The solar envelope: its meaning for energy and buildings

Ralph L. Knowles*
School of Architecture, University of Southern California, University Park, WAH 204, Los Angeles, CA 90089-0291, USA

Abstract

The solar envelope, first conceived and tested by the author working with architecture faculty and students at the University of Southern California (USC), regulates development within imaginary boundaries derived from the sun’s relative motion. Buildings within this container will not overshadow their surroundings during critical periods of solar access for passive and low-energy architecture. If generally applied as an instrument of zoning, the solar envelope will not only provide for sustainable growth but will open new aesthetic possibilities for architecture and urban design.

Keywords: Solar access; Solar energy; Solar envelope; Sustainable architecture; Interstitium

1. Introduction

We have worshipped at the altar of growth. Partly, this is the consequence of a need to house continuing migrations of people being drawn from traditional to cosmopolitan settings. Partly, it is the result of a swelling world economy that rewards ever-expanding markets over constancy, development over a steady state, novelty over tradition. Our predilection in favor of growth over maintenance has raised doubts about a sustainable future.

So far, there has been little incentive for developers to worry about the long-term energy costs of keeping our buildings comfortable and repaired. Pressures are so enormous to build fast and move on quickly to the next project that construction techniques emphasize rapid assembly over the effects of long-term wear and tear. Developers do not pay the bills for heating, cooling and lighting over time and seasons. Consequently they have demanded that architects specify energy-intensive systems rather than make the effort to design with nature. In the simplest ungrammatical terms, we “grow cheap” and “maintain expensive”.

Spreading awareness of a global imperative is just now forcing attention toward a more sustainable architecture. Steele, in a recent book, defines sustainable architecture as “an architecture that meets the needs of the present without compromising the ability of future generations to meet their own needs”[1]. He continues with this warning, “pushed not only by many pundits and the press, sustainable architecture will also be forced upon architects by an overwhelming confluence of ecological, social, and economic forces unless architects reach out to embrace and take control of it first”.

Design research at the School of Architecture, University of Southern California (USC) has anticipated the concerns voiced by Steele and others about energy and buildings. The author began, in 1976, to develop and test the solar envelope, a zoning concept to provide urban solar access[2–4]. The underlying premise of this work has been that solar-envelope zoning would eventually result in a shift from fossil fuels to sustainable energy. Furthermore, it would evoke a profound change in the way we identify with our environments, a different way of judging the aesthetics of buildings.

2. Solar access

The sun is fundamental to all life. It is the source of our vision, warmth, energy, and the rhythm of our lives. Its movements inform our perception of time and space and our scale in the universe. Guaranteed access to the sun is, thus, essential to energy conservation and to the quality of our lives.

A thousand years ago in North America, settlements provided for solar access. Acoma Pueblo, located on a high-desert plateau about 50 miles west of modern Albuquerque, NM, exemplifies such early planning. Terraced houses face southward. Walls are of thick masonry. Roofs and terraces are of timber and reeds, overlaid with a mixture of clay and grass[5].

The Acomans built houses well-suited to a high-desert climate (Fig. 1, left). The sun’s low-winter rays strike most

* Fax: +1-323-666-8182.
E-mail address: rknowles@usc.edu (R.L. Knowles).
directly south-facing walls where thick masonry stores heat during the day, then releases it to warm inside spaces throughout the cold nights. In contrast, the summer sun passes high overhead, striking most directly the roof-terraces that store heat less effectively. Finally, adjacent houses cover each other’s side walls, thus, reducing the impact of summer rays directed from low in the east and west.

More important for this discussion, a study of Acoma shows that spacing between rows avoids winter shadowing of the terraces and heat-storing walls (Fig. 1, right). It was actually this critical relationship of building-height to shadow-area that originally gave rise to the solar-envelope concept.

2.1. Space–time construct

The solar envelope is a construct of space and time: the physical boundaries of surrounding properties and the period of their assured access to sunshine. These two measures, when combined, determine the envelope’s final size and shape [6].

First, the solar envelope avoids unacceptable shadows above designated boundaries called “shadow fences”. The height of shadow fences can intentionally respond to any number of different surrounding conditions, such as windows or party walls. Their height may also respond to adjacent land-uses, for example, with housing demanding lower shadow fences than commercial or industrial uses. Different heights of shadow fence result in contrasting shapes and sizes of the solar envelope (Fig. 2, left).

Second, the envelope provides the largest volume within time constraints, called “cut-off times”. The envelope accomplishes this by defining the largest theoretical container of space that would not cast off-site shadows between specified times of the day. Greater periods of assured solar access will be more constraining on the solar envelope than shorter periods (Fig. 2, right).

2.2. Street patterns

Street patterns greatly influence the solar envelope’s size and shape. In the US, regular subdivisions of the US Land Ordinance of 1785 have set street patterns between Ohio and the Pacific Ocean. Typically, throughout the mid-west and the west, streets run with the cardinal points so that rectangular blocks extend in the east–west and north–south directions. Los Angeles, the site of most solar-envelope research, additionally contains the much older diagonal grid of the original Spanish settlement (Fig. 3).

The size of the solar envelope and, hence, development potential, varies with street orientation. Generally, more envelope height is attainable at either of the two possible block orientations within the US grid while less volume is possible within the Spanish grid. This has made downtown Los Angeles a very challenging problem.

The shape of the solar envelope also varies with street orientation, thus, enhancing urban legibility. Lynch said, “to become completely lost is perhaps a rather rare experience . . . but let the mishap of disorientation once occur, and the sense of anxiety and even terror that accompanies it reveals to us how closely it is linked to our sense of balance and well-being” [7]. Pathways, districts, and directions take on clear perceptual meaning when the solar envelope becomes a framework for urban design.

3. Sustainable growth

As part of ongoing design research in the USC’s School of Architecture’s Solar Studio, a 10-year housing study has tested the possibilities for sustainable growth under the solar envelope. The study concludes that dwellings of 3–7 stories generally represent the best size range for passive and low-energy strategies in Los Angeles. These figures can vary among cities but the underlying suppositions of solar-access policy are broadly applicable to places of density everywhere.

Fig. 1. Acoma Pueblo: thick masonry walls and timber roof-terraces respond well to seasonal migrations of the sun (left); the spacing between Acoma’s rows of houses is strategic, just far enough to avoid winter shadows while conserving precious space on a high, small plateau (right).

Fig. 2. Space–time constraints: shadow fences may have different heights on adjacent properties to avoid overshadowing such elements as windows or rooftops that could benefit from direct sunshine (left); specifying different cut-off times can increase or decrease volume under the solar envelope because of changed sun angles (right).
Each test comprising the study typically embraces 16–18 separate but contiguous land parcels, one for each member of a design class. This approach not only helps architecture students to see urban-design issues beyond a single parcel but it also has the effect of advancing research; more parcel variety provides greater statistical reliability for understanding development potential.

Each test proceeds in two major steps. The first is generation of solar envelopes to match the actual land-uses and economics of diverse settings throughout Los Angeles. The second step is designing buildings within separate envelopes, following all relevant municipal codes as well as proven strategies for passive and low-energy architecture. An early test-project on the Spanish grid near downtown Los Angeles shows the transition from solar envelope to building design that characterizes all projects in the 10-year study (Fig. 4).

Viewed from the east, solar envelopes appear crystal-like while existing buildings are rectilinear blocks (Fig. 4, left). Different times and seasons generate separate facets of the envelopes providing 4 h of sunshine in winter and 8 h in summer. The envelopes are consistently higher on the south than the north. They slope downward toward a 20 ft shadow fence at all property lines to accommodate a base of street-front shops under housing. Since, envelope rules allow shadows to extend northward across streets, tower-like shapes extend upward at some corners.

When building designs replace the envelopes, architectural elements appear that typify many subsequent tests in
the 10-year study (Fig. 4, right). Roof-terraces appear where the rectangular geometry of construction meets the sloping envelopes. Courtyards center many designs to achieve proper exposure for light and air. Facades are elaborate; porches, screens, and other devices, all vary by orientation to sun and wind.

3.1. Los Angeles zoning as a study reference

Los Angeles zoning provides the urban housing reference for this study. First, the dwelling classifications are the actual ones used in the design studio. Second, the classifications illustrate in which part of the density range the greatest variety of housing types occurs. Finally, each part of the density range symbolizes not only different dwelling classifications but a separate grouping of possibilities for energy usage.

A graph initially compares the reference of two critical measures of Los Angeles housing types (Fig. 5). The vertical axis of the graph indicates the ratio between building volume and surface area ($V/S$). Calculations for volume (ft$^3$) include only the space within dwelling units, not support facilities. Calculations for surface (ft$^2$) include exposed portions of the lot as well as the building’s faces.

The $V/S$ acts both as an energy-based descriptor of form and an expression of design choices. Small buildings, with a low $V/S$, use energy mainly to overcome surface or “skin” loads; this also means a potentially strong architectural bond to sunshine, fresh air, and view. Large buildings, on the other hand, have a high $V/S$ requiring that more energy be used to handle the internal stresses of overheating; consequently, architects are less able to design with nature.

Density (dwelling-units/acre, du/a), on the horizontal axis of the graph, varies with housing classification. One-family dwellings generally include more yard space than multiple housing. Also, one-family houses tend to have more floor space than a unit within an apartment building.

Density generally expresses development options. High densities correspond with inflated land values; units and even whole buildings, become compact and essentially repetitive. Low densities coincide with smaller land costs; developers concentrate on one-family houses multiplied over enormous areas. In downtown Los Angeles, developers usually try for the highest densities the market and zoning will support.

3.2. Exemplary housing projects

Four projects, covering a range of settings and densities, illustrate the housing study as a whole (Fig. 6). The research protocol for solar envelopes has been systematically adjusted to increase density in successive projects. The design program for all projects calls for solar access and cross-ventilation to all dwelling units. As density increases and buildings become larger, solar access and cross-ventilation to individual dwelling units becomes progressively harder to achieve. The corresponding rise of $V/S$ accurately...
measures this growing difficulty as well as a general lessen-
ing of design variety and choice.

The research protocol for solar envelopes progressively changes to increase building volume on successive projects. Shadow fences rise from 6 ft up to 10 ft at residences and to 20 ft at commercial properties. Cut-off times are also adjusted to reduce the period of solar access in winter from 6 hr to 4 hr, the minimum generally recommended for passive design in the “Mediterranean” climate of Los Angeles. The added density resulting from increased envelope volume corresponds with higher land values in urban settings.

Additional variations of envelope protocol conform as much with street aspect and wind direction as with solar access and density. For example, unlimited shadowing at property sidelines allows development of a continuous street facade in some projects. Shadow fences on other projects act at side property lines as well as front and back, thus, generating a street facade that systematically rises and falls. Such differences acknowledge the local character of streets. They also signal opportune adaptations of building mass to ease the free-flow of cooling summer breezes through the city.

The first project illustrates low-density housing on a fairly steep suburban site (Fig. 6, upper-left). The density range is 7–18 du/a with a corresponding $V/S$ range of 2.5–6.0. Individual units are in the 2–4 bedroom range or about 1350–2500 ft$^2$. The rules for generating solar envelopes call for guaranteeing 6 h of sunshine on a winter day and 10 h in summer for outdoor recreation and for gardening. Shadow-ing is allowed at any time below 8 ft at front and rear property lines, but is unlimited at side property lines, thus, allowing continuous street facades. The solar envelope presses hard against terraced designs to protect existing housing further down a west-facing slope.

The second project, located on a more gentle eastern slope of the same hill, nearly doubles the density (Fig. 6, upper-right). The range is 14–28 du/a with a related $V/S$ range of 3.9–6.2. All programmatic requirements for dwelling types, and also the solar envelope rules, are the same as for the first project. Design characteristics are similar to those on the west side of the hill. Also, portions of otherwise buildable volume are intentionally cut away and clerestories installed over stairwells to capture south sun for day-lighting and especially for winter heating. The solar envelope, as in the first project, clearly accentuates the downward tilt of the natural topography.

The third project increases density again, this time on an urban site near downtown (Fig. 6, lower-left). The density range is 38–72 du/a with an accompanying $V/S$ range of 6.4–9.4. The program calls for replacing dilapidated one-family dwellings, but not existing multiple-dwellings, with a market mix of units averaging 1000 ft$^2$. Parking is below grade on some lots, but is naturally ventilated. Higher urban property values justify a change of solar-envelope rules. Instead of 6 h of guaranteed solar access as in the first two projects, the modified rules here provide only 4 h. Shadow fences rise from 6 ft in the first projects to 10 ft, dropping at
side property lines as well as at front and back to allow the
free-flow of summer breezes.

Two European prototypes provide solar access and cross-
ventilation to individual units in apartment buildings (Fig. 7).
Higher densities in the US generally depend on “double-
loaded” corridors and mechanical systems. But in these
European designs, hallways systematically skip some floors
allowing units to pass freely both over and under for access
to light and air in opposite directions. Units are deeper when
facing E–W, shallower when facing N–S.

Finally, the fourth project, located on a hillside close to
downtown, achieves the highest densities of the 10-year
study (Fig. 6, lower-right). The density range is 76–128 du/a
with a matching V/S range of 7.9–10.5. Design requirements
for unit size and parking are the same as for the third project,
and the building sections diagrammed there are used here as
well. The solar-envelope rules for cut-off times are the same
as for the third project, but the space constraints have been
significantly altered. The solar envelope does not drop at
side property lines. Also, overshadowing is purposely
allowed on a north-facing slope that has been left open as
a park. Combined, these changes provide exceptional envel-
lope height and additional space for construction.

3.3. Study findings

A composite graph, representing all 150 student designs,
falls short of the full range of Los Angeles zoning but for two
different and opposing reasons (Fig. 8). The lowest density
of the study (7 du/a) is deliberate, the result of an initial

Fig. 7. Housing sections: the upper two sections, developed in Europe by Jacob Bakama and Le Corbusier, are best for E–W exposures. USC’s Solar Studio
adapted the two lower sections to be both shallower and internally arranged for N–S exposures where the winter sun enters from only one side.
4. Design potential

After completion of the housing study, the solar studio shifted direction. Instead of housing, the studio undertook the design of a library. The actual list of programmatic requirements came from the Los Angeles library planners. The spirit of the work relied more on a comment by Louis Kahn. He said about his own design for the Exeter Library, “you get a book and move toward the light”. He, thus, hints at what became the locus of the library study: a concept of architectural space that is both rhythmic and ceremonial.

4.1. The mama plane

A simple demonstration on the sun machine introduces the library study. An east–west facing wall accentuates a daily rhythm; shadows extend first to the west and then to the east, regardless of season. A north–south facing wall, on the other hand, will emphasize a seasonal rhythm; the shadow extends much farther northward in winter than in summer. Finally, if the wall faces diagonally to the cardinal points, the accents will be complex and contrapuntal. In each case, a person seeking either sunlight or shadow must repeatedly move through a gateway in the wall, a rudimentary rite of passage.

The wall gains architectural relevance when, instead of standing open on the sun machine, it lodges inside the solar envelope. By following strategic ridges, it can act as a source of form and space. Over time and seasons, it fills the empty space of the envelope with overlapping shadows. It, thus, acts as a theoretical generator, an allusion to invisible form. When the form becomes real, sunlight replays a series of rhythmic connections that can influence perceptions and actions. The wall, dubbed the “mama plane”, sometimes appears quite directly in the library study.

One design for a library develops a literal interpretation of the wall or mama plane (Fig. 9, left). Beginning with an initial plane, the designer cuts a “gateway” allowing sunshine to reach a second plane where the lighted area is removed. After a prescribed interval of time, sunshine passes through both gateways to a third plane where the lighted area is again removed. The designer continues this process throughout the course of a simulated day, interval-by-interval, until the final design embraces the entire set of planes. The designer’s intention in following this procedure is twofold. First, it will generate a system of transverse spaces. Second, on all future days, it will act in sunlight to recite the original sequence of connections with seasonal variations.

A second design for a library uses shadows cast from edges of the mama plane to create both the building and a garden (Fig. 9, right). The mama plane, with a diagonal orientation to the cardinal points, has thickness that serves as book storage, service, and circulation. To the south–west of the plane, morning shadows progressively mark off the terraces of a garden with parking below. To the north–east, afternoon shadows define the shapes of floor plates: one set on a winter day, alternate plates on a summer day. As with
the previous design, the creative process will automatically repeat over time.

4.2. Celebrating nature’s rhythms

“Rhythm itself is a mysterious fact of aesthetic experience”. Thus, Gross wrote about poetry, not architecture [8]. Yet he strikes a sympathetic chord when he goes on to say, “rhythm is the way our bodies and our emotions respond to the passage of time. Seasons recur, autumn follows summer” the following two library projects show how their separate designers have strengthened different natural rhythms by initiating space from the mama plane.

The first library project accentuates a diurnal rhythm (Fig. 10). The site yields a solar envelope and, hence, a mama plane, that stretches long in the north–south direction. The resulting design, by following this orientation, has a tall, long space with major exposures to east and west. Following the analogy of the garden wall, daily passages of the sun transfigure the space. Morning light, entering from the east, casts shadow patterns onto the opposing west wall. Midday light, entering from overhead, casts shadow patterns directly onto the floor. Afternoon light, entering from the west, casts shadow patterns eastward but not up onto the opposing wall where the designer is storing books. This sequence is experienced daily with little seasonal variation.

The solar envelope over a second library site has a north–south exposure that favors a seasonal rhythm (Fig. 11). The resulting design directs sunlight through fixed layers of colored glass, blending hues according to season as the sun passes from south to north and back again. Cool, blue light enters during summer; amber light colors the space in spring and fall; rose-colored light in winter. (The use of color, though admittedly questionable in a library, opens many design possibilities for other building types.)

The intention of the library studies is to advance a way of judging the aesthetics of buildings based on the appreciation of flux itself rather than on static composition. Toward that end, the library studies have examined rhythm as a medium of design, a universal means of touching experience and conveying meaning in our lives.

Louis Kahn alludes to perceptual enrichment by linking rhythm and ritual in the places we occupy. Close analysis of the way traditional societies have identified with their
environments also hints at the value of such a linkage for modern design. This is not to say that we should all return to primitive shelters, nor should we simply aim to describe solar phenomena by architectural means. The problem is more involved than that.

The places we occupy do need to reduce stress on our minds and bodies, but there is a real question of means. Does architecture have to hide from us every small variation that might repeatedly summon us to action? Something reassuring comes from matching our actions with the motions of nature. The something may remain forever unknown. Perhaps it is nothing more than the cyclic re-proportioning of our bodily fluids. More likely it is a reaffirmation of our own existence, a continuously repeating call for re-creation. Designers should neither trivialize nor underestimate this call.

5. Future work

The aim of our future work at USC is to link solar-access zoning more directly to the rhythms of nature. Early work on the solar envelope posited the importance of urban solar access for passive and low-energy architecture. More recent efforts have affirmed an architectural connection between rhythm and aesthetic experience. The purpose now is to connect energy and aesthetics in buildings by providing a dynamic framework for sustainable development.

While originally conceived by the author as a fixed volume, the solar envelope’s boundaries can actually cycle between extremes of season. Between the winter envelope and the generally higher summer envelope lies a region of active space that adjusts for modern programming and for adaptations to climate. Such adjustments can occur without denying year-round solar access to surrounding properties. Analyses drawn from nature and from vernacular architecture provide both a name and purpose for this region.

Physiology provides the name for such an active zoning space: “interstitium”. The interstitial space of the lung is that area of tissue between the alveoli (tiny air sacs) and the capillaries that carry the blood. During inspiration, the alveoli expand with air, and the interstitial space stretches into a very thin layer. In this way, alveoli and capillaries are brought into close proximity so the oxygen has less distance to travel in its diffusion from outer world (alveolus) to inner world (capillary) [9]. In its cyclicity, if not its direct function, the active space of the solar envelope resembles the interstitial space of the lung.

Some traditional building adaptations hint at modern architectural uses for the interstitium. In a paper delivered at the Twenty-first National Passive Solar Conference in 1996, Carrasco and Reynolds described how Carrasco’s own courtyard house in Bornos, Spain uses several rhythmic adjustments to nature [10]. Bornos is in southern Spain with extremely hot and dry summers where cooling is the major problem. The adjustments they described are complex and contrapuntal, modifying space both by day and by season.

One of the most appealing characteristics of Carrasco’s courtyard is the sound of water. Several small fountains echo softly in the resounding space. Additionally, a layer of absorbent brick covers the courtyard floor. This floor is capable of absorbing water, splashed on it during the watering of plants and deliberately sprayed for cooling several times daily.

In addition to water, Carrasco’s courtyard employs a movable horizontal white transparent canvas cover or toldo for shading (Fig. 12). The toldo casts shade over the whole patio during the hot summer day; at night it sweeps away to facilitate both ventilation and cold-sky radiation. Winter reverses the cycle. Open during the day to let sunlight flood
the winter patio, the toldo closes at night to hold the collected warmth.

Rhythmic adjustments of water and shade modify the quality and boundaries of courtyard space. The splashing water not only cools the courtyard but enhances the fragrance of flowers, heightens the activity of stray birds and draws children into a round of puddle-jumping games. The toldo provides desirable shade. It also changes the limits and color of space. Such repeated adjustments are more than habitual actions; they often evolve into ritual celebrations of life in a place.

Such instances of traditional adaptation have now set the stage for a thorough examination of the interstitium as an active zoning space. The research, to be carried out with students, will take place in USC’s Natural Forces Laboratory. Co-directed by Prof. Pierre Koenig, the program will make wind tunnel, sun machine, and computer studies to find ways of adapting the interstitial space for climate control.

Preliminary investigations made with Prof. Karen Kensek have already suggested ways that the interstitium can act as an adjustable shield, a zone of defense against climatic extremes [11]. Within its cycling boundaries, shading devices can rise and spread for summer cooling, lower and contract to admit winter sunshine. Such devices might be small as a parasol or large as a circus tent, operated manually or completely automated with a kinetic device responding to light and heat (Fig. 13).

Ventilation stacks can also follow interstitial boundaries, rising in summer to catch the cooling breeze, lowering in winter when no longer needed. Hence, the summer landscape unfolds with clusters of diamond-shaped sails or kites floating motionless and weightless above the rooftops. The winter landscape collapses inward, appearing lower and smoother than in summer. All such means are expansions of the way people have traditionally achieved comfort while conserving energy.

Architects may, thus, imagine a kinetic landscape. The winter scene has the lowest profile. Equinox brings an additional layer of architectural space. Finally, summer adds a third layer into which buildings can expand to complete the yearly cycle.

Seasons cycle. Nature reacts. Buildings also adjust. While solar-access zoning typically provides only a fixed image of the city, the interstitium of the solar envelope allows us to conceive of architecture in active terms: expanding and contracting; growing and decaying.

By so examining the influence of seasons on form and space, research in USC’s School of Architecture aims both to conserve energy and to reintroduce rhythm as a mysterious fact of aesthetic experience. The interstitium expresses and affirms that possibility.

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Fig. 12. Courtyard house in Bornos, Spain: the toldo adjusts by day and season, thus, rhythmically changing the quality and boundaries of space (photos, Reynolds (1996)).

Fig. 13. The interstitium as climate control: the interstitial space of the solar envelope lies between the low-winter boundary and the generally higher summer boundary (left); a diagram of the building’s winter mode has a lower, smoother profile with open courtyard to capture the sun (middle); the summer mode expands with the addition of wind scoops for ventilation and a sun screen to shade the courtyard (right).
6. Conclusions

Twenty years ago, the solar envelope was first proposed by the author as a zoning device to achieve solar access by regulating development within limits derived from the sun’s relative motion. Buildings within its boundaries will not shadow surrounding properties during critical energy-receiving periods of the day and year. Guaranteed solar access, thus, offers to society a chance to develop a renewable energy source; to architects it extends aesthetic possibilities based on the dynamics of sunlight. Recent studies now suggest that while originally conceived as a fixed space, the solar envelope’s size and shape can actually vary without denying year-round access to sunshine for energy and life quality. The resulting interstitial space of the solar envelope allows a building to change, decay, move or disassemble in response to the seasons. While solar-access zoning typically provides only a fixed image of the city, the interstitium allows architects to conceive a kinetic landscape driven by the rhythms of nature.

References