# PARAMETRIC ANALYSIS OF ENVIRONMENTALLY RESPONSIVE STRATEGIES FOR BUILDING ENVELOPES SPECIFIC FOR HOT HYPERARID REGIONS

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## ABSTRACT

The deep hot hyperarid valley between Israel and Jordan presents unique design and construction challenges in terms of energy conservation and thermal comfort. Winters are relatively mild, summers are extremely hot during the day and at night the air temperature remains above 25°C. Such conditions present real challenges in this sparsely populated yet rapidly developing region. Such development depends on the ability to provide acceptable indoor environments at a low energy investment. Potential solutions were investigated through a parametric analysis including physical and operational elements aiming at establishing benchmarks for free running and low energy buildings under extreme conditions. First, building performance was simulated for a limited number of parameters. Additional operational and physical parameters were introduced and results compared. The data were analyzed to determine the best performing options for building assemblies.

Results of permutations investigated confirmed that simulated conventional building systems did not allow for free running operation and that mechanical systems for both heating and cooling were needed. This research concluded that it is imperative to extensively insulate building envelopes in order for them to be free running in the winter. Buildings need extensive shading in the transition seasons to allow for free running operation and avoid overheating. Buildings with complete shade, high efficiency window systems and levels of insulation above and beyond those currently employed when simulated with summer climate conditions had significantly lower energy consumption requirements for mechanical cooling than other building designs. The research showed that energy efficiency in this region is a function of particular combination of extensive insulation, full shade, high performance windows, air tight buildings and seasonal operation of window shutters utilized together.

## KEYWORDS

Free-running buildings, hyperarid environment, insulation, thermal mass, ventilation

## 1 INTRODUCTION

Settlement in hyper-arid regions has usually been scarce and sparse, yet the continuous processes of desertification and climate change on the one hand, alongside human expansion and search for new places to settle on the other hand, are bringing more people closer or inside deserts, and often bring the deserts to the doorsteps of people used to much more temperate climates. Urbanization and population growth processes are also exacerbating housing related issues in such regions. The need to provide sustainable, low energy housing in deserts is thus becoming all the more pressing, as has been stressed in a number of recent publications (e.g., Beer et al., 2012; Meir et al., 2012).

The case study dealt with in this paper is the Southern Arava Valley, part of the long Afro-Asian Rift, a natural border between Israel and Jordan. To the north lies the Dead Sea (over 400m below Mean Sea Level – MSL), and to the south the port city of Eilat on the Red Sea coast, with a higher middle part rising to appr. 210m above MSL. It is considered one of the climatically harshest parts of Israel. Its climate is unique in Israel and unusual when compared to deserts worldwide. Winters are relatively mild, frost is rare and no occurrences of snow have been recorded within the valley. Winter daily maxima range between 21-23°C, and night minima between 9-11°C. Rarely do temperatures go below 5°C, and the absolute minimum registered ever was 1.2°C. Summers are extremely hot during the day with temperatures often reaching 42°C and above, and at night the air temperature remains above 25°C, with katabatic winds from the cliffs to the west often keeping it higher. The absolute maximum registered was above 47°C. Only one out of four nights reaches a minimum temperature below 24°C. During the summer and transition seasons months relative humidity may go as low as 10% and below (Bitan and Rubin, 1991), though in recent years there have been anecdotal reports of high relative humidity, which renders climatic conditions nearly unbearable without mechanical cooling.

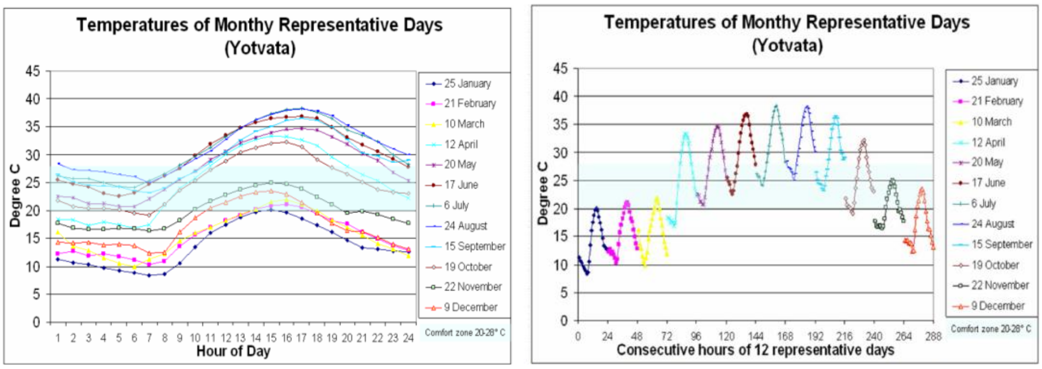


Figure 1: Left: external temperatures of representative days from Typical Meteorological Year (TMY). Right: temperature measurements of representative days for each month selected from the Yotvata TMY. The consecutive hours in the graph are multiples of 24 times the numerical month of the year (– after Faiman et al., 2004).

The region of Eilot Regional Council stretching 102 km northwards from the port city of Eilat on the Red Sea has been traditionally sparsely populated. Within the valley nine modern communities have been established in the past 50 years along with limited industrial, commercial and municipal facilities. The region has announced its commitment in the next decade to become energy independent using solar technologies and other alternative and renewable resources electricity production. The master plan for the region calls for tripling the population of around 3,000 residents in the next decade. Both of these goals depend on building housing units in each of the existing communities. The existing models of housing are recognized as energy inefficient and inappropriate for the region. This is because they are copies of units built in (but not necessarily planned to be adapted to) other regions of the country and either transported to the Arava or built in situ according to plans that only marginally relate to the particular extreme climate. Common building types and technologies include concrete, flat roofed non-insulated houses which were marginally improved post construction by the addition of "thermal" external plaster (a mix of cement with polystyrene beads, applied to exterior concrete walls); aerated autoclaved concrete (AAC) blocks; introduction of the most basic model of double glazed windows (in aluminum frames with no thermal breaks); and roof shading. Recently, lightweight housing units have been introduced.

In all cases, the level of satisfaction has not increased and HVAC use is high. The development of architectural strategies that are particular to this region with an emphasis on energy efficiency should be recognized as a component in the renewable energy plan and the physical development master plan of the regional council and the communities.

Residents of the southern Arava are quite aware that heating and cooling systems and their associated costs are inseparable with living in this region. Winter days, normally sunny and often moderate are pleasant outdoor, but marginally tolerable indoor, while nights are cold and internal walls and windows feel very cold. Temperatures in the spring and fall are moderate during day and night, allowing daily ventilation, with windows open or closed at night. Summer daytime cooling can begin as early as late April and even March during sandstorms with hot wind events blowing up from Africa. By late May air conditioners are running during the day and night until cool nighttime breezes begin again in September. In Israel residential buildings, and public and commercial ones account for 30.0% and 32.4% respectively of the overall annual electricity consumption (IEC 2011). Summer air conditioning accounts for appr. 16% of the overall electricity consumption in Israel (40% of the May-Oct. summer electricity use). A case study surveyed in the Arava (Kibbutz Grofit) showed cooling loads comprised 49% of the annual residential electricity use (46% of the Apr.-Oct. summer electricity use) (Daniels, 2009).

The goal of the research presented here was to determine the components of residential buildings that would allow houses to be heated passively using solar gain and to be cooled using less energy than that currently needed for mechanical cooling. An analysis of the southern Arava's climate presented three seasonal conditions that must be addressed when designing free running as well as low energy use buildings: a clear or partially cloudy skied winter during which sufficient heating can be provided using solar gain; spring and fall with comfortable ambient temperatures and risks of overheating from solar gain; and summer in which ambient temperatures are above comfort levels during the day and most nights.

## 2 TOOLS AND METHODS

The research methodology selected to determine energy efficient building design guidelines was a parametric analysis of operational as well as physical elements.

### 2.1 Parameters

A 100 $m^2$ building with internal height of 3 m, of one zone (no internal differentiation between thermal zones or rooms), was modified in accordance with the variations of physical building element parameters. The climate data for each month were taken from the Typical Meteorological Year (TMY) file of the Yotvata Israel Meteorological Service (IMS) station. Data sets of simulated interior temperatures for each set of parameters were created by the QUICK II simulation software for each month of data. The building element parameters selected for this project appear in Table 1. There were 55,296 possible combinations of these building elements and operational scenarios. Instead of running all the possible permutations and comparing all of the results, a progressive method parametric analysis was employed. The process began with simulating building performance for a limited number of parameters. The data were analyzed to determine the best performing options out of the simulation set. This process was repeated as additional parameters were added to the building assembly.

Operational parameters, for example shuttering windows completely during warm spring days to avoid overheating, are as significant to the free running operation of a building as are building elements such as wall and roof insulation. Within the time limitations of this work and because of the understanding that numerous combinations of parameters were inappropriate for this climate, it was decided to progressively compare parameters instead of running all the possible permutations and comparing all of the results. The process began with collecting site specific climatic data from the IMS, which are not readily accessible, and selecting naturally occurring representative days for each month of a standardized TMY.

## 2.2 Simulation tool

The computer program selected for the parametric analysis of the building system was QUICK II, developed by the Centre for Experimental and Numerical Thermoflow, University of Pretoria, South Africa (Mathews et al., 1994a; Mathews et al., 1994b; Mathews, 1997), which was validated for local use in collaboration with the Desert Architecture and Urban Planning Unit of the Jacob Blaustein Institutes for Desert Research, Ben Gurion University (Mathews et al., 1997).

Table 1: Parameters analyzed in this research.

| | | | | |
|---|---|---|---|---|
| **Geometry** | Square bldg 10/10m | Rectangular bldg 20/5m | | |
| **Orientation** | N-S axis | E-W axis | | |
| **Construction** | Lightweight [LW]: wood frame drywall construction envelope walls and roof (low thermal mass) | Medium weight [MW]: 22 cm thick AAC block envelope walls and roof (medium thermal mass) | Heavyweight [HW]: 20 cm thick cast concrete envelope walls and roof (high thermal mass) | |
| **Wall shading** | Unshaded/none | N, S walls shaded during all daylight hours | E, W walls shaded during all daylight hours | N, S, E, W walls shaded during all daylight hours |
| **Roof shading** | Flat, un-shaded roof | Shaded, well ventilated roof | Unventilated clay terracotta tile roof | Well ventilated clay terracotta tile roof |
| **Insulation** | Un-insulated [0] - No thermal insulation on walls/roof | Insulated [5] - 5cm layer of external thermal insulation (expanded polystyrene) on walls/roof | Insulated [10]- 10cm layer of external thermal insulation (expanded polystyrene) on walls/roof | Insulated [20] - 20cm layer of external thermal insulation (expanded polystyrene) on walls/roof |
| **Window size** | 6 $m^2$ on N, S walls | 6 $m^2$on N, 12 $m^2$on S walls | | |
| **Window treatment** | Glazed openings not shaded by shutters | Glazed openings shaded by shutters | Seasonal operation of shutters – summer/closed in daytime; winter/opened in daytime. | |
| **Window insulation** | Low: single glazing | High: triple glazing | | |
| **Ventilation – Air Changes per Hour (ACH)** | 10 ACH | 20 ACH | 30 ACH | 50 ACH |
| **Finish** | Light color: reflective white finish of external walls/roof (absorption coefficient = 0.3) | Medium color: dark brown finish on external walls/roof (absorption coefficient = 0.65) | Dark color: dark brown finish on external walls/roof (absorption coefficient = 0.8) | |

The program functions by simulating the effect of seasonal external climate (radiation, temperature, humidity and wind) on the building envelope (physical and thermal properties of components and materials) and calculates the internal temperature of the building for a representative day of each month. The program also derives the energy consumption needed by mechanical heating and cooling systems for reaching/maintaining set temperatures. The process began with simulating building performance for a limited number of parameters. Additional operational and physical parameters were added and the results compared. The data were analyzed to determine the best performing options for building assemblies.

## 3 RESULTS AND DISCUSSION

The results of the permutations investigated confirmed that simulated conventional building systems did not allow for free running operation and that mechanical heating and cooling systems were needed for significant parts of the year. The conclusion of the research was that it is imperative to extensively insulate building envelopes in order for them to be free running in the winter. Buildings need extensive shading in the transition seasons to allow for free running operation and avoid overheating. Buildings with complete shade, high efficiency window systems and levels of insulation above and beyond those currently employed when simulated with summer climate conditions had significantly lower energy consumption requirements for mechanical cooling than other building designs. The research showed that energy efficiency in this region is a function of particular combination of extensive insulation, full shade, high performance windows, air tight buildings and seasonal operation of window shutters utilized together.

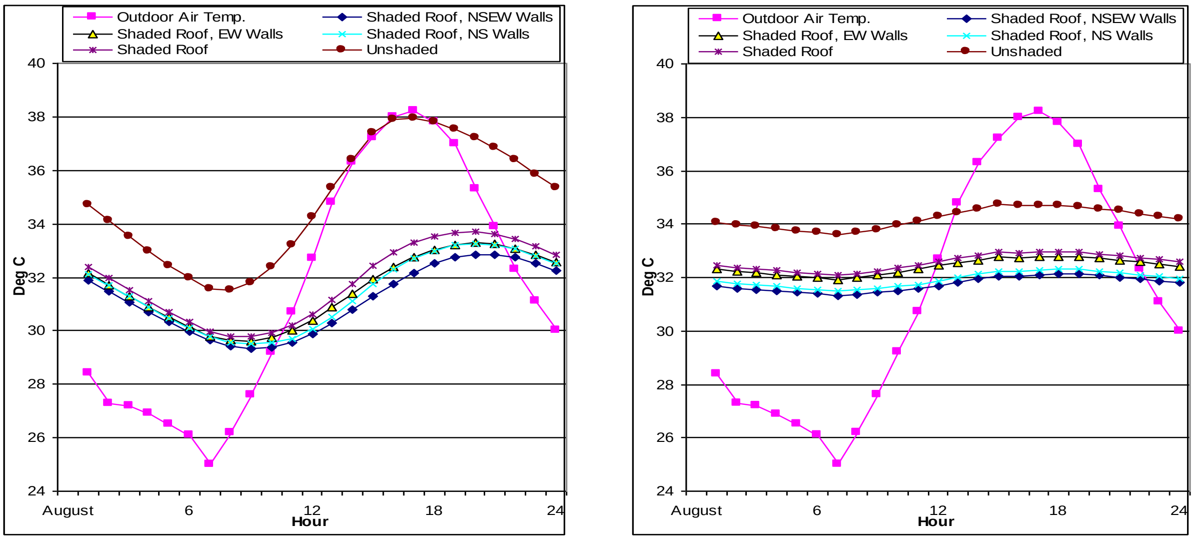


Figure 2: Effect of shading on buildings with increasing insulation on walls and roof in summer (August). Buildings had 6m$^2$ south facing windows and 200mm concrete walls and ceiling. Left: non-insulated; right: 50 mm polystyrene insulation.

The climatically advantageous geometry was a rectangular rather than a square building unit. The walls of the rectangular building had 25% greater surface area than the square building, which could be considered detrimental in a region where reduction (in summertime) of the surface area to volume ration would be preferential. However, the rectangular building allowed for substantially lowered wall area exposure in the summer when properly oriented. The preferred orientation of the rectangular building was along the east-west axis so as to make expanded solar gain options available in the winter and to reduce exposed east and west walls in the summer.

Wall shade in the winter months was not beneficial for the building. Nevertheless if the building was warmer because of un-shaded walls (not including windows) it suggested heat gain through the walls which is not a positive characteristic of the external envelope. Analysis of roof construction strategies showed that the insulated roofs were a necessity for reducing conduction of energy through the envelope. Shading of the roof, along with its insulation reduced internal heat in most months of the year. Ventilated roof shading options correlated with lower energy use for cooling in the summer.

Window size - for winter solar gain 6m$^2$ of south facing windows for a 100m$^2$ building proved insufficient for solar gain needed to raise simulated interior temperatures above the lower threshold for thermal comfort (20°C). Increasing the window area to 12m$^2$ increased the internal temperatures and was sufficient when highly insulated windows were used. In summer larger windows were associated with increased simulated internal temperatures. In practice reflective and insulated external shutters would reduce this effect.

Higher performing windows (low conductivity/high insulation, in this study taken as U=3 and 1.5 W/m$^2$K; R= 0.333 and 0.666 m$^2$K/W for double and triple glazing, respectively) were associated with higher interior temperatures in the winter and lower energy use in the summer when mechanical cooling was employed. Better tools with a higher resolution based on a more complex analysis of glazing systems could be used to determine the cost/benefit ratio for windows. This is of particular interest because of the high cost of good glazing options.

Ventilation was simulated on a hypothetical building system that should be more appropriate for the southern Arava because of its high interior mass and large level of insulation and shading. The effectiveness of night time ventilation for cooling the building increased as air speed increased. The question of utility of night time cooling in the summer is one relating to personal preferences and acclimation to the high ambient temperatures. In general, and in accordance with ASHRAE standards for populations in industrialized countries, thermal comfort would only be reached by maintaining high air flow ventilation during the few hours that temperatures were below, but near the upper threshold of thermal comfort (28°C). For most of the summer day ventilation from outdoors could not be used.

Three commonly used construction techniques were compared in the summer in order to determine their relative efficiency in energy use for cooling. Commonly used roofing systems were also parameters simulated. The lowest energy use was associated with the heavy weight building with high levels of insulation. Lightweight and heavy weight buildings with low levels of insulation had similar energy usages. Lightweight buildings with unventilated roofs needed more energy to cool. The simulated building built from AAC blocks, marketed as an environmentally superior material, demanded more energy for cooling than all of the other options. A medium color of external surfaces (absorption coefficient = 0.65) was used throughout the analysis process. A final check of the response to light or dark colored surfaces on the best performing envelope showed that even in full shade darker colors would absorb and conduct heat to the interior of the building due to reflected and diffuse radiation.

Therefore it is preferable to use light colors on buildings in the southern Arava in particular because the airborne dust is dark and all textured surfaces will become darker in time. The parametric analysis process used ended with the selections of a building that incorporates many architectural elements in use in the southern Arava, but not necessarily incorporated into one building. The results suggest that such incorporation should produce a building which would be energy efficient because of its appropriateness to this specific environment.

Further research could determine what the effect of trade-offs would make, for example lowering the internal mass while adding more insulation. This would be useful when examining the functioning of alternative building materials and technologies, such as the straw bale and earth plaster domes recently built in Kibbutz Lotan (Golding, 2010). Apparently these un-shaded and dark colored buildings which have 5cm of earth mass on the interior and 50cm of straw insulation, when cooled to 25°C in the summer using air conditioners, do not heat up from conduction of heat through the walls and have very small daily temperature fluxes due to infiltration of hot air. This would be a case of reaching energy use goals by using levels of insulation beyond those addressed in this analysis.

Table 2: Simulated cooling loads for buildings with same geometry, shading and windows as a function of different wall components: 5x20m ($100m^2$) buildings oriented on EW axis; single glazed windows: $6m^2$ north facing, $12m^2$ south facing; windows, walls and roofs shaded. Set temperature 25ºC, 24 h/day, August.

| | | | | | |
|---|---|---|---|---|---|
| **Wall and roof** | 200mm concrete | 200mm concrete | AAC | 19mm gypsum wallboard | 19mm gypsum wallboard |
| **Insulation of wall and roof** | 200mm XPS | 50mm XPS | - | 50mm fibreglass batt | 50mm fibreglass batt |
| **Roof** | Well ventilated, no mass | Well ventilated, no mass | Well ventilated, no mass | Clay tile, unventilated | Well ventilated, no mass |
| **Daily (24h) energy consumption, August typical day [kWh]** | 27.82 | 53.61 | 79.96 | 62.69 | 51.66 |

## 4 CONCLUSIONS: BUILDING DESIGN GUIDELINES FOR FUTURE CONSTRUCTION

The conclusion of this research is that it is imperative to dictate extensive envelope insulation, insulated windows and doors units and frames with low infiltration and low convective heat loss in order to make the buildings free running during all winter months. Extensively shading the insulated envelope and windows in accordance with daily ambient temperatures and solar radiation levels allows for free running operation of buildings during the transition seasons. Significant reductions in energy consumption in the summer months can be realized by completely shading the buildings, utilizing high efficiency window systems, preventing convective heat gain from infiltration and ventilation and enveloping the building with levels of insulation above and beyond those currently employed.

This research proved building design guidelines would have a significant impact on the thermal performance of buildings in the southern Arava and subsequent minimization of energy consumption to employ auxiliary heating and cooling when they incorporate:

- a significant increase of exterior insulation on all types of building construction systems (this research simulated insulation thickness of up to 20cm of expanded polystyrene U=0.035W/m°C);
- employment of full shading of the building envelope in the summer months;
- integration of operable, insulated, externally ventilated and highly reflective external window shading on all windows;
- the advantages of high efficiency double and even triple glazed windows assuming high quality of construction and installation.

Additional energy savings design techniques should be utilized in particular to reduce convective heat gain and loss. These include:

- entrance halls "air locks" with double sets of insulated doors;
- heat exchangers for use with A/C units to supply fresh, heated/cooled air at ACH levels that meet standards.

This project suggests that issues of boundary cases of insulation and mass should be evaluated again when designing buildings for the southern Arava. The following discussion and estimates are based on 2009-10 prices and tariffs. Material cost makes up a relatively small portion of total cost of construction. The cost of standard construction in the southern Arava is around $1200/m^2$, therefore a 100m$_2$ house would cost around $120,000. The cost of 200mm XPS at $50/m^3$ (around $50m^3$ is needed) is $2,500 or 2% of the total cost. At energy prices at the time of the research ($0.15/kWhr) average yearly heating and cooling costs for the $80m^2$ kibbutz houses (see Kibbutz Grofit residential energy use, Daniels, 2009) is approximately $580/year per household. The payback period could be calculated as function of energy saved by having the insulation. If the energy savings would be 30% then the payback period would be 14 years. These preliminary calculations illustrate that implementing energy savings strategies in building design can be cost efficient in the short to medium term, yet energy price rises since then (0.18 $/kWh, June 1, 2013) shorten the insulation payback period even more.

This research showed that commonly accepted architectural norms should be reevaluated when building in the southern Arava, as well as in similar hyper arid regions. Recent building in the southern Arava has disregarded design norms that were shown in this research to have been beneficial to energy efficiency. These include building houses along the east-west axis so as to shade each other (and, if connected, reduce external surfaces), high and well ventilated roofs of light colored materials and painting buildings white. However, use of light hue reflective finish materials dictates shading them extensively to avoid high reflectance and glare, making the use of outdoor spaces thermally and visually uncomfortable even in winter days, and could negatively affect neighboring buildings by exacerbating cooling loads.

These design directives should not be lost in the name of expedient building or "personal choice" instead of following local building strategies. Each of these elements plays a part in the mosaic of components in designing an energy efficient building in this particularly extreme climate. All of the components need to be included if reduction of energy use for heating and cooling is to be achieved.

## 5 ACKNOWLEDGEMENTS

This research was carried out within the graduate program of the Albert Katz International School for Desert Studies of the Jacob Blaustein Institutes for Desert Research, Ben Gurion University of the Negev. The active support and cooperation of the Arava Institute for Environmental Studies, the Tzel HaTamar Association, and Kibbutz Lotan’s Center for Creative Ecology is kindly acknowledged.

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