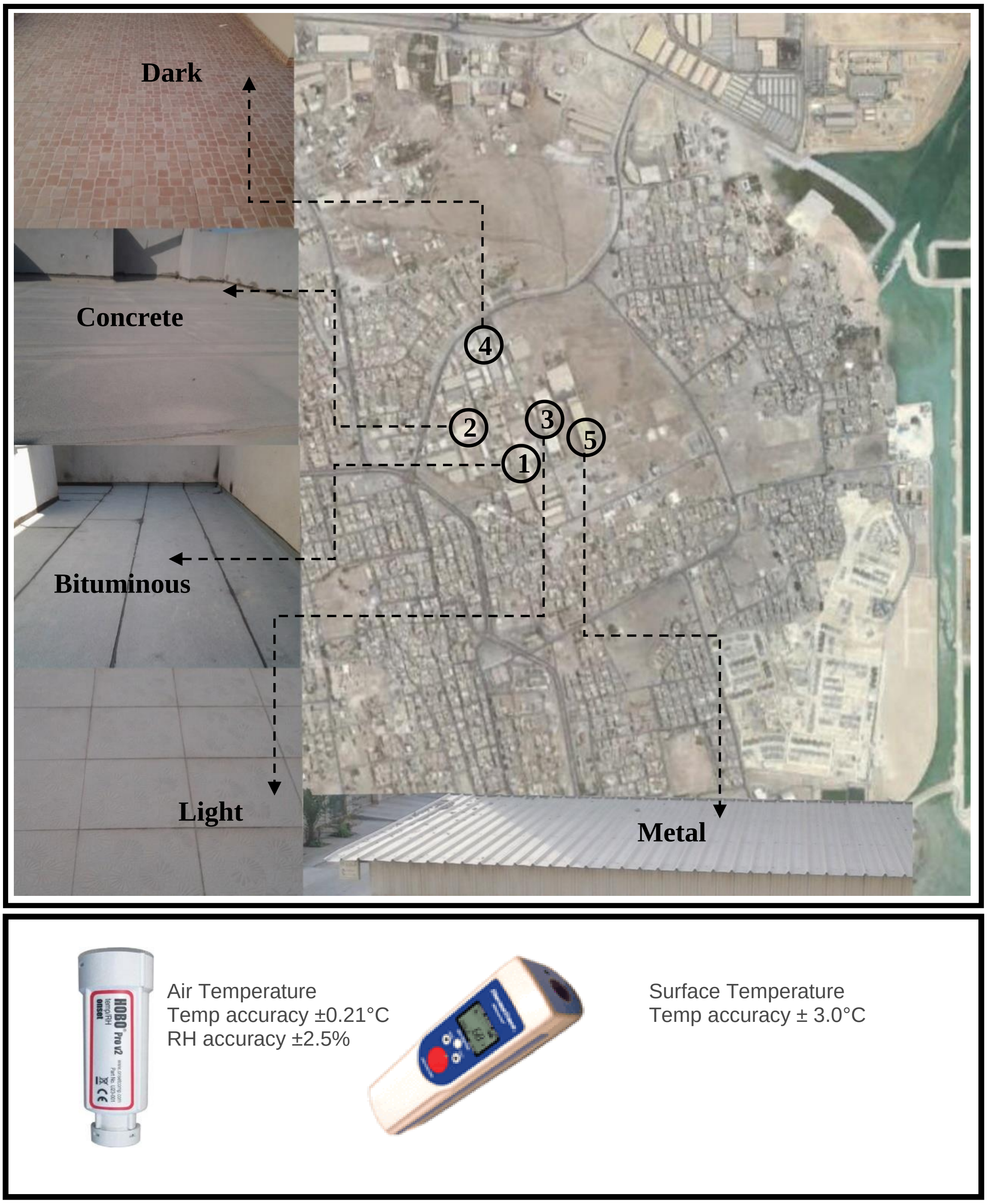


Figure 4: Location of roofs under study for the field measurements

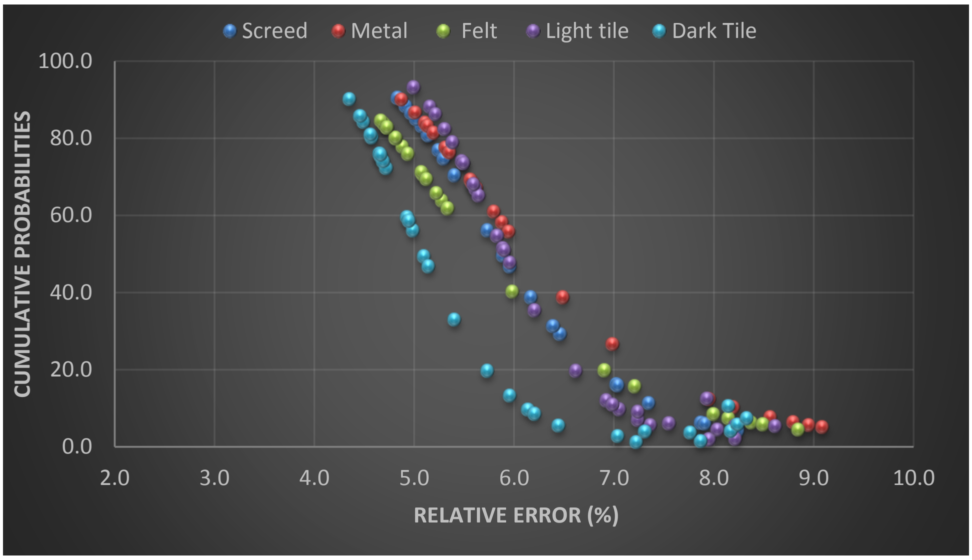


Figure 5/a: Probability and cumulative probability of surface temperatures for the monitored roofs

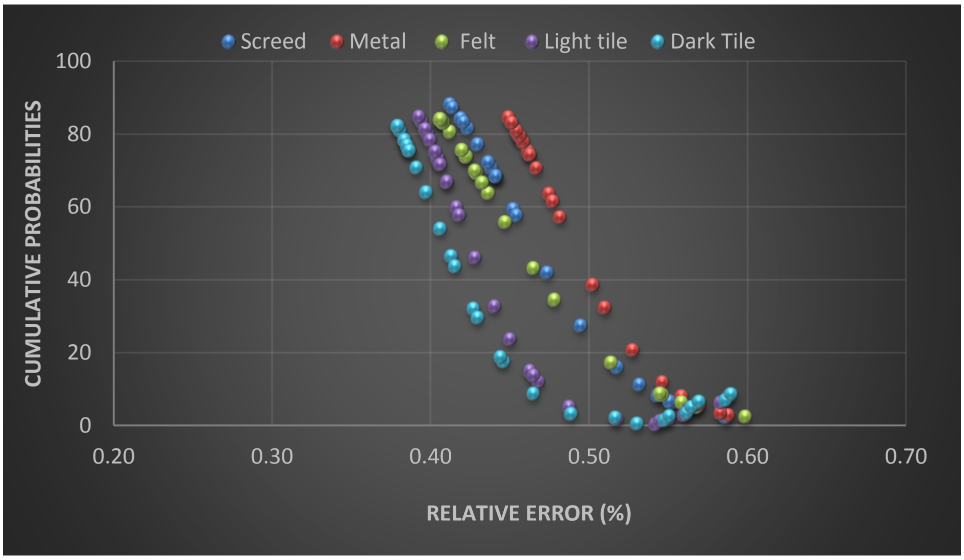


Figure 5/b: Probability and cumulative probability of Air temperature for the monitored roofs

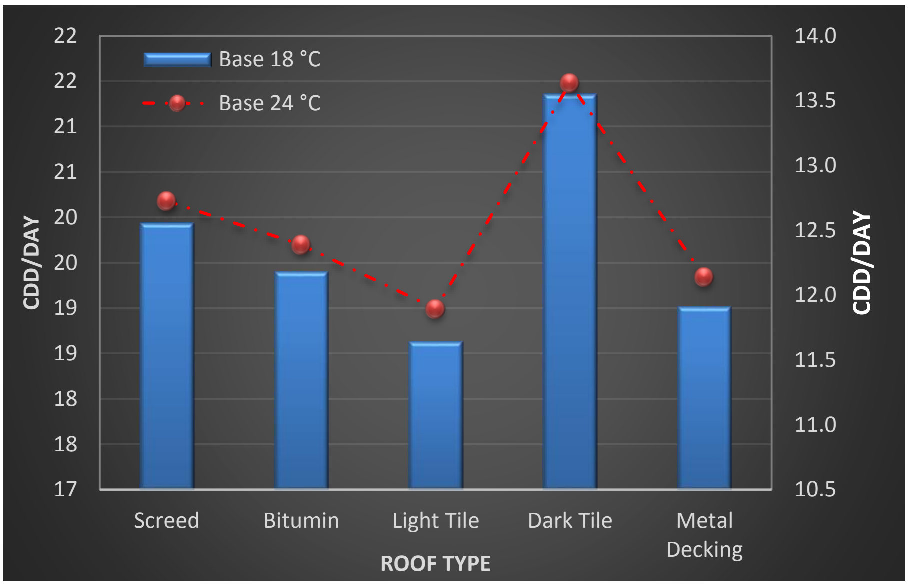
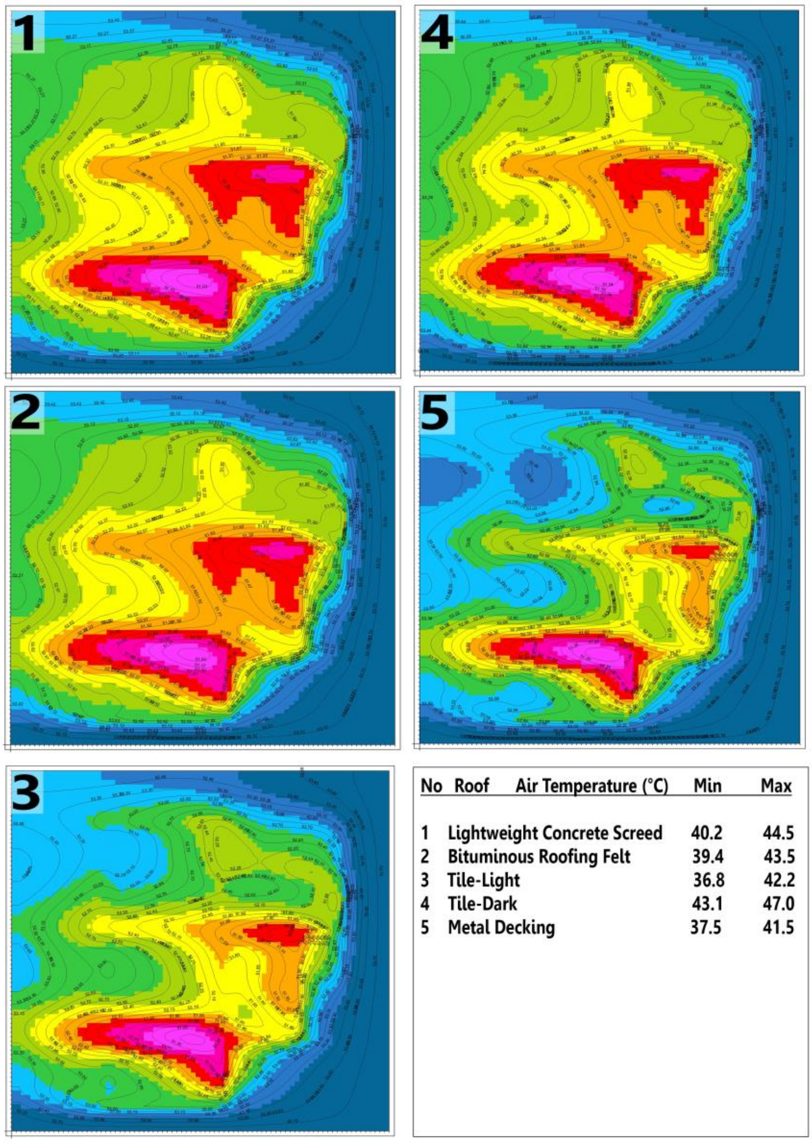


Figure 6: Variation in cooling degree-days due to different roof types



No	Roof	Air Temperature (°C) Min	Max
1	Lightweight Concrete Screed	40.2	44.5
2	Bituminous Roofing Felt	39.4	43.5
3	Tile-Light	36.8	42.2
4	Tile-Dark	43.1	47.0
5	Metal Decking	37.5	41.5

Figure 7: Patterns of air temperatures and contours of relative humidity at the roof top

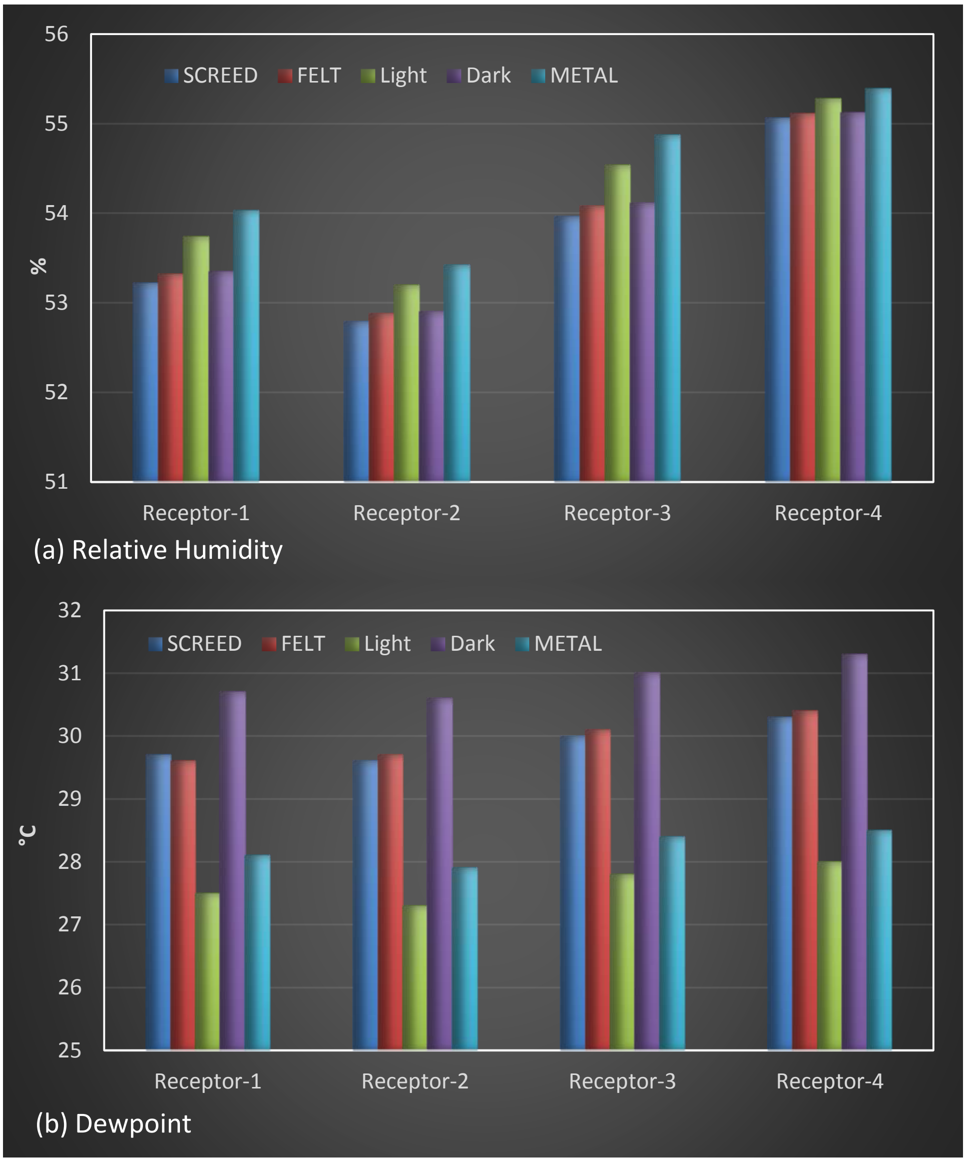
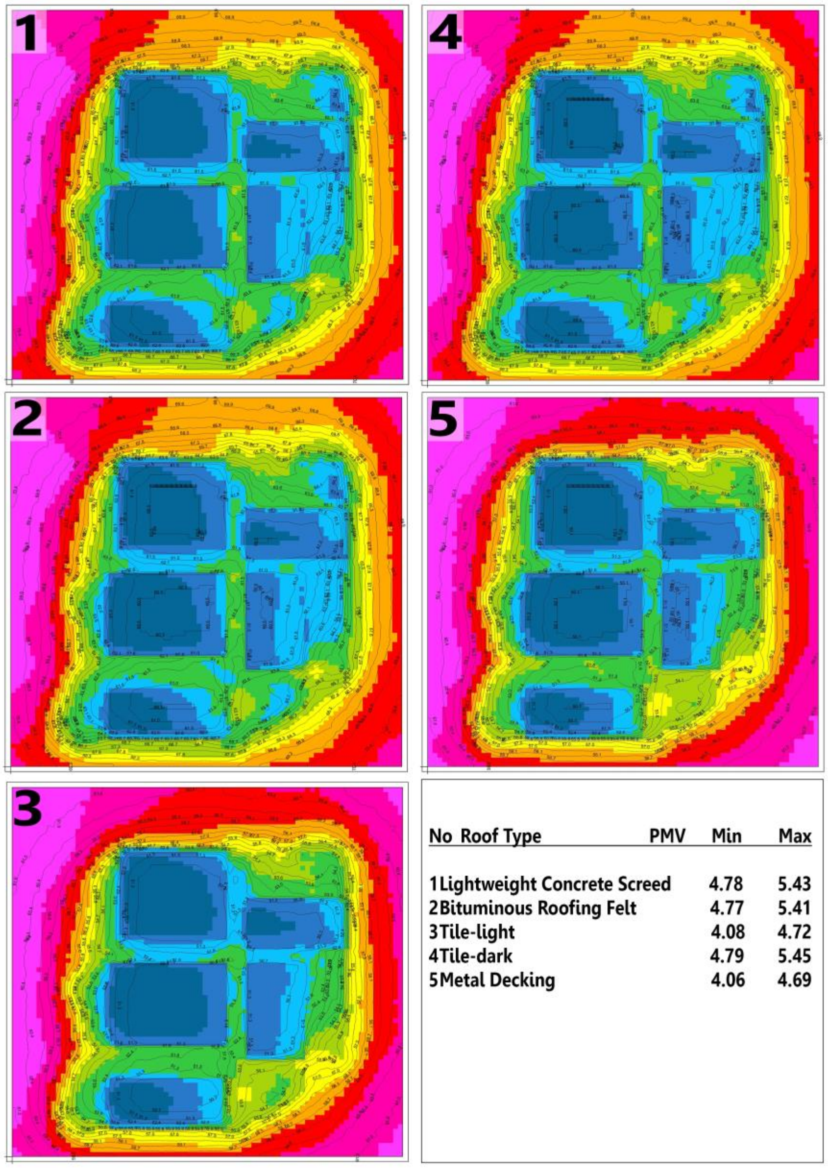


Figure 8: Effect of roof type on the level of dew point temperature and humidity at rooftop

Figure 8: Effect of roof type on the level of humidity



No	Roof Type	PMV Min	Max
1	Lightweight Concrete Screed	4.78	5.43
2	Bituminous Roofing Felt	4.77	5.41
3	Tile-light	4.08	4.72
4	Tile-dark	4.79	5.45
5	Metal Decking	4.06	4.69

Figure 9: PMV patterns and contours of mean radiant temperature due to each roof type

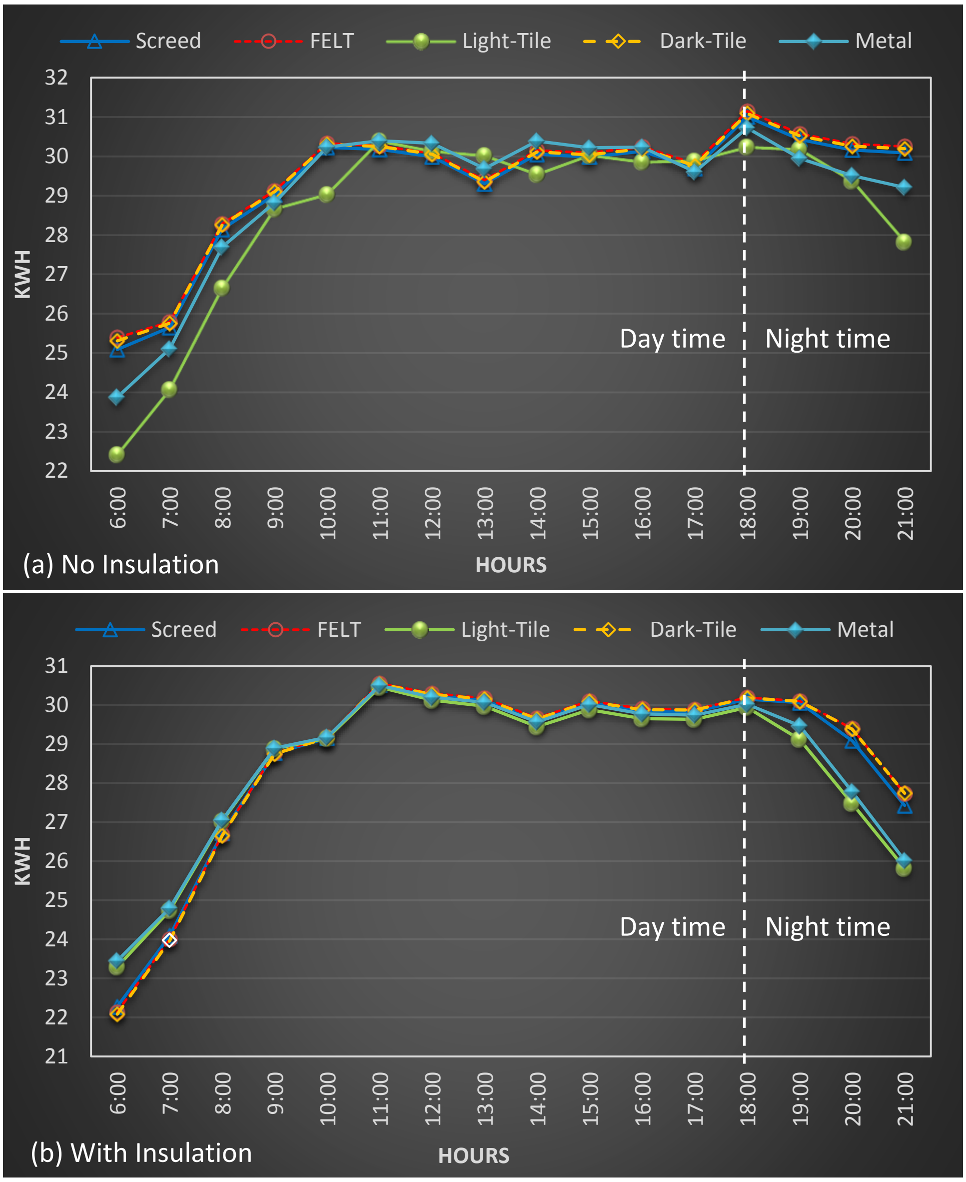


Figure 10: Variation in hourly electricity used for cooling the studied building due to each roof type

Table 1: Materials and compositions of examined roofs

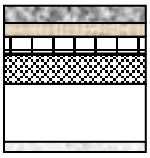
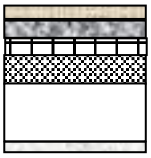
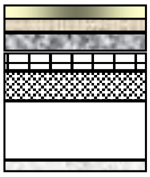
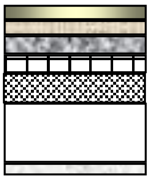
Roof	Construction	Layers	Thick m	Conductivity W/m/k	Density Kg/m^3	S. heat kJ/kg.K	Roof Surface			U-value W/m^2 °C
							Albedo	Emitance	SRI	
Lightweight Concrete Screed		Concrete screed water proofing Polystyrene Concrete slab Air gab Gypsum board	0.052 0.004 0.050 0.150 0.300 0.012	0.719 0.152 0.020 1.31 0.027 0.420	2050 1121 1000 2200 1.13 1200	890 1510 1700 920 1005 840	0.38	0.90	0.45	0.35 1.52*
Bituminous Roofing Felt		Roofing felt Pained screed Polystyrene Concrete slab Air gab Gypsum board	0.004 0.050 0.050 0.150 0.300 0.012	0.85 0.22 0.020 1.31 0.027 0.420	2400 1490 1000 2200 1.13 1200	1000 0.26 1700 920 1005 840	0.23	0.87	0.21	0.35 1.50*
Tile-light		Light tile Mortar Sand screed Polystyrene Concrete slab Air gab Gypsum board	0.006 0.025 0.050 0.050 0.150 0.300 0.012	0.80 0.719 1.818 0.020 1.31 0.027 0.420	2400 2050 1700 1000 2200 1.13 1200	920 840 800 1700 920 1005 840	0.77	0.94	0.88	0.35 1.51*
Tile-dark		Dark tile Mortar Sand screed Polystyrene Concrete slab Air gab Gypsum board	0.006 0.025 0.050 0.050 0.150 0.300 0.012	0.80 0.719 1.818 0.020 1.31 0.027 0.420	2400 2050 1700 1000 2200 1.13 1200	920 840 800 1700 920 1005 840	0.30	0.9	0.30	0.35 1.51*
Metal Decking		Alum panel Polystyrene Air gab Gypsum board	0.005 0.050 0.300 0.012	45 0.020 0.027 0.420	7800 1000 1.13 1200	480 1700 1005 840	0.71	0.89	0.87	0.36 1.82*
All roof were simulated with and without Exp Polystyrene (Insulation). * U-value of roof without insulation										

Table 2: Errors and uncertainties in readings of surface and air temperatures

	Surface temperature *Ts* (°C)				Surface air temperature *Ta* (°C)				Uncertainty in *Ta*estimation				Uncert in
	Mean	STD	*Sm*	*SER*	Mean	STD	*Sm*	*SER*	Intercept	Uncer	Slope	Uncert	expt data
Screed	51	8.4	1.9	1.4	43	4.5	1.0	0.7	16.60	1.67	0.52	0.03	1.24
Felt	52	11.2	2.5	1.8	43	5.3	1.2	0.8	19.41	1.31	0.46	0.02	1.24
Tile light	48	8.7	1.6	2.0	44	6.8	1.2	1.2	9.63	2.37	0.73	0.05	2.08
Tile dark	53	13.1	2.4	2.9	44	7.5	1.4	1.3	15.19	2.32	0.56	0.04	2.62
Metal	49	9.8	2.2	1.6	41	3.6	0.8	0.6	23.26	0.93	0.36	0.02	0.83

Table 3: Building description used as input for the simulation program

Table 3: Building physical characteristics for thermal simulation

Parameters	Specification
No. of Floors	2
Total Area	360 m^2
Floor Height	3.6 m
External walls	200 mm concrete block-24 mm of plaster inside and outside
Internal wall	150 mm concrete block-24 mm of plaster inside and outside
Roof	4 mm bitumen,50 mm screed, 50 mm Exp-polystyrene
	150 mm concrete slab
Window area	20%
Glazing	6mm double glass 2.72 W/(m^{2o}K)
Infiltration rate	5.0 m^3(hm^2)
Thermal Zones	Multi-zones
Equipment	45 W/m^2
Lighting	30 W/m^2
HVAC	Central
Set point temperature	(22-24ºC) Summer & (20-22ºC) Winter
Occupancy	2.5 m^2/person

Table 4: Mean, minimum and maximum of surface and air temperatures and hour of recording

Roof Type	Min Ts (°C)	MinTa (°C)	Δtmin (°C)	Time 24-h	Max Ts (°C)	Max Ta (°C)	Δtmax (°C)	Time 24-h	Mean Ts (°C)	Mean Ta (°C)	Δ Ts Ta (°C)	Δ TBond Ta (°C)
Concrete Screed	36.4	34.1	2.3	5:00	68	48.5	19.5	13:00	52.2	41.3	10.9	3.72
Bituminous Felt	33.9	33.4	0.5	5:00	65	49.2	15.8	13:00	49.5	41.3	8.2	4.0
Light tile	36.5	35.2	1.3	23:00	52	42	10	13:00	44.3	38.6	5.7	1.0
Dark tile	38.1	36.6	1.5	23:00	62	51.9	10.1	13:00	50.1	44.3	5.8	6.96
Metal decking	33	34.3	1.3	5:00	53	44	9	13:00	43.0	39.2	3.9	1.95
Mean air temperature at the boundaries (T Bond) of the study site (37.5 °C)												