ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

EMPA
Materials Science & Technology

How can we solve our urban climate and energy problems?

An integrated approach from material to city scale

Prof. Dr. Jan Carmeliet

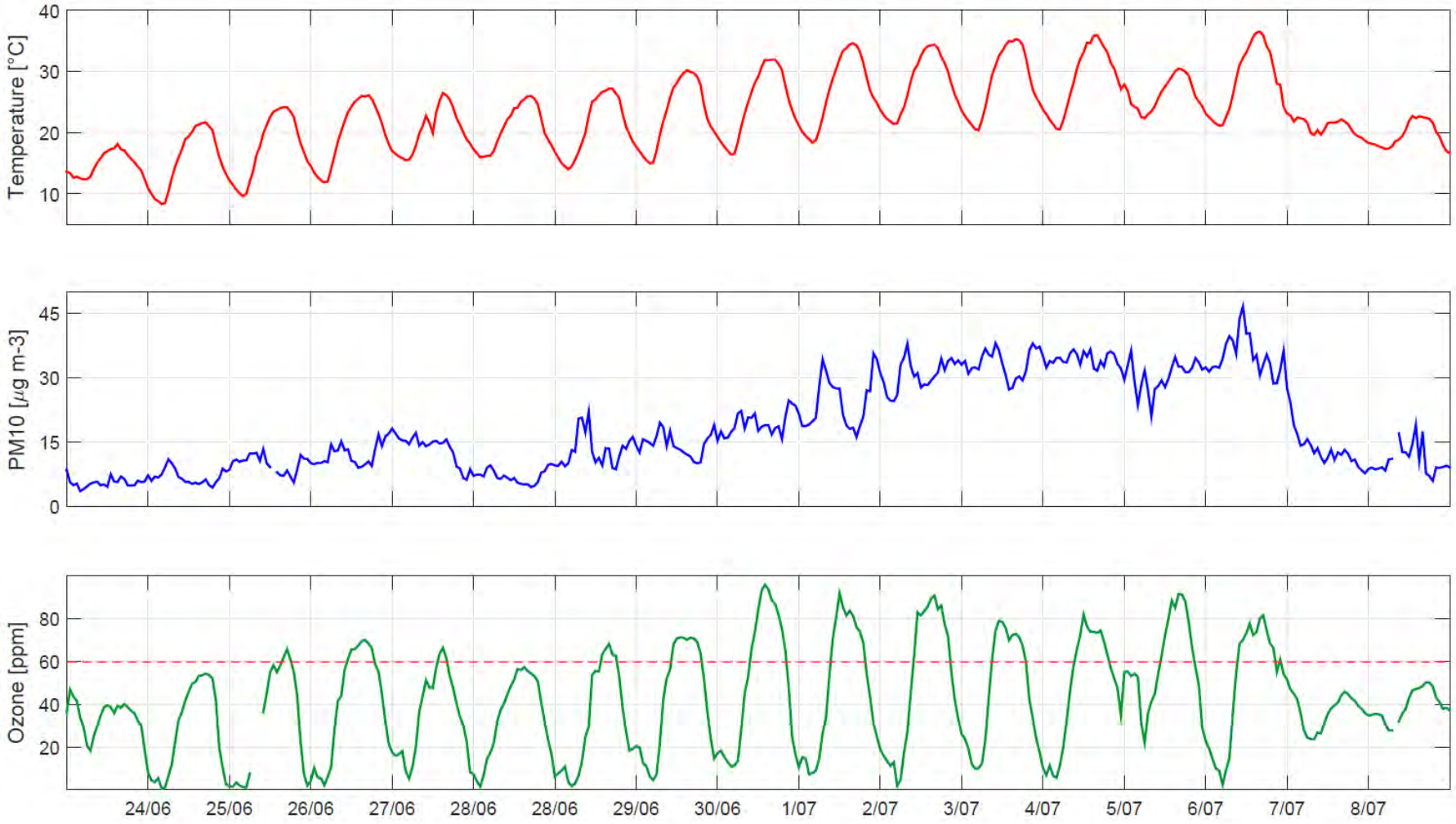
Chair of Building Physics , ETH Zurich, Switzerland
Laboratory for Multiscale Studies in Building Physics, Empa, Switzerland

Zurich, Switzerland

Climate with no excessive heat, cold nor humidity

Winter smog due to inversion in Zurich valley

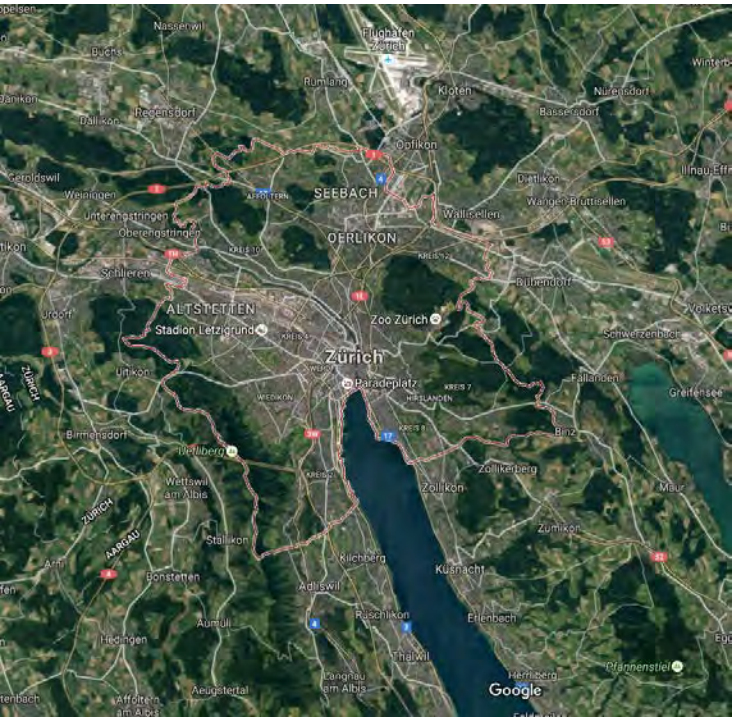
Heat wave June - July 2015: Zurich area

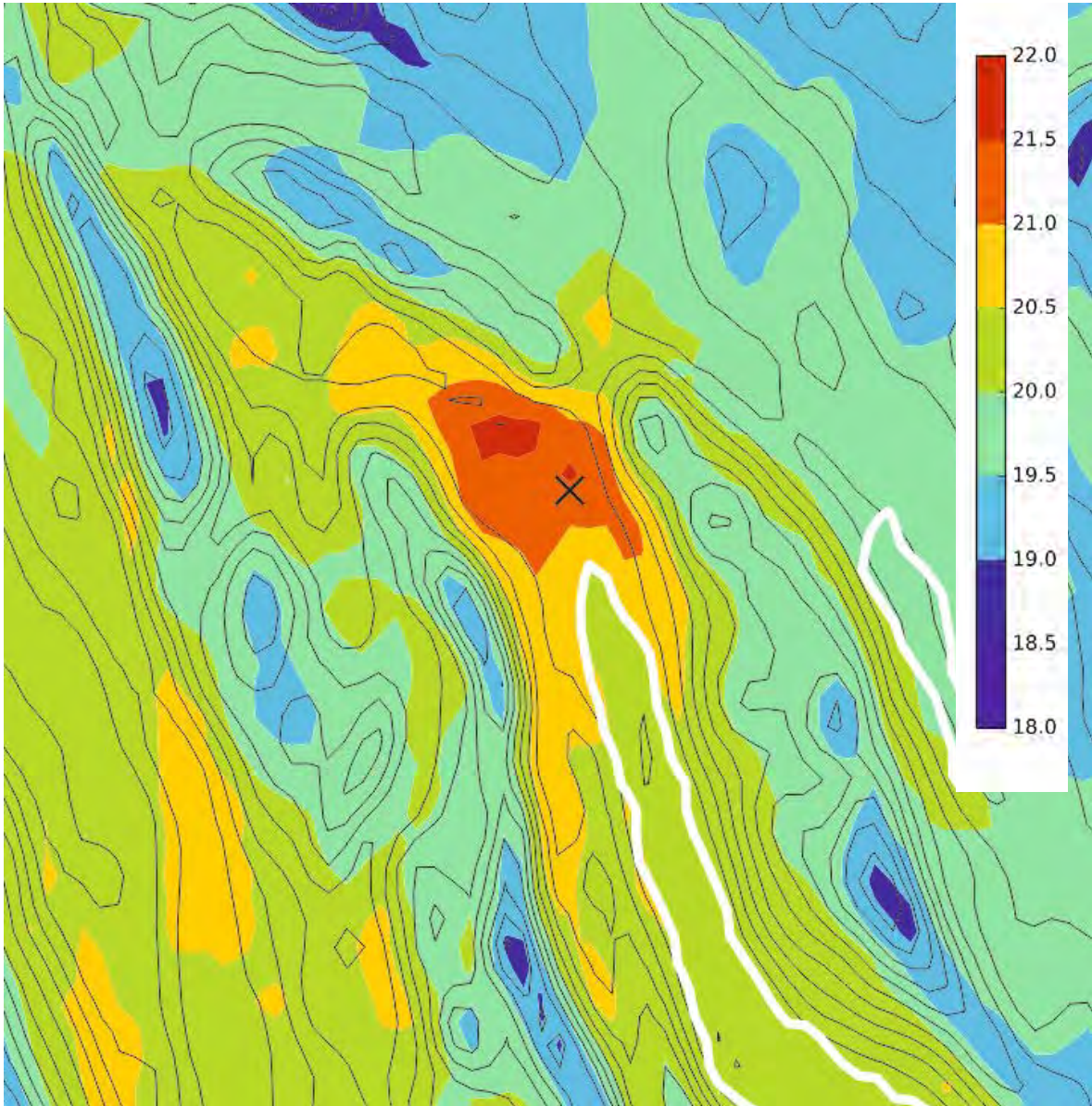


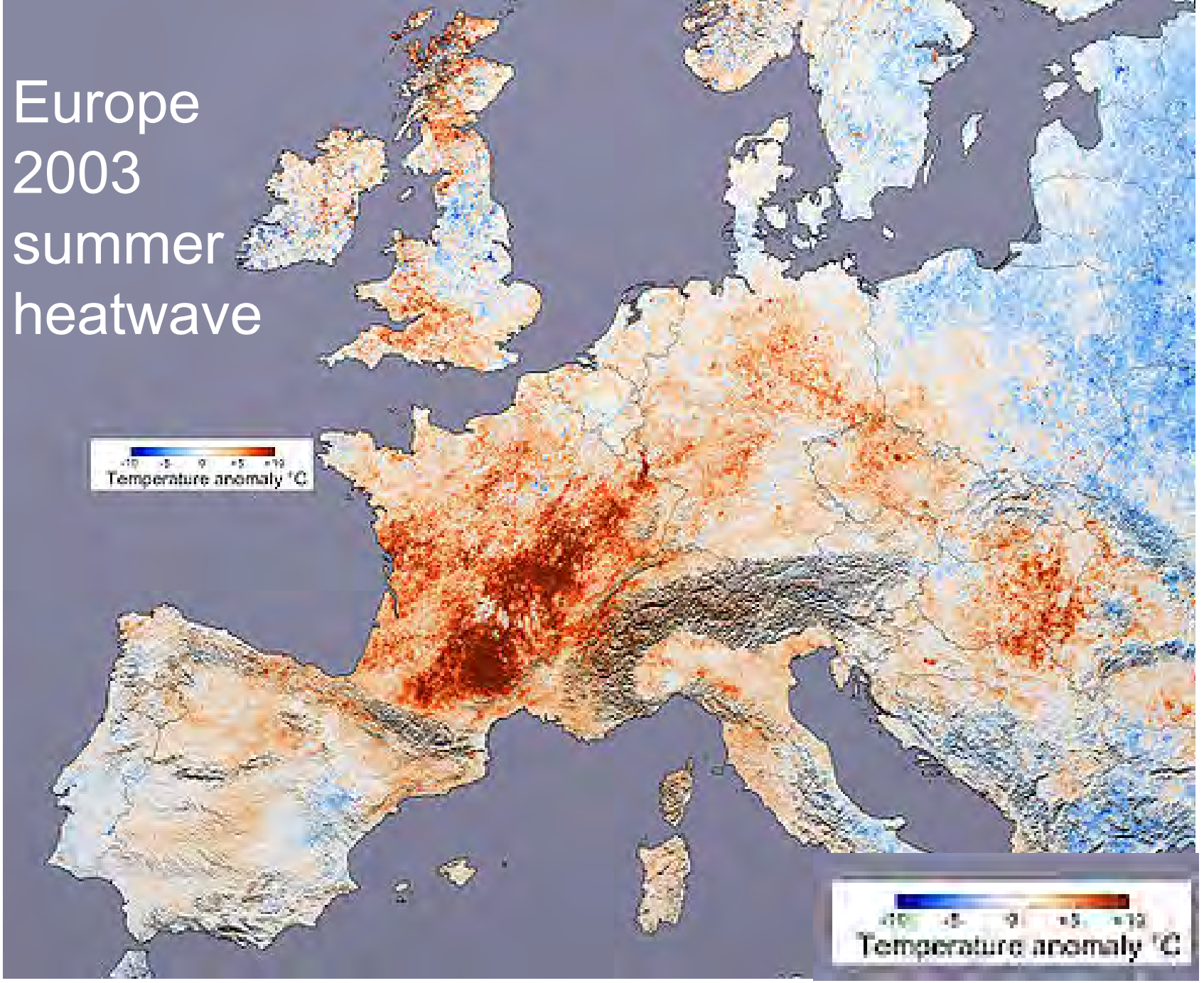
NABEL Station – Empa, Dübendorf (Zurich area)

Urban heat island in Zurich during heat wave June – July 2015

Air temperature at 2m, 12 pm, period averaged





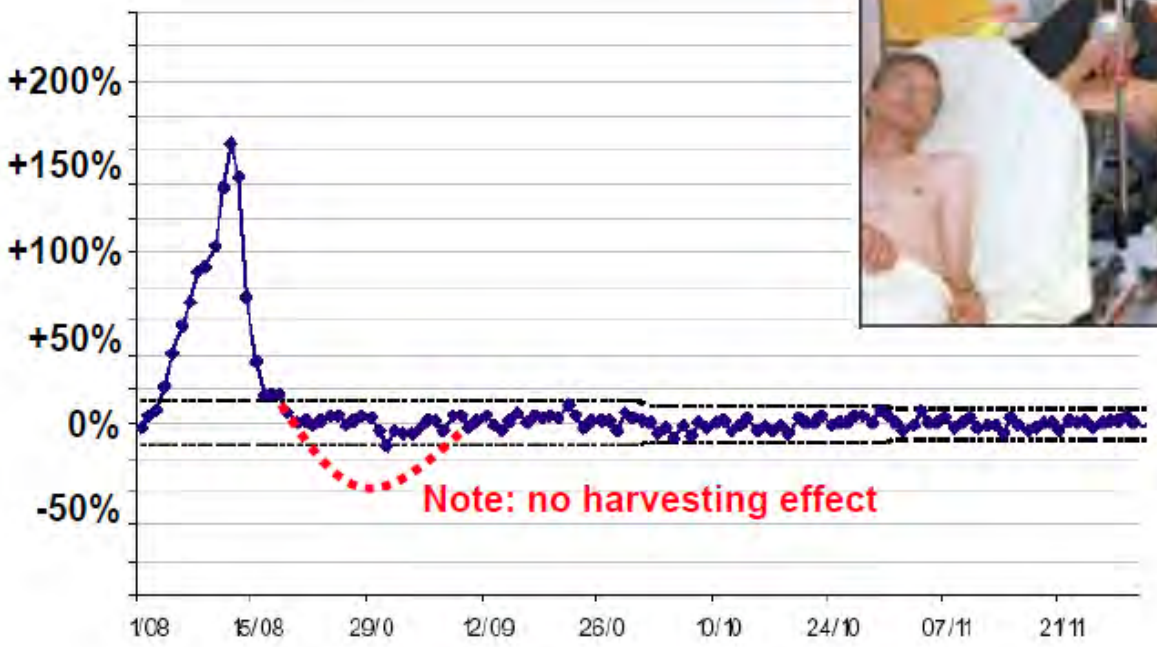


J.F. Barlow, U. Reading

Heat waves have a dramatic impact on quality of life and health

Excess mortality in France

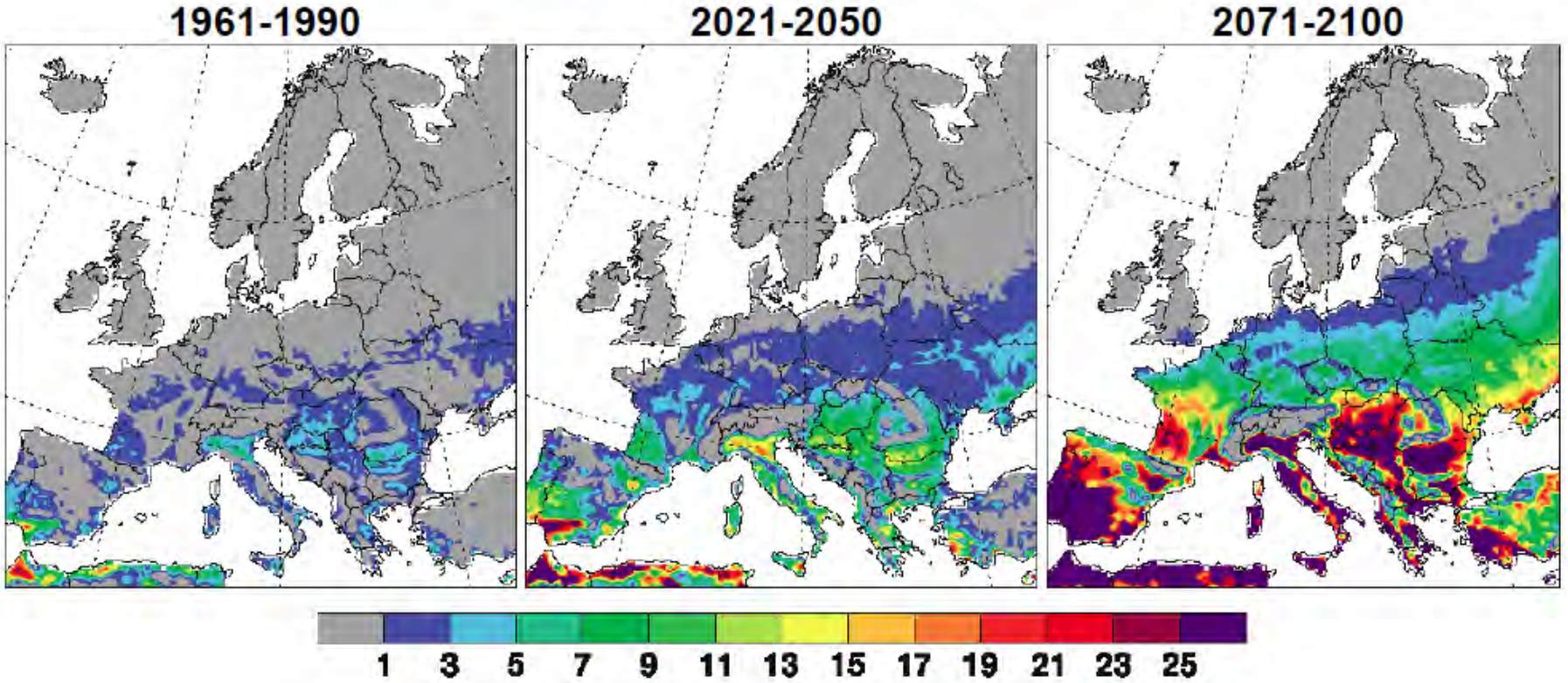
Excess mortality = mortality beyond longterm mean



Date: August 1 - November 30, 2003

(INSERM 2004)

Heat wave occurrence will increase due to climate change

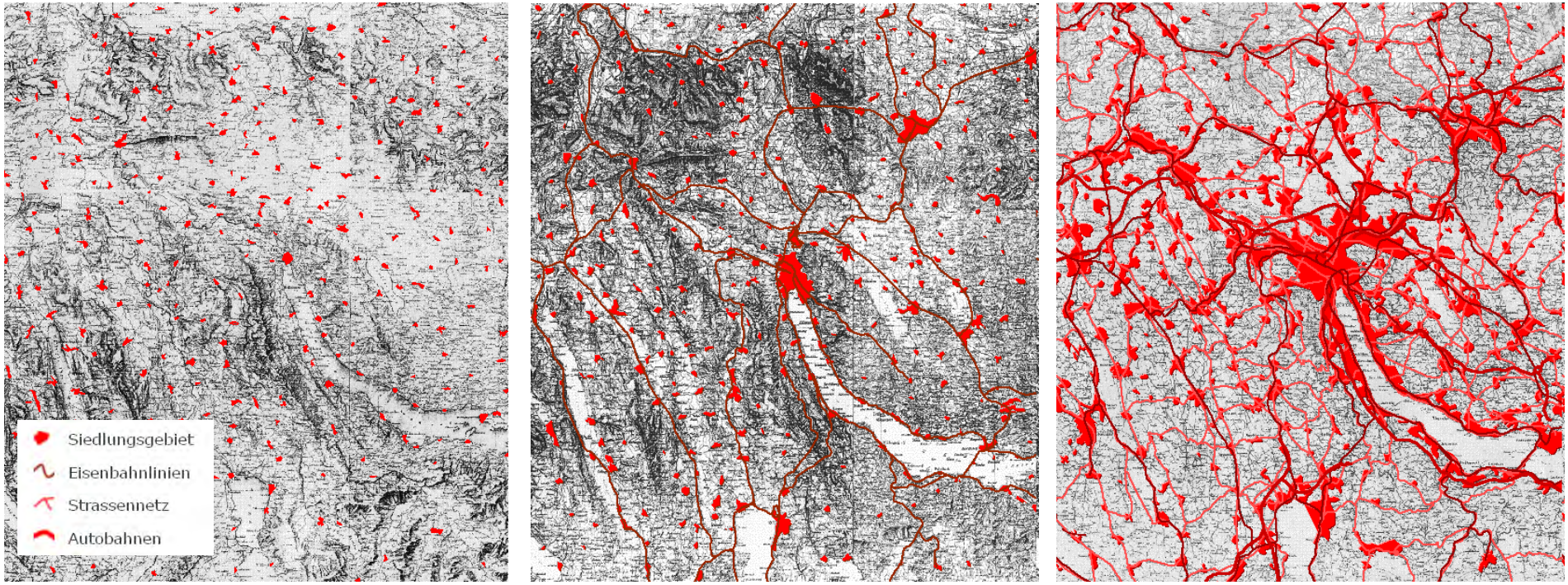


Dramatic increases in low-altitude Mediterranean (river basins and coasts)

Fischer and Schär 2010, *Nature Geoscience*, ENSEMBLES, mean of 6 models, scenario A1B

There is a growing trend to urbanization in the Zurich area

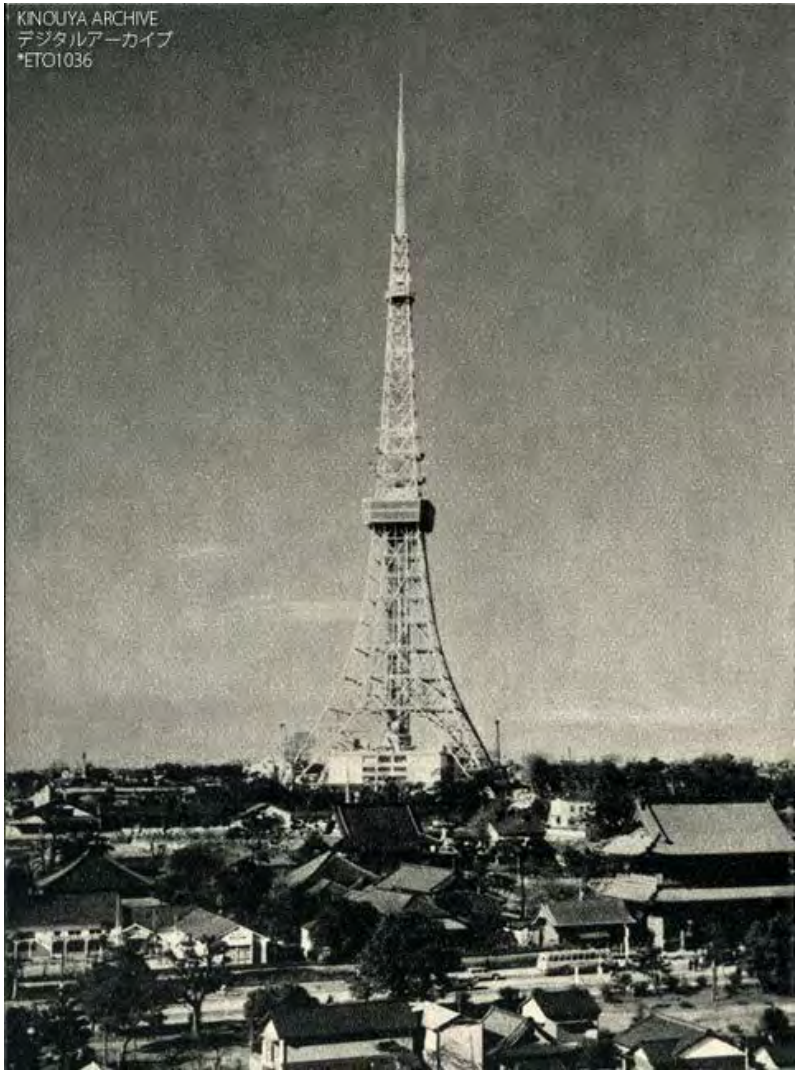
1847 1912 1990 10 km



Densification of the Zürich area

- 70% of people living in urban environment by 2050 (UN 2009)
- 83 % of people living in cities in Switzerland by 2050
- Energy consumption in cities is likely to follow urbanization trend

Trend to urbanization in Tokyo area

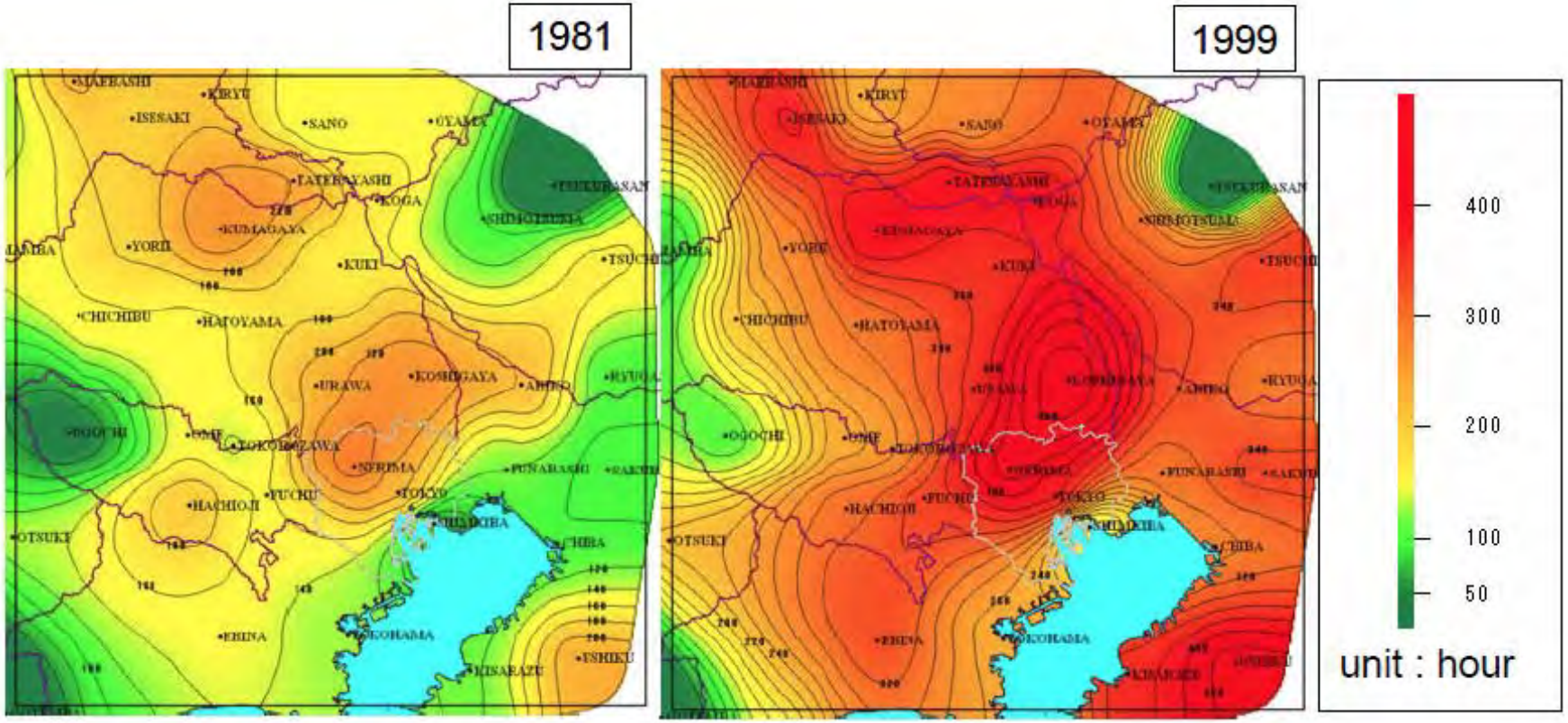


Tokyo 1960

Tokyo 2010

Source: http://www.japansugoi.com/

There is an important urban heat island in Tokyo area

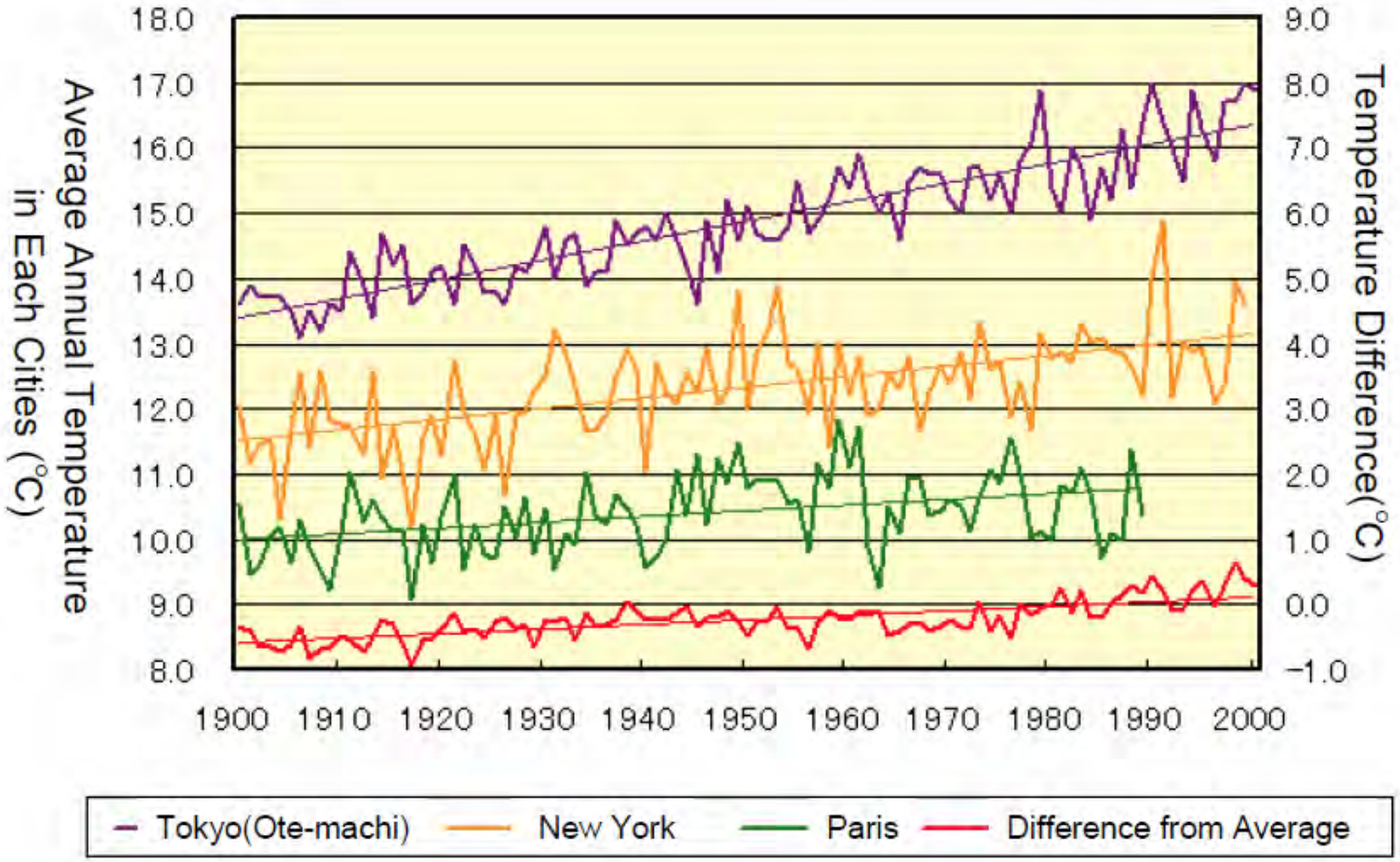


Distribution of cumulative hours temperature exceeding 30°C

Source: OUTLINE OF THE POLICY FRAMEWORK TO REDUCE URBAN HEAT ISLAND EFFECTS
March 2004, Inter-Ministry Coordination Committee to Mitigate Urban Heat Island

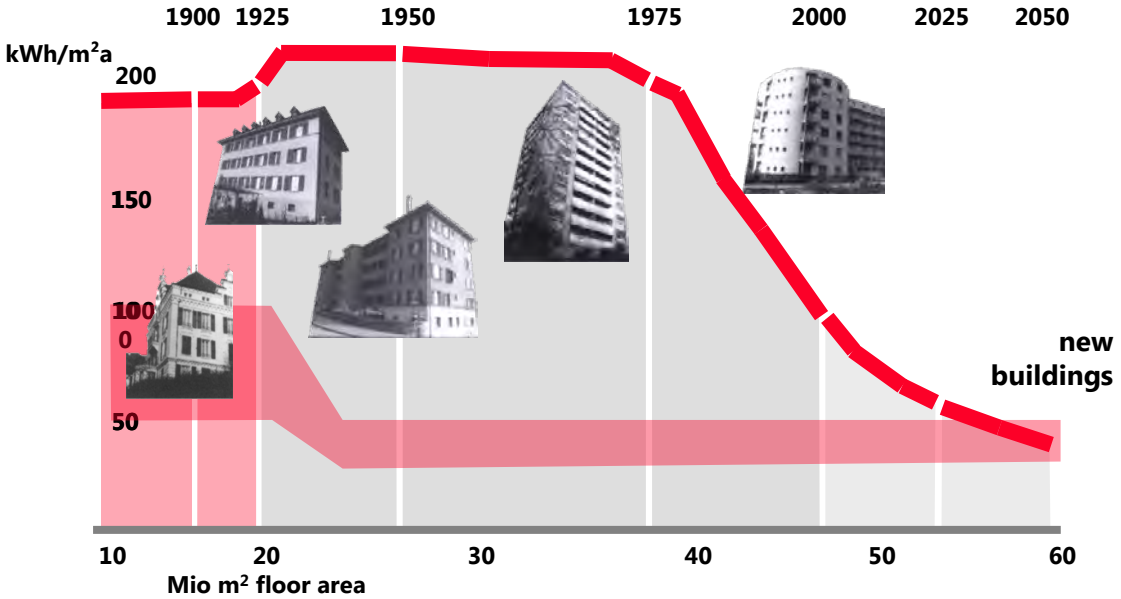
Urban heat island in Tokyo more important than in New York

Temperature difference in world cities (meteorological agency)



Source: OUTLINE OF THE POLICY FRAMEWORK TO REDUCE URBAN HEAT ISLAND EFFECTS
March 2004, Inter-Ministry Coordination Committee to Mitigate Urban Heat Island

Buildings are responsible for a large part of energy consumption



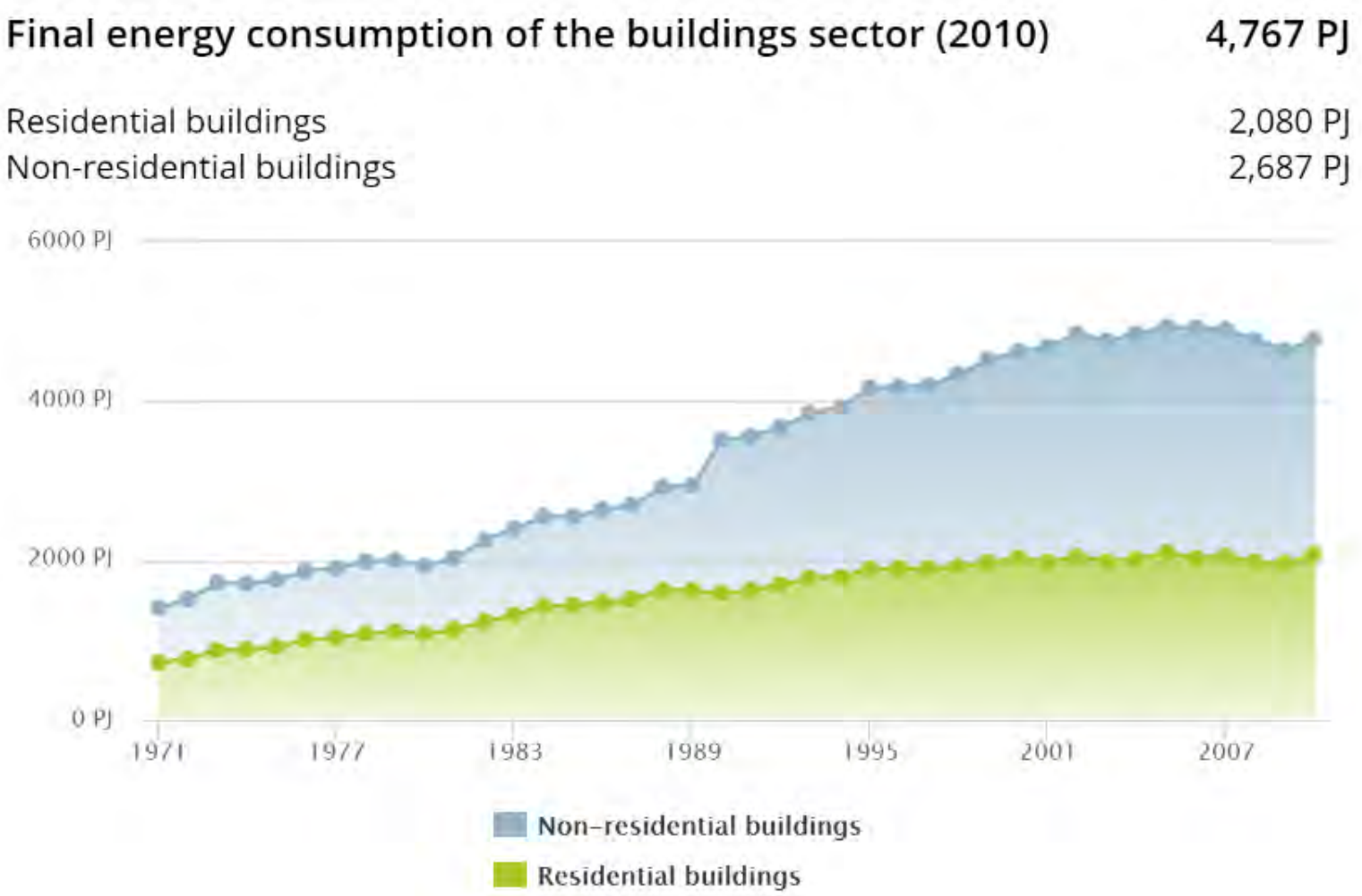
Heat Energy Demand and Heated Floor Area of Dwellings in Zurich

Buildings are responsible for

- 40% of total EU energy consumption
- 48 % in Switzerland, 68% fossil fuel based
- 36% of the EU's total CO_2 emissions (*COM 2008)*

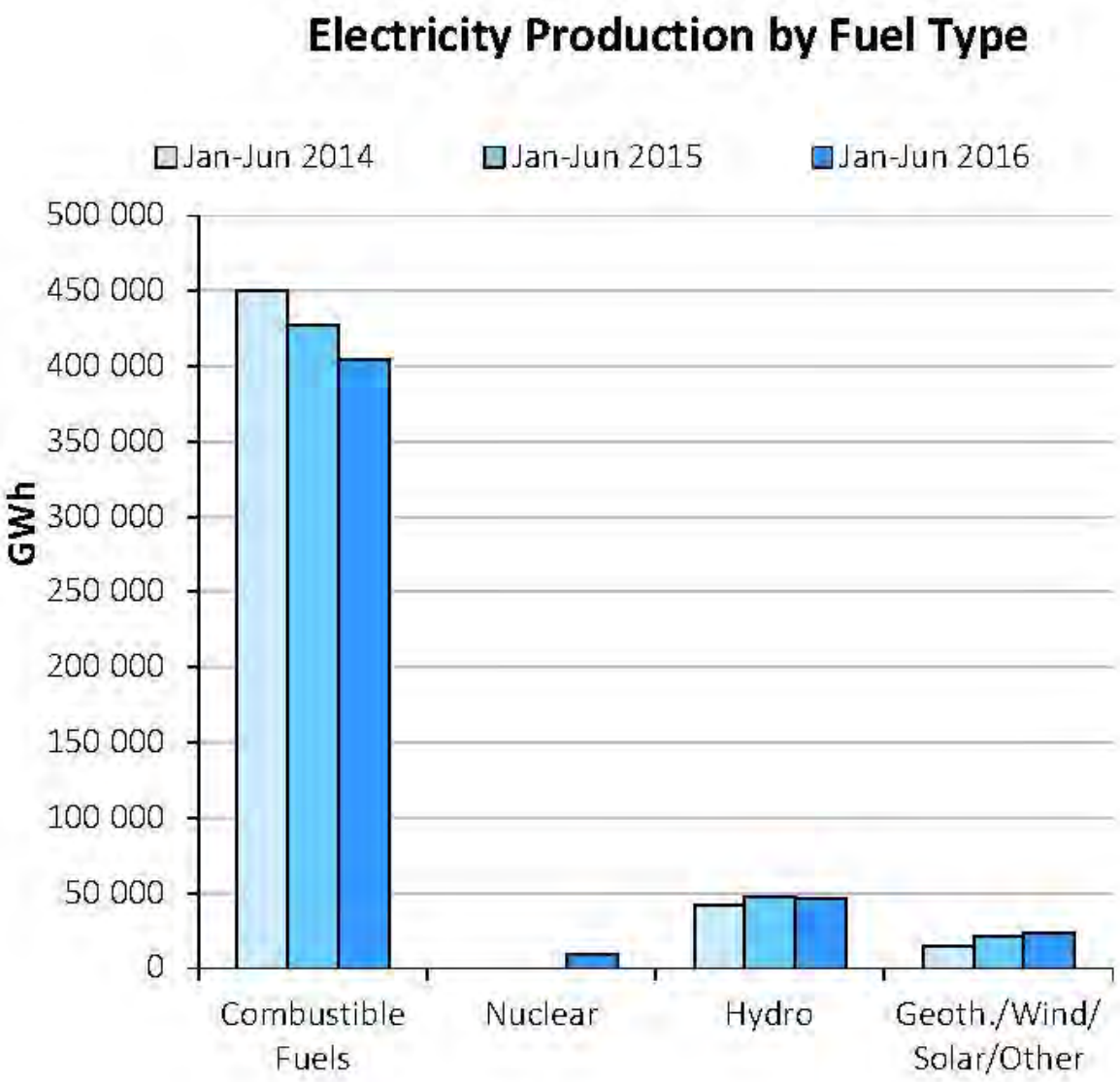
by 2050 existing buildings will be responsible for 80% of the total energy consumption (no interaction scenario)

The energy use by buildings in Japan is growing



Source: International Energy Agency

Electricity production in Japan is still highly fossil-based



Source: International Energy Agency

Observations

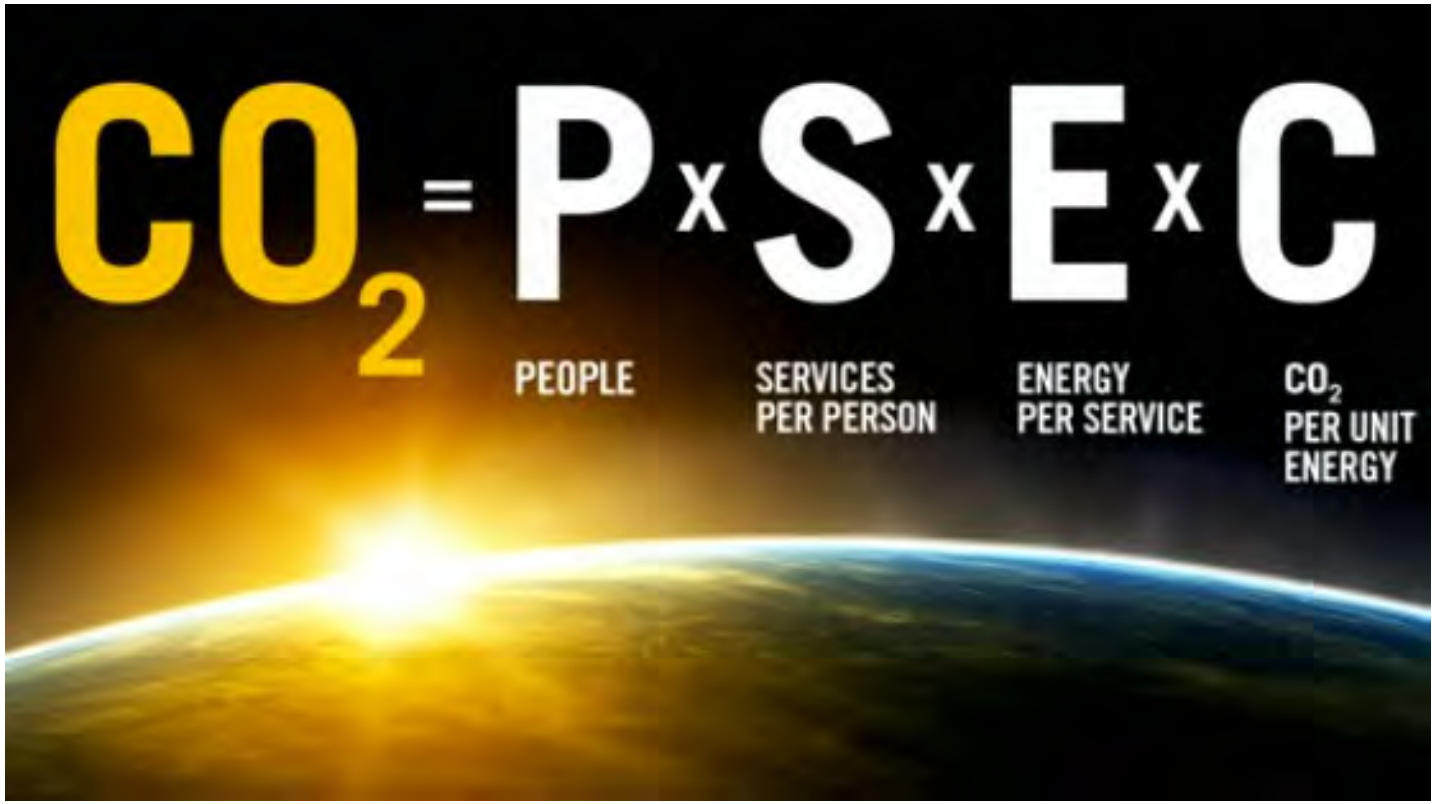
1. Urban heat island effect is growing
2. Urban densification is growing
3. Energy use in cities is growing
4. Energy use is still highly fossil fuel based

Question

How can we reduce CO_2 emissions related to the energy use by buildings and as well mitigate the urban heat island effect and its impact on health ?

Which new materials are needed ?

Kaya identity



Decomposition of CO_2 emissions into driving forces
to enable
carbon emissions reduction strategies

Kaya,Y, 1990; Prognos, 2012

Kaya identity applied to buildings

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{A} \times A$$

E Energy consumption building

A floor area building

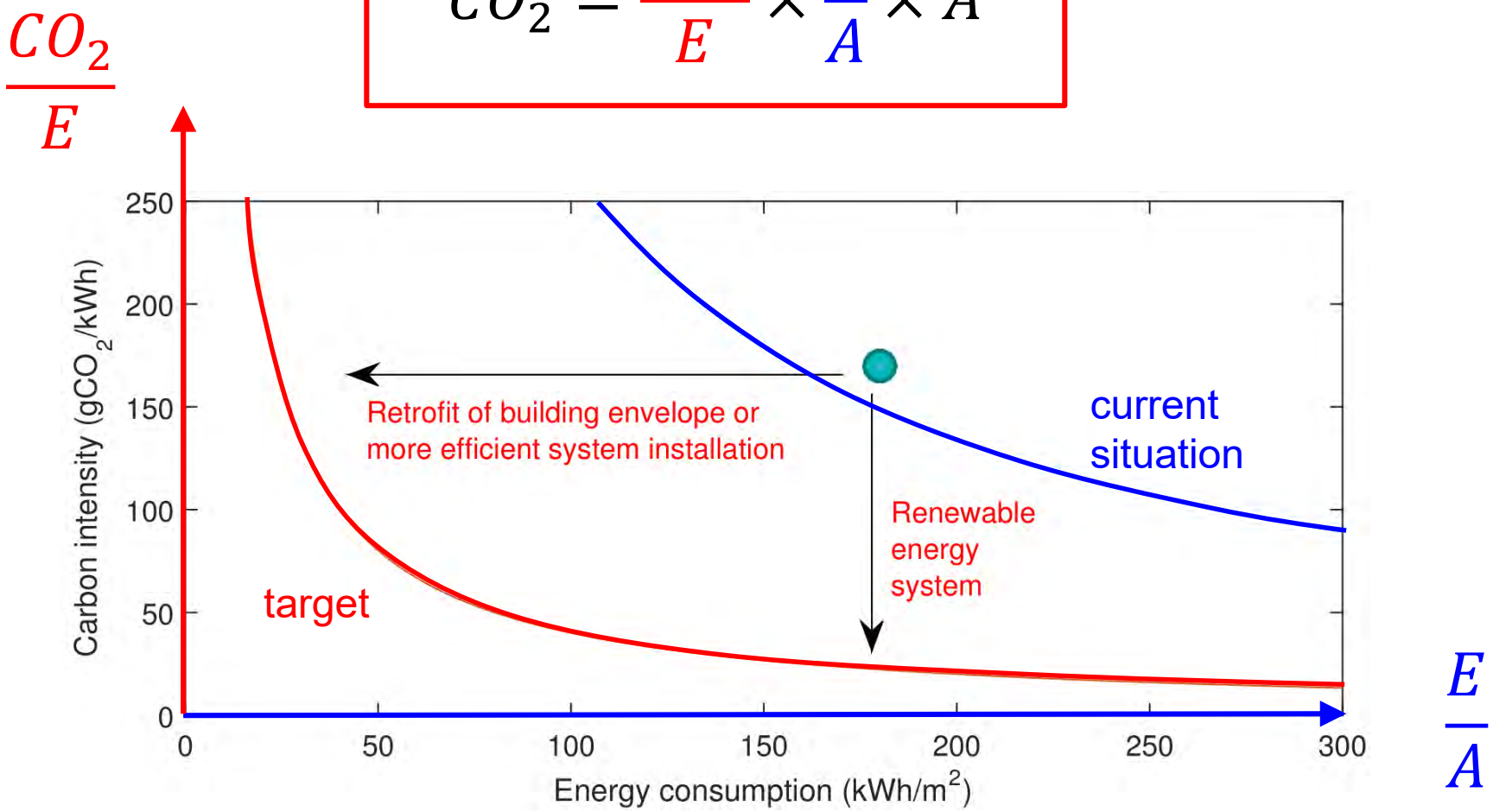
C02/E Carbon intensity of the energy system [kgCO2/J]

E/A Energy intensity: energy consumption per area [kWh/m2]

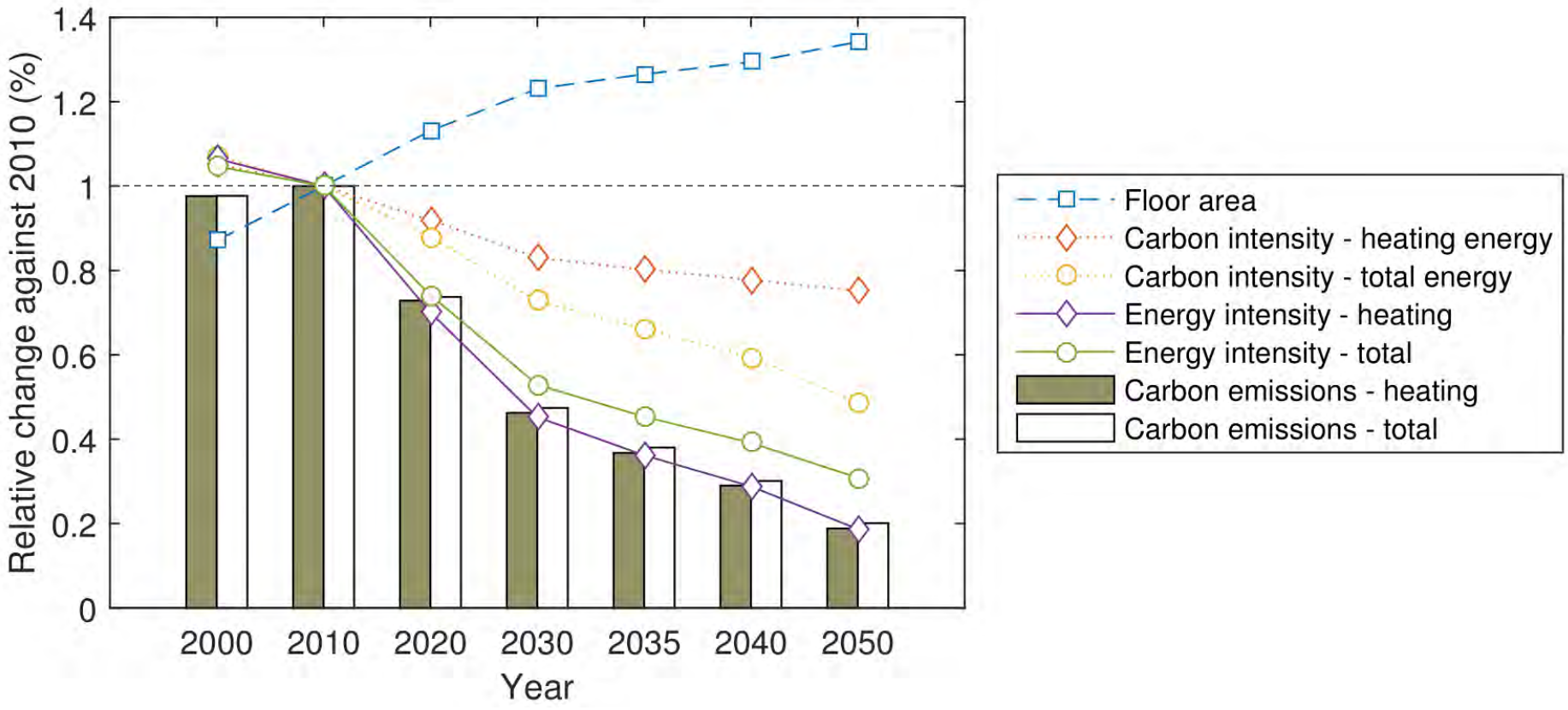
Mavromatidis et al. 2016

Strategy from Kaya identity for buildings

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{A} \times A$$

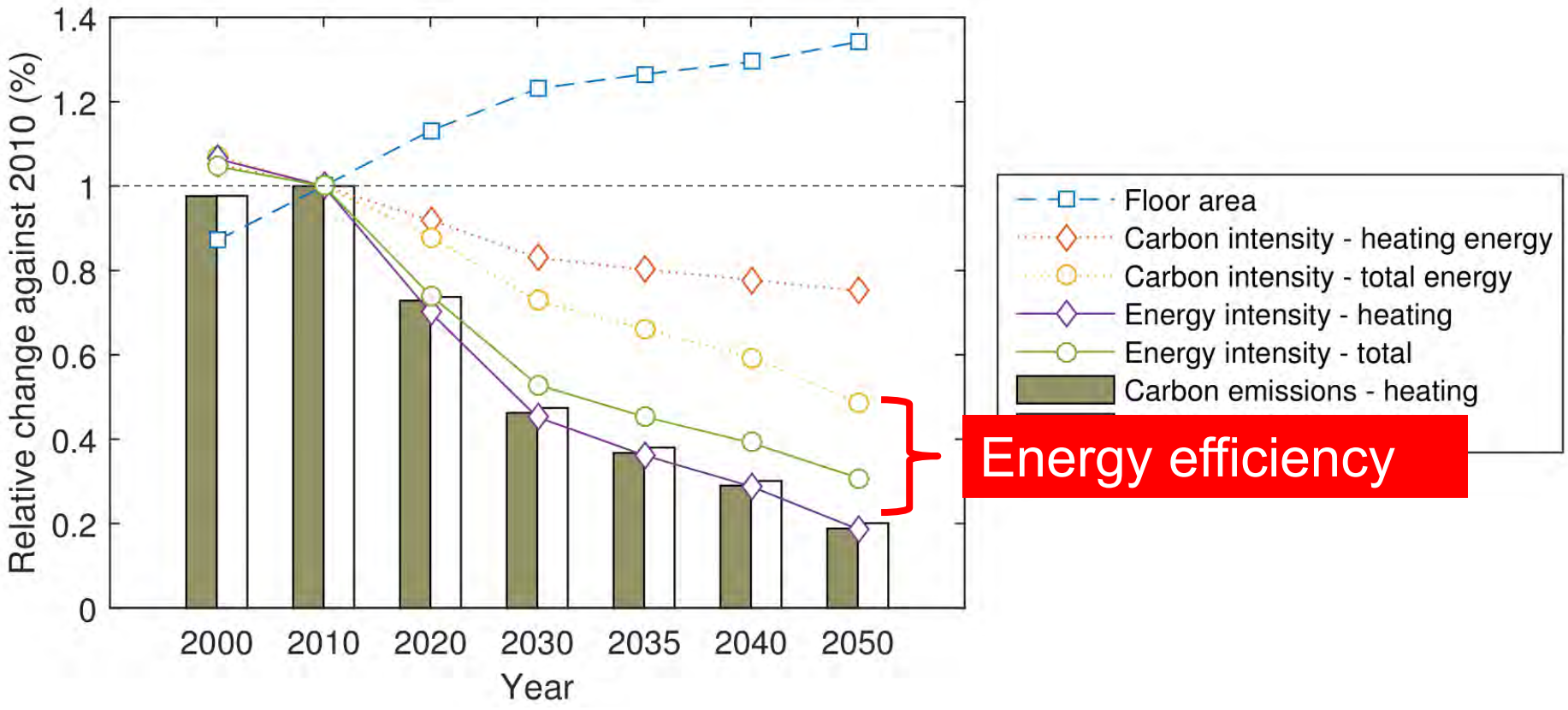


Buildings heating & total energy supply: trend drivers CO_2 emissions



Mavromatidis et al. 2016

Buildings heating & total energy supply: trend drivers CO2 emissions

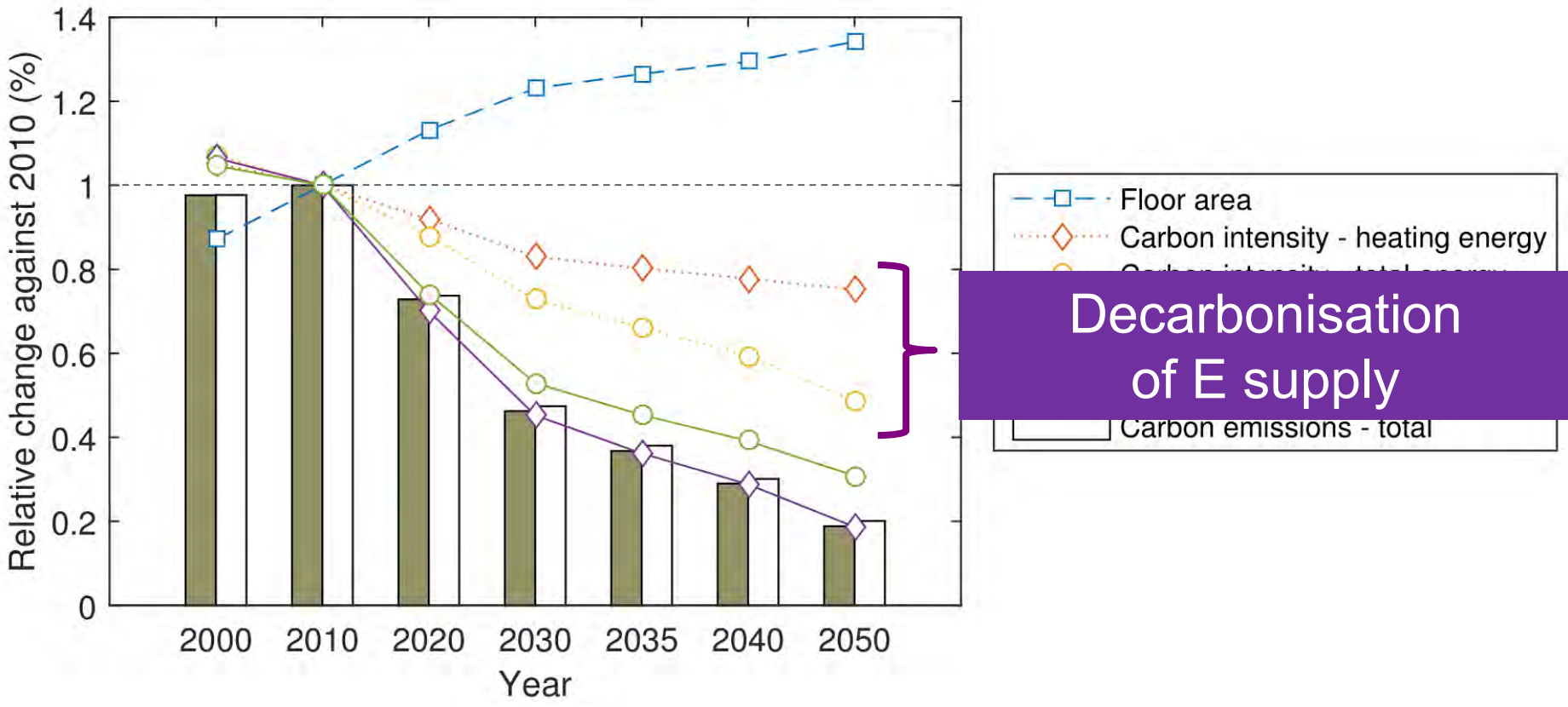


Energy intensity reduction by

- renovation building stock, more efficient buildings
- more efficient technologies

Mavromatidis et al. 2016

Buildings heating & total energy supply: trend drivers CO_2 emissions



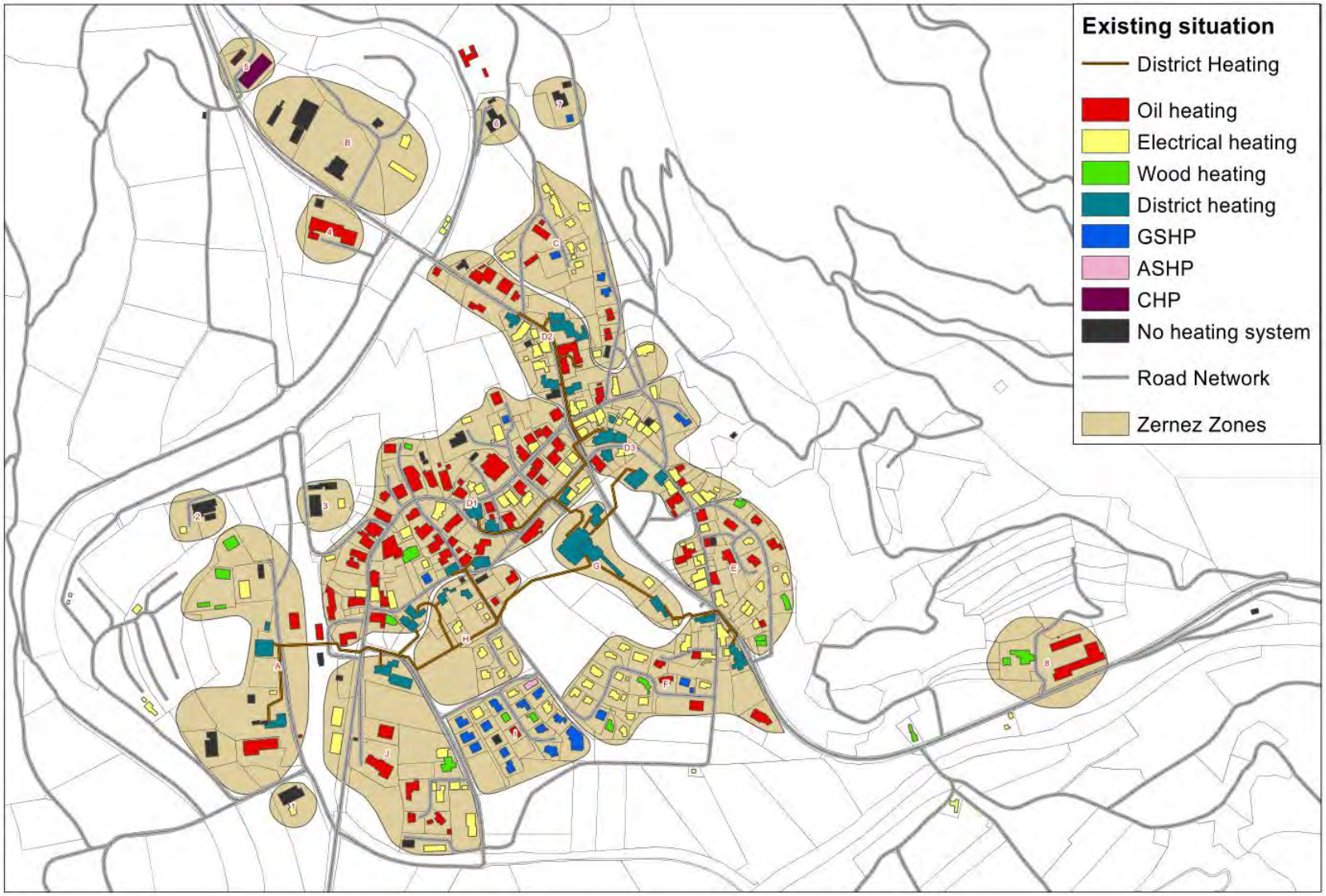
Mavromatidis et al. 2016

Example: Swiss mountain village Zernez

Transformation of buildings and sites/districts to decarbonized energy efficient systems

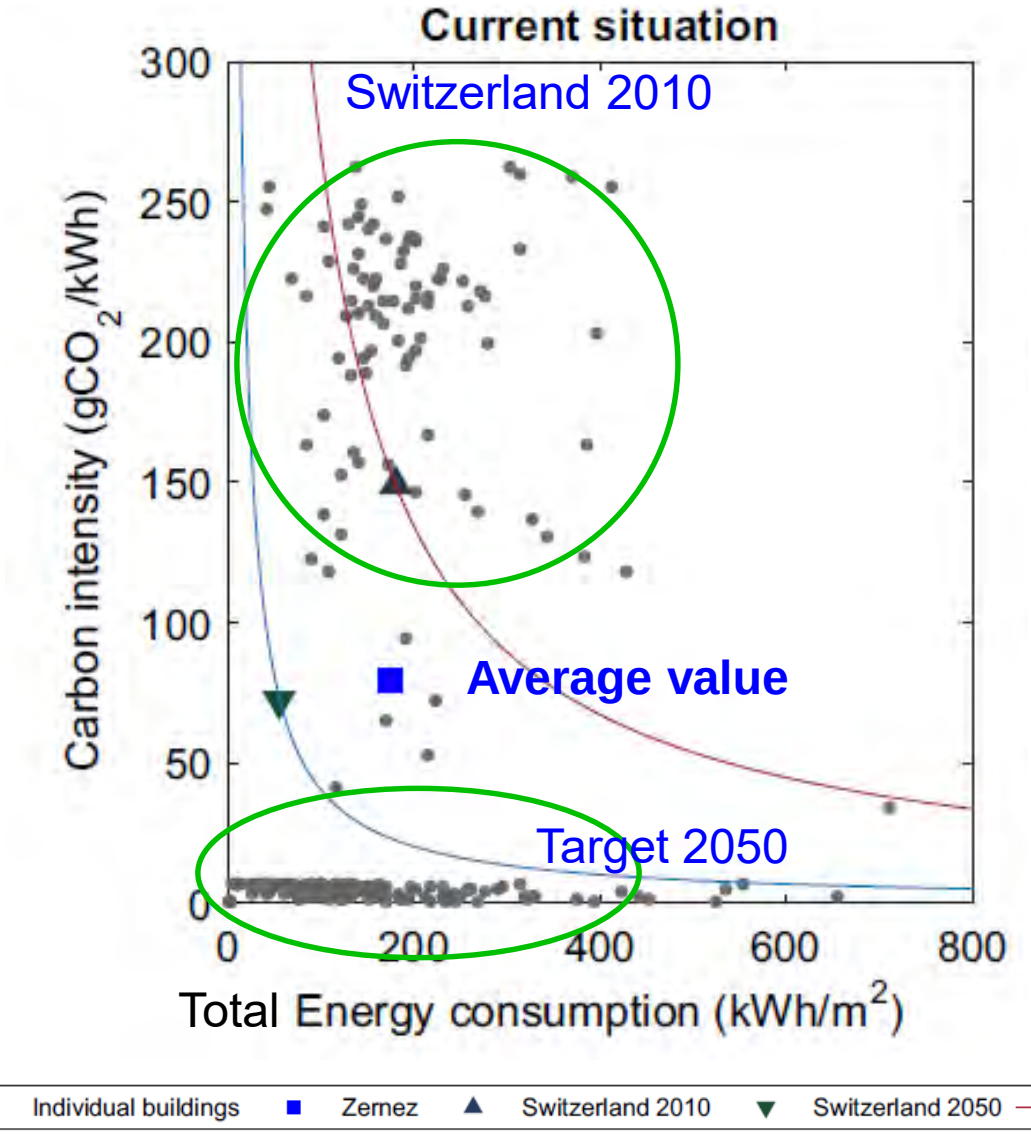
Capture present status	

Present status of building heating systems in Zernez



GSHP: ground source heat pump, ASHP: air source heat pump, CHP: Combined Heat and Power

Present status: carbon intensity versus energy use



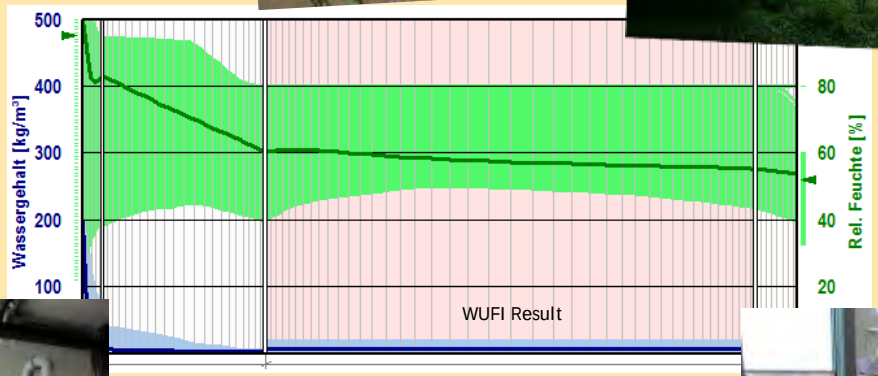
Two main groups

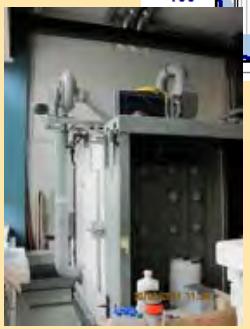
- Oil-based non retroffited buildings with high carbon intensity
- New renewables based buildings with low carbon intensity

Transformation of buildings and sites/districts to decarbonized energy efficient systems

Capture present status	
Retrofit building envelope HVAC/control technologies	
Local renewable energies	

CCEM – SuRHIB : wall insulation concepts

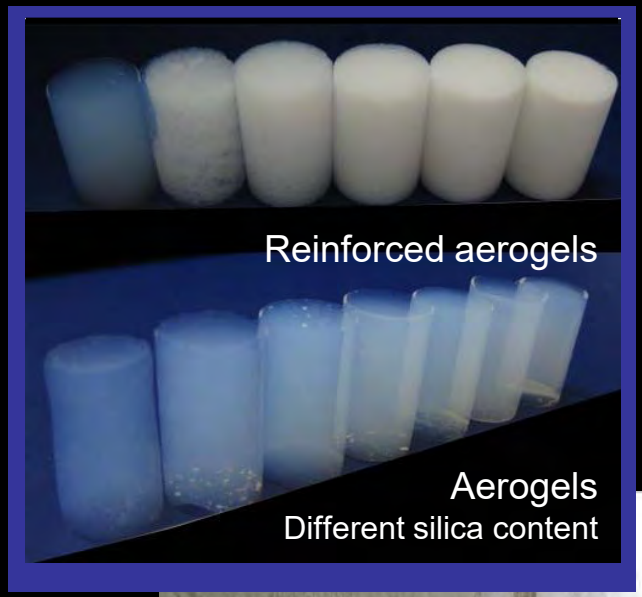




Determination of physical parameters for detailed hygrothermal performance simulations

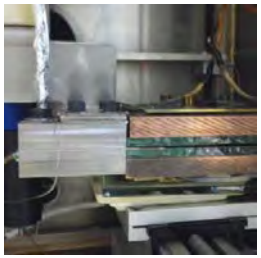
Weathering tests at Empa‘s climate chamber

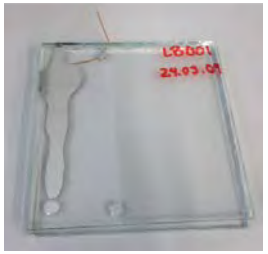
Timber framework for natural weathering



Aerogel rendering

New window types



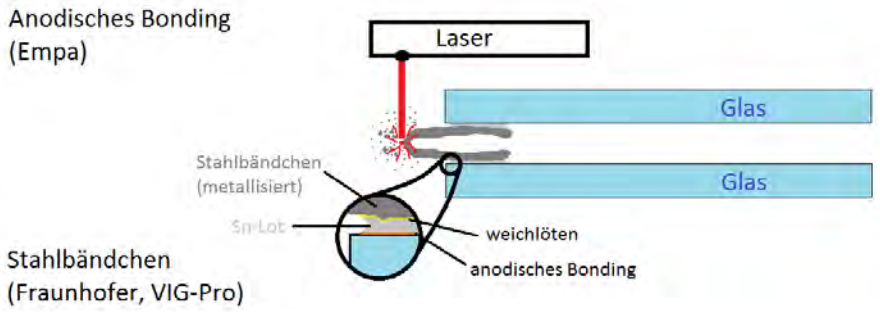


EuFP7 – WinSmart: concept

«Smart» Vacuum glazing

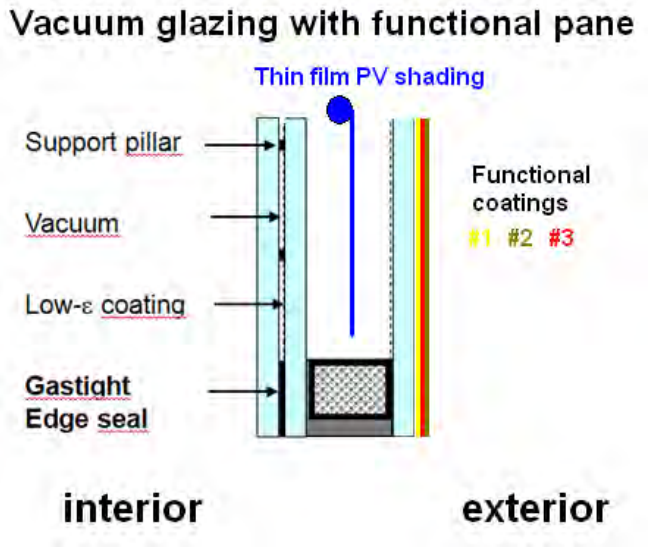
- **VG Technology**

Production technologies
Liquid metal injection / anodic bonding
Scalability aspects of VG
Sash and frame redesign



- **Smart properties (coatings)**

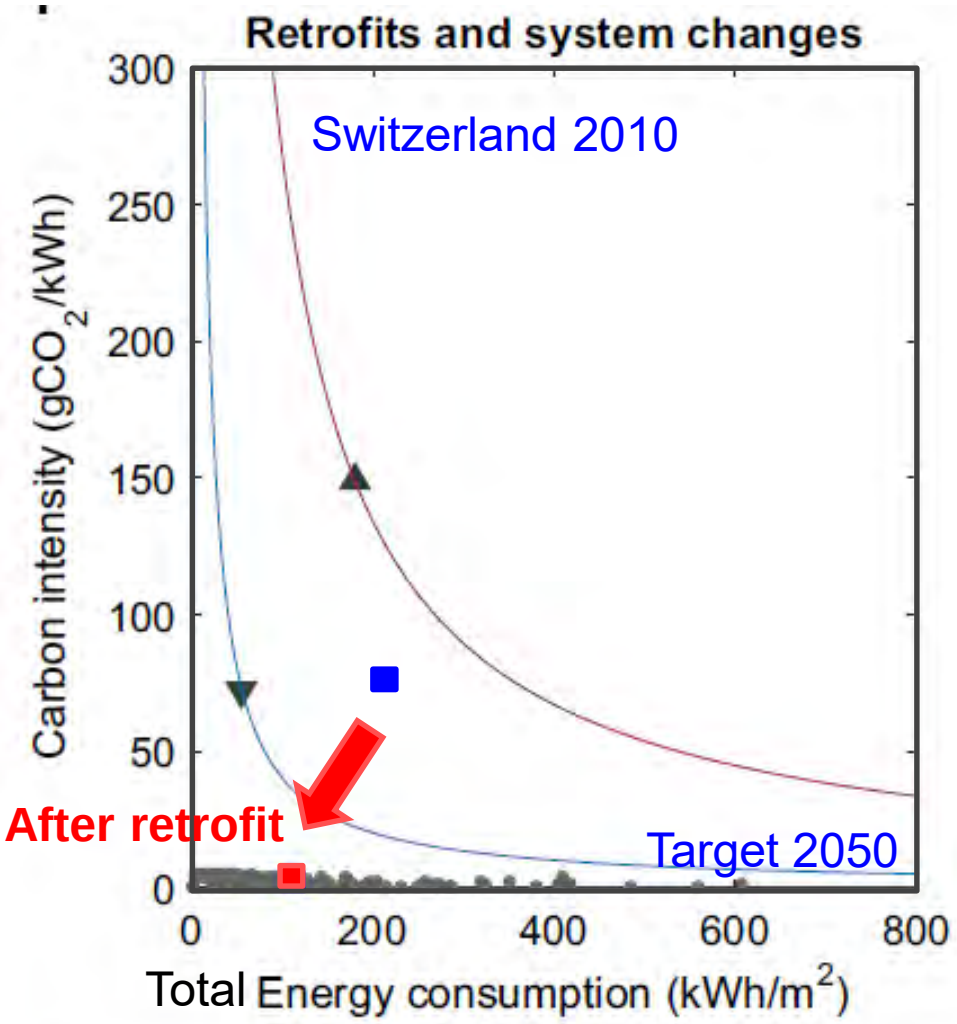
«Switchable»
Photoelectrochromic
Electrochromic state of the art comparison



Needs for material development

1. New highly insulation materials at low cost
2. Multi-functional ‘smart’ windows / new coatings
   → from niche to larger market pentration

Retrofit of buildings & heating systems in Zernez

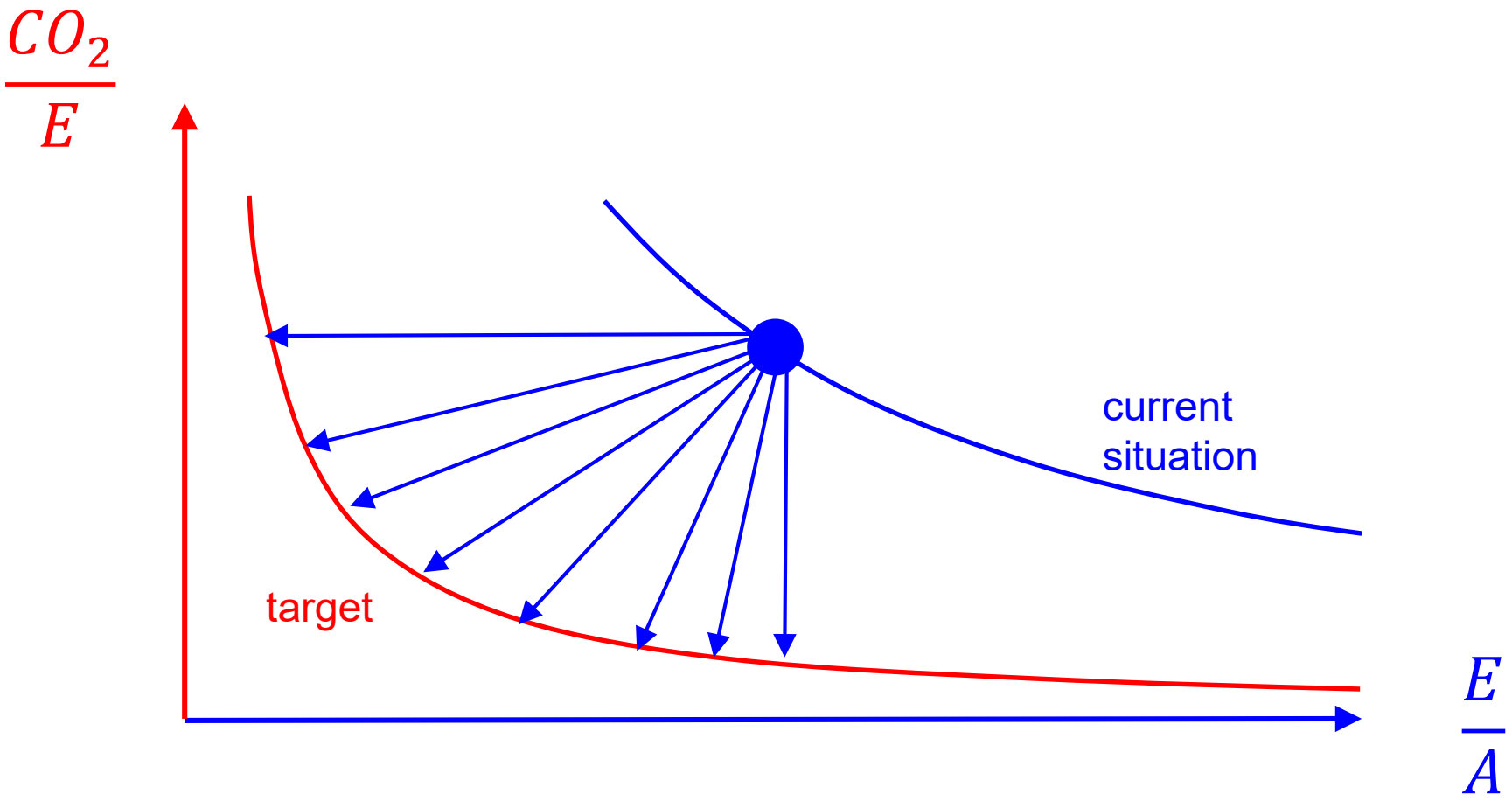


Building retrofit

Update building systems

- Bio-energy sources
- Efficient heat pumps

How to achieve decarbonisation targets ?



- Lots of freedom in finding new solutions to achieve the same target
- Heterogeneity of buildings complicates general solutions
- Solutions to be found on the scale of communities → urban scale

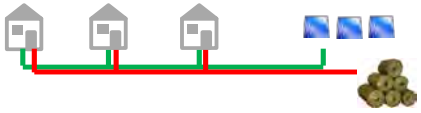
Transformation of buildings and sites/districts to decarbonized energy efficient systems

Capture present status

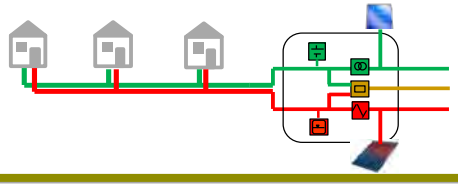
Retrofit building envelope
HVAC/control technologies

Local renewable energies

Local electric grids and
heat networks

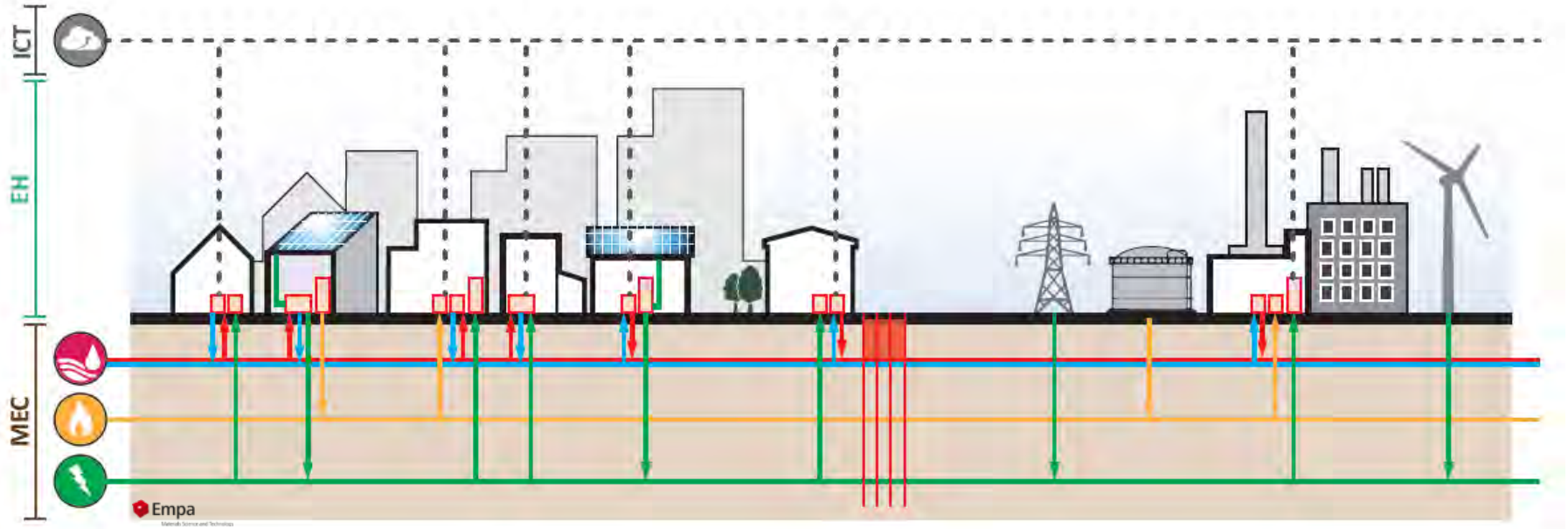


Multi-energy grids
Energy-hub



OPTIMIZATION

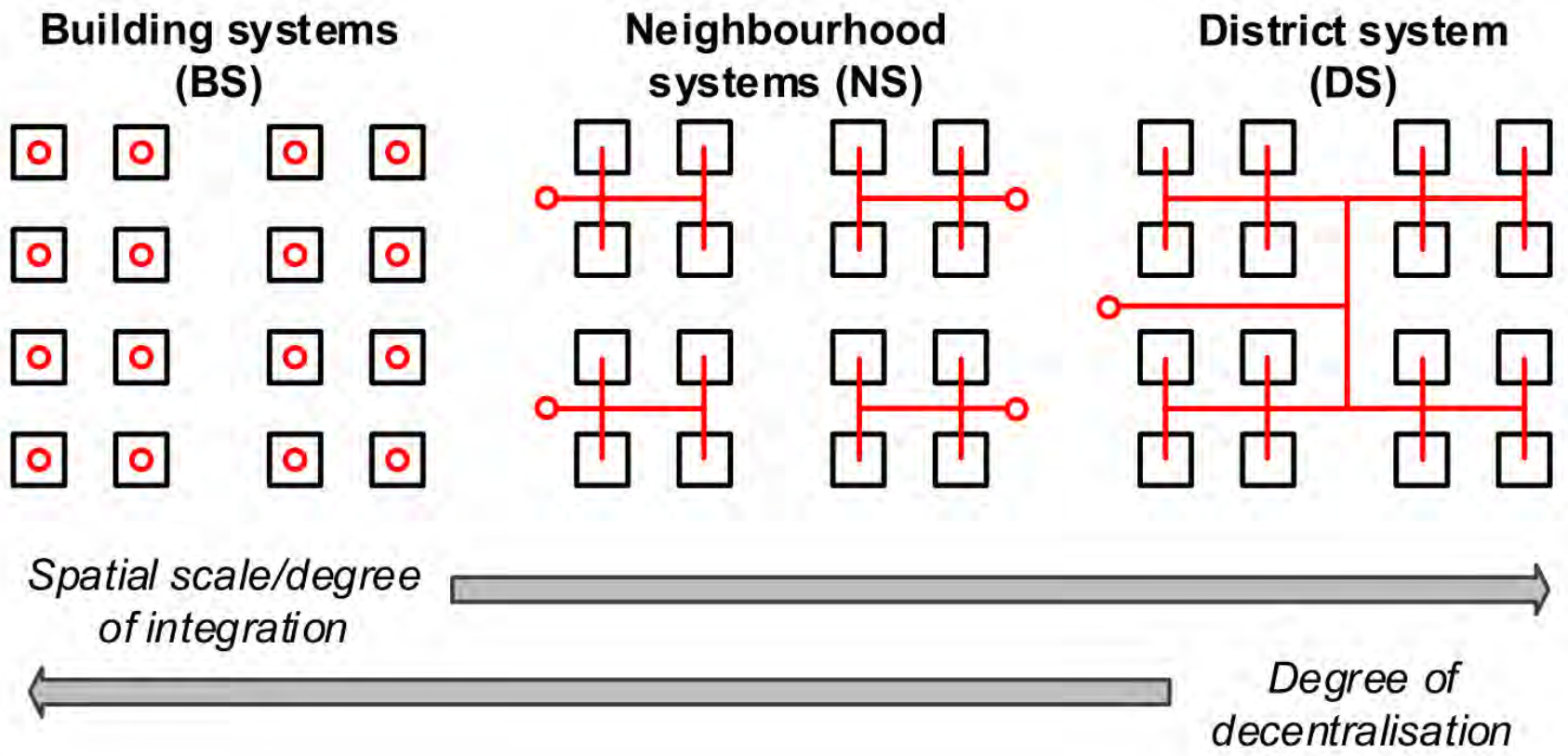
Buildings connected by multi-energy grids



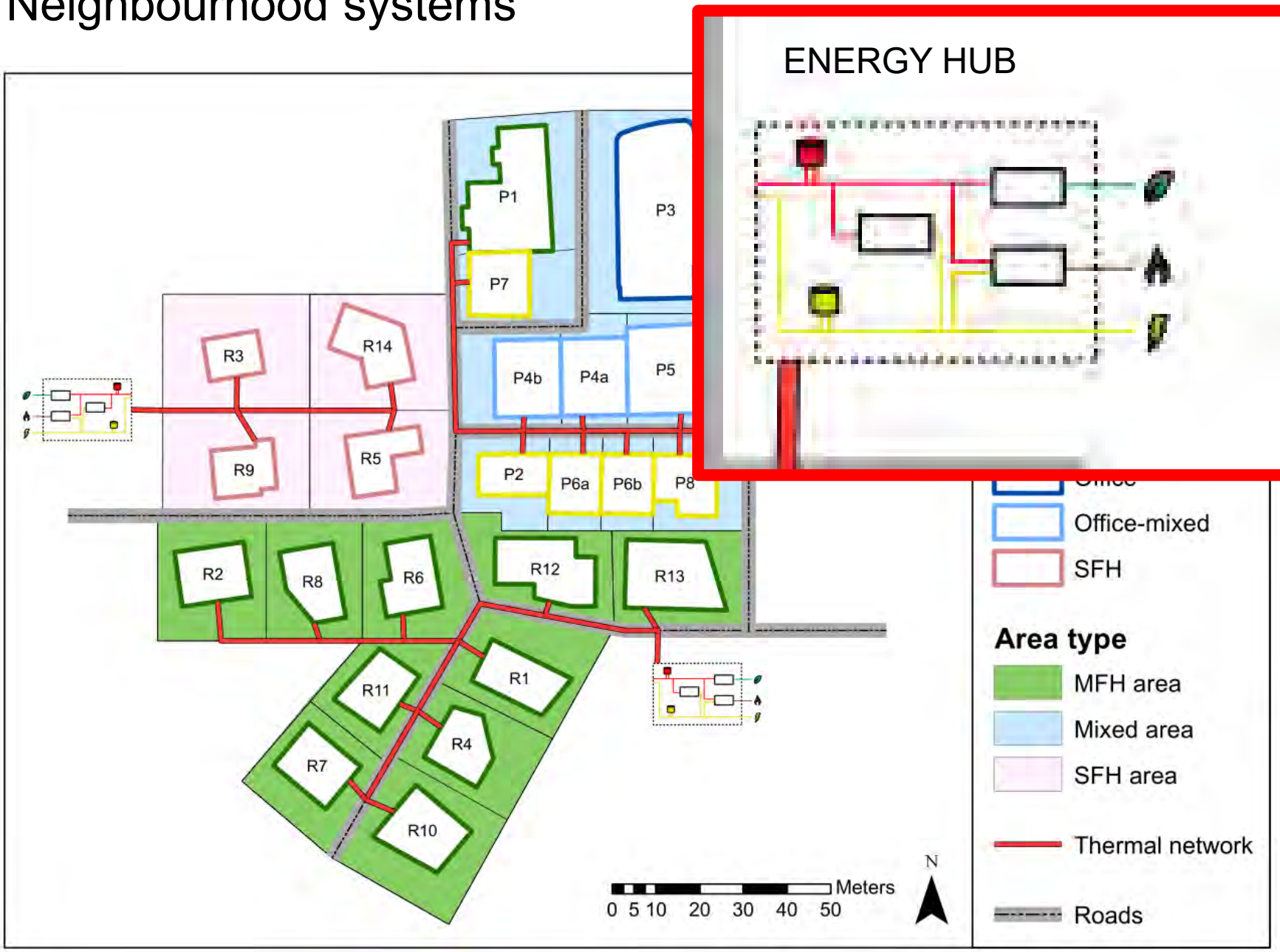
- Buildings become prosumers (production and consumption)
- Renewables and waste energy is integrated
- Connection between gas, heat and electricity & storage & conversions
- Connection with ICT grid

Example: district of residential buildings, offices, shops, ….

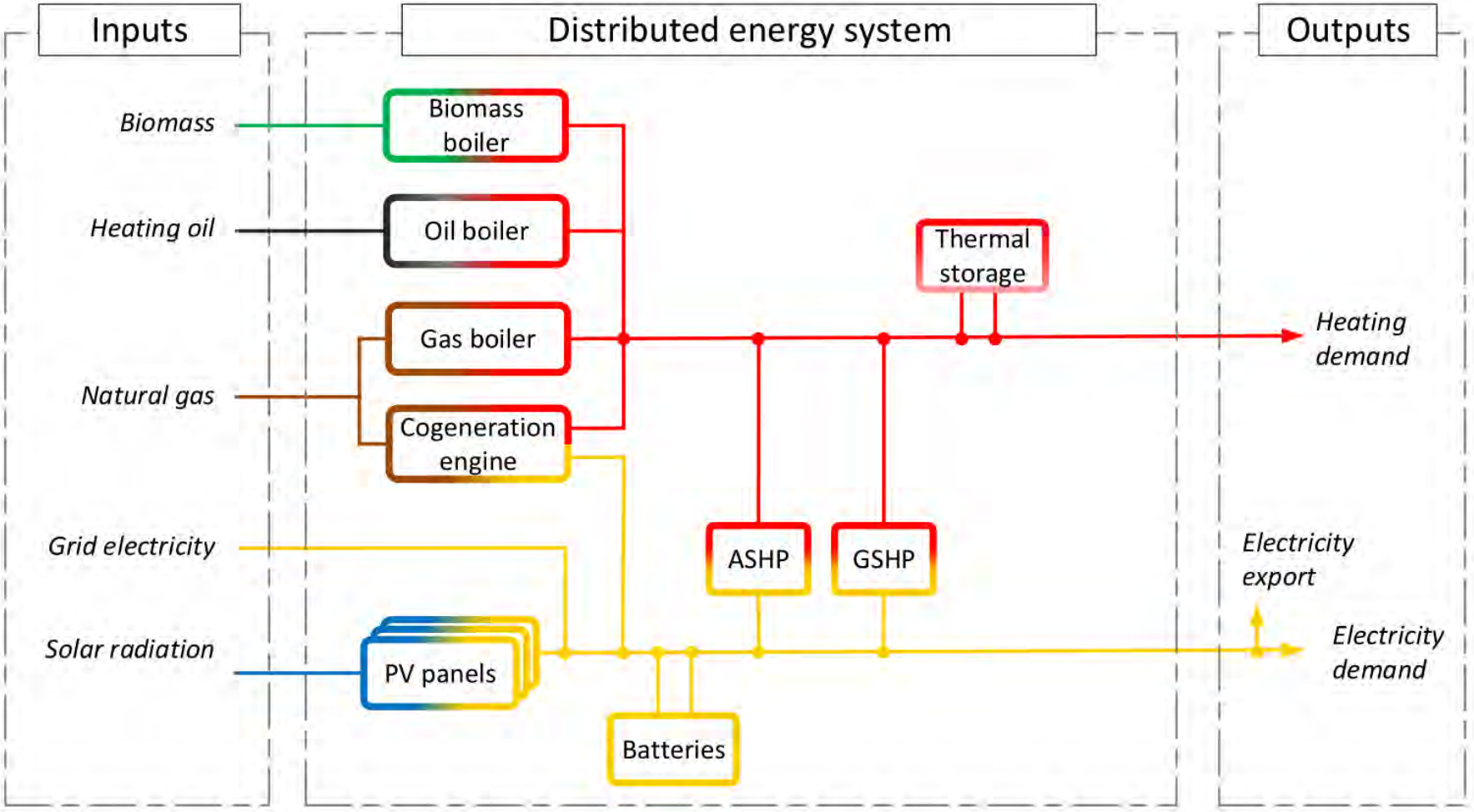
Candidate configurations for connecting building from building to district scale



Neighbourhood systems



Energy hubs are essential elements of the future energy system



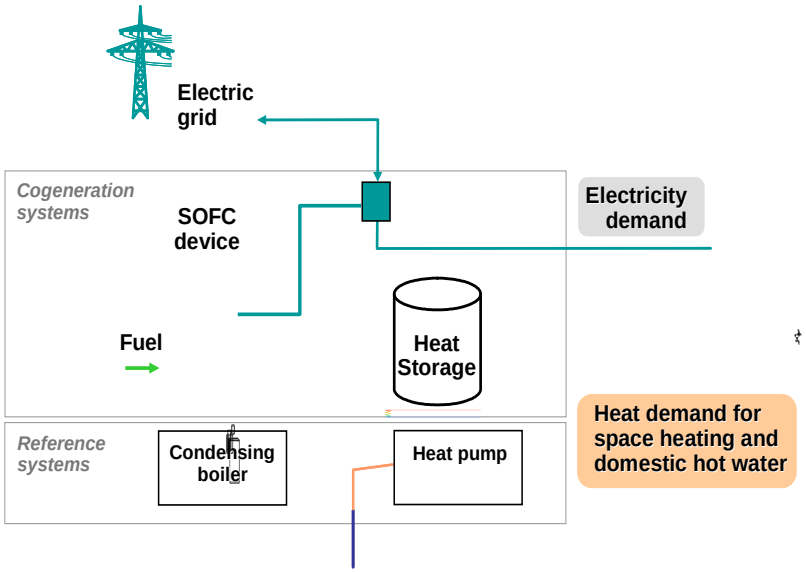
Input → production + conversion + storage → output : demands

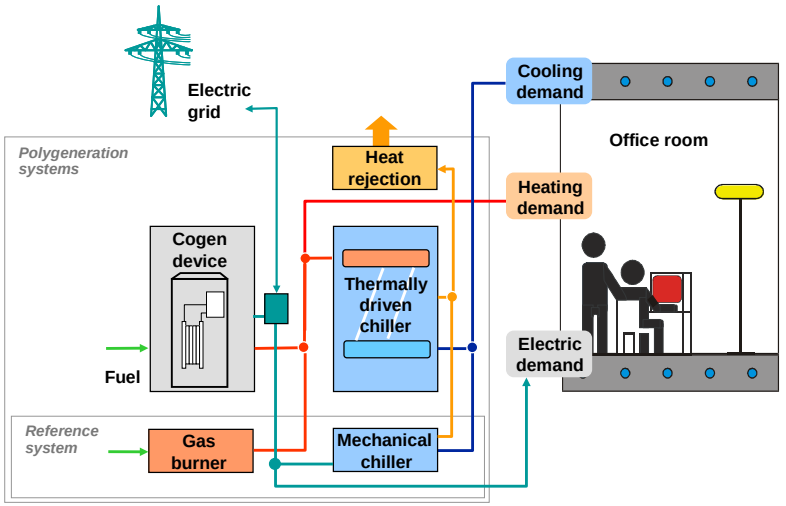
ASHP : air source heat pump, GSHP: ground source heat pump

Cogeneration systems



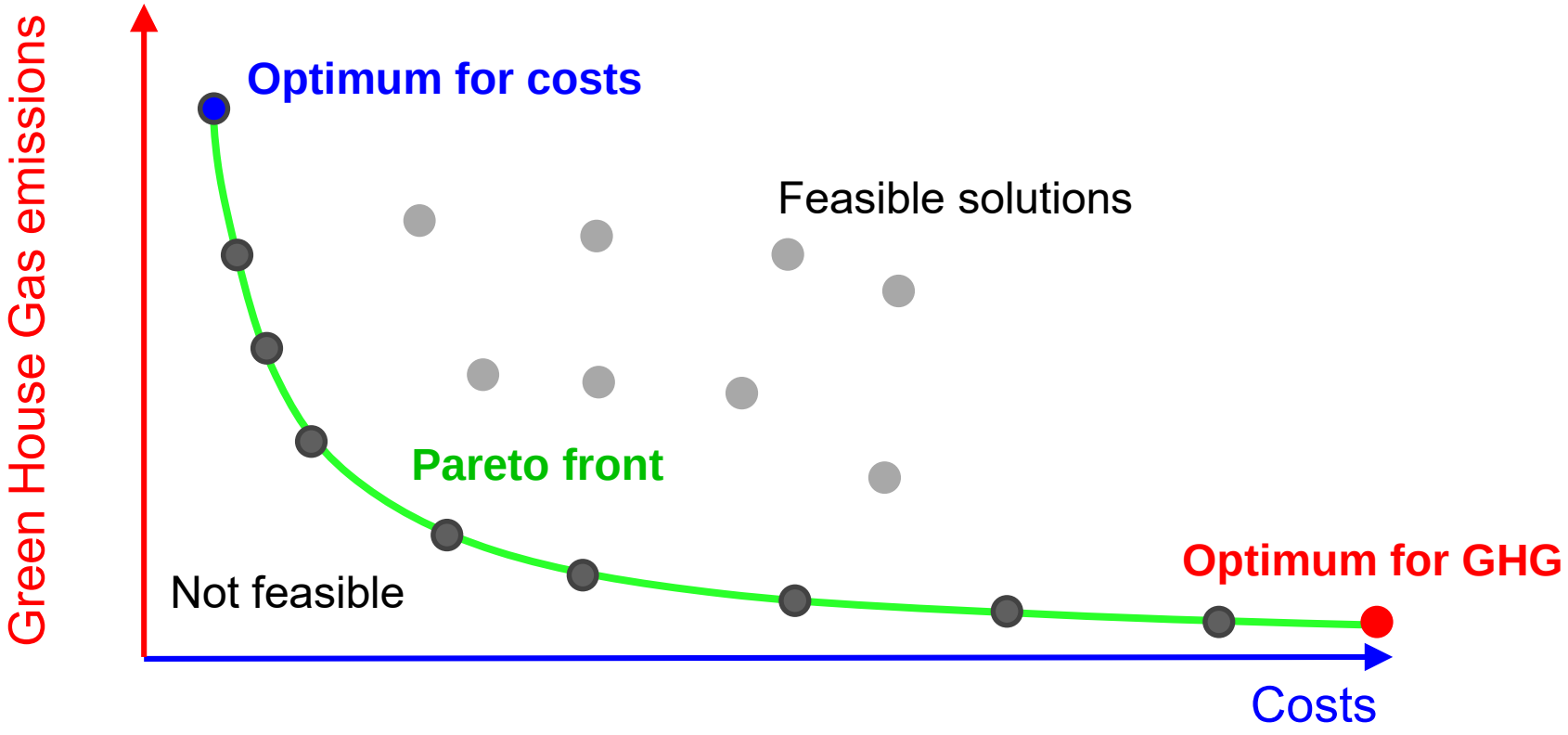

- Fuel Cell Modelling *(EU GenFC)*
- Fuel Cell and Cogeneration System Modelling *(BFE / IEA Annex 42)*
- Polygeneration with advanced thermal cooling (*EU PolySMART*)
- Micro-Polygen / Kraftwerk Haus *(BFE, brenet)*



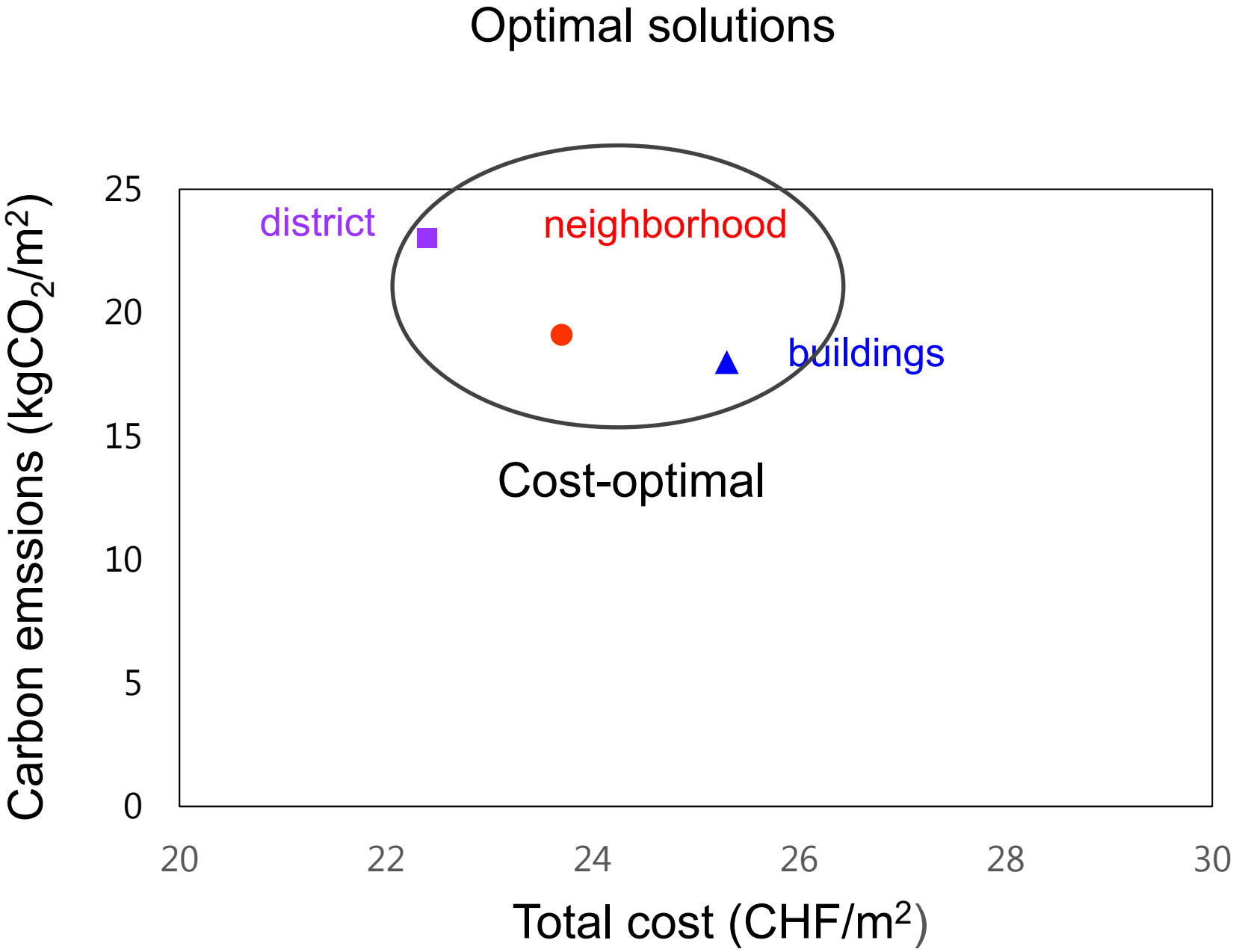


District system: one energy hub / district

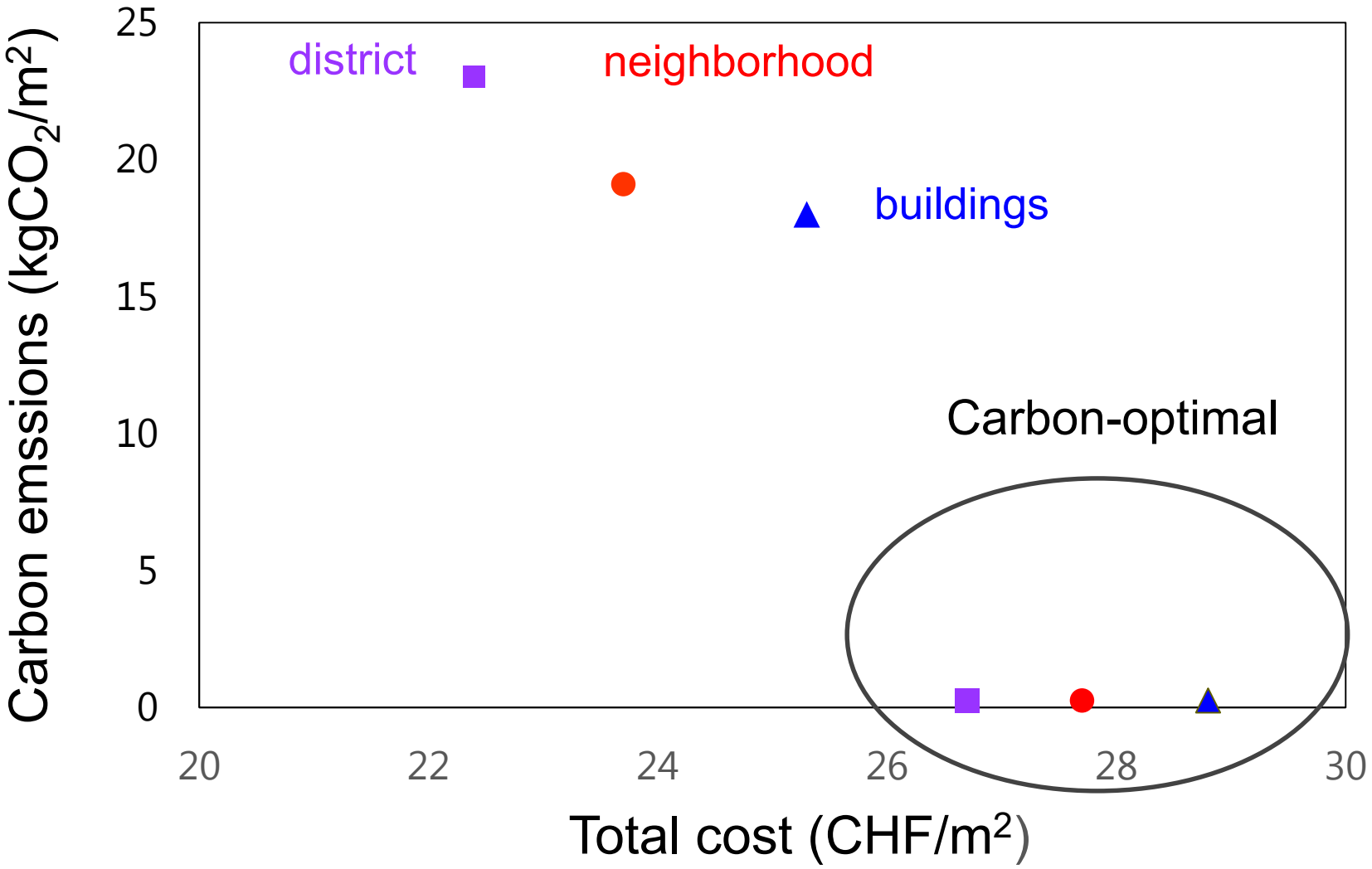
Scenarios are evaluated based on decarbonisation and costs



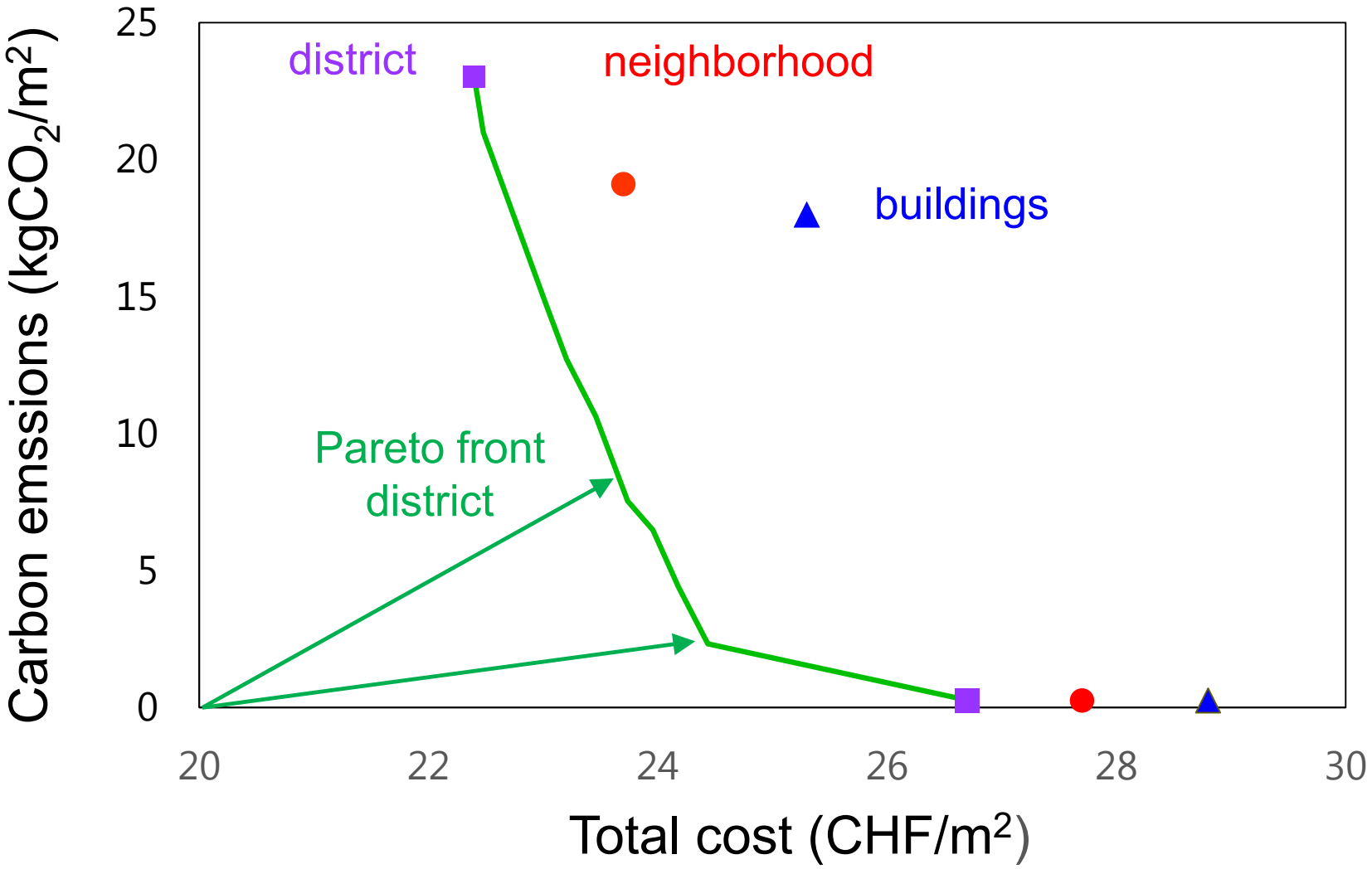
Optimal solutions for cost and GHG are on the Pareto front


Optimal solutions
district
neighborhood
buildings
Cost-optimal
Carbon emssions (kgCO2/m2)
Total cost (CHF/m2)
25
20
15
10
5
0
20
22
24
26
28
30

Optimal solutions



Optimal solutions

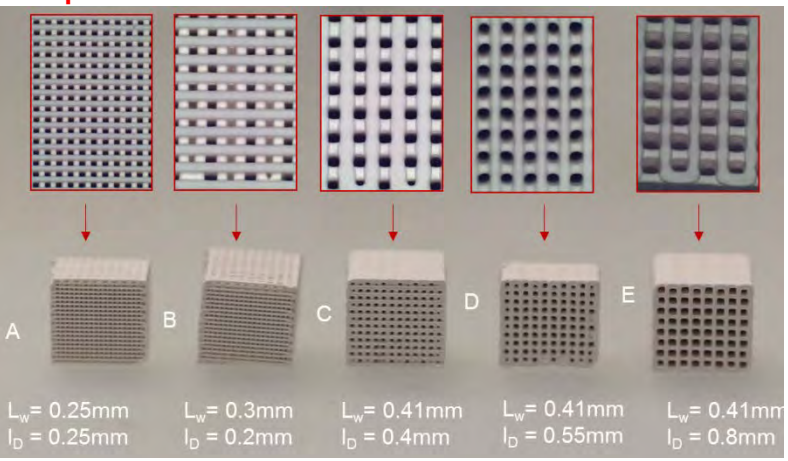


SNF project with IBM

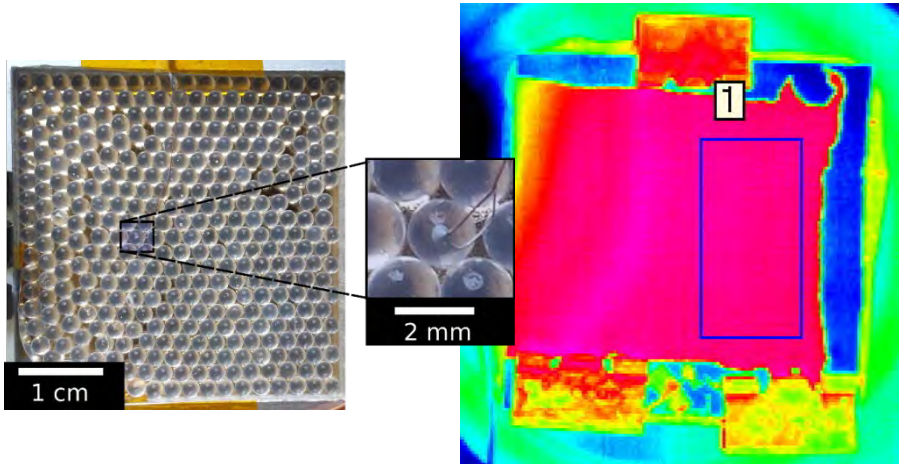
NFP Project THRIVE
Sorption-driven heat pump
Lead IBM: Bruno Michel, Patrick Ruch

Design of hierarchical porous structure of absorbent
IBM affiliated PhD Jens Ammann, ETHZ PhD Clara Minas
Post-docs at Empa Andrea Radu

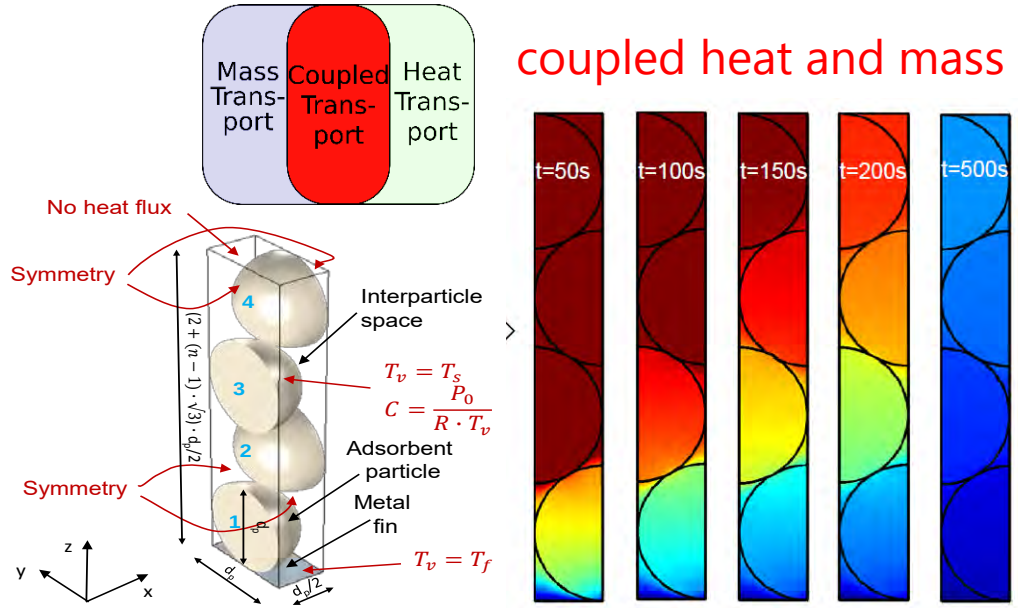
printed absorbants - ETHZ

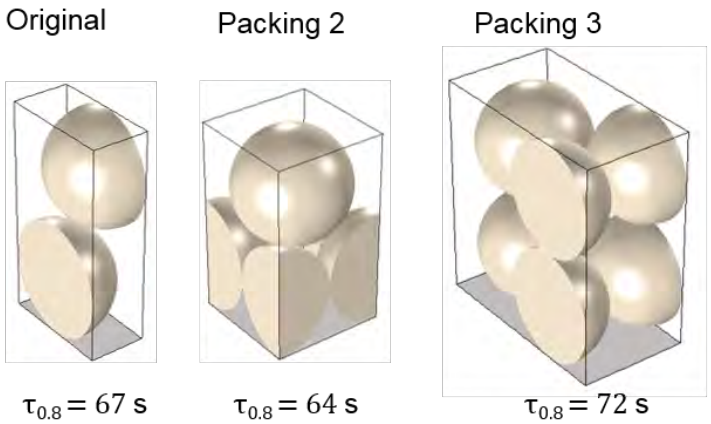


advanced characterization - IBM



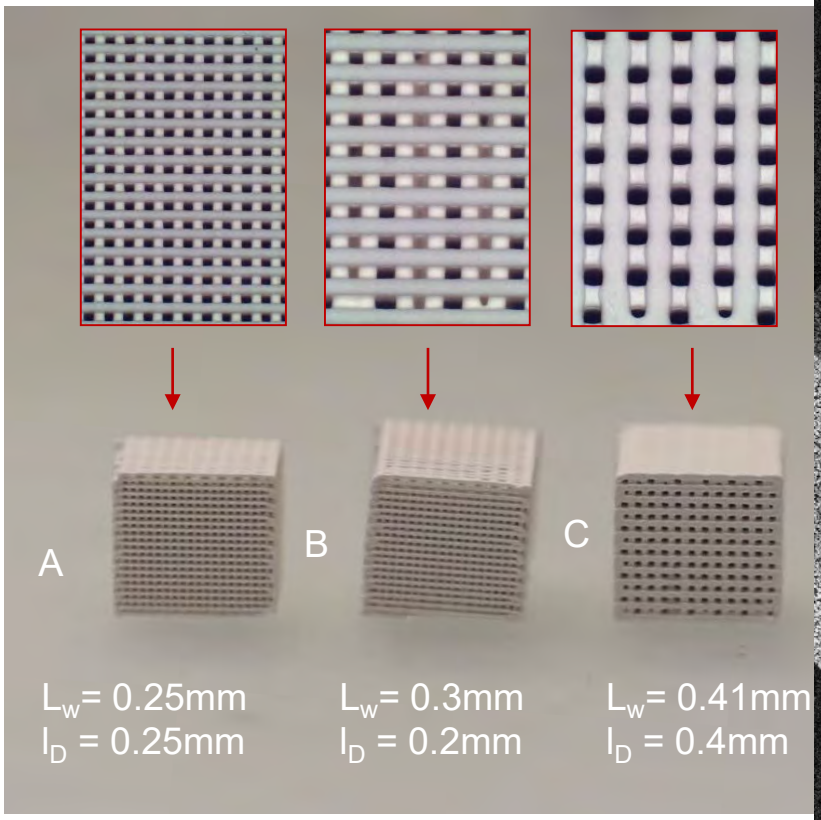
coupled heat and mass modeling- Empa

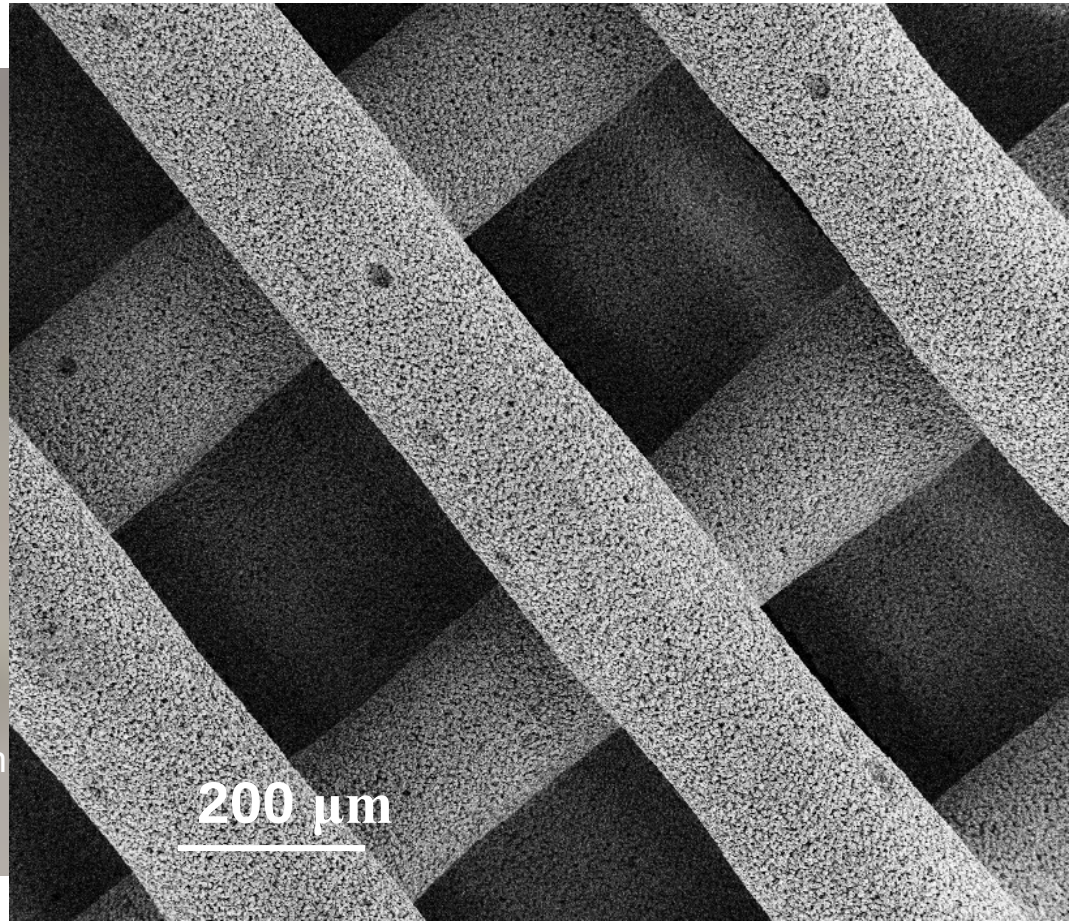




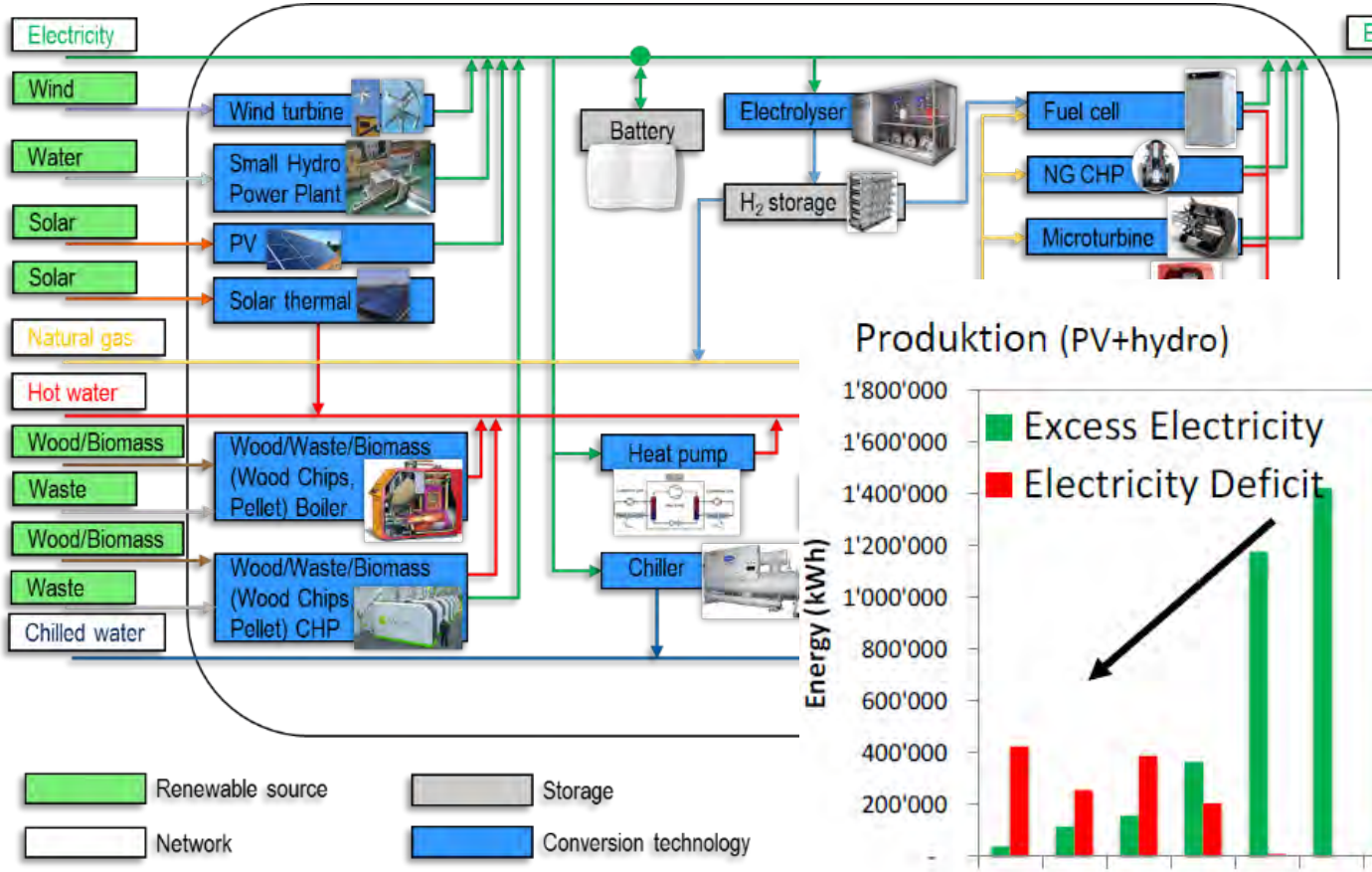
3D printed model adsorber structures

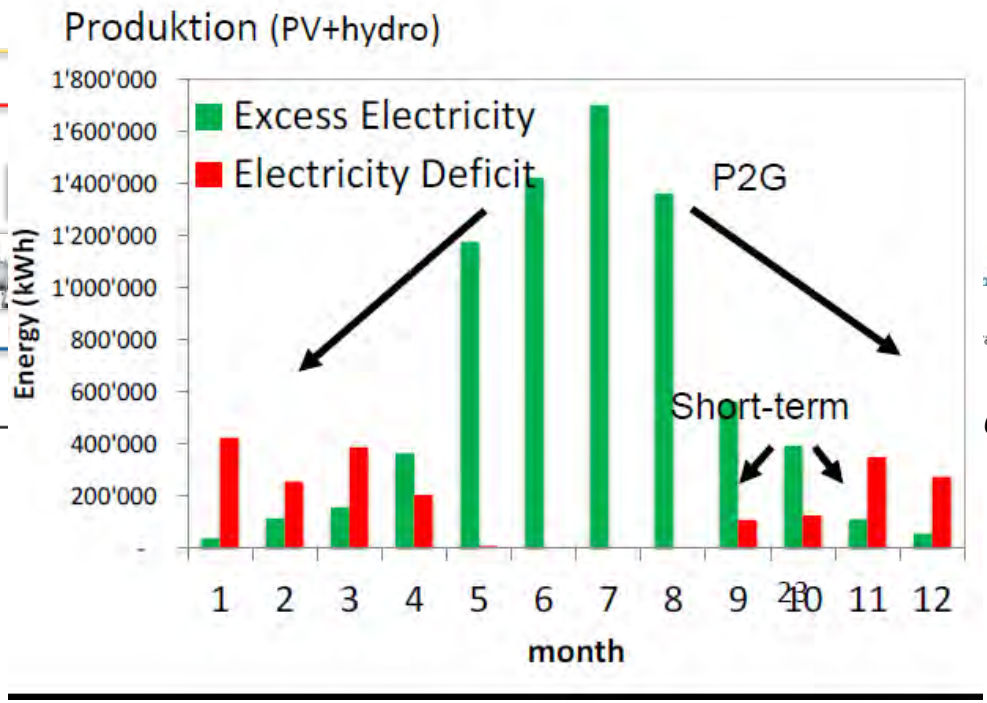
Investigation of sorption properties in respect to sample geometry
(pore size, wall thickness, interconnectivity)





Power-to-gas systems





Needs for material development

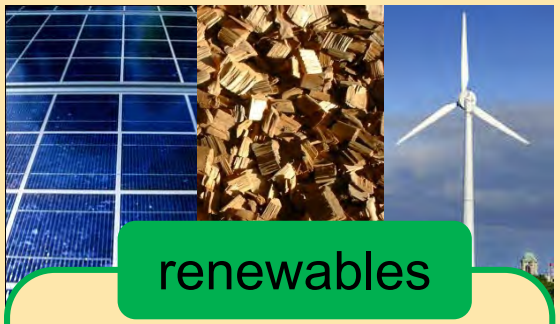
1. New highly insulation materials at low cost
2. Multi-functional ‘smart’ windows / new coatings
   → from niche to larger market pentration
3. Materials for Renewable energy generation at lower cost
4. Materials for higher energy efficieny and lower cost of integrated energy systems at urban scale

Approach of Urban Optimisation

Components

to be

Optimised

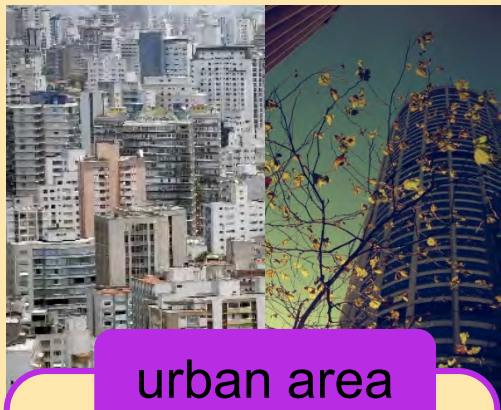


renewables

PV

wind

biomass



urban area

arrangement

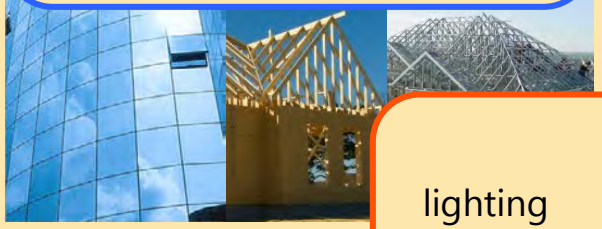
environment

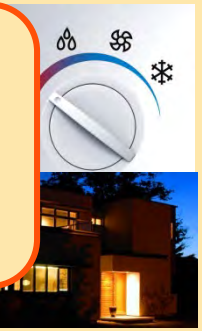
building fabric

form

materials

glazing





heating &
cooling

lighting

ventilation

building systems

district networks

co-generation

ground storage

energy systems

@ Empa NEST – a research facility

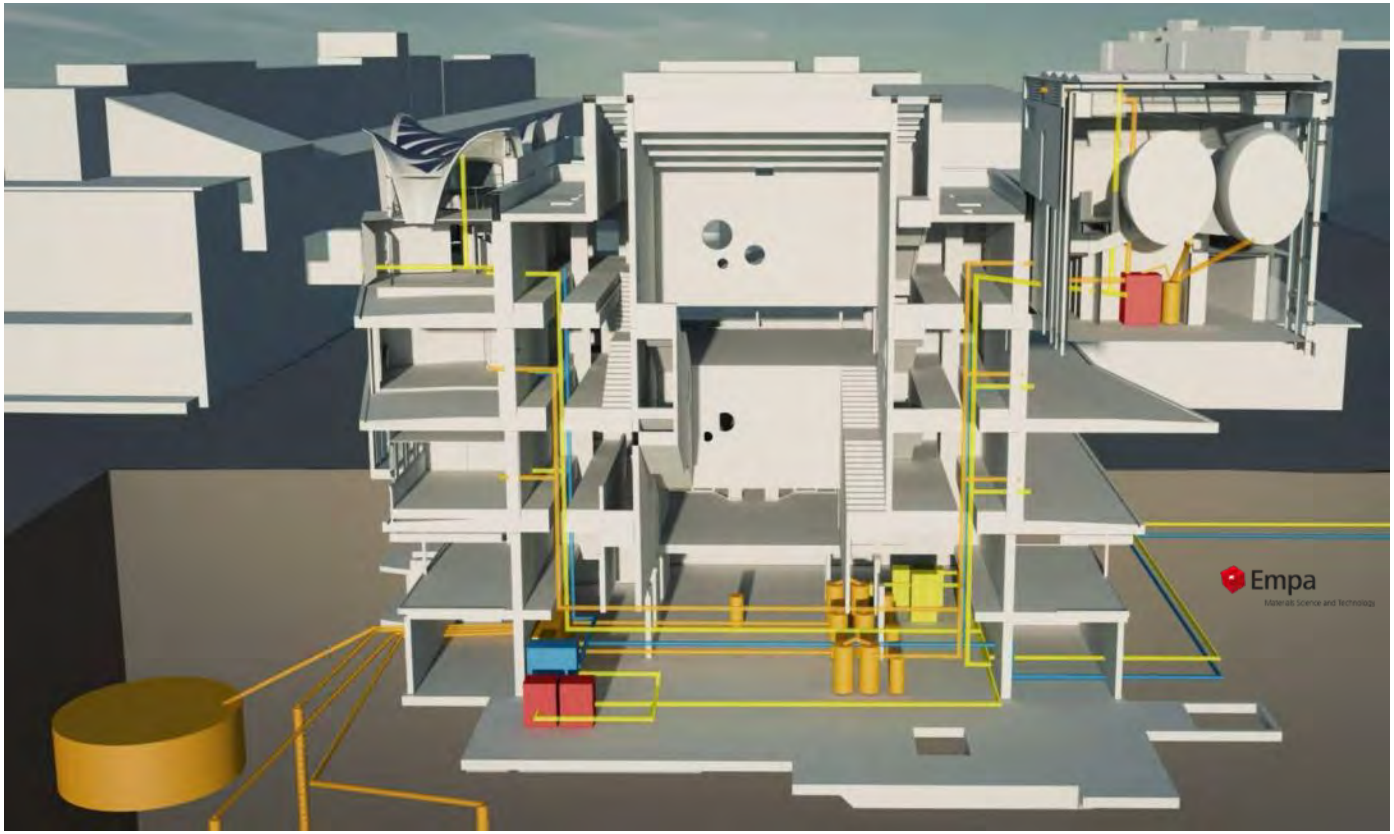
Backbone
Energy-hub

- Thermal networks
  and storage
- Gas grid

Micro-
Grid

Building as a vertical city quarter with different living units

@ Empa The Nest Energy-hub - a research facility



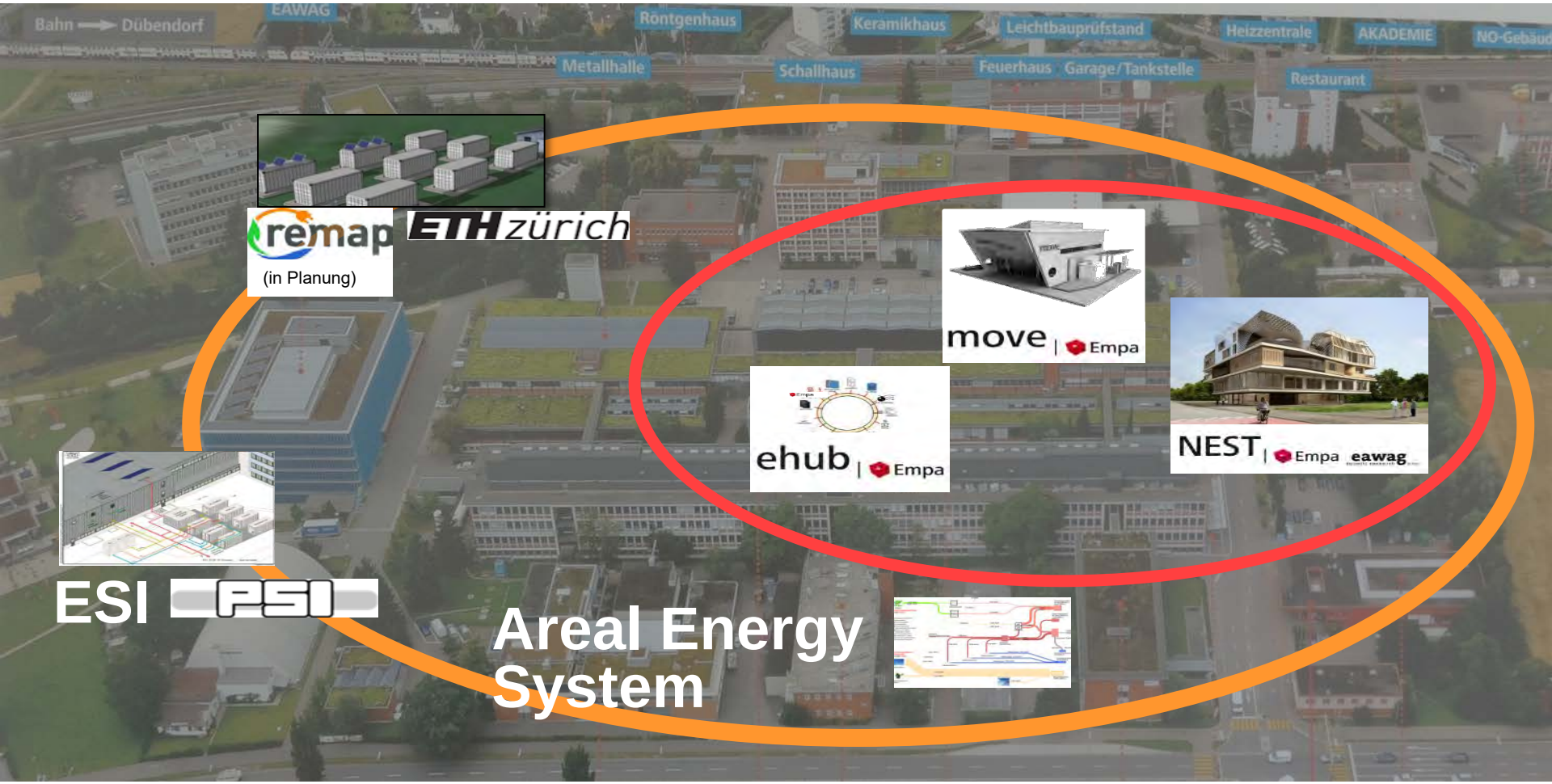
NEST

Move

Video see http://www.empa.ch/web/empa/energy-hub/

Integration of energy systems of different living units

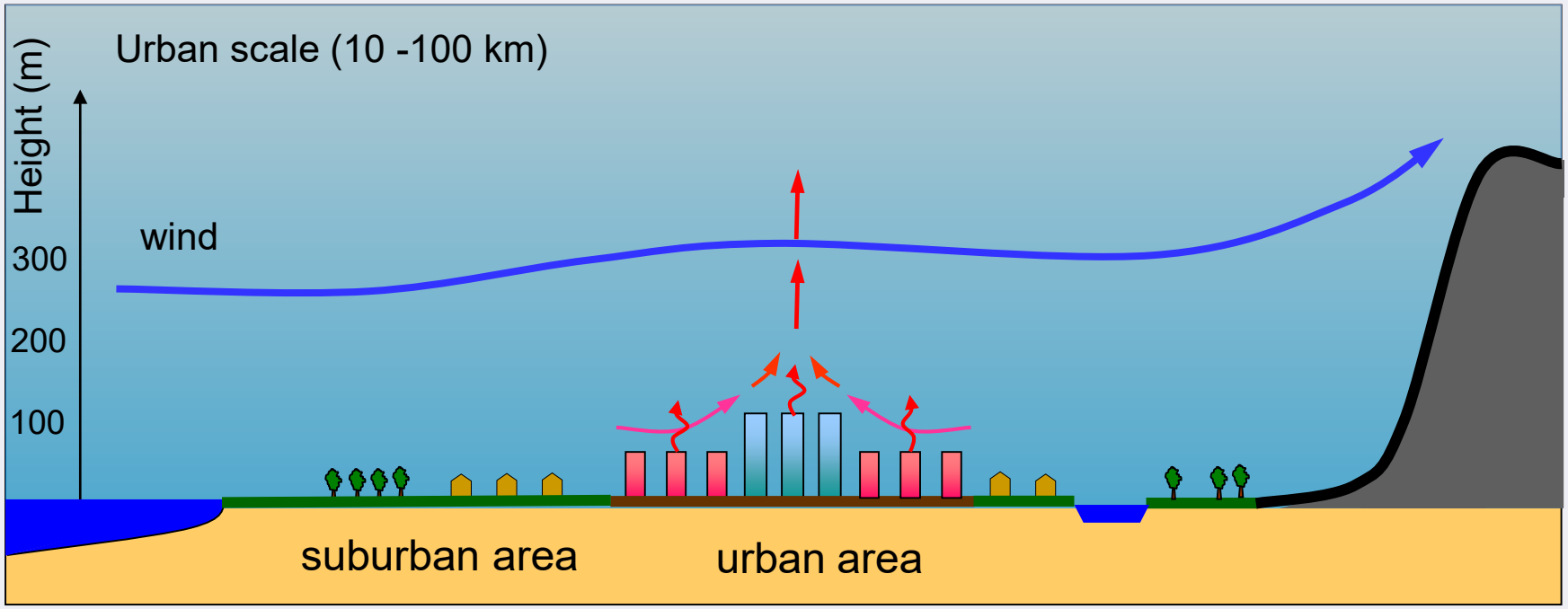
@ Empa The District Energy system



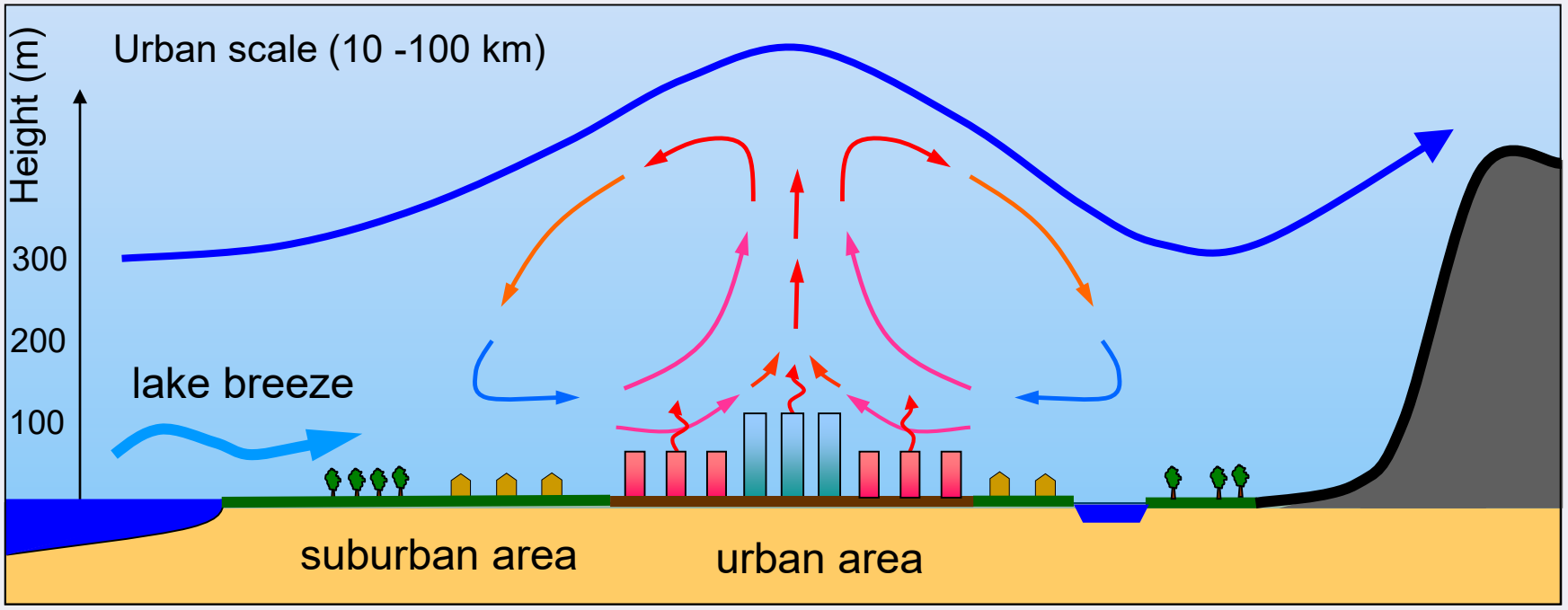
Integration of energy systems on different scales

The urban heat island effect and its mitigation

Physics of the Built Environment



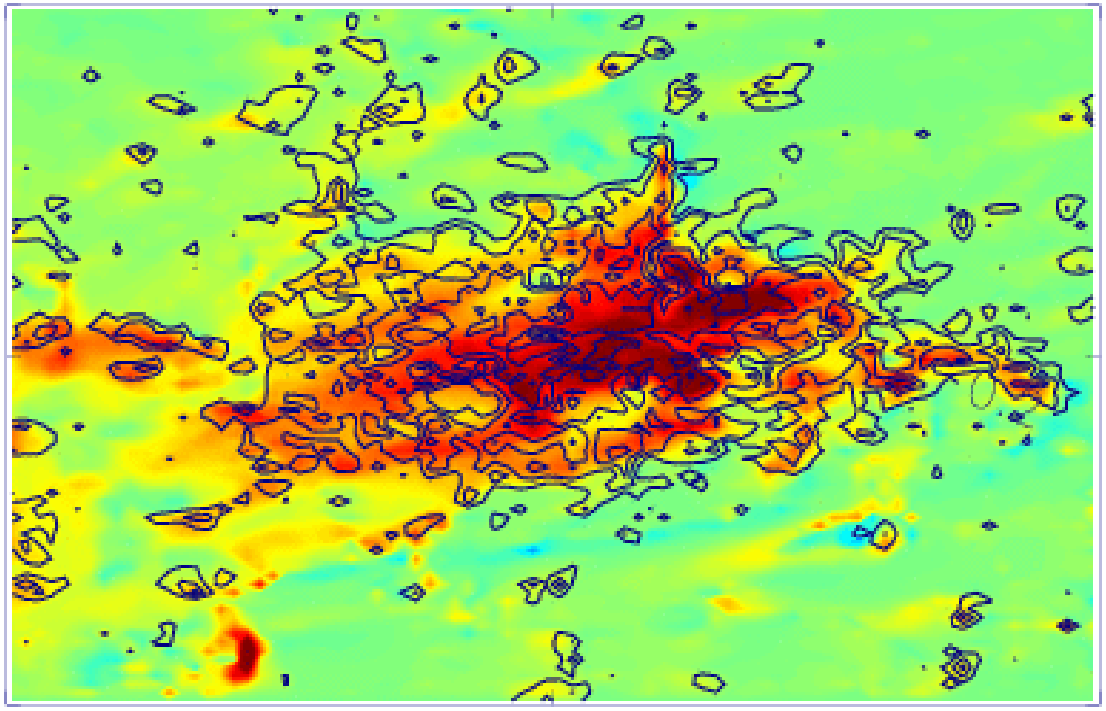
Physics of the Built Environment



Simulating Urban Heat Island - London

At 00Z on 7/ 5/2008,

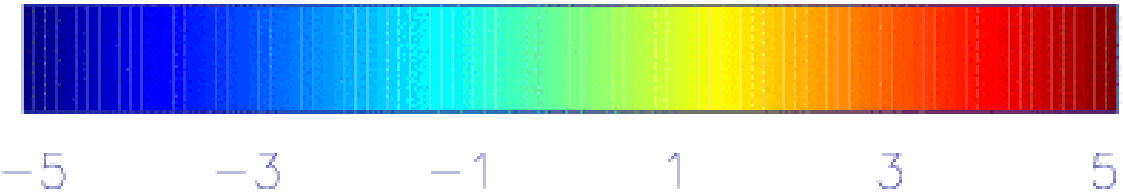
Temperature difference at 1.5m
"city" minus "no city"



Dr Sylvia Bohnenstengel

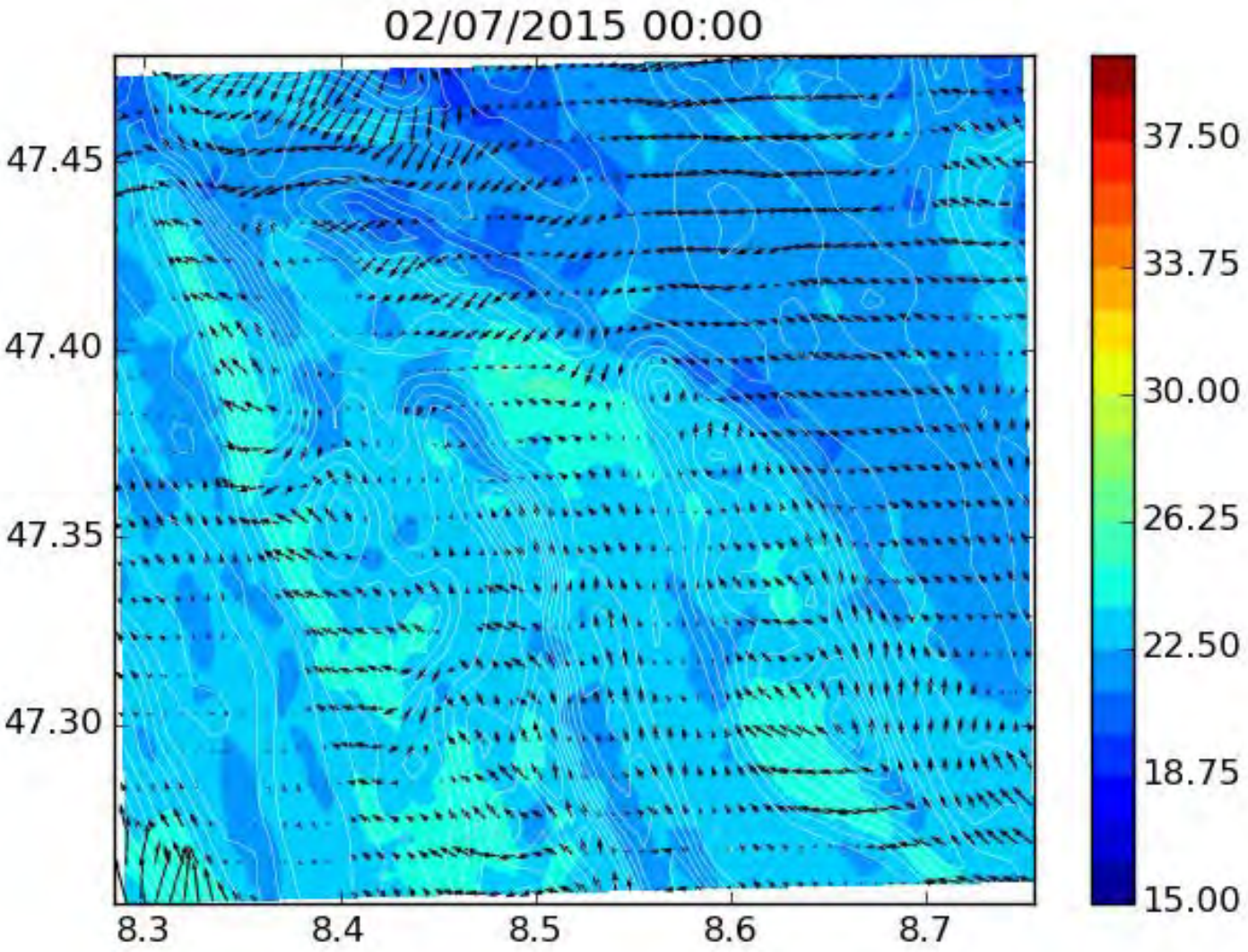
LUCID project

University of Reading



Modelling of urban climate on city scale: Zurich

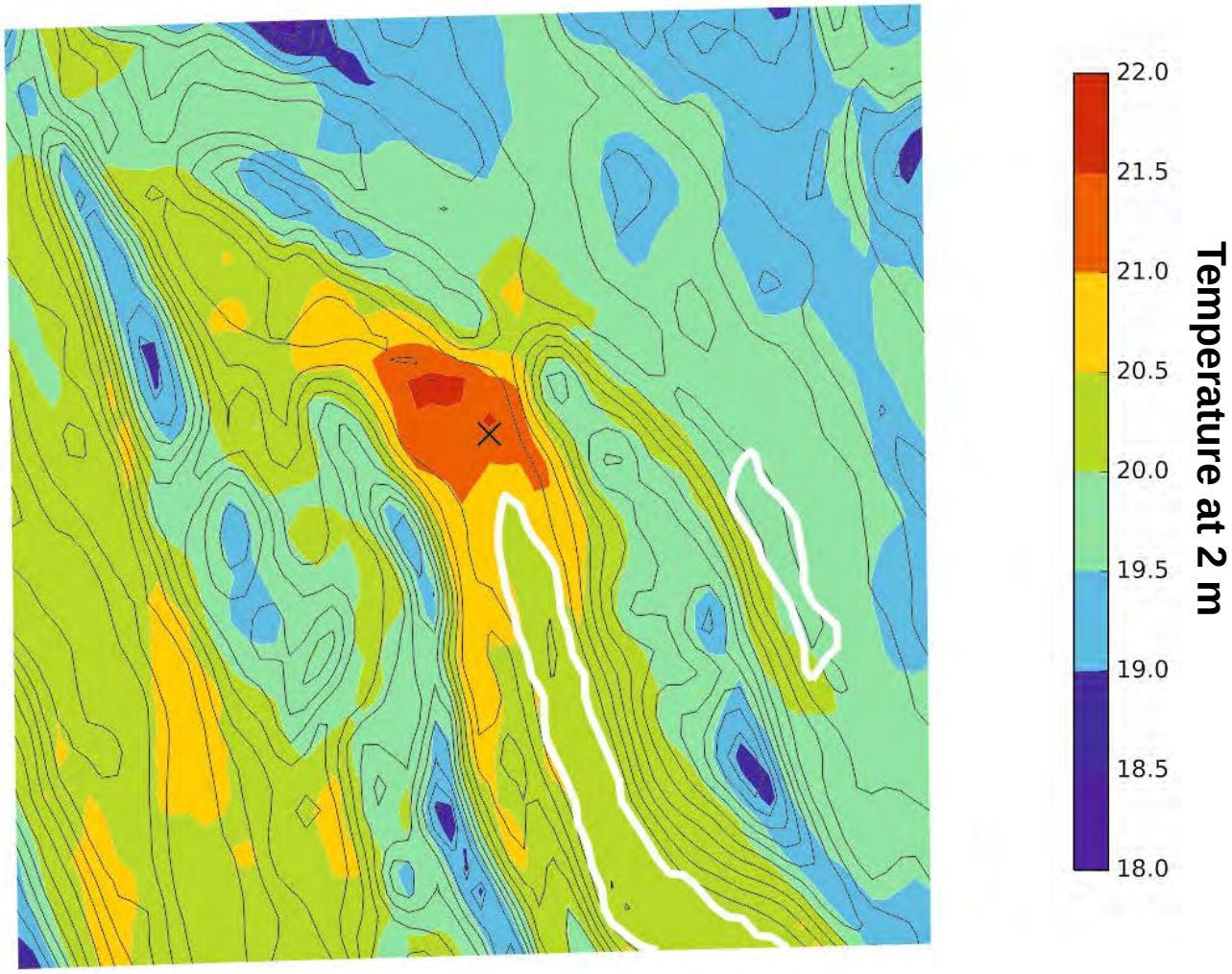
Air temperature at 2m



Gian Luca Mussetti

Modelling of urban climate on city scale: Zurich

Air temperature at 2m



Time = 00 UTC, period averaged

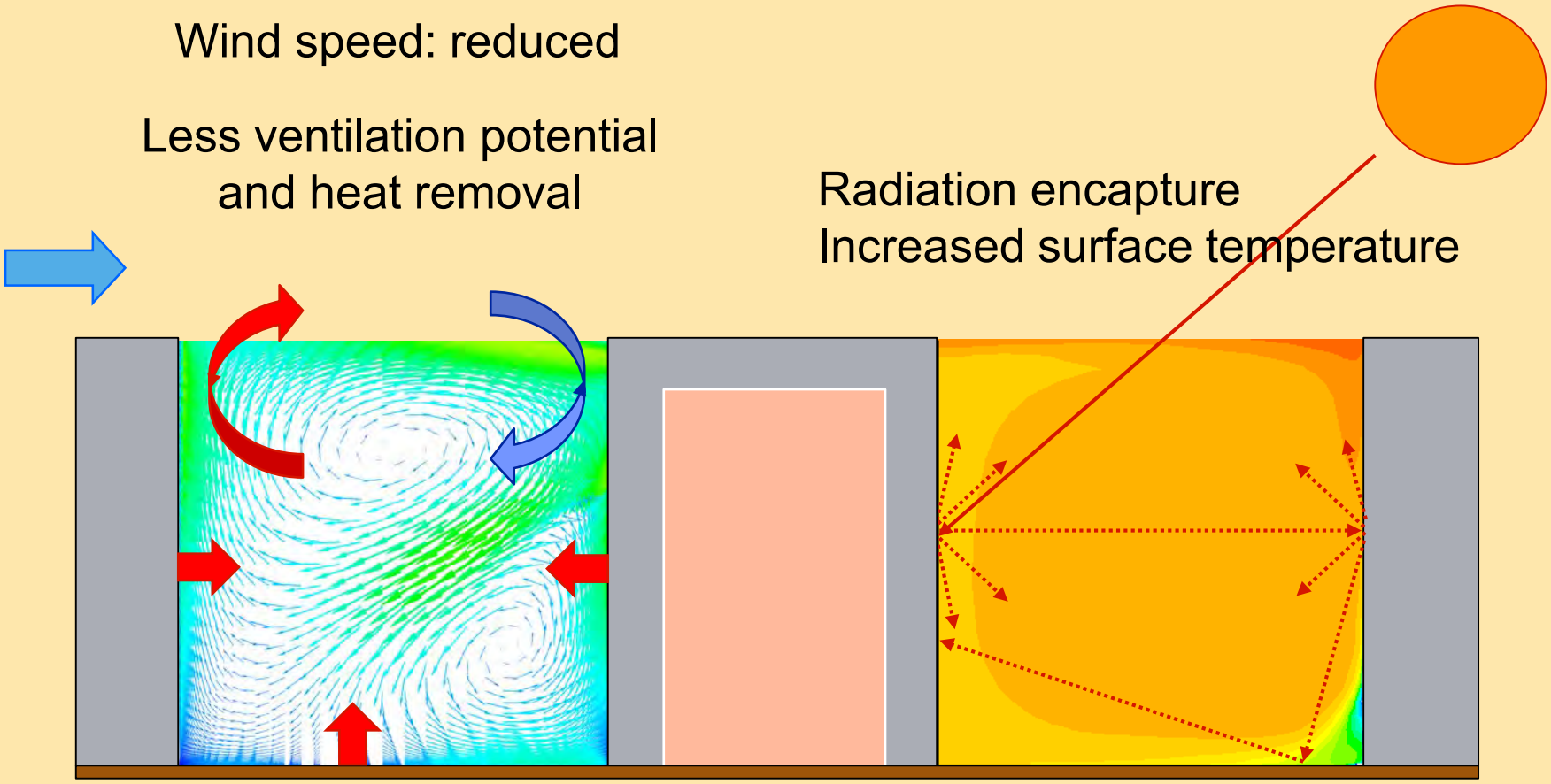
Gian Luca Mussetti

Physics at street canyon scale

Wind speed: reduced

Less ventilation potential
and heat removal

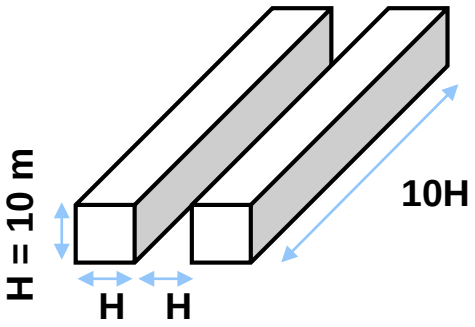
Radiation encapture
Increased surface temperature



Lower convective heat
transfer coefficients

Increased air temperatures
Buoyancy driven ventilation

Buoyancy is an important heat removal mechanism at low wind speed



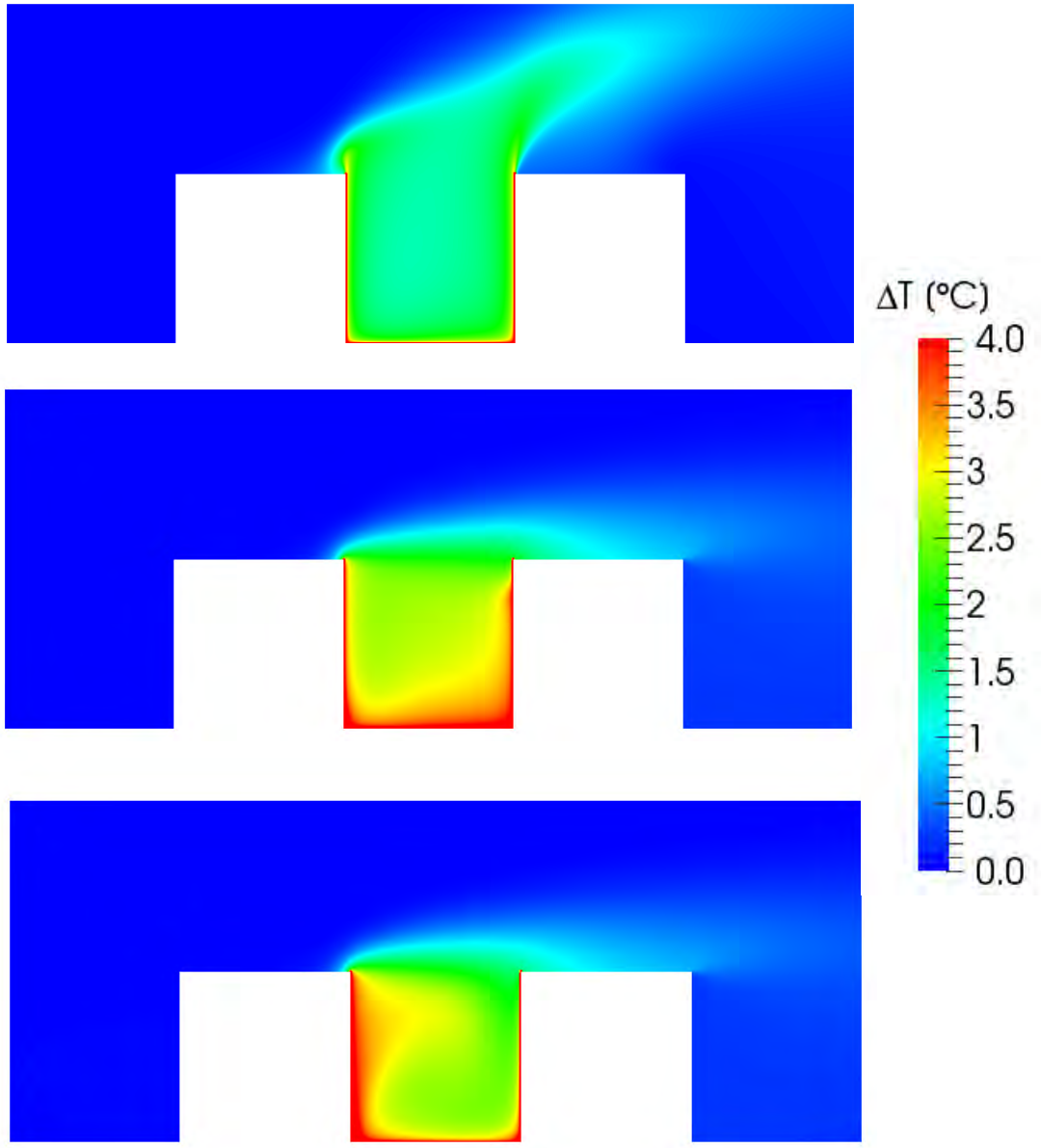
Richardson number:

$$Ri = \frac{g\beta(T_w - T_0)h}{U^2}$$

U_{ref} = 1 m/s
Ri = 4.9
wind

U_{ref} = 5 m/s
Ri = 0.2
wind

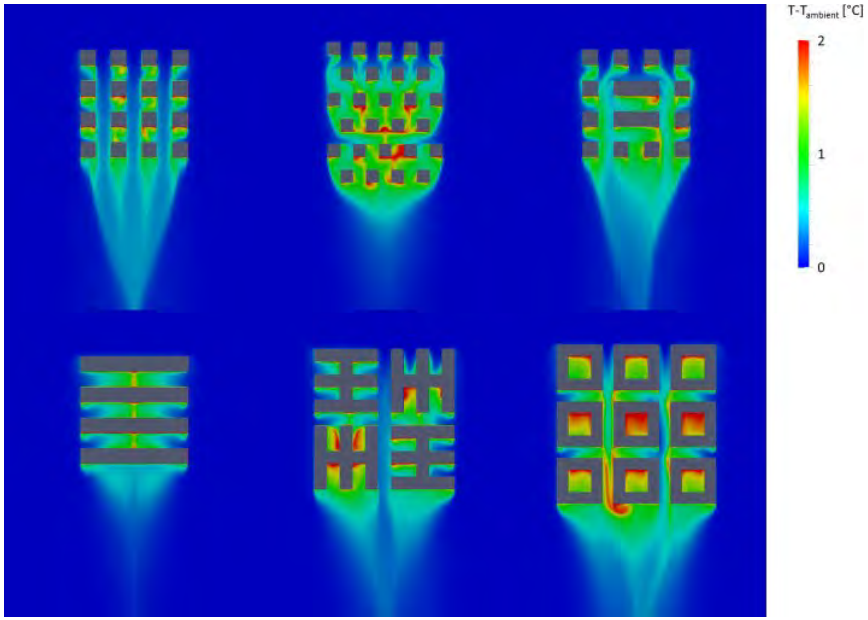
U_{ref} = 10 m/s
Ri = 0.05
wind



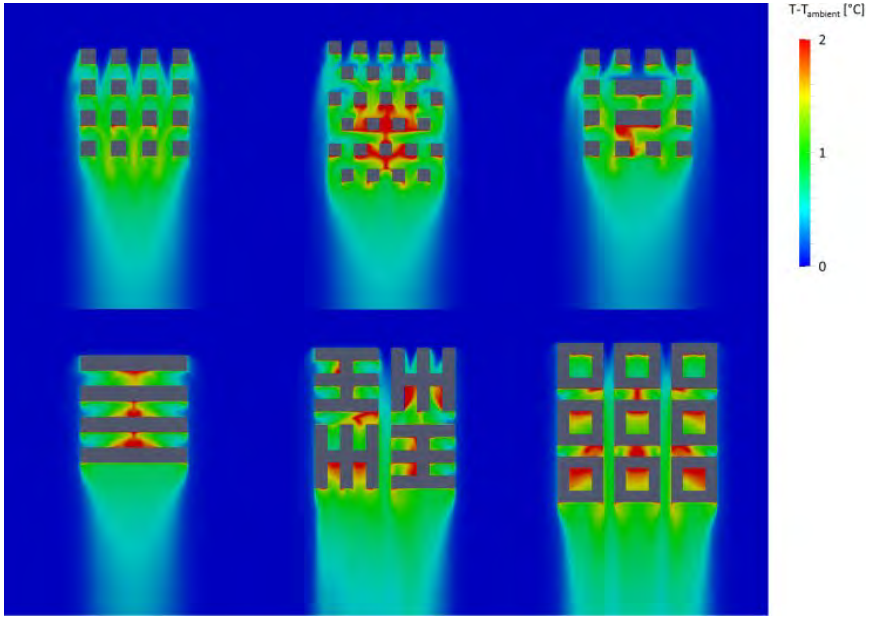
Local heat island (hot spots) appears at street canyon scale

temperature difference between the local air temperature and the ambient air temperature at 1.75m height

U_{10}=1 m/s



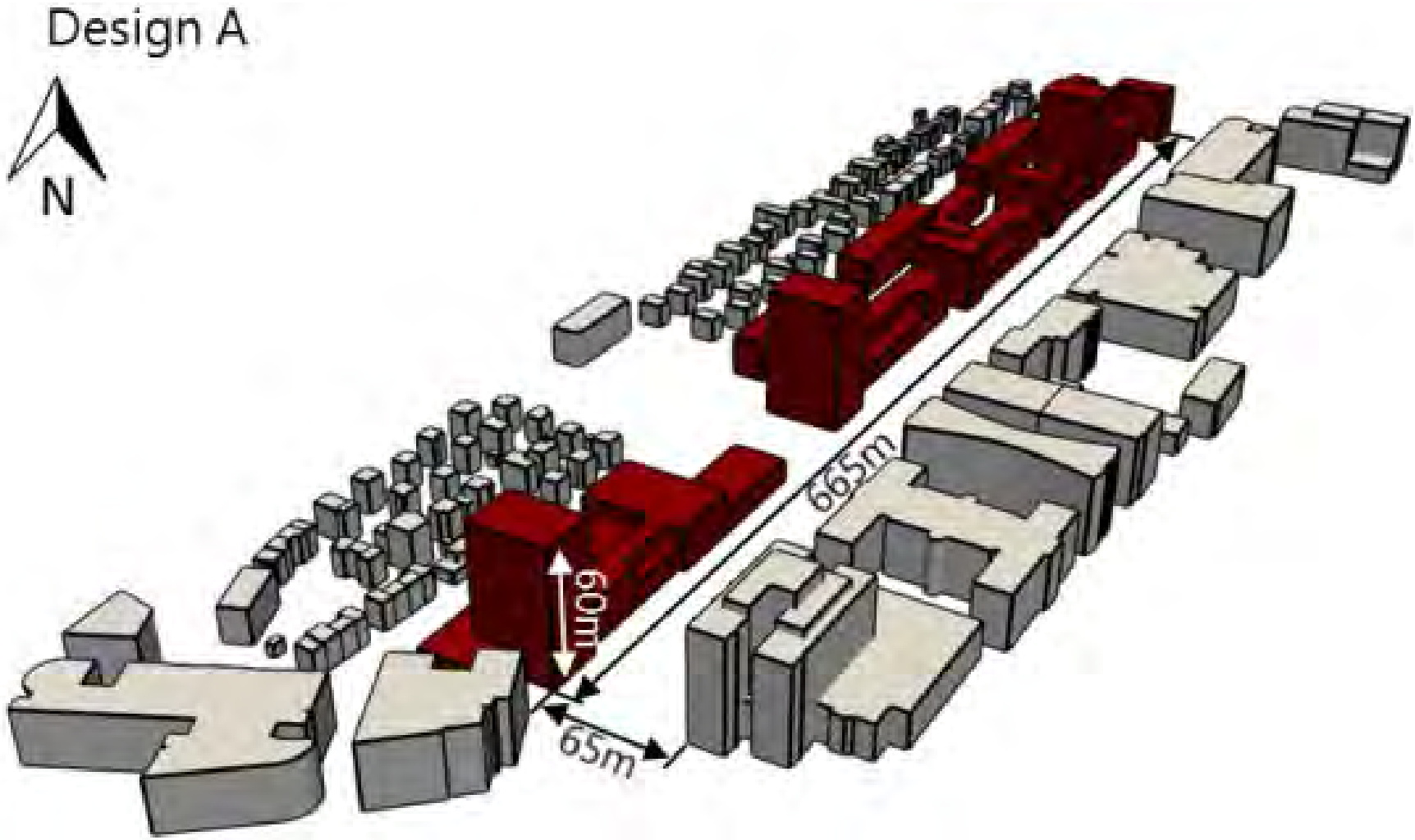
U_{10}=5.5 m/s



For low wind speeds, more hot air can leave the street canyons through the shear layer due to stronger buoyancy effects.

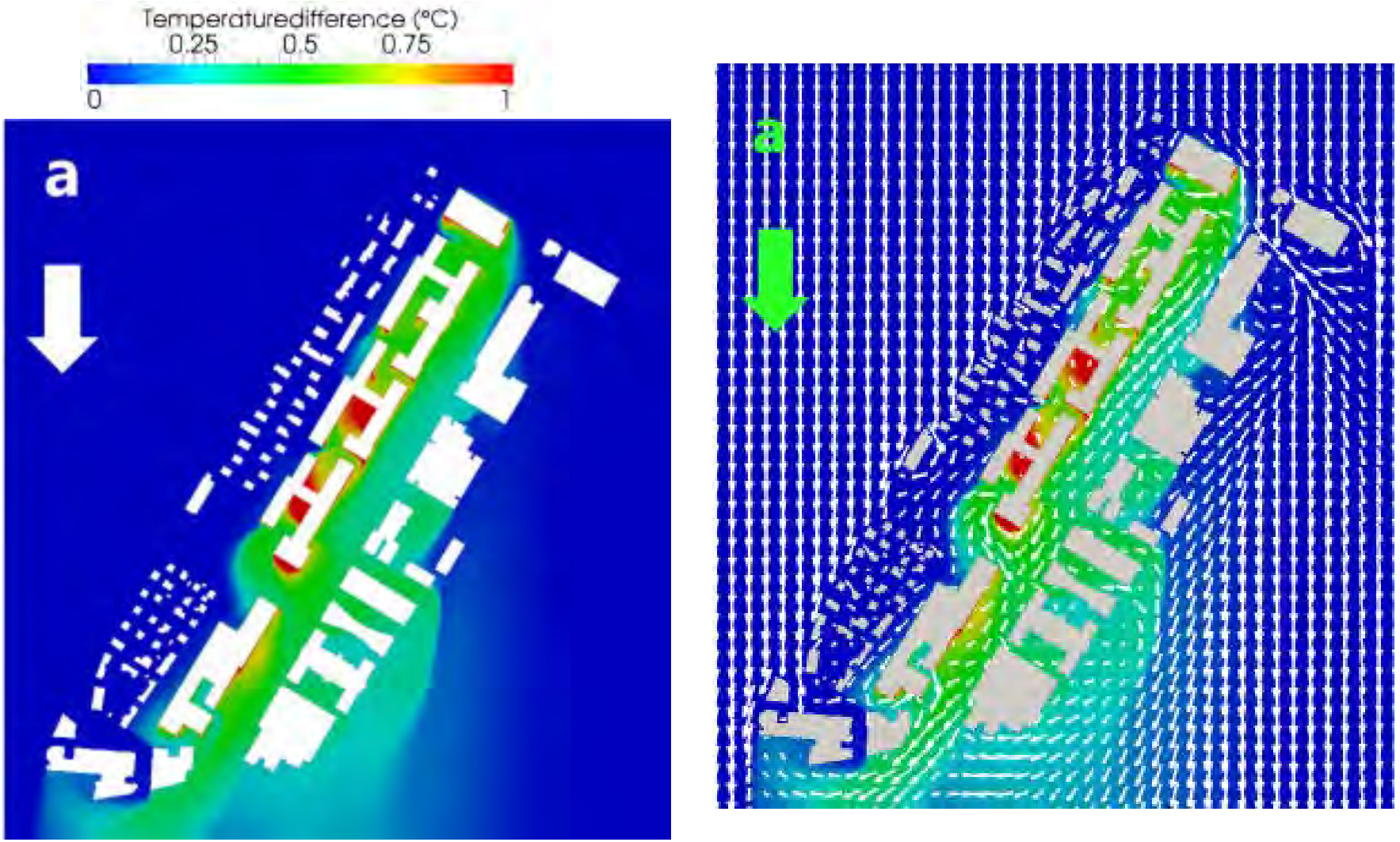
Local heat island (hot spots) appears at street canyon scale

Case study of densification in Zurich



Local heat island (hot spots) appears at street canyon scale

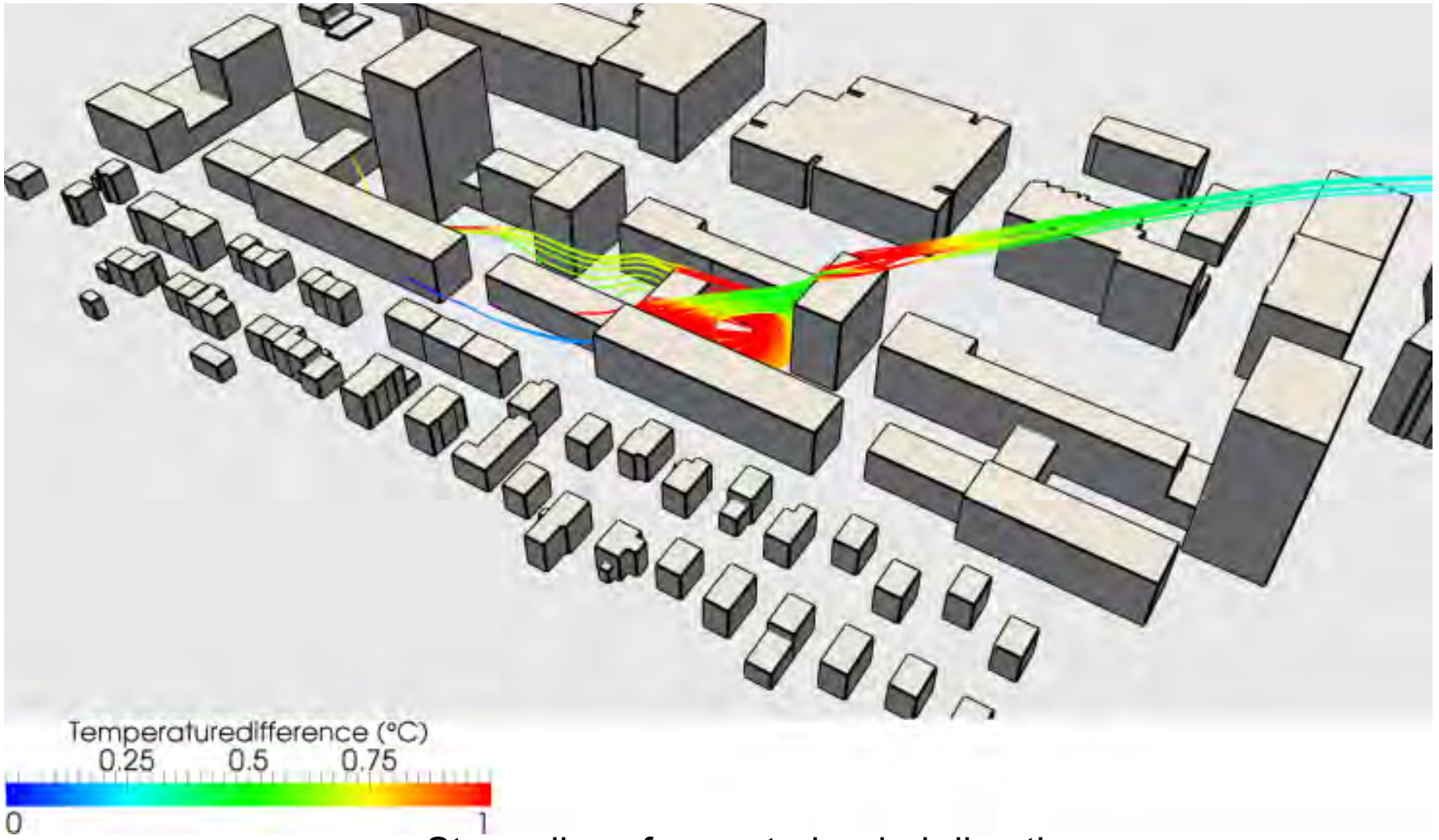
Case study of densification in Zurich



temperature difference between the local and ambient air temperature

Local heat island (hot spots) appears at street canyon scale

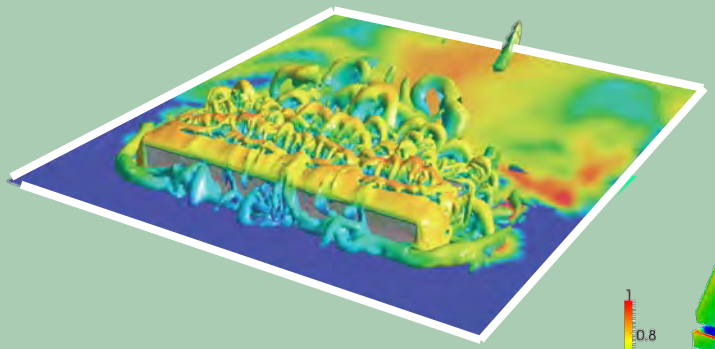
Case study of densification in Zurich



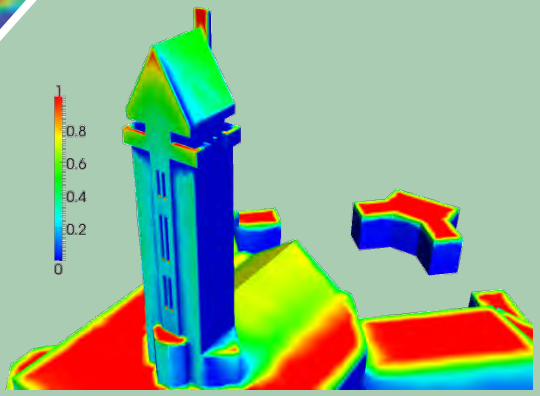
Streamlines for westerly wind direction

Temperature difference between the local and ambient air temperature

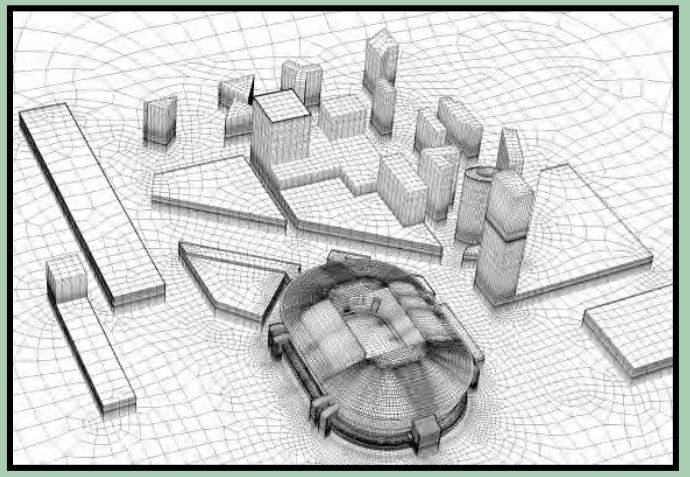
Urban flow modeling



Turbulent flow in street canyon



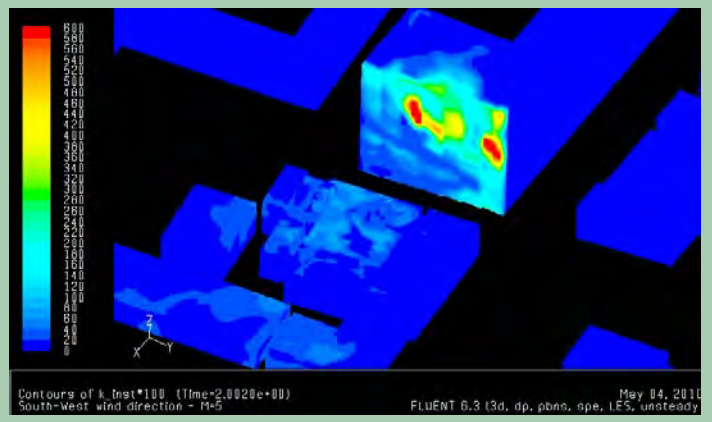
Driving rain on historical building



CFD grid of Amsterdam Arena extension

Urban Wind tunnel ETHZ/EMPA

HIGRAD (collaboration
Los Alamos National Laboratory)

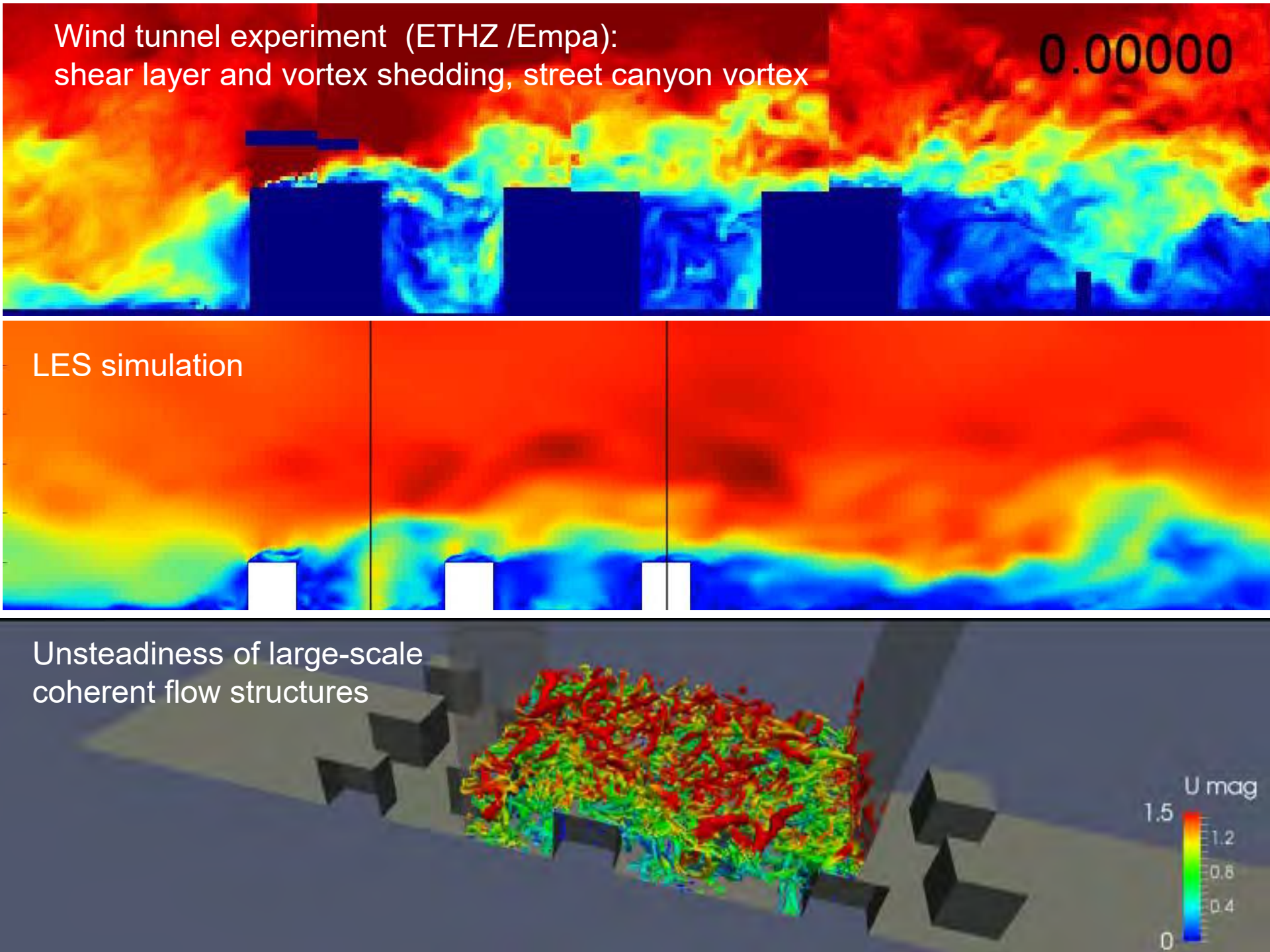


Pollutant gas dispersion in downtown Montreal

Study of urban flow in ETHZ / Empa wind tunnel

Time Resolved Stereo-Particle Image Velocimetry System

Processing Cluster (40 cores)


Wind tunnel experiment (ETHZ /Empa):
shear layer and vortex shedding, street canyon vortex
0.00000
LES simulation
Unsteadiness of large-scale
coherent flow structures
U mag
1.5
1.2
0.8
0.4
0

The urban heat island effect

Mitigation measures
for heat waves

Evaluation of urban thermal comfort

Universal Thermal Climate Index (UTCI)

Equivalent ambient temperature of a reference environment providing the same physiological responses of a reference environment

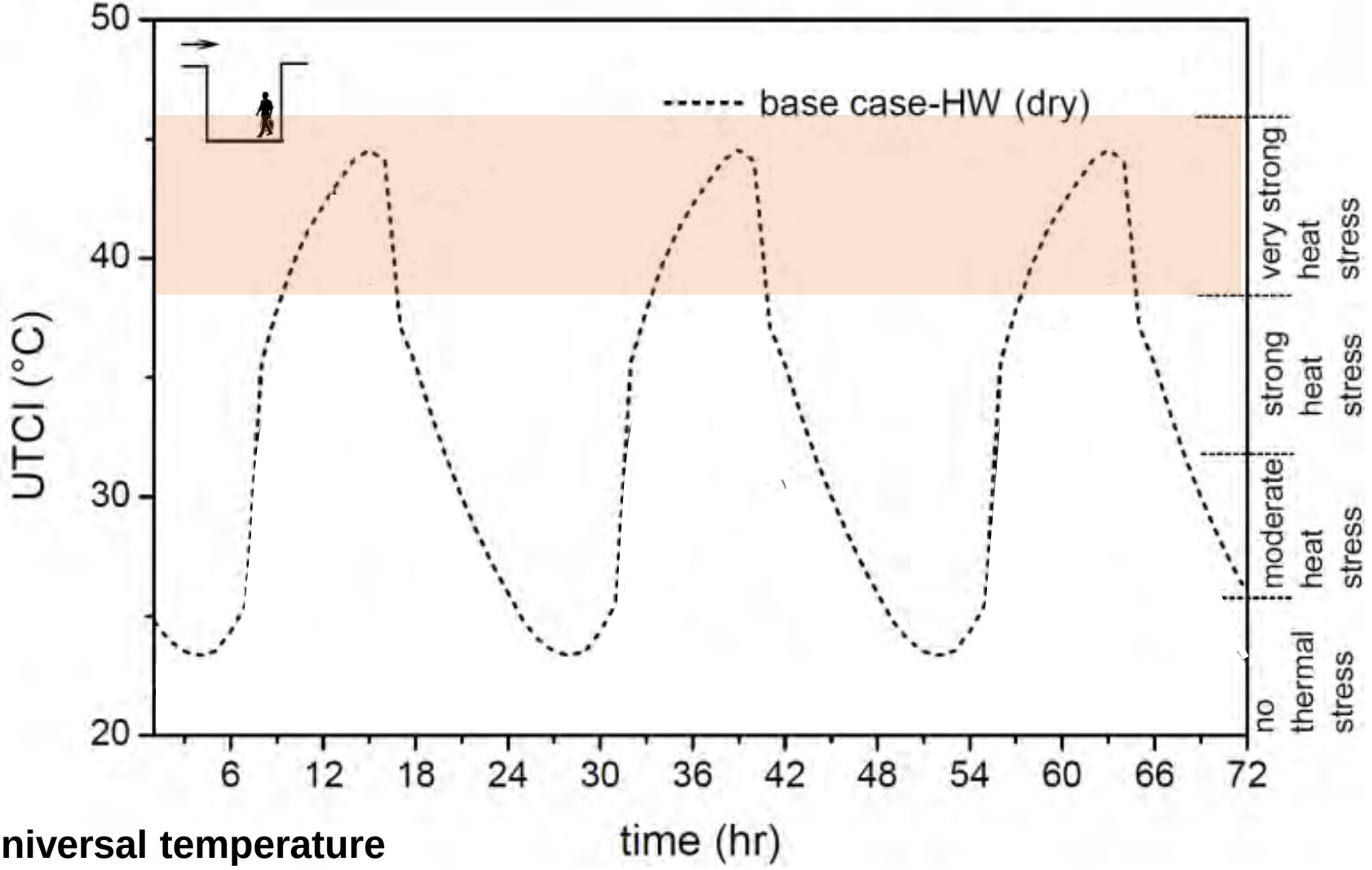
- ❑ air temperature
- ❑ mean radiant temperature
- ❑ relative humidity
- ❑ wind speed
- ❑ clothing
- ❑ activity

$$T_{mrt} = \left[T_{umrt}^{\ 4} + \frac{f_p \, \alpha_p \, I_{dir}}{\varepsilon_p \sigma} \right]^{0.25}$$

Surface temperatures of environment radiating to the person

Direct solar radiation on person

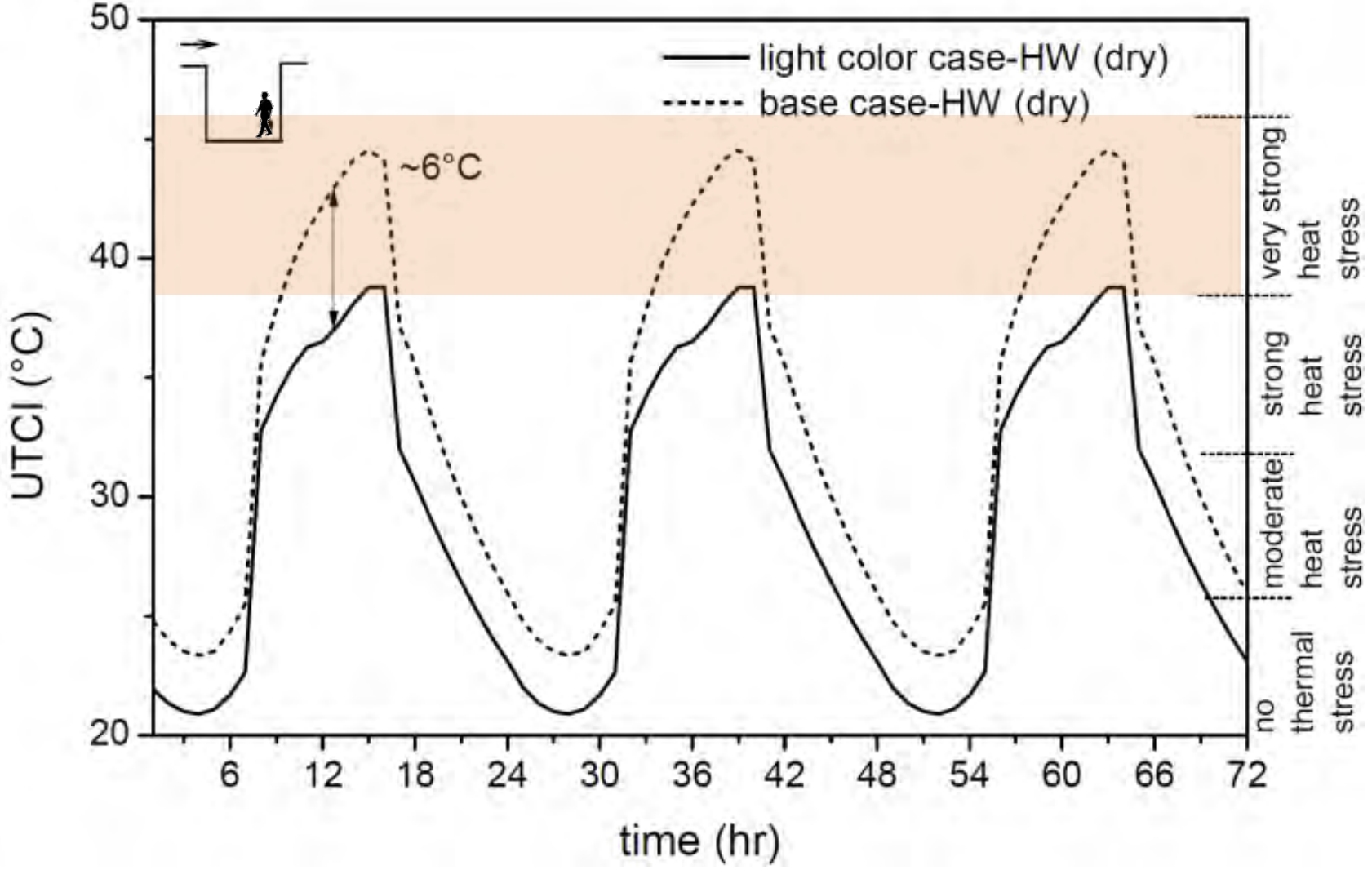
Heat wave (Zurich 2003)



Universal temperature comfort index

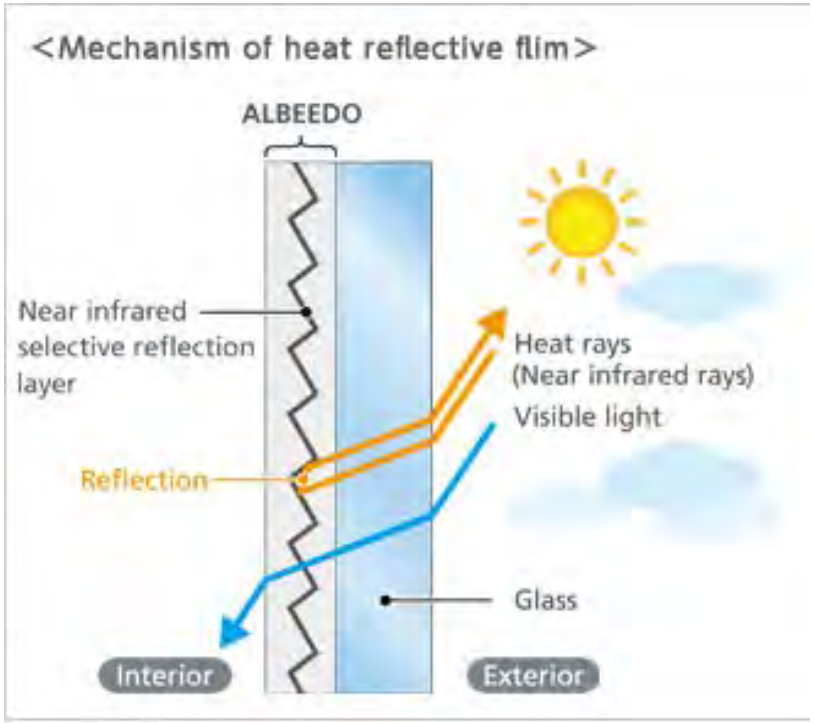
Materials with high albedo value

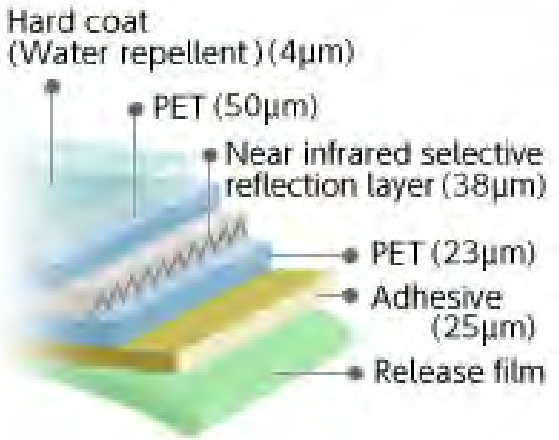
Heat wave : white colors

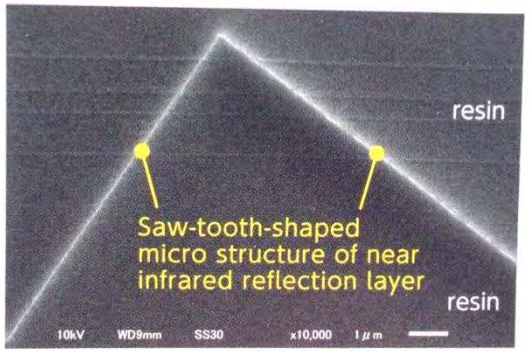


Heat reflective film

Heat reflective film improving thermal environment of both inside the building and the street by reflecting heat rays upward (ALBEEDOTM)





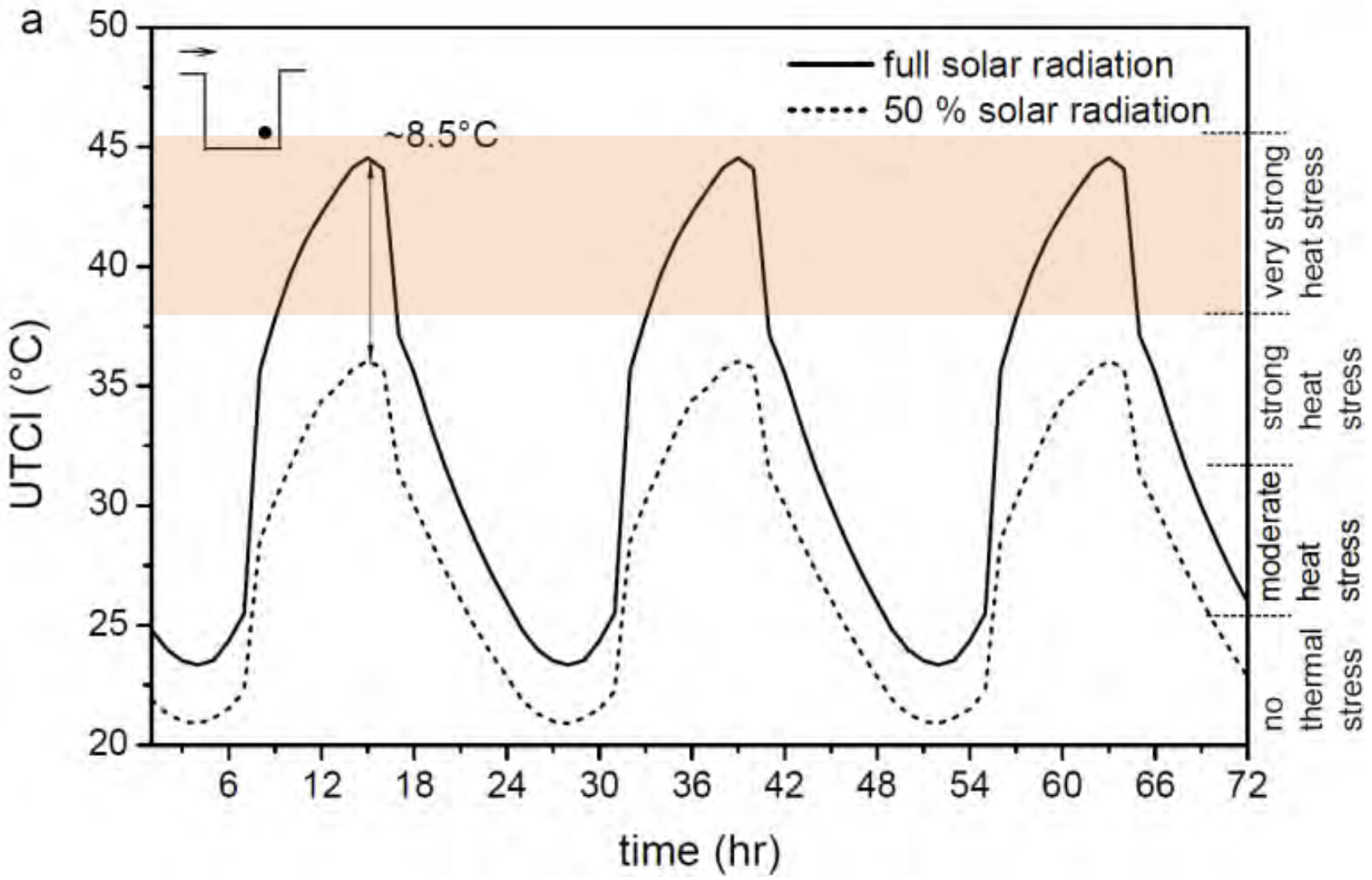


Cross sectional image of saw-tooth-shaped edge (SEM)
The corner radius is about R0.2μm.

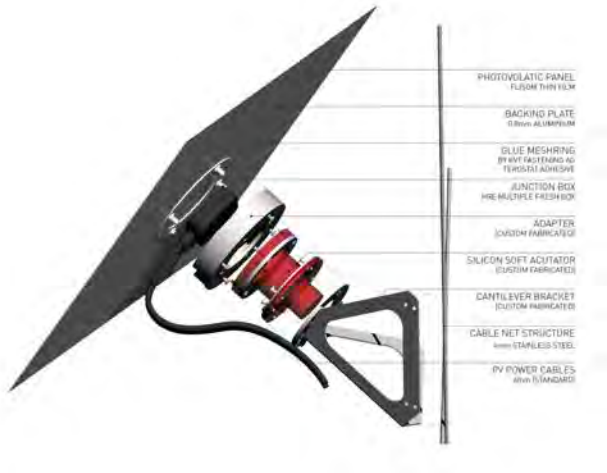
Films interposed between glass layers of the facades to increase the heat-shielding efficiency and decreasing transmissivity in the NIR range. These films generate a retro reflection of the solar radiation back to the sky, instead to the street level, decreasing the overheating effect on the surroundings.

Shadowing

Heat wave : 50 % shadowing



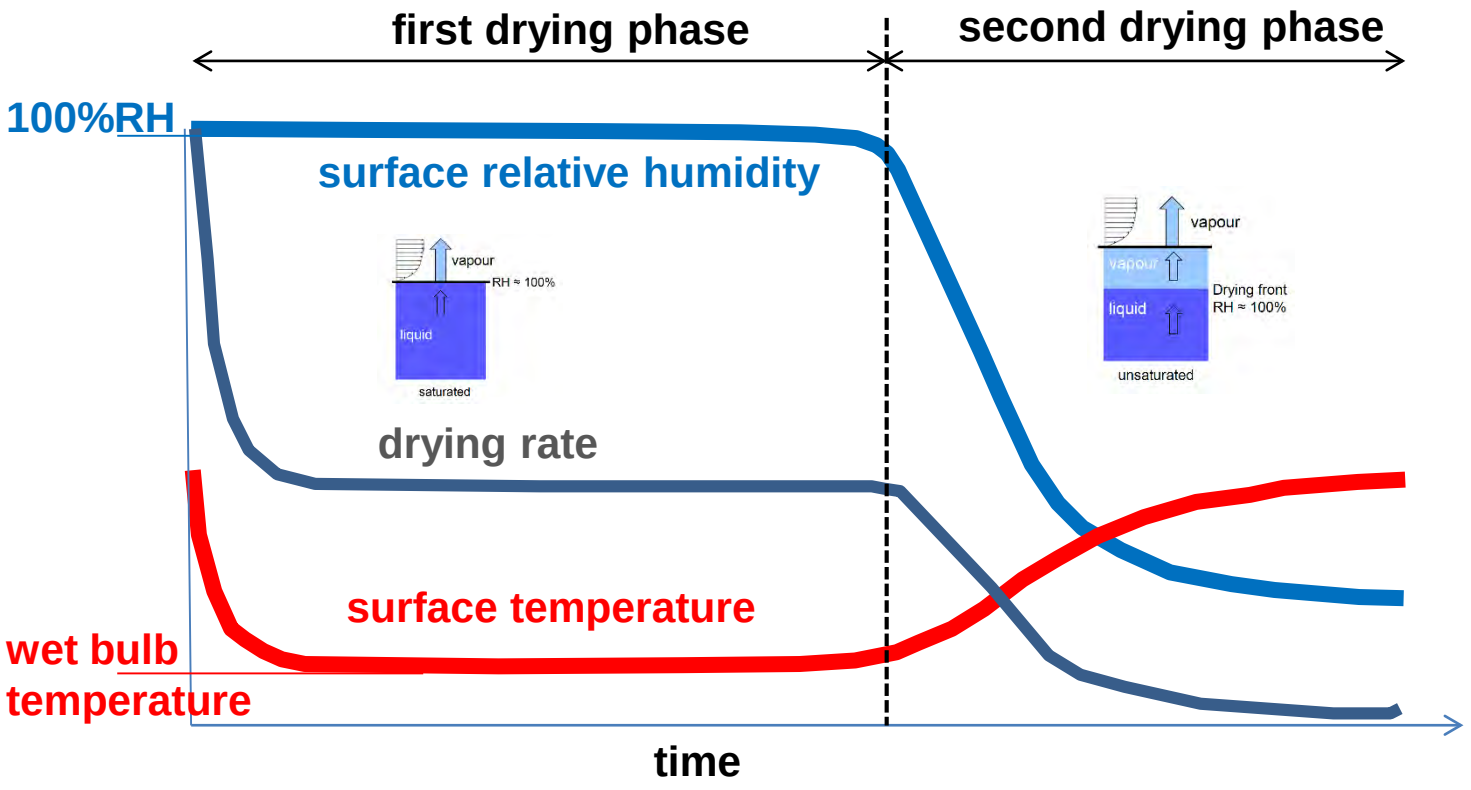
Adaptive solar facades (A. Schlueter, ETHZ)



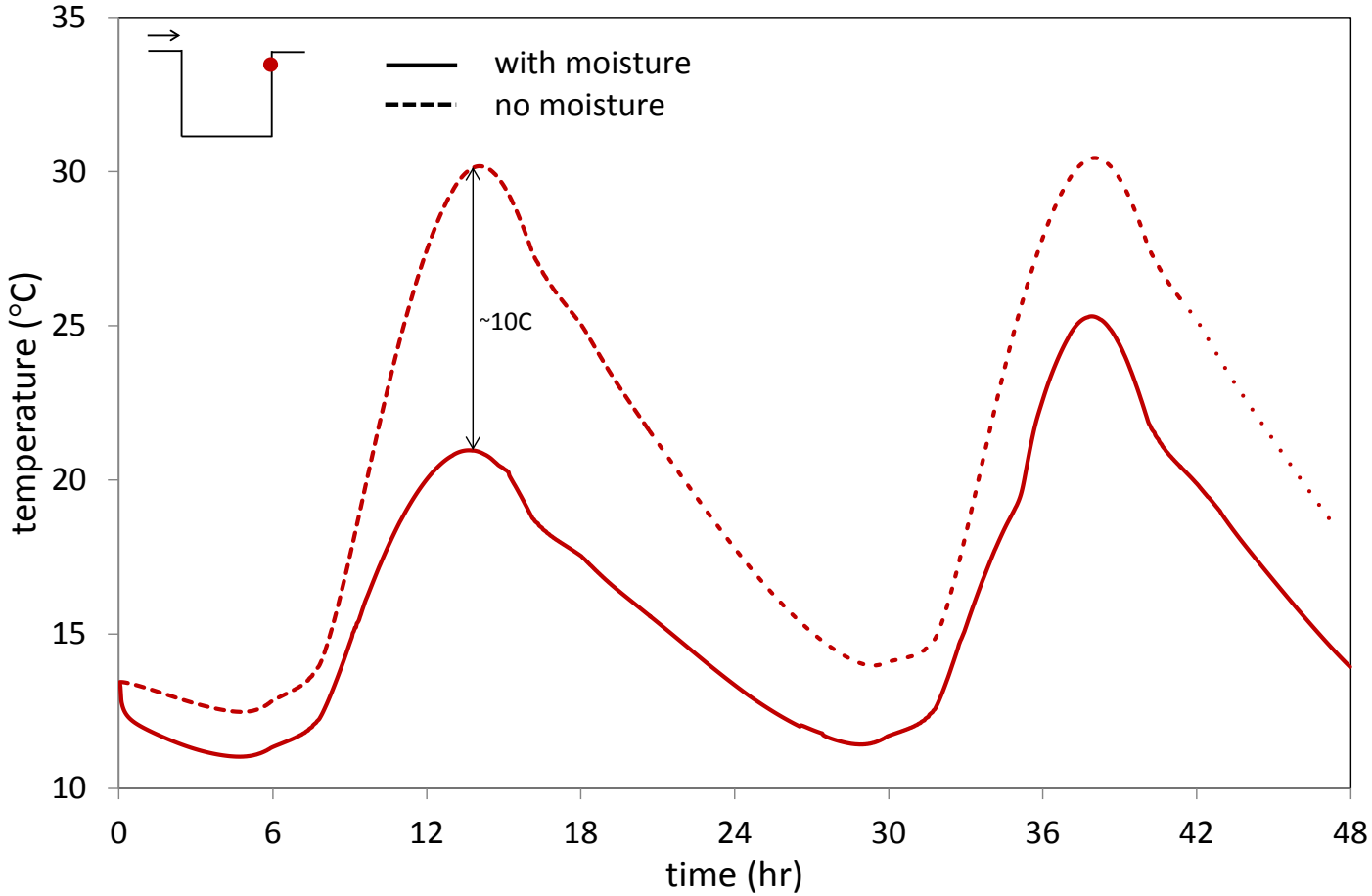
Heat wave : evaporative cooling

Evaporative cooling – drying of materials

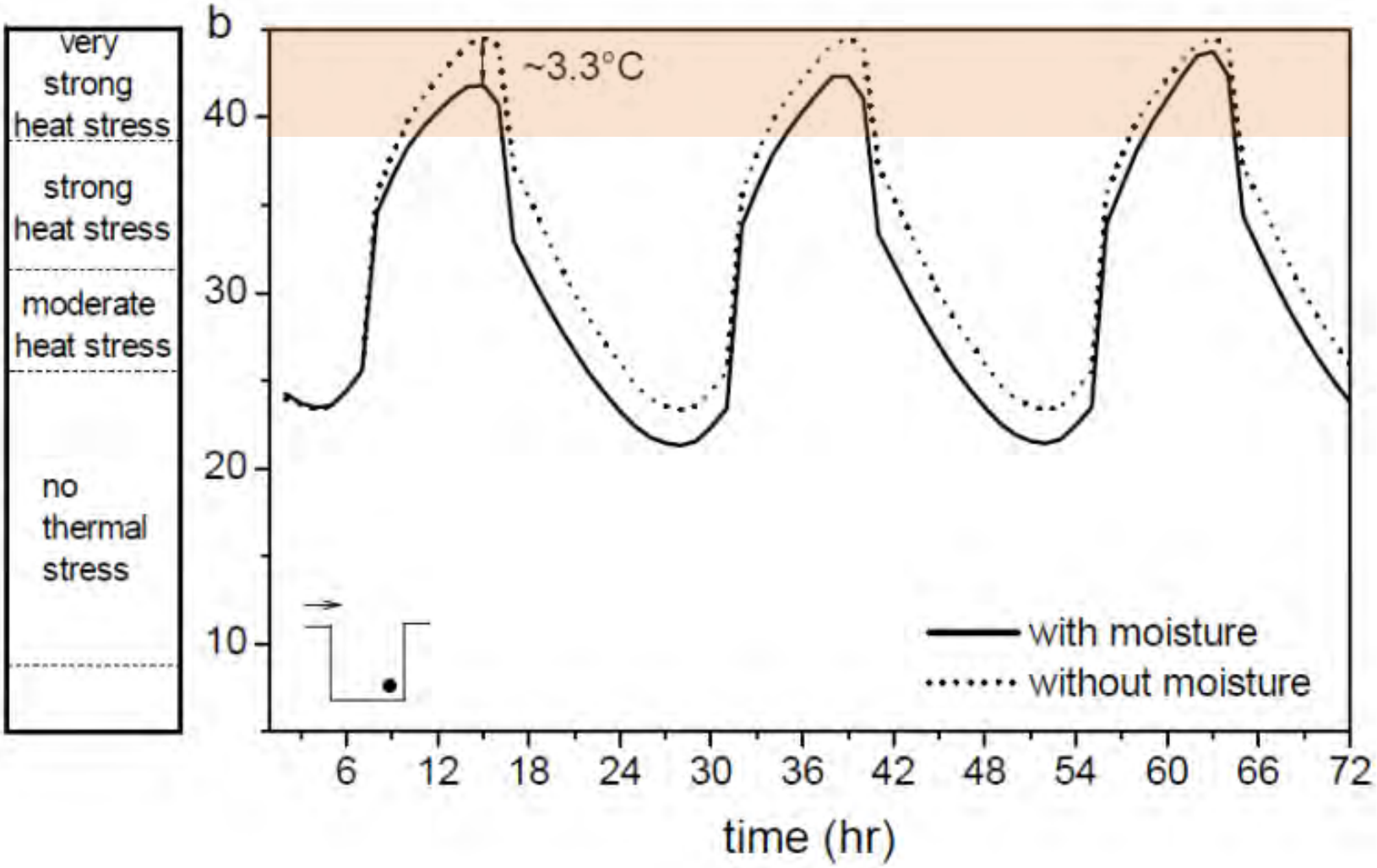
$L_v = 2.5 \times 10^6$ J/kg



Surface temperature: cooling of evaporating wall

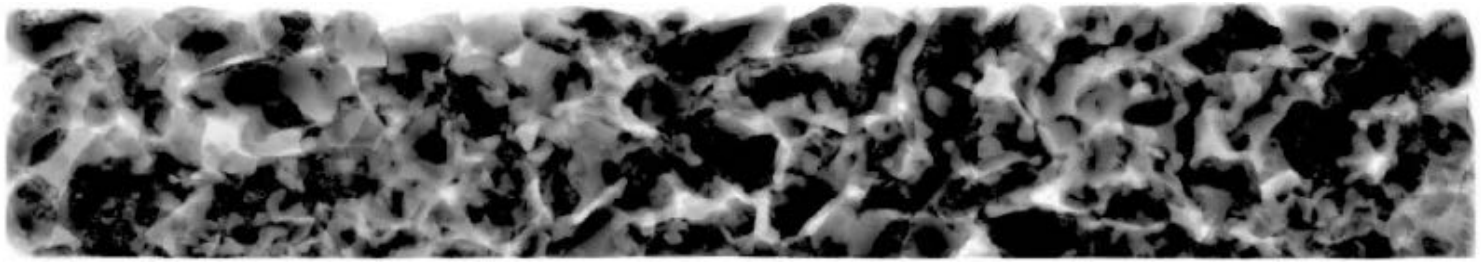


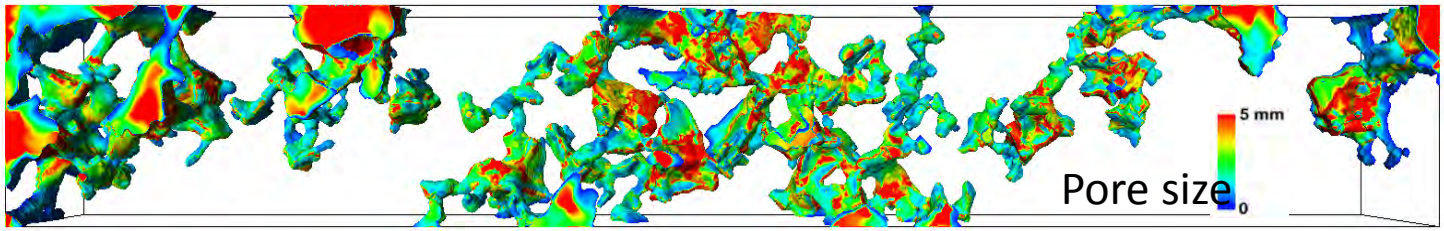
Heat wave : evaporative cooling



Saneinejad et al., 2013

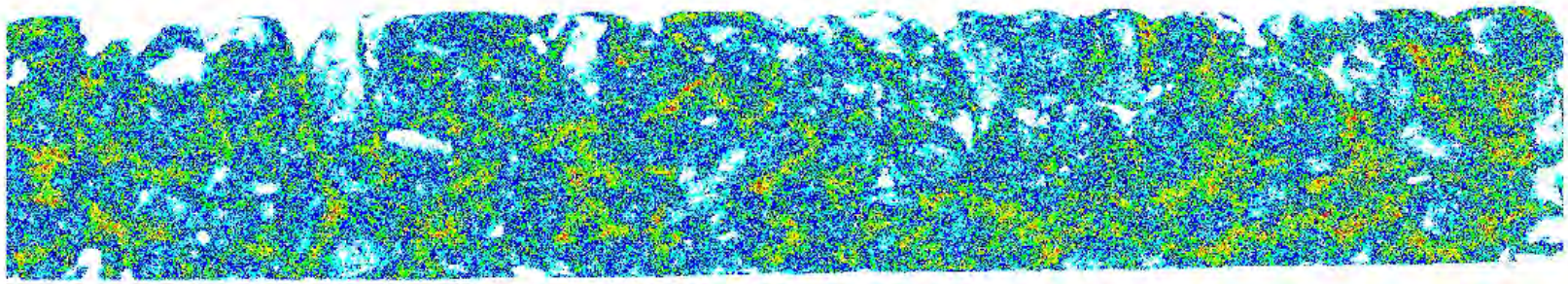
Evaporative cooling of porous asphalt (Improved water drainage and noise absorption)





Droplet wetting for 5 minutes – followed by drying until 69 minutes

t = 1.0 mins

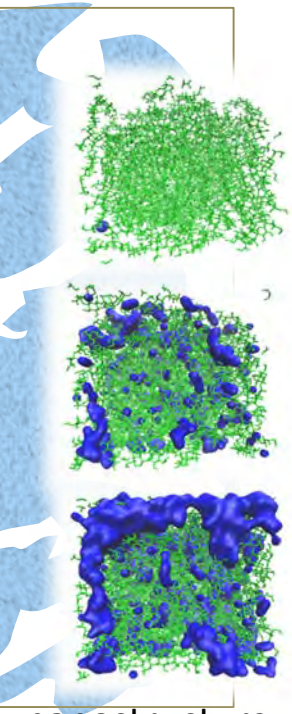


Fluids/porous media interactions:

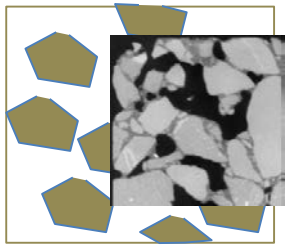
from nano- to macroscale and from very short to long time scales.

experimental

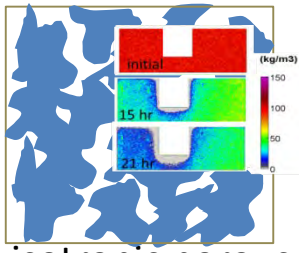
imaging – neutron, Xray, ESEM microscale tests material characterization macroscale tests



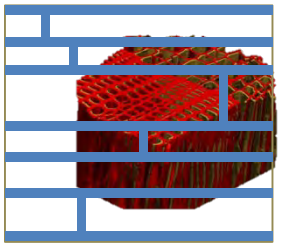
nanostructure



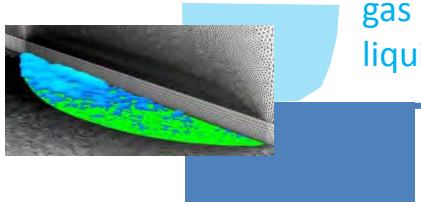
granular media



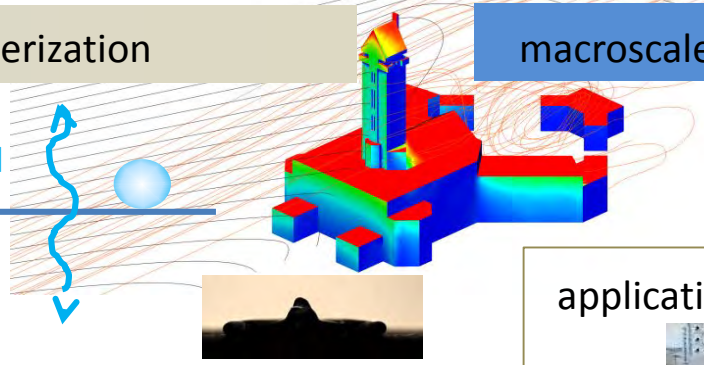
isotropic porous



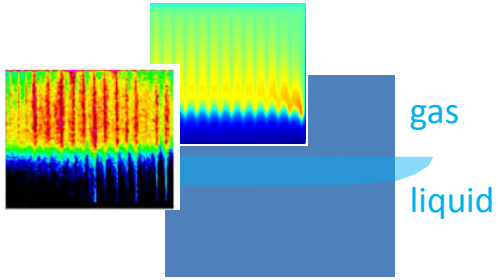
orthotropic porous



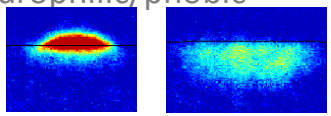
surface phenomena

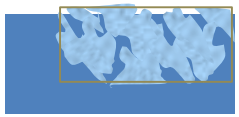


interface
(im)permeable
hydrophilic/phobic



transport





skeleton
(non)hygroscopic
(non)softening

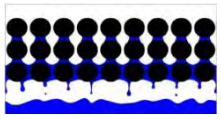
applications

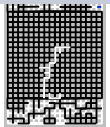
durability of building materials

industrial drying processes

leaching of biocides

Molecular Dynamics Lattice Boltzmann VOF poromechanics upscaling CFD- Eulerian FEM–HAM





modeling

high/low temperature hysteresis

Needs for material development

1. New highly insulation materials at low cost
2. Multi-functional ‘smart’ windows / new coatings from niche to larger market pentration
3. Renewable energy generation at lower cost
4. Materials for higher energy efficieny and lower cost of integrated energy systems at urban scale
5. Reflective coatings for glass
6. Multifunctional shading devives
7. New porous materials for evaporative cooling

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

EMPA
Materials Science & Technology

Thank for your attention

Questions?

Prof. Dr. Carmeliet Jan

Chair of Building Physics , ETH Zurich, Switzerland
Laboratory for Multiscale Studies in Building Physics, Empa, Switzerland