TOWARDS THE BUILDING AS POWER PLANT: COMPUTATIONAL ANALYSIS OF BUILDING ENERGY SELF-SUSTENANCE

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ABSTRACT

In recent years there have been a number of research and development initiatives directed at integrated energy generation systems which can meet the energy requirements of a building substantially or even completely on-site. With the appropriate integration of passive and active technologies, it may even be possible for buildings to be net exporters of energy - the "Building as Power Plant".

This paper focuses on the computational modeling of such systems. We begin with an overview of the concept, motivation and objectives of the Building as Power Plant. We then define and describe indices for building Energy Self-Sustenance (ESS), which take into account the degree of "fit" between energy supply and demand profiles. Through a series of illustrative examples, we demonstrate the use of these indices to support the analysis of alternative design options for the Building as Power Plant.

In the latter part of the paper, we propose and outline a Building-as-Power-Plant design support tool, which will allow users to evaluate the energy self-sustenance of a building. This tool will build upon existing energy simulation tools, extending them to include the analytical simulation of current and emerging building-integrated energy generation systems.

INTRODUCTION

The development of systems and technologies to reduce energy use has been an important area of research and development in the building industry, particularly since the energy crisis of the mid-1970s. Broadly speaking, there have been two strategic and complementary thrusts for building energy effectiveness:

1. *Reducing building energy requirements:* This includes the use of "passive" approaches, such as higher insulation, and the use of daylight and natural ventilation.
2. *Use of sustainable energy systems:* This includes the use of advanced energy generation and storage technologies to meet building energy requirements, with a particular emphasis on renewable energy sources. Examples of these "active" systems include solar-powered heating and cooling, and photovoltaic arrays.

With regard to the second thrust, in recent years there have been a number of research and development initiatives directed at integrated energy generation systems which can meet the energy requirements of a building substantially or even completely on-site, particularly through the use of renewable energy resources. Manifestations of such systems include building-integrated photovoltaic systems (Humm and Toggweiler 1993), and high-efficiency co-generation systems. In the U.S. there has been a growing interest in distributed generation, particularly in the context of utility deregulation. It is projected that up to 20% or more of all new generating capacity built in the U.S. could be for distributed applications (Moore 1998). Some have surmised that with the appropriate integration of passive and active technologies, it is even possible for buildings to be net exporters of energy - the "Building as Power Plant" (Hartkopf et al. 1998). This approach also holds much promise for the current and projected energy needs of rapidly industrializing countries, with the corresponding pressure on global energy resources and environmental quality. Building integrated energy systems that maximize the use of renewable technologies may have the potential to significantly alleviate these circumstances.

Parallel to the above-mentioned research in energy-efficient building systems, there has also been considerable research in computational tools to model the energy use of buildings, resulting in a broad array of analysis tools. Most of these tools are directed at the first thrust of energy-effectiveness mentioned earlier i.e. reducing building energy requirements. A few of these tools can also model energy systems (e.g. DOE-2 can model various co-generation systems). Other stand-alone tools have been developed for specific energy systems (e.g. PV-DesignPro for modeling the electricity generation from photovoltaic arrays). With the increasing interest in distributed generation, it imperative to initiate efforts to extend current modeling tools to encompass the modeling and evaluation of emerging energy generation technologies for buildings. These extended models should allow building designers to evaluate the overall energy "self-sustenance" of a building i.e. not only the energy needs of buildings, but also the energy generation potential of buildings using technologies such as building-integrated photovoltaics and "energy cascade" systems.

In the remainder of this paper, we introduce an index for, and describe the analysis of building energy self-sustenance, using illustrative examples from parametric simulation studies of an office building in different climatic contexts. We then present the objectives and approach to a computational energy self-sustenance evaluator that builds on current and emerging energy analysis tools.

ENERGY SELF-SUSTENANCE INDICES

The effectiveness of various generation options for a particular building configuration and context depends on the generation capacity as well as the degree of fit between the demand profiles and generation profiles. As such, energy self sustenance (ESS) indices can be defined for different energy measures (e.g. building load, secondary system energy use, end-energy use). To illustrate this, we describe below ESS indices based on end-energy use. The site energy self-sustenance of a building configuration, for end-energy type *x*, is defined as:

$$ESS_x = \frac{\sum_{t=1}^{n} disp_{x,t}}{\sum_{t=1}^{n} dem_{x,t}} \qquad [-]$$

where:

ESS_x: site ESS for energy type x

$disp_{x,t}$: energy displaced by generation system, for energy type x at time t

$dem_{x,t}$: energy demand of building without generation, for energy type x at time t

n: total number of time steps in a year

"Energy demand" ($dem_{x,t}$) in this context refers to the end-energy demand of the building configuration if *no* generation system were used. The energy displaced by the generation system ($disp_{x,t}$) has three components: *1)* the energy that was generated/stored by the system and utilized to meet building demand; *2)* energy used by the generation system, if any (e.g. a cogeneration system uses auxiliary electrical energy); and *3)* reduction in the energy demand itself, if any (e.g. the use of a cogeneration system reduces boiler electric demand). Therefore:

$$disp_{x,t} = gen_{x,t} - use_{x,t} + red_{x,t} \qquad [\text{kWh}]$$

where:

$gen_{x,t}$: generated/stored energy utilized to meet building demand for energy type x at time t

$use_{x,t}$: energy type x used by the generation system at time t

$red_{x,t}$: reduction of building demand, for energy type x at time t

In addition to the ESS for each energy type, an overall ESS_T, which totals all site energies can also be defined. Furthermore, a source energy ESS (ESS') can also be defined, which takes into account source-site efficiency for each energy type.

We define a utilization efficiency for each type of energy *x* from a generation system *g* ($U_{g,x}$), as follows:

$$U_{g,x} = \frac{\sum_{t=1}^{n} gen_{x,t}}{\sum_{t=1}^{n} GEN_{x,t}} \times 100 \qquad [\%]$$

where:

$gen_{x,t}$: generated/stored energy utilized to meet building demand for energy type x at time t

$GEN_{x,t}$: energy type x generated at time t

Given these definitions, the following features of the above ESS indices bear mention:

- Typically, an "optimal" scenario, from a self-sustenance standpoint, would be one that has an ESS_T of 1 *and* a utilization efficiency of 100%.
- ESS can be negative. For example, a cogeneration system may increase electricity ESS, but may increase net fuel use when compared to the building without cogeneration.
- ESS is a relative index. The ESS for a particular combination of building configuration and generation system is defined relative to the building configuration sans generation system.
- Since ESS is a relative index, it a complement to, and not a substitute for absolute measures such as total site and source energy use. Indeed, a holistic evaluation of a generation system should include indices beyond energy itself, particularly life-cycle costs and environmental impact indicators.

ANALYSIS OF SELF-SUSTENANCE: ILLUSTRATIVE EXAMPLES

Overview

The following analysis is drawn from a comprehensive simulation study of the "Building as Power Plant", specifically the impact of advanced, "intelligent" enclosure, lighting, and HVAC systems in office buildings. The prototype mid-size office building has a rectangular geometry (52m x 18m) with the longer sides facing north-south. The building has a total area of 5685m^2 (about 950m^2 per story). Window area is approximately 50% of the facade area. The geometry and occupancy characteristics of the building are based on ASHRAE Standard 90.1 (ASHRAE 1989).

Parametric simulations were carried out for different climatic contexts and enclosure, HVAC, and lighting options, as shown in table 1. Table 2 shows the energy generation options that were considered for this study. The studies were carried out for climatic contexts in North America (Pittsburgh, San Francisco, Los Angeles, Houston) and South-east Asia (Singapore and Bangkok).

The simulations were done using DOE-2.1E. A spreadsheet-based post-processor application was developed to determine the ESS indices, based on detailed hourly data output from DOE-2.1E.

Numerous combinations of the various building systems and energy generation options were considered for this study, and a detailed analysis of the results is beyond the scope of this paper. Rather, we will focus here on the energy self-sustenance analysis of a sub-set of the results. Figure 1 indicates the end energy use at site and source for selected building configurations. The trends correspond to findings in other, similar simulation studies (e.g. Mahdavi et al. 1995). However, the heating loads and impact of daylight-based dimming are more pronounced in this building, given its greater perimeter compared to typical office buildings in the North American context.

Marginal trade-off between PV and solar collector

Figure 2 shows the electrical energy self-sustenance (ESS$_e$) and total self-sustenance (ESS$_T$) for selected building configurations integrated with various solar generation options (see again table 2). As expected,

TABLE 1: Parametric building system options for the simulation study

Enclosure	Lighting	HVAC
E1: Walls - 10 cm fiberglass; Roof - 15 cm fiberglass; Windows - tinted double glass. E2: Walls - 15 cm fiberglass; Roof - 25 cm fiberglass; Windows - tinted low-e double glass. E3: E2 except Windows - high-perf. low-e clear double glass E4: E3 w/ 0.9m window overhang	L1: Combined task-ambient lighting @ 17 W·m^{-2} L2: Split task-ambient lighting @ 11 W.m^{-2} L3: L2 + daylight-based continuous dimming (setpoint @ 500 lux)	H1: Packaged VAV H2: Built-up VAV w/ electric chiller and hot water boiler H3: Built-up VAV w/ absorption chiller and steam boiler

TABLE 2: Energy generation options for solar and co-generation systems

Solar	Co-generation
S1: Photovoltaics on roof (effective area = 50% of roof area) S2: S1 + Photovoltaics on opaque area of south-facing walls S3: S1 + Photovoltaics on opaque area of south, east, and west facing walls S4: Solar concentrating collectors on roof (effective area = 50% of roof area) + Photovoltaics on opaque area of south, east, and west facing walls	G1: 50 kW gas turbine running at max capacity G2: 50 kW gas turbine tracking thermal demand during HVAC on-hours G3: 100 kW gas turbine tracking thermal demand during HVAC on-hours

Notes: Photovoltaics efficiency = 10% of total insolation; Collector efficiency = 50% of direct insolation; Collector system efficiency = 80%. Combined solar-cogeneration systems were also studied, and are annotated as SxGy (e.g. S1G2, etc.)

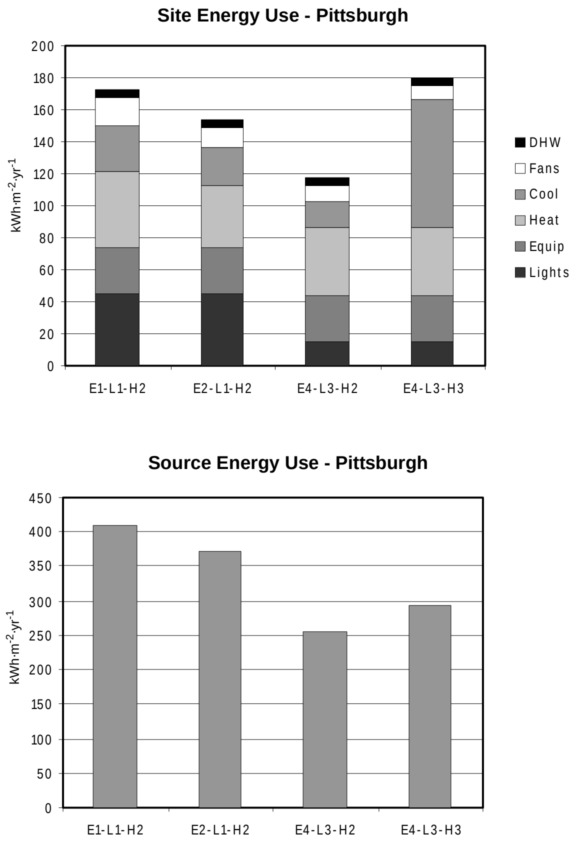


FIGURE 1. Site and source energy use for different building configurations, for Pittsburgh climate. See table 1 for system option codes.

the increase in PV area from options S1 to S3 causes a corresponding increase in ESS_e. Among the various building configurations, the largest marginal increase in ESS_e occurs as a result of clear high-performance glass with daylight-based dimming (E4-L3-H3). These trends were similar for other climates studied. S4 is a combination of electricity generation from PV and hot-water generation from concentrating collectors. The absence of roof-mounted PV in S4 causes a drop in the ESS_e, although the ESS_T is approximately the same as that of S3. Figure 3 shows the utilization coefficients for the same cases. PV utilization efficiencies are high. An analysis of the daily profiles indicated that PV electricity is fully utilized on weekdays, and under-utilized only on sundays, which in turn suggests that a 24-hour storage system would bring the utilization factor close to 100%. The utilization efficiency of generated hot water from the solar collector in option S4 is very low, due to a seasonal mismatch of supply and demand i.e. generation is high in the summer months, when the demand is very low (essentially for domestic hot water only). Figure 4 illustrates this mismatch, which could be alleviated through the use of seasonal storage systems.

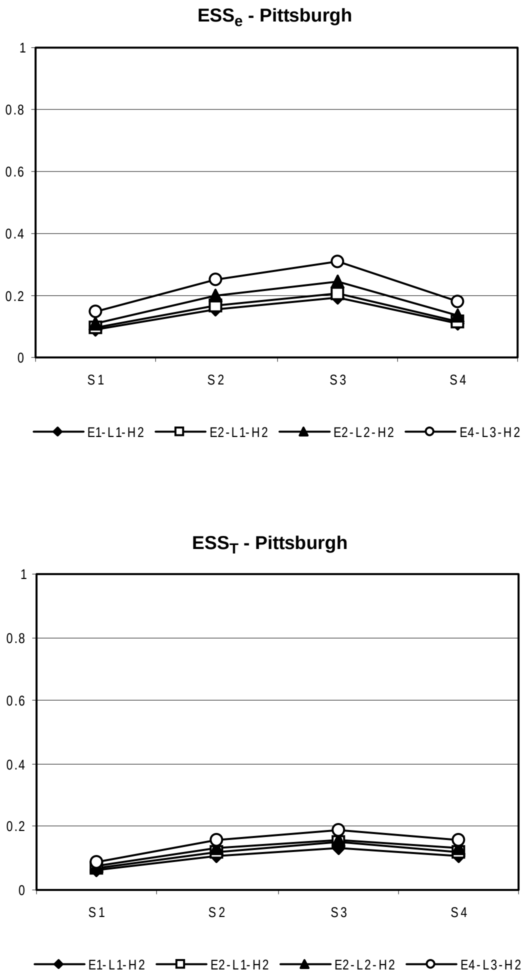


FIGURE 2. ESS_e and ESS_T for different building configurations and solar generation options in Pittsburgh climate. See tables 1 and 2 for system option codes.

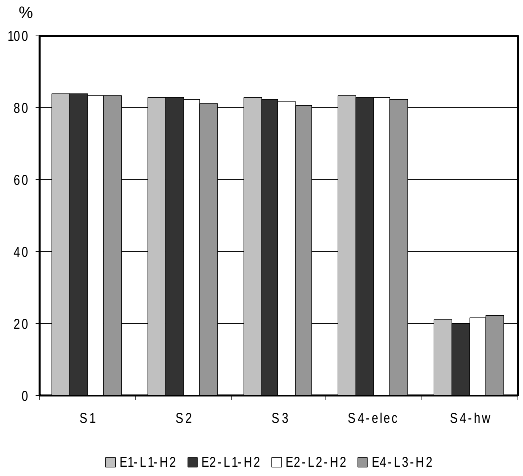


FIGURE 3. Utilization efficiencies for different building configurations and solar generation options in Pittsburgh climate.

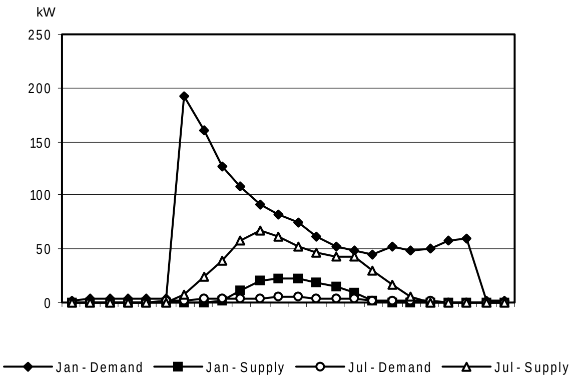


FIGURE 4. Hot water demand and supply profiles in January and July, for building configuration E4-L3-H3 and solar option S4, Pittsburgh climate.

Impact of chiller type on ESS

Absorption chillers create a demand profile for hot-water that typically follows the generation profile of solar collectors. Figure 5 indicates the ESS_T for building configurations with electric (E4-L3-H2) and absorption (E4-L3-H3) chillers, for different solar generation options, and in different climatic contexts. For options S1-S3 the ESS_T of the absorption chiller option is lower than the electric chiller, which has a much higher coefficient of performance (COP). However, for option S4, the ESS_T for the absorption chiller almost doubles, and surpasses that of the electric chiller, essentially because the generated hot-water compensates for the low COP of the absorption chiller. This effect is particularly pronounced in San Francisco, where the direct solar radiation (needed for concentrating collectors) is relatively high, while the cooling-season climate is fairly mild. The S4 hot water utilization coefficients for the absorption chiller option are 60-80% compared to 10-20% in the electric chiller option.

Impact of co-generation on ESS at site and source

Co-generation systems can increase ESS_e to any desired level by selecting the appropriate generator size. However, the total self-sustenance of a co-generation system at site (ESS_T) and source (ESS'_T) is largely dependent on the degree to which the waste heat can be utilized to offset fuel-based heating demand. Figure 6 shows ESS indices for a 50kW thermal-tracking co-generation system (option G2 in table 2) in the Pittsburgh climate, for electric (E4-L3-H2) and absorption cooling (E4-L3-H3) cases. The ESS_e is higher for absorption cooling option, since it creates a greater thermal demand than the electric chiller option, thereby generating more electricity. The ESS_T for both options is negative, indicating that the generated electricity does not offset the fuel use by the cogeneration system. This is largely because the cogeneration system is inefficient at part-load operation. However, the ESS'_T is positive, a consequence of the low source efficiency of utility electricity (0.33), when compared to natural gas (1.0). Note that all the solar options S1-S4 have a higher ESS_T and ESS'_T than the co-generation option G2 in this context (cp. figure 2). This trend was also found in other climates studied.

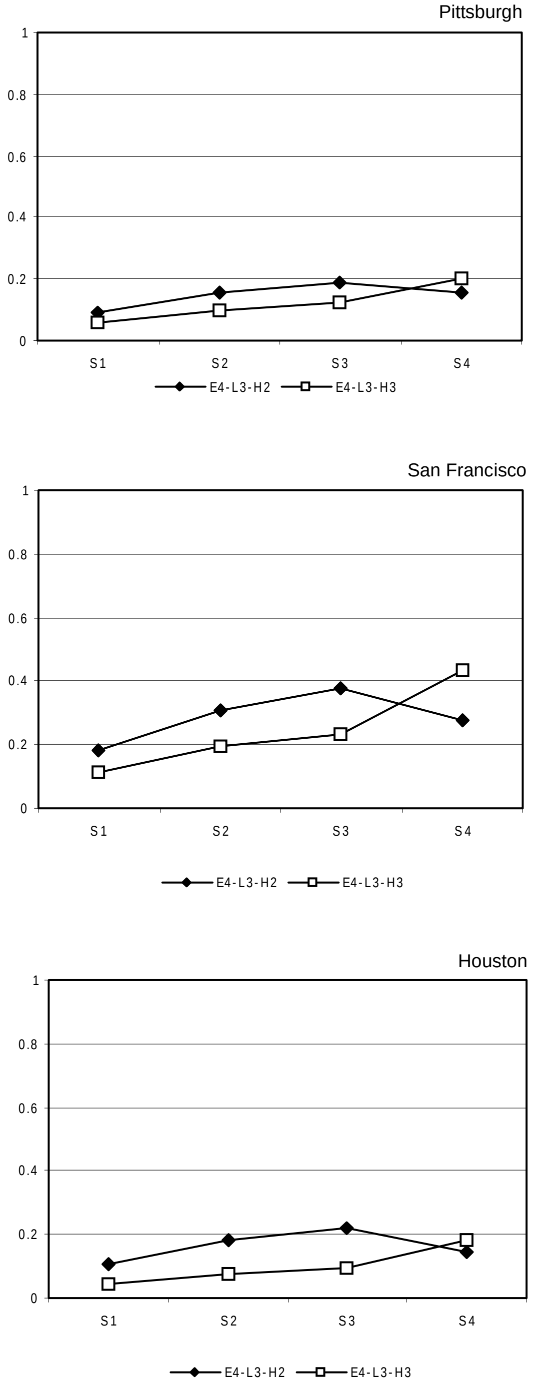


FIGURE 5. ESS_T for electric vs. absorption chiller building configurations and various solar generation options

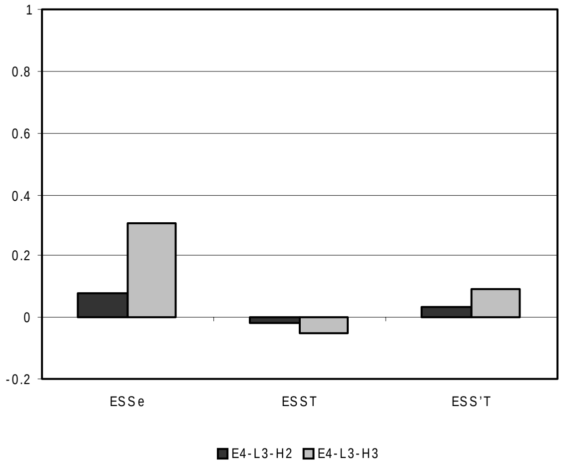


FIGURE 6. ESS for electricity, total site, and total source energy for co-generation option G2, for electric and absorption cooling options in Pittsburgh climate.

Generally, given the demand characteristics of office buildings of this scale (low domestic hot-water needs), co-generation is much more effective when absorption cooling is utilized. Figure 7 shows the ESS_e, ESS_T and ESS'_T for combinations of co-generation and PV, for a high-efficiency building option that uses absorption cooling (E4-L3-H3). Co-generation is more effective in Houston (ESS_e = 0.4), where the thermal demands from high cooling loads causes the co-generation system to run at full capacity for longer periods of time than in San Francisco (ESS_e = 0.1). This is further evident from thermal demand and co-generation supply profiles shown in figure 8.

DESIGN SUPPORT FOR THE BUILDING AS POWER PLANT

Overview

In order to effectively support the computational design and analysis of demand and supply side options for the Building as Power Plant, we propose that current and emerging energy analysis tools should be extended in the following three areas, which are further elaborated below:

- Simulation of advanced demand-side technologies that leverage the effectiveness of generation technologies;
- Simulation of building-integrated generation technologies;
- Energy self-sustenance analysis.

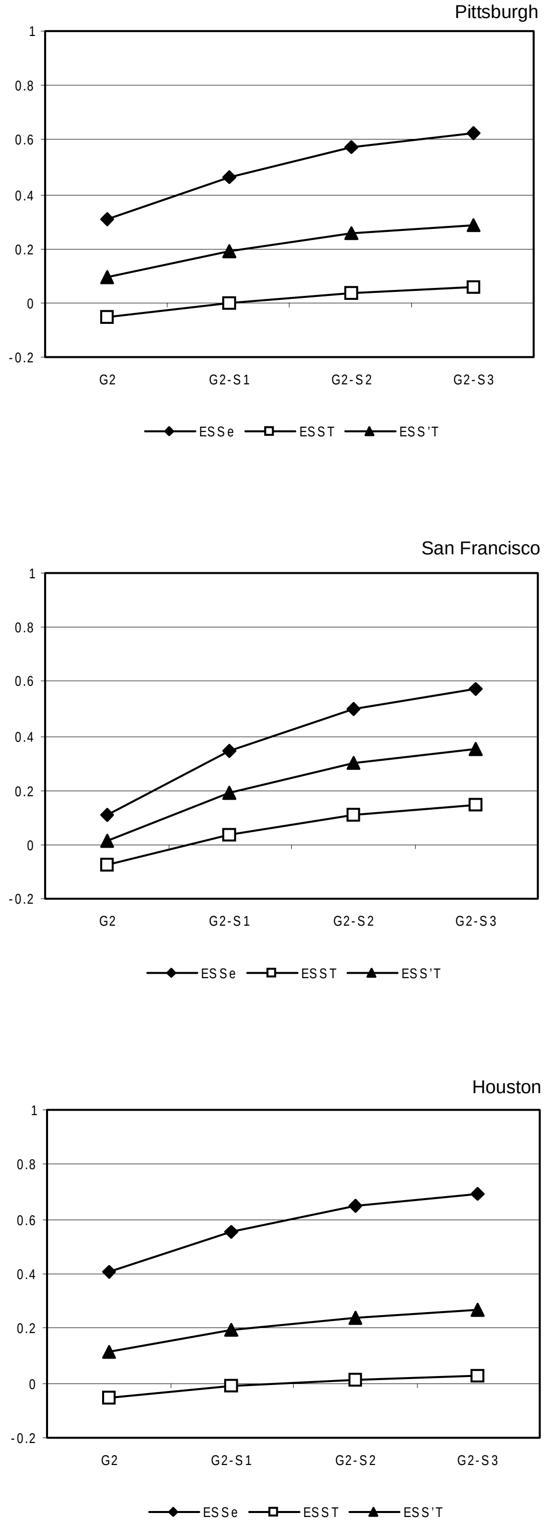
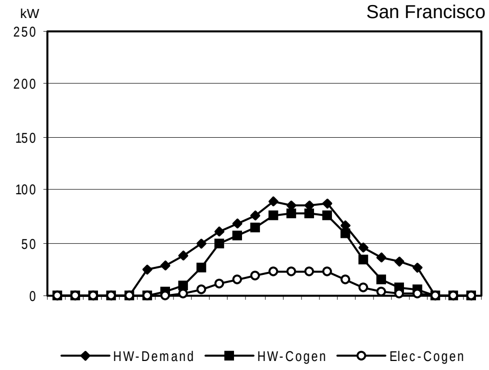


FIGURE 7. ESS for electricity, total site, and total source energy for co-generation and combined options, for a high-efficiency building with absorption cooling



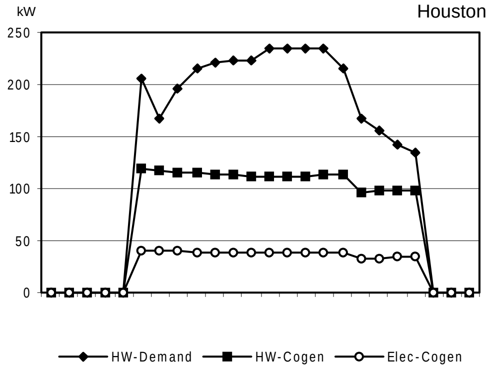


FIGURE 8. Thermal demand and co-generation (option G2) supply profiles in July, for a high-efficiency building with absorption cooling (E4-L3-H3).

Simulation of advanced demand-side systems

We believe that the use of innovative and sustainable energy systems for buildings will be technologically and economically feasible only if buildings are inherently "intelligent" in that they minimize their energy needs to start with, through the use of advanced building systems. The examples discussed earlier showed that even with relatively energy efficient buildings, the extensive use of facade-integrated PV still yielded an ESS_e of only about 0.3-0.4. However, there are a number of demand-side systems that could increase ESS_e, such as operable windows integrated with HVAC controls, radiant cooling systems, and split-task ambient thermal conditioning. Moreover, some of these systems can leverage the effectiveness of generation technologies. For example, radiant cooling can operate with much higher chilled-water temperatures than conventional air-based cooling, which can increase the viability and efficiency of solar-powered absorption cooling. Most detailed simulation tools do not allow for the analysis of these systems, let alone their analysis in the context of energy generation systems. Therefore, these tools should be extended to include first-principles-based modeling of such systems. From an implementation stand-point, we emphasize the further development of current tools rather than the development of yet another energy analysis tool.

Simulation of building-integrated energy systems

As we noted in the introduction, there are a limited set of tools to simulate distributed generation systems, and very few that simulate these systems for a specific building context. A design support tool for the Building as Power Plant should necessarily be capable of simulating building-integrated generation technologies, taking into account time and context-dependent load and efficiency. The tool should also allow for the simulation of emerging commercially available technologies such as fuel cells and micro-turbines, through highly parameterized modular component models. This would allow for the simulation of integrated multi-component systems such as the "energy cascade" (Hartkopf and Loftness 1996), shown in figure 9.

Energy self-sustenance analysis

As shown with the illustrative examples, the evaluation of a Building as Power Plant (BAPP) requires an analysis of daily and seasonal demand and supply profiles, as well as aggregate measures such as energy self-sustenance at site, source, and by energy type. Accordingly, a BAPP design support tool should include an ESS evaluation module that combines analytical and knowledge-based computational techniques, allowing building designers to interactively evaluate both energy

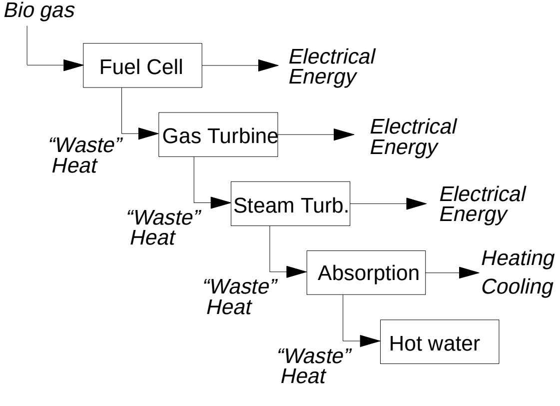


FIGURE 9. Conceptual scheme for a building-integrated energy "cascade" system

requirements as well as energy generation potential of various building configurations and generation systems. It would support analysis such as:

- Assessing the effective solar income on building and site over different seasons and match these to solar-powered absorption cooling and heating systems, taking into account peak loads, daily and seasonal load profiles, as well as annual energy use.
- Optimizing the configuration of integrated energy systems such as the "energy cascade", including trade-off analysis between the size of generators and the capacity of energy storage systems, operation schedules, etc.
- Deriving the Energy Self-Sustenance indices for the building, and comparing it to other buildings of a similar type situated in a similar context.

CONCLUDING REMARKS

We have presented a framework for the computational analysis of the Building as Power Plant, including energy self-sustenance indices to support such analysis. These indices will be further developed to provide a broader scope of analysis.

We intend to implement an ESS evaluation module, building on the ESP-r simulation environment (Clarke 1985), as well as the SEMPER design and simulation environment (Mahdavi 1996).

We plan to test and apply the tool for the design development of a Building as Power Plant demonstration project at Carnegie Mellon University, in conjunction with the Robert L. Preger Intelligent Workplace - a 600 m^2 "living" laboratory for high-performance building systems (figure 10).

FIGURE 10. Exterior view of the Robert L. Preger Intelligent Workplace at Carnegie Mellon University. The IW incorporates dynamic enclosures and task-ambient HVAC systems to reduce energy needs.

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