GREENING THE BUILDING ENVIRONMENT – CLIMATIC CHALLENGES, IMPACT, MITIGATION AND ADAPTATION SOLUTIONS

On the magnitude of Urban Climate Change, Its impact on Energy, Health, Productivity, Vulnerable Population, Economy and Environmental Quality. Heat Mitigation and Adaptation Potential and Proposals to Counterbalance Urban Heat

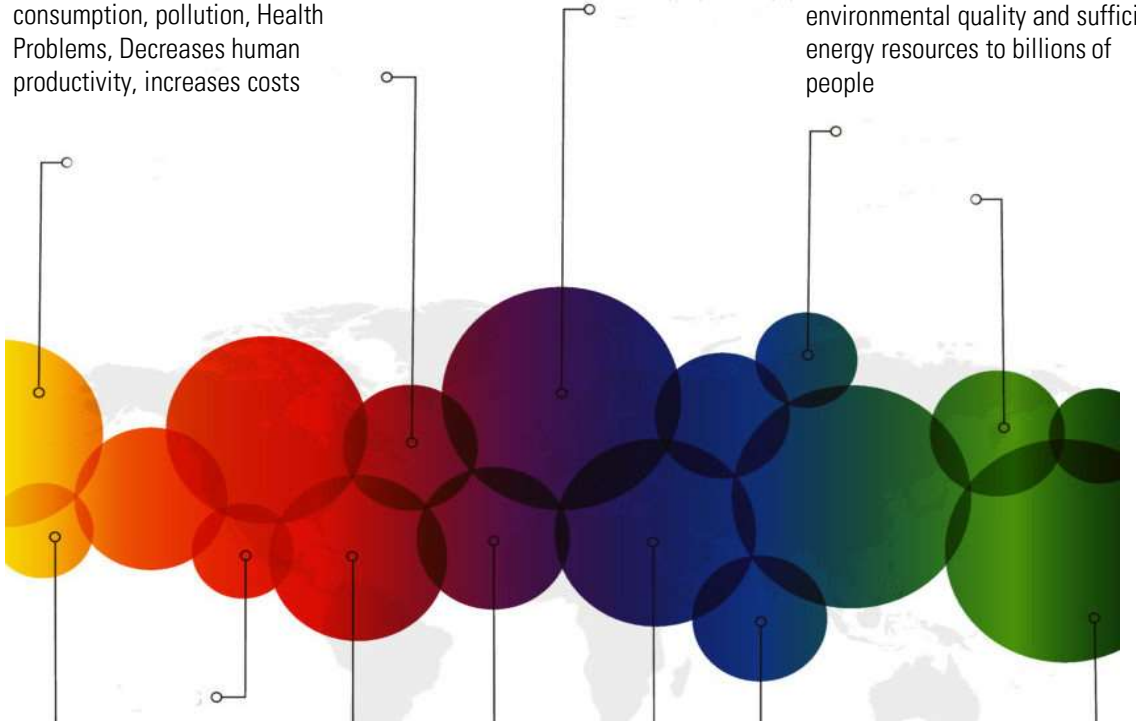
M. Santamouris, UNSW, Sydney, Australia

Greening the Built Environment - Main Challenges of the Building Sector

Global and Local Climate Change
Increases the energy consumption, pollution, Health Problems, Decreases human productivity, increases costs

Overpopulation
Increases the need for additional housing and Infrastructures

Poverty
A huge need to provide adequate and healthy housing, Indoor environmental quality and sufficient energy resources to billions of people



Urbanisation
Need for Sustainable Urban Planning and implementation of green technologies in the housing sector

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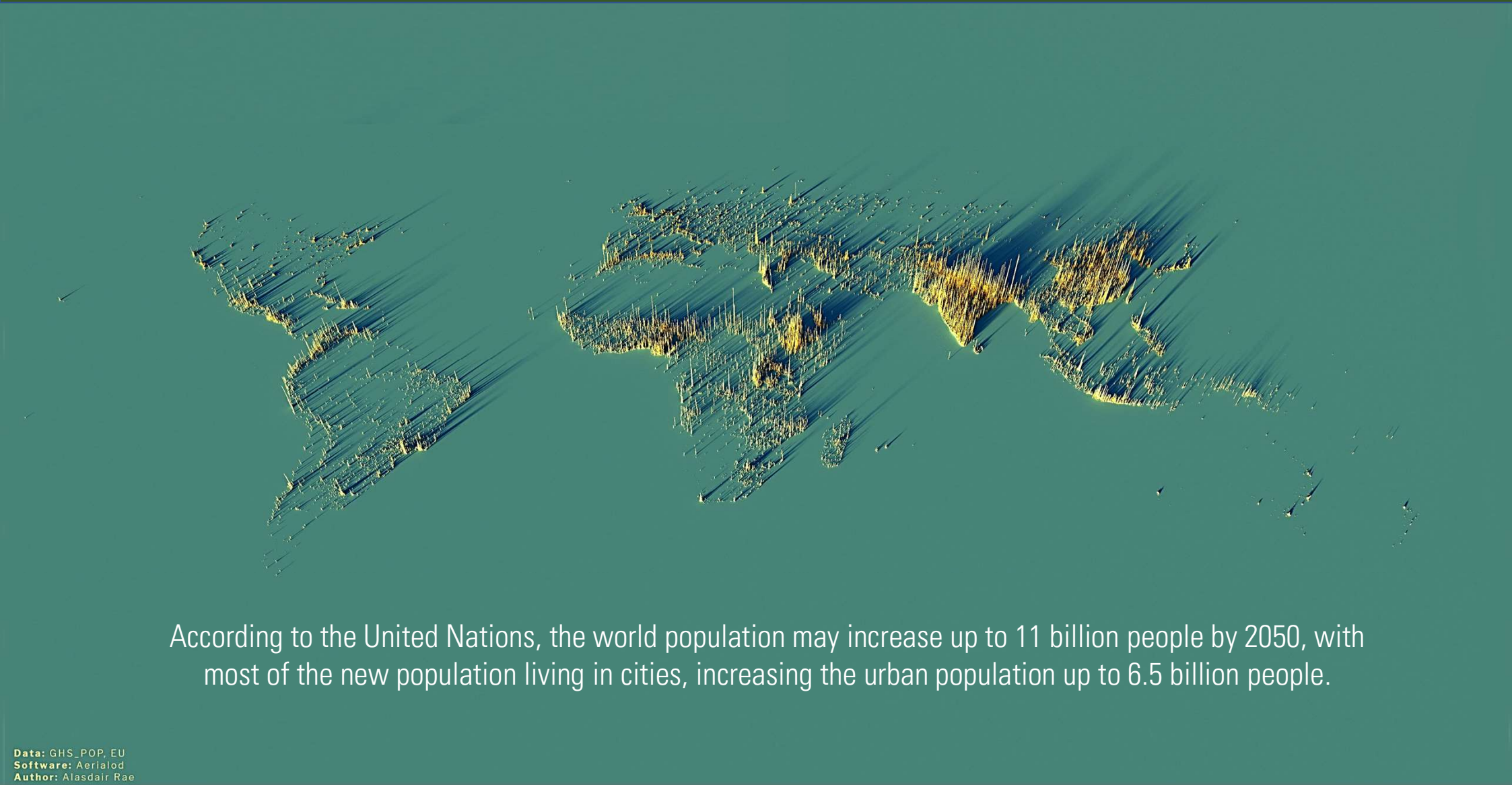
Provision of Sustainable Energy
Need to provide affordable and sustainable Energy

Economic Growth and Quality of Life
Need to provide the proper space, housing quality, sustainable building regulations and development opportunities

Urbanisation is a Main Driver of Energy and Environmental Problems



According to the United Nations, the world population may increase up to 11 billion people by 2050, with most of the new population living in cities, increasing the urban population up to 6.5 billion people.

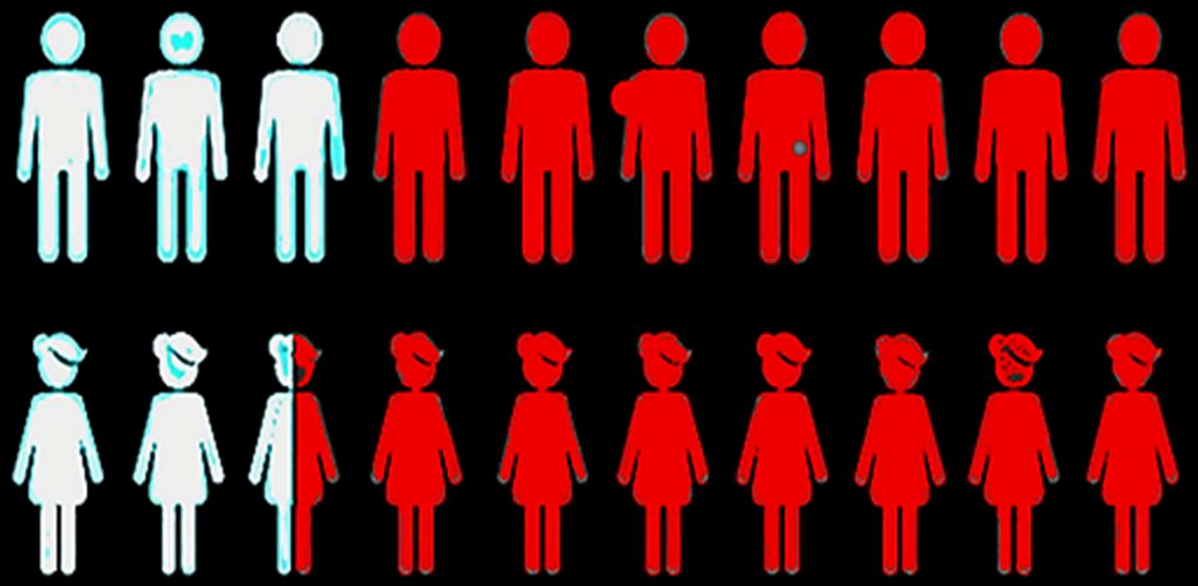
Urban Overheating is the most documented Problem of Climate Change

13,000 OVERHEATED CITIES

1.7 BILLION PEOPLE UNDER SEVERE OVERHEATING

THREE TIMES MORE OVERHEATING HOURS SINCE 1980

118 BILLION OVERHEATING MAN HOURS



C. Tuholske *et al.*, "Global urban population exposure to extreme heat," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 118, no. 41, pp. 1–9, 2021, doi: 10.1073/pnas.2024792118.

Global Impact of Urban Overheating

Synergetic results between urban overheating, UHI, and heat waves cause a total urban stress higher than the sum of the background stress caused by the UHI and heat waves independently. Increased urban temperatures

IMPACT OF URBAN OVERHEATING

- Rise the cooling energy consumption in cities
- Decrease the efficiency of power plants,
- Increase the emission of pollutants,
- Rise the peak electricity demand,
- Intensify heat related mortality and morbidity,
- Lower the productivity of population and
- Affect the survivability of low-income households

Energy Impact of Urban Overheating

M. Santamouris, "Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change," *Energy Build.*, , 2020.

Increases the Cooling Energy Consumption

Urban overheating is inducing an additional energy penalty at the city scale close to 0.74 kWh/m2 /°C, while the average energy penalty per person, is close to 237 (± 130) kWh/p

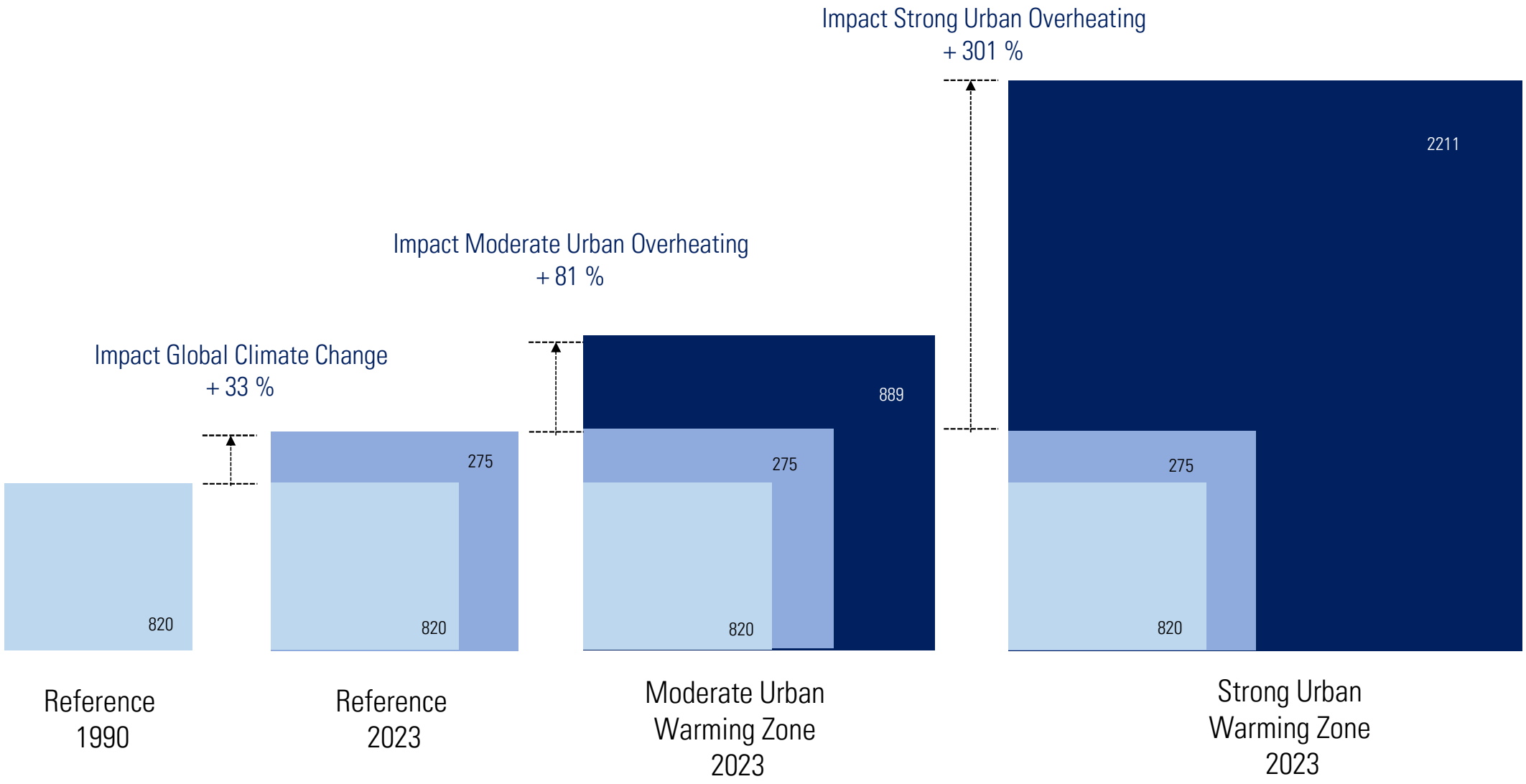
Decreases the Efficiency of Power Plants

A 1 °C rise of the ambient temperature reduces the power output of thermal and nuclear power stations by 0.6%

Increases the Peak Electricity Demand

The peak electricity rise per degree of temperature increase varies between 0.45% and 4.6%, corresponding to an additional electricity penalty close to 21Watts (± 10.4) per degree of temperature increase and per person

Energy Impact of Urban Overheating - Cooling Degree Hours in Sydney



On August 2022, the UK Met Office recorded the country's first-ever temperature above 40 degrees Celsius (104 degrees Fahrenheit) at London's Heathrow Airport just before 1 p.m., as temperatures were still rising.

High demand sent power prices in the UK up 5% in one day.
Across the Channel, things have been even more volatile. Europe's heat wave has reduced France's available nuclear power, as the river water used to cool nuclear plants became too hot to be effective.

As a result, day-ahead baseload power prices settled at 610 euros per megawatt-hour — about 10 times higher than prices from 2017 to 2021.

Environmental Impact of Urban Overheating

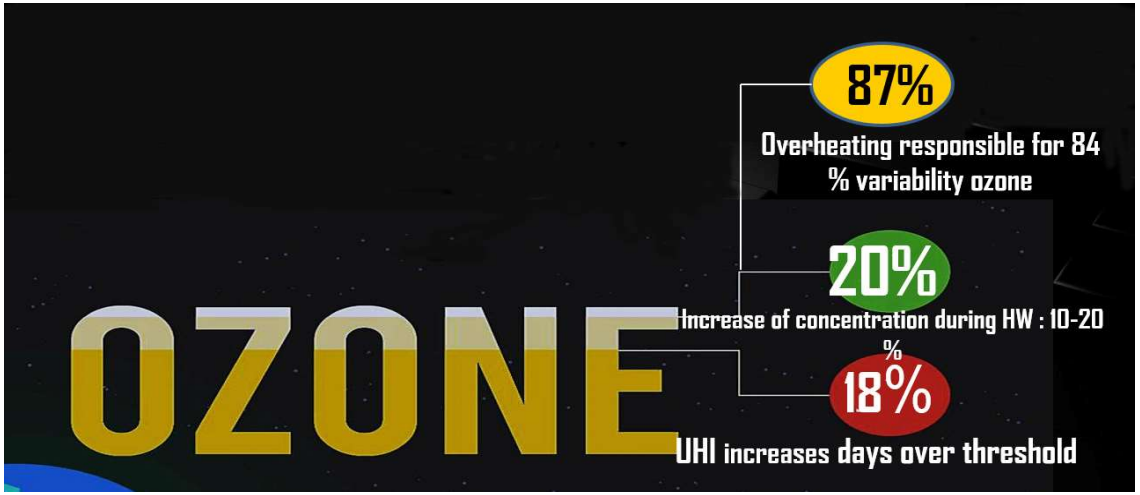
Overheating affects the urban environmental quality increasing the concentration of harmful pollutants.

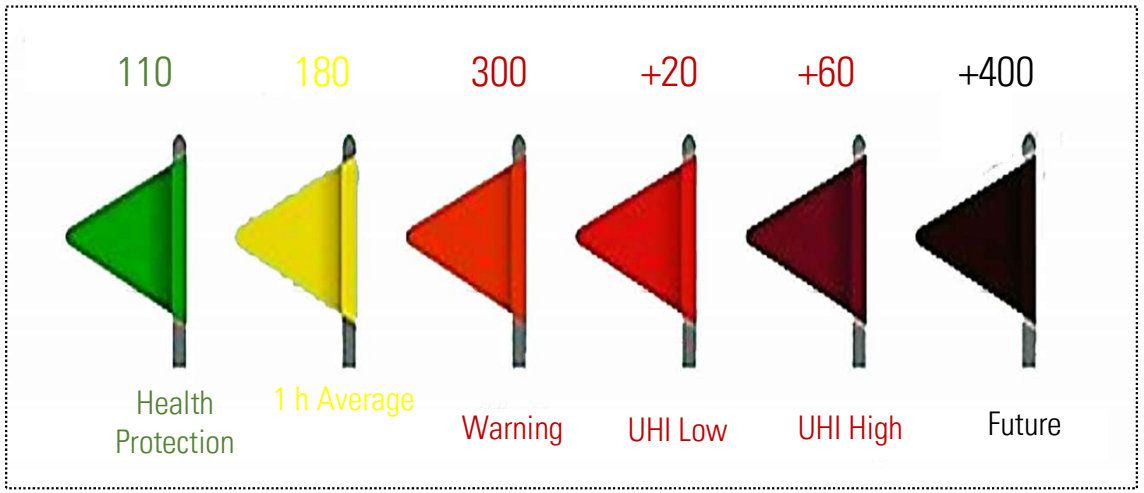
Higher urban temperatures accelerate the formation of ozone precursors like VOC's and NOx combining photochemically to generate ground level ozone.

Ozone is toxic and an oxidant affecting the human respiratory and cardiovascular systems.

The expected future increase of the ambient temperature is expected to further increase the concentration of the ground level ozone and the frequency of future severe ozone episodes, as well as the concentration of other pollutants.

It is estimated that the frequency of severe ozone episodes in four Canadian cities may increase up to 50 % by 2050 and 80 % by 2080.





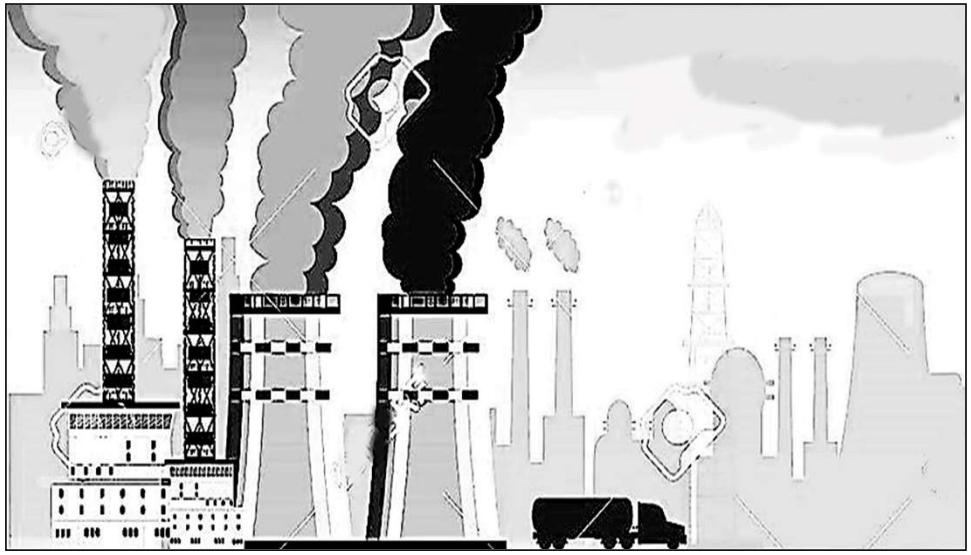
Environmental Impact of Urban Overheating

Urban overheating obliges utilities to operate power plants for an extended period to satisfy the peak electricity demand.

Increased operation of thermal power plants significantly rises the emissions of pollutants and increases the concentration of secondary pollutants like the ground level ozone.

Each degree of temperature rise in the Eastern United States during the period between 2007-2012, resulted in a rise by 3.35%/°C ±0.50%/°C of the SO_2 emissions, 3.32%/°C ±0.36%/ °C rise in CO_2 emissions, and a 3.60%/°C ±0.49%/°C increase in NO_X emissions.

It is predicted that in 2050 the corresponding NOx emissions may increase by 16%, and the SO_2 emissions by 18%.



3.32%/°C ± 0.36%/°C increase in CO_2 emissions,

3.35%/°C ± 0.50%/°C increase in SO_2 emissions,

and

3.60%/°C ± 0.49%/°C increase in NO_X emissions

M. Santamouris, "Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change," *Energy Build.*, vol. 207, 2020

Impact of Urban Overheating on Vulnerable Population

Overheating affects the urban socioeconomic and biophysical vulnerability and has a serious impact on low-income population.

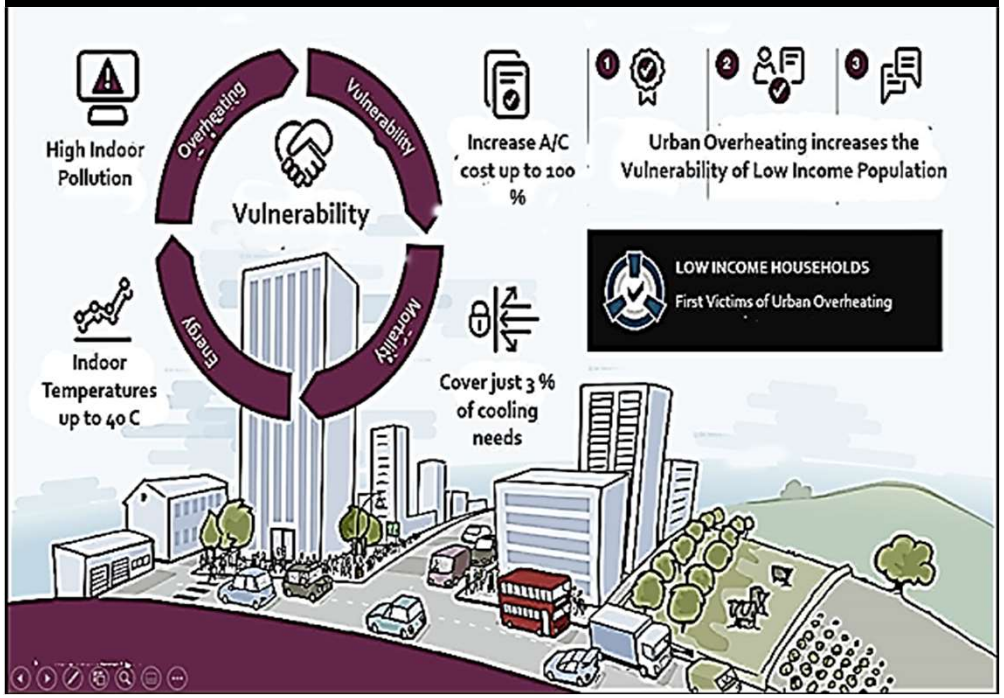
Vulnerable population lives in districts of disproportionately high UHI intensity, excess heat stress, higher risk of heat related mortality and significant socioeconomic vulnerability.

A significant correlation between exposure to extreme heat and the socioeconomic vulnerability exists for several cities resulting in almost twice the mortality risk in the deprived districts.

Vulnerable population lives in buildings of considerably lower thermal quality. Extreme indoor temperatures, 35-40°C, are recorded during extreme events in low-income houses.

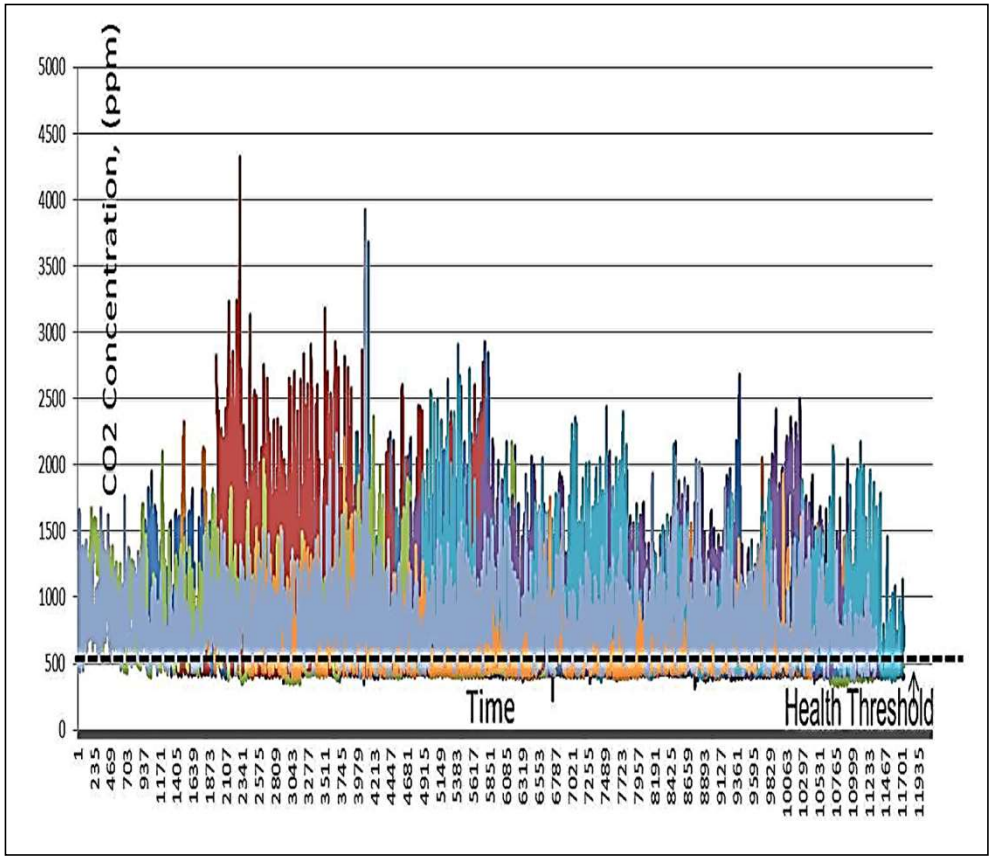
Only 2% of the necessary cooling load is covered by low-income population in Portugal, while in Greece the cooling cost for low-income households is approximately double the average cost.

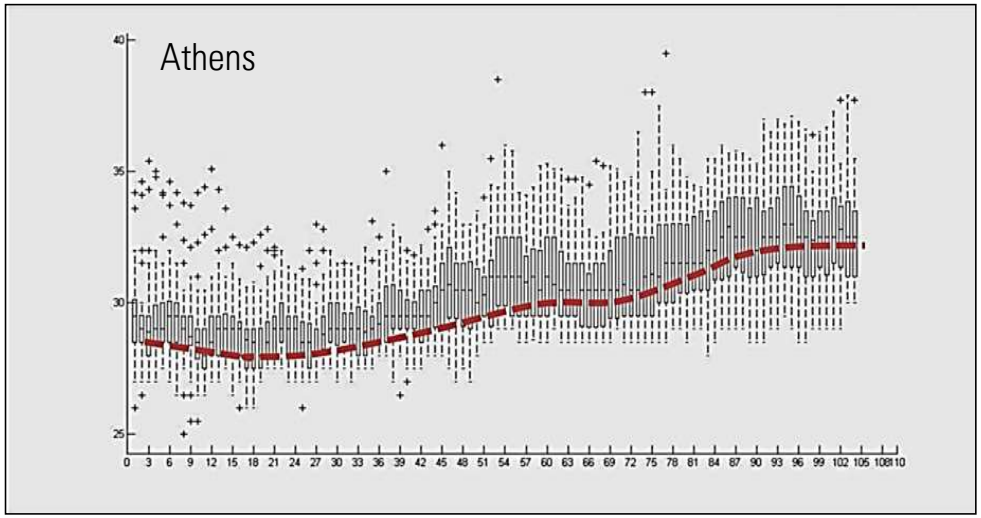
Low-income population lives in deprived urban zones with high overheating. Urban Overheating results in high mortality, energy cost and discomfort.

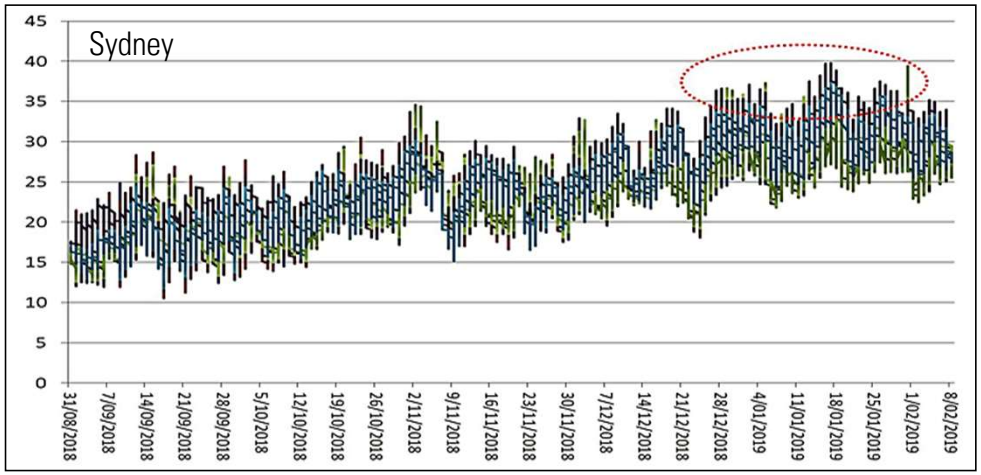


M. Santamouris and D. Kolokotsa, "On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe," *Energy Build.*, 2015

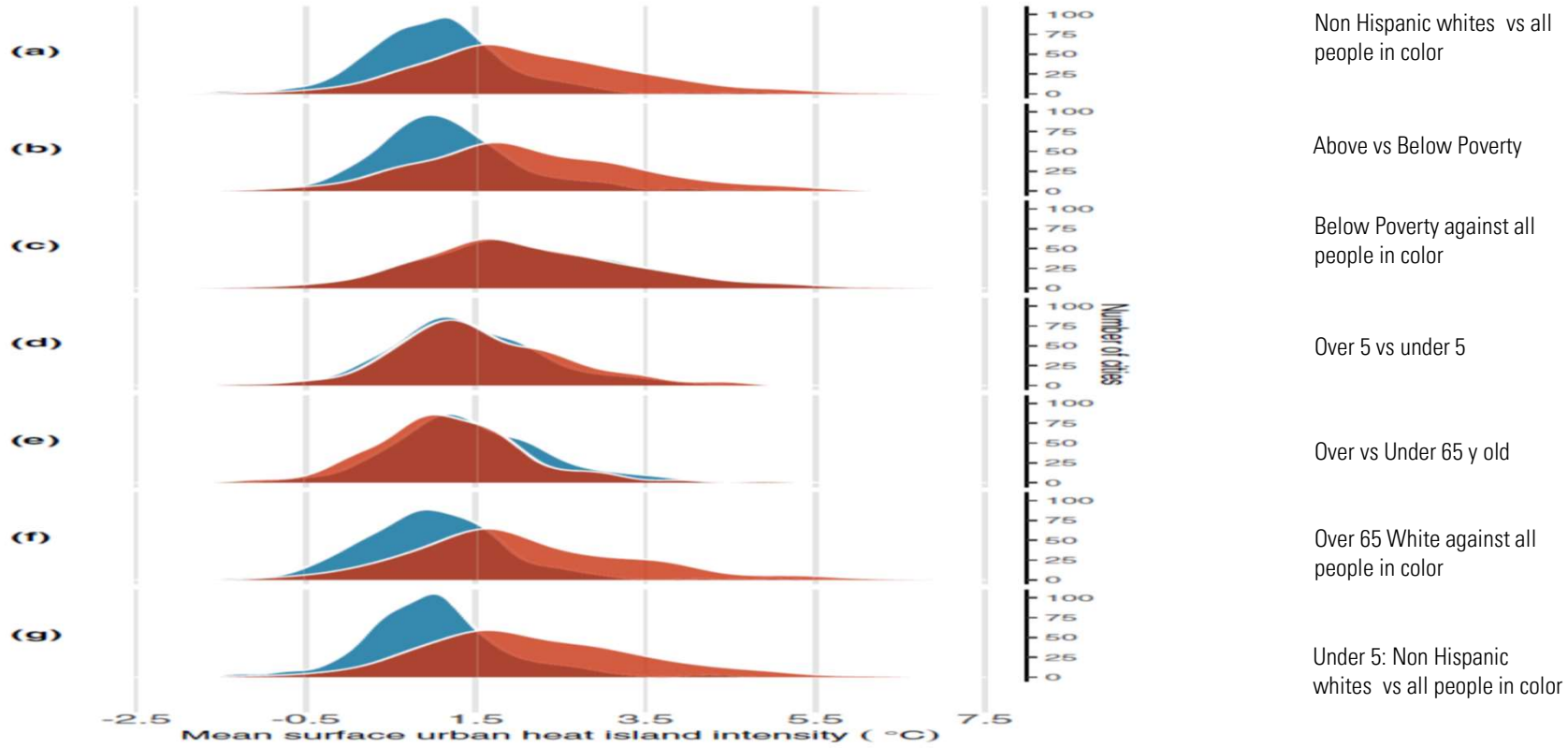
Impact of Urban Overheating on Vulnerable Population





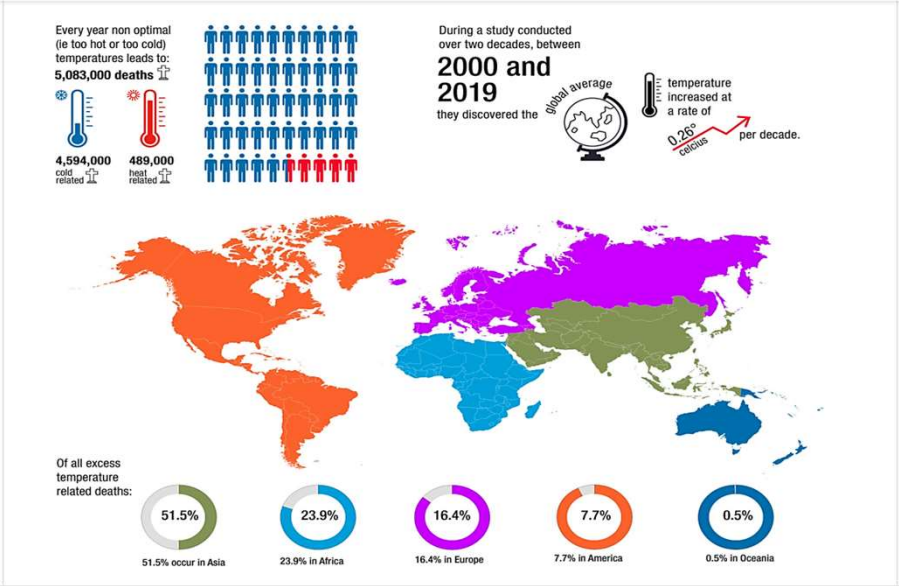


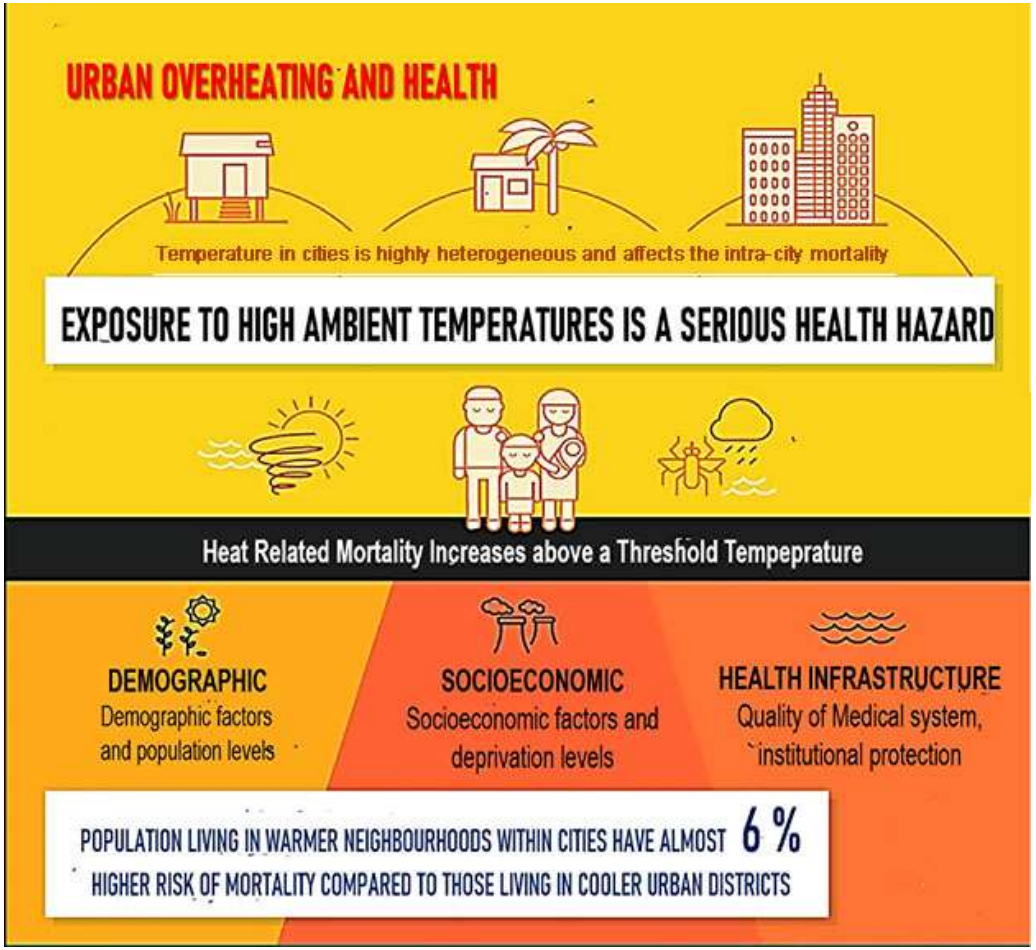
175 USA Cities



A. Hsu et al : Disproportionate Exposure to Urban Heat Island intensity across Major US cities, Nature Communications,

Urban Overheating and Health



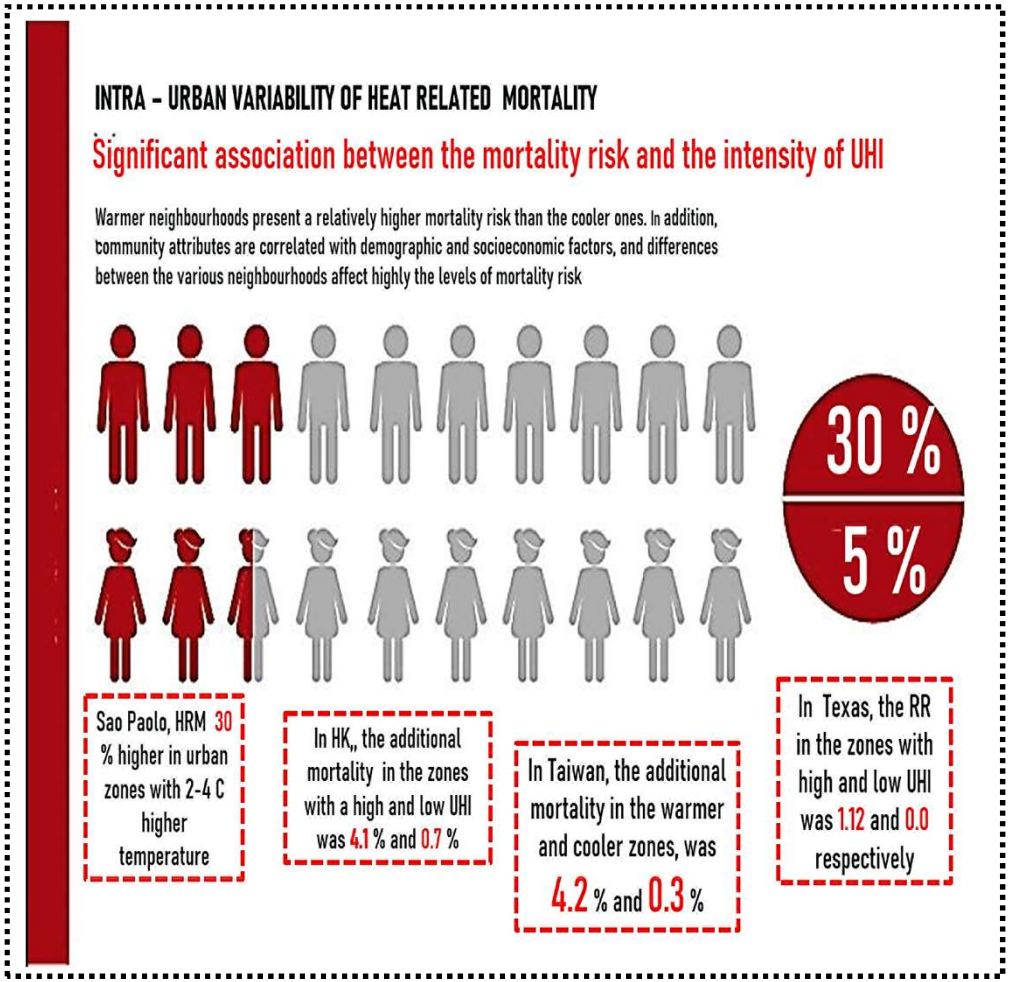


Heat related morbidity and mortality caused by the local climate change, is highly alarming, and it seems to be one of the current and future peak scientific topics. According to the existing epidemiological records almost 59,114 people passed away between 2000 and 2007 during 52 extreme heat events around the world.

L. H. Schinasi et al, "Modification of the association between high ambient temperature and health by urban microclimate indicators: A systematic review and meta-analysis," *Environ. Res.*, 2017.

Based on existing data collected from developed countries only, heat-related mortality may increase up to 30% in deprived areas of overheated cities.

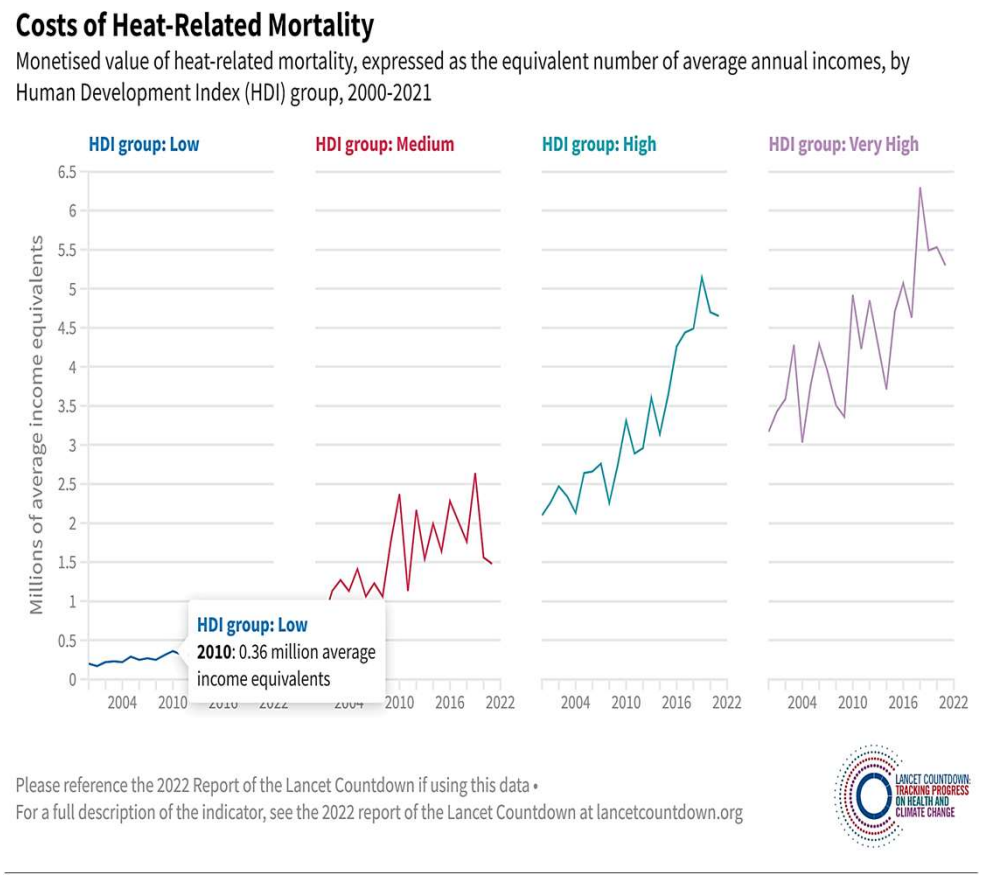
In Europe, the number of people at high risk of mortality will triple at 3°C overheating compared to 1.5°C warming, in Central and Southern Europe and urban areas.



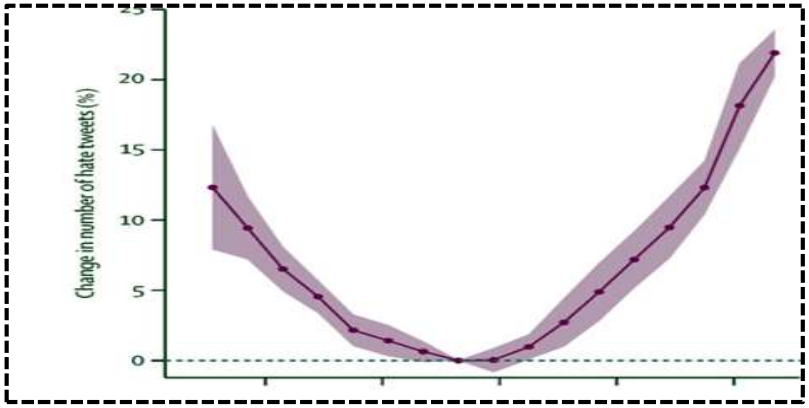
M. Santamouris, "Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change," *Energy Build.*, vol. 207, 2020,

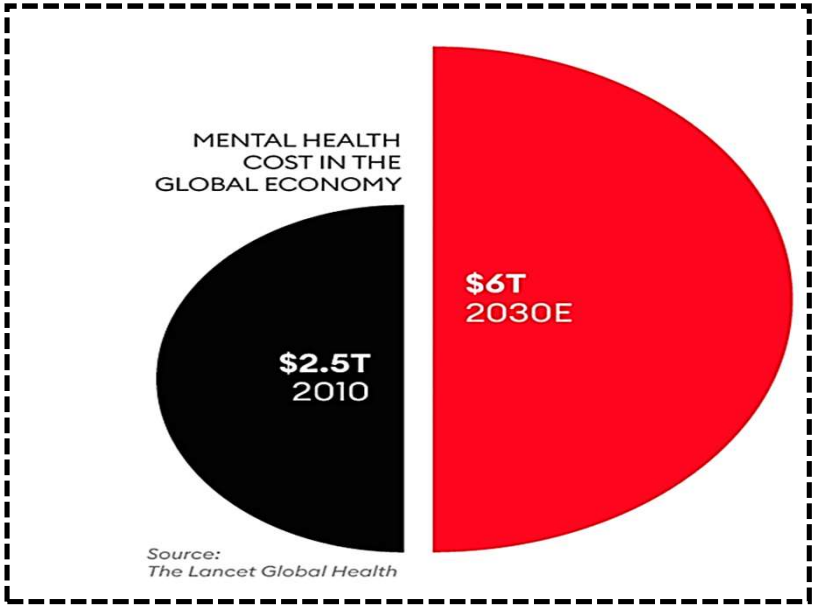
The monetized value of global heat-related mortality was estimated to be US$ 144 billion in 2021, equivalent to the average income of 12.4 million people.

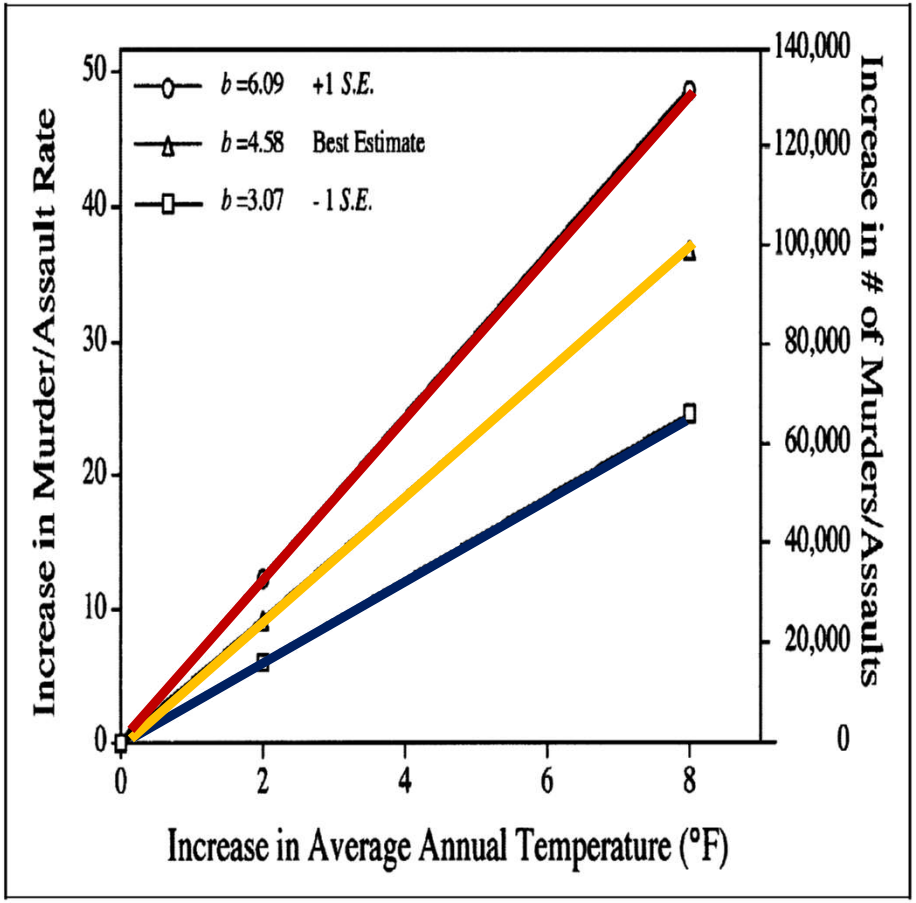
In France Between 2015 and 2019, the economic impact of selected health effects of heat waves amounted to €25.5 billion.



Urban Overheating increases Mental Health Problems

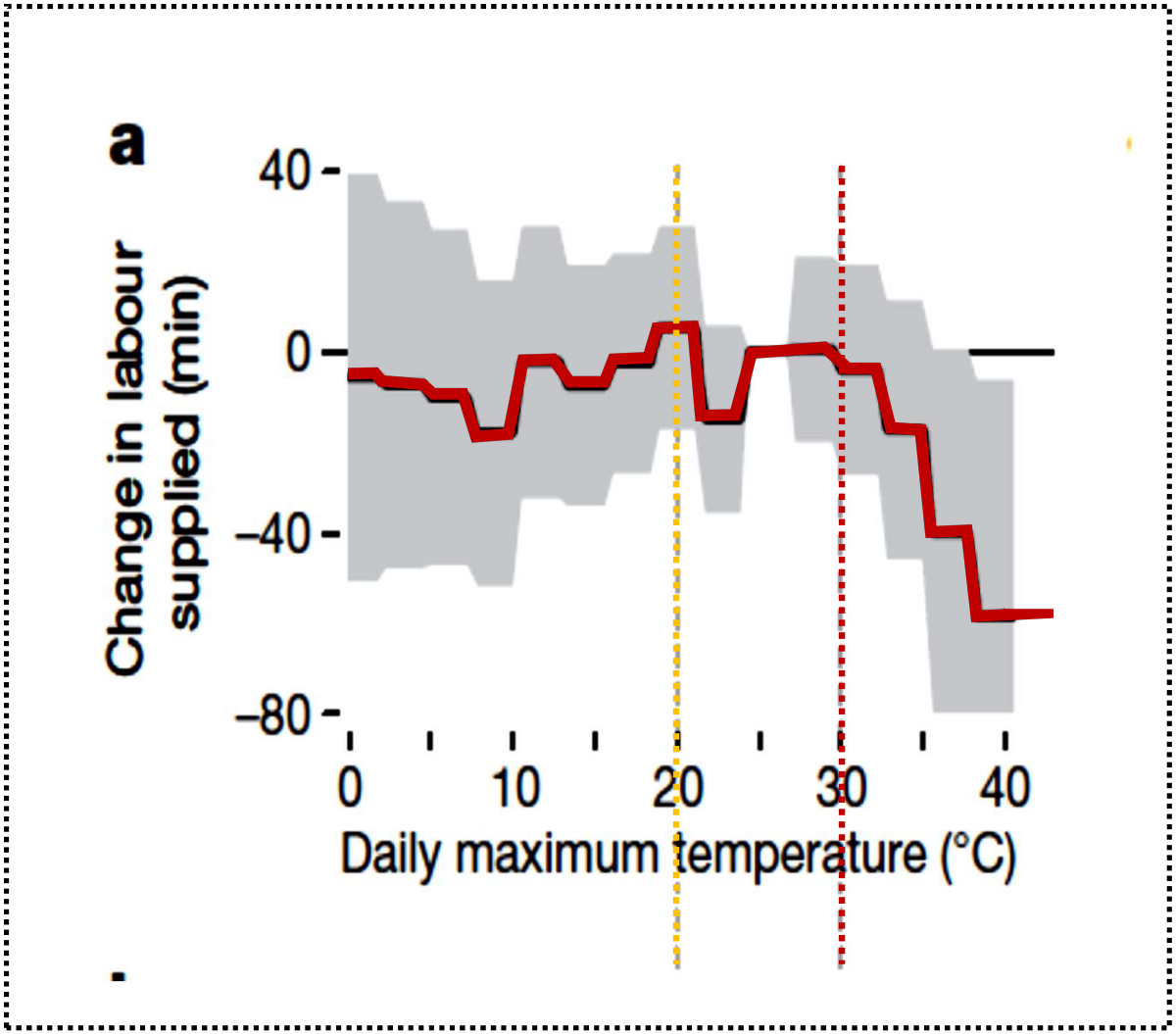






Heat and Violence. Article *in* Current Directions in Psychological Science · February 2001
DOI: 10.1111/1467-8721.00109

Labour supply and human productivity may decrease up to 60% when ambient temperature exceeds 30-35 C.



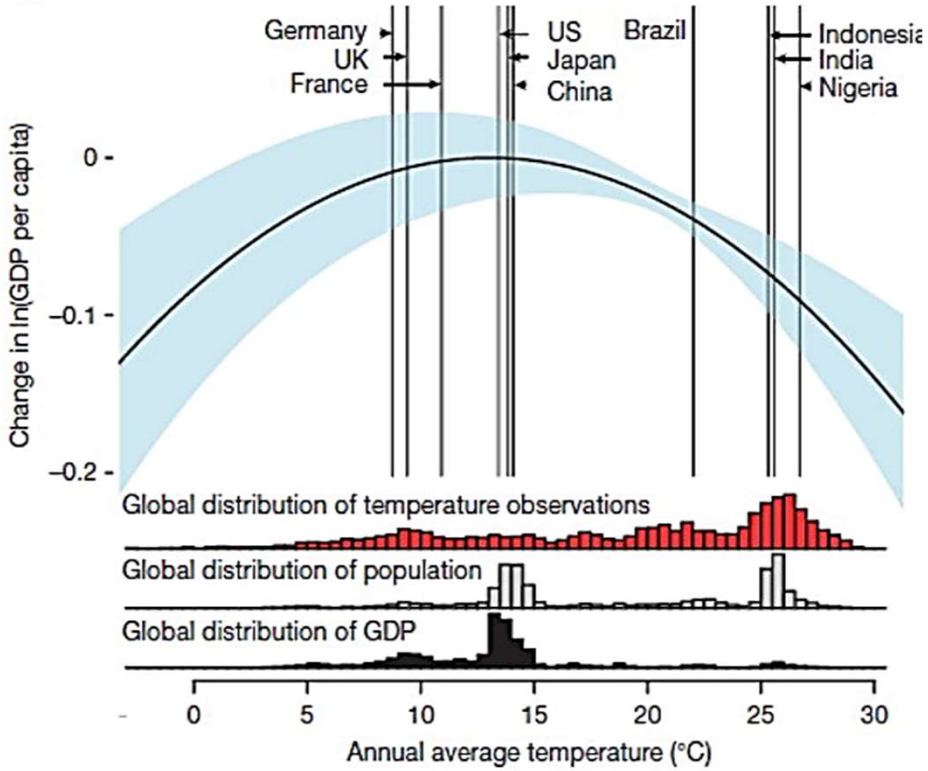
Graff Zivin, J. & Neidell, M. Temperature and the allocation of time: Implications for climate change. J. Labor Econ. 13, 1–26 (2014).

Warming is expected to reshape the global economy by reducing average global incomes by roughly 23% by 2100 and widening global income inequality, relative to scenarios without overheating.

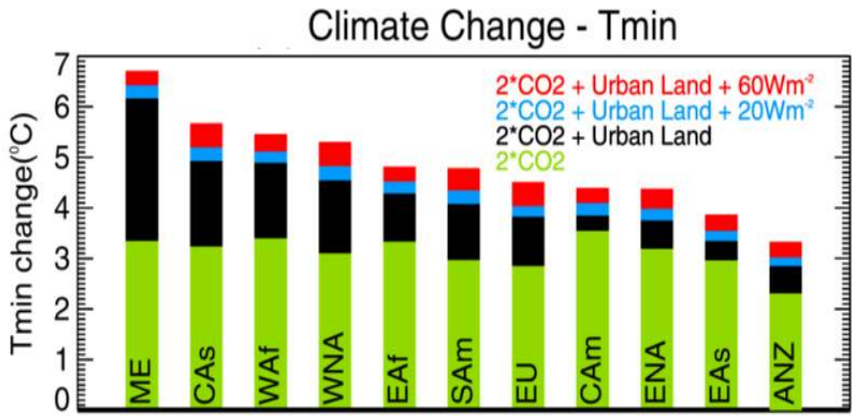
Economy in U.S. grows at a slower pace during hot summers. The annual growth falls 0.15 to 0.25 % for every 1 F increase of the average summer temperature.

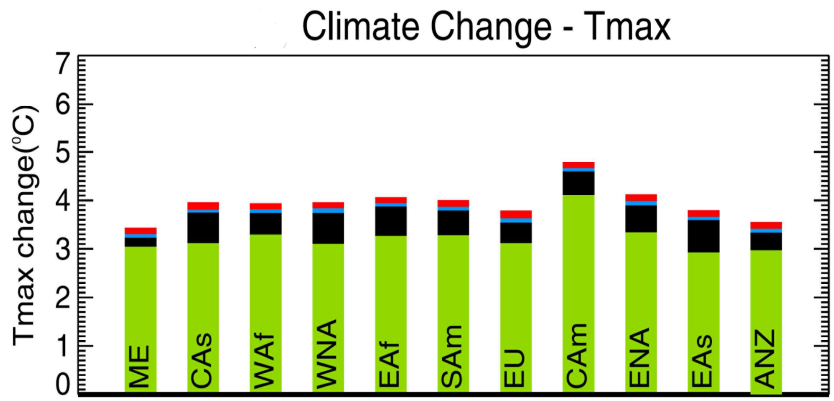
United States could lose approximately $100 billion annually from heat-induced loss in labor productivity.

About 1 Million work life-years are projected to be lost by 2030 due to operational heat stroke fatalities with 70 million work life-years lost because of reduced labour productivity.



Source : Global non-linear effect of temperature on economic production, Marshall Burke, Solomon M. Hsiang*& Edward Miguel, 12 NOVEMBER 2015 | VOL 527 | NATURE | 235





Simulated Increase of the Urban Temperature and UHI caused by the combined impact of greenhouse gas and urban expansion forcing, (RCP 8.5)

- Increase in the Surrounding Rural zone (2 x CO2)
- Increase in the City (2 x CO2)
- Increase in the City (2 x CO2)+ 20 w/m2 anthropogenic heat
- Increase in the City (2 x CO2)+ 60 w/m2 anthropogenic heat

Middle East (ME), Central Asia (CAs), West Africa (WAf), West North America (WNA), East Africa (EAf), South America (SAm), Europe (EU), Central America (CAm), East North America (ENA), Australia and New Zealand (ANZ)

Ref : Climate change in cities due to global warming and urban effects. Mark P. McCarthy, Martin J. Best, and Richard A. Betts, GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L09705

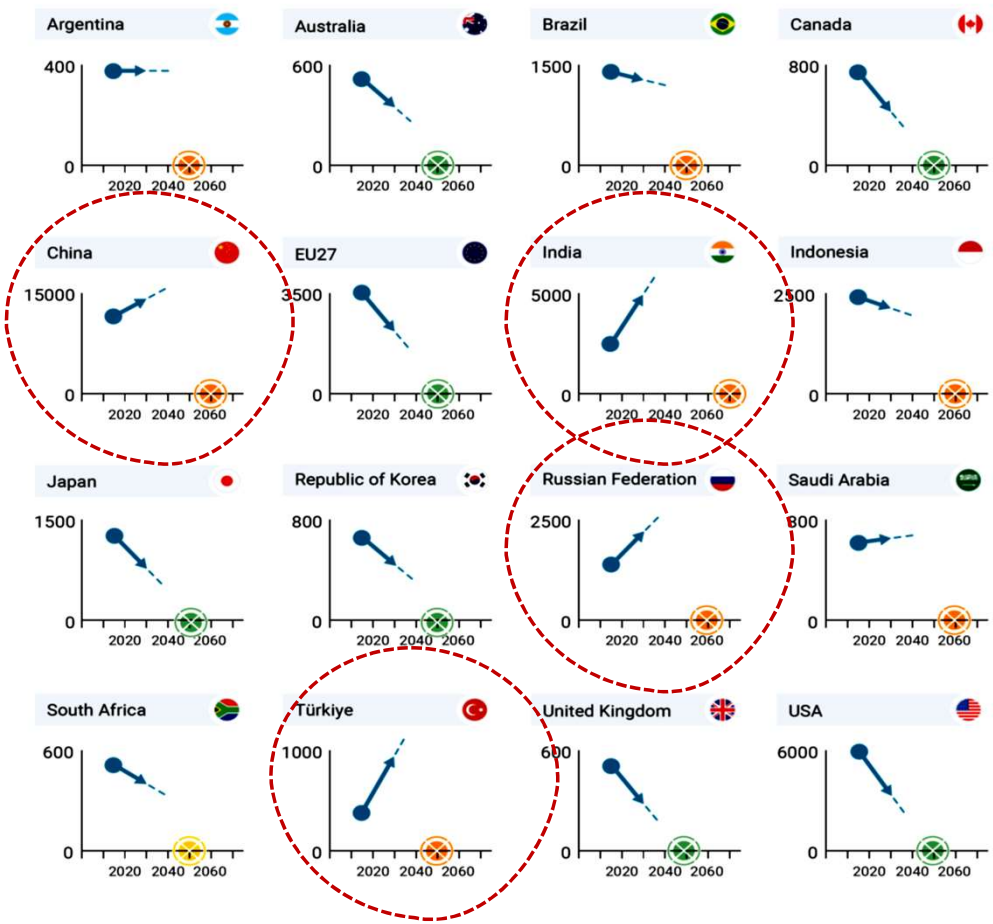
Serious Increase of the Energy Consumption in Developing Countries

We are able to built Zero Energy Buildings and Zero Energy Settlements.

However, the serious population increase, the tremendous increase of the penetration of A/C, the growth of floor area per person and the lack of technical knowledge and resources may result in a serious increase of the building energy consumption in the developing world.

There are almost 3.6 billion cooling devices in the world, increasing with a rate of ten devices per second
While in USA and Japan the penetration of air conditioners exceeds the 90 % of the population, it is much lower in Southeast Asia, 15 %, India and Africa, (5%).

It is estimated that only 10 % of the 2.8 billion people living in the hottest parts of the planet have access to air conditioning,



Source : UNEP 2022

Future Energy Consumption of Buildings – Penetration of A/C

200% and up to 2,000% by 2050,

depending on the evolution of the main economic and climatic drivers.

Increased penetration of cooling devices, causes a very serious increase of the peak electricity demand, obliging utilities to build additional power plants that may operate for a limited time.

It is projected that the direct and indirect emissions from air conditioning and refrigeration devices may rise by 90 % by 2050 above the 2017 levels.

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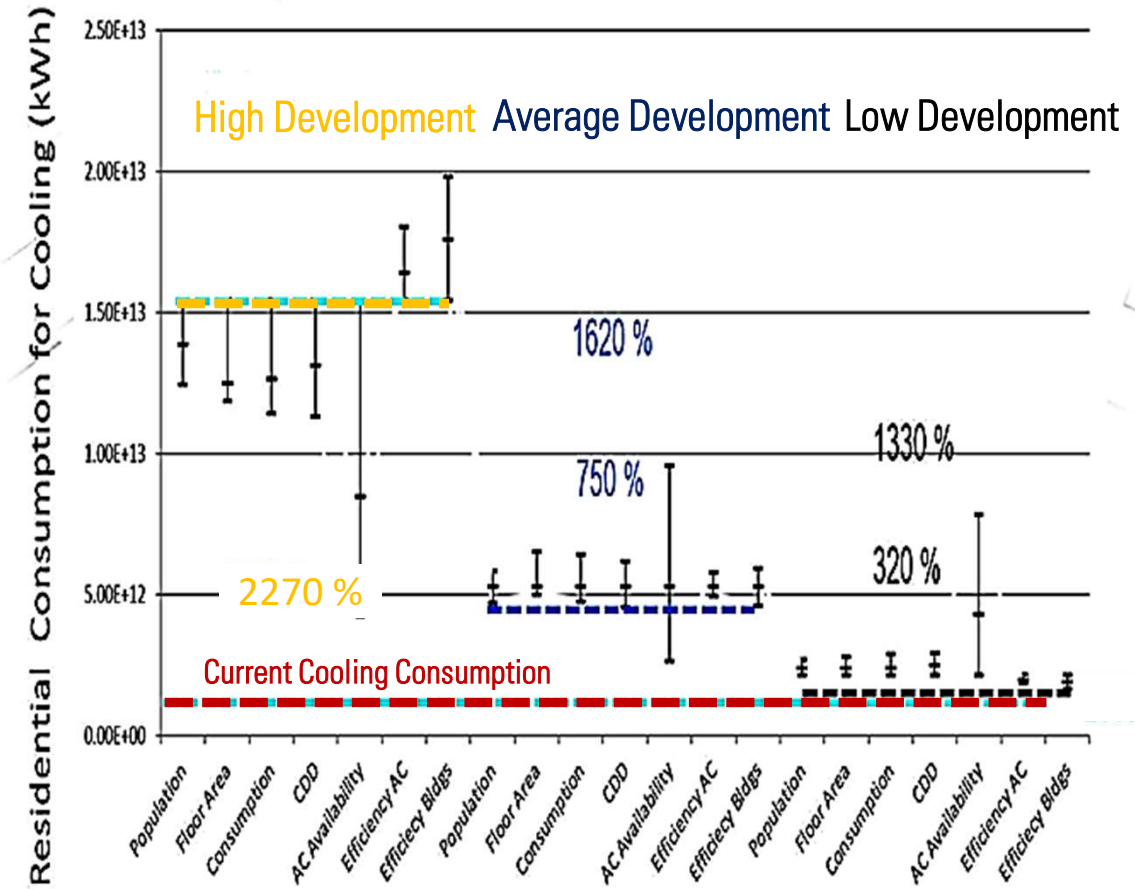
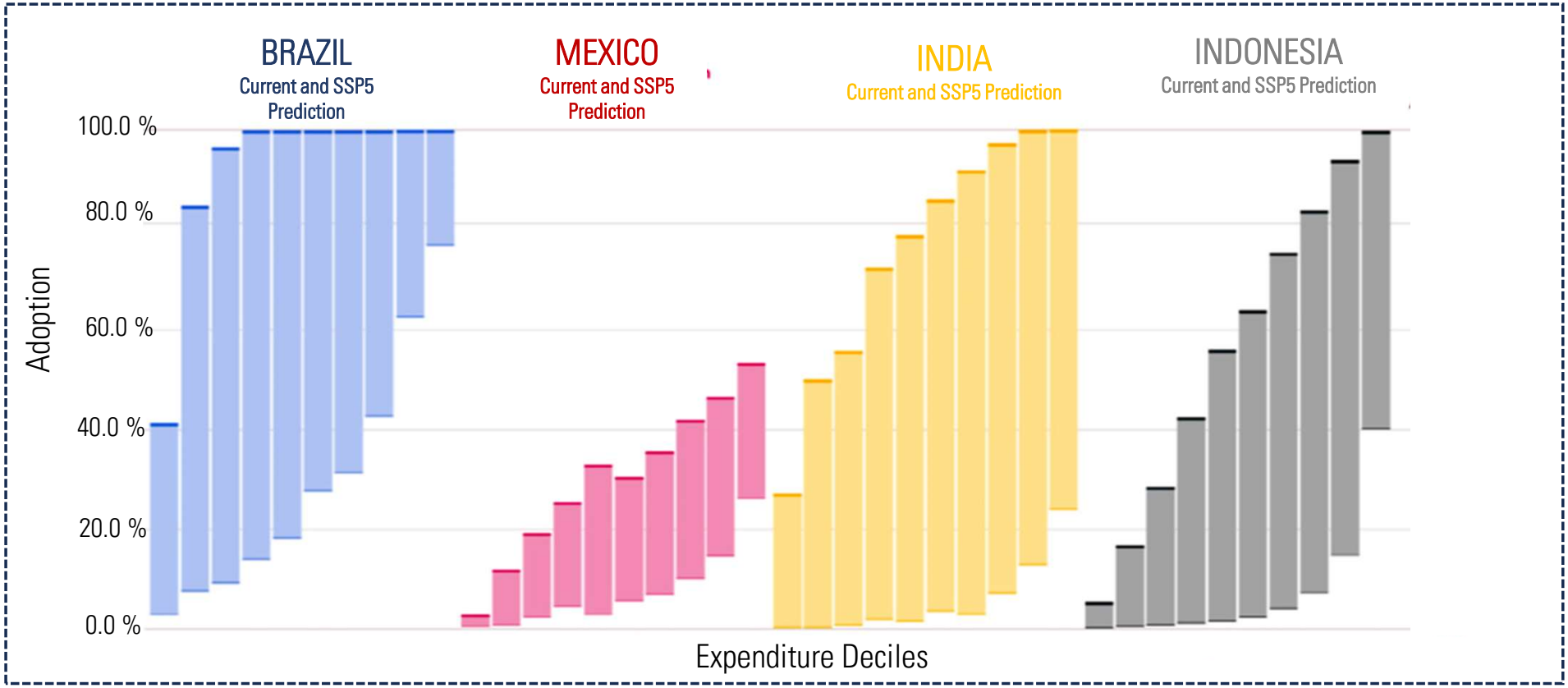


Cooling Energy Consumption of Buildings by 2050

M. Santamouris : Cooling of Buildings. Past, Present and Future, Energy and Buildings, 128 (2016)

Future Energy Consumption of Buildings – Penetration of A/C

Current and Future Penetration of A/C in Emerging Economies per Income Group

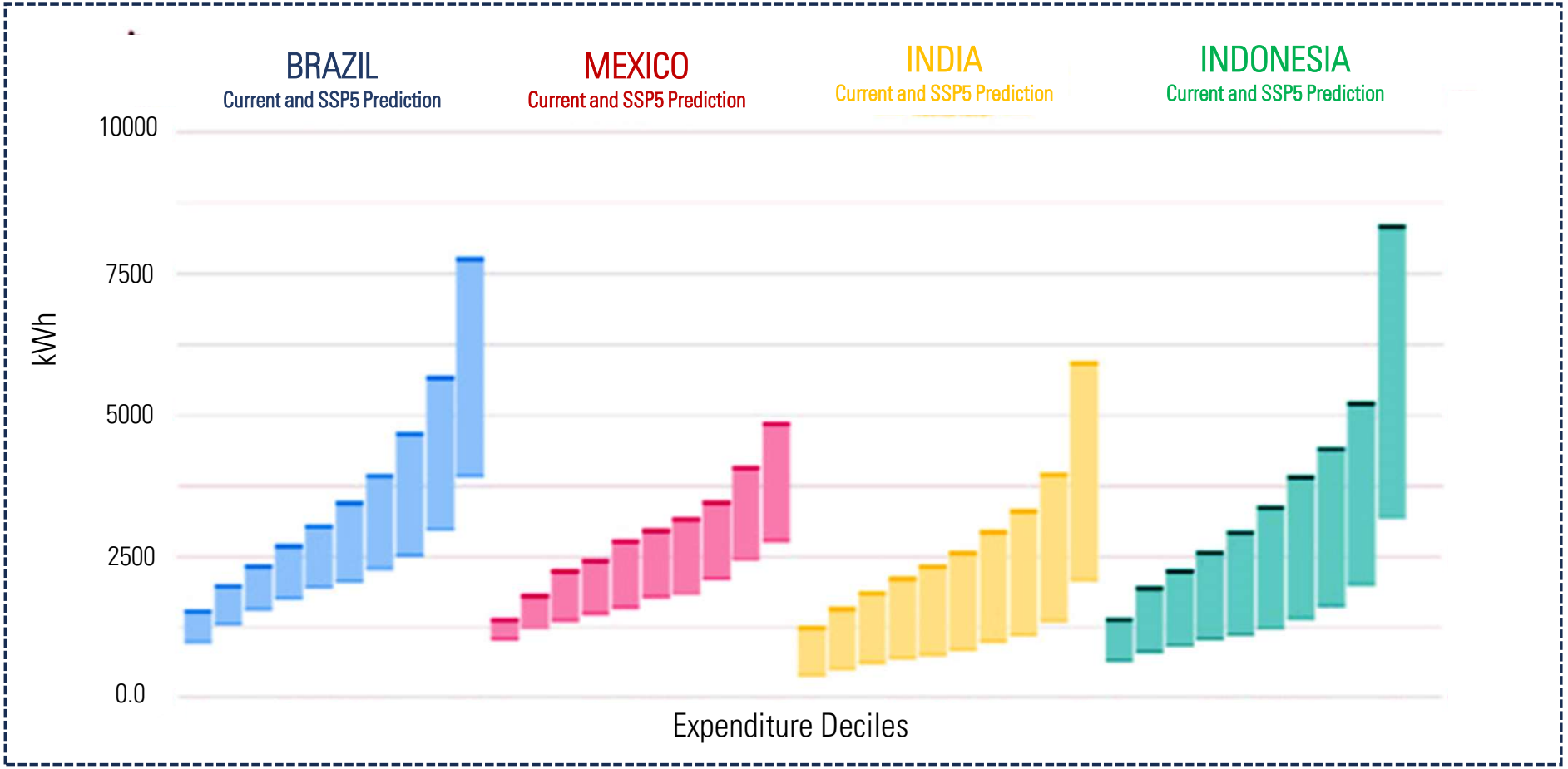


By 2040, a nonnegligible fraction of the population will be left behind. On 2040, between 64 and 100 million households out of the total number of households living in the four countries considered in the latest waves of 343 million will face an adaptation cooling deficit.

NATURE COMMUNICATIONS | (2021) 12:6460 | https://doi.org/10.1038/s41467-021-26592-2 | www.nature.com/naturecommunications

Future Energy Consumption of Buildings – Penetration of A/C

Current and Future Cooling Energy Consumption in Emerging Economies per Income Group

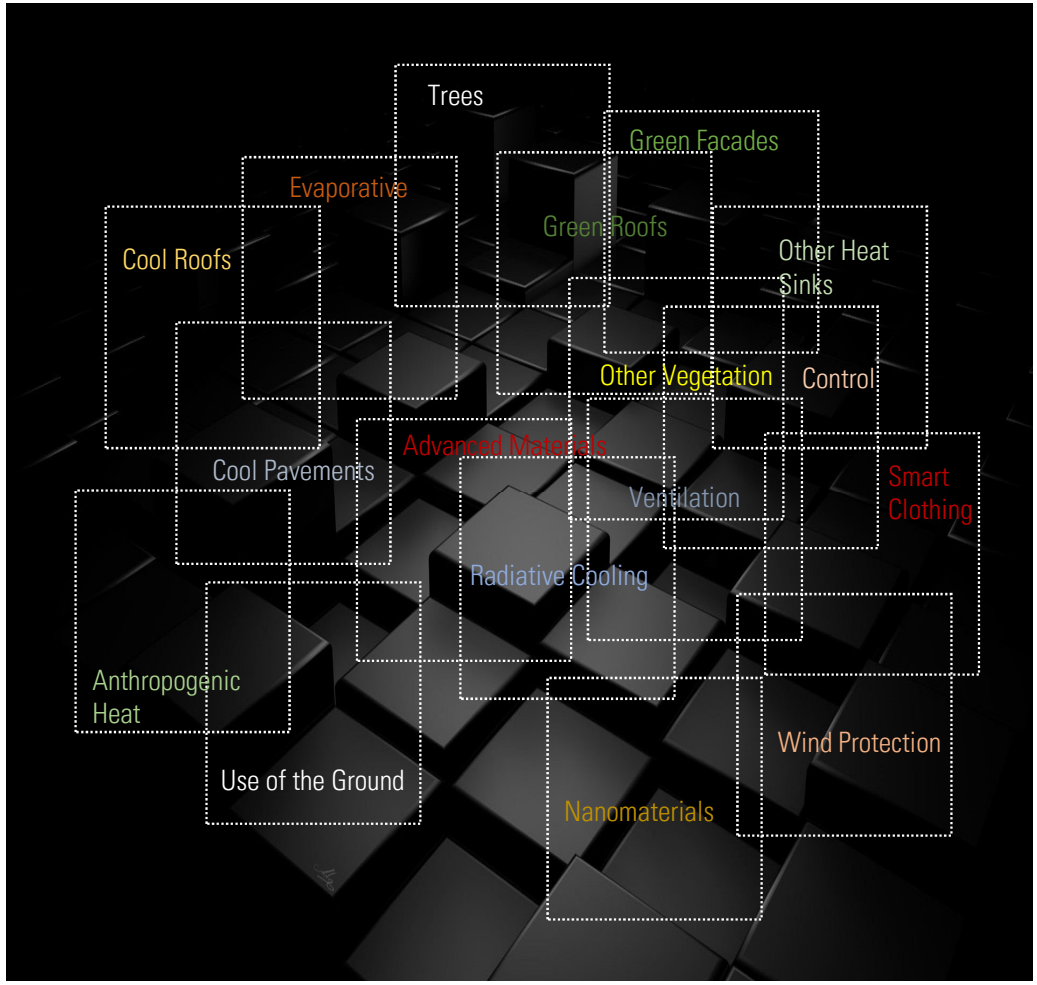


NATURE COMMUNICATIONS | (2021) 12:6460 | https://doi.org/10.1038/s41467-021-26592-2 | www.nature.com/naturecommunications

Solutions : Our Potential to Mitigate Urban Heat and Decarbonize the Built Environment

To counterbalance the impact of urban overheating, heat mitigation techniques are developed, and successfully implemented.

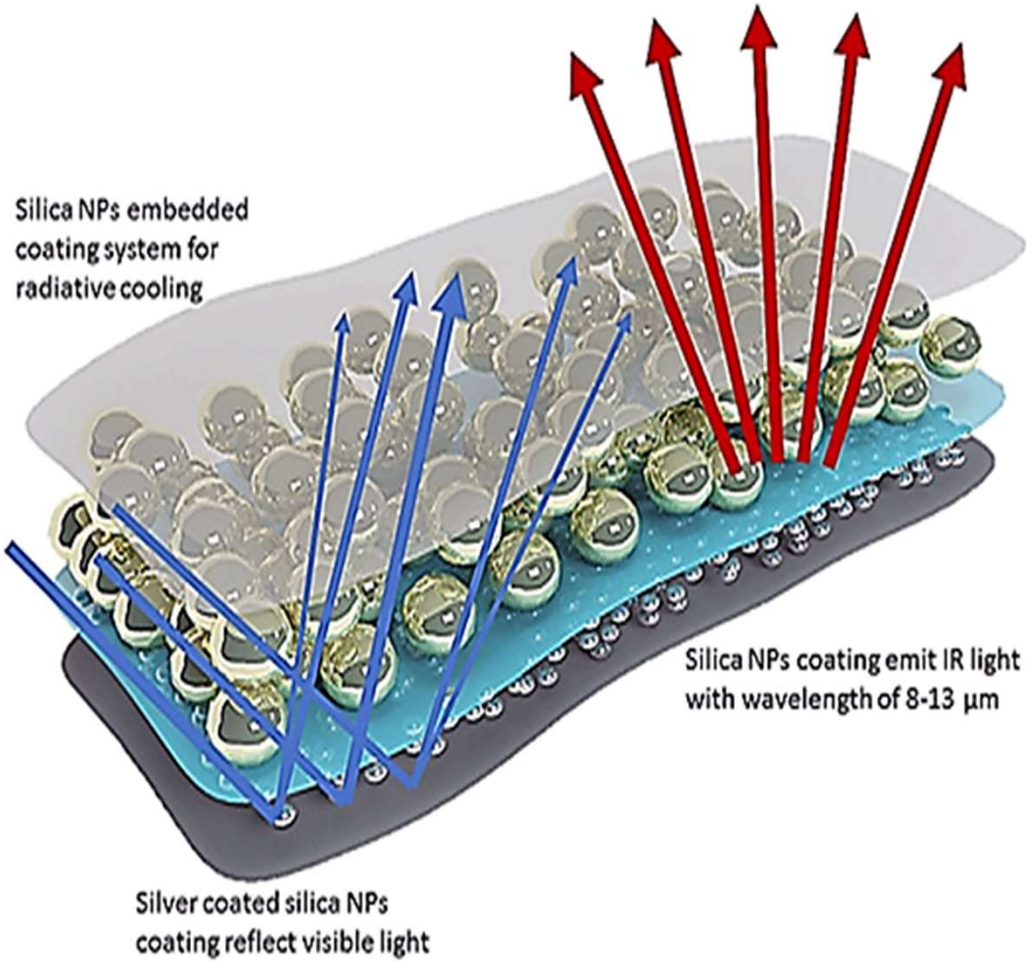
Mitigation technologies involve the use of advanced urban materials, like reflective, thermochromic, photonic, plasmonic and fluorescent materials, the increase of the urban green infrastructure, the use of evaporative systems, dissipation of the excess urban heat to low temperature heat sinks, or a combination of the previous technologies.



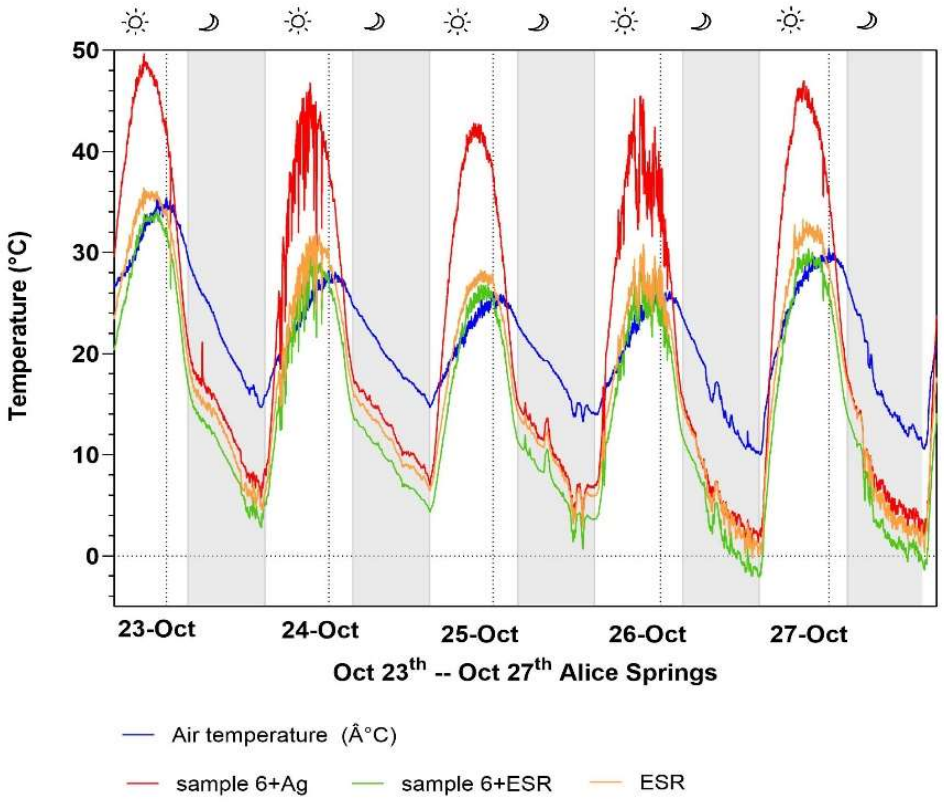
The recent development of

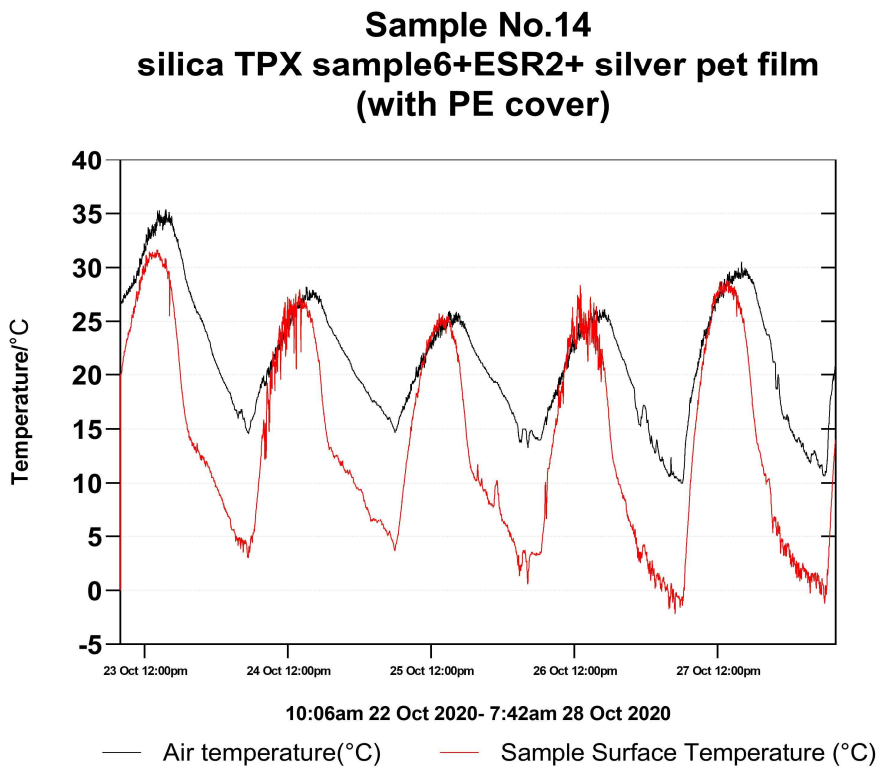
Super Cool Materials

like the photonic and fluorescent materials, permits decrease of the surface temperature of buildings and urban structures up to 15 C below the ambient temperature under the summer sun.



Mitigation : Photonic Day Time Radiative Materials Exhibit up to 10 C Sub Ambient Temperature under the Sun

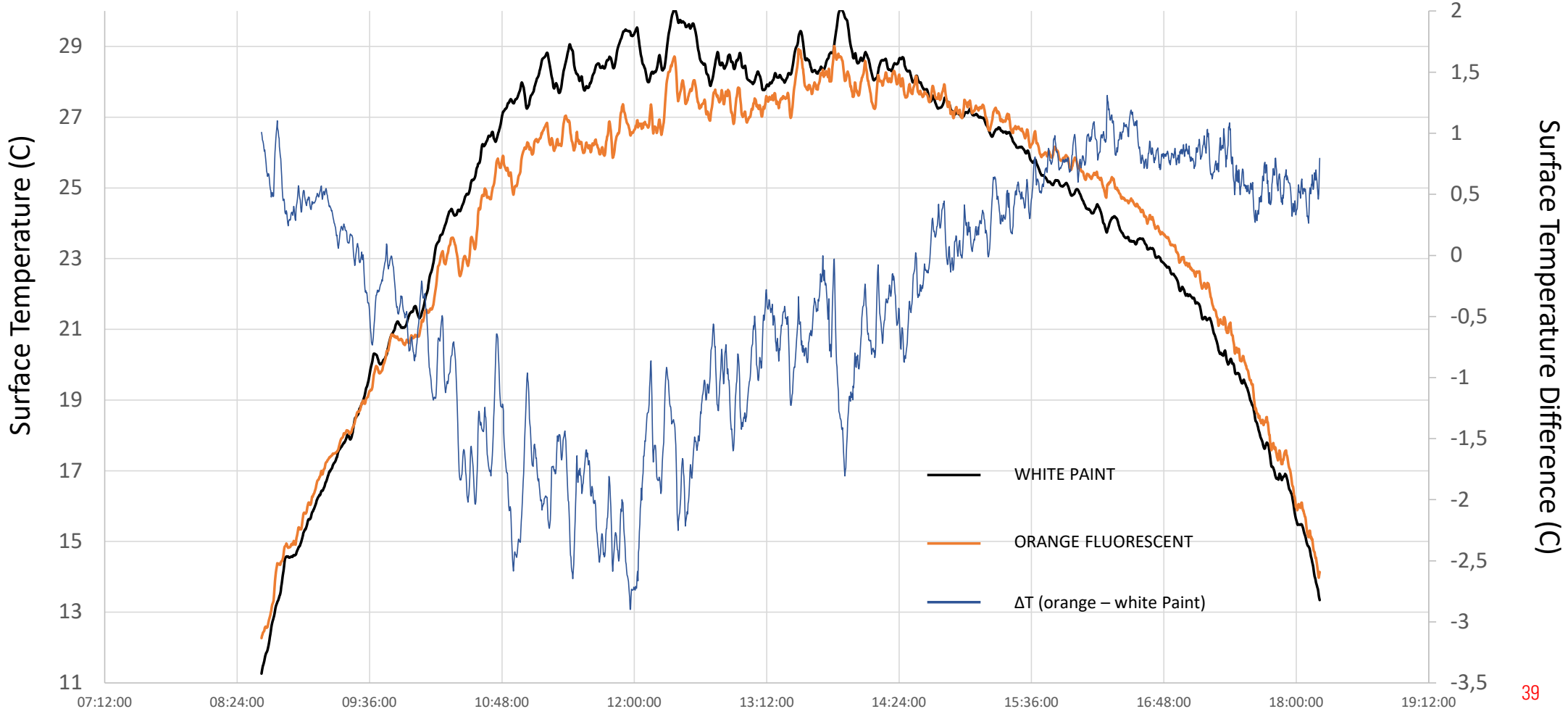




Mitigation : Colored Photonic Day Time Radiative Materials exhibit 4 C lower Temperature than White Paints Under the Sun

25/5/2023 – Alice Springs- Max Amb Temp : 27.4 C –Max SR : 740 W/m2 – RH (noon) : 20 %, Max Atm Rad : 370 W/m2

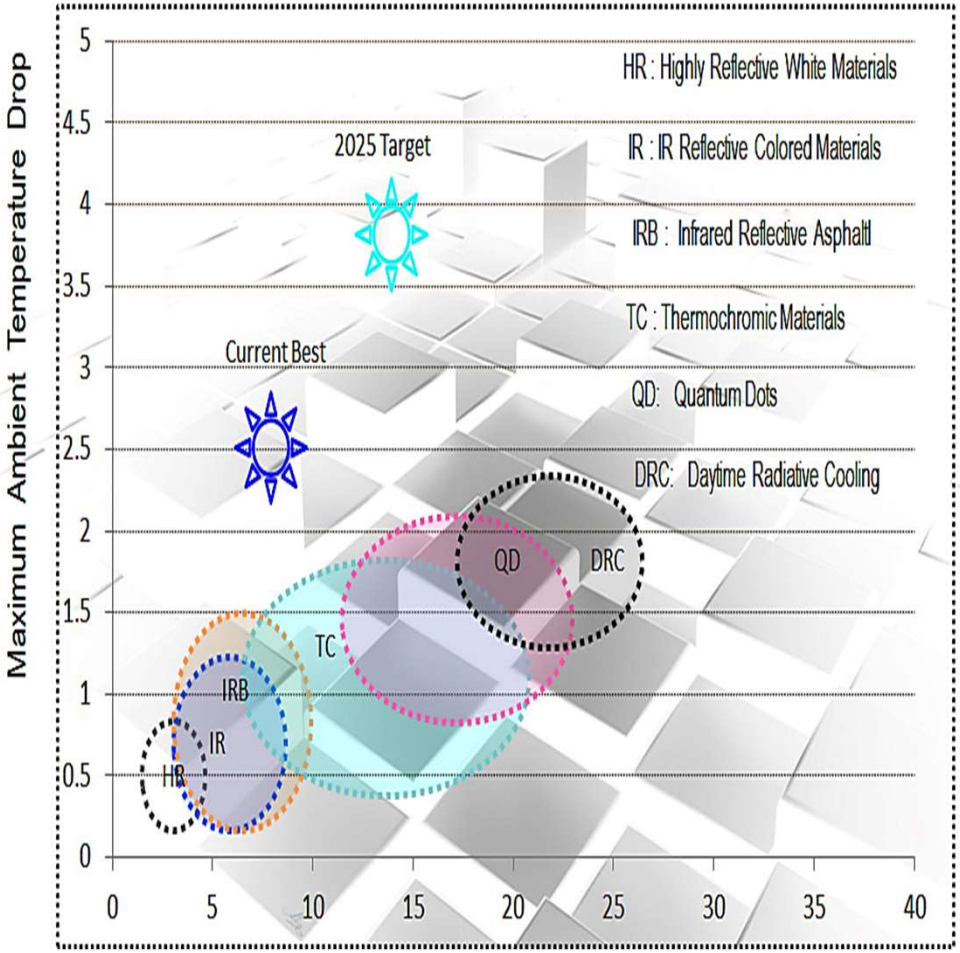
AVERAGE DAY TIME TEMPERATURE : WHITE PAINT : 24.6 C - ORANGE FLUORESCENT : 24.1 - AVERAGE ΔT =-0.36 C - MAX DT : 3 C



Mitigation : We can Decrease the Peak Temperature of Cities up to 4.5 C

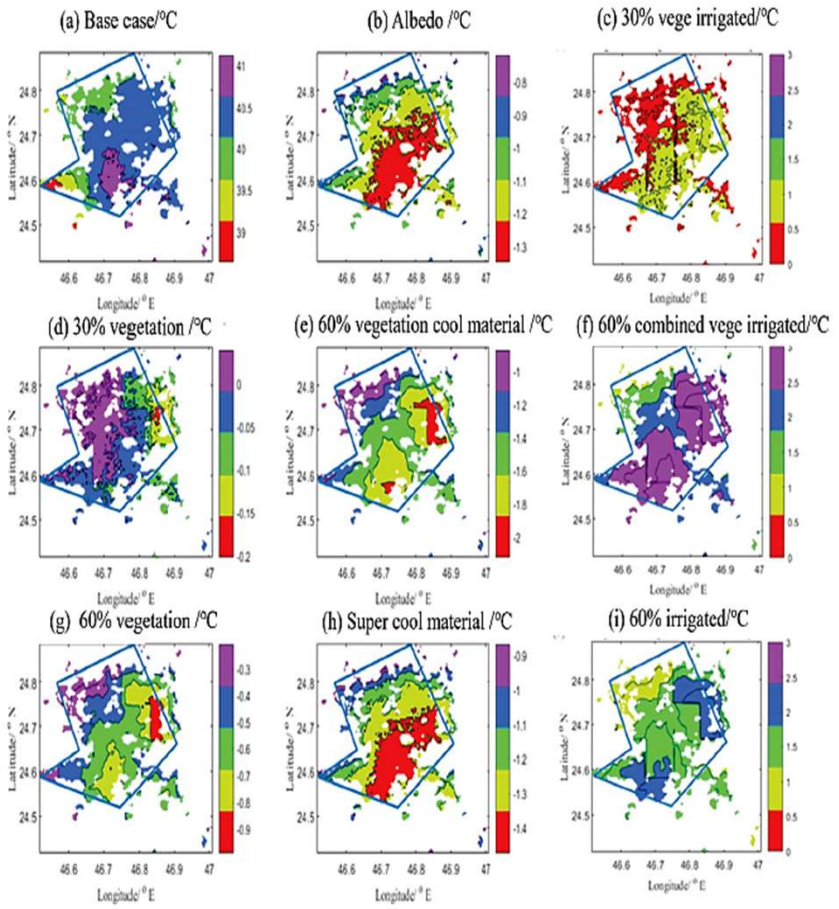
Performance data from numerous urban mitigation projects show an average reduction of the peak ambient temperature up to 3°C. The recent development of innovative mitigation technologies is expected to increase the mitigation potential up to 4.5°C.

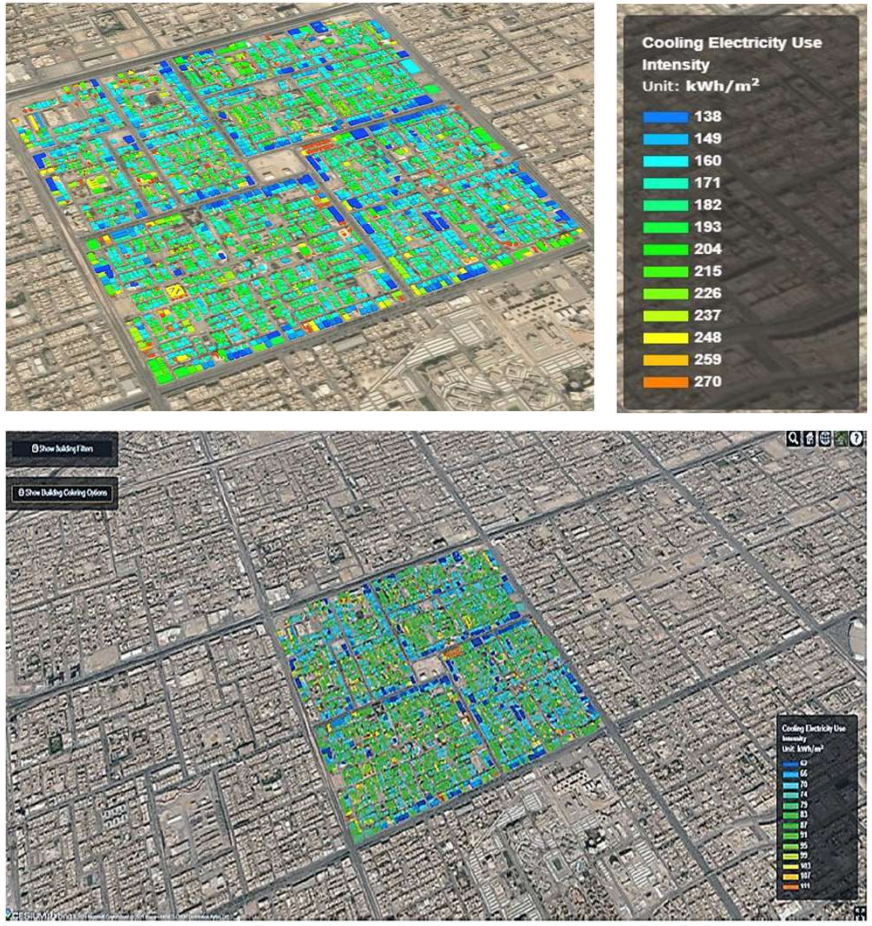
Implementation of urban mitigation technologies can decrease substantially the cooling energy consumption, the peak electricity demand and the heat related mortality and morbidity.



M.Santamouris Geun Young Yun: Recent development and research priorities on cool and super cool materials to mitigate urban heat island, Renewable Energy, 792-807, 2020

Mitigation : We can Decrease the Peak Temperature of Cities up to 4.5 C and Reduce the Cooling Energy consumption by 35 % - Riyadh KSA

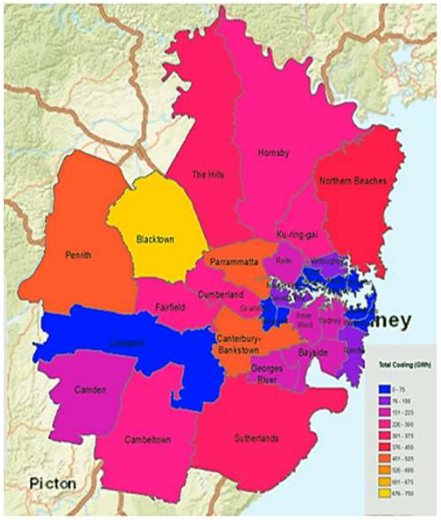




Mitigation : We can Decrease the Peak Temperature of Cities up to 4.5 C and Reduce the Cooling Energy consumption by 49 % - Sydney AU

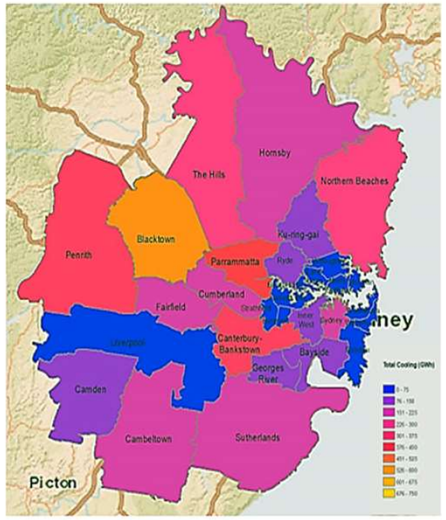
Energy Impact of Heat Mitigation Technologies

Reference



Total Cooling Consumption Residential and Commercial Buildings : 6300 GWh

Cool Roofs at the Building Scale

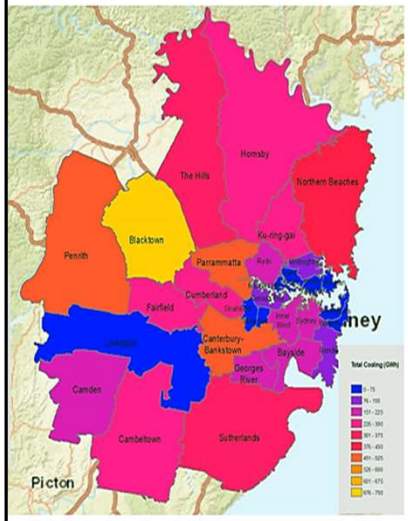


Total Cooling Consumption Residential and Commercial Buildings : 4400 GWh

29 %

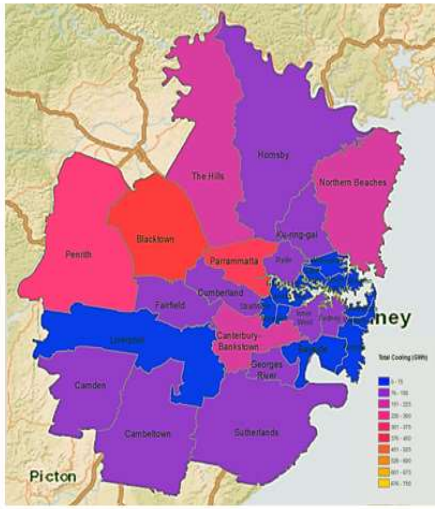
Energy Impact of Heat Mitigation Technologies

Reference



Total Cooling Consumption Residential and Commercial Buildings : 6300 GWh

Cool Roofs at the City and Building Scale



Total Cooling Consumption Residential and Commercial Buildings : 3260 GWh

49 %

More than **225 billion square meters** of floor area will be built in emerging economies and mainly in India, Indonesia and Brazil.

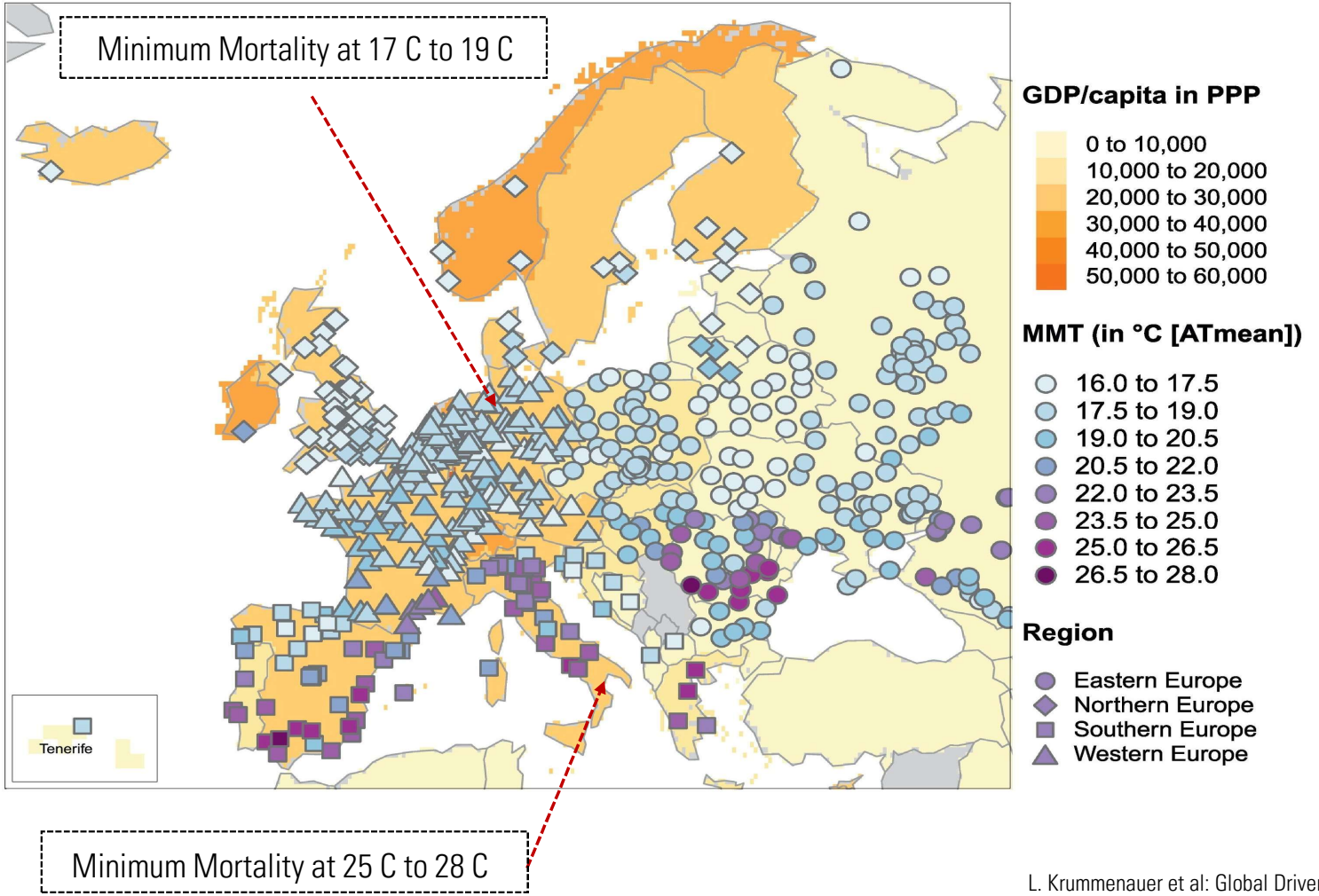
There currently is a shortfall of about 330 million homes in the world, and is expected to increase up to 440 million by 2025.

By 2030 the additional housing needs will grow by more than 77 billion square meters of floor space, equivalent or greater than the actual area of China.

We add a total floor area equal to the city of Paris per week.

M. Santamouris : Minimizing Energy Consumption, Energy Poverty and Global and Local Climate Change in the Built Environment: Innovating to Zero, Causalities and Impacts in a Zero Concept World, Elsevier, 2019

Temperature of Minimum Mortality in Europe

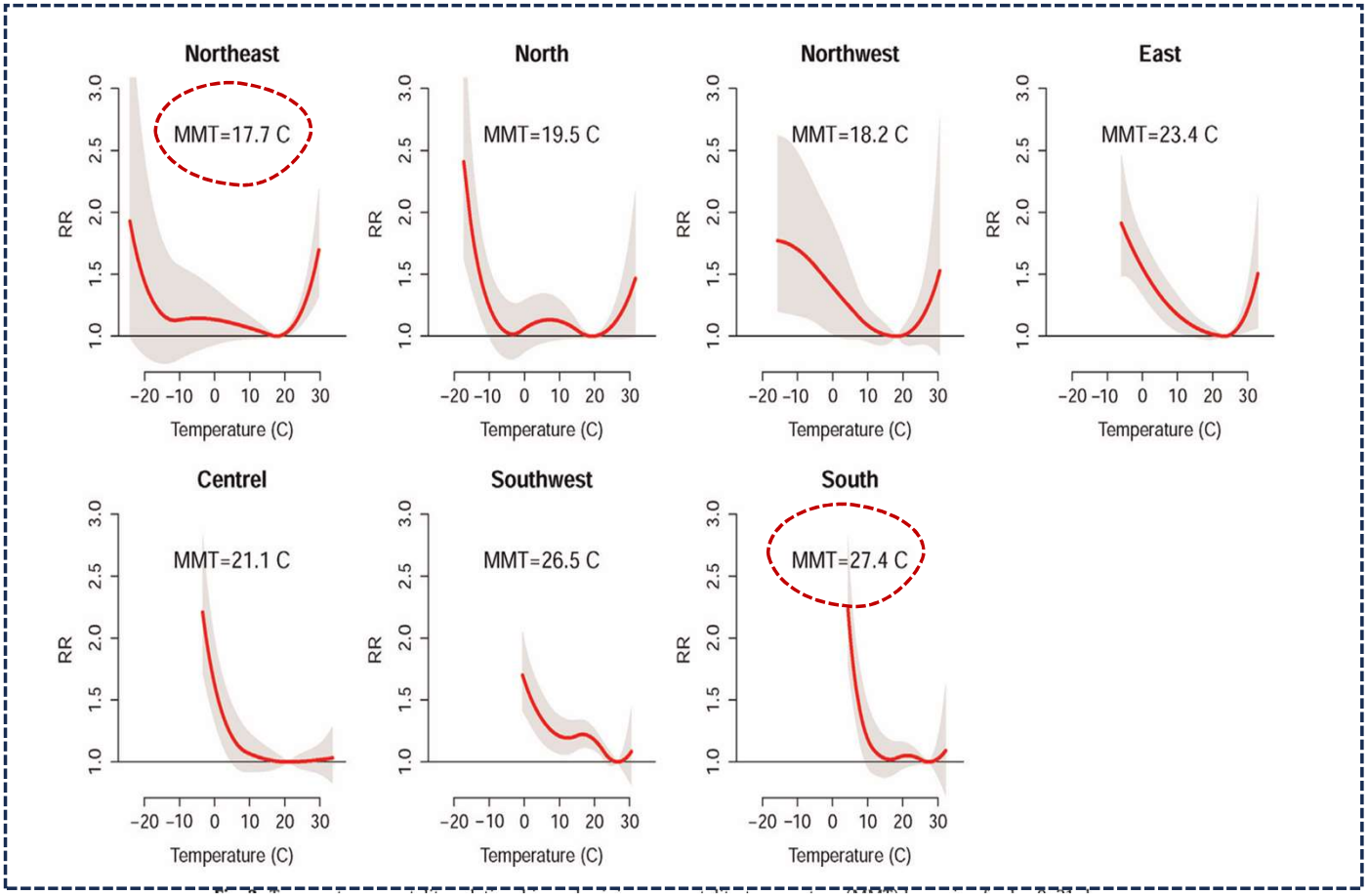


The Human Thermoregulation System is not Responding to Heat the Same Way.

Building Operational Standards must not be the same everywhere.

L. Krummenauer et al: Global Drivers of Minimum Mortality Temperatures in Cities, Sc. Tot. Env. 2019

Temperature of Minimum Mortality in China

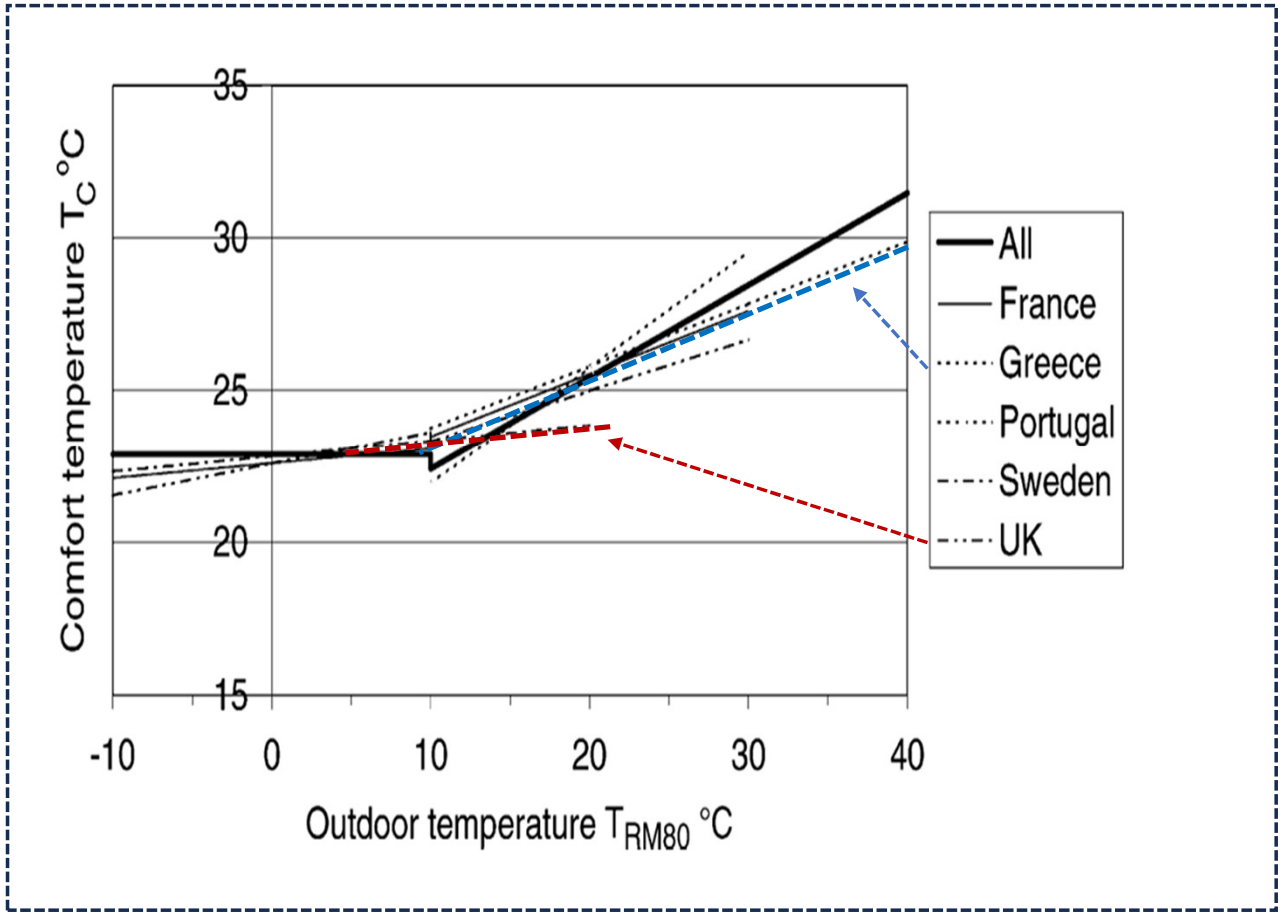


The Human Thermoregulation System is not Responding to Heat the Same Way.

Building Operational Standards must not be the same everywhere.

W. Ma et al: The Temperature – Mortality Relationship in China, Env Research 2015

Temperature of Comfort Sensation in Europe – Results of SCATS

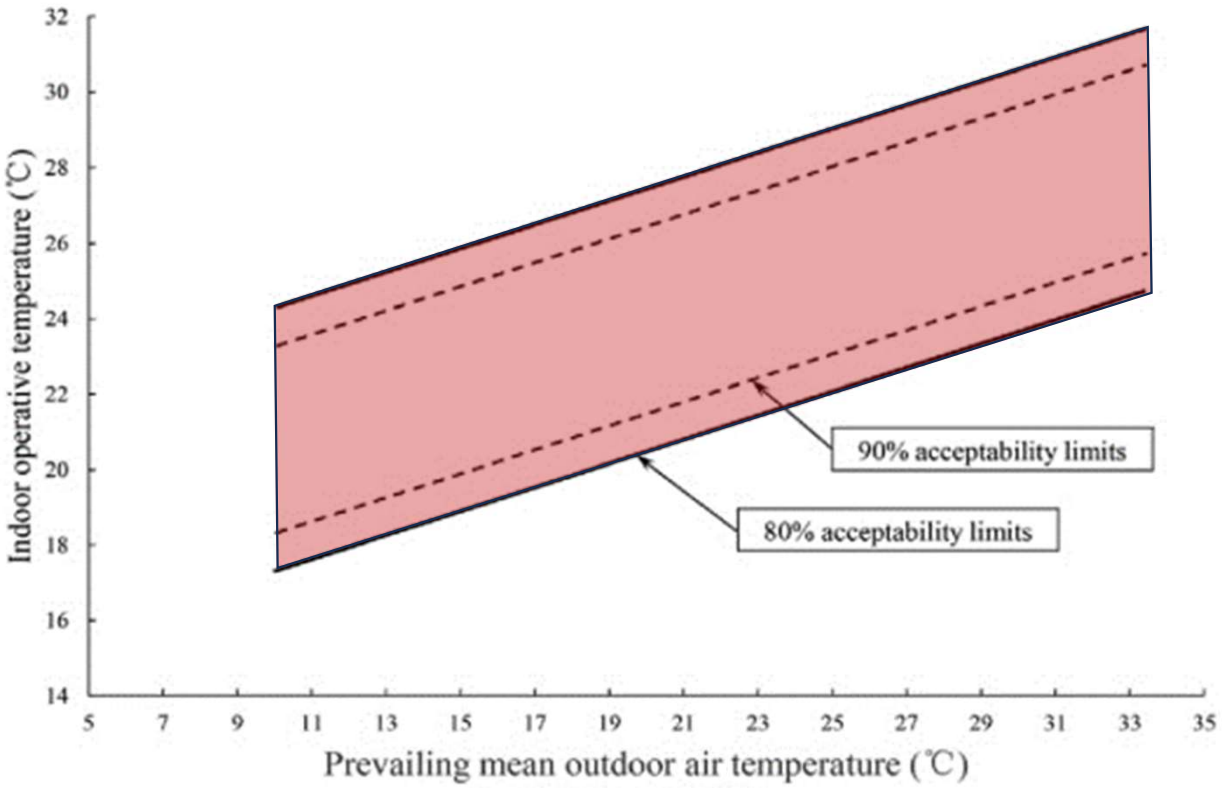


K.J. McCartney, J. Fergus Nicol / Energy and Buildings 34 (2002) 623–635

Human Sensation of Thermal Comfort depends on the levels of thermal adaptation of the population.

Building Operational Standards must not be the same everywhere.

International Standard on the levels of Indoor Thermal Comfort

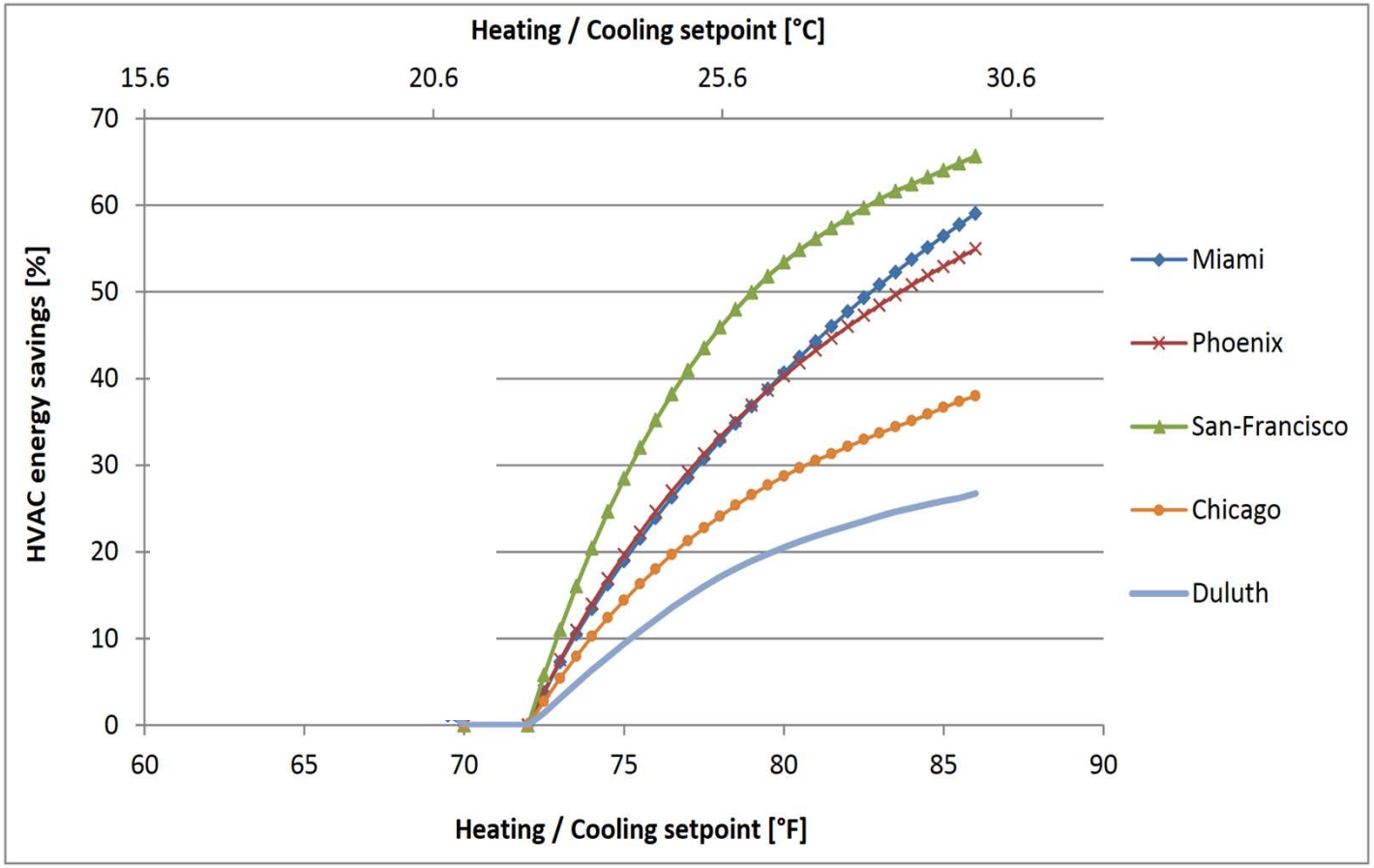


ANSI/ASHRAE 55:2017

Human Sensation of Thermal Comfort depends on the levels of thermal adaptation of the population.

Building Operational Standards must not be the same everywhere.

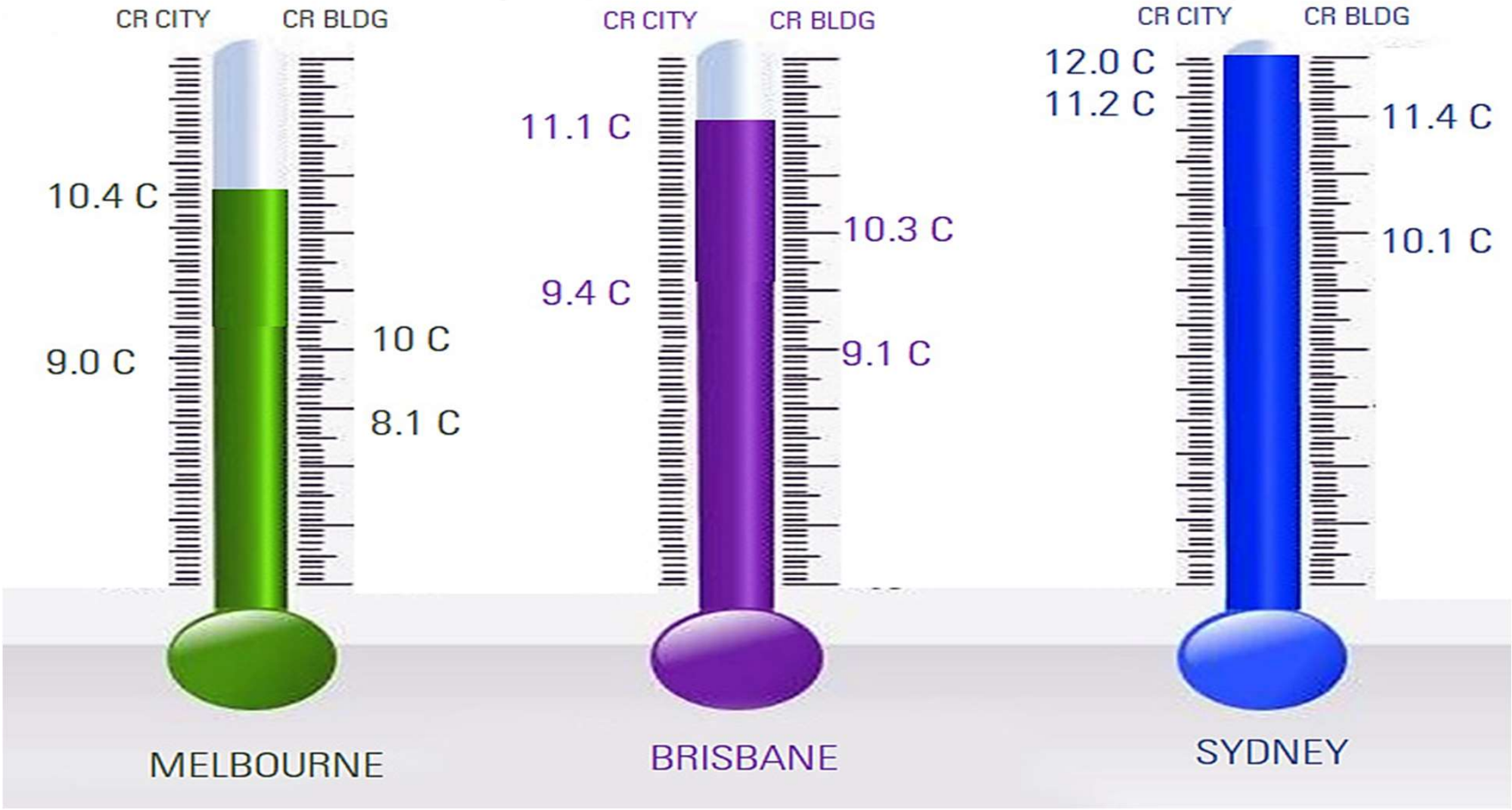
Cooling Energy Reduction when Proper Set Points and Comfort Standards are Used



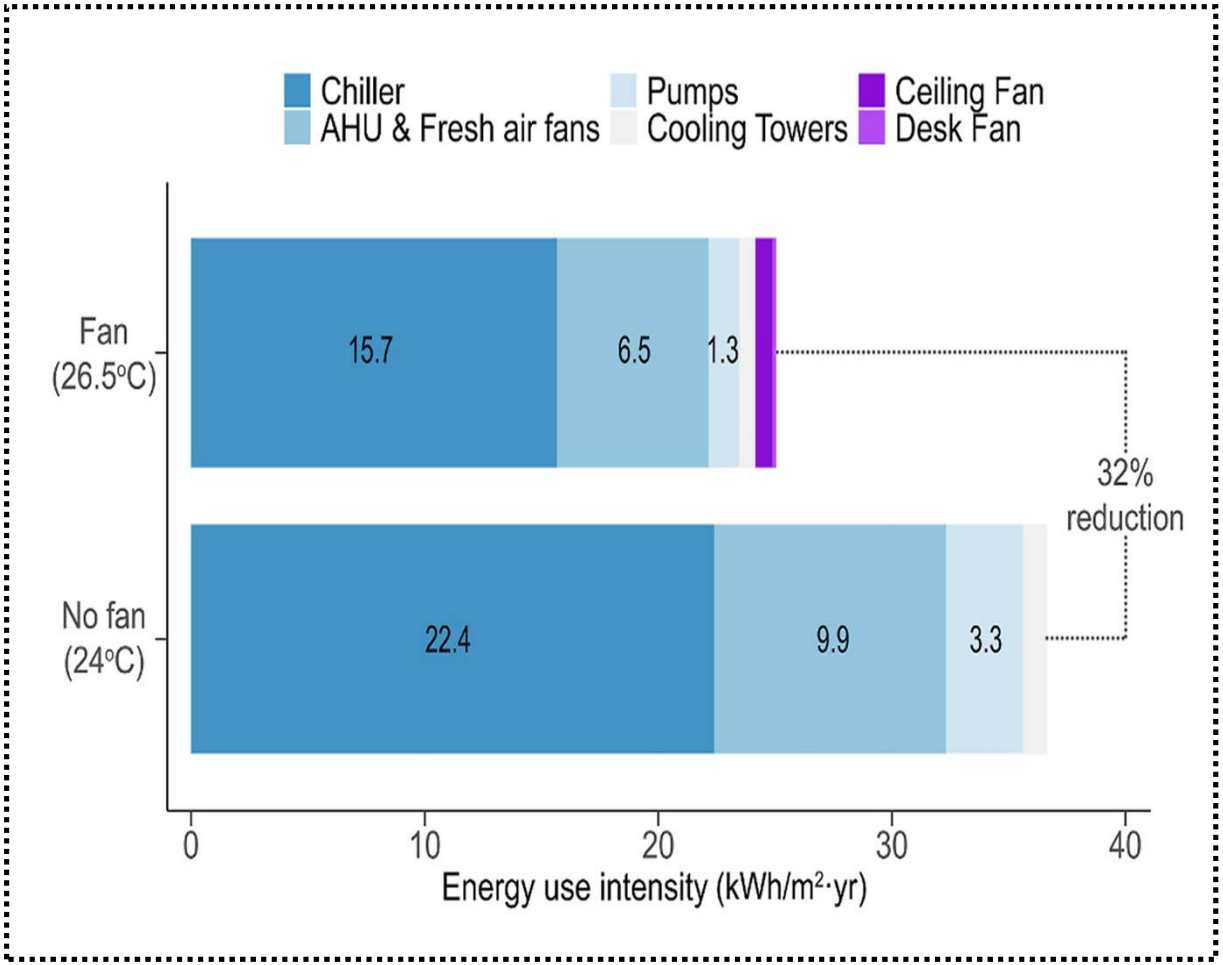
The use of proper Adaptive Comfort Standards considering the local adaptation levels can result in tremendous reductions of the cooling demand in buildings.

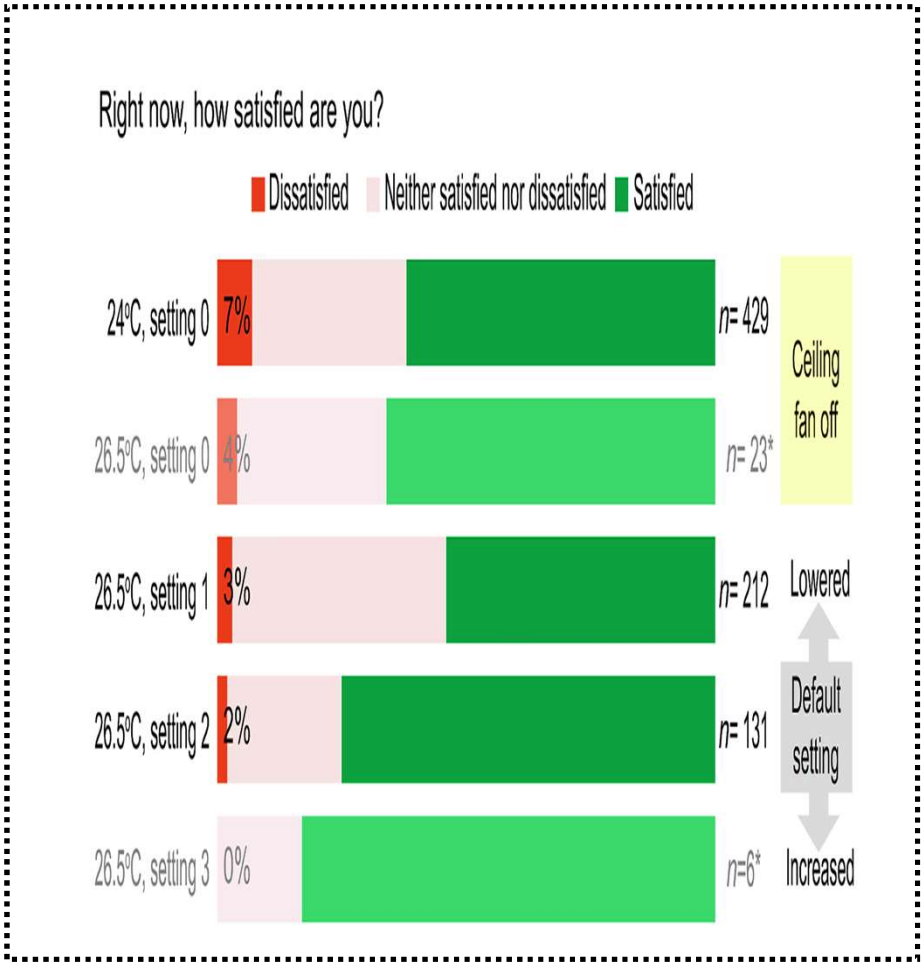
Hoyt T, Arens E, Zhang H. Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings. Build Environ 2014

Reduction of the maximum indoor air temperature when cool roofs are used



Reduction of the Cooling Demand and Thermal Satisfaction when Advanced Ceiling Fans are used



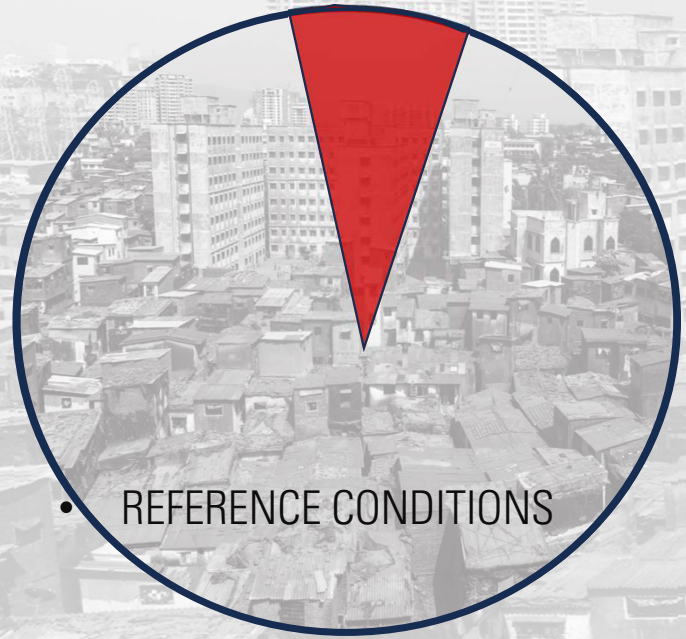


Michael G. Kent : Energy Savings and Thermal Comfort in a zero Energy Office Building in Singapore, Building and Environment, 2023

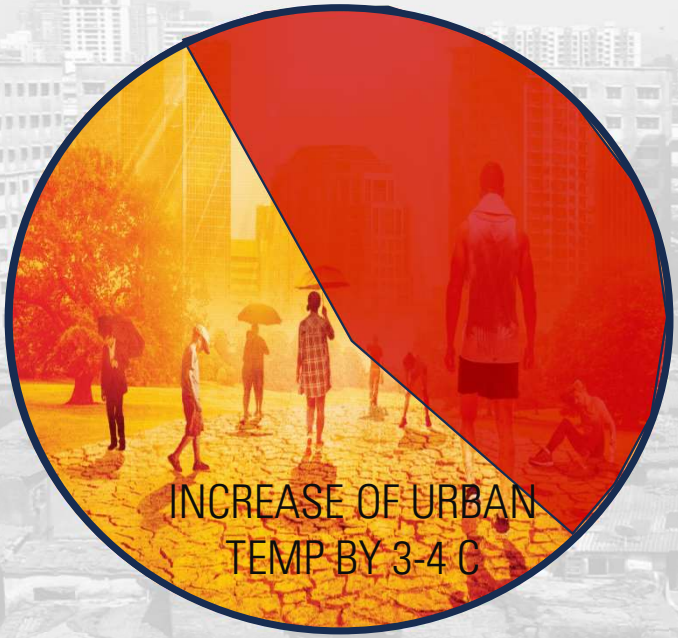
Zero Energy Buildings in the Tropics – NUS SDE4 - Singapore

NUS SDE4's performance (April 2019 to March 2020)	
Actual energy use during performance period	470,750 kWh
Actual energy produced during performance period	619,345 kWh
Net Energy Use	-148,595 kWh
Energy Use Intensity (EUI)	55 kWh/m2/year

Moving Towards a Gray Ecosystem in the Built Environment



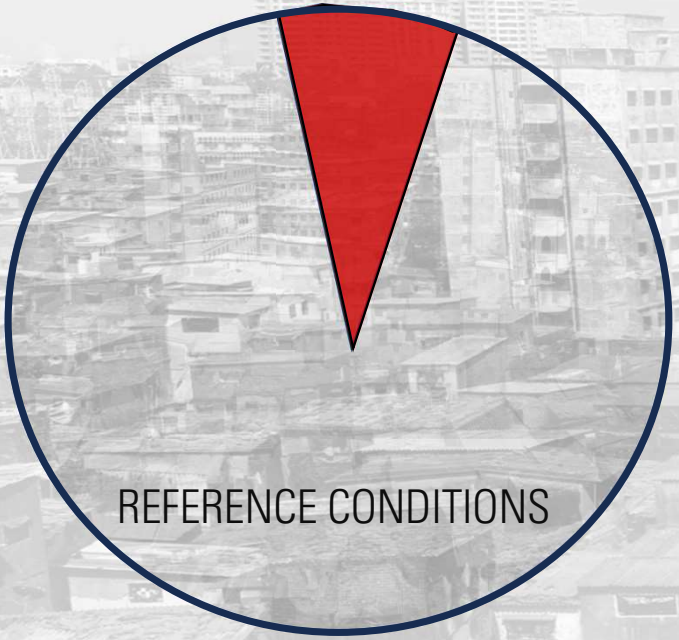
- Low Energy Consumption
- Discomfort up to 30 % of the year
- People mostly adapted to Current Temperatures

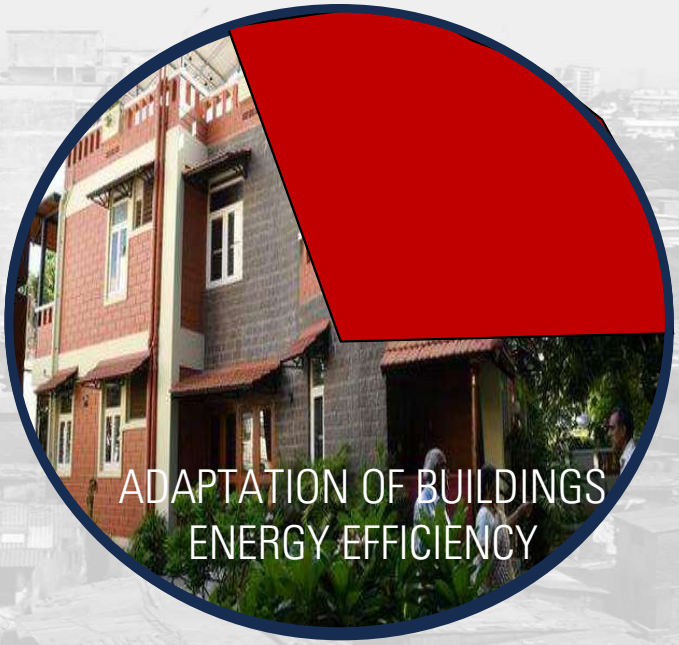


- Increase of the Energy Requirements up to 150 %
- Discomfort up to 70 % of the year
- People partly or non-adapted to High Temperatures
- Increase of Heat Related Mortality up to 40 %
- Increase of Ground Level Ozone up to 70 %

- Increase of the Energy Consumption up to 400 %
- Use of Cheap Low Efficiency A/C's
- People living in A/C buildings adapted to low Indoor Temperatures
- Huge Increase of the Peak Electricity Demand – need for Huge new Infrastructures
- Heat from A/C increases the urban temp up to 2 C
- Low Survivability Levels of Low-Income Population
- Very Low Local Added Value.

Moving Towards a Green Ecosystem in the Built Environment





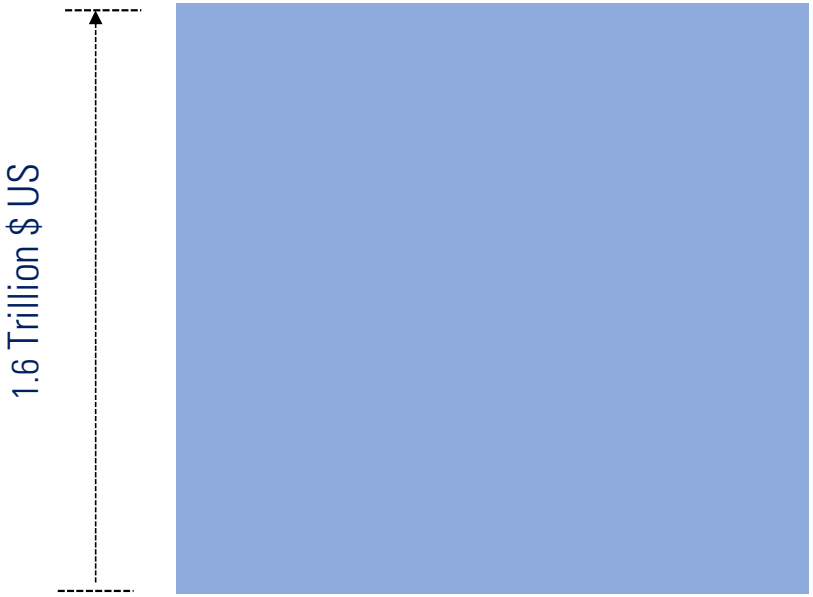
- Low Energy Consumption
- Discomfort up to 30 % of the year
- People mostly adapted to Current Temperatures

- Decrease of Peak Ambient Temperature up to 4 C
- Energy Requirements remains constant
- Discomfort up to 20 % of the year
- People fully adapted to urban climatic conditions
- Decrease of the Heat Related mortality up to 30 %
- Decrease of the Ground Level Ozone up to 20 %
- High Local Added Value

- Increase of the Energy Efficiency up to 75 %
- Increase of the Energy Consumption up to 50 % because of the rebound effect and the partial use of A/C
- Low to Medium Increase of the Peak Electricity Demand moderate need for new Infrastructures
- Further decrease of the Heat Related Mortality
- Better Survivability Levels for Low-Income Population
- High Local Added Value

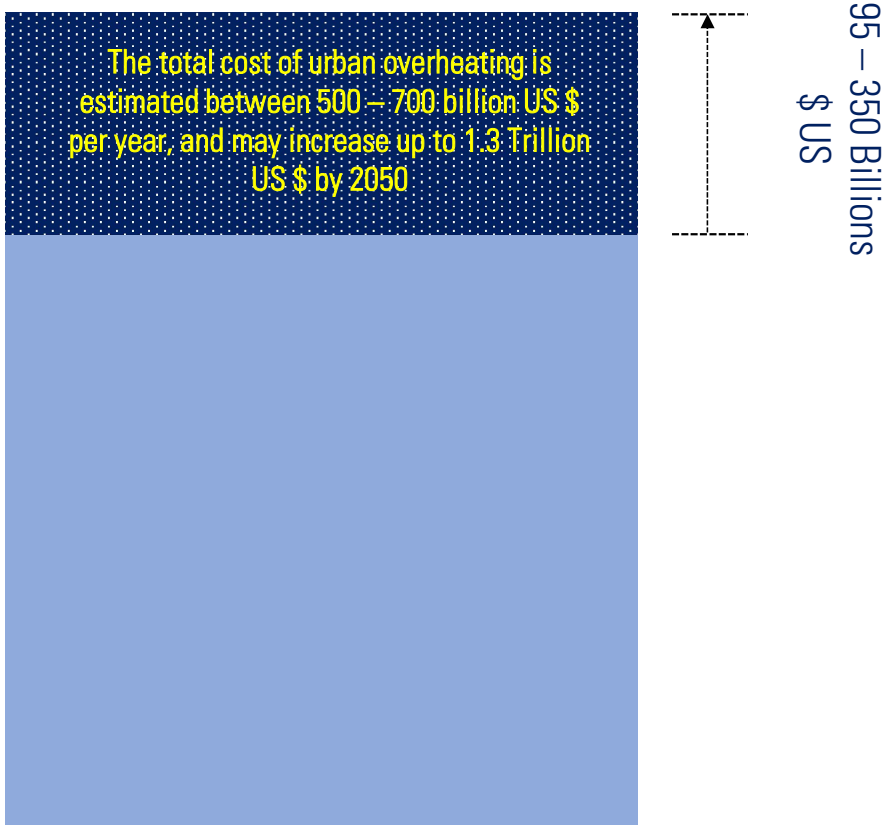
Estimated Cost to Mitigate Urban Heat and Decarbonize the Built Environment

Annual Cost of Decarbonisation of Buildings



Source : Mc Kinsey Analysis

Annual Cost Mitigation Urban Heat



Source : Personal Calculations and Data

Urban Warming Markets

Helping Counterbalance Urban Overheating

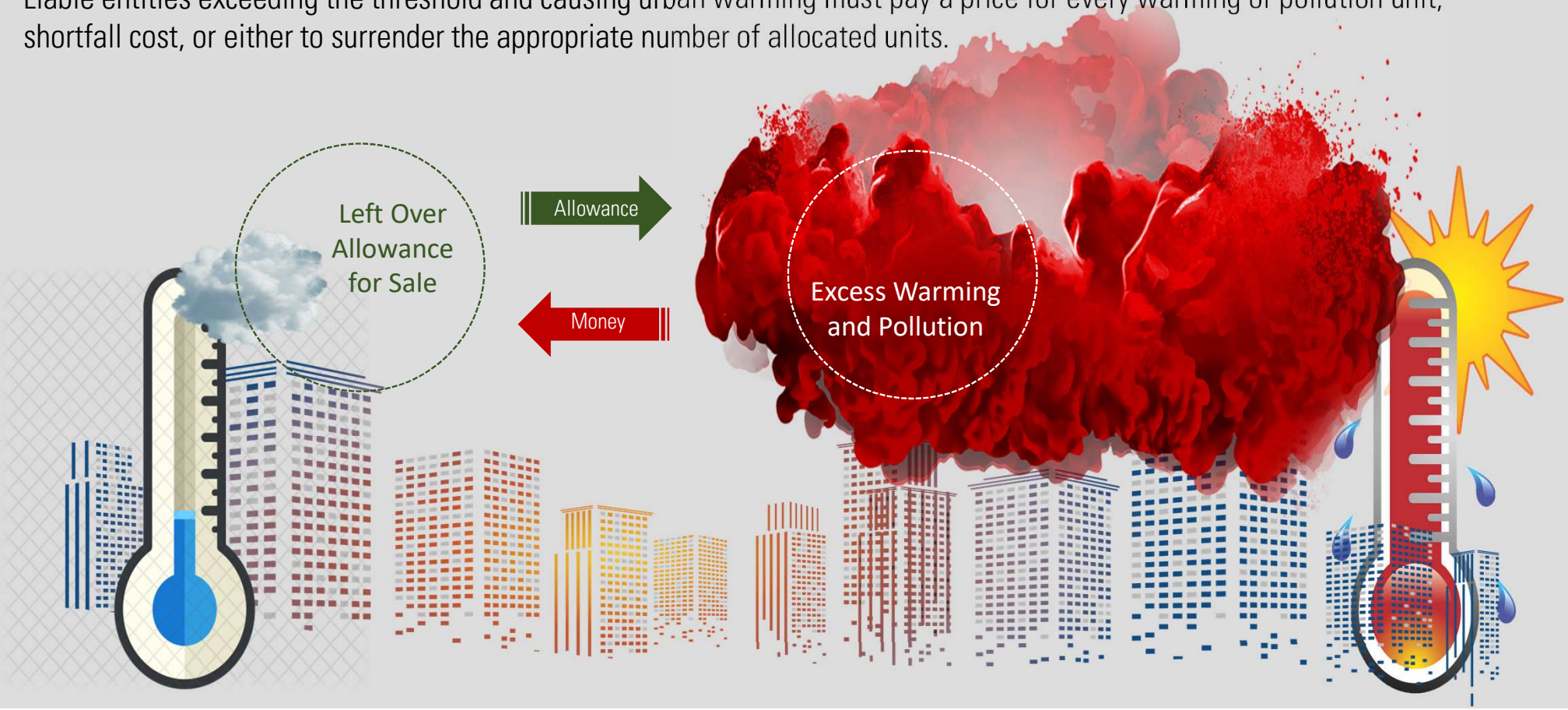
Setting as a goal a minimum urban overheating and pollution involves limiting the strength of warming and polluting sources and increasing the strength of urban heat sinks to balance the urban heat budget.

Achieving a Zero Urban Thermal and Pollution budget requires to:

- Change the way we design, built and operate urban buildings, spaces and infrastructures and transition to less warming and polluting patterns and policies.
- Put a value on the urban mitigation and adaptation capital that limits the strength of local climate change and environmental quality.

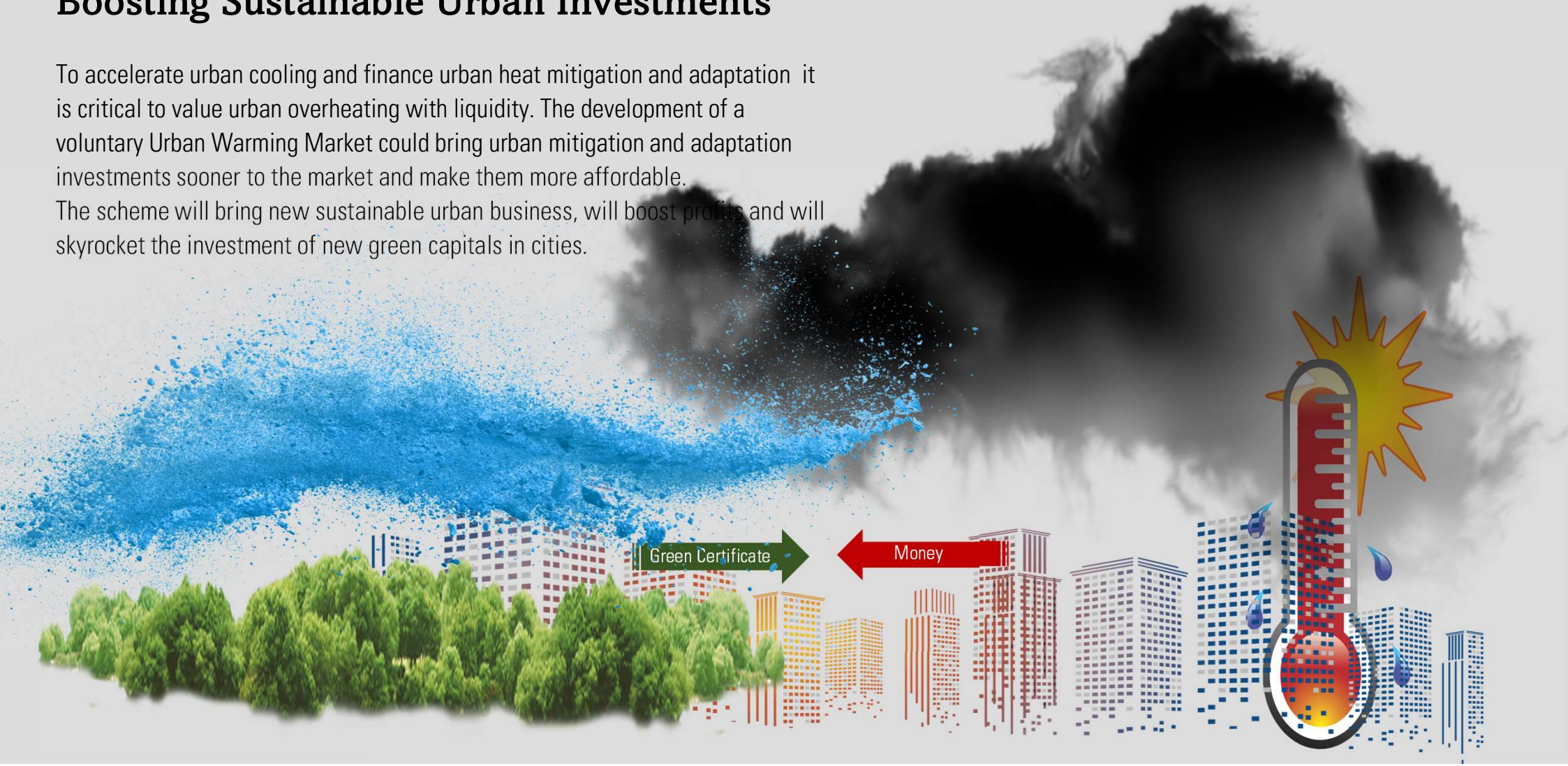
Putting a Price on Urban Warming

The magnitude of overheating and pollution caused by selected major urban activities has to be assessed and controlled. Liable entities exceeding the threshold and causing urban warming must pay a price for every warming or pollution unit, shortfall cost, or either to surrender the appropriate number of allocated units.



Boosting Sustainable Urban Investments

To accelerate urban cooling and finance urban heat mitigation and adaptation it is critical to value urban overheating with liquidity. The development of a voluntary Urban Warming Market could bring urban mitigation and adaptation investments sooner to the market and make them more affordable.
The scheme will bring new sustainable urban business, will boost profits and will skyrocket the investment of new green capitals in cities.



Strong Synergies between the Sectors Affecting Urban Climate Change

The serious heterogeneity of the quantitative and qualitative conclusions drawn by the existing studies can be mainly attributed to the differentiation of the synergetic association of energy, pollution, health and vulnerability in the considered cases.

The need to adopt a more extended and interdisciplinary frame for impact studies considering all possible synergies is quite evident.

Studies on the impact of overheating on energy, pollution, vulnerability and health, provide knowledge on the specific impact on energy consumption, peak electricity, efficiency of the power plants, concentration of ozone, emission of power plants, vulnerability and health.

While the provided information is rich in quantified data, it is highly fragmented and fails to consider the problem of the overheating impact in an integrated and holistic way.

Investing and Counterbalancing the Urban Climate Change is the Next Productivity Engine to Drive Growth