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# Development of a Framework for Quantifying the Environmental Impacts of Urban Development and Construction Practices

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To encourage sustainable development, engineers and scientists need to understand the interactions among social decision-making, development and redevelopment, land, energy and material use, and their environmental impacts. In this study, a framework that connects these interactions was proposed to guide more sustainable urban planning and construction practices. Focusing on the rapidly urbanizing setting of Phoenix, Arizona, complexity models and deterministic models were assembled as a metamodel, which is called Sustainable Futures 2100 and were used to predict land use and development, to quantify construction material demands, to analyze the life cycle environmental impacts, and to simulate future ground-level ozone formation.

## Introduction

The second half of the 20th century saw enormous growth of the human population, from 2.5 billion in the early 1950s to 6.2 billion by the end of the century. Associated with this growth was the so-called brown revolution (*1*), a surge of population influx to urban centers with its concomitant increase in urban pollution. Currently ∼49% of the world's population and ∼81% of the U.S. population lives in urban areas, a figure which is expected to grow to ∼61% and ∼87%, respectively, by 2030 (*2*).

With this anticipated urban growth, the built environment in the U.S. is estimated to increase by more than 40% by 2030, and half the needed buildings (213 out of 427 billion $ft^2$, including renovated and new development) will be erected between now and then (*3*). Currently, there are over 76 million residential and 5 million commercial buildings in the U.S. Activities associated with constructing and using these buildings consumes 30% of all wood materials and 65% of electricity. These buildings and their occupants generate 35% of solid waste, 36% of $CO_2$, and 46% of $SO_2$ emissions (*4*). Because rapid urbanization is a global phenomenon, these material-use and waste-generation issues are of critical importance to sustainable urban development worldwide (*5*). Consequently, strategies are needed that minimize the deleterious environmental impacts of expanding urban infrastructure while improving social and economic value. It is critical to find comprehensive solutions to manage the development boom, while facing increasing limitations in available natural resources and negative environmental impacts, e.g., greenhouse gas emission or ground level ozone formation. A good test bed is Phoenix, where explosive growth is ongoing and is expected to continue in a fragile environment.

Urban systems are complex adaptive systems that consist of many nonlinearly interacting elements which can adapt their dynamic behavior to external influences. For example, the character of the built environment, the type of transportation systems, among others, determine urban−rural temperature differences (e.g., urban heat island effect), which in turn, affect water use, noise, energy demand, microclimate, air quality (e.g., particulate matter, ozone, and carbon monoxide concentrations), and the quality of life of urban habitants. The challenge that we face is to engineer the emergent patterns. This is complicated because it is far removed from the traditional focus of engineers who design technology around a purpose (*6*). Therefore, a holistic systems approach is required to provide an integrated knowledge base for the future impacts of current decision making.

In this study, a metamodel framework, called Sustainable Futures 2100 (SF 2100), was constructed to examine urban futures under certain land use and construction practices, based on the understanding of interactions among social decision making, development and redevelopment, land, energy and material use, and their environmental impacts. The SF 2100 framework is sketched in Figure 1. Urban growth scenarios (element 1) are used to predict land development patterns (element 2) and construction patterns (element 3) using models that capture the societal and economic interactions among developers, planners, and households. The resulting land development pattern generates realizations that are described in a variety of terms including the distributions of households and economic activities in the urban environment and associated material demands (element 4). Life-cycle analysis (LCA) (element 5) is used to estimate the discharge of air and water pollutants as well as generation of solid waste during the extraction, construction, operation, and demolition of the built environment. These environmental impacts are then quantified using deterministic domain models (element 6). These outcomes then, in

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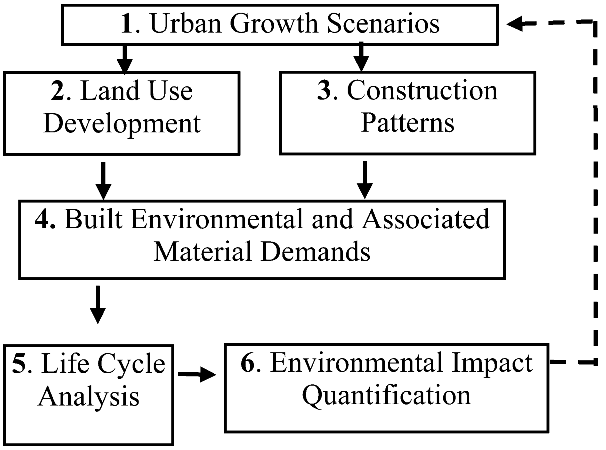

**FIGURE 1. Structure of the SF 2100.**

principle, would be feedback, together with economic and social factors, into the formation of new scenarios (shown as a dashed line). The present model is not tightly coupled. Accordingly, this feedback is not currently considered in the present model.

With this framework, different land use patterns, construction methods, and material choices could be examined and compared against their overall impacts. In this paper, we provide a proof of concept using the business-as-usual land use scenario, and two construction scenarios, i.e., single-story residential construction versus two-story residential construction.

## Approach

Based on the proposed framework, a prototype metamodel of SF 2100 was constructed by integrating state-of-the-art models of urban growth simulation, material demand, life-cycle analysis, and ground-level ozone simulation, as shown in Figure 2. Future land use development and layout of households and jobs was projected by a hybrid urban growth simulation model. The projected household growth enables the quantification of the demands of 10 types of construction materials that are commonly used in the Phoenix area. The material demands for two construction designs, i.e., single-story and two-story residential buildings, were analyzed. Life-cycle impact analysis of the construction materials was then performed to quantify energy use and pollutant discharges associated with residential building development. From the future spatial urban growth pattern and the life-cycle analysis, a variety of subsequent environmental impacts can be quantified spatially and temporally. For this initial study, the emission inventory of ozone precursors, i.e. $NO_x$, CO, VOC, and $SO_x$, was calculated. The inventory was used as an input into chemical mechanism and meteorological models to project the formation and spatial distribution of ground-level ozone.

More detailed descriptions of SF 2100 components are provided below.

**Urban Growth Simulation Models.** Construction of urban models facilitates heuristic and dialectic exploration into the form and function of urban systems. This is essential to theory-building and policy-making, allowing us to experiment with phenomena that are inaccessible to inquiry on the ground.

The urban growth model employed in this study is UrbanSim (*7*−*10*), a land-use model that has been well-tested operationally across the United States and has become the de facto toolkit in the urban studies community as well as enjoying popular use by several metropolitan planning agencies.

UrbanSim is not a single model, but a microsimulation system consisting of a family of models reflecting key choices of households, businesses, developers, and policy-makers, and capturing their interactions in the land development process. Households, businesses, and developers interact dynamically through supply− demand relationships, mediated by the influence of policy-makers and framed within the backdrop of existing land-use and geographic conditions in the city (A more detailed description of UrbanSim is available at http://www.urbansim.org/index.shtml).

The input data for UrbanSim were obtained from Maricopa Association of Governments (MAG), a regional agency that studies land use, transportation, and air-quality monitoring for the 24 municipalities comprising the Phoenix metropolitan area. The preparation of UrbanSim input database is discussed in our previous study (*11*). In this study, Maricopa county was divided up into 9511 1-square mile grid cells and UrbanSim predicted the future job and household growth within these grids using 1990 data.

UrbanSim predicts future land use and residence development, demographic transition, and spatial distribution of households and jobs. The projected development patterns allow one to estimate construction material demands and ozone precursor emissions, and provide information of land-use type for ground-level ozone simulation.

**Material Demand Quantification and Life-Cycle Analysis (LCA).** Material demands for two residential design scenarios were quantified. Energy demand and life cycle impacts were then analyzed using the building energy simulation program and LCA tools.

In this study, a single-story house and a two-story house were chosen from 16 typical residential building designs collected from local builders as two residential construction scenarios. Both designs have the median square footage of Phoenix houses, stucco exteriors with concrete tile roofs, and post tension foundations. The two designs use the same standard materials with the same R-values for exterior walls and roof. More design details are provided in Table 1.

ATHENA Environmental Impact Estimator version 3.0.1, was used to estimate the construction material demands and the life-cycle environmental impacts for two house design scenarios. Developed by Athena Sustainable Material Institute, ATHENA software provides life-cycle inventory data covering 90−95% structural and envelope building materials and these data are collected from North America (*12*). ATHENA was used to quantify the demands for the following construction materials: aggregate, wood, limestone, sand, clay and shale, gypsum, cement, iron and steel, and aluminum. The future construction material demands for the future development of Maricopa County were generated by multiplying the material demands for a single house with the number of housing units that would be built as projected by UrbanSim.

As for life-cycle analysis, ATHENA enables assessment of the following environmental impacts: energy consumption; solid waste; air pollution index; water pollution index; global warming potential (GWP); and resource (water, oil, etc.) use. The air pollution index and water pollution index are measured by the volume of ambient air or water that would be required to dilute contaminants to acceptable levels, where acceptability is defined by the most stringent standards (e.g., drinking water standards). For the global warming potential, all greenhouse gases are measured by carbon dioxide equivalence based on their heat trapping capability compared to that of carbon dioxide, and the unit of the global warming potential is carbon dioxide equivalent mass.

Energy consumption, an important metric in LCA, includes embodied energy and operational energy. Embodied energy is the total energy embodied in construction materials during extraction, manufacturing, transportation, assembly,

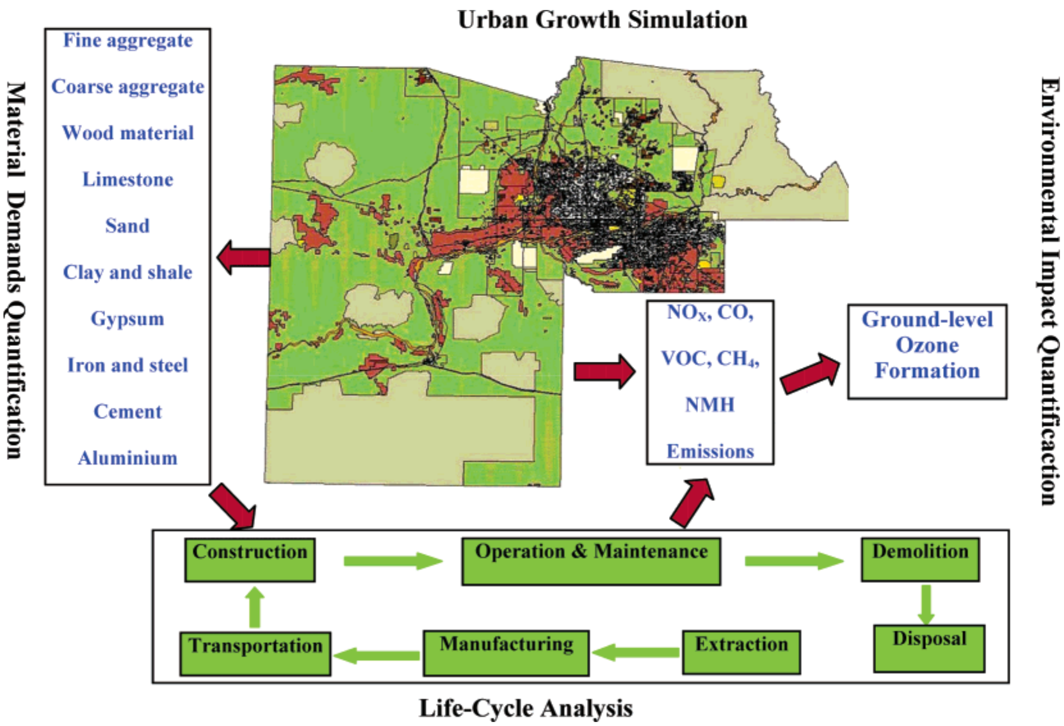

**FIGURE 2. Prototype of SF 2100 metamodel that was used in this study.**

**TABLE 1. House Designs and List of Materials**

| house design | single story | two Story | | single story | two story |
|---|---|---|---|---|---|
| total floor area: $ft^2$ | 2142 | 2220 | garage: $ft^2$ | 442 | 410 |
| livable area first floor: sf | 2142 | 941 | bedrooms | 4 | 4 |
| livable area second floor: sf | 0 | 1279 | baths | 2 | 2.5 |
| bill of materials | | | | | |
| concrete 20 MPa: $yd^3$ | 45.0 | 25.2 | joint compound: tons | 0.75 | 0.83 |
| nails: tons | 0.37 | 0.38 | paper tape: tons | 0.0086 | 0.0095 |
| welded wire mesh/ladder wire: tons | 0.26 | 0.13 | water based latex paint: gallons | 88.6 | 149 |
| rebar, rod, light sections: tons | 0.44 | 0.32 | stucco over metal mesh: $ft^2$ | 1520 | 2620 |
| galvanized sheet: tons | 0.49 | 0.60 | aluminum: tons | 0.61 | 0.63 |
| softwood lumber, kiln-dried: $m^3$ | 9.81 | 11.0 | vinyl: $ft^2$ | 14 500 | 15 000 |
| oriented strand board: msf (3/8 in. basis) | 6.97 | 7.97 | #15 organic Felt: 100 $ft^2$ | 17.1 | 29.3 |
| batt. Fiberglass: $ft^2$ (1") | 55000 | 39100 | #30 organic Felt: 100 $ft^2$ | 131 | 70 |
| 6 mil polyethylene: $ft^2$ | 7750 | 5870 | EPDM membrane: pounds | 581 | 599 |
| 1/2" regular gypsum board: $ft^2$ | 5800 | 5470 | concrete tile: $ft^2$ | 6860 | 3710 |
| 5/8" regular gypsum board: $ft^2$ | 1520 | 2620 | low E Tin argon filled glazing: $ft^2$ | 2080 | 1970 |

maintenance, demolition, and final disposal processes, while operational energy stands for the energy use for spatial heating and cooling, water heating, lighting, and miscellaneous energy consumption. Electricity is the major source for the operational energy in Maricopa County.

In this study, the embodied energy was calculated using ATHENA, and the operational energy was calculated by a building energy simulation software, eQUEST (more information of eQUEST is available at http://www.doe2.com/equest/). The eQUEST simulates the building energy consumption over an entire year based on the house design and construction features (e.g., U-value) and the hourly weather data of the Phoenix area.

**Ozone Precursor Emission Analysis.** Ozone is linked to at least 15 chemical precursors with the most significant contributors being oxides of nitrogen ($NO_x$), volatile organic compounds (VOCs), carbon monoxide (CO), and oxides of sulfur ($SO_x$), among which VOCs and $NO_x$ are the two most important precursors. In the urban environment, these precursors are generated from a wide variety of sources, which are often grouped into five categories: on-road mobile sources, nonroad mobile sources, point sources, area sources, and biogenic sources. To comply with the U.S. Environmental Protection Agency (EPA) regulations, the Maricopa County Environmental Services Department (MCESD) has created a Periodic Ozone Emissions Inventory every 3 years since 1990. The reported inventory indicated that all five category sources are important and need to be considered when preparing the precursor inventory. In this study, in addition to these five major sources, the construction of residential buildings was considered as the sixth ozone precursor source. However, the operation and maintenance (O&M) of residential buildings was not counted as a source, although generating the energy for the O&M emits ozone precursors. The reason is that the electricity generation facilities are point sources and their emissions are counted in the inventory. To avoid double-counting, O&M of residential buildings should not be counted. In addition, the power plants are not located in the City of Phoenix.

**On-road Mobile Sources.** The ozone precursor emissions from on-road mobile sources equal to the products of vehicle emission factors, which are estimated by the MOBILE6 modeling program (more information about MOBILE6 is available at http://www.epa.gov/otaq/m6.htm), and annual vehicle miles traveled (VMT), which is projected based on increasing population.

The emission factors from MOBILE6 are 2.55 g $NO_x$/mile, 1.46 g VOC/mile, 16.2 g CO/mile, and 0.113 g $SO_x$/mile for the year of 1999, and 0.59 g $NO_x$/mile, 0.42 g VOC/mile, 5.20 g CO/mile, and 0.046 g $SO_x$/mile for the year of 2015. The technical advance and increasingly strict regulations would result in a significant decrease in the emission factors of 2015 in comparison with those of 1999.

The population-based VMT projection was calculated by two steps. First, the per capita VMT was calculated by dividing the total VMT value from the 1999 Periodic Ozone Emissions Inventory (*13*) by the population in Maricopa County in 1999. Then the per capita VMT was multiplied by the future year population projected by UrbanSim, to get the annual VMT of the future year.

**Nonroad Mobile Sources.** According to the 1999 Periodic Ozone Emissions Inventory, nonroad mobile sources include "aircraft, locomotives, diesel equipment, 4-stroke gasoline equipment, and 2-stroke gasoline equipment" (*13*). The emissions from these nonroad equipments were estimated by running NONROAD2005 (more information about NONROAD2005 is available at http://www.epa.gov/oms/nonrdmdl.htm).

**Point Sources, Area Sources.** The point source and area source emissions were projected based on the 1999 base year emission data from the 1999 Periodic Ozone Emissions Inventory (*13*) and the industrial growth factors from the ancillary files prepared for the Emissions Modeling System for Hazardous Pollutants (EMS-HAP) (available at http://www.epa.gov/ttn/chief/emch/projection/emshap30.html).

**Biogenic Sources.** The biogenic emissions were modeled by Biogenic Emissions Inventory System (BEIS, more information of BEIS at http://www.epa.gov/asmdnerl/biogen.html), which is embedded in Sparse Matrix Operator Kernel Emissions (SMOKE, more information of SMOKE at http://www.smoke-model.org/index.cfm). SMOKE was also used to allocate emissions at next step for the ground-level ozone simulation.

**Construction of Residential Buildings.** The number of residential buildings to be built in future year 2015 was projected by UrbanSim. And the ozone precursor emissions from the construction of a single house were estimated by ATHENA. Accordingly, ozone precursor emissions from the construction of all newly built residential buildings in future year 2015 were calculated.

The ozone precursor emissions from five major sources and residential building construction were added up as an input for the followed simulation of ground-level ozone formation.

**Ground-Level Ozone Simulation Models.** The Penn State University/National Center for Atmospheric Research Mesoscale Model 5 (MM5) was used to predict air-flow patterns and the Community Multiscale Air Quality model (Models-3/CMAQ) was used to predict ground level ozone formation in the Phoenix area.

MM5 has been thoroughly used and validated for the Phoenix area in our previous work (*14*−*16*). A 5 day simulation of MM5 is performed to provide real-time 3D wind field forecasting for the following 5 day period of CMAQ simulation.

Models-3/CMAQ is a comprehensive multiple-pollutant modeling system released by the U.S. EPA that encapsulates the state-of-the-science approaches to assess and predict air quality, particularly the levels of criteria pollutants. Each CMAQ simulation covered a 5 day period including a 2 day spin-up time.

Meteorological conditions obtained from MM5 together with hourly gridded ozone precursor emissions from the preprocessor SMOKE provide the required input for the Models-3/CMAQ. SMOKE prepared the emission data based on the projected ozone precursor emission inventory from five major sources and residential building construction and the information of land use type fractions in grid cells from UrbanSim simulation.

## Results and Discussion

**Urban Growth of the Phoenix Area: 1990−2015.** 1990 was used as the base-year case for the urban simulation, and this provided a convenient 10 year time span for validating UrbanSim. Practical constraints on creation of historical data for use in validation often preclude the feasibility of historical validation of this sort, but this remains as one of the most informative ways to validate the model before putting it into operational use (*10*, *17*). To validate UrbanSim, the model was used to project the year 2000 growth patterns from 1990 data. The correlation between the projection and data for the number of households, employment, and housing units in the gridcells level are 76, 80, and 79%, respectively (*18*).

Once the validation tests provided satisfactory results, UrbanSim models were run for another 15 years to the year 2015. The results show that total households would double from 1990 to 2015. In the future 9 years (2006−2015), the number of households was projected to increase by 350 000. The construction material demands associated with this household-increasing trend were quantified in the following analysis.

An animation of the household location change from 1990 to 2015 and a table that shows the change in demographics is provided in the Supporting Information. Most of the areas projected to evolve into new communities are in the West Valley along Interstate 10 and Highway 89. In addition, there are smaller concentrations along Highway 87 east of the urban agglomeration. Current building activity seems to confirm our expectations about the West Valley area of Maricopa County as being the focus of most new growth in this region. The transition of ethic compositions of the local population is also analyzed in the Supporting Information.

**Construction Material Demands for the Residence Development.** Construction material lists for single story and two-story designs are shown in Table 1. For the same living size, the material demand analysis show that a one-story house uses 45% more concrete (mainly in the footings and foundation), 29% more insulation and 48% more concrete tile (larger roof area) than the 2 story home. The two-story house has 53% more stucco over wire mesh because of the increased exterior wall area. The one-story and two-story houses have similar inputs of other construction materials.

As mentioned above, the number of households in the Greater Phoenix is projected to increase by about 350 000 within 9 years (2006−2015). The raw construction material demands for the future 9 year residence development in the Phoenix area were calculated (See Figure 3) based on two scenarios, one-story residence scenario assuming all future residential building are one-story houses, and two-story residence scenario assuming all future residential building are two-story houses. Compared with the one-story residence scenario, the two-story residence scenario saves 44% of the cement, 41% of the aggregate, 33% of the limestone, 34% of the clay and shale, and 15% of the sand, but consumes 50% more gypsum and 13% more wood. In total, the two-story residence scenario will use 32% less raw construction materials by mass than the one-story residence scenario.

**Life-Cycle Impacts of Two House Designs.** If the impact from the operational energy consumption is not considered, the life cycle impacts of the two-story house are less than

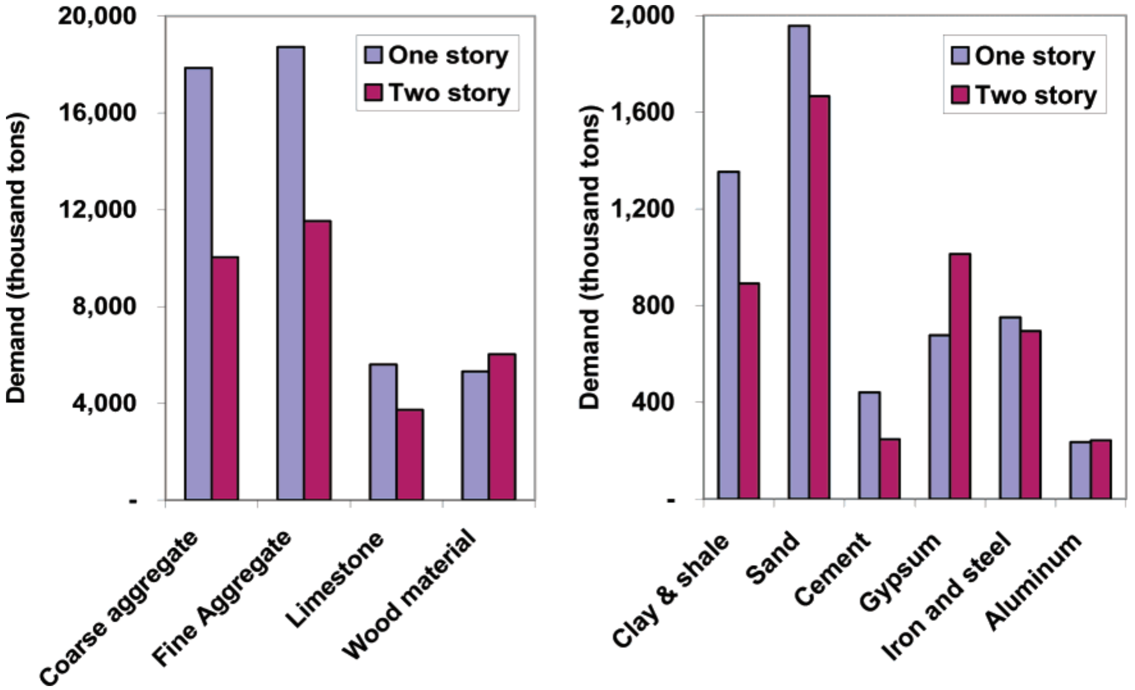

**FIGURE 3.** Construction material demands for residential building in future nine years (2006–2015).

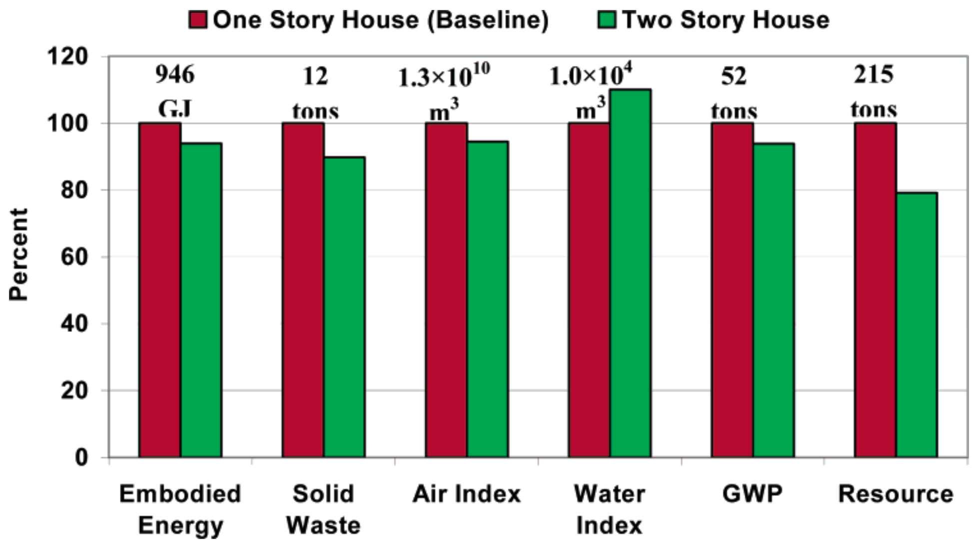

**FIGURE 4.** Environmental effects of one-story and two-story house designs (without operational energy).

those of a one-story house in general, as shown in Figure 4. Without considering the operational energy, the embodied energy of the two-story house (889 GJ) is 6% less than that of the one-story house (946 GJ), and the two-story house generates 10.2% less solid waste, 5.5% less air pollution, and 6.1% less green house gas emissions. The lower environmental impacts of the two-story house are due to its lower construction material demands.

The total energy consumption for the one story house according to eQUEST was 8.84 kWh/sqft and for the two story house was 9.05 kWh/sqft. As a result, the two-story design has a larger life cycle impacts than one-story design, as shown in Figure 5. The difference between the two designs represents a 2.32% increase in the operating energy consumption on the two story house. This electrical usage increment mainly caused by increased heating and cooling loads because of the larger wall surface area expose to direct solar radiation and wind movement. On one hand, this difference between one-story and two-story designs could be diminished by increasing the R value of the exterior walls so as to decrease the heat gains and losses through walls and windows. This action could potentially equalize the energy performance between the two designs. On the other hand, the day-lighting opportunities could be increased on the two story house by 25% due to a larger exterior wall area. This opportunity has also potential setbacks by incrementing the changes of heat gain and losses. However, utilizing the right amount of glaze could eliminate the problem with minimal or no additional expenses to the builders. The overall comparison of the two designs will have to consider other important factors, such as footprint, open space, and traffic implication, etc.

**Ozone Precursor Inventory.** The ozone precursors from five major sources (i.e., on-road mobile, nonroad mobile, point, area, and biogenic sources) and the construction of residential houses are listed in Table 2. Despite the rapid population and urban growth, all four main ozone precursor emissions show a decrease from 1999 to 2015 (The Supporting Information contains an animation showing the spatial and temporal difference of $NO_x$ and VOC distribution in a typical

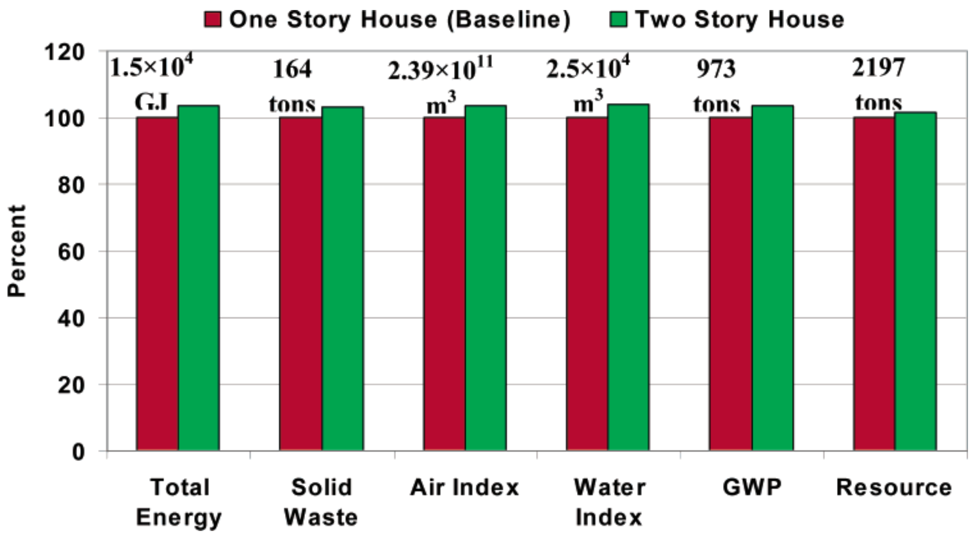

**FIGURE 5. Environmental effects of one-story and two-story house designs (with operational energy).**

**TABLE 2. Ozone Precursor Emissions**

| | | $NO_x$ | VOC | CO | $SO_X$ |
|---|---|---|---|---|---|
| emissions from five major sources (tons/yr) | 1999 | 113 341 | 121 029 | 597 634 | 3 793 |
| | 2015 | 59 833 | 111 465 | 390 240 | 2 570 |
| construction emissions of a single house (kg) | one-story | 7.8 | 0.6 | 3.8 | 6.1 |
| | two-story | 6.3 | 0.4 | 3.0 | 7.1 |
| total construction emissions in 2015 (ton) | one-story scenario | 304 | 23 | 148 | 237 |
| | two-story scenario | 245 | 15 | 117 | 276 |

summer day of 1999 and 2015), because of technological advances and increasingly strict regulations. Further investigation into the emission data shows that the drastic declines of the emissions from on-road and nonroad mobile sources are responsible for the reduction of the total ozone precursor emissions.

As stated in the approach section, the emission of constructing a single residential house (one and two stories) was estimated by ATHENA. The total emissions from constructing residential houses in 2015 were calculated by multiplying the single house emission with the 390 000 new residential buildings projected by UrbanSim. As shown in Table 2, the emissions of $NO_x$, VOC, CO, and $SO_x$ for constructing a one-story house are, respectively, 19, 35, 21, and 16% higher than that for constructing a two-story house. However, the total emission from constructing all new houses only account for less than 0.5% of the total $NO_x$ and VOC emission. Therefore, the difference of the two construction scenarios is negligible and only the emission inventory of one-story scenario was used in the ground-level ozone concentration projection.

**Ground Level Ozone Concentration for Base Year and the Year 2015.** Using EPA 1999 emission inventory for a base-year simulation, and the projected 2015 emissions inventory and land-use patterns from UrbanSim simulation, CMAQ models were used to calculate the of ground level ozone

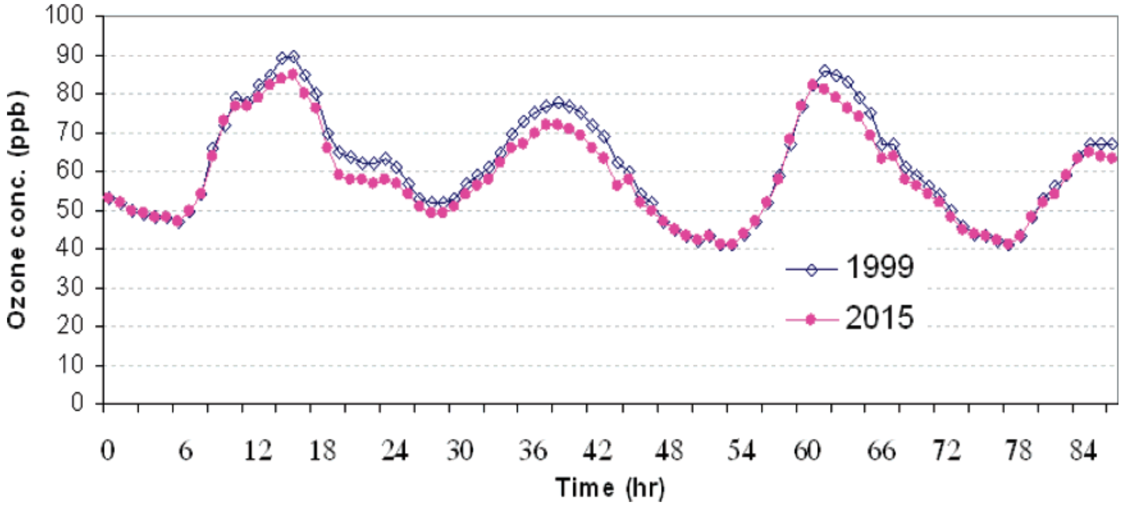

**FIGURE 6. Difference of maximum ozone concentration in the entire domain.**

concentration. Because of the decrease in the emission of ozone precursors, the ozone concentrations during daytimes are slightly decreased in 2015. In particular, hot spots with high ozone concentration are decreased. The temporal and spatial distribution of ozone in the base and future year are illustrated as animations in the Supporting Information. Figure 6 shows the fluctuation of the maximum concentration in the entire domain during simulation periods. The National Ambient Air Quality Standards (NAAQS) (*19*) requires the annual fourth-highest daily maximum 8 h average ozone concentration should be less than or equal to 80 ppb. The 2015 projection shows that the duration for ozone levels exceeding the 80 ppb standard will be approximately 3 h shorter and the maximum ozone concentration will be about 5 ppb lower than that in the base year of 1999. This result is statistically significant at a significant level of 0.05.

**Model Uncertainty.** Interactions among individual models in SF 2100 show intrinsic complexity of the entire system. On one hand, these interactions will compound uncertainty. On the other hand, the coupling of the models reduces the degree of freedom and provides a way to validate submodels. The uncertainty comes from a variety of factors ranging from systematic factors, data variation, and uncertainties intrinsic to methodologies. For example, energy simulation program DOE-2, the engine of eQUEST, was applied to a two-story single-family house and showed a 3% difference between prediction of annual energy use and the measured value (*20*). Cutoff error, in which data limitations lead to some industrial activities being excluded from the analysis, inevitably arises in process life cycle assessment. Also, there are additional types of uncertainties, such as geographical and temporal, which can be substantial (*21*). The incomplete knowledge about uncertainty in the life cycle assessment impede us from carrying out a thorough sensitivity analysis. Instead, as stated in previous sections, the models are validated separately. A simple sensitivity analysis about the dependence of ozone formation on construction practices and urban development indicates that total emissions from constructing all new houses in the 9 years only account for less than 0.5% of the total $NO_x$ and VOC emission, which are the determining factors affecting the ozone concentration. Therefore, the ozone concentration is not sensitive to the emission from the construction of the houses. Instead, the on-road and nonroad mobile emission are more important. The analysis on those will need a microscale traffic simulation model, which is under implementation.

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## Supporting Information Available

An animation showing spatial change of household, a table showing the transition of demographic profile, animations showing the spatial and temporal difference of $NO_x$ and VOC distribution, as well as animations showing spatial and temporal distribution of ground level ozone in the 1999 base year and 2015 future year This material is available free of charge via the Internet at http://pubs.acs.org.

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