Supporting Century-Long Lives through Efficient Energy Use and Livable Urban Environments

Chenghao Wang, Robert B. Jackson

Department of Earth System Science, Stanford University, Stanford, CA 94305, USA

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Abstract: Global urbanization amidst climate and environmental change poses numerous challenges to the healthy aging of populations. To better support century-long lives in an aging society, substantial changes in various aspects of the current world, especially in the domain of Environment and Climate, are imperative. In this report, we focus on two key aspects of this domain, energy consumption and urban environments, and examine their influence on human well-being. We first examine the trajectories of energy consumption and human well-being based on data analysis. We identify the minimum level of per capita energy use to support secure and high-quality lives. The decoupling of human well-being from energy consumption in high-consumption countries, including the U.S., signifies the potential of reducing energy use without harming the life quality. We also analyze major climate- and weather-related threats that urban residents are facing under climate and environmental change. To identify alternative approaches toward a sustainable future, we review existing efforts on energy saving and the improvement of urban environmental quality. These evidence-based alternatives suggest the opportunities to further improve energy efficiency, enhance the livability of U.S. cities, and foster healthy longevity of Americans.

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1. Introduction

The environment we live in is changing. With unprecedented urbanization and the highest anthropogenic greenhouse gas emissions in history, human activities unequivocally affect global climate and the environment (IPCC, 2014). In particular, the increase in global mean surface temperature (weighted average of land surface air temperature and sea surface temperature) has reached approximately 1 °C as compared to pre-industrial levels (1850–1900) (IPCC, 2018; World Meteorological Organization, 2020). Extensive studies conducted worldwide have documented clear changes in not only temperatures, but also the melting of multiyear sea ice, reduced snow cover, permafrost thawing, rising sea levels, and changes in the frequency, intensity, and duration of various extreme events such as heat waves, wildfires, droughts, and floods (Herring, Christidis, Hoell, Hoerling, & Stott, 2021; Perkins, Alexander, & Nairn, 2012; USGCRP, 2017; Westra et al., 2014). These changes are projected to be sustained and even amplified if the current rate of warming (~0.2 °C decade^{-1}) continues; in fact, global warming is projected to reach 1.5 °C between 2030 and 2052 (IPCC, 2018).

Meanwhile, global climate and environmental changes strongly influence various aspects of human well-being throughout the entire life course from early childhood to later life (McMichael, Woodruff, & Hales, 2006). According to the estimate by the World Health Organization, global climate change is responsible for at least 150,000 deaths each year (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). The most common environment–health connections include mortality and morbidity related to heat waves, floods, storms, and fires (McMichael et al., 2006). For instance, the 2003 heat wave resulted in 14,947 additional deaths in France, attributable to increased dehydration, heat stroke, respiratory illnesses, and cardiovascular mortality (Poumadère, Mays, Mer, & Blong, 2005). Global environmental change is also reflected in altered air pollution concentrations and distribution, pollen production of plants, microbial contamination and transmission, crop yield, water resources, etc., leading to adverse health impacts such as allergic diseases, infectious diseases (e.g., vector-borne diseases like malaria), and malnutrition (Barnett, Adam, & Lettenmaier, 2005; Haines, Kovats, Campbell-Lendrum, & Corvalan, 2006; Haines & Patz, 2004; Wheeler & Braun, 2013). In addition, mounting evidence has suggested the close relationships of climate and environmental changes with economic growth and violent conflicts, both can significantly influence the well-being of a 100-year life (Hendrix & Salehyan, 2012; Roson & van der Mensbrugghe, 2012). Substantial changes in various aspects of the current world, especially in the domain of **Environment and Climate**, are needed to support healthy longevity in an aging, long-lived society in the near future. As the first step, here we review the achievements, opportunities, and challenges, and envision possible avenues toward such a society, with a focus on two key aspects of the environment and climate domain, *energy consumption* and *urban environments*.

To reduce the threat of global climate and environmental change to well-being, it is important (although challenging) to hold the global average temperature increase well below 2 °C (even 1.5 °C) above pre-industrial levels (IPCC, 2018). However, the increasing trend of global energy consumptions and the associated carbon emissions over time significantly threatens this target. Carbon dioxide (CO_2) emissions from fossil fuels and industry account for approximately 90% of all anthropogenic CO_2 emissions (Jackson et al., 2017). Considering the close connections between global environmental changes, carbon emissions from human activities, and human well-being, accelerating the transformation of energy use and production toward no- or low-carbon sources and high energy efficiency is imperative to reduce environmental impacts and support secure and high-quality lives for 100 years or even more (Jackson et al., 2016, 2019, 2018; Peters et al., 2017; Rogelj et al., 2015). Traditionally, increasing energy consumption is thought to be a prerequisite for the advancement of human well-being (Goldemberg, Johansson, Reddy, & Williams, 1985). This conventional viewpoint has been challenged by findings based on global and regional data: countries with a similar level of energy consumption per capita can have huge differences in well-being such as life expectancy and human development (Arto, Capellán-Pérez, Lago, Bueno, & Bermejo, 2016; Lamb & Rao, 2015). Such discrepancies primarily result from different consumption patterns and lifestyles (Casillas & Kammen, 2010). An in-depth analysis is necessary to determine the minimum energy requirements of a healthy and productive life and to reveal potential pathways to reduce energy consumption and maintain or even improve human well-being.

Around 55% of the global population lives in urban areas today (cf. 33.8% in 1960), and cities are hotspots of anthropogenic climate changes. This percentage is projected to increase to 60% by 2030, accompanied by increasing life expectancy (United Nations, 2019b). In the United States, the rate of urbanization is even higher: the proportion of the population residing in cities increased to 83% in 2019 (from 70% in 1960) (United Nations, 2019b). This profound increase in both urban population and older population is accompanied by intensive landscape changes, such as the use of impervious surfaces, closely spaced buildings, and the lack of vegetation; these features result in local and regional urban climate patterns that are different from rural and natural ones, which significantly affect the well-being of urban residents (Oke, Mills, Christen, & Voogt, 2017; Stewart & Oke, 2012). One of the most well-known urban climate effects is the urban heat island (UHI), with cities usually warmer than their surroundings (Manoli et al., 2019; Oke et al., 2017). Amplified human exposure to heat stress due to UHI during heat waves has been observed in many cities around the world, posing great challenges to the health of urban dwellers of all ages (Tan et al., 2010; Ward, Lauf, Kleinschmit, & Endlicher, 2016). Residents in cities (especially those in developing countries) also suffer from severe urban air pollution. Several diseases have been proved to be linked to air pollution (Cohen et al., 2005). For instance, 29% of all deaths and diseases from lung cancer and 43% from chronic obstructive pulmonary diseases are attributable to air pollution (WHO, 2018). The use of impervious surfaces increases the risk of flooding during extreme rainfall events, which may lead to significant economic loss and social disruption and threaten human lives (Galloway et al., 2018). These negative consequences can be even worse because of background climate change (IPCC, 2018). Judicious urban planning and design strategies are imperative to limit global warming and reduce the negative impacts of environmental change on urban populations of all ages.

In this report, we aim to elaborate on energy consumption and urban environments and their impacts on human well-being based on data analysis and literature review. In the first half of this report (Section 2), we leverage data analysis to examine the trajectories of per capita energy consumption and human well-being (especially life expectancy) in different countries worldwide and all U.S. states. We then estimate the minimum level of per capita energy use for people to live secure and high-quality lives, and discuss the potential avenues to sustainably reduce energy use without harming human well-being. In the second half of this report (Section 3), we scrutinize existing studies to investigate the impact of urban environments (especially urban climates) on human well-being, and to identify optimal pathways to improve environmental quality and livability in U.S. cities. In Section 4, we summarize major findings and several directions for future investigation.

2. Energy consumption and human well-being

2.1 Current state of energy consumption and human well-being

Chapter 2.1 will be updated upon the acceptance of the manuscript (Jackson et al., 2021).

2.2 Relationship between country-level human well-being and energy consumption

Chapter 2.2 will be updated upon the acceptance of the manuscript (Jackson et al., 2021).

2.3 Relationship between state-level human well-being and energy consumption

We now turn to the state-level relationships between human well-being and energy consumption in the U.S., one of the highly developed countries in the world. Different from the country-level analysis, studies on state-level energy use and human development are very rare. However, state-level analysis can reveal the inequality within the same country. We are curious about how different states performed while the entire U.S. on average shows clear decoupling of human development from energy use (see Section 2.2).

For energy data, we use the U.S. EIA's state-level total energy consumption per capita by end-use sector (sum of residential, commercial, industrial, and transportation sectors) in 2017 (million Btu; 1 million Btu = 1.06 GJ) (U.S. EIA, 2020c). We retrieved 20 metrics related to human well-being, primarily following the United Nations' 17 Sustainable Development Goals (United Nations, 2019a): poverty rate (in 2017), food insecurity (%; in 2017), health index (in 2017), life expectancy (years from birth; in 2017), depressive episode rate (mental health; in 2017), happiness (in 2019), education index (in 2017), women equality (in 2019), access to clean and safe water rate (in 2013), renewable energy rate (in 2017), real income per capita (U.S.$; in 2017), unemployment rate (in 2017), Gini coefficient (in 2017), urban population rate (in 2010), air quality index (AQI, population-weighted; in 2017), vehicle miles of travel per capita (in 2014), total ecological footprint per capita (global acres or g-a; in 2015), murder rate (per 100,000; in 2017), household access to internet rate (in 2017), and human development index (HDI; in 2017). Data sources of these metrics are provided in Appendix C. According to the analyses in Section 2.2, we hypothesize that the dependence of these 20 metrics on annual per capita energy consumption was relatively weak in 2017.

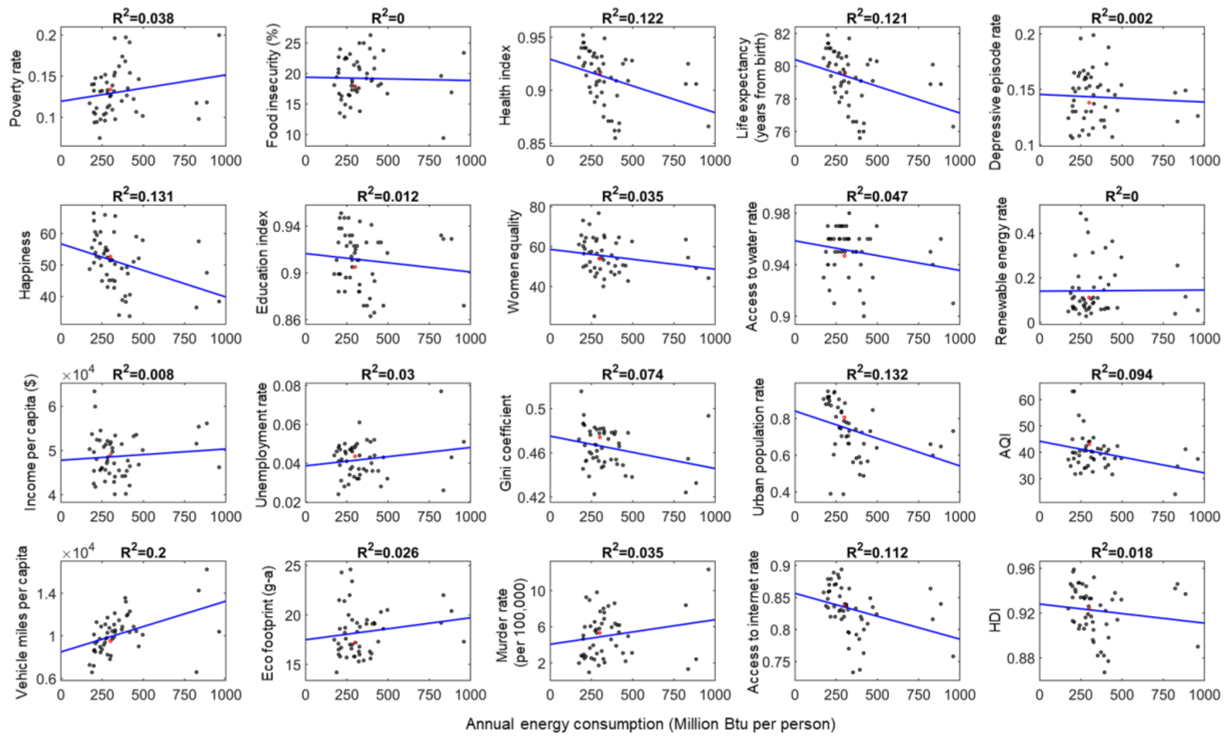

Fig. 4. Twenty well-being metrics plotted against annual national per capita total primary energy consumption (GJ) by state in 2017. The blue lines are linear regression fits. The black dots are for individual states, whereas the red dots are for the U.S. level. The coefficient of determination (R^2) for each linear regression is shown in the title of the subplot.

Figure 4 shows the state-level well-being metrics plotted against annual per capita energy consumption. Here the dependency is tested using a simple linear regression model. It is clear that all metrics are weakly correlated with per capita energy consumption ($R^2 < 0.15$) except one metric, which is (not surprisingly) vehicle miles of travel per capita. The relatively strong correlation between vehicle miles and energy consumption can be partly explained as the contribution of transportation energy use to total energy consumption. Nevertheless, the weak (positive) correlations observed in Fig. 4 still suggest a strong decoupling between human well-being and per capita energy consumption for the U.S. states in 2017: a higher per capita energy use does not result in a significant improvement in well-being. Interestingly, some human well-being metrics (e.g., health index, life expectancy, happiness, Gini coefficient, urban population rate, and access to internet rate) even tend to decrease with rising energy consumption. This is likely because per capita energy consumption in some states decreased due to, e.g., energy efficiency improvement, while human well-being kept increasing (similar to the high-consumption group in Fig. 3).

We further investigate the historical trajectories of energy consumption and human well-being level for individual states. Similar to Section 2.2, here we choose life expectancy (Woolf & Schoomaker, 2019) as a representative metric of human well-being. Figure 5 shows the trajectories of individual states for the period 1960–2016. In general, the average life expectancy increased by 9 years to 79 years in this interval at a rate of 1.9 months yearly, relatively slower than the global average (2.5 months yearly). Ten states had life expectancy over 80 years in 2016 (Hawaii, California, New York, Minnesota, Connecticut, Massachusetts, New Jersey, Washington, Colorado, and Rhode Island), in which Hawaii had the highest life expectancy among all states (~82 years), although these states still underperformed some countries where people live the longest (e.g., Iceland, Japan, and Switzerland). New York had the greatest improvement in life expectancy (> 11 years) and now is among the top states with the longest life expectancy. In contrast, life expectancy in states such as Oklahoma, West Virginia, Kentucky, and Arkansas increased slowly during the past 56 years (1.2 months yearly).

During the same period, the national average per capita energy consumption gradually increased from 249 million Btu person^{-1} in 1960 to 359 million Btu person^{-1} in 1978 and decreased to 301 million Btu person^{-1} in 2016. Peak per capita energy use in most states (27 states out of 50) occurred in the 1970s, primarily because of the 1970s oil crisis (Ratner & Glover, 2014). Energy consumptions in Texas and Nevada have dropped by 217 and 177 million Btu person^{-1}, respectively, since their peak values in 1973. Per capita energy use in eight states in 2016 (Nevada, Utah, Delaware, Rhode Island, Oregon, New Mexico, California, and Arizona) even dropped below the level in 1960. Turning points in per capita energy consumption are observed in the trajectories of most states. Life expectancy has been decoupled from the further increase in energy use since then, which is in general consistent with most industrialized countries (see Fig. 3). Nevertheless, life expectancy in four states, Iowa, Nebraska, North Dakota, and South Dakota, steeply increased with per capita energy use for decades and eventually approached the saturation point in recent years. The trajectories of these four U.S. states largely resemble the global quantile regression curves in Fig. 2. Such discrepancies among states in a highly developed country suggest strong inequality in both energy use and human development. This within-country disparity might exist in other industrialized countries as well. On the other hand, the general decoupling also suggests the opportunity to reduce per capita energy consumption while maintaining the current level of well-being in all U.S. states.

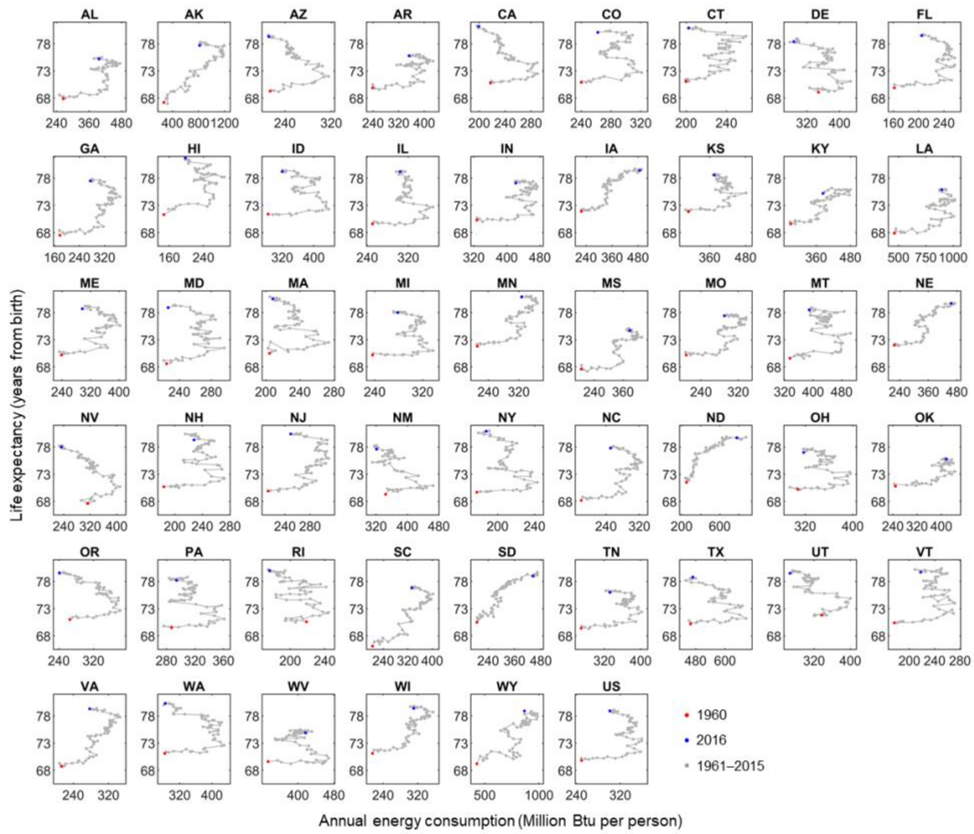

Fig. 5. *Historical trajectory (1960–2017) of life expectancy plotted against annual per capita energy consumption for all U.S. states.*

2.4 Evidence for alternative approaches to reduce energy consumption

2.4.1 Evidence-based alternatives

The decoupling of human well-being performance from per capita energy use observed in many countries (including the U.S.) is encouraging, considering the strong impact of energy consumption, as a vital determinant of carbon emission, on global climate change. In particular, per capita energy consumption in all U.S. states is much higher than the estimated 95% threshold globally (see Section 2.2), suggesting a high potential of energy saving in the U.S. without negative impacts on human well-being. In this section, we review approaches and successful examples to reduce per capita energy consumption while sustaining or even improving the human well-being level with a focus on the U.S.

The per capita energy use in the U.S. has gradually decreased in the past decade with several major changes in energy systems. Domestic oil and gas production has significantly increased owing to the adoption of new technology. For example, petroleum production has increased from 9.53 million barrels day^{-1} in 2010 to 19.33 million barrels day^{-1} in 2019 (U.S. EIA, 2020a). The installed capacity of wind and solar energy increased. Renewable energy consumption exceeded coal consumption for the first time since 1885 (U.S. EIA, 2020d). Smart grid technologies have increasingly been used across the country to improve the efficiency and reliability of the electric power system (U.S. EIA, 2012). All these changes brought opportunities but also challenges to all energy sectors.

The building sector, including residential and commercial buildings, consumes around 40% of total U.S. primary energy and over 70% of the electricity to sustain our daily lives (U.S. EIA, 2020b). Building energy use for heating, ventilation, and cooling is closely related to the quality of the interior environment such as thermal comfort and air pollution level. The properties of walls, roofs, foundations, and windows of a building determine the exchange of moisture and heat between indoor and outdoor environments and therefore the energy consumption. For instance, an experiment in China found that using an external wall insulation system can reduce air conditioning (AC) energy use by 23.5% during summer (Fang, Li, Li, Luo, & Huang, 2014). Al-Homoud (2005) provides a detailed review of performance characteristics and some practical applications for several thermal insulation materials commonly used in buildings. Reflective materials have also been extensively used for roofs and walls to increase the reflected solar radiation and reduce energy consumption for cooling on hot days (R. Levinson & Akbari, 2010; Santamouris, 2014). Due to their efficacy in reducing the temperature, these materials are often referred to as “cool materials” (Santamouris, Synnefa, & Karlessi, 2011). Various ventilation systems are used to reduce indoor air pollution and improve thermal comfort. Note that indoor air pollution such as contaminants released from furnishings and construction materials (like radon and formaldehyde), mold, and secondhand smoke can significantly influence human health and has been proved to be a major risk factor for global disease burden (Lim et al., 2012). U.S. Department of Energy (DOE) has suggested several ways to reduce energy lost in building ventilation (U.S. DOE, 2015), such as reducing leaks in buildings to minimize uncontrolled infiltration and using natural ventilation if possible.

Improving the efficiency of equipment and devices is another way of reducing building energy consumption. Heat pump systems, including air-source, water-source, and geothermal ones, are an energy-efficient alternative to conventional air conditioners and furnaces for regions with moderate cooling and heating needs (Sarbu & Sebarchievici, 2014; U.S. DOE, 2021). The

ENERGY STAR program established by the U.S. Environmental Protection Agency (EPA) has certified ~70,000 product models that can be used to save electricity. For example, ENERGY STAR certified homes can be 10% more energy efficient than conventional homes (ENERGY STAR, 2020). A national study has shown that using ENERGY STAR technologies can reduce residential energy consumption and commercial energy consumption by 30% and 21%, respectively (U.S. DOE, 2015). U.S. DOE's Office of Energy Efficiency & Renewable Energy also provides a database of energy-efficient products certified by different efficiency programs, ranging from light bulbs and dishwashers to hot food holding cabinets and vending machines (U.S. DOE, 2020). With new technologies such as voice-enabled devices and wireless sensor networks, smart buildings (and smart homes) have been developed to enable automated building operations and control (e.g., smart thermostats to adjust temperature automatically) (Alaa, Zaidan, Zaidan, Talal, & Kiah, 2017). Smart buildings have been proved to reduce energy consumption and improve occupant comfort and safety (Bhati, Hansen, & Chan, 2017; King & Perry, 2017; Zhang, Shah, & Papageorgiou, 2013). In addition to energy-saving potentials, smart homes have been suggested to effectively improve the health and safety of vulnerable groups, especially older adults, via, e.g., sensors for fall detection (Greene, Thapliyal, & Carpenter, 2016; Reeder et al., 2013).

Different from commercial and residential sectors in which major energy sources are electricity and natural gas, the U.S. industrial sector mainly consumes natural gas and petroleum (40% and 34%, respectively, in 2019) (U.S. EIA, 2020e). Energy saving in the industrial sector can be partially achieved via energy efficiency improvements. One example is combined heat and power systems, which generate electricity or mechanical power and produce useful thermal energy that is commonly wasted in conventional systems (Hinnells, 2008; U.S. DOE, 2015). These systems can have much higher energy efficiencies (> 75%) when compared to those that produce heat and power separately (~50%) (U.S. DOE, 2015). Waste heat recovery systems have also been proved to reduce fuel consumption and hazardous emissions and improve energy efficiency, which can capture and transfer the waste heat back to the system as an extra energy input (Jouhara et al., 2018). Energy management is another option to improve industrial energy efficiency and reduce energy use. Common practices include energy audit and accounting (e.g., inspections of energy flows to reduce energy input and operating costs) and efficiency course and training programs (Abdelaziz, Saidur, & Mekhilef, 2011). The combination of new technologies and management tools for industrial economies will not only save energy and costs, but also reduce waste and pollution. This is meaningful given the strong influence of industrial pollution (e.g., air pollutants and water contaminants) on human health through short-term and long-term exposures (Giusti, 2009).

The vast majority (>90%) of energy sources/fuels in the U.S. transportation sector are petroleum products (e.g., gasoline and diesel), representing the largest share of the petroleum consumption in this country (U.S. EIA, 2020e). One of the most effective ways to reduce per capita energy use in transportation is the switch from conventional cars (internal-combustion engine, or ICE cars) to electric or hybrid electric ones (EVs or HEVs). According to U.S. DOE's data, EVs can convert more than 77% of the electrical energy from the grid to power at the wheels, much higher than the efficiency of gasoline cars (12-30%) (U.S. DOE Office of Energy Efficiency & Renewable Energy, 2020). HEVs also have much better fuel economy than similar conventional ones. In addition, efforts have been made in vehicle design, such as weight reduction and changes in engine and transmission technologies, to continuously improve fuel efficiency. For example, the average estimated fuel economy has increased from 13 mpg to 25 mpg in the past 45 years (U.S. EPA, 2021). As a result, the average CO_2 emission has decreased from 681 g to ~350 g per mile. Public transit is also effective in reducing per capita transportation energy use when compared to private vehicles, although the selection of transportation types can be significantly influenced by population density and urban structures (Lefèvre, 2010).

2.4.2 Examples of programs and interventions

California is one of the U.S. states with very low per capita energy consumption and high human well-being outcomes (e.g., life expectancy), as suggested in Section 2.3. During the past six decades (since 1960), with many energy-related public policies designed and adopted, total per capita energy consumption in California has dropped by 7% to ~200 million Btu, much lower than the national average of 300 million Btu (U.S. EIA, 2020c). In contrast, national total per capita energy consumption has increased by 24% during the same period; some states even experienced an increase of over 100% (e.g., 247% for North Dakota, 209% for Alaska, and 139% for South Dakota). In particular, per capita energy consumption for the residential sector in California remained nearly unchanged in the past 60 years, despite a population increase of

~150% over the same period. Although some researchers have argued that the mild climate in California and demographical changes in other states (migration and shrinking household size) might have partly contributed to this low and relatively stable per capita residential energy use (A. Levinson, 2014), this achievement would not be possible without a set of innovative public policies and programs toward reducing energy use and improving energy efficiency. Established by the Warren-Alquist Act in 1974 during a nationwide energy crisis, the California Energy Commission plays a key role in implementing state-wide energy policies ranging from energy efficiency advances and technological innovations to clean transportation and responsible electricity infrastructure (California Energy Commission, 2021a). To achieve a cumulative doubling of energy efficiency savings by 2030, the commission has developed appliance efficiency regulations and building energy efficiency standards for both new and existing buildings (California Energy Commission, 2021b). The commission funds innovative projects that improve energy systems and reduce energy use and costs as well as the associated carbon and air pollutant emissions. Other standards in California also contribute to the reduction of per capita energy use. In addition to building energy efficiency standards, California has the first-in-the-nation mandatory green building code (CALGreen) (Building Standards Commission, 2019). For transportation, California Air Resources Board has the Zero-Emission Vehicle Program that aims to reduce petroleum use and emissions. The improvement of energy efficiency and the increasing use of clean energy has benefited air quality in many California cities. For instance, the reduction of regional air pollution ($PM_{2.5}$ and NO_2) in Southern California from 1993 to 2014 was significantly associated with decreasing incidence of asthma among children (Garcia et al., 2019).

Beyond the experience of individual states, what lessons can we learn from other countries? We first look at member states of the European Union (EU), of which most are highly developed ones with a high level of human well-being. Analysis in Fig. 3 suggests that many EU countries with relatively high per capita energy consumption (> 100 GJ), such as France, Spain, and the Netherlands, have experienced clear decoupling between energy use and life expectancy at birth (and other well-being metrics) in recent years. In fact, the total primary energy consumption of the 27 EU member states has dropped by 11% since 2006, despite the continuing population growth and increasing floor areas and the number of appliances in buildings. This primarily resulted from a series of climate strategies and targets (as binding legislation) set by the EU toward climate-neutral. For example, the 2030 climate and energy framework set out a target of at least 32.5% improvement in energy efficiency (or reduction in total energy consumption) by 2030 compared to projections (European Commission, 2017). In compliance with the 2012 energy efficiency directive (and its 2018 amendment), measures have been adopted by each EU member state to effectively improve energy efficiency (European Commission, 2020). Each EU country is required to prepare national energy efficiency action plans every three years, develop national renovation strategies for the building stock, and follow minimum energy efficiency standards and labeling for products and appliances. Smart meters and smart grid projects have been implemented in member states to save energy use and costs of maintenance and operation. The end-use energy efficiency, if measured using ODEX indicator, has improved by 30% from 1990 to 2016: the industrial sector experienced the largest improvement in energy efficiency (increased by 38%), followed by the household sector (35%), services (26%), and transportation (20%) (European Environment Agency, 2021). The priority of improving energy efficiency and reducing energy consumption has also been highlighted in the European Green Deal, a roadmap that the EU is using to improve the health and well-being of its citizens in response to global climate and environmental change (European Commission, 2021; Haines & Scheelbeek, 2020).

We then turn to China. Being the most populous country in the world, China consumed 24% of the global total primary energy, and contributed to 77% of the increase in global net energy demand in 2019, while going through rapid economic growth and improvement in life expectancy and human well-being level (BP plc, 2020b). Despite this period of rapid economic growth, the increases in both total and per capita primary energy consumption have slowed down in China (Jackson et al., 2018). For example, per capita energy use increased by 30% from 2010 to 2019, much lower than that from 2000–2009 (118%). The slowing growth in energy demand is mainly due to decreasing energy intensity and partly consumption patterns (Guang & Wen, 2020). Its economy is shifting from energy-intensive industries to service-oriented ones. These transitions are driven by the growing demand for energy conservation, emission reduction, and pollution removal. The improvement in energy saving is achieved through many centralized and decentralized policies and initiatives implemented by its multi-level governance system, such as Five-Year Plans and Top-1000 Energy-Consuming Enterprise Program (Abdelaziz et al., 2011; Zhou, Levine, & Price, 2010). The Five-Year Plan, in particular, serves as an important governance tool for energy saving in China, by promoting energy and resource management with target responsibility systems and achievement evaluations; the plan has also contributed to the improvement of local air quality in recent years (Hu, 2016; Lo, 2020; Zheng, Yi, & Li, 2015).

2.5 Opportunities and recommendations for energy saving in the U.S.

Reducing energy consumption will significantly benefit emission reduction, climate change mitigation, and environmental quality improvement in the U.S. Research has shown that the improvement of energy efficiency alone can cut national primary energy use and greenhouse gas emissions in half by 2050 (Nadel & Ungar, 2019). Achievements in some U.S. states and other countries have proved plenty of approaches likely to be effective across the U.S. For residential and commercial sectors, retrofit and renovation such as lighting upgrades, replacement of heating, cooling, and ventilation systems, and roofing upgrades are the key to improving the energy efficiency in existing buildings. For new buildings, ENERGY STAR certified appliances and equipment can achieve consumption reductions, and smart sensors and renewable energy systems can be integrated to cut energy load and carbon emissions. For the industrial sector, thorough life-cycle assessments and regular energy management (such as auditing and housekeeping) can help identify opportunities to improve energy saving in manufacturing processes and supply chains. Efforts are still needed to promote innovative technologies and systems. These strategies are particularly important for states dominated by energy-intensive activities like oil and natural gas refining and chemical manufacturing (e.g., Louisiana, Wyoming, and Alaska). The transportation sector is also critical. An increasing number of vehicles have led to a further increase in gasoline consumption, despite the continuous improvement in fuel economy as required by national standards. Federal standards should therefore be regularly updated. Increasing the market share of electric vehicles through regulations and incentives is also effective for energy saving and emission reduction. In addition, per capita transportation energy use can be reduced through other mobility options such as public transit systems and the promotion of walkable communities.

Especially, research has established strong connections between per capita energy use patterns and city structures. For mature cities with relatively high economic activities like most U.S. cities, a compact urban structure coupled with high gasoline prices can incentivize residential and transport energy saving (Creutzig, Baiocchi, Bierkandt, Pichler, & Seto, 2015).

This is partly reflected in state-level energy data: states with a smaller population density like Alaska and Wyoming have much higher per capita transportation energy use than densely populated states such as New York and Rhode Island (U.S. EIA, 2020f). Higher population density also promotes compact homes with higher residential energy efficiency. It should be noted that changing the existing structure of U.S. cities can be very challenging, but the concept of compact cities can be embedded in the development of new communities, the construction of infill housing, and the optimization of current public transit systems (e.g., the distance between new light rail and bus rapid transit systems and communities) (Lefèvre, 2010).

As mentioned above, national and local policies are strong instruments for energy saving and efficiency improvement. A national analysis conducted by the American Council for an Energy-Efficient Economy (Nadel & Ungar, 2019) has estimated the efficacy of government energy efficiency policies in achieving energy saving: a quarter of the total energy saving in 2050 is from the current measures and emerging technologies, followed by utility programs (11%), appliance standards (11%), car and light truck standards (10%), and other standards and programs. For example, building (energy) codes, standards, and rating systems have been developed by national and local governments, associations, and private companies that can be used for both existing residential and commercial buildings and new constructions (Livingston, Cole, Elliott, & Bartlett, 2014; C. Wang, Wang, Kaloush, & Shacat, 2021a). While in many states builders are required to comply with mandatory standards, voluntary green rating systems (e.g., LEED) have also been widely used to reduce cost, energy use, and pollutants. Energy benchmarking is another tool that has been used to inform and motivate energy efficiency for commercial and public sector institutions. In addition, financial incentives such as grants, loans, and tax incentives can accelerate the implementation of energy efficiency projects. One useful resource is a database of state incentives for renewables and efficiency operated by the Clean Energy Technology Center at North Carolina State University (NC Clean Energy Technology Center, 2021), which can potentially promote communications and knowledge transfer in terms of financial incentives. Public education is also very important to raise the awareness of energy use behavior among citizens to achieve energy saving in daily life (U.S. DOE Office of Energy Efficiency & Renewable Energy, 2021). It is noteworthy that local policies have been proved to benefit policymaking in other states through information spillover (Fredriksson & Millimet, 2002), which can potentially be used to facilitate developments of regional or even nation-wide energy saving strategies.

Besides governments, the private sector can also lead energy revolution. Compared to the public sector, private enterprises have more freedom to develop and apply innovative energy efficiency techniques as driven by profit and competition against other companies. However, the implementation of such technologies in the public sector is often left behind, due partly to the lack of knowledge. Collaboration with governments is therefore highly encouraged. On the one hand, governments can promote innovations through investment and incentives toward private-sector research and development, which might help remove capital barriers. On the other hand, private enterprises can widen the applications of techniques and make a profit. Collaborations between the private sector and academia are conducive to reducing energy consumption as well. For example, private companies can serve as the testing ground of some cutting-edge techniques launched by research institutes.

Technological development has made possible the decoupling between human well-being improvement and further increases in per capita energy use. Nevertheless, several unknowns still exist, which require future investigation. First of all, compared to the well-known relationships between human well-being and income, socioeconomic status, or carbon emission, the relationship between the well-being of different ages and per capita energy use is more complex and less studied (Brown et al., 2011; Fuso Nerini et al., 2018). One potential research direction is to examine the relationship between well-being metrics and energy use of transportation and buildings among countries and regions, given their close connections to lives. Secondly, this section only focuses on per capita energy use and energy saving. Less attention is paid to how the increasing use of clean and renewable energy sources may influence per capita energy use patterns in industrialized countries, and whether reducing per capita energy use is still necessary if a complete switch to renewables can meet energy needs. Lastly, although the per capita energy consumption in every U.S. state is much higher than 100 GJ, great inequalities still exist among states and communities, highlighting the need of appropriate policies.

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3. Urban environments and human well-being

3.1 Current state of urban environments and human well-being

Americans living in urban areas are experiencing climate and environmental change. Consistent with global warming, mean annual temperature over the contiguous U.S. (CONUS) has increased by about 1 °C since the beginning of the 20th century, and is projected to further rise by ~1.4 °C in the near term (2021–2050) relative to 1976–2005 (USGCRP, 2017). Meanwhile, annual precipitation has increased in most states over the 1901–2015 period (on average by ~4% over the CONUS), although seasonal changes exhibit strong variations (USGCRP, 2017). Future precipitation changes remain uncertain in the projections, but in general high-latitude regions will become wetter, and subtropical regions will be drier. The global mean sea level has risen by ~0.2 m since 1901, and is projected to continue rising with an accelerating rate in this century (IPCC, 2014; USGCRP, 2017). Changes in temperature and precipitation have profound impacts on extreme events. For example, the frequency and intensity of heat waves and heavy precipitation events have increased and are expected to further increase over much of the CONUS, significantly affecting the safety of infrastructure, ecosystems, social systems, and the public health (Dahl, Licker, Abatzoglou, & Declet-Barreto, 2019; Janssen, Wuebbles, Kunkel, Olsen, & Goodman, 2014; USGCRP, 2017). Even worse, cities with anthropogenic heat and pollutant emissions have been proved to interact with climate change and extreme events, further exacerbating the losses of urban residents and threatening their well-being (Shuster, Bonta, Thurston, Warnemuende, & Smith, 2005; Tan et al., 2010). In Table 1, we summarize the major climate- and weather-related threats that urban residents are facing across nine U.S. regions (USGCRP, 2017, 2018).

Table 1. *Major climate- and weather-related threats for urban residents in nine U.S. regions*

Regions (states)	Major climate- and weather-related threats for urban residents
Northeast (CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT, and WV)	Increasing rainfall intensity, extreme heat, amplified storm impacts (surges), increasing coastal flooding, and air pollution
Southeast (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, and VA)	Increasing heat waves (heat stress), extreme precipitation, and droughts, increasing coastal flooding, hurricanes, increasing wildfire risks, air pollution, and vector-borne diseases
Midwest (IA, IL, IN, MI, MN, MO, OH, and WI)	Increasing extreme heat and heavy rain events, deteriorated water quality, flooding, and air pollution
Southern Great Plains (KS, OK, and TX)	Increasing temperature and extreme precipitation, sea level rise and storms (hurricanes) in coastal areas, tornadoes, flooding, increasing drought duration and severity, and wildfires
Northern Great Plains (MT, NE, ND, SD, and WY)	Increasing heavy precipitation events, flooding, and increasing heat waves and droughts
Northwest (ID, OR, and WA)	More frequent heat waves, wildfires, prolonged droughts, storms and flooding, sea level rise and storm surge, and air pollution due to fire smoke
Southwest (AZ, CA, CO, NM, NV, and UT)	Increasing heat waves and droughts, air pollution, wildfires, vector-borne diseases, sea level rise, and occasional floods
Alaska (AK)	Sea level rise, increasing coastal flooding and erosion, and increasing wildfires and related pollution
Hawaii (HI)	Sea level rise, urban flooding, and increasing extreme rainfall events and droughts

Temperature in cities has profound impacts on various aspects of human health and well-being. Extremely high and low temperatures can lead to rising mortality and morbidity (Curriero et al., 2002). Heat and cold waves also increase energy demands for cooling and heating, aggravating burdens on electricity grids and other urban infrastructure (Morakinyo et al., 2019). Increasing heat stress has been identified as the major temperature-related threat in the U.S., given that both extreme cold and warm days become warmer. On the other hand, anthropogenic heat emissions, lack of green spaces, and the use of construction materials result in higher temperatures in cities than in surrounding areas: the UHI effect is estimated to be 0.5–4 °C and 1.0–2.5 °C in daytime and nighttime, respectively (USGCRP, 2017). As a result, during heat waves and hot days, residents in most U.S. cities experience higher heat stress than rural residents (Zhao et al., 2018). High temperature can induce many illnesses such as heat stroke, heat exhaustion, heat syncope, heat cramps, heat rash, and rhabdomyolysis, which may cause permanent damages to organs, severe functional impairment, and decreasing life expectancy for people of all ages (Kovats & Hajat, 2008). Most studies focused on the impact of heat on mortality as limited by data availability. A study of 43 U.S. cities found that nonaccidental mortality increased 3.7% in heat waves when compared with non-heat wave days (a rate of 2.49% per 1 °F), and the mortality is affected by the intensity and duration of heat waves as well as whether the heat wave was the first in summer (Anderson & Bell, 2011). Epidemiological studies indicated that heat-related mortality is also associated with age and medical conditions (Kovats & Hajat, 2008). Children, older adults, and people with certain chronic diseases (e.g., cardiovascular diseases, diabetes, and respiratory diseases) are more vulnerable to heat stress (Kenny, Yardley, Brown, Sigal, & Jay, 2010; Kravchenko, Abernethy, Fawzy, & Lyerly, 2013). In addition, some studies found that gender influences heat mortality risk, although its effect can be diluted by differences in socioeconomic status (Kenney, 1985; Yu, Vaneckova, Mengersen, Pan, & Tong, 2010).

Urban residents experience high risks imposed by air pollution. One out of every nine deaths in the world results from air pollution-related conditions (WHO, 2016). Although air pollutants (e.g., particulate matter or PM and ozone) in the U.S. have been reduced since the implementation of the Clean Air Act, many U.S. cities still have severe air pollution issues. Outdoor air pollution in cities is mainly induced by anthropogenic activities such as traffic and industrial emissions and, in some cities, wildfire activities, while indoor air pollution is mainly from fuel combustion (e.g., for heating), cigarette smoke, and contaminants released from construction materials and furnishings. Air pollution exposure is strongly associated with respiratory and cardiovascular mortality and morbidity, lung-cancer mortality, asthma and allergic diseases, and shortening of life expectancy (Brunekreef & Holgate, 2002; Huang, Zhang, Qiu, & Chung, 2015). Exposure to common urban air pollutants like carbon monoxide and PM can also affect pregnancy outcomes and lead to low birth weight and preterm birth (Stieb, Chen, Eshoul, & Judek, 2012). Maternal exposure to air pollutants can impair brain development and childhood cognition and behavior, and lead to childhood obesity and many other long-term damages (Finch & Morgan, 2020). Older adults and people with existing diseases are another group vulnerable to air pollution exposure. For example, studies have shown that high exposure is associated with later-life cognitive decline and dementia risks (Paul, Haan, Mayeda, & Ritz, 2019).

In addition to heat waves and air pollution, other climate and weather disasters also threaten the well-being of urban residents. In 2020, there were 22 climate and weather disasters with overall damage costs reaching or exceeding $1 billion, and 20 of them were related to hurricanes, tropical cyclones, or severe storms (NOAA National Centers for Environmental Information, 2021). These cyclones and storms often result in severe flooding in cities with a large amount of impervious surfaces and aging drainage systems, causing not only damages to homes, commercial properties, and public infrastructure, but also increasing risks of drowning, injuries, waterborne diseases, exposure to contaminated water, and other secondary hazards related to power outages (Curriero, Patz, Rose, & Lele, 2001; Galloway et al., 2018; Lane et al., 2013). Flood risks in coastal cities such as New Orleans can be further amplified by sea level rise. Wildfires Intensified wildfire activities have been observed in the U.S.: climate change in 1984–2015 has doubled the area of burned forest in the western U.S. (USGCRP, 2018). Wildfires emit PM and contribute to ozone formation, together with urban air pollution, causing a substantial burden of health issues. Studies have shown that exposure to wildfire smoke is associated with increased respiratory morbidity (especially asthma and chronic obstructive pulmonary disease) (Black, Tesfaigzi, Bassein, & Miller, 2017; Reid et al., 2016). It is noteworthy that extremes that occur concurrently or in sequence can have aggregated impacts on urban residents (Zscheischler et al., 2020). For example, concurrent drought and heat wave cause much greater heat stress, and are associated with rising risks of wildfires and air pollution episodes (AghaKouchak, Cheng, Mazdiyasni, & Farahmand, 2014).

Changing global climate is expected to increase the damage of these weather and climate extremes in U.S. cities. Future urban residents will likely experience more intensive heat waves, more frequent air pollution episodes, and higher risks of wildfires. Therefore, judicious urban planning and design strategies are imperative to improve human well-being and promote resilience to these extreme events.

3.2 Evidence for alternative approaches for livable urban environments

3.2.1 Evidence-based alternatives

Nature-based solutions that use natural elements in urban environments have been advocated in many cities to combat climate change, rising heat stress, and air pollution. The efficacy of green spaces in improving thermal comfort and filtering air pollutants have been demonstrated in numerous studies (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Gill, Handley, Ennos, & Pauleit, 2007). Compared to other impervious construction materials, green spaces can effectively reduce temperature and improve pedestrian thermal comfort mainly through the shading effect of trees and evapotranspiration (Shashua-Bar, Pearlmutter, & Erell, 2011; C. Wang, Wang, Wang, & Myint, 2019). As a result, green spaces can potentially lower the risk of heat-related diseases. In addition, urban vegetation can filter air pollutants via wet and dry deposition and has the potential to improve air quality (Janhäll, 2015). Epidemiological and psychological evidence suggests that green spaces can promote physical activity and the sense of safety and adjustment, and are associated with improved physical and mental health outcomes for people of all ages (Beyer et al., 2014; Kondo, Fluehr, McKeon, & Branas, 2018; Lee & Maheswaran, 2011). Childhood exposure to green spaces is associated with enhanced cognitive development and reduced risk of psychiatric disorders (Dadvand et al., 2015; Engemann et al., 2019). Significant associations between the availability of walkable green spaces and the life expectancy of senior people have been observed in a longitudinal cohort study (Takano, Nakamura, & Watanabe, 2002).

Green spaces can be designed to incorporate water and water-related features such as rivers, lakes, wetlands, irrigation systems, and rain gardens in cities; these are often referred to as green and blue infrastructure (Demuzere et al., 2014). They are not only effective in reducing heat stress, air pollution, and noise, but attenuate the risk of high stormwater runoff and urban flooding, enhancing mental health and well-being at all ages (Andreucci, Russo, & Olszewska-Guizzo, 2019). Green roofs, green walls, and green façades are another type of nature-based solutions in many cities, which use vegetation on rooftops or walls to improve (outdoor and indoor) thermal comfort and reduce building energy consumption and carbon emissions (Besir & Cuce, 2018; Perini & Rosasco, 2013).

Various engineering solutions have also been widely used in cities worldwide to mitigate heat stress, reduce air pollution, and lower flooding risk. Compared to conventional impervious surfaces, permeable pavements infiltrate rain water and reduce runoff, and help lower temperature with enhanced evaporation (Drake, Bradford, & Marsalek, 2013; Li, Harvey, Holland, & Kayhanian, 2013). Reflective materials can be used for building surfaces (“cool roofs” and “cool walls”) and pavement surfaces (reflective pavements or “cool pavements”) to reduce the absorption of solar radiation during the daytime (C. Wang et al., 2021a). Their effectiveness in reducing temperature and building energy consumption has been demonstrated in many studies (R. Levinson & Akbari, 2010; Santamouris, 2014; Yaghoobian & Kleissl, 2012). In addition, indoor thermal comfort and energy efficiency can be substantially improved via the proper design of thermal insulation, weatherization, and natural ventilation systems (Al-Homoud, 2005; Fang et al., 2014; Song et al., 2018). Enhanced thermal insulation and weatherization of homes can increase the resilience of residents during unusually extreme weather events such as the cold wave in Texas in 2021. Proper design of urban morphology is also important to enhance human well-being. The orientation and arrangement of buildings and streets collectively determine solar access, ventilation conditions, and shading effect, and can influence outdoor heat stress, air pollution level, and building energy use for cooling and heating (Andreou, 2014; Wong et al., 2011). The efficacy of engineering solutions in improving thermal comfort and air quality has been widely studied. However, their impact on other health outcomes remains relatively unexplored.

Strategies related to optimal urban structures and zoning are equally effective to improve urban environmental quality. Compact cities with mixed land use can reduce transport and commuting time, promote the use of public transport and physical exercise (e.g., neighborhoods with high walkability), and improve public health (e.g., lower obesity risk) and life satisfaction (Mouratidis, 2018; Sha, Li, Law, & Yip, 2019). Compared to relatively dispersed cities, compact cities tend to have better air quality (Borrego et al., 2006). Spatial structures of cities also influence urban temperature and the UHI effect. Studies have observed strong associations between the distribution of urban land surface temperature and landscape configuration (e.g., edge length and shape of landscape patches) in many cities (Connors, Galletti, & Chow, 2013; Yue, Liu, Zhou, & Liu, 2019). Especially, the spatial configuration (size, shape, and arrangement) of green spaces can significantly affect their cooling effect on hot days (Chang, Li, & Chang, 2007; Gioia, Paolini, Malizia, Oltra-Carrió, & Sobrino, 2014; Z.-H. Wang, Fan, Myint, & Wang, 2016). The distribution of residential, commercial, and industrial areas within a city is largely determined by the planning of local governments, and has profound impacts on the well-being of citizens. Residential areas close to industrial zones and major roadways will likely be influenced by emitted air pollutants. For example, exposure to roadway traffic-related pollution can result in high risks of asthma-related diseases and deficits in children's lung development (Brandt et al., 2014; Gauderman et al., 2007; Perez Laura et al., 2012). These negative effects can be reduced by implementing emission control policies or relocation. In addition, significant inequalities in access to public green spaces and exposure to air pollution have been observed in many cities (Wolch, Byrne, & Newell, 2014). Racial minority groups and people with low socioeconomic status are often associated with high exposure to various environmental risk factors and relatively low health conditions (Evans & Kantrowitz, 2002), signifying the importance of equitable urban planning to promote the health and well-being of all populations. Note that the differentiated exposure to environmental risks among urban communities throughout the life course and its potential solutions are covered in detail in the Built Environment domain report.

3.2.2 Examples of programs and interventions

Green roofs have been used in many U.S. cities, of which Chicago has become a national and global leader with hundreds of green roofs installed on public and private buildings. One of the earliest and most famous green roofs is the City Hall rooftop garden, a demonstration project installed in 2000 to replace the original black tar roof (City of Chicago, 2019). It has more than 150 species of shrubs, vines, and trees, most of which are native species. Initial evidence has shown that this rooftop garden is much cooler than conventional roofs and can reduce energy use for cooling during summers. The garden also provides benefits for stormwater management such as rainwater filtration and storage. The success of green roof projects in Chicago largely benefits from the implementation of the Chicago Sustainable Development Policy in 2004 (City of Chicago, 2017). This policy applies to development projects that receive financial supports or special approvals from the city government, of which green roofs are one of the key elements. It also includes assessments of building features that influence public health and safety. In addition, the local government has promoted the installation of green roofs through incentive programs. For example, the Department of Buildings has a Green Permit Program that offers qualified projects expedited permits and fee waivers (City of Chicago, 2020). It is noteworthy that private sectors have been heavily involved in the planning and implementation of the city's green roof policies (e.g., as the advisory committee members), during which government officials have received valuable feedback and extensive public input. Similar programs have now become available in many U.S. cities to promote the wide implementation of green roofs. New York City offers private property owners green roof retrofit funding through its Green Infrastructure Grant Program (City of New York, 2021). The primary goal is to use green roofs for stormwater management and reduce burdens on municipal sewer systems. The program determines financial supports for green roof projects mainly based on the green roof area and soil depth, and regularly holds public webinars to provide guidance. In addition to incentives, the use of green roofs has been included in state or city zoning and building codes, for example, Green Factor in the Seattle Municipal Code (City of Seattle, 2021) and ecoroofs in Portland's Central City Plan District zoning code (City of Portland, 2020).

Similarly, engineering solutions have also been advocated by many state and local governments. California has some of the most rigorous mandates and policies related to roofing and pavements to combat climate change and improve human well-being. In particular, California has prescriptively required energy-efficient cool roofs to be installed for newly constructed (and certain types of altered) residential and nonresidential buildings in some climate zones in its Building Energy Efficiency Standards (California Energy Commission, 2018). In addition to state-level standards, various cool roof programs and/or policies have been developed in many California cities. For example, Chula Vista planned to expand its cool roof standards to include re-roofs and additional climate zones after cost-effectiveness assessment in the city's Climate Action Plan (City of Chula Vista, 2017). Rebates and incentives for cool roof installation are available in many cities. Los Angeles Green Building Code has been requiring certain standards (values of aged solar reflectance and thermal emittance) for roofing materials used in residential buildings since 2014, and the city offers rebates to partially offset increased costs of new roofing products (LADWP, 2015). Despite the potential increase in energy use for heating in cold seasons (heating penalty), cool roofs in California cities have been suggested to attenuate current and future summer heat stress, reduce energy consumption for cooling (especially peak demand), and potentially reduce ozone concentration (Akbari, Levinson, & Rainer, 2005; Epstein et al., 2017; Vahmani, Jones, & Patricola, 2019). Similar to cool roofs, cool pavements are also beneficial for heat mitigation and energy saving. Los Angeles was the first city in California to widely install cool pavements on public streets (International Road Federation, 2019). In response to the rising temperature and the UHI effect, the city plans to install reflective pavements in ~1500 blocks with high heat stress in 10 years (Barboza, 2019). Although cool pavements in Los Angeles are effective in reducing temperature, concerns about thermal comfort have been raised: the solar radiation reflected by pavement coatings can increase human thermal exposure (Middel, Turner, Schneider, Zhang, & Stiller, 2020).

National air quality standards are commonly used tools and have been quite effective in controlling air pollution worldwide (e.g., the Clean Air Act in the U.S.). However, many state and local governments have developed additional programs to reduce harmful urban air pollution. One example is the low emission zones (LEZs) introduced in many European cities. LEZs are critical areas that limit vehicles with high levels of pollutant emissions, which may cover several roads or a large urban area (e.g., inner city) (Holman, Harrison, & Querol, 2015). Typical LEZ requirements include strict bans on high emission vehicles, retrofit options with emission control devices, and charging schemes (DieselNet, 2015). Currently, more than 250 EU cities have implemented LEZs, and many of them have contributed to the reduction in PMs, NOx, and other pollutants and have benefited public health (Bannon, 2019; Holman et al., 2015; Panteliadis et al., 2014). Nevertheless, some studies have also found insignificant improvement in air quality and some health conditions (e.g., the prevalence of respiratory and allergic symptoms among children) (Mudway et al., 2019; Wood et al., 2015). As a result, many EU cities now resort to more restrictive and ambitious LEZ requirements to further reduce urban air pollution. For example, London has implemented several ultra-low emission zones to control traffic pollution emission, and expansion of existing zones is underway (Transport for London, 2012).

3.3. Opportunities and recommendations for U.S. cities

Extensive evidence beyond the examples in Section 3.2.2 has demonstrated the effectiveness of various strategies to improve the urban environmental quality and health of people of all ages, and unlike those related to energy consumption, most of these strategies can be easily transplanted in U.S. cities. To mitigate urban heat stress, a combination of nature-based and engineering strategies, including green and blue infrastructure, reflective surfaces, and proper design of block morphology should be used, especially in cities that experience frequent heat waves. To prepare for sea level rise and increasing frequency of extreme rainfall events and storms, local governments should upgrade municipal infrastructure (e.g., sewage systems) and develop stormwater management programs with green infrastructure. To tackle air pollution issues, U.S. cities may implement more ambitious emission standards, reduce residential exposure to pollutants through zoning regulations, and promote the use of low emission or zero emission vehicles (e.g., EVs). Special attention should be paid to areas that are extremely vulnerable to potential future climate- and weather-related disasters. For example, housing units in areas with risks of future wildfires or flooding can be constructed with proactive standards and planned with proper rescue and emergency services. These strategies will not only improve the resilience of cities in climate and environmental change and health of urban residents, but also have co-benefits of energy saving, consistent with the goals in Section 2.

Policy instruments play a vital role in the sustainable development of livable communities and cities for human well-being. The performance of buildings, such as indoor thermal comfort, air pollution level, and energy efficiency, is significantly influenced by legislative mandates or building/energy standards imposed by state and local governments. Similarly, traffic and industrial emissions of air pollutants can be restricted by the enforcement of federal and local emission standards, and the potential exposure of residents to contaminants can be limited by proper zoning codes. On the other hand, voluntary actions, e.g., installing green roofs, can be promoted via policies like economic incentives, rebates, and/or loan programs. These programs can offset upfront costs and partially remove some financial barriers. The lack of public awareness has been identified to be a considerable obstacle to the implementation of climate regulation plans, which can be resolved through policies related to public education, such as regular workshops held by governments (Eliasson, 2000; C. Wang, Wang, Kaloush, & Shacat, 2021b). City-wide planning policies like OneNYC (The City of New York Mayor Bill de Blasio, 2019) can be promoted, as these initiatives are able to coordinate multiple local departments with various goals to holistically improve the urban environmental quality. In addition, many U.S. cities now have the chance to connect with cities in other countries through international networks such as the C40 Cities and Global Cool Cities Alliance. Such interactions will help cities identify and implement innovative and cost-effective policy agendas that have worked in other places.

Private sector is an important component of urban planning in response to climate and environmental change. Private sector is the core of many voluntary programs. The climate and environmental actions of most private individuals and enterprises are more likely driven by profits than the general human well-being. With available financial incentives and awareness of potential economic benefits (e.g., energy saving and avoiding climate-related risks), wide implementation of climate mitigation and adaptation strategies can be achieved in private sector (Bierbaum et al., 2013). On the other hand, private actors have been heavily involved in the development of policies, standards, and innovative techniques. Their expertise and feedback can help governments make locally tailored decisions to improve the urban environment quality.

Furthermore, private companies such as insurance companies can potentially increase the resilience of urban residents with high risks of disasters (e.g., flood and wildfires) and reduce their losses through differentiation of insurance fees (Mees, 2017).

Numerous new technologies have been developed in both academia and industry in recent years. Some innovative technologies are engineering solutions to known problems of commonly used reflective surfaces, such as glare issues and visual discomfort. For example, coating materials using infrared reflective pigments have been devised to reduce visible reflection (Santamouris et al., 2011). Novel pavement systems that do not use reflective materials have been designed to mitigate urban heat stress and harvest solar energy, which internally convert the harvested energy to electricity or/and heat for other uses (Jiang et al., 2017; Pan, Wu, Xiao, & Liu, 2015). In addition, numerical models have been developed by researchers to reproduce urban meteorological and climate conditions at multiple spatial and temporal scales with reasonable accuracy. These models can be used to evaluate the potential impacts of different urban planning strategies on, e.g., heat stress and thermal comfort, air pollution level, and building energy consumption, which can significantly benefit the human exposure assessment and decision making of local governments; they can also be incorporated into early warning systems for hazard prevention and disaster management (Corburn, 2009; Hammond, Chen, Djordjević, Butler, & Mark, 2015; Santamouris et al., 2017; Xu, Yang, & Wang, 2017).

Sustainable urban development relies on effective strategies in response to emerging environmental issues. Despite various strategies available, future studies on several aspects are still needed. First, although the effectiveness of many strategies reviewed in Section 3.2 has been demonstrated by both measurements and numerical simulations, their large-scale implementation (e.g., all buildings in an entire city) can be very challenging and will require careful investigations. These ambitious large-scale projects will certainly involve many political and financial issues, in which coordinations among different sectors will be critical. Second, most studies on public health mainly focus on how urban environmental degradation, such as high air pollution or heat stress, has negatively influenced mortality and morbidity among people of different ages. Assessments on the efficacy of (aggressive) urban environmental policies, especially those based on epidemiological evidence, are highly needed. Third, inequalities in exposure to environmental risk factors are prevalent in many U.S. cities, which have led to severe disparities in health outcomes among different racial and socioeconomic groups. There are no simple solutions to this issue, but specific policies toward vulnerable communities and populations should be developed to alleviate these inequalities. In a changing climate with increasing frequency of potentially catastrophic extreme events, planning and design need to take into account the trade-offs of various strategies (e.g., capital and operating costs and potential negative effects). A holistic consideration that maximizes the potential co-benefits of urban planning strategies and other broad climate actions (e.g., energy saving and carbon emission reduction) is also critical to improving the livability of cities throughout the life course.

4. Summary

Continuous improvement in health conditions and life expectancy marks the great success of human development. However, global urbanization amidst climate and environmental change is posing numerous challenges to populations of all ages. Healthy century-long lives in cities call for the enhanced understanding of different environmental factors that influence human well-being. As the first step, in this report, we focus on the impacts of per capita energy use and urban environments on human well-being, and investigate the potential pathways of sustainably reducing per capita energy use and improving urban environmental quality.

We first examine the relationship between 18 human well-being metrics and per capita energy consumption for 135 countries based on quantile regression models. Results show that the possible maximum performance of human well-being typically improves steeply with increasing per capita energy use and then peaks at an average annual energy use of ~90 GJ person^{-1}. Additional energy use beyond this threshold only produces negligible improvement in well-being outcomes. Further temporal analysis for life expectancy reveals that these decoupled relationships and threshold values are relatively consistent over time, suggesting the potentials of reducing per capita energy use while maintaining human well-being in many high-consumption countries (such as the U.S.). Our analysis of 20 state-level human well-being and per capita energy use also confirms these decoupled relationships in most states.

We review various possible pathways to sustainably reduce per capita energy consumption in residential, commercial, industrial, and transportation sectors without negative effects on human well-being. Potential solutions include energy-efficient building design, building retrofit, equipment, and appliance, life-cycle assessments and regular energy management, and the promotion of low- and zero-emission vehicles. Several programs in the

U.S. and other countries are analyzed as examples. We also discuss the role of policy instruments and private sector for energy saving and efficiency improvement.

In addition, we investigate the impact of urban environments on human well-being in a changing climate. We scrutinize the climate- and weather-related risks and challenges (e.g., rising temperature and air pollution) that Americans are facing in cities, and their detrimental impacts on urban residents, especially children, older adults, and people with certain diseases. We summarize alternative strategies to improve urban environmental quality and health outcomes based on existing evidence, including nature-based solutions such as green infrastructure, engineering solutions such as reflective materials, and urban structures and zoning regulations. In particular, three examples of programs and interventions that have positively affected human well-being are discussed in detail. We also elaborate on how policy interventions, private sector actions, and innovative technologies can benefit urban environmental quality.

Furthermore, we identify several aspects that require further studies: (1) evidence-based studies on how per capita energy use can directly influence human well-being of all ages are relatively rare; (2) how the increasing share of clean and renewable energy in industrialized countries can influence per capita energy use is unclear; (3) policies are needed to reduce inequalities in per capita energy consumption among and within states; (4) large-scale implementation of urban climate mitigation and adaptation strategies is challenging and full of uncertainty; (5) epidemiological evidence on the efficacy of environmental policies is needed; (6) policies mitigating inequalities in exposure to environmental risk factors among racial and socioeconomic groups are imperative; and (7) planning of livable cities in a changing climate demands a holistic consideration of the trade-offs of different strategies. Future investigation in these areas will benefit the adaptation of a long-lived society to climate change and contribute to the well-being of century-long lives.

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Appendix A: Model description

Appendix A will be updated upon the acceptance of the manuscript (Jackson et al., 2021).

Appendix B: Data sources of the well-being metrics used in Section 2.2

Appendix B will be updated upon the acceptance of the manuscript (Jackson et al., 2021).

Appendix C: Data sources of the well-being metrics used in Section 2.3

Here we summarize the data sources of the 20 well-being metrics used in Section 2.3:

(1) *Access to clean and safe water rate*: https://analyticscampus-gallup-com.stanford.idm.oclc.org/Tables (2013)

(2) *Air quality index*: https://aqs.epa.gov/aqsweb/airdata/download_files.html#Annual (2017)

(3) *Depressive episode rate (adolescents)*: https://www.kff.org/other/state-indicator/adolescents-reporting-a-major-depressive-episode-in-the-past-year-by-gender/ (2017)

(4) *Education index*: https://globaldatalab.org/shdi/edindex/USA/?interpolation=0&extrapolation=0&nearest_real=0&colour_scales=national (2017)

(5) *Food insecurity*: https://map.feedingamerica.org/ (2017)

(6) *Gini coefficient*: https://data.census.gov/cedsci/table?q=gini%20coefficient&tid=ACSDT1Y2018.B19083&vintage=2018&hidePreview=true&g=0100000US.04000.001 (2017)

(7) *Happiness*: https://wallethub.com/edu/happiest-states/6959/ (2019)

(8) *Health index*: https://globaldatalab.org/shdi/healthindex/USA/?interpolation=0&extrapolation=0&nearest_real=0&colour_scales=national (2017)

(9) *Household access to internet rate*: https://data.census.gov/cedsci/table?q=S28&d=ACS%201-Year%20Estimates%20Subject%20Tables#acsST (2017)

(10) *Human development index*: https://globaldatalab.org/shdi/shdi/USA/?interpolation=0&extrapolation=0&nearest_real=0&colour_scales=national (2017)

(11) *Life expectancy*: https://globaldatalab.org/shdi/lifexp/USA/?interpolation=0&extrapolation=0&nearest_real=0&colour_scales=global (2017)

(12) *Murder rate*: https://deathpenaltyinfo.org/facts-and-research/murder-rates/murder-rates-by-state (2017)

(13) *Poverty rate*: https://www.kff.org/other/state-indicator/distribution-by-fpl/ (2017)

(14) *Real income per capita*: https://www.bea.gov/data/income-saving/personal-income-by-state (2017)

(15) *Renewable energy rate*: https://www.eia.gov/state/seds/seds-data-complete.php?sid=US#Consumption (2017)

(16) *Total ecological footprint per capita*: https://www.footprintnetwork.org/2015/07/14/states/ (2015)

(17) *Unemployment rate*: https://www.bls.gov/lau/#tables (2017)

(18) *Urban population rate*: https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2010-urban-rural.html (2010)

(19) *Vehicle miles of travel per capita*: https://www.fhwa.dot.gov/policyinformation/quickfinddata/qftravel.cfm (2014)

(20) *Women equality*: https://wallethub.com/edu/best-and-worst-states-for-women-equality/5835/ (2019)

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