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The 2050 City

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Abstract

Virtually all of the growth in human population in the next generation is projected to be in cities. Given the environmental stresses on the planet today, it is critically important that these new urban areas have little or no negative impacts. A comprehensive assessment of these impacts will include all operational factors – energy, water, food, and transportation – as well as all the embodied consequences of construction and maintenance. This analysis can be expressed in units of energy (to build and operate the city, grow food, treat and desalinate water, and travel); as well as in units of area required to accommodate housing, grow food, and generate solar energy (photovoltaic generation area is used as the most universally available form of renewable energy). This study models a new city for 1,000,000 inhabitants in a temperate climate, built in the year 2050. A comprehensive footprint of the city is established, given certain assumptions about lifestyle, diet and technology. The resulting area required for the city to be self-sustaining is then evaluated in terms of density. In other words, can cities themselves be entirely sustainable, and can a self-sustaining community be considered a city?

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1. Introduction

In 2008, for the first time in history, human society became primarily urban. For the foreseeable future the world's population will continue to move to cities, so that by 2050 almost 70% will be city dwellers. By then the UN projects the population increasing by 2.3 billion people, to around 9.3 billion. Consequently almost all the additional people will live in cities, either expansions of existing ones or entirely new ones. This rate of urban growth is hard to conceive: from 2013 until 2050, the world will gain the equivalent of 7.2 New York Cities per year (current population 8.2 million); one Singapore per month (5.0 million); one Hyderabad each week (1.2 million); a San Francisco every 5 days (815 thousand); or one Providence, RI (172 thousand) every day.[i]

In this context, the ecological performance of cities is becoming an increasingly critical issue. The earth is already overstressed in terms of carbon emissions, fresh water availability, pollution from agriculture, and many other areas. Solving today's environmental problems will be difficult enough, requiring technical innovations and significant changes in behavior. Adding 50% more people will make these problems far more severe. But our unprecedented urban future is an opportunity as well as a problem: if we can make new cities truly sustainable, we can reduce or eliminate future environmental burdens. And, the transformation to self-sustaining urbanity may be an opportunity to make cities better places to live in.

This is a study of the technical and spatial limits of environmental urbanism, looking to determine how sustainable a city can be. We stipulate that the 2050 City will be completely self-sustaining, receiving all energy inputs and producing all its food and goods within its boundaries – imagine a domed city on another earthlike planet, which has to function entirely on solar energy and internal processes. We ask two principal questions about this city: first, what kind of infrastructure does it need to support itself; and second, how big is the infrastructure – and to what degree can it be integrated into the rest of the city? The answers to these questions may define an urban vision that is impractical or even undesirable in today's world, but we wish to understand the limits of self-sustainability as a basis for future planning. Hopefully, this extreme vision of urban performance will inform more nuanced approaches to tomorrow's development.

We study two related quantities: resource consumption (expressed in terms of energy); and the size of the required urban systems (expressed as land area). Our model is human-centric, based on the activities of the city's inhabitants (food, travel, consumption of goods), as well as the construction, operation, and maintenance of the physical city.

Energy is the principal input into the 2050 City, and is the first unit of our analysis. We measure its consumption for day-to-day operations, city infrastructure, food production, production of goods, material resources, and internal and external transportation. Solar radiation – the most unambiguously sustainable form of energy – is delivered as electricity to the city by Photovoltaic (PV) devices. Often environmental performance is measured in terms of carbon emissions. In this study all energy is solar (including the embodied energy of the PV system), so the project is inherently zero carbon.

Our spatial analysis includes the area of the city itself (the relatively dense areas within a city's legal limits, which we call the Urban Core), as well as the area occupied by the systems serving the city (the Urban Infrastructure). Of course, with unlimited space, any city could be made self-sustaining by using enough land area for solar energy generation, farming, water collection, and so on. But today this would require a very large amount of land: contemporary cities have a tributary footprint that is over 50 times as large as the city itself.

The relationship between these two metrics – energy and space – is not a simple one. It may seem evident that the sustainable city will simultaneously minimize energy use, resource consumption, and land use – but these goals may at times be in conflict with each other. Environmental impact, food security, water availability, and resiliency are all issues of growing importance, and finding the appropriate balance between them will be one of the defining tasks of future urbanism.

Faced with the current reality of cities as ecological parasites feeding off ever larger regions of the earth's surface, we ask: with improvements in technology, and the integration of productive services with urban infrastructure, can the footprint of the self-sufficient 2050 City, including all its infrastructure, be reduced to a scale we would consider "urban"?

2. Methodology

A city is a complex web of physical parameters and operational systems. To make our calculations manageable, we have made a set of simplifying assumptions:

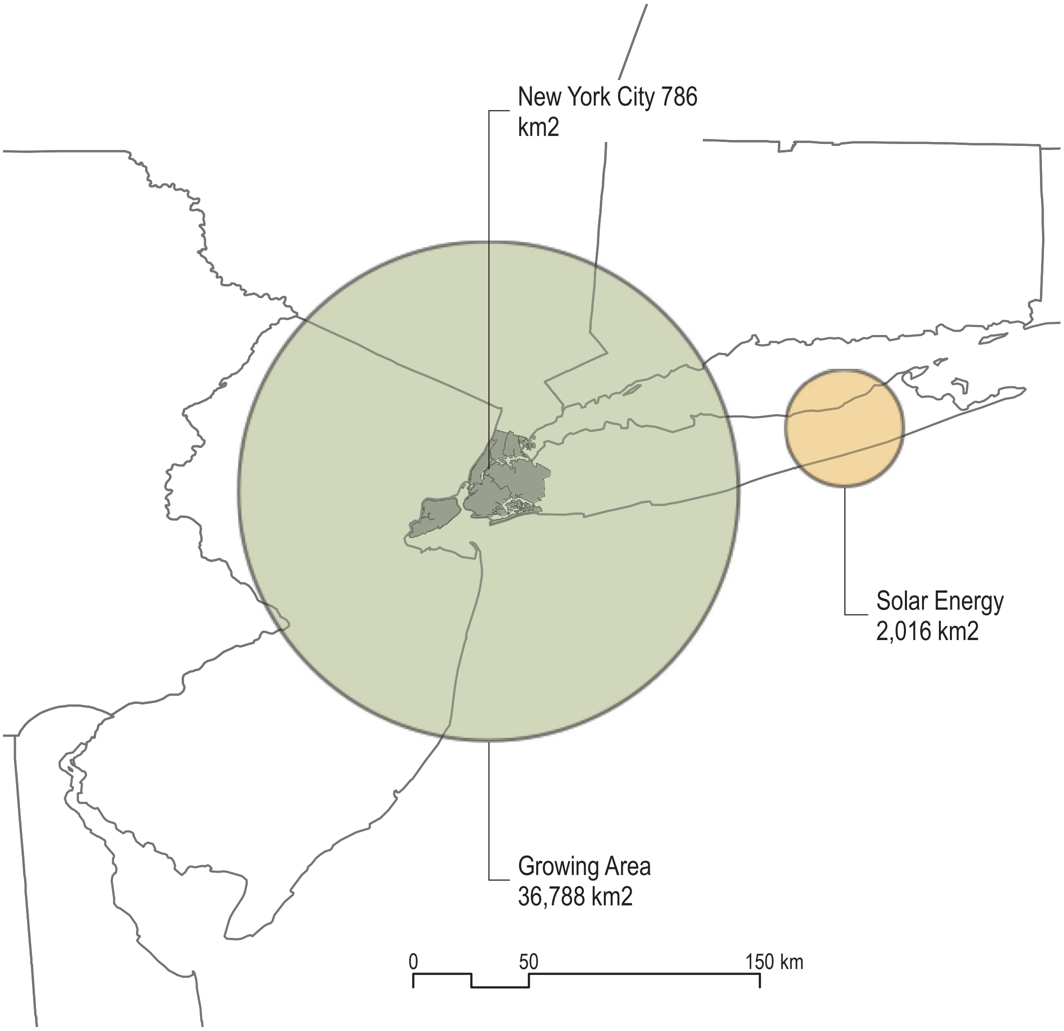


Figure 1. New York City and its energy and food infrastructure in 2013. The areas required for growing food and generating solar energy total 38,804 km2, or about 50 times the size of the city itself.

- The 2050 City is essentially self-sufficient – the major input is solar energy; other elements of the system exist within city boundaries, with the exception of seawater for desalination, and some physical resources such as minerals for manufacturing.
- The operating processes of the city, including food, water, transportation, and production, are evaluated only in terms of energy flows and spatial requirements (not in terms of materials, money, or people.)
- Nonrenewable resources, particularly raw materials for production, will not be constraints to the operation of the city, due to high levels of recycling and development of alternative materials when necessary.
- The city is new. While most urban growth by the year 2050 will be expansions of existing cities, a new city is simpler to evaluate in technical and spatial terms. Also, creating a new city requires us to account for all the material resources to build it in the first place.
- Significant technological advances are projected by the year 2050, in a self-reinforcing loop of decreasing energy consumption, and increasing renewable energy production efficiency.

3. Energy

Sunlight is the only external input to the Earth's ecosystem. The planet contains a fixed amount of matter, which is animated on every level – from weather patterns to the processes of life itself – by the sun's energy. Accordingly we express the quantitative results in this study in terms of energy (typically in gigawatt-hours per year – GWh/yr), and the related unit of solar area required to generate it (in square kilometers of photovoltaics – km2).

3.1. Comprehensive Analysis

Energy use in cities is routinely evaluated in terms of operating energy: heating and cooling buildings, powering traffic lights, water treatment systems, and running subways and buses. But if we wish to understand the true dimensions of a city's environmental impact, we must include every activity that contributes to it.

We have grouped these types of energy use into five categories: internal operating energy; growing food; embodied energy of production (everything from small products to buildings and bridges); water desalination and purification; and external transportation for the city's residents.

Adding these categories together gives a complete accounting of all the energy consumed in the creation and operation of the 2050 City and the activities of its inhabitants. If all this energy is generated by renewable sources, the city will have no negative energy-related impact, such as carbon emissions, water use for thermal energy cooling, growing crops for bio-energy, etc. This comprehensive approach makes the problem a larger scale than any current measure of sustainability, which tend to account for internal operating energies only.

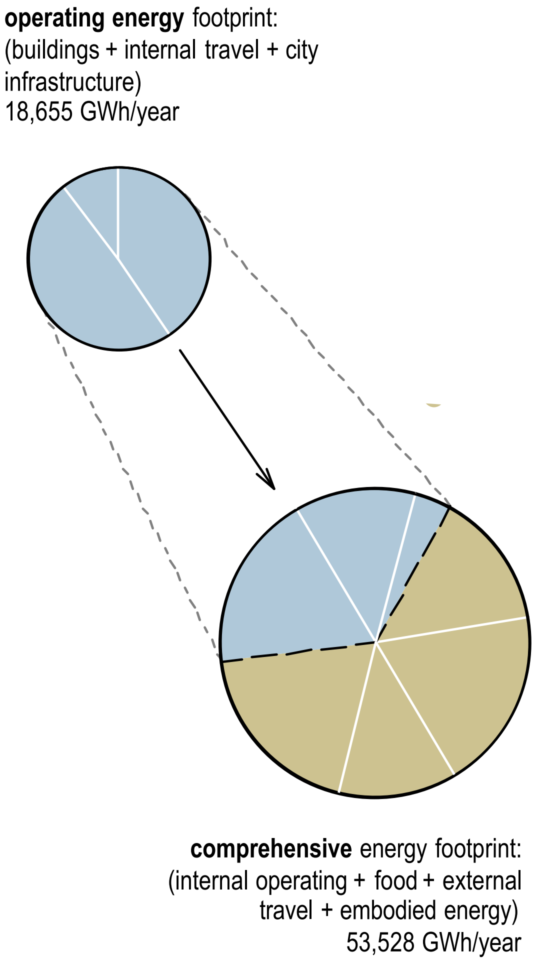


Figure 2 2050 City: operating energy (upper left) is less than 1/3 of total comprehensive energy use in 2013.

3.2. Embodied Energy

Energy is used in the extraction of raw materials, in the manufacturing of products, in growing, transporting, and storing food, and in the processing of water and wastes. Energy is embodied in products at every step of their existence: production, use (in the form of maintenance and alterations), and at end of life in terms of reuse or disposal.[ii]

For manufactured products, which include everything from small, short-lifespan consumer products to long-lasting buildings and infrastructure, we provide an equivalent amount of solar generation to offset the energy of production, maintenance, and recycling.[iii] Even the embodied energy of the solar generating systems is accounted for.

Significant energy is embodied in the use of water as well, from treatment and storage of rainwater, to its extraction from waste streams, and for desalination (extraction from seawater).

3.3. Energy Generation

The 2050 City operates entirely on renewable energy. In our model, all of the city's energy is solar, harvested by photovoltaic (PV) devices. Solar is the most universally available form of renewable energy; electricity is the most flexible and widely applicable way to use energy; and PV is the most direct conversion of sunlight to electricity.

Other methods of capturing renewable energy like solar thermal, wind, and hydropower might be used in self-sufficient cities, but to keep the model simple we have not included them in the analysis. In fact, with the exception of geothermal energy, all other types of renewables are second or third order derivatives of solar energy. The variation in solar energy over most of the inhabited world is a factor of about 3-4 (on an annual basis), whereas there are many parts of the world where there is no hydropower or little usable wind energy.

Generating energy on site – at the point of use – avoids the transmission losses that are associated with off-site generation. PV can be deployed at a range of scales, and can be economically integrated into building facades and roofs as Building Integrated PV (BIPV), and urban infrastructure. In addition to transmission efficiency benefits, multiple local generation sources add robustness and redundancy to the city's energy grid.

3.4. Energy Storage

The use of any intermittent energy source such as solar requires storage to provide power whenever it is needed, day or night. The 2050 City will need to have an adequate energy storage capacity, the size of which is dependent on the variability of local sunshine, as well as on short or long term changes in the city's use of power. The city's generation capacity is sized to provide all its energy, including losses for storage.

With the exception of some pumped hydropower installations, there are presently no municipal-scale energy storage systems. Batteries, thermal storage, compressed air, flywheels, and hydrogen fuel cells are all possible technologies for future use at that scale. Some storage methods are suited to short-term use, in periods of seconds to hours; others are appropriate for longer durations up to weeks or months. By 2050, storage will become more integrated into every scale of infrastructure. Energy storage is already universal in portable electronic devices; it is growing in importance in vehicles; and we believe it will be eventually routinely integrated into buildings and the civic network. Since we are not investigating technical details of energy storage, we postulate that appropriate combinations of these technologies will be accommodated within our city boundaries without requiring additional space.

All activities in the city function directly on electricity, or indirectly on fuels derived from it. At present, the most challenging application for renewable-electric energy is transportation, particularly aviation, which is the largest part of the 2050 City's external transportation energy. Currently, storing renewable energy in fuels with sufficiently low weight and volume is a technical problem. However, options such as hydrogen fuel or metal oxides could be technically and economically feasible by 2050.[iv]

Since the sun is our only source of power, by definition our zero-energy city is also a zero-carbon emission city. There will be some (smaller) amounts of embedded carbon in materials and some greenhouse gasses produced in agricultural processes. As we focus on energy and not carbon, we have not addressed these emissions in this study.

4. Water

Water is as fundamental an issue as energy for the future. Many of the new cities that will be built by 2050 will be in areas with little or no fresh water supply. Regions of the world with significant rainfall typically have no spare capacity to supply new urban development, and conflicts between traditional agriculture and cities intensify. The energy sector also is a major user of water – as large a user as agriculture in the US – for cooling of thermal fossil fuel power plants. The boom in natural gas extraction via hydraulic fracturing will increase demands on water supply, while posing risks to aquifers.

For this study we take a conservative approach to the question of how much surface water (from lakes and rivers) and how much aquifer water can be sustainably extracted. According to some, it is appropriate to extract all the water from a river system (such as the Colorado in the western US, where so much water is withdrawn that little or none reaches the sea). From another point of view, any extraction of surface waters alters the ecology of the watershed, and should not be done. In any case, sustainable extraction rates of water will be location-specific, and may change significantly by 2050 as the climate changes, making some regions wetter, others drier. Consequently the 2050 City uses no surface water or aquifer water: all water supplies will be from rainfall within the city, plus desalinated seawater.

Because of its enormous volume, seawater can be regarded as a sustainable resource. Currently, human society uses 9,000 billion cubic meters of fresh water per year, the equivalent of 0.0007% of the 1.3 billion cubic kilometers of seawater. At this rate, in 1,000 years less than 1% of sweater would be "consumed". But of course most water is not permanently lost, and some could be resalinated and returned to the sea.

There are economic and environmental issues with desalination. Most desalination today is by thermal processes using waste heat from fossil fuel power generation. For this study, we assume all desalination will be by reverse osmosis processes powered by PV electricity.

Another issue with desalination is the proximity of inland cities to seawater. For better or worse, however, most urban development occurs on or near coastlines. Of the forty largest cities in 2009, twenty were directly on the coast or within 25 kilometers of it; the average distance to the coast of all 40 was 200 km. For cities very far from seawater, pipeline construction and pumping costs could be significant issues, but today major cities such as Los Angeles pump fresh water thousands of kilometers over mountain ranges to the sea coast, so comparable infrastructure could pump water in the other direction, from the coast inland.

Disposal of brine (concentrated saline solution, a byproduct of desalination) is another issue to be dealt with sustainably. Today, some valuable resources are extracted from brine. In the future, we believe the trend toward intensive resource extraction processes and recycling will render most or all of the components of seawater into useful resources.

5. Food

All the food consumed by the population of the 2050 City will be grown within the city boundaries.

Current industrial food production has high environmental costs in terms of water and energy use, pollution via runoff of fertilizers and pesticides, and loss of habitat and wilderness. It also consumes a great deal of land, far more than what could fit within an urban area.

The 2050 City concept depends on producing all foods with the lowest possible physical, environmental and energy footprints. All food production is within the boundaries of the city, so remote growing is not considered. A solution to many food-related problems (land area, water use, food security) is controlled environment agriculture (hydroponics), which consumes one-tenth the amount of land and one-twentieth the amount of water as field agriculture today. Hydroponically grown produce and fodder can be grown without pesticides or traditional fertilizers, year round, without disruptions due to weather or drought.

We evaluate two types of controlled environment agriculture: greenhouses, or indoor growing. Greenhouse crops are grown primarily using "free" direct sunlight (sometimes supplemented with artificial lighting during darker months). A significant advantage for urban applications is that greenhouses can be integrated into building facades and roofs, with a variety of possible symbiotic benefits. Depending on the climate, however, greenhouses can require a large amount of energy for heating and/or cooling.

A second option is "indoor" agriculture, using electric light instead of sunlight. Indoor growing can require much less heating or cooling than greenhouses, as it can be done inside well-insulated buildings, or even underground – and spaces without access to sunlight are generally less valuable, as they are less suited to human use. On the other hand, it takes a great deal of light to grow food crops – the equivalent of full sunlight for most crops – and, due to the inefficiencies of light fixtures, delivering that amount of light artificially takes more energy than what is available directly from the sun.

The human diet, particularly the amount of meat consumed, has a disproportionate effect on food growing area (as well as on energy use), as land area to feed livestock is considerably greater than land used to grow vegetables for human consumption. Trends show meat consumption increasing globally, as well as (at a lower rate) within North America. To be conservative, our model is based on the 2010 North American diet, with no change in the consumption of meat by 2050.

6. Urban Quality: Density and Physical Parameters

The 2050 City is meant to have a physical infrastructure that supports a high quality of life for its residents.[v] We chose a medium size population of 1 million for the 2050 City. UN demographic projections predict the largest share of urban population by the year 2025 will be in the smallest size class of cities (less than 500,000 inhabitants); of the larger city size classes, the greatest population is projected to be in cities in the 1-5 million range.[vi]

The population density of the 2050 City core is 15,000 inhabitants per square kilometer, a mid range number among major cities. To put this in perspective, Paris has a density of about 21,000 persons/km2; all of New York City is 10,500 persons/km2; Manhattan borough is 27,000; and Brooklyn is 14,000. We designate 20% of the core city area as green space.[vii] At this density the area of the 2050 City's urban core is 67 km2.

The 2050 City model is currently evaluated for one climate zone: Humid Continental, specifically using New York City data. Other climate zones will be modeled in future studies.

7. Consumption

Individual quality of life drives the resource consumption of the 2050 City. The amount of dwelling space per person, comfort standards for buildings, diet, travel patterns, and many other factors determine how much energy, water, and mineral resources are consumed. Historically, consumption increases with time and with increasing wealth. North Americans have among the highest rates of consumption in the world today, with the developing world trending in the same direction. We believe it is conservative to assume that the world will approach this level in the future. Therefore we base space standards, diet, personal travel, and other personal parameters for the 2050 City on those of urban North Americans today.

8. Technological Progress

The 2050 model depends on efficiency improvements in every aspect of the city's operation. Between 2010 and 2050, we expect efficiency to increase for heating and cooling buildings, for consumer devices, and for cars, buses, and aircraft. Assumptions about technological progress are listed in Table 1. Many of these are optimistic in terms of timing, but all are based on improvements in current technology – no fundamental breakthroughs required. These are discussed in more detail following.

Table 1 Key technological improvements in the 2050 City

Item	**Change by 2050**
PV efficiency	200%
Building energy consumption in 2050:	-75%
Controlled Environment Agriculture:	
Greenhouse heating/cooling consumption	-75%
Greenhouse lighting:	-75%
Field Agriculture	
Land	-20%
Cultivation energy	-20%
Food processing	-20%
Transportation	
Road vehicles:	-40%
Trains and subways:	-30%
Air travel:	-20%
Water	
Personal consumption	-50%
Agriculture	-94%
Recycling	525%
Net Water Use	-99%
Overall Land Use	
Energy	-52%
Food	-95%
Net Land Use	-91%

8.1. Photovoltaics

Improvements in Photovoltaic technology are central to the viability of the 2050 City. We have projected that PV module efficiency will reach 36% or higher by 2050, so that the overall efficiency of the PV systems (including power conversion and other losses) will be 30%, almost double today's typical efficiencies. Today, non-concentrating PVs[viii] are commercially available at a maximum efficiency of about 20%. Laboratory efficiencies for non-concentrating PVs reached almost 36% by 2011. For commercial PVs, this will require an efficiency increase that is generally consistent with historical trends, though many technical uncertainties remain.[ix] Note that the theoretical limits for non-concentrating, multijunction PV devices approach 68%.[x] Thin film modules at this efficiency level could be very cost effective, possibly producing electricity at lower prices than any commercial energy source today.

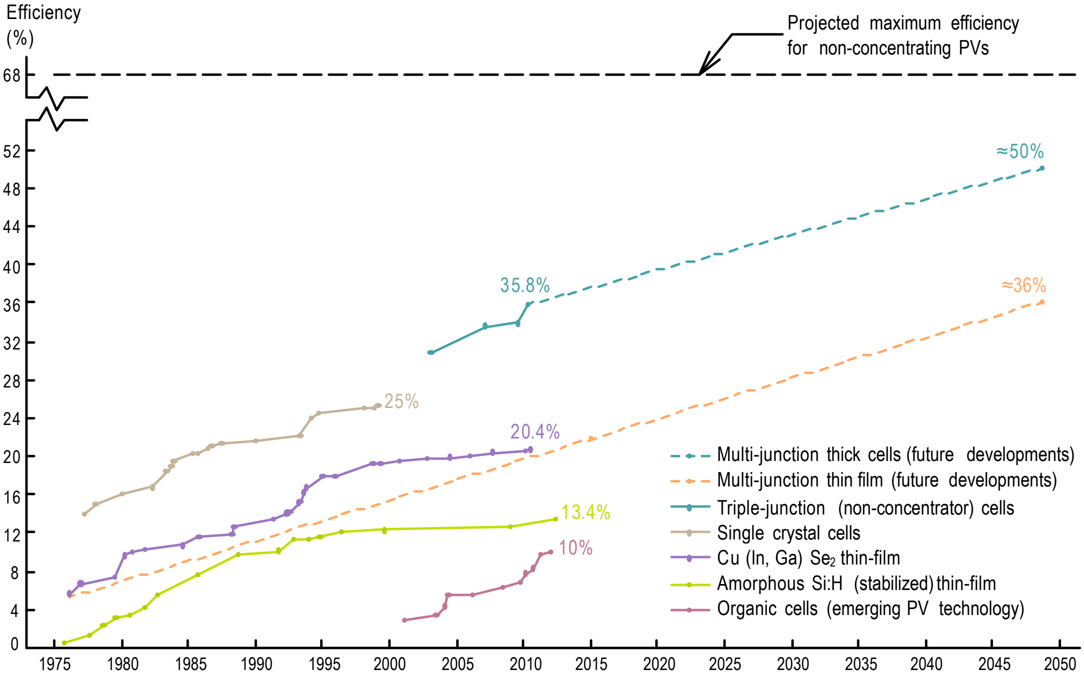


Figure 3 Historical trends in PV efficiency, with projections to 2050 (source for existing data: National Renewable Energy Laboratory)

8.2. Controlled Environment Agriculture (CEA)

CEA is essential for space- and water-efficient food production for the 2050 City. **Hydroponic** crops are fully commercialized today, principally lettuces, tomatoes, peppers, and cucumbers. Most other vegetable and fruit crops are being developed for hydroponic cultivation. Nuts and grains currently are the least advanced in terms of hydroponic deployment, but we assume that these will be viable by 2050 as well.

Although hydroponic growing systems use much less water and less energy for cultivation and transportation than conventional outdoor farming, the greenhouses that contain the hydroponics presently can consume very large amounts of energy (depending on the local climate). Artificial lighting, which is commonly used in greenhouses, can also consume significant amounts of energy. Solving these two issues – limiting energy use to heat and cool greenhouses, and using artificial lighting efficiently – are essential to achieving space- and water-efficient urban agriculture. Even with substantial progress in efficiency for heating/cooling and lighting these spaces, however, controlled environment agriculture will consume more energy than field growing. this must be balanced against the benefits of land use reduction, water savings, and resiliency and security.

We believe that a great deal of progress can be made in these areas. Greenhouses can be made more airtight, conditioned volumes drastically reduced through optimizing the size of the greenhouse itself, and/or conditioning the air within energy curtains. More efficient heating and cooling systems can be used.

The most space-efficient growing scenario would be indoors, where entirely artificially-lit systems can be stacked at very high densities. Indoor systems could be in the center of large buildings, where there is little or no natural light available, or underground. These will require more energy use for artificial lighting than greenhouses, but may have lower space conditioning loads. If indoor systems are underground, their spatial footprint effectively goes to zero, but there may be more PV generation area required to power them. The balance between space and energy efficiency will determine their applicability to the self-sustaining city.

Note that in the category of hydroponics we include related technologies like aeroponics, fogoponics, and aquaponics.

8.3. Water

In many parts of the world, access to fresh water is the single biggest health and environmental issue. Through a combination of systems – CEA food production, treatment and reuse, rainwater capture, and desalination, the 2050 City reduces net water use by almost 99%.

8.4. Transportation

Compared to agriculture and civic energy use, the 2050 City model projects modest increases in transportation efficiency, ranging from a 40% reduction for cars and trains, to a 20% reduction in air travel.

8.5. New Technologies and Unforeseen Demand

While it is impossible to predict all the consequences of technological change over 40 years, we should address the Jevons Paradox, which holds that increasing efficiencies are cancelled by lower costs and increasing wealth and consumption.[xi] In the case of the 2050 City, the potential for this effect should be minimized by the supposition that the 2050 City's density remains the same over the next 40 years (many cities are limited in extent by geographic features, political boundaries or land use policies), limiting easy expansion of living space and commuting distances. Also, given the already high level of consumption by world standards, we do not expect large increases. However, we have included a category for new, unanticipated energy consumption that increases from zero in 2010 to about 5% of the city's operating energy use in 2050 (this is admittedly an arbitrary number).

9. Production/Manufacturing

Although we do not study the economic and social operations of the 2050 City, the ability to manufacture within the urban environment is central to the idea of self-sufficiency. In the developed world, manufacturing's share of urban economies has been declining for decades, with much of that capacity moving to cities in the developing world. For the 2050 City, we include the embodied energy of goods consumed by the city's residents. We assume that the manufacturing capacity to produce the equivalent of these goods exists within the city limits as part of the urban infrastructure.

For illustrative purposes, the Foxconn manufacturing campus in Shenzhen, China, that manufactures a variety of computers and other personal electronics provides about 230,000 jobs, and houses over 57,000 workers. This single complex provides more manufacturing jobs than needed for the entire 2050 City population of 1 million.

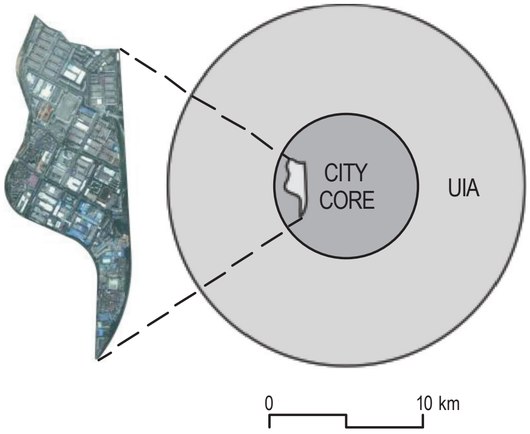


Figure 4 2050 footprint showing manufacturing area - Foxconn campus, Shenzhen (2.8 km2, 230,000 workers, 58,000 dwellers), overlaid on the upper left.

10. Nonrenewable Resources and Recycling

It is difficult to predict the availability of non-renewable resources such as minerals by 2050. Already many resources used in manufacturing are constrained. Photovoltaic panels are one example of this, with thin film products reliant on limited elements such as indium, tellurium, and several others. For the purpose of this study, we take the (perhaps optimistic) view that a combination of increased recycling and alternative technologies will manage these problems. It may be that alternative materials will be less efficient or more expensive, but as economics are not explicitly part of this study, we assume these developments will be generally economically feasible.

11. The 2050 City Model

We developed a spreadsheet model that includes weather data New York's climate zone, as well as provisions for energy consumption and generation, water consumption and collection, embodied energy, and food production requirements. All quantities in this model are expressed in terms of energy – kilowatt hours (kWh) or gigawatt hours (GWh) and space – square meters (m2), or square kilometers (km2).

We have not included the effects of climate change in the model, leaving input parameters such as temperature and rainfall fixed for the duration of the study.

The most significant variable in our model is the agricultural system. This affects both energy and spatial results (with implications for water use, food security/resilience, and other issues as well). We have included five scenarios:

Figure 6 The components of analysis for the 2050 City.

1. Current field agriculture (2013 conditions)
2. Hydroponic greenhouse-based agriculture (2020 conditions)
3. Field agriculture (2050)
4. Hydroponic greenhouse-based agriculture (2050 conditions)
5. Indoor hydroponic-based agriculture (2050 conditions)

The spreadsheet model inputs are organized in the following categories:

Table 2 Input Parameters for the Model

- CITY PARAMETERS
  - Population
  - Area
    - Density
    - Green Space
    - Net Buildable Footprint (nominal blocks)
    - Built footprint
  - Built Area
    - Residential
    - Commercial
    - Average Urban FAR
    - Average Built FAR
- RESOURCE AVAILABILITY
  - Energy
    - Insolation
    - Built area coverage
    - PV Area rooftop
    - PV Efficiency roof
    - PV Façade %
    - PV Area Façade
    - PV Efficiency facade
    - Total renewable energy demand
    - Storage losses
    - Total Energy demand
  - Water
    - Rainfall
    - Utilization %
    - Available Rainwater/Recycling rate/ Desalination quantity

Table 3 Output Categories for the Model

RESOURCE CONSUMPTION	
Energy	(GWh/year)
	Operating
	Building energy consumption
	residential
	non-residential
	City Infrastructure
	Other Internal - New
	Food Energy
	Water Energy
	Transportation - internal
	passenger car
	transit buses
	railroad
	Transportation - external
	air domestic
	air international
	Embodied Energy Total

12. Model Results

12.1. Energy: Comprehensive Analysis

An output summary for New York City climate conditions in 2010 and 2050 is shown in Table 3. Highlights include a substantial increase in the efficiency of traditional operating energies, which reduces operating energy consumption by more than 50% from 2010 to 2050. At the same time, the switch from open field farming to controlled environment agriculture brings substantial increases in the energy of food production. The 2050 hydroponic greenhouse scenario is the lowest energy CEA option; in total it represents a slight decrease in total energy use from today's scenario. The indoor growing scenario results in total urban energy use over twice that in 2013. A doubling of PV efficiency by 2050 cuts the area of the solar infrastructure in half.

Table 4 Results Overview for NYC Climate

Energy	Unit	2013 (Field Agriculture) GWh/year	2020 (Greenhouse Hydroponics) GWh/year	2050 (Greenhouse Hydroponics) GWh/year	2050 (Indoor Hydroponics)	2050 (Field)
Total Operating Energy		19,085	14,131	8,486	8,486	8,486
Embodied Energy/year	GWh/year	6,644	6,644	5,315	5,315	5,315
External travel	GWh/year	10,315	10,315	7,368	7,368	7,368
Food	GWh/year	7,717	161,879	30,469	53,740	5,867
Water - Desalination + Rainwater Treatment	GWh/year	10,197	847	33	33	4,500
Total Energy Consumed	GWh/year	53,958	193,815	51,670	74,941	31,536
Area						
Urban Core	km2	67	67	67	67	67
Total Solar Generation Area	km2	244	661	116	169	438
Total Food Growing Area	km2	4,500	338	236	-	3,600
Total City Area	km2	4,810	1,065	419	236	4,105

Note that in all sectors except food production, energy use declines between 2013 and 2050. On an area basis, however, the reduction in growing space associated with CEA techniques more than compensates for the additional PV.

Figure 7 illustrates the five scenarios. The energies for the current, field-agriculture based city is about one third internal operating energy, one third food-related plus the energy to desalinate all water, with the remaining third composed of embodied energies and external travel by the city's inhabitants. We have included one case for 2020 – the near future – to illustrate the near-term implications of hydroponic technology, with its large energy consumption.

For 2050 we have three scenarios – greenhouse CEA, indoor CEA, and field agriculture. As outdoor farming is a much more mature practice than CEA, we have assumed smaller increases in efficiency and productivity over this period. This is by far the lowest energy option illustrated – but as modeled here, we ignore the solar energy inputs on outdoor farmlands. If the sun's energy input were included, the outdoor farming option would consume approximately 100 times as much energy as the CEA alternatives.

In the two CEA alternates, lower heating/cooling energy in the indoor scenario is offset by higher artificial lighting.

Note also that embodied energy, external travel by the city's inhabitants, and the desalination and processing of water account for a large amount of energy in absolute terms, as well as in relative terms – over 50% of the total in three of these five scenarios.

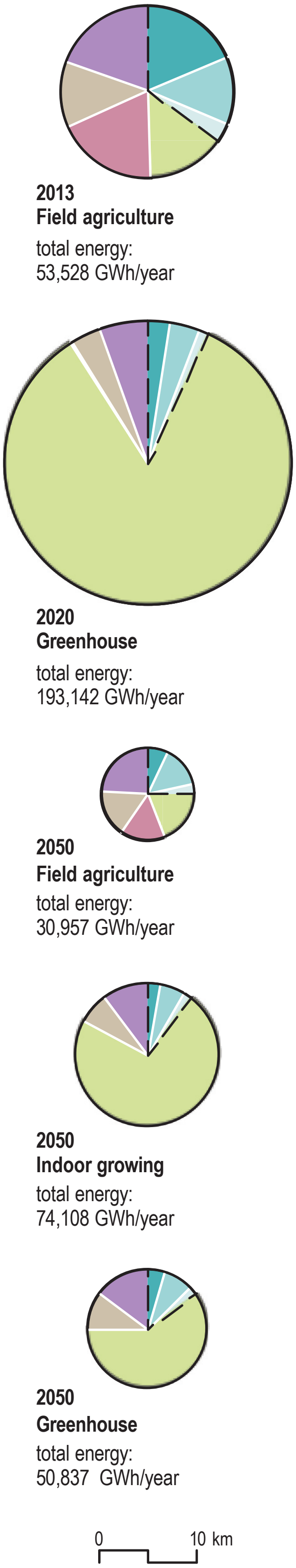


Figure 5 Comprehensive energy use for various scenarios for the 2050 City. The area of each pie chart is proportional to the PV area required to generate it.

12.2. Water Supply and Energy Use

Our model in the 2010 case is based generally on North American water usage, which is among the highest in the world. We predict a large reduction in usage by 2050, to a level about 50% less than European usage in 2010. New York is fortunate in having a significant amount of rainfall – about 1m/year.

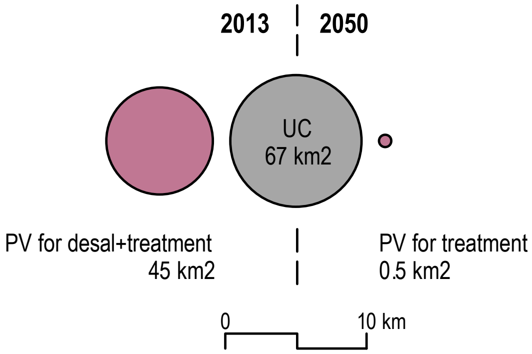
There is essentially no rainwater capture or water recycling in 2010, transitioning to high levels in 2050. Combining these factors with energy efficiency improvements in desalination, there are dramatic reductions in water use and water energy-related consumption. We have budgeted 5 kWh/m3 to desalinate in 2010, decreasing to 3 kWh/m3 by 2050.

Key points in the evolution of water practice and technology are:

- Between 2010 and 2050, there is more than a fourfold reduction in water use per capita (from 200 LPD, current North American usage, to 100 LPD, which is 50% less than current German usage)
- Water recycling rates increase from 1% to 80%
- Rainwater utilization increasing from 0% to 50%
- Desalination energy efficiency increases 40%

These result in:

- The 2050 City functioning on collected rainwater alone by 2050 – the need for desalination ends between 2020 and 2050 (cities in climates with less rainfall would likely still need to desalinate in 2050)
- The only water-related energy cost coming from rainwater treatment systems.



- Figure 6 PV area required to treat water sources (desalinate sea water and/or treat rain water) for the 2050 City.

12.3. Transportation Energy

Transportation will account for more than a third of energy consumption in today's (field agriculture-based) City. Once energy intensive CEA is included, transportation energy becomes proportionally smaller, but still significant. Internal travel in cities is generally highly efficient, depending on the availability and quality of mass transit. The largest component of transportation energy is external travel, and of this the largest component is air travel. We account for the energy consumption of external travel for the city's residents (but not for visitors, as their travel footprint would be accounted for in their home cities).

We assumed 3,300 km of domestic air travel per person per year, and 789 km international travel per person per year. We show no change in travel distances between now and 2050. There are statistics showing increasing travel in both developing and developed countries, but also some evidence of saturation, or "Peak Travel" effects in developed countries.[xii]

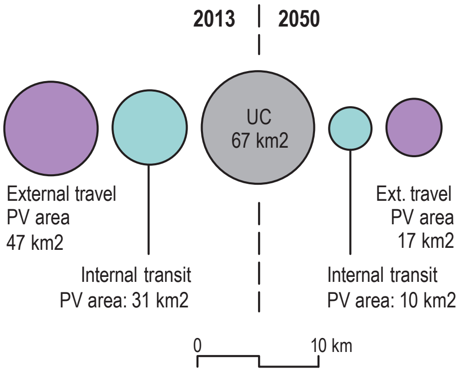


Figure 7 PV areas required to generate the energy used in various forms of transportation, 2013 and 2050

12.4. Food Energy

Food is a large part of the energy mix of the 2050 City. From about 14% of the total in the current agricultural system, the percentage of food energy increases to over 80% for hydroponic greenhouses in 2020 (when the technology is not fully mature) to 59% for greenhouses in 2050, and 72% for indoor growing in 2050. For 2050 field agriculture, the percentage is 19%.

Clearly there is a price to be paid in energy for controlled enviornment agriculture, even with our aggressive assumptions about improved efficiencies. The benefits of CEA are discussed further in the spatial analysis, following.

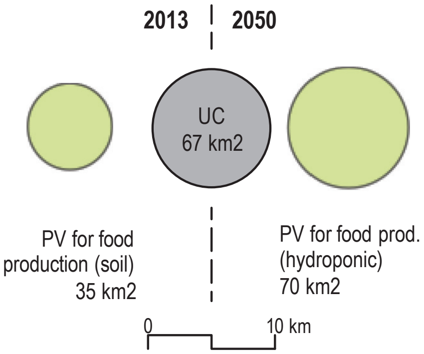


Figure 8 PV area to supply energy for food production for the 2050 City.

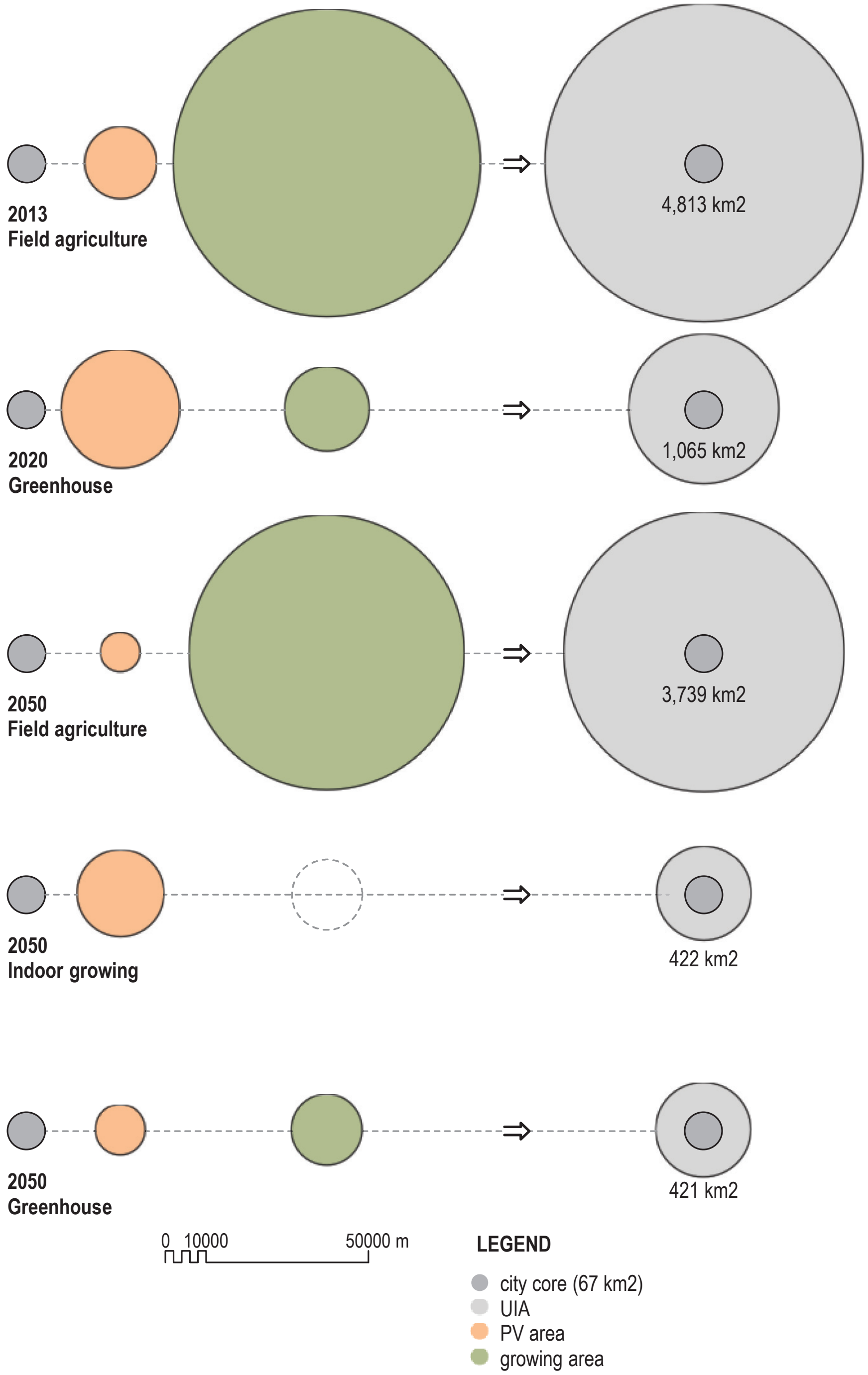


Figure 9 The spatial dimensions of 5 scenarios for the 2050 City.

13. Spatial Analysis and Density

The first part of the 2050 City analysis quantifies all urban processes in units of energy. Providing this energy by photovoltaics is functionally and environmentally self-sustaining, but requires substantial land areas. Figure 11 summarizes the space requirements of our five options. The energy areas (orange circles) are the same as those in Figure 7; added to these is the urban core area (67 km2 in each case), plus the area required to grow food. For indoor agriculture, the food growing area is shown as zero – denoted by a dotted circle of equal size to the 2050 greenhouse area. Of course indoor growing does take up space, but since it can be underground, it potentially will not add to the footprint of the city.

The total area of the city, including infrastructure, is indicated by the gray circles at the right.

13.1. Growing Food

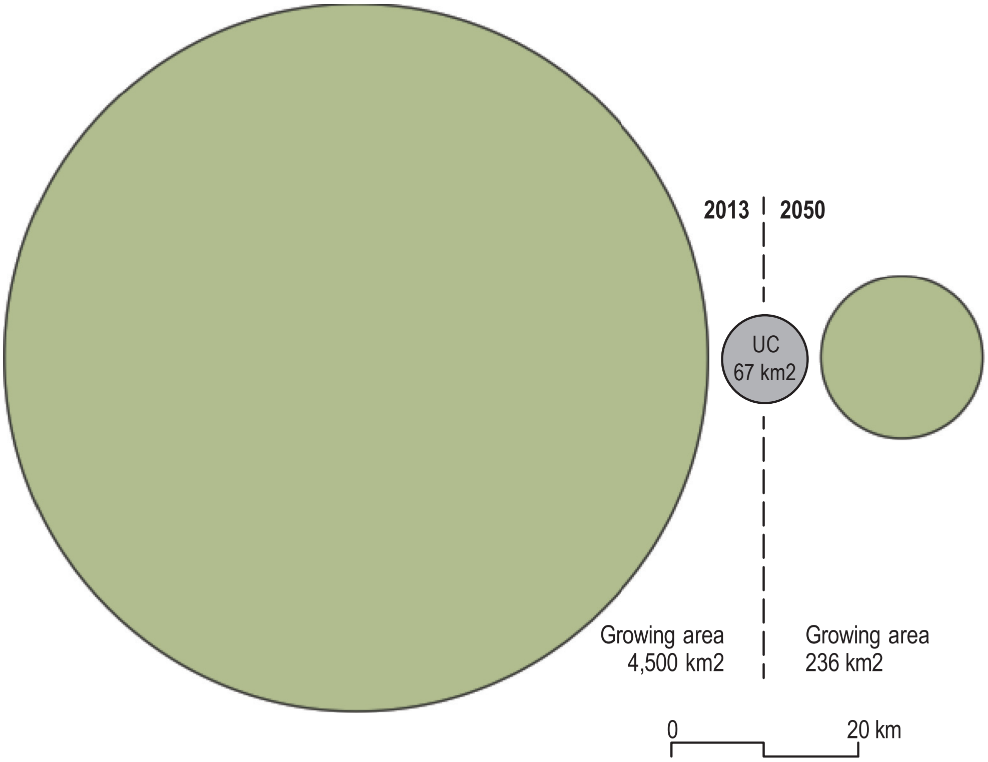


Figure 10 Areas required to grow food by field agriculture, 2010, vs. hydroponic cultivation, 2050

In three out of five of our scenarios, food growing is the single largest component of the city area.

Currently, the food system footprint is more than 67 times larger than the area of the city it serves. Shifting crop and animal feed production to hydroponic greenhouses, combined with other efficiency improvements, reduces the food system footprint to about 3.5 times the city area – an almost fourfold reduction.

Our model shows the productivity of hydroponic greenhouses (in kilograms of crops produced per square meter) increasing by 30% by 2050, which reduces the required greenhouse area by the same amount. Further reduction in the spatial footprint of greenhouses could be achieved by increasing the amount of artificial lighting.

Any greenhouse area savings due to artificial lighting space savings would be offset (partly or completely, depending on the net PV-lighting-growing efficiency) by increased solar area to power the additional lighting load. Whether artificial lighting via optimized LEDs can be as energy-efficient as the direct use of natural light remains to be seen. It will be a technological challenge to come up with a system where PV – at a conversion efficiency of 30% in 2050 – driving LEDs (with conversion losses of their own) will ever be more energy- or space-efficient than daylit greenhouses.

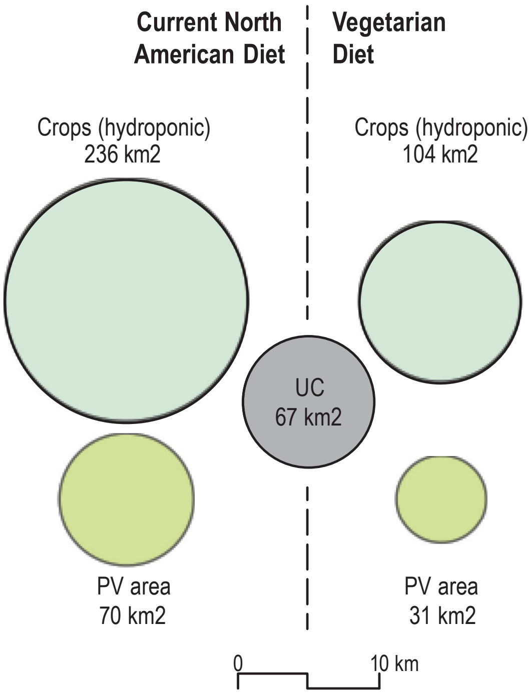


Figure 11 Areas required to grow food hydroponically, for the current North American diet (top) and a vegetarian diet (bottom).

13.2. Diet

Animal feed takes up a large percentage of the total growing area for the 2050 City. As animals eat about 60 kg of feed per kilogram of meat produced, they are a very inefficient way to use agricultural resources. Accordingly, reducing the amount of meat in the human diet will have a disproportionate effect on the spatial requirements of the 2050 City. Eliminating meat from the diet reduces greenhouse areas by a factor of more than 2, even after accounting for an increase in human vegetable consumption.

13.3. Integrating the Infrastructure

There will be challenges in locating the entire food system within the city. In addition to the complexities of integrating greenhouses into buildings and public spaces, there will be issues involving animal accommodation, slaughtering and processing. We assume that physical issues such as sanitation and odors can be controlled, but other cultural and religious objections may have to be overcome as well.

The area of the 2050 City is the sum of two components: the Urban Core (UC) plus the Urban Infrastructure Area (UIA). The Urban Core is equivalent to the legal city limits of a contemporary city, not including suburbs and other peripheral areas. (Note that the extent of city limits varies greatly between cities, yielding very different densities.) The Urban Infrastructure Area is the land required to generate solar energy to supply the city's comprehensive energy requirements, plus the area required for growing food. For a typical city today, the UIA is highly dispersed, including remote farming, energy extraction and generation, and industrial production areas. In the 2050 City, all these areas are consolidated together and are contiguous with the UC.

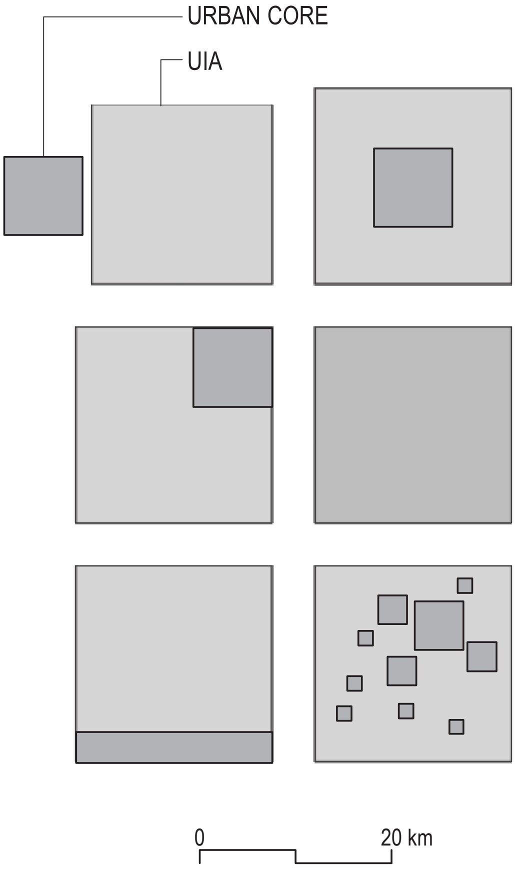


Figure 12 Zoning scenarios for the 2050 City.

Will a self-sustaining city optimally consist of separate districts, one type for living (served spaces) and another for resource production (servant spaces)? Or would it integrate the district types together, and still be of a size and density that feels and functions like a city? Will it have the necessary density to support urban transit, commerce and culture? Or perhaps a hybrid urban type could be developed, with lower density districts with a suburban quality.

For a contemporary city, the infrastructure area is much larger than the urban core. For New York City today, the infrastructure area (40,830 km2) is about 52 times the size of the city, clearly too large to be integrated into it. It is larger than the State of Maryland (32,000 km2). Needless to say, it is also a widely dispersed area, with food, goods and energy coming from many different parts of the world.

Table 5 Urban areas/infrastructure areas comparison.

	NYC-2010	2050 City (Greenhouse)
Urban Core (UC)- Km2	781	67
Urban Infrastructure (UIA)-Km2	40,830	418
Ratio UIA/UC	52	6

For the 2050 City, the Urban Infrastructure Area is dramatically smaller, due to increased efficiency (decreased demand) on the consumption side, more efficient PV technology (requiring half the area to generate the same power), and most significantly, switching from outdoor farming to indoor hydroponics, which uses one tenth the land area.

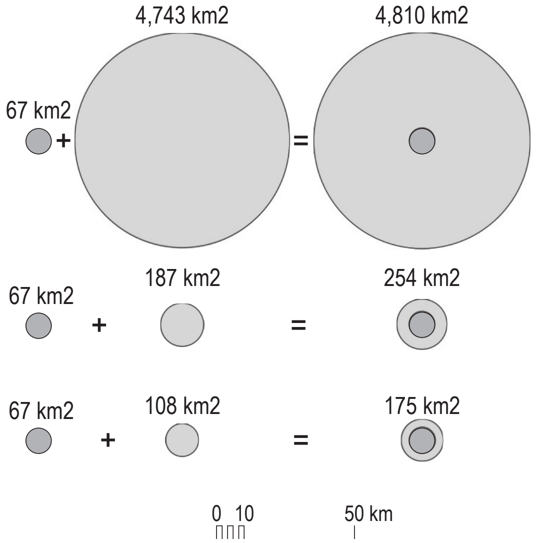


Figure 13 Comparison of Infrastructure Area with Urban Core for the 2013 City (soil-based Agriculture), top; the 2050 City (hydroponic agriculture), center; and the smallest possible 2050 City (indoor, vegetarian diet), bottom.

The 2050 City has a population of 1,000,000 and a density of 15,000 people/km2. This is greater than New York City's overall density, slightly greater than the density of the Borough of Brooklyn and significantly less than that of Manhattan. Table 5 lists the density of the 2050 City in two ways – the Urban Core alone, and with the Urban Infrastructure area added. Note that for the indoor growing option, the combined density drops to 4,240. The combined number, while much lower than New York or Paris, is similar to less dense cities such as Los Angeles. As density is one of the essential determinants of the viability and quality of a city, managing the lowered density 2050 City will be an important design challenge.[xiii]

Table 6 Density comparisons between urban areas.

		Population	Area(km2)	Density (people/km2)
2050 city	UC	1,000,000	67	15,000
(Greenhouse)	UIA		352	
	TOTAL		421	2,376
(Indoor, vegetarian)	UIA		108	
	TOTAL		175	5,716
NYC overall (2013)		8,200,000	781	10,500
Manhattan		1,601,148	59	27,138
Brooklyn		2,532,645	183	13,840
Paris		2,211,297	105	21,060
Los Angeles		3,792,621	1,302	2,913

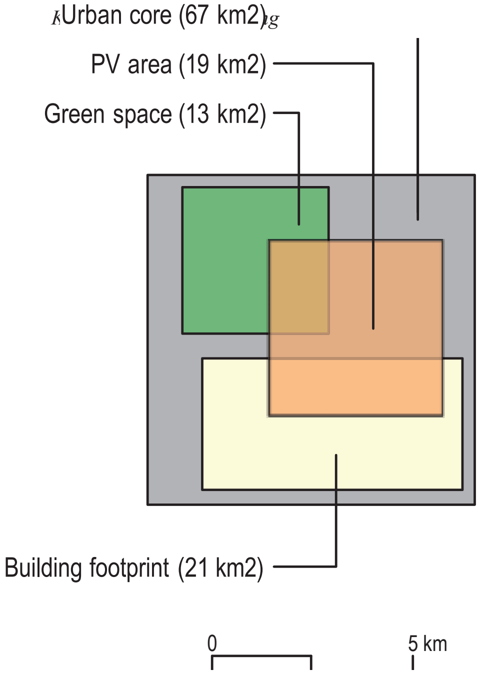


Figure 14 Infrastructure Areas for operating energy and vegetable production superimposed on the Urban Core, based on 2050 conditions.

13.4. "Net Zero" Cities

By the less stringent performance standards of a "zero energy" or "zero carbon" city – as it is typically defined today, considering internal operating energy only – in the New York climate, the UIA for the 2050 City (including solar generation for internal operations) is only about 19 km2, less than one third the Urban Core area and less than the rooftop area of the city's buildings. By the zero-operating energy standard, a self-sustaining city in 2050 could look much like a typical US city today.

14. Summary and Conclusions

The 2050 City is possible. In the most optimistic case, an entirely self-sustaining city can be accomplished at a net density of just over a third of the original urban core of 15,000 residents per square kilometer. Technically, this is a significant accomplishment; it remains to be seen how the components can be integrated into a viable city.

In terms of energy, the scale of the problem is more than three times larger than presently imagined. If a goal of policy makers, developers and designers is to move toward zero negative environmental impact, the scope of solutions must address every impactful source. Including embodied energy of production and transportation energy increases the total energy requirement by a factor of three compared to operation energy only. Fortunately, an urban-scale solution seems possible on a technical (and spatial) level.

The self-sustaining city can be achieved by technical means only, but behavior changes make the process easier, and possibly the result better. Switching to a vegetarian diet would drastically reduce the 2050 City footprint, while possibly improving the inhabitants' health.

Agriculture is a dominant issue. Spatially, it is the largest component of most of the 2050 scenarios. Based on the current North American lifestyle, the area needed to grow food for the 2050 City is very large – currently more than 50 times the size of the urban core. Our most optimistic technical scenarios for agriculture have growing areas more than three times the size of the urban core. the degree to which CEA is implemented will be based on judgments of the value of land and water saved, pollution and pesticides eliminated, and food security and resilience enhanced. It is quite possible that the best solution for real locations will be based on the amount of land available locally for sustainable outdoor farming, and local climate conditions.

On a practical level, the closed-loop city will probably not be a serious option – but its equivalent may be. A system providing the *equivalent* of 100% on-site production may be a more useful planning goal than full autonomy. It may be realistic to provide 100% energy generation on site, on a net basis, but in an interconnected world it would not be necessary to provide full energy storage for times the sun does not shine. If other cities (or other energy sources) were generating only renewable energy, the sharing of power would be subject only to transmission losses (which might be lower than losses incurred in local storage systems, for a net efficiency benefit). In such a renewable network, especially one dispersed over a wide enough area to cover different weather and time zones, the need for local storage would be greatly reduced.

The production of food and products could also even more from a distributed model. Again, a standard could be set to produce the equivalent of 100% of both of those categories, but this would be done on a net basis, so each city would produce at least the total mass (kg) of food it consumes, but would be able to overproduce in some areas and under produce in others.

Likewise, manufactured products could be produced in a similar system, where the equivalent of 100% of production in terms of monetary value, or embodied energy, or mass, would be produced locally.

Our model is entirely city-based. It might be that in the context of the real world forty years from now – assuming the 2050 City model does not become the norm, impacts and solutions will be divided differently. Responsibility to account for environmental impact could be assigned to the economic sphere and the corporation, so that energy and emissions of the construction industry would be repaid by that industry, with methods and in locations of their choice; likewise with the travel and food industries. Or, responsibility could be at the political level, by nation, or state, or region. Our city-based model has the advantages of simplicity and comprehensiveness (all costs are paid for at the point of use), and clarity in terms of the world's development in the next generation (essentially all of which will be urban).

Embodied energy is becoming more important relative to operating energy. As operational efficiencies increase, embodied energy becomes a greater fraction of lifetime energy use. Analyzed in this light, designers will need to shift their attentions to material selections, construction techniques, phasing, maintenance, and flexibility in planning, disassembly and reuse of materials.

External transportation is a significant issue. Long distance travel, especially air travel, is one of the greatest users of energy and sources of environmental emissions. City planning solutions must address regional and global transportation as seriously as internal design.

By current definitions, the "zero energy/zero carbon" city will be easy to accomplish. Today's green development standards, achieving zero operating energy will be possible with no impact on urban form or density. A total area of photovoltaics less than one third the city footprint would be sufficient to accomplish this. Most of this solar capacity could be installed inconspicuously on rooftops, with additional areas on facades and on urban infrastructure making up the rest.

The 2050 City is a city. Density is one of the defining characteristics of a city. For the 2050 City, adding the Urban Infrastructure Area will substantially reduce the density of the Urban Core. In our model the UIA ranges from about 3.5 to 62.2 times the area of the UC. Certainly some density can be regained by integrating infrastructure elements into conventional urban elements, such as rooftops, building facades, and certain parts of infrastructure. But there will be no avoiding the net loss in density, and the challenge will be to find creative and efficient ways to combine infrastructure with traditional residential, commercial, and cultural elements.

Nonetheless, compared to contemporary cities, in which the urban infrastructures are more than 150 times the area of their associated cities, we can say that a practical and psychological line has been crossed. No one would say that the 2010 version of the 2050 City – a district of 1 million people that comprises 4,810 km2 in area, or 208 people per km2 – is a city. By 2050, the combined city and infrastructure will have compacted to a district of as little as 236 km2 with 1 million people, a density of 4,240 people per km2 – comparable to many lower-density cities today. It remains to be seen whether cities with theses characteristics can enjoy the same density-derived qualities of transit and cultural and economic concentration as current cities do. Or the 2050 City may be zoned much like most cities today: a high-density center (with relatively little UIA) that has the characteristics of contemporary major cities, and less dense outer boroughs in which the major part of the UIA is integrated.

15. Further Study

This study leaves many important issues for future investigation:

15.1. Consumption and Quality of Life

The current North American lifestyle is the basis for our model. We do not make judgments about whether this lifestyle is indeed the highest quality, but the reality is that the world is presently trending toward it. However, this level of consumption may be regarded as a worst case: there may be saturation or even reductions with enough time and prosperity[xiv]. Policy and the economic effects of resource depletion may also force or incentivize reductions in consumption, which will make the performance goals of the 2050 City easier and cheaper to accomplish. Simple changes in diet or travel patterns would have a profound effect on the energy and spatial consequences of the 2050 City. A study seeking to optimize lifestyle based on health or happiness might yield a smaller, denser, less expensive city than the one in this study.

15.2. The Scale of Sustainability

Is the city the best (or the only) scale at which to be sustainable? It is a given that we must be sustainable on the scale of the planet, but it is not clear on what other scales sustainability can best be accomplished: the scale of a climate zone, a nation-state, a region, a city, a neighborhood, or a building?

Our current economic system generally assumes that bigger is better (or at least more efficient or economical), but does this principal apply to sustainability? One way to evaluate the options will be to compare self-sustainability at the scale of a city with larger and smaller regions. The 2050 City study provides a data point in a larger investigation. For example, we could imagine a network of cities of various sizes, none self-sufficient in themselves, connected with highly efficient transit, their size, location and economic activities optimized according to local cultural, political, and economic factors. Self-sufficient regions may be more efficient and interesting, with more variety and local character, than entirely self-sufficient cities.

Some sustainable systems may work better on smaller scales. In recent years there have been technological and commercial trends toward smaller, distributed systems, as in communications (cell phones), computing and entertainment devices (laptops, tablets, and smart phones), and distributed power (rooftop solar and electric cars).

Perhaps individual buildings of certain types, or districts of a particular use and density, could be self-sustaining; whereas other aspects of urban infrastructure (food or manufacturing systems) could be self- sustaining on a regional basis. Criteria might be developed to require self-sustainability on the smallest possible scale, on the principle that a finer grain of sustainability will lead to a more robust and resilient world.

15.3. Productive Cities and Aspiration

In some cases, an even higher level of performance than self-sufficiency is possible: by sustainably producing a surplus of resources (energy, water, food), a city can have a positive environmental benefit. We call this a *Productive* City. Productive cities may counterbalance less productive regions of the world, or existing cities that cannot be made self-sufficient.

It may not always be possible to achieve the level of positive performance on the urban scale, but we believe that the high aspirations such as these will encourage better quality development in other projects as well.

15.4. The 2050 City in Context

Planning the urban future is not just about the design of future cities, but also about the world they exist in. If self-sustaining cities are possible, the rest of the world could take on almost any imaginable form. Many current urban-rural relationships such as large-scale agriculture, centralized energy generation, and remote manufacturing would become less important, or even unnecessary.

We can refer to today's world to get a sense of how self-sustaining cities would fit within it. If we look at the densest part of the US, the northeast corridor between Washington and Boston, we can see the relationship between these cities, their individual footprints, and the density of the whole region. While Figure 18 leaves out the context between these cities (itself quite dense and extensive, by some definitions one continuous city), one might intuitively see that, in the best case, if the city footprints are barely larger than the city limits for these densest parts of the country, that there should be extra space to develop the rest of the region to the same standard.

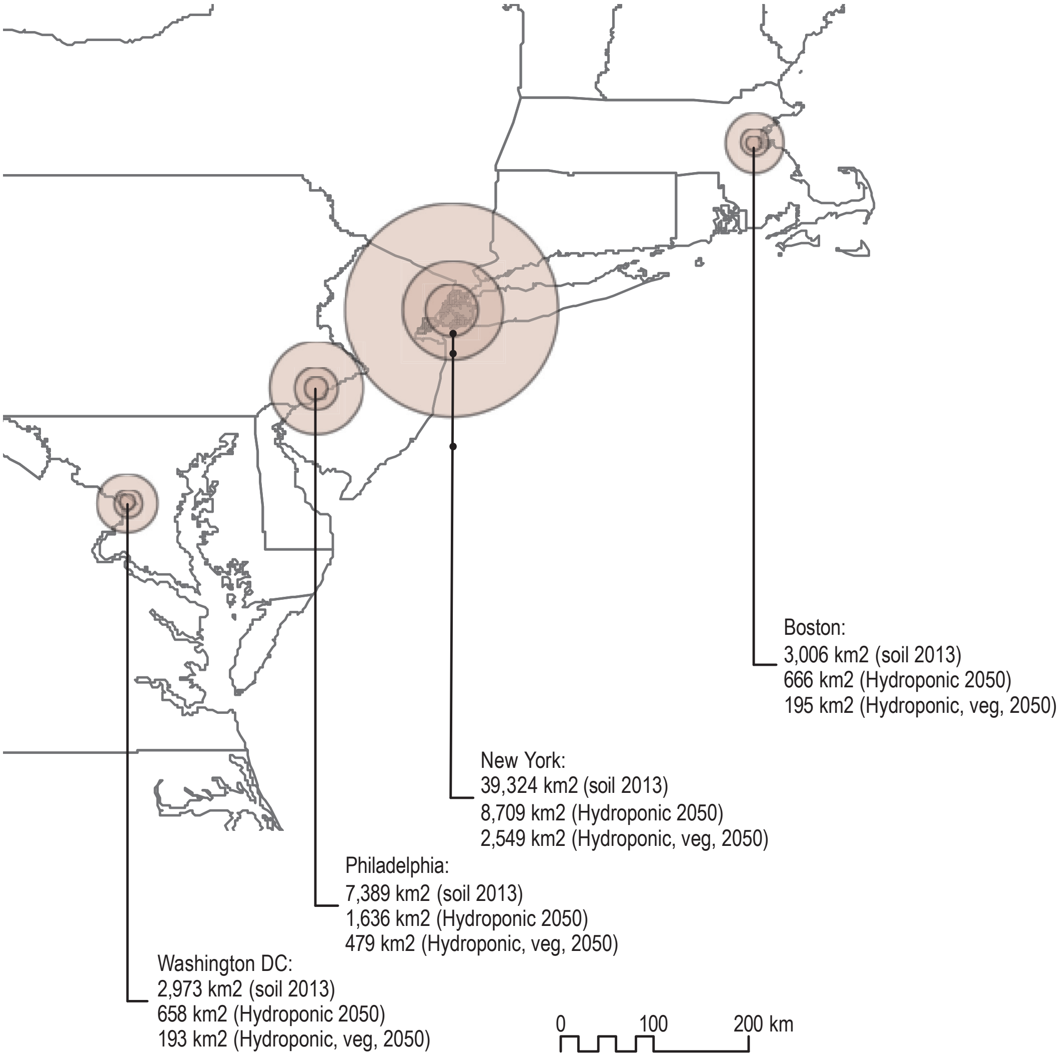


Figure 15 Three levels of environmental footprint for Northeast US cities.

An extreme vision for 2050 could be a planet of self-sufficient cities embedded in wilderness. This could allow agricultural and suburban land to revert to nature, which would enormously enhance natural habitat and could be a very large carbon sink. Drawing a sharper line between the city and the country could enhance the identity of each.

Of course, as a practical matter the world will never become exclusively urban. Many people will not choose to (or be able to) live in cities. For those who do not, increasingly self-sufficient urban areas could free up land occupied by industrial agriculture and energy infrastructure. This would create options for smaller scale agriculture, small town development, or new suburban models.

Figure 16 An extreme vision: self-sufficient cities surrounded by wilderness.

15.5. Designing the 2050 City:

The results of the 2050 City model provide a basis for more detailed and specific design. The design process will answer certain questions, some applicable in every case, some specific to climate, location, and culture: What will the 2050 City look like? To what degree can the UIA systems be integrated into the Urban Core; how do districts of differing densities and environmental functions integrate within the city; how might this environmental zoning impact internal and external transportation; and what will be the new relationship between cities, and between the city and the countryside?

Most likely, the 2050 City will not look like a 2010 city. It will not be possible to integrate all the new infrastructure within a contemporary urban core. At our specified density of 15,000 people per km2, less than 14%

of the required solar and greenhouse area can be accommodated on building rooftops and facades, leaving additional infrastructure 1.5 to 6.5 times the size of the core to be located elsewhere. This will force choices whether to lower the maximum density of the city to a uniformly lower level, or to create districts of varying function and density.

Lessons from the 2050 City could be applied at a more limited scale to other new or existing urban developments. If the criteria for this study were changed for example to "zero energy plus" – internal operating energy only, the current benchmark for sustainability, plus production of all human-consumed fresh produce – the 2050 City could have an overall density similar to current urban cores. If the rigorous standard of the 2050 City is unrealistic in practice, there would still be benefits to setting clear standards of operating self-sufficiency for cities – as long as it is clear that this would not represent true sustainability. It may be reasonable to split the problem into parts, with operating self-sufficiency according to well defined standards within the city, and to designate a peri-urban zone or zones in which the remaining embodied energy, food and goods are produced.

15.6. Economic investigations:

The 2050 City study has not considered financial costs, paybacks, or other economic implications of the self-sustaining infrastructure. We have been operating on the (perhaps optimistic) belief that environmentally positive development is inherently economical – in the long run economic viability will follow technical viability. And by 2050, current economic calculations may become moot: as time passes, self-sustainability may become a requirement, not an option.

15.7. Upgrading the Existing World:

Much of the new urban world in 2050 will not be new cities, but additions to and transformations of existing ones. In this study we have not looked at site-specific solutions, adapting existing infrastructure, or growth patterns and social movements spurred by migration and economic or social inequality. The confluence of technological with social and economic trends will create problems and opportunities we have not imagined.

Current trends are moving some cities in the direction of efficiency and autonomy. Buildings are becoming more efficient. The renewable energy industry is growing fast, and when it adapts to provide customized BIPV systems at little or no cost premium, integrated renewable energy generation will become a matter of course.

Individuals and entrepreneurs are already addressing an intense interest in urban agriculture, with rooftop greenhouses and vertical farm prototypes being built in cities around the world.

In the past, urban infrastructure and industry – coal-burning power plants, factories, stockyards and slaughterhouses were blights whose removal to the countryside made the twentieth century city what it was. In the future, clean, integrated versions of energy and food production could be reintroduced into newly multifunctional, robust and interesting urban environments. The inhabitants of the 2050 City may be empowered in unprecedented ways.

References

[i] World Population Prospects The 2010 Revision

http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2010_Highlights.pdf

[ii] Adapted from David Fridley et al., *Urban RAM: Assessing the Energy Impact of Having People in Cities*, 2012: http://btus.lbl.gov/sites/all/files/lbl-5740e-urban-ram-aceeejune-2012.pdf accessed July 2013

[iii] http://www.ecy.wa.gov/beyondwaste/bwprog_dataWasteComposition.html

http://perigordvacance.typepad.com/files/inventoryofcarbonandenergy.pdf

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[iv] http://www3.imperial.ac.uk/pls/portallive/docs/1/7294712.PDF

[v] Urban quality is hard to define: definitions are dependent on a wide range of criteria that are ultimately quite subjective. A number of cities (from such diverse locations as Auckland, Copenhagen, Singapore, and New York) are frequently cited in quality of life studies, and could have served as a basis for the urban character of the 2050 City. We use New York City as the principal model for the basic urban characteristics of this study (density, amount of open green space, etc.), not least because of its familiarity to the authors.

[vi] http://esa.un.org/unup/pdf/WUP2011_Highlights.pdf

[vii] This is somewhat more than New York's green space, which accounts for 14% of the city's total area http://www.nycgovparks.org/opportunities/support

[viii] Concentrating PVs require mirrors or lenses to focus sunlight on the active cell. These systems must track the sun to work, and only function on direct beam (non-diffuse) sunlight. Given that this quality of light is not available equally in all climates, and that the mechanical tracking systems make them more difficult to integrate into buildings and city infrastructure, we do not include them in our calculations.

[ix] http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

[x] http://iopscience.iop.org/0022-3727/13/5/018/

[xi] http://en.wikipedia.org/wiki/Jevons_paradox

[xii] http://www.tandfonline.com/doi/abs/10.1080/01441647.2010.518291#preview

[xiii] http://www.theatlanticcities.com/jobs-and-economy/2012/11/cities-denser-cores-do-better/3911/

[xiv] http://www.carboncommentary.com/2011/10/31/2123