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Toward Sustainable Desert Architecture: Recent Studies in the Negev, Israel

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Abstract: What is meant by the term desert architecture? Why should buildings or towns in arid regions be conceived differently than they are anywhere else, and what would make such an architecture sustainable? This article discusses a number of ways that architectural design may be adapted to the opportunities and constraints of a desert climate, and in so doing allow for dramatic increase in the efficiency of energy consumption – which is perhaps the greatest challenge for long-term sustainability. A series of recent examples, taken from both research and application in the arid Negev region of Israel, is presented to illustrate some of the concrete possibilities for creating more sustainable patterns of desert architecture.

Key words: Desert architecture, energy consumption, energy saving, passive cooling, buildings.

Sustainability, Energy Consumption and The Built Environment

As the long-term sustainability of development patterns in the industrialized world becomes more and more questionable, two particular trends may be identified which, according to a broad consensus, are patently unsustainable. One is the rate at which greenhouse gases and other pollutants are being emitted to the atmosphere, and the other is the rate at which non-renewable resources are being depleted. The first trend constitutes an environmental threat with impacts on health and global climate; the second is seen as an economic and geopolitical threat. But clearly, both trends are expressions of society's ever-increasing appetite for energy, which is still predominantly supplied through the combustion of fossil fuels. With worldwide demand projected to quadruple in the coming century (Holdren, 2007), an awareness is taking hold that energy consumption represents the greatest challenge in realizing a sustainable future (Szuromi *et al.*, 2007).

To the extent that the energy "crisis" has even been recognized as an ongoing, rather than a transient phenomenon, the search for solutions has focused most notably on alternative energy production. Developing clean, renewable energy sources that are competitive and can keep pace with rising demand will, indeed, require investment on a grand scale. However, increasing production is rarely as cost-effective as increasing the efficiency of consumption. As pointed out by Lovins (2005), saving fossil fuel is a lot cheaper than buying it.

To identify potential sources of energy savings, it is necessary to examine the end-uses to which energy is put. These may be small and numerous like private vehicles, or they may be large and visible like manufacturing or power plants. But neither of these sectors – transport or industry – consumes as much energy as do buildings (Fig. 1). In the US., nearly 40% of all energy is required for the maintenance of commercial and residential buildings (EIA, 2006) – and in residences especially, the bulk of this energy is used for heating, cooling and otherwise making the space habitable. Even this formidable proportion does not account for fuel consumed by buildings before they are ever inhabited, in the production of their materials and in the construction process itself. Nor does it reflect the energy that must be expended because of the relative location of buildings (i.e. commuting from home to work). The common denominator shared by these processes is that they are all directly influenced by planning and design of the built environment, and by this measure it may be reasonably claimed that architectural decisions are responsible for the majority of all energy consumed (Mazria, 2003).

Climatic Responsiveness in Arid Regions

The ongoing energy-efficiency of architecture can, and in recent decades has been, improved by "isolating" buildings from their surroundings – that is, by controlling the internal climate with mechanical air-conditioning and heating systems, and using thermal insulation and

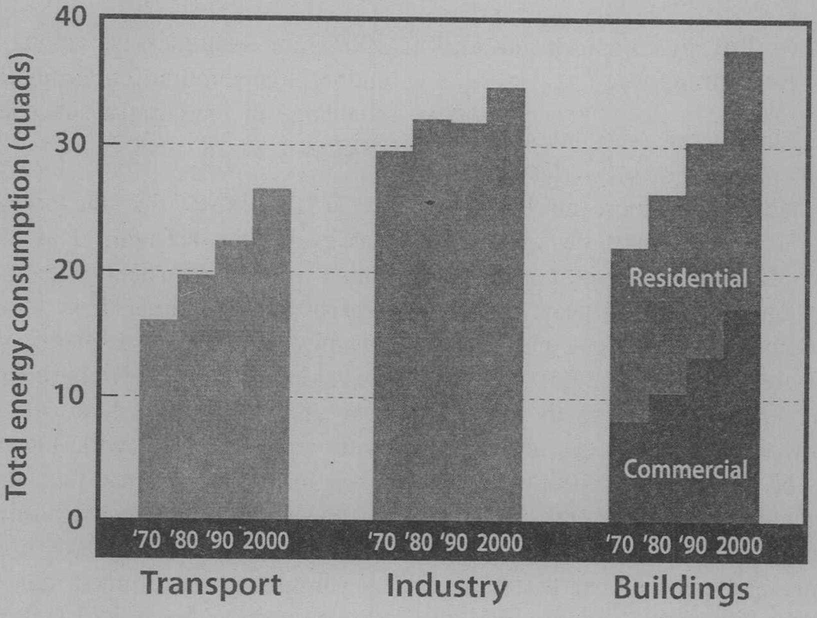

Fig. 1. Total energy consumption by economic sector in the US, which is by far the world's largest consumer. Data represent annual totals reported in quads (quadrillion Btu) for the years 1970, 1980, 1990 and 2000 (EIA, 2006). In the year 2000, residential and commercial buildings were responsible for 22% and 18%, respectively, of the total.

air-tight windows to minimize unwanted heat loss or gain. While the technological ability to achieve this sort of efficiency has raised the standards of comfort and allowed larger spaces to be climatized, it has not arrested the overall growth of energy consumption. To do this requires not just universal, prescriptive measures, but also locally adaptive ones. The bioclimatic approach to architectural design (Olgyay, 1963; Knowles, 1974; Givoni, 1976; Mazria, 1979; Watson and Labs, 1983; Fathy, 1986) is predicated on understanding the climatic context in which a building is designed, and responding to that context. Climatic design is selective (Hawkes *et al.*, 2002), in the sense that the building is seen not as a barrier but as a filter – protecting against unwanted thermal stress (like cold winter winds or intense summer sun) and admitting environmental energy that is beneficial (such as solar radiation in winter or cool night breezes in summer).

Such "passive" uses of environmental energy are not applied with equal effectiveness in every type of climate. Cold winter conditions combined with persistent cloudiness or scarce daylight hours make it difficult to utilize solar energy directly for heating, and in warm humid regions the means for passive cooling are limited. In fact, dehumidification – the key feature of energy-intensive air conditioning – has historically been the most difficult aspect of thermal comfort to achieve with low-energy means (Banham, 1984).

Deserts, on the other hand, present a reverse situation. While prevailing conditions in arid regions may be especially harsh, they are amenable to improvement through passive and low- energy means. Solar radiation is typically abundant in winter as well as in summer, meaning that the potential for passive heating is pronounced. In addition to cloud-free skies, aridity usually brings low daytime relative humidity, so that thermal comfort can be felt at higher temperatures and it can be enhanced with evaporation. Perhaps most importantly, deserts characteristically experience wide diurnal temperature swings, which can be exploited for both heating and cooling.

It is thus apparent that the ubiquity of air-conditioning in modern desert cities has as much to do with cheap energy as it does with the lack of alternatives – and alternative strategies have indeed been developed for creating more sustainable forms of desert architecture. These strategies range from the details of a building to the pattern of settlements in a desert region, and the key to sustainability lies in their integration – which often means crossing the perceived boundaries of scale and specialization (Pearlmutter and Meir, 1999). In creating a cohesive approach to sustainable development in desert regions, challenges still remain at every level. The following discussion reviews some of the recent efforts that have been made to meet these challenges at three levels of scale (towns, buildings and materials), in a particular desert region – the arid Negev of Israel.

Urban Design and Pedestrian Comfort

One possible avenue for turning hot-arid conditions from a burden into an advantage is through responsive urban design. In traditional desert settlements, the urban fabric commonly developed as a tightly-knit pattern of narrow streets and courtyards, with the need for climatic protection presumably being one of the motivations. Over time, however, outdoor thermal comfort gradually became less of a concern, as cities came to rely on vehicular transport and eventually on air-conditioning – and only in recent years has the importance of the "pedestrian realm" been reexamined (Lillebye, 2001). In Israel's arid Negev region, modern towns were established only in the middle of the 20th century – and their planning largely followed the "Garden City" concept imported from Europe, which prescribed a broad dispersal of buildings and large open green spaces throughout the landscape. As described by Gradus and Stern (1985), the result of this conceptual transplanting was a mismatch between the intentions of planners and the physical reality of the desert – with internal deserts created within the city, and inhabitants suffering from extensive walking distances in oppressive heat. In response, attempts were made to create denser, more compact residential environments, with one of the goals being the improvement of microclimatic conditions. "Patio house" neighborhoods with a compact structure of walled courtyards and narrow pedestrian paths were built as examples of the "new" approach, though in fact they echoed the traditional urban patterns typically found in the Middle East.

The assumption that such a "compact" urban fabric would necessarily enhance pedestrian comfort in desert cities was never confirmed, however, and such a conclusion is far from trivial. Current knowledge in the field of urban climatology would suggest that compact planning could in fact prove detrimental in a hot climate due to the urban heat island effect, whose contributing factors include both the "trapping" of radiation and weakening of ventilation which occur in highly constricted streets. On the other hand, the direct shading of pedestrians in these streets provides relief from physiological heat stress. An in-depth microclimatic analysis in one of the "patio house" neighborhoods (Pearlmutter *et al.*, 1999) showed that solar radiation is indeed the most dominant factor in the energy exchanges that influence overall pedestrian discomfort, such that compactness may contribute to greater comfort even if air temperatures are simultaneously higher and wind speeds lower.

In order to broaden the findings of this particular case study, an innovative modeling approach – using an open-air, scaled urban surface – was developed to analyze and describe the more general relationship between urban street geometry and pedestrian comfort in an arid climate. The main innovation introduced by this method was the ability to vary and compare urban features in a controlled manner, without oversimplifying the complex interactions with the atmosphere – in this case, by measuring energy exchanges under the actual climatic conditions of the Negev Highlands. A number of validation studies showed that this small-scale model was thermally and aerodynamically similar to a full-scale urban setting, and it was able to reproduce energy exchange patterns similar to those observed in actual cities (Pearlmutter *et al.*, 2005).

Measurements were made within scaled urban streets of varying proportions and orientation (Pearlmutter *et al*, 2006), and

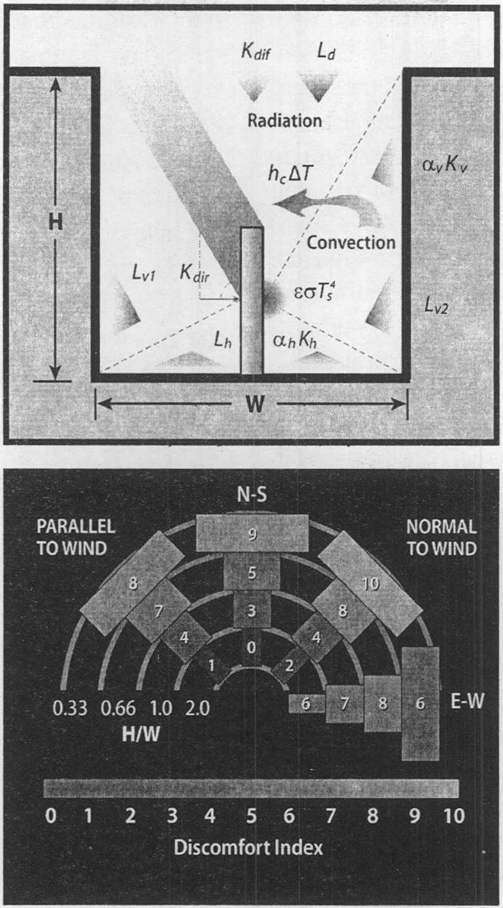

Fig. 2. *Schematic section (top) showing the energy exchanged between a person and an urban street environment of given height/width proportions (H/W), accounting for short- and long-wave radiation as well as air temperature and wind speed. The physiological stress experienced by a pedestrian in streets of varying H/W ratio and axis orientation is expressed in an index (bottom) accounting for the number of hours and relative severity of discomfort.*

the data were used as input to a pedestrian-centered energy exchange model (Fig. 2). The model was expanded to account for evaporative heat loss as well as radiation and convection, and provided a measure of thermal stress that expresses the level of physiological discomfort experienced by a pedestrian (Pearlmutter *et al.*, 2007a).

This integrated modeling approach revealed that increased urban density, while serving to increase radiative trapping and storage of heat within the urban fabric, can qualitatively reduce – or even eliminate – the thermal stress felt by pedestrians during the critical daytime hours, and this is due primarily to their reduced exposure to both direct and indirect solar radiation. This "cool island" effect is enabled by the high thermal inertia of the built-up area, and the sharp diurnal fluctuations that are peculiar to a hot-arid climate, and it has also been identified, using different methods and indices, in Algeria (Ali-Toudert *et al.*, 2005) and Morocco (Johansson, 2006). What the Negev modeling results demonstrated clearly, though, is that the impact of a compact street geometry is contingent upon the street's orientation with respect to prevailing winds, and particularly to shading from direct sun – increasing as street-axis orientation approaches north-south and becoming negligible in the east-west direction (Fig. 2). When combined with results from the winter season, what emerges from this pattern is the potential advantage of a "selective" urban fabric – in which preference is given to compact streets in most directions (and especially those running north-south), and more open streets running east-west.

Experiments in Passive Cooling

Though the climatic quality of outdoor spaces has been neglected in many desert cities, the proliferation of air-conditioning has generated a demand for more comfortable building interiors – and a parallel increase in the demand for electricity has in turn motivated interest in low-energy cooling. Ongoing research in the Negev has focused on developing passive cooling techniques for a range of spatial types, including not only rooms, but also large semi-open spaces which would be impractical to cool by conventional means.

Cool towers for public spaces

Wind towers or wind catchers have been used in traditional architecture throughout the Middle East and Central Asia for centuries to promote natural ventilation, sometimes incorporating evaporative cooling. They are known variously as the *malqaf* in Egypt or as the *badgir* in Iraq and Iran, and are found as far east as Pakistan and Afghanistan (Al-Megren, 1987). In a traditional wind tower, air entering through the windward opening at the top with positive wind pressure leaves the tower through any of the openings that have a lower pressure coefficient (Bahadori, 1985). The air may be cooled by evaporation if it flows over moist surfaces, either within the tower or in the form of a water pond at the base of the tower.

Inspired by these traditional models, down-draft evaporative cool towers (DECTs) have earned attention in recent years as a low-energy option for the cooling of public open or semi-open spaces (Bowman *et al.*, 2000; Francis, 2000; Ford and Diaz, 2003). Such towers vary not only in their aerodynamic design, but also in the method employed for supplying the water to be evaporated. Experimental towers in Arizona and other locations in the American southwest have used a wetted pad as the evaporating medium (Cunningham and Thompson, 1986), and demonstration projects in Spain and elsewhere in southern Europe have employed a fine mist of water droplets sprayed into the tower (Alvarez *et al.*, 1991). Water sprayers were used in a down-draft cool tower that was integrated in a multipurpose educational building at Sede-Boqer in the Negev desert of Israel. In this tower, relatively large drops of water are sprayed at the top of the tower and are partially evaporated, with unevaporated water collected in a pool at ground level and recirculated to the spraying system. Such a configuration allows drops to descend at high velocity and increase the air flow rate due to momentum transfer from the drops to the air, and several experimental "shower towers" of this type have also been monitored by Givoni (1997) in different climates. Monitoring of the Sede-Boqer tower (Pearlmutter *et al.*, 1996) showed that temperatures could easily be reduced close to the ambient wet bulb temperature (the theoretical limit by evaporation alone), but that the overall cooling capacity was limited by the aerodynamic efficiency of the tower.

Recently this limitation has been addressed in the development of an experimental tower that makes use of two separate air intakes and has contoured inlet and outlet air deflectors (Erell *et al.*, 2007; Pearlmutter *et al.*, 2007b). The objective of this two-stage design is to conserve water while providing equal or superior cooling to a conventional system, in which dry ambient air is drawn in through a single inlet at the top and cooler moist air is delivered at the bottom. The particular sprayers used in the improved system were determined after considering the efficiency of evaporation, energetic efficiency of pumping, and maintenance concerns connected with different drop-size distributions (Guetta, 1993).

To test the performance of such a design, measurements of temperature reduction and cooling output were made using an 8 m high prototype tower constructed at Sede -Boqer (Fig. 3). It was found that when the sprayers are activated, the temperature at the outlet drops abruptly and is maintained within 1-2°C of the WBT until the water supply is turned off. At mid-day when the ambient temperature peaks, the magnitude of the temperature depression exceeds 10°C. This is in contrast to the more modest depression achieved in the upper tower section alone, with temperatures at this stage stabilizing about 3°C higher than at the bottom outlet.

Nominal cooling output was calculated on the basis of the airflow rate through the tower and the temperature differential between ambient air and air at the outlet of the tower. Statistical correlations showed that volumetric air flow through the secondary inlet was about 40% of the total flow through the tower for a wide range of velocities in both fan-assisted and wind-driven operation, and the cooling output reached a total of over 90 kW in the fan-assisted mode and up to 60 kW when driven by wind only.

The curved deflector installed at the tower's bottom outlet (Fig. 3) was found to improve the transition from vertical downward airflow to horizontally directed outward flow with a minimal loss of momentum, but only if a substantial flow is generated initially. Thus, in fan-assisted operation with wind speeds in excess of 3 m s^{-1}, the volumetric flow rate with the deflector cone installed was typically 15-25% higher than without it.

Roof cooling for desert buildings

As described recently by Yannas *et al.* (2006), many of the best opportunities for cooling a building passively can be found on its roof – which of all building elements is best positioned for dissipating heat to

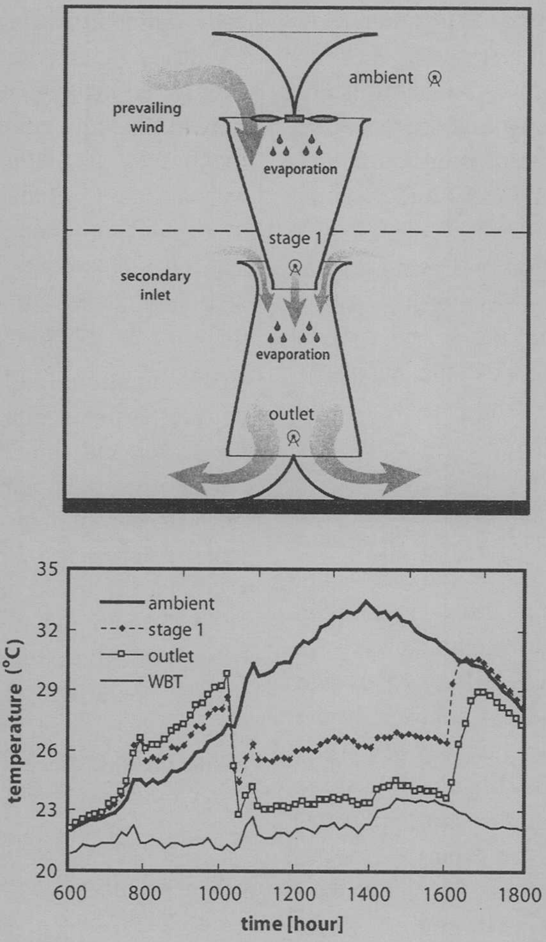

Fig. 3. *Two-stage evaporative down-draft cool tower, shown in section (above), with typical daily progression of temperatures over a summer day (bottom). Operation is from 1000 until 1600 hr, during which time the cooled air supplied at the outlet of the tower remains close to the wet bulb temperature (WBT) – which represents the theoretical limit of cooling by evaporation.*

the atmosphere. What has come to be known as the "green" or planted, roof combines three mutually reinforcing mechanisms: the thermally stabilizing influence of a layer of soil, the evaporation of water from its irrigated surface, and shading of the wetted soil surface by the leaves of plants growing in it.

This type of strategy is sometimes seen as an impractical addition rather than an integral part of the architecture, but it is here that the role of the architect comes into play: green roofs can have added value, enriching the visual design or serving multiple roles as rooftop gardens. On the other hand, they can be made utterly simple by using low maintenance shading elements in place of actual vegetation, since transpiration from leaves is relatively inefficient for cooling the building itself (Givoni, 1994). This idea was tested in recent experiments by Rosenfeld (2006), which revealed that a combination of simple elements on the roof of a conventional building can provide effective cooling under hot dry summer conditions. In this study, the contribution of a watered soil with two types of shading was assessed using two small test buildings with flat concrete roofs, monitored during the summer season. Both roofs were covered with a 16 cm layer of soil: on one roof the soil was dry and untreated, while on the other the soil was consecutively watered and shaded alternatively by means of an overhead shading mesh and a layer of lightweight gravel (Fig. 4).

Temperatures measured on the inside ceiling surfaces of the two roofs showed the cumulative contributions of these treatments. First, it was observed that the addition of a modest soil layer dramatically stabilizes the sharp temperature swings generated on a bare concrete roof – maintaining a temperature in the range of 30°C, and introducing a substantial time lag so that the highest temperature falls late at night. With the addition of a simple drip irrigation system (providing 8 liters of water per square meter of roof each morning), evaporative cooling from the wet soil surface lowers the ceiling temperature to the range of 26-28°C. Though substantial, these reductions are insufficient for comfort cooling, and much of the cooling effect is "spent" offsetting the heating effect of solar absorption. Thus temperatures are further reduced with the addition of a layer of lightweight gravel, which is essentially a waste product in the manufacturing of lightweight autoclaved aerated concrete blocks. While this treatment allows a fairly constant ceiling temperature of about 25°C to be maintained at all hours, (and also cuts the water requirement by half), it inhibits to some extent the potential for removal of heat by evaporation and convection. As a final alternative measure, an overhead shading mesh was used in place of the gravel and found to yield slightly greater cooling – though the additional structure required for this strategy somewhat reduces the simplicity of the system (Fig. 4).

Embodied energy and life-cycle analysis

The thermal efficiency of a building may be improved through numerous means, and a wide range of products (specialized insulating windows and glazing materials are prime examples) have been developed in recent years for this purpose. However, the actual energy savings afforded by such architectural products can only be gauged after accounting for the considerable energy that is "embodied" in their production – that is, the energy, which is required to extract, manufacture and transport both raw and finished materials.

Because of the uneven geographical distribution of available resources – as well as the varying distances over which these resources must be transported, and the differences in local technologies used to turn them into finished products – the embodied energy of a given material is to an extent site-specific, and can vary

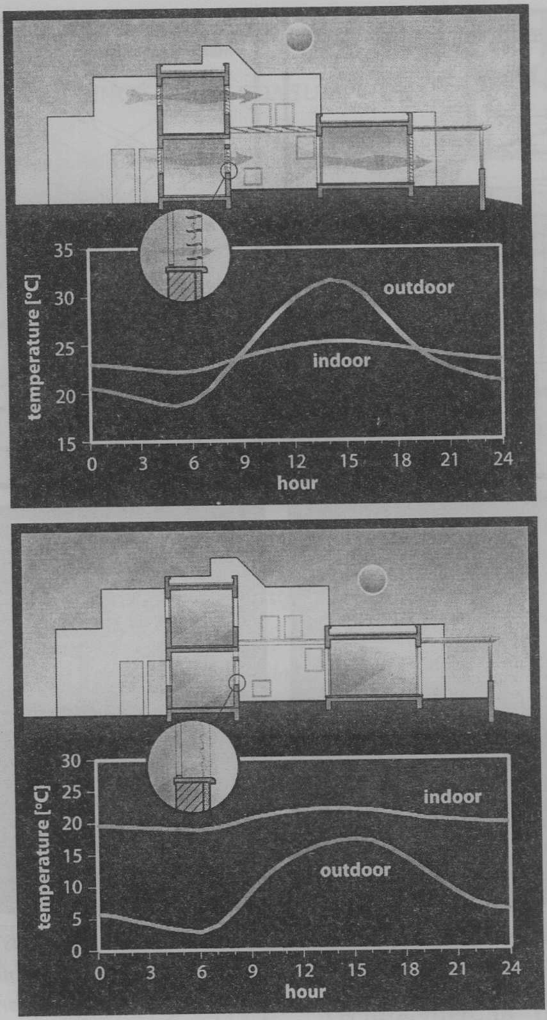

Fig. 8. Case-study house: sections and typical clear-day temperature curves showing climatic response in summer (top) and winter (bottom).

Water-intensive landscaping in common areas is kept to a minimum, and is concentrated in tightly defined public spaces that are actively used, while the irrigation of private gardens is carried out at the discretion of individual residents.

The Neve-Zin plan encourages residents to adopt principles of climatic design under the conditions of the desert. The application of these principles is illustrated in Fig. 8 for a 140 m^2 house, employing internal mass, external insulation, and operable shutters on strategically-placed windows for solar gain in winter and night ventilation in summer. In winter, south-facing windows admit solar radiation during daylight hours and thermal energy is stored in the concrete floors, ceiling and block walls – while at night, insulated shutters are closed to complete the layer of external envelope insulation and prevent heat loss. In summer, the shutters' slats can be adjusted to prevent both direct and indirect solar penetration, or to admit daylight and views – and at night they are opened along with the windows to allow cross-ventilation, with cool air chilling the thermal mass and allowing it to absorb excess heat the following day.

Typical daily temperatures under clear-sky conditions are shown for each of the two seasons (Fig. 8), with results reflecting a level of thermal stability, or "natural climatization", that reduces annual energy expenditures for heating and cooling by over 90% compared to "standard" houses of similar size (Pearlmutter, 2000). The house's yearly energy consumption is shown also in Fig. 6, as part of the life-cycle energy analysis discussed previously. This analysis emphasizes that the desert's "natural" energy income can indeed be exploited to dramatically reduce a building's long-term fuel dependence – and to make a significant contribution towards architectural sustainability.

Prospects for the Future

Although about a third of the earth's land surface is covered by desert, arid regions have until now not often been the focus of architectural or urban climate research. This may seem natural, since deserts tend to be sparsely populated. But according to the Millenium Ecosystem Assessment (2005), the population of "drylands" – which encompass not only deserts but also adjacent areas threatened by desertification, now constitutes over a third of humanity, with nearly half of this population living in cities. This proportion is projected to increase further, reaching 60% by 2030.

Sustaining an acceptable quality of life for this growing population may depend to a critical extent on our understanding of the modifications induced by urbanization and resource-intensive buildings. It is imperative, then, to recognize the qualitative differences between arid and non-arid environments, and respond to these opportunities and constraints in a sustainable manner. As the modest examples, which have been presented here show, solutions exist at a variety of scales, from the details of buildings and their materials to the patterns of urban settlement. Certainly one of the keys to a sustainable future will be the application of such solutions as appropriate in each and every location, with an eye always fixed on the common global realities.

References

Alcorn, J.A. and Baird, G. 1996. Embodied energy analysis of New Zealand building materials – methods and results. *Embodied Energy – The Current State of Play*. Deakin University 61-71.

Ali-Toudert, F., Djenane, M., Bensalem, R. and Mayer, H. 2005. Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. *Climate Research* 28: 243-56.

Al-Megren, K. 1987. Wind towers for passive ventilated cooling in hot-arid regions. *Ph.D. Thesis*, Dept. of Architecture, University of Michigan.

Alvarez, S., Rodriguez, E. and Molina, J.L. 1991. The Avenue of Europe at Expo '92: Application of cool towers In *Architecture and Urban Space: 9th PLEA International Conference* (Eds. S. Alvarez, J. Lopez de Asiain J, Yannas S and De Oliviera Fernandes E.), Seville, Spain.

Bahadori, M. 1985. An improved design of wind towers for natural ventilation and passive cooling, *Solar Energy* 35(2): 119-129.

Banham, R. 1984. *The Architecture of the Well-Tempered Environment.* The Architectural Press Ltd., 2nd Edition.

Bowman, N., Eppel, H., Lomas, K., Robinson, D. and Cook, M. 2000. Passive down-draft evaporative cooling: Concept and precedents. *Indoor and Built Environment* 9: 284-290.

Chani, P.S., Najamuddin, D. and Kaushik, S.K. 2003. Comparative analysis of embodied energy rates for walling elements in India. *Architectural Engineering* 84: 47-50.

Cunningham, W. and Thompson, T. 1986. Passive cooling with natural downdraft cooling towers in combination with solar chimneys. In *5th International PLEA Conference: Passive and Low Energy in Housing* (Ed. A. Zold), pp. 23-24. Pecs, Hungary.

Der-Petrossian, B. and Johansson, E. 2000. Construction and environment – Improving energy efficiency. *Building Issues - Reports* 10(2): 1-21.

Energy Information Administration 2006. *Annual Energy Review 2005.* Report No. DOE/EIA-0384, posted July 2006 (http://www.eia.doe.gov/emeu/aer/contents.html).

Erell, E., Pearlmutter, D. and Etzion, Y. 2007. A multi-stage down-draft evaporative cool tower for semi-enclosed spaces: Aerodynamic performance. *Solar Energy*, submitted for publication.

Fathy, H. 1986. *Natural Energy and Vernacular Architecture*. University of Chicago Press, Chicago.

Fay, R. and Treloar, G. 1998. Life-cycle energy analysis – A measure of the environmental impact of buildings. *Environment Design Guide – GEN* 22 1-7.

Francis, E. 2000. The application of passive downdraft evaporative cooling (PDEC) to non-domestic buildings. In *17th PLEA International Conference: Architecture, City, Environment* (Eds. K. Steemers and S. Yannas), Cambridge, UK.

Freidin, C. and Motzafi-Haller, W. 1999. Cementless building units based on oil shale and coal fly ash binder. *Construction and Building Materials* 13(7): 371-382.

Ford, B. and Diaz, C. 2003. Passive downdraft cooling: Hybrid cooling in the Malta Stock Exchange. In *20th Plea International Conference: Rethinking Development : Are We Producing a People Oriented Habitat?* (Eds. W.G. Bustamante and G. Collados), Santiago, Chile.

Givoni, B. 1976. *Man, Climate & Architecture*. Van Nostrand Reinhold, NY.

Givoni, B. 1994. *Passive and Low-energy Cooling of Buildings*. Van Nostrand Reinhold, NY.

Givoni, B. 1997. Performance of the "shower" cooling tower in different climates. *Renewable Energy* 10(2/3): 173-178.

Gradus, Y. and Stern, E. 1985. From preconceived to responsive planning: Cases of settlement design in arid environments. In: *Desert Development: Man and Technology in Sparselands* (Ed. Y. Gradus), pp. 41-59. D. Dordrecht, Netherlands: Reidel Publishing Co.

Guetta, R. 1993. Energy from Dry Air - A Mathematical Model Describing Airflow and Evaporation of Water Drops in Vertical Tubes. *Ph.D. Thesis*, Technion – Israel Institute of Technology, Haifa, 177 p.

Hawkes, D., McDonald, J. and Steemers, K. 2002. *The Selective Environment: An Approach to Environmentally Responsive Architecture.* Spon Press, London & NY.

Holdren, J.P. 2007. Energy and sustainability. *Science* 15(5813): 737.

Huberman, N. 2006. Life cycle energy costs of building materials: Alternatives for a desert environment. *M.A. Thesis* Department of Man in the Desert, Katz International School for Desert Studies, Ben-Gurion University of the Negev.

Johansson, E. 2006. Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment* 41: 1326-1338.

Knowles, R. 1974. *Energy and Form: An Ecological Approach to Urban Growth.* MIT Press, Cambridge.

Lawson, B. 1996. Building materials, energy and the environment: Towards ecologically sustainable development. RAIA, Canberra.

Lillebye, E. 2001. The architectural significance of the street as a functional and social arena. In

The Sustainable Street: Environmental, Human and Economic Aspects of Street Design and Management, pp. 3-44. WIT Press, Southampton.

Lovins, A. 2005. More profit with less carbon. *Scientific American* 293(III): 74-82.

Mazria, E. 1979. *The Passive Solar Energy Book.* Rodale Press, Emmaus, Pa.

Mazria, E. 2003. It's the architecture, Stupid! *Solar Today*, May/June 2003, pp. 48-51.

Millennium Ecosystem Assessment 2005. *Ecosystems and Human Well-being: Desertification Synthesis.* World Resources Institute, Washington, DC.

Olgyay, V. 1963. *Design with Climate.* Princeton Univ. Press, Princeton, NJ.

Pearlmutter, D., Erell, E., Etzion, Y., Meir, I. and Di, H. 1996. Refining the use of evaporation in an experimental down-draft cool tower. *Energy and Buildings* 23: 191-197.

Pearlmutter, D., Bitan, A. and Berliner, P. 1999. Microclimatic analysis of 'compact' urban canyons in an arid zone. *Atmospheric Environment* 33: 4143-4150.

Pearlmutter, D. and Meir, I.A. 1999. Building a language for sustainable community development in arid regions. *Sustaining the Future: Energy-Ecology-Architecture, Refereed Papers of PLEA'99*, Brisbane Australia, September 1999, pp. 783-788.

Pearlmutter, D. 2000. Patterns of sustainability in desert architecture. *Arid LandsNewsletter* 47 (http://ag.arizona.edu/OALS/ALN/aln47/pearlmutter.html).

Pearlmutter, D., Berliner, P. and Shaviv, E. 2005. Evaluation of urban surface energy fluxes using an open-air scale model. *Journal of Applied Meteorology* 44(4): 532-545.

Pearlmutter, D., Berliner, P. and Shaviv, E. 2006. Physical modeling of pedestrian energy exchange within the urban canopy. *Building and Environment* 41(6): 783-795.

Pearlmutter, D., Berliner, P. and Shaviv, E. 2007a. Integrated modeling of pedestrian energy exchange and thermal comfort in urban street canyons. *Building and Environment* 42(6): 2396-2409.

Pearlmutter, D., Erell, E. and Etzion, Y. 2007b. A multi-stage down-draft evaporative cool tower for semi-enclosed spaces: Experiments with a water spraying system. *Solar Energy*, submitted for publication.

Pearlmutter, D., Freidin, C. and Huberman, N. 2007c. Alternative materials for desert buildings: Comparative life-cycle energy analysis. *Building Research and Information* 35(2): 144-155.

Rosenfeld, S. 2006. The passive cooling potential of watered roofs. *M.A. Thesis*. Department of Man in the Desert, Katz International School for Desert Studies, Ben-Gurion University of the Negev.

Scheuer, C., Keolian, G.A. and Reppe, P. 2003. Life cycle energy and environmental performance of a new university building: Modeling challenges and design implications. *Energy and Buildings* 35(10): 1049-1064.

Struble, L. and Godfrey, J. 2004. How sustainable is concrete? In *International Workshop on Sustainable Development and Concrete Technology*, Beijing.

Szuromi, P., Jasny, B., Clery, D., Austin, J. and Hanson, B. 2007. Energy for the Long Haul, *Science* 315(5813): 781.

Venkatarama, Reddy B.V. and Jagadish, K.S. 2003. Embodied energy of common and alternative building materials and technologies. *Energy and Buildings* 35: 29-137.

Watson, D. and Labs, K. 1983. *Climatic Design.* McGraw-Hill, NY.

Yannas, S., Erell, E. and Molina, J.L. 2006. *Roof Cooling Techniques - A Design Handbook.* James & James, London.