Orienting the Neighborhood: A Subdivision Energy Analysis Tool

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ABSTRACT

In subdivisions, house orientations are largely determined by street layout. The resulting house orientations affect energy consumption (annual and on-peak) for heating and cooling, depending on window area distributions and shading from neighboring houses. House orientations also affect energy production (annual and on-peak) from solar thermal and photovoltaic systems, depending on available roof surfaces. Therefore, house orientations fundamentally influence both energy consumption and production, and an appropriate street layout is a prerequisite for taking full advantage of energy efficiency and renewable energy opportunities.

The potential influence of street layout on solar performance is often acknowledged, but solar and energy issues must compete with many other criteria and constraints that influence subdivision street layout. When only general guidelines regarding energy are available, these factors may be ignored or have limited effect. Also, typical guidelines are often not site-specific and do not account for local parameters such as climate and the time value of energy. For energy to be given its due consideration in subdivision design, energy impacts need to be accurately quantified and displayed interactively to facilitate analysis of design alternatives.

This paper describes a new computerized Subdivision Energy Analysis Tool being developed to allow users to interactively design subdivision street layouts while receiving feedback about energy impacts based on user-specified building design variants and availability of roof surfaces for photovoltaic and solar water heating systems.

Background

Residential Street Patterns

Street patterns have evolved from early city plans and developed under various models of city planning (see Figure 1) (Southworth and Ben-Joseph 1997). Street patterns can be compared in terms of a range of metrics, including percent of area for streets, percent of buildable area, transportation efficiency, and walkability. Approaches such as new urbanism may revert to some aspects of traditional street layout. Different patterns of street layout may have different effects on building energy efficiency and utilization of renewable energy, but any street pattern will likely be amenable to improvement through redesign, although perhaps to varying degrees.

Figure 1. Evolution of Street Patterns since 1900 Showing Gradual Adaption to the Car

	Gridiron (c. 1900)	Fragmented parallel (c. 1950)	Warped parallel (c. 1960)	Loops and lollipops (c. 1970)	Lollipops on a stick (c. 1980)
Street patterns					

Solar Access and Street Orientations

In the 1970s, significant research was done on solar access (Knowles 1974) and the issues of protecting solar access for residential development (Jaffe and Erley 1979), solar access law (Hayes 1979), and site planning for solar access (Erley and Jaffe 1979). The emphasis at that time was on solar access for rooftop collectors for active solar and south windows for passive solar heating. Later work (Calthorpe 1993) asserted that strict solar orientation for buildings may be less important in mild, cloudy climates and that there are tradeoffs between solar access and other community planning objectives. Today, general guidelines are sometimes provided (Kone 2006): east-west streets are favorable, north-south streets are problematic.

Energy and Subdivision Design

For new construction, houses are typically built in subdivisions where street layouts largely determine the distribution of house orientations. Energy and peak demands for heating and cooling are functions of house orientation, window area distributions (front, back, left, right), and shading from neighboring houses. Orientations of solar hot water (SHW) collectors and photovoltaic (PV) arrays depend on available roof surfaces (front, back, left, right) and house orientation. Therefore, street layouts fundamentally influence both the energy efficiency and energy generation opportunities for houses in subdivisions.

Energy, however, is only one factor competing with many other criteria and constraints that determine street layout for a given subdivision. If only general guidelines are available regarding energy, they may be ignored or have limited effect. On the other hand, if energy impacts can be quantified interactively for specific subdivision layout alternatives, there is a better chance to influence the outcome. Although this information could be generated and analyzed manually, creating a tool to automate the process provides flexibility of inputs to the user and generates real-time feedback that is much more useful.

With this goal in mind, a new computerized Subdivision Energy Analysis Tool (SEAT) is being developed that will allow users to interactively design subdivision street layouts while receiving feedback on energy impacts. Potential users include developers, site planners, planning departments, utilities, government agencies, researchers, and educators. A wide range of information, both input and output, is needed to make such a tool relevant and useful in the real world. For example, the user will input specific house designs, climate, and a range of reference-case assumptions and constraints such as house design variants, roof surfaces available for solar, and minimum acceptable output levels. Real-time outputs (based on hour-by-hour building simulations run prior to the subdivision design session) will include lot-by-lot variant, PV, and SHW assignments as well as end use and overall energy savings. In this paper, we will discuss the particulars of this tool, its potential for use in sustainable community design, and issues of building energy use at the community scale.

Energy Impacts of Subdivision Design

All the effects described in this section will be explicitly calculated for each lot and house in SEAT. They are described here simply to elucidate cause and effect and to provide some background on expected trends. Street layout primarily affects energy use through orientation of windows and rooftop collectors and shading from neighboring houses (see Figure 2).

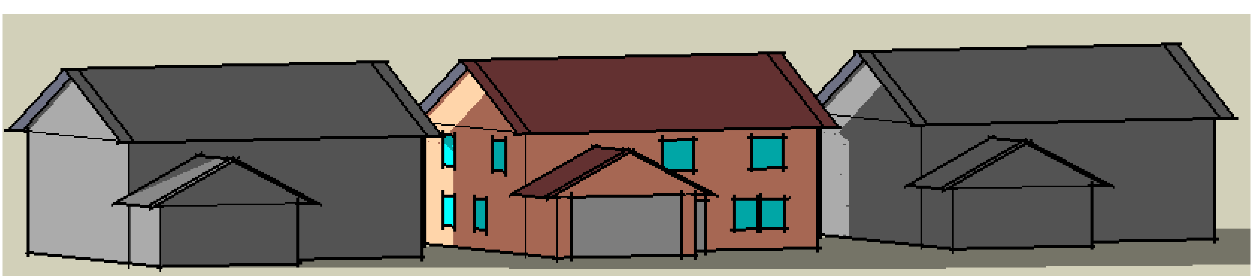
Heating

Heating energy is affected by solar gains through windows during the heating season, primarily as a function of south-facing window area, glass type (solar heat gain coefficient [SHGC]), overhangs to ameliorate summer overheating, and possibly thermal mass to store heat from day to night. Solar gains through south windows are significant, because the sun is low in the south sky throughout midday in winter. For east and west windows, solar gains in winter are more minimal because the sun rises south of east and sets south of west.

Cooling

Cooling energy is affected by solar gains through windows during the cooling season as influenced primarily by east and west window areas and glass type (SHGC). Solar gains through east and west windows are significant, because during the summer the sun rises north of east and sets north of west so that during the early morning and late afternoon and evening, solar radiation impinges directly on east and west windows, respectively. Because the sun is low in the sky during these times, overhangs or eaves do not provide effective shading.

Figure 2. House Geometry with Neighboring Houses Used for Shading Analysis



South windows have less impact on cooling energy use, because the sun is high overhead during midday so that incident angles are high and windows can be effectively shaded by overhangs or eaves. In climates where the cooling season extends into the spring and fall, the cooling impacts of south windows can become more important. Also, if south window areas are particularly large (for sun tempering or passive solar heating), cooling impacts increase from diffuse solar gains.

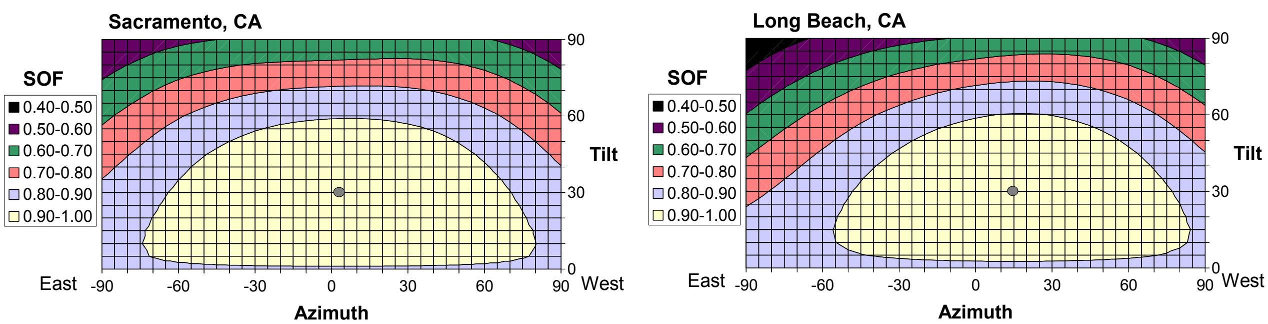
Shading from Neighboring Houses

Neighboring houses to the front or rear are typically too far away to cause shading. Neighboring houses to the left and the right, however, can cause significant shading. For houses on east-west streets, shading from neighboring houses occurs primarily during the summer when the sun is low in the eastern and western skies and can reduce air-conditioning energy use. For houses on north-south streets, shading occurs primarily during the winter when the midday sun is low in the southern sky and can increase heating energy use.

Photovoltaics and Solar Hot Water Production

PV and SHW production depends largely on the magnitude of incident solar radiation. Solar Orientation Factors (see Figure 3) (Christensen and Barker 2001) show the ratio of incident radiation for a surface with a particular tilt and azimuth compared to a surface oriented for maximum incident radiation. In terms of annual energy production, incident solar radiation is typically maximized for south-facing collectors (see Figure 3a for Sacramento, California). However, for some coastal locations, weather patterns that include the presence of morning fog

Figure 3. Solar Orientation Factor (SOF) Charts



lead to optimal collector azimuths somewhat west of south (see Figure 3b for Long Beach, California). This may seem counterintuitive, given that the fog comes from the ocean to the west. However, the shading occurs when the fog covers the entire sky at a given location and obscures the sun to the east in the morning. Conversely, clear afternoons allow solar collection when the sun is in the western sky.

For PV and SHW, relatively low tilt angles (say, at roof tilt) can be used because much of the energy is collected during the summer. At these low tilt angles, collector azimuths can differ significantly from due south with little reduction in performance. For example, in Fresno, with a collector tilt of 25 degrees (mounted flush on a 5:12 roof), collector azimuths up to 75 degrees west of south and 70 degrees east of south suffer only a 10% reduction in annual incident radiation. The sensitivity of performance to collector azimuth increases for steeper collector tilt angles.

Time-of-Use and Time-Dependent Valuation

Energy consumption and production have traditionally been evaluated based on annual results with every hourly value equally weighted. However, at a more detailed level, the timing of consumption and production (hour-of-day and day-of-year) is also important. This is reflected in time-of-use (TOU) utility tariffs that approximately indicate to a ratepayer the cost of energy at different times. On a policy and societal level, California's Title 24 building energy standards use time-dependent valuation (TDV) hour-by-hour factors (Price 2002) to weight electricity (see Figure 4) and natural gas consumption at every hour of the year. Where the use of TOU or TDV factors is appropriate, these multipliers will play an important role in evaluating the effects of building orientation (and street layout). TOU tariff rates (based on time-of-day and seasonal time blocks) have lower resolution than hour-by-hour TDV factors. The overall trends, however, will be similar with high values for electricity during the summer and particularly during afternoon and evening hours.

Figure 4. Hourly Electricity TDV Factors

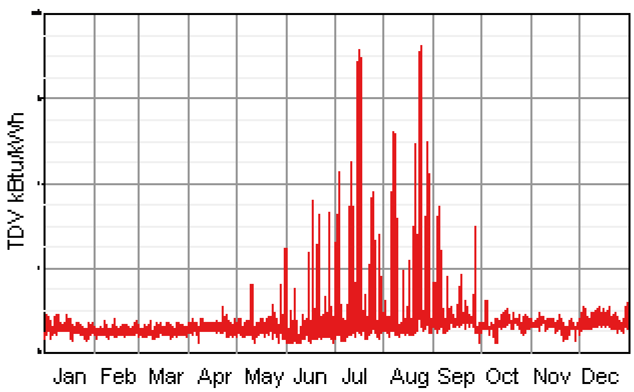
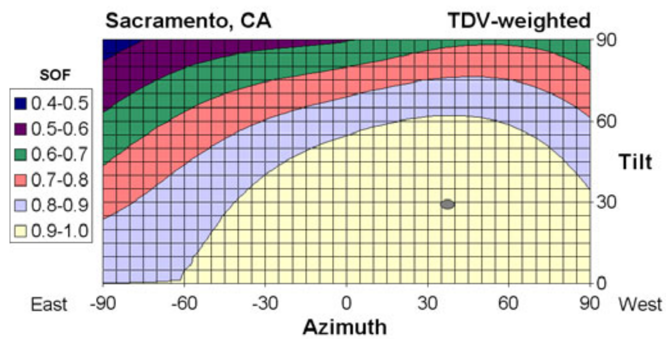


Figure 5. TDV-Weighted SOF Chart



When annual TDV-weighted energy rather than total annual energy is used, collectors facing west of south may be optimal because of the extra weighting for afternoon and evening energy production during the summer (see Figure 5). Similarly, with annual TDV-weighted energy and electricity-driven cooling, unshaded west windows will have a more negative impact than east windows because of the extra weighting for afternoon and evening cooling energy use.

Subdivision and Building Parameters

Neighborhood Areas

Within a subdivision, different neighborhood areas, distinguished by lot size and house plans, may be selected for separate energy analysis followed by aggregation of the results into subdivision totals.

House Plans

For a particular area within a subdivision, a builder will typically offer a number of house plans (distinguished by floor plans, square footage, number of bedrooms and bathrooms, etc.) for sale. Although such plans will not typically be intentionally designed for different lot orientations, the energy performance of different plans may have different sensitivities to orientation. However, the number of houses built to certain plans will often be determined by the expectations of sales and other non-energy factors. Therefore, these numbers will usually be treated as constraints in subdivision energy analysis.

With specified numbers for particular house plans, there remains the assignment of house plans to particular lots. This may also be constrained, say to a more or less uniform distribution based on expected sales or a desire for architectural diversity (avoiding too many identical house plans adjacent to each other). However, if house plan assignment is not constrained, plans may be assigned to lots based on their orientation sensitivities to optimize overall subdivision energy performance.

Design Variants

Orientation-specific variants of house plans can be designed to achieve energy efficiency on particular lots while maintaining the general architectural appearance of the original house plan. For example, specifying different glass properties for windows would create a variant that that would be visually indistinguishable from the original plan but would have potential heating and cooling energy savings if assigned to appropriate lot orientations.

Other variants, such as changing the distribution of window areas or use of overhangs or fins on different sides of a house plan, may have acceptably minor changes in visual appearance and still offer heating and cooling energy savings. To the degree that variants are visually acceptable and interchangeable in their assignments to particular lots, they can be optimally assigned within a subdivision area to achieve energy efficiency over a range of lot orientations.

Roof Surfaces

Roof surfaces are house plan dependent. For a given house plan, the floor plan may determine the direction of ridgelines, with the roof style dictating the direction and tilt of roof surfaces. For example, a simple floor plan with a side-to-side ridgeline and a gable style roof would have front and back roof surfaces only. A hip style roof would have front, back, left, and right roof surfaces. Aside from the roof surface areas, availability for rooftop solar (PV and/or SHW) may be limited by issues such as aesthetic acceptability of placing collectors on a particular roof surface (say, the front roof).

Algorithms and Calculations

Simulations

In SEAT, the energy-related results of subdivision design will be based on detailed hour-by-hour simulations for individual house plans, variants, and possibly PV and/or SHW. For example, if 4 variant strategies are applied across 5 house plans, 20 building designs will need to be simulated. Each design will be simulated across a range of orientations (say, at 12 compass directions) and require 240 simulations for plans and variants. Additional simulations will be required to evaluate the performance of possible PV and SHW systems as a function of orientation (say, at 12 compass directions), and require 24 simulations for solar systems.

Therefore, 264 simulations will be required, which at approximately 6 seconds each would require about 30 minutes of computational time. If more plans or variants or solar systems are evaluated, or if other areas in a subdivision have different plans, more computational time will be required. In any case, these simulations will likely be pre-run to prepare a dataset for use during an interactive subdivision design session.

Simulations will be run with a building energy simulation program such as BEopt (Christensen et al. 2006). For each building plan, design variant, PV system, and SHW system, inputs will include a full set of characteristics sufficient for simulation.

Orientation Factors

The results of simulations will be displayed as orientation factors. For PV or SHW, the orientation factor equals the energy production at a given collector orientation. For heating or cooling energy use, the orientation factor is equal to the energy consumption at a given building orientation. In SEAT, orientation factors will be displayed for heating and cooling for each design variant and for PV and SHW (see Figure 6). The numerical value on each orientation factor chart indicates the full-scale value in TDV energy units.

Total orientation factor curves (see Figure 7) show net consumption based on orientation factor values (from Figure 6). At each orientation, heating and cooling values for the assigned design variant are added, and SHW and PV values are subtracted. Availability of variants, PV and SHW depends on user inputs as described in the Inputs and Outputs section, and assignment to lots is described in the next section. The curves in Figure 7 differ based on the roof surfaces available for SHW and PV: (a) none, (b) front, and (c) front and back. The depression in the curves at north orientations is caused by savings from a Passive Solar variant with extra glazing

Figure 6. SEAT Orientation Factors

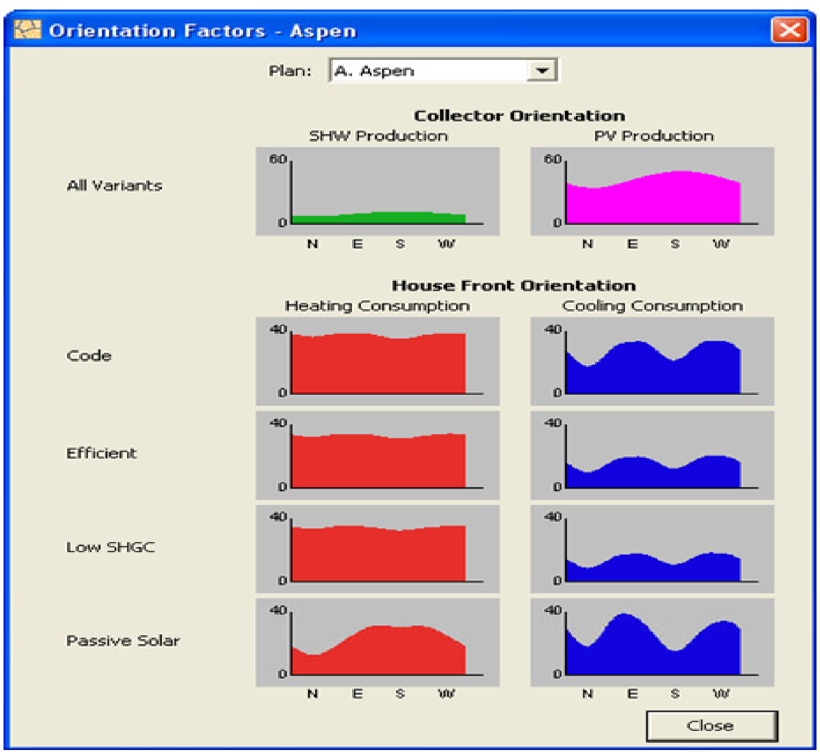
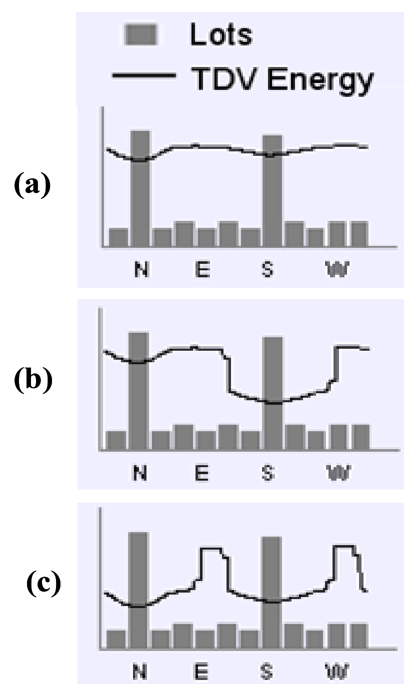


Figure 7. Lot Orientations and Total Orientation Factors



area on the back of the house. Total subdivision energy consumption will be calculated by multiplying the number of lots at each orientation times the corresponding total orientation factor. So, the best design strategies will involve street layouts that align the most lots with low points in the total orientation factor curve.

Assignment to Lots

As a street layout is drawn or modified, each lot will be assigned a plan, a variant, and possibly PV and/or SHW.

House plans will typically not be assigned to optimize energy use/production, but rather according to the expectations for spec building or sales. One option will be to assign house plans in a cyclic fashion according to the proportion inputs. For example, if inputs call for three house plans (A, B, C) in equal proportion, then every third lot along a street would be assigned a different house plan (ABCABC…). Other options will allow specific plans to be assigned to particular street segments, sides of the street, or individual lots.

User-selected available variants will be assigned dynamically to achieve optimal energy performance as a street layout is drawn or modified. For each lot, available variants of a house plan will be evaluated to identify the single variant that will optimize the objective function (e.g., minimum TDV-weighted energy). Similarly, PV and SHW systems will be assigned optimally to available roof surfaces as a street layout is drawn or modified. A minimum energy output may be specified to ensure that PV or SHW systems are assigned only are sufficiently cost effective.

If inputs specifying the availability of variants and roof surfaces are modified after a street layout has been drawn, then assignments of design variants, PV, and SHW will be dynamically updated on the lots shown on the street layout, and the energy results will change accordingly.

Reference Case

TDV energy savings will be calculated relative to a user-specified reference case. Variants and roof surface availability for PV and/or SHW will be specified for each house plan. For lot orientation distribution, the user will be able to set the reference to certain nominal distributions such as 'uniform' or 'grid' or equal to the distribution of a particular drawn street layout. A fully user-specified reference will facilitate flexible use across a wide range of users and situations. For example, a developer or builder might compare a new subdivision design to a previous design, or a municipality might establish a reference case to set a standard for incentives such as fast-tracking.

Inputs and Outputs

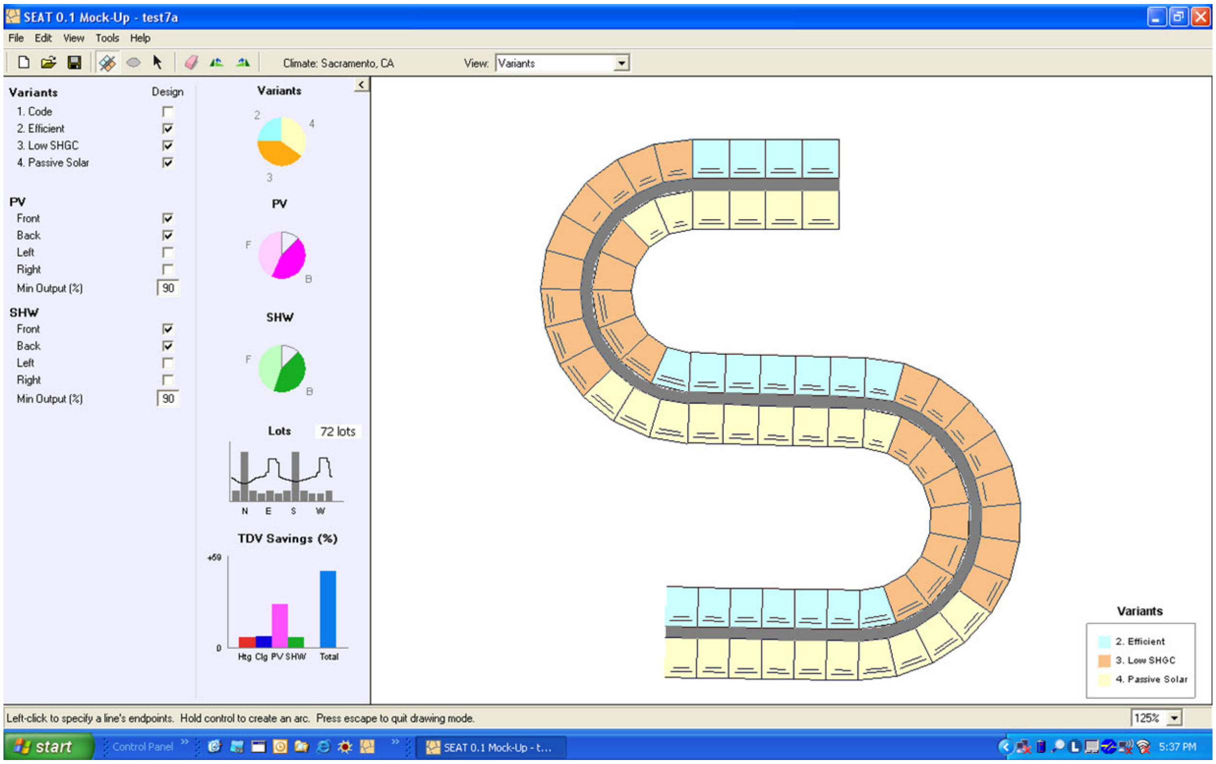
Simulation-related inputs for plans, variants and PV and SHW systems were described in the Simulations section. A user will supply those inputs before running the simulations separate from the interactive process of subdivision energy design. The following inputs, on the other hand, will be executed during subdivision energy design.

Figure 8 shows the main screen for SEAT. On the left, the input panel shows inputs for the current design case. The drawing screen allows a user to draw/modify a street layout. The output panel includes a series of charts showing results based on the current inputs and street layout.

Input Panel

The user will indicate (via check boxes) the availability of variants and the availability of roof surfaces (front, back, left, right) for PV and/or SHW. The user will also enter minimum

Figure 8. SEAT Input/Output Screen



output values, so that PV and/or SHW systems will not be assigned to roof surfaces with orientations so sub-optimal that output is below the minimum.

Drawing Screen

The main drawing screen allows the user to draw/modify a street layout and see the results change dynamically in the output panel. The drawing screen can also show different views of results with lot-by-lot color coding, including: 1) variant assignments, 2) net consumption, 3) heating consumption, 4) cooling consumption, 5) PV production, and 6) SHW production. Calculations will be based on the underlying assignment of specific plans to lots, but the user may choose output views that are either plan-specific or averaged. Assignments of PV and SHW systems to roof surfaces are shown by indicator lines on lot sides. PV is shown by indicators closest to the perimeter and SHW shown by indicators nearer to the center of the lot.

Output Panel

As the user changes inputs, the effect is seen in the total optimal orientation factor curve, and as the user draws a street layout, bars indicate the number of lots at different orientations (Figure 6b). As the user draws a street layout or changes inputs, pie charts in the output panel dynamically show the proportions of variant assignments and PV and SHW assignments. Finally, a bar chart shows TDV-weighted energy values for reductions in heating and cooling consumption and for increased PV and SHW production and total reduction in net consumption. The values are: 1) averaged across all lots, 2) relative to the reference case, and 3) percentages of total average TDV-weighted household energy use (including uses such as appliances and lighting that are not orientation sensitive). Positive values indicate savings relative to the reference case: either reduced consumption or increased production.

Input Modes and Use Scenarios

SEAT can be used in various modes depending on design phase: 1) draw mode as described above for conceptual and preliminary design, allowing the user to draw a new street layout with specifications for minimum lot size, etc., and 2) trace mode for evaluation, allowing the user to trace an existing street layout. The input and output capabilities of the tool can be used to discern: 1) the impacts of street layout (while keeping variants and roof availability constant), 2) the impacts of design variants and roof availability (while keeping street layout constant), or 3) the combined impacts of street layout, variants and roof availability.

Example Results

Figure 8 shows results for an example subdivision energy analysis for Sacramento, California. The analysis assumes 2-story single-family-detached houses 10 feet apart using natural gas for space and water heating. The Efficient variant has energy specifications somewhat better than the IECC 2006 code (International Code Council 2006.) and a window area distribution of 20%, 40%, 20%, 20% on the front, back, left, and right sides of the house. For the Low SHGC variant, all windows have low solar heat gain coefficient (SHGC) glass. The Passive Solar variant has a window area distribution of 10%, 70%, 10%, 10% on the front, back, left, and right sides of the house, high SHGC glass, and increased thermal mass.

The reference case for this example includes a Code variant with energy specifications approximately equivalent to IECC 2006, no roof surfaces available for PV or SHW, and a uniform distribution of lot orientations.

Output Panel Results

For the inputs and sample street layout shown in Figure 8, the output panel shows the Efficient, Low SHGC, and Passive Solar variants assigned to 19%, 49%, and 32% of the lots, respectively. Approximately 86% of the lots have PV and approximately 85% have SHW. Consistent with the example street layout, the lot orientation distribution shows some lots at all orientations with a concentration of lots at north- and south-facing orientations. The TDV Savings chart shows reductions in heating and cooling consumption and increases in PV and SHW production, as percentages relative to the reference case consumption.

Variant Assignments

Figure 9 shows variant assignments for various variant availability choices. When only the Efficient variant is available (Figure 9, left), it is of course assigned to all lots. When the Low SHGC variant is also available (Figure 9, middle), it is assigned to lots where front/back windows (unshaded by neighboring houses) face east-west. Reduced solar gains for these lots lead to cooling savings that outweigh any increase in heating. When a Passive Solar variant is also available (Figure 9, right), it is assigned to lots where the back of the house (with most of the window area) faces from southeast to southwest. Figure 10 shows heating consumption for various variant inputs, and Figure 11 shows cooling consumption for various variant inputs.

Figure 9   Variant Assignments for Various Variant Choices

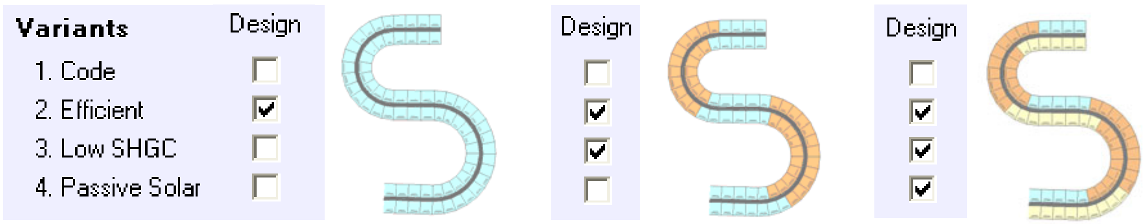


Figure 10 Heating Consumption for Various Variant Choices

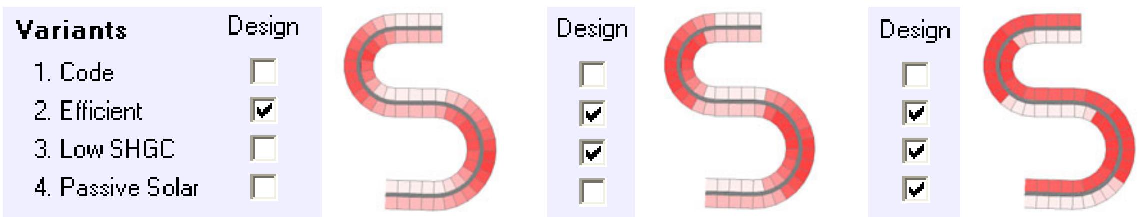


Figure 11   Cooling Consumption for Various Variant Choices

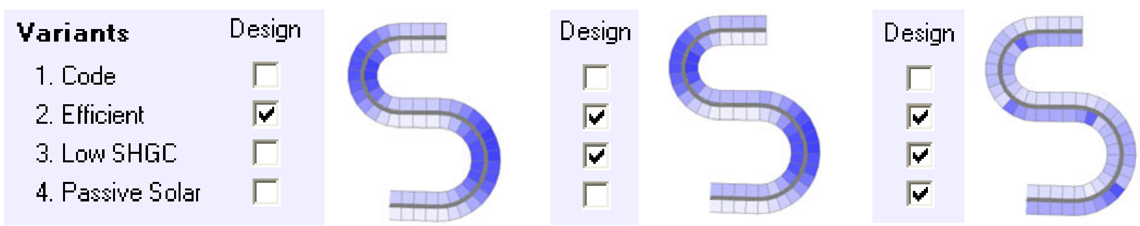


Figure 12   PV Roof Assignments for Various PV Roof Surface Availability Choices

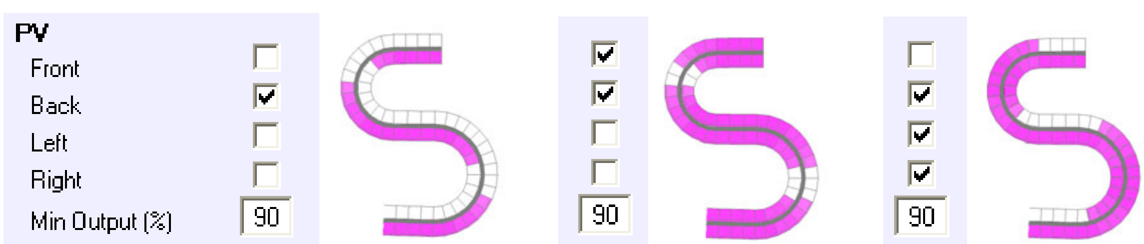
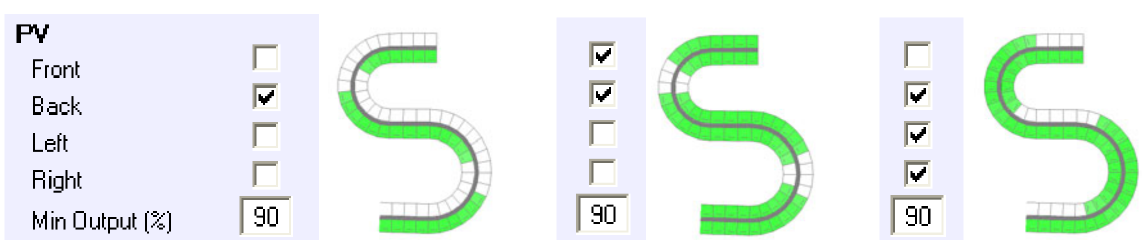


Figure 13   SHW Roof Assignments for Various SHW Roof Surface Availability Choices



PV Assignments

Figure 12 shows PV assignments for various roof availability choices. When only back roofs are available (Figure 12, left), PV is assigned to lots where the back roofs face from southeast to west. The bias towards west is due to increased TDV weighting of PV production during afternoon/evening hours during the summer. The shift would be larger except that PV efficiency is reduced during the afternoon when ambient temperatures are high. When both back and front roofs are available (Figure 12, middle), PV is assigned to the lots across the street from those in Figure 12a, essentially doubling the number of PV installations. When back and side roofs are available (Figure 12, right), PV is assigned to nearly all lots. When front, back, and side roofs are available (not shown), PV is assigned to all lots. Of course, PV arrays on different roof surfaces (front, back, left, right) may be of different sizes based on available roof areas.

Solar Hot Water Assignments

Figure 13 shows SHW assignments for various roof availability choices. The results are similar to the PV assignment results, but with a small shift from south toward west. The shift is likely caused by less available solar radiation during winter mornings in Sacramento. The shift is not due to TDV factors, because water heating is assumed to use natural gas, and TDV factors for gas are nearly constant throughout the year.

Summary

A new computerized Subdivision Energy Analysis Tool is being developed to allow users to interactively design subdivision street layouts while receiving feedback on energy impacts including energy consumption for building heating and cooling along with energy production by solar hot water systems and photovoltaic systems. Potential users include developers, site planners, planning departments, utilities, government agencies, researchers, and educators. A wide range of information, both input and output, will be included in an attempt to make the tool relevant and useful in the real world. For example, the user will input specific house designs, climate, and a range of reference-case assumptions and constraints. As the user draws a street layout, real-time outputs (based on hour-by-hour building simulations run prior to the subdivision design session) will include lot-by-lot assignments of house design variants, PV systems, and SHW systems as well as end-use energy and overall energy savings. Time dependent valuation or time-of-use rates will be used to account for the time value of energy.

Future Work

This preliminary version of SEAT will be user tested, and suggestions will be solicited from domain experts. Anticipated enhancements include modifications to handle corner lots, cul-de-sacs, shading effects from neighboring houses of different sizes, shading from trees including growth over time, PV arrays on multiple roof surfaces per house, and variable PV array sizes as a function of roof area. Additional capabilities will include zoom, pan, select, and editing of street layouts. Additional outputs will include economics, site energy, energy demand, source energy, and carbon emissions.

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