Science on Vertical Green Systems

Dr. habil. Thomas Nehls
Technische Universität Berlin
Institute of Ecology, Chair for Ecohydrology
Center for Innovation and Science on Building Greening (CIBG)

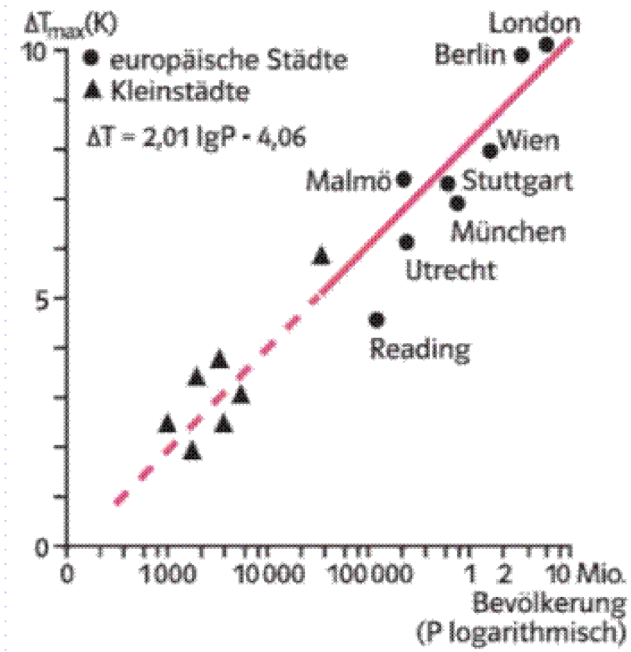
thomas.nehls@tu-berlin.de

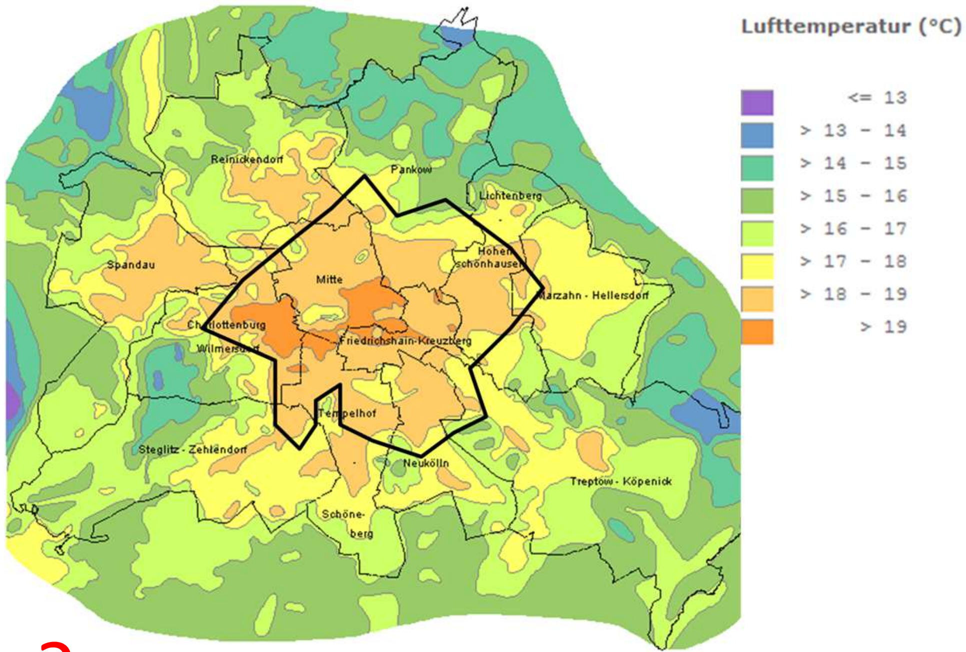
Science on Vertical Green Systems

Content:
- Urban heat island (as connected to heat hazards)
- Measuring cooling effects
- Predicting the cooling energy saving potential of facade greening
- Water demand
- Conclusions and outlook

www.ucahs.org
DFG Forschergruppe
Center for Innovation and Science on Building Greening
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730254
FASSADENBEGRÜNUNG UND BIOMASSEVERWERTUNG FÜR KLIMASCHUTZ AN SCHULEN
BMUV.de
BENE
(EFRE)

The urban heat island (summer, night)





Reason?

Averages of maximum temperature difference between city and surrounding in Europe

(Oke 1973, Danzeisen 1983)

long year average of the T_{air}(!) in cloud-free nights

(Environmental Atlas Berlin)

Phenomenon recorded in bigger cities

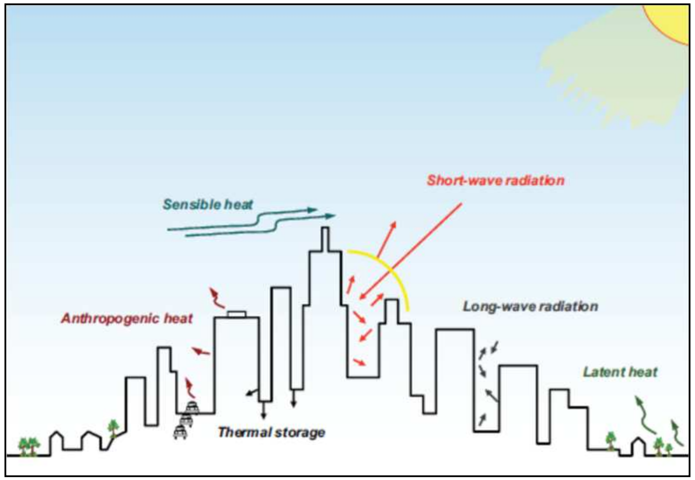
Reason for the urban heat island formation (in summer)

Heating

- solar radiation in mid latitudes (summer: 300-1000 Wm^2, winter: 50-500 Wm^{-2})

- cities do not have a lower albedo than forests and meadows, but
    - high absorbing surface due to buildings (v/h in Berlin 3, in NYC > 10)
    - high density, heat capacity, heat conductivity of building materials

- anthropogenic heat emissions: summer 30 Wm^{-2}, winter 100 Wm^{-2}



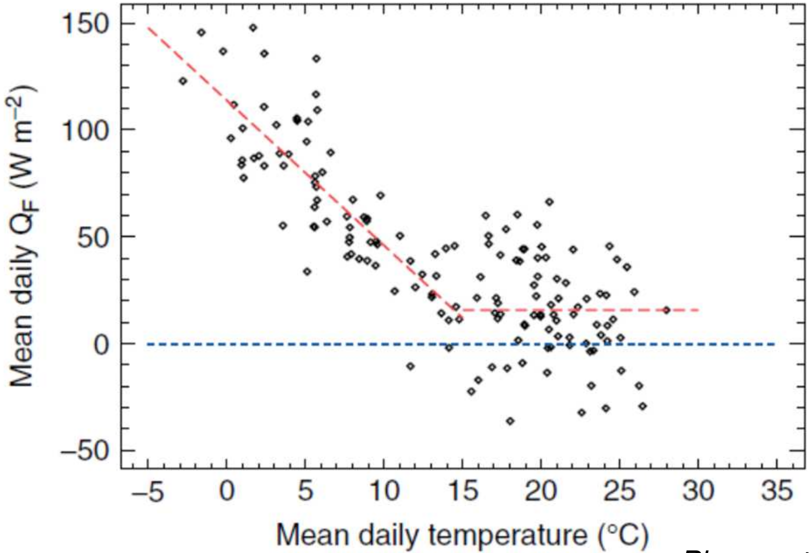
EPA, online

Changed energy transformation (less cooling):

- lower plant density than in natural surroundings
  → less shade, less transpiration, less insulation

- usually less water in the system (surface sealing, drainage)
  → less evaporation

- limited turbulent heat exchange with surrounding areas
  → less heat export



Pigeon et al., 2007

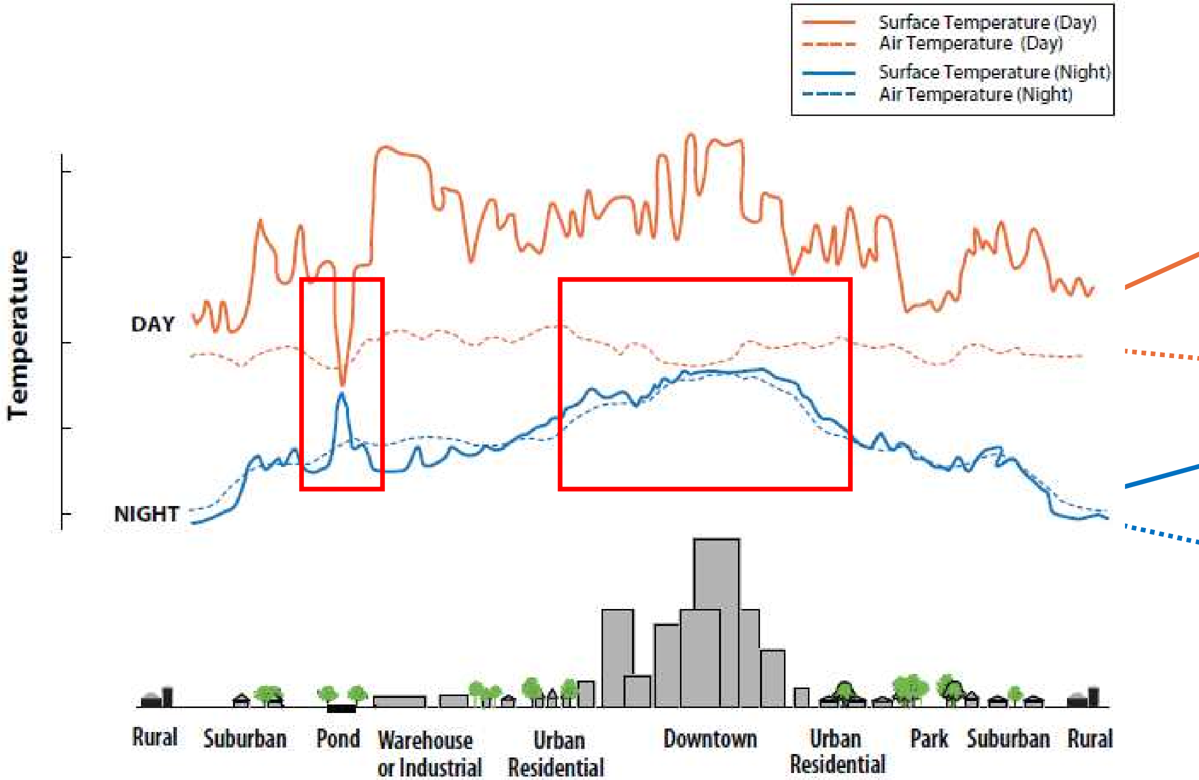
Reaons for the urban heat island formation (in summer)

Vienna (Photo: Nehls)

Surface	Typical albedo
Fresh asphalt	0.04[5]
Open ocean	0.06[6]
Worn asphalt	0.12[5]
Conifer forest (Summer)	0.08,[7] 0.09 to 0.15[8]
Deciduous trees	0.15 to 0.18[8]
Bare soil	0.17[9]
Green grass	0.25[9]
Desert sand	0.40[10]
New concrete	0.55[9]
Ocean ice	0.5 to 0.7[9]
Fresh snow	0.80[9]

wikipedia, online

Urban heat island formation: summer, night time



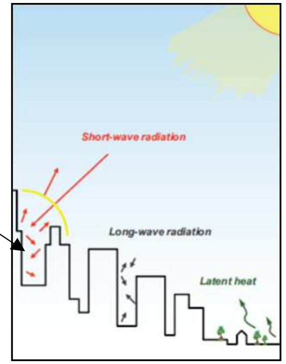
EPA, online

radiative characteristics: α, ε
thermal characteristics: ρ, c

sensible heat transfer, buffer

no short-wave incoming radiation

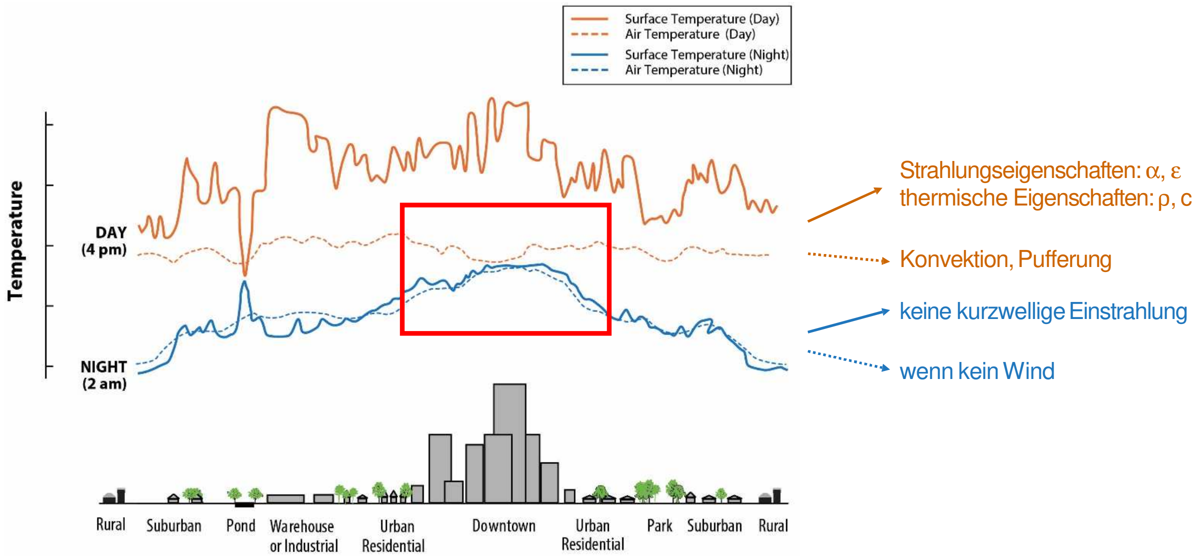
if no wind



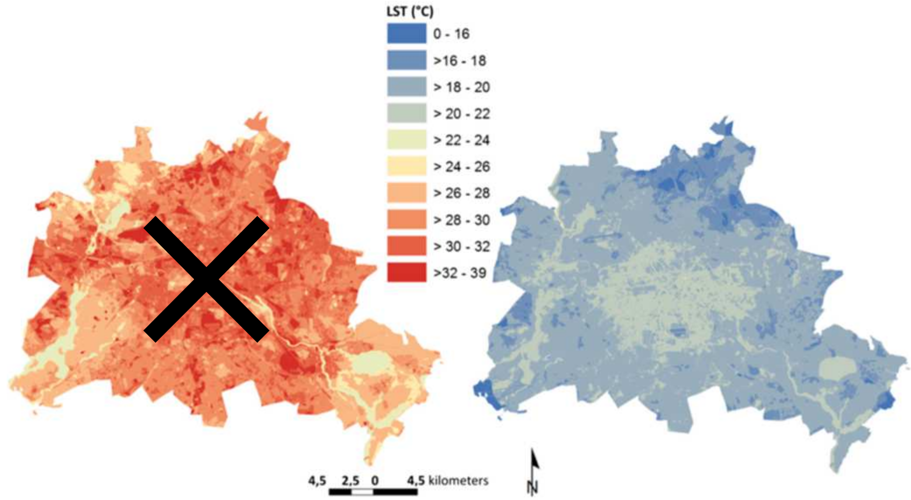
daytime: city sometimes cooler than surrounding
nighttime: almost always hotter than surrounding

→ Don‘t believe in day-time $T_{surface}$ UHI
→ Why does UHI matter? → heat hazard!

Formation of nighttime urban heat island



EPA, online



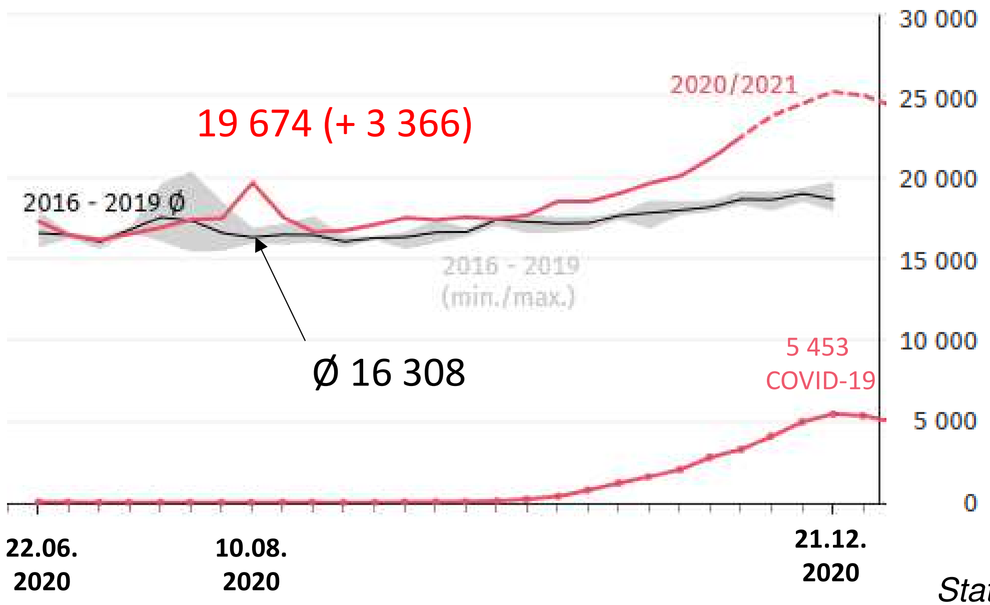
Dugord et al., 2014

- Day: City sometimes cooler than the surrounding area, Night: Temperatures in the city are almost always higher
- Surface temperatures during the day unsuitable for analyzing heat stress:
    - 3rd dimension missing
    - remember thermal optimum: T_{air} is relevant!

Urban heat island and indoor heat stress

second-hottest summer since 1881, $T_{08/2020}$ = 19.9°C = $T_{08/1961\text{-}90}$ + 3.4°C, $T_{08/2020}$ (Berlin) = 21.8°C

05.08. - 22.08.2021: 15 Hitzetage (hot days) T > 30°C; T_{max} = 38.6°C *(DWD, online)*



Statistisches Bundesamt, destatis.de, 2021

Urban heat island and indoor heat stress

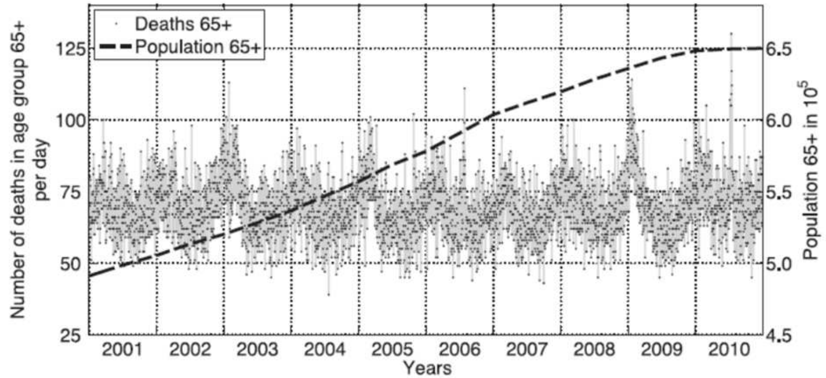
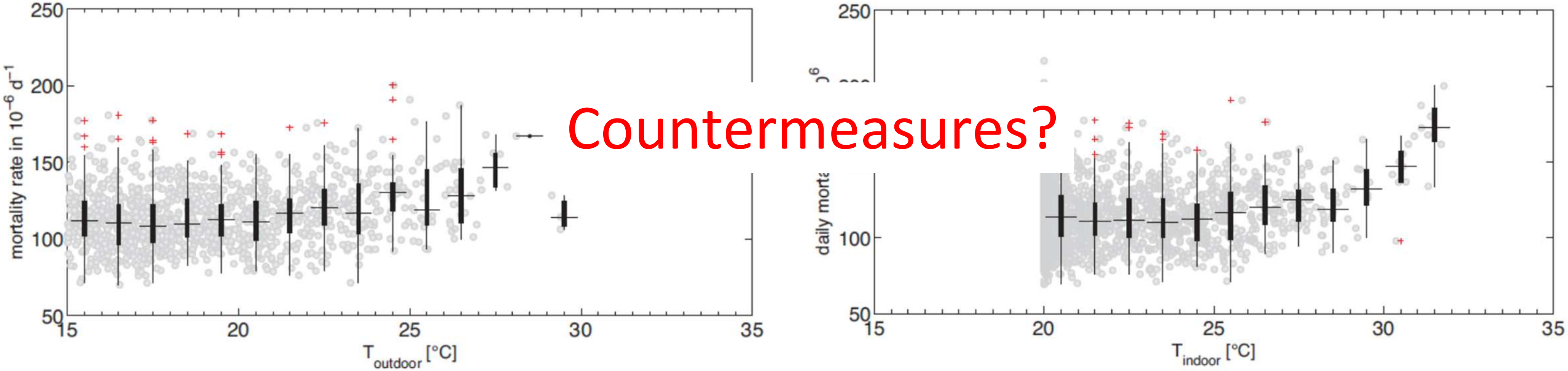


Fig. 2. Number of deaths and population for the group of people in the age of 65 years and older in Berlin from 01.01.2001 to 31.12.2010.



Countermeasures?

→ T_{indoor} best predictor for mortality in the group adults > 65years (2001-2010)

Buchin et al, 2016, Energy & Buildings

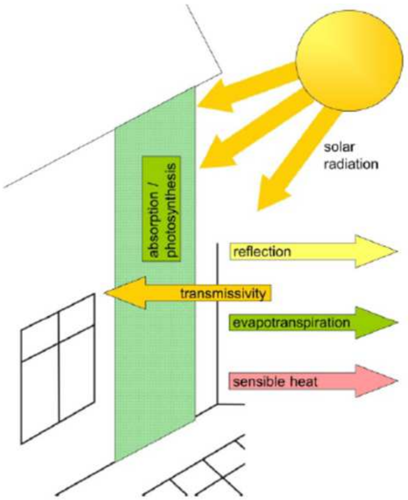
Practical countermeasures?

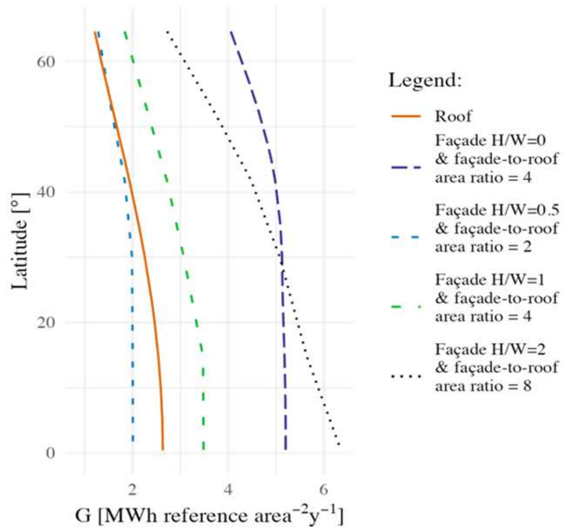
- air conditioning? insulation of buildings? green roofs? shutter blinds?

- rather: systemic approach! need for vegetation at the radiation-absorbing surfaces!

- mid latitudes: green the facades!

- need for quantification of cooling effects and dynamics!





Measuring cooling effects – Material & Methods

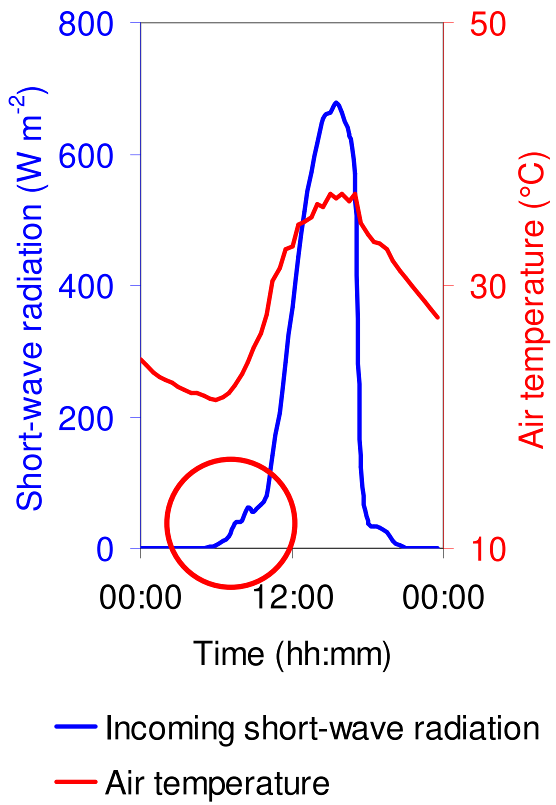
direct greening (*P.tricuspidata*),
south-west oriented wall

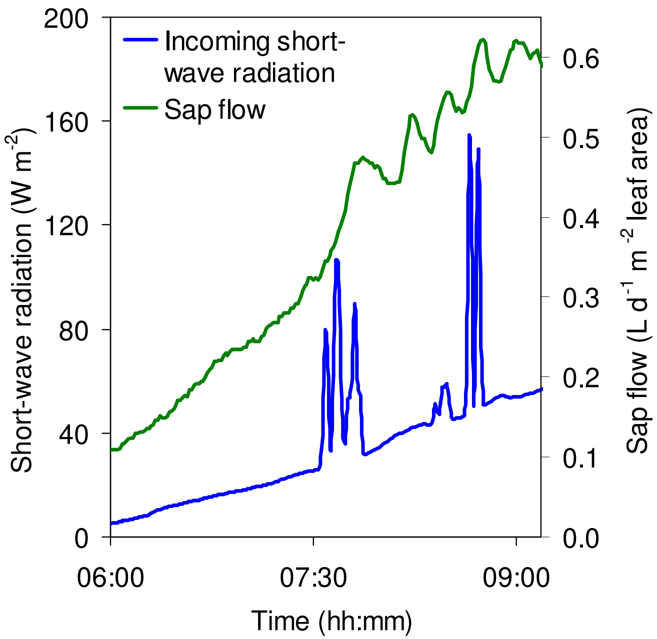
30 cm air g-gap indirect greening (*F.baldschuanica)*
west oriented wall

- July & August 2013, 2014, T_{air} up to 38°C, warmest days of summer
- walls half greened, half bare
- measurements of all relevant parameters:
    - T_{air}, $T_{surface}$, interior & exterior wall, rH, radiation
    - lysimetry, sap flow, LAI

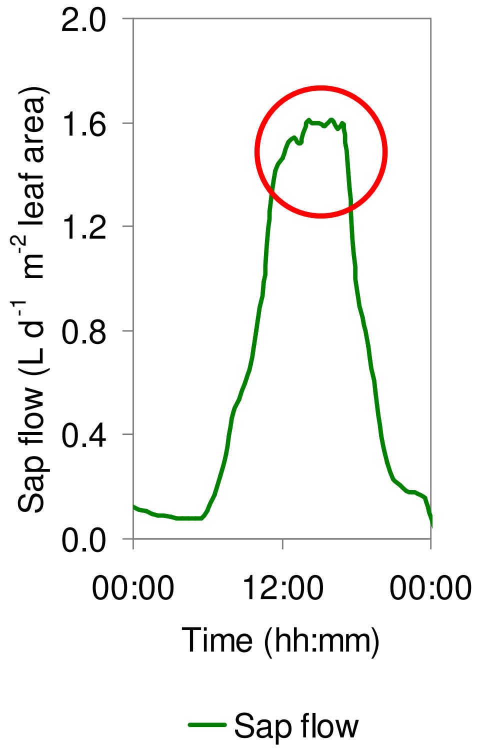
Measuring cooling effects – Results

- meteorological data and transpiration, hot day (02.08.2013)





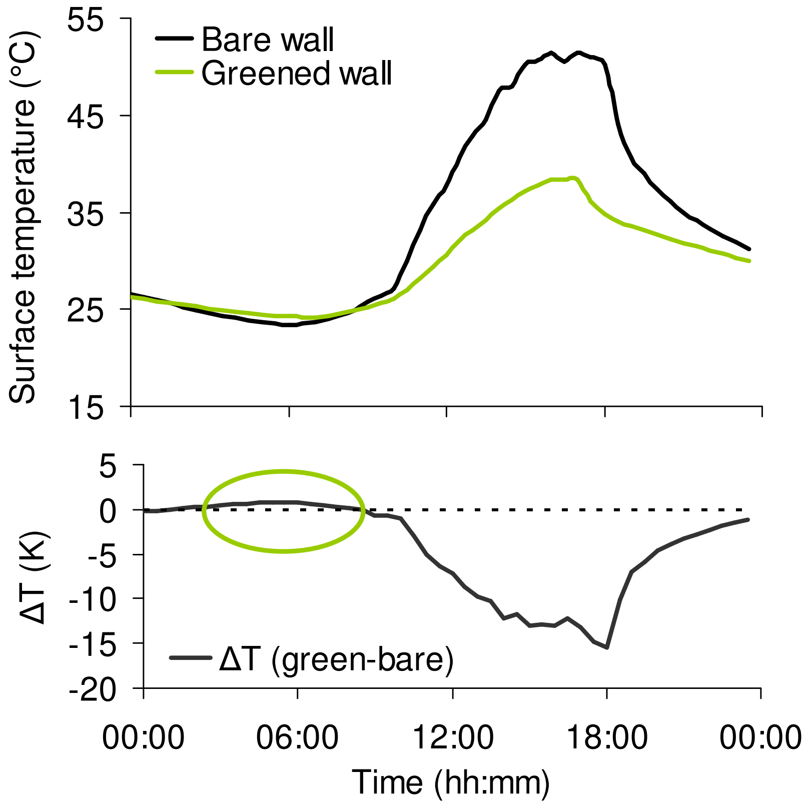
Reflected sunlight 7:00



Hoelscher et al, 2016, Energy & Buildings

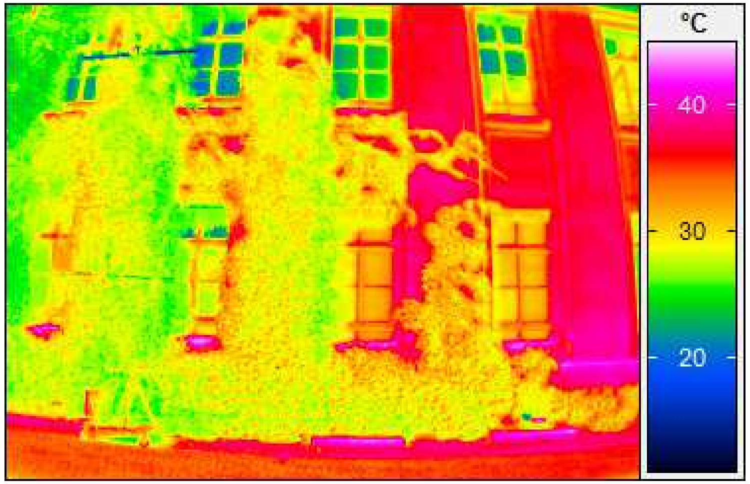
Measuring cooling effects – Results

direct greening, $T_{surface}$ exterior wall, 2013, hot day



max. ΔT = -15.5 K

min. ΔT = 0.8 K



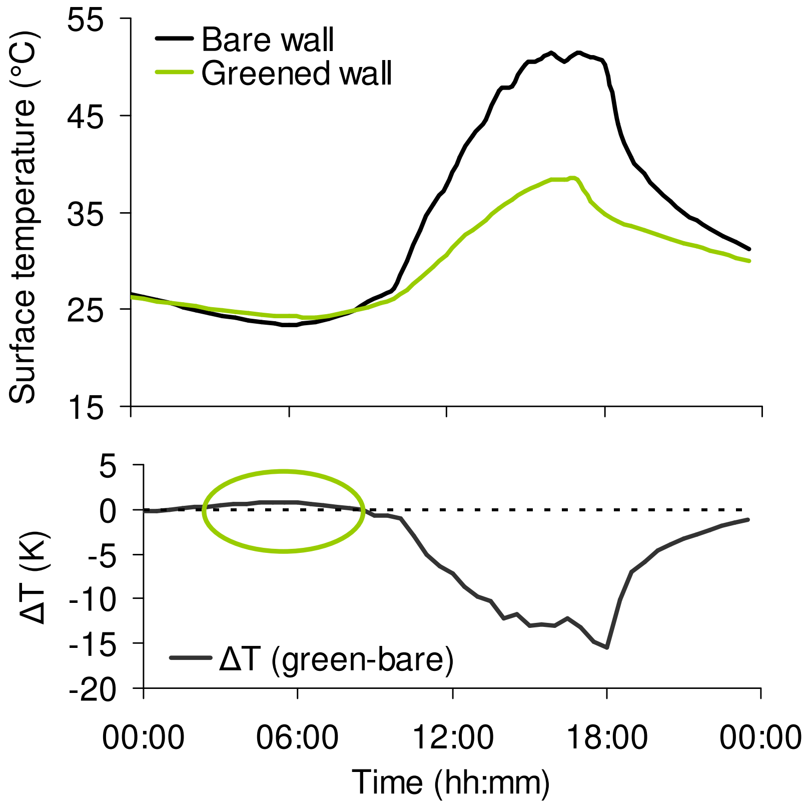
insulation effect!

- greened wall cannot cool down like bare wall
- design matters

Hoelscher et al. (2016) Energy and Buildings

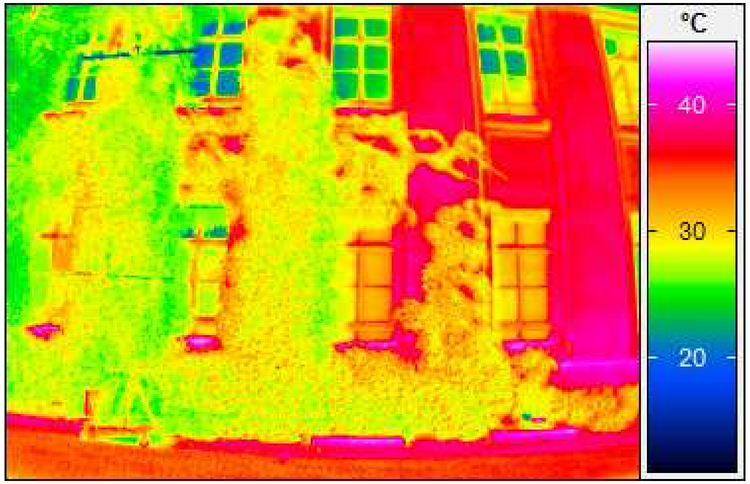
Measuring cooling effects – Results

direct greening, $T_{surface}$ exterior wall, 2013, hot day



max. ΔT = -15.5 K

min. ΔT = 0.8 K



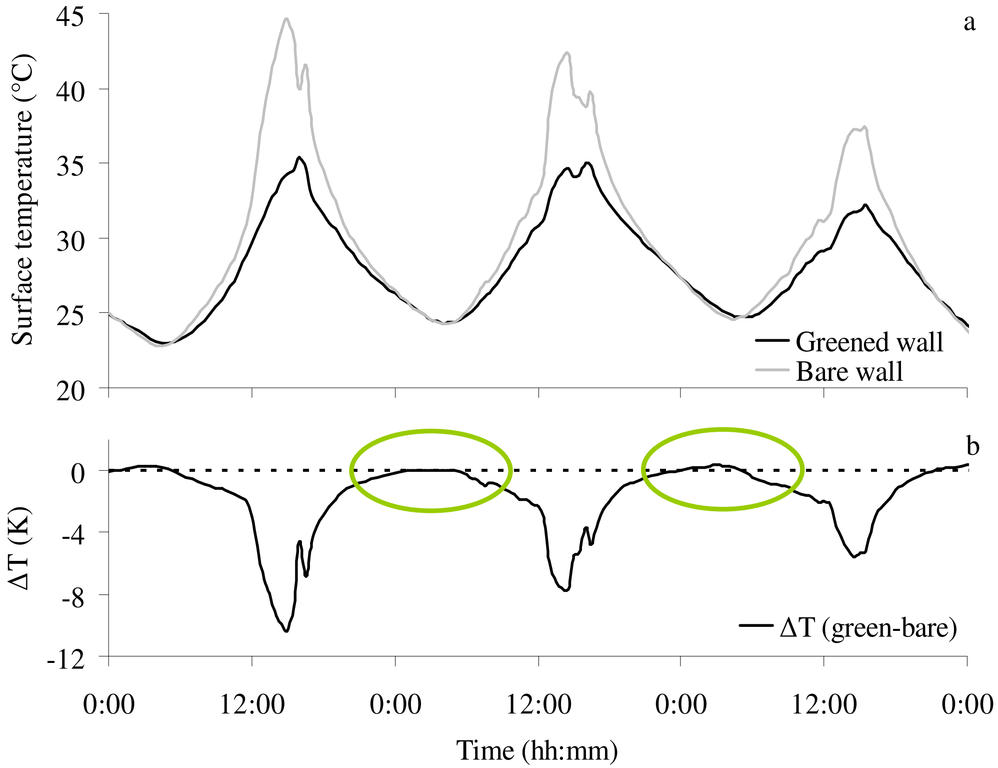
insulation effect!

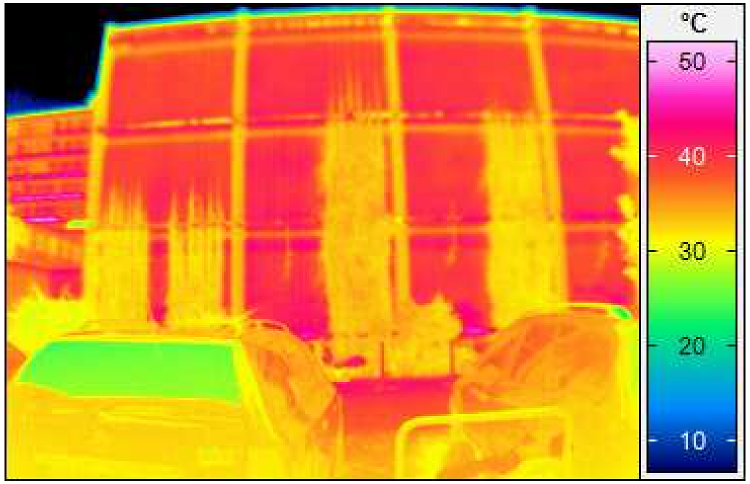
- greened wall cannot cool down like bare wall
- design matters

Hoelscher et al. (2016) Energy and Buildings

Measuring cooling effects – Results

indirect greening, mean $T_{surface}$ exterior wall, hot days 2014



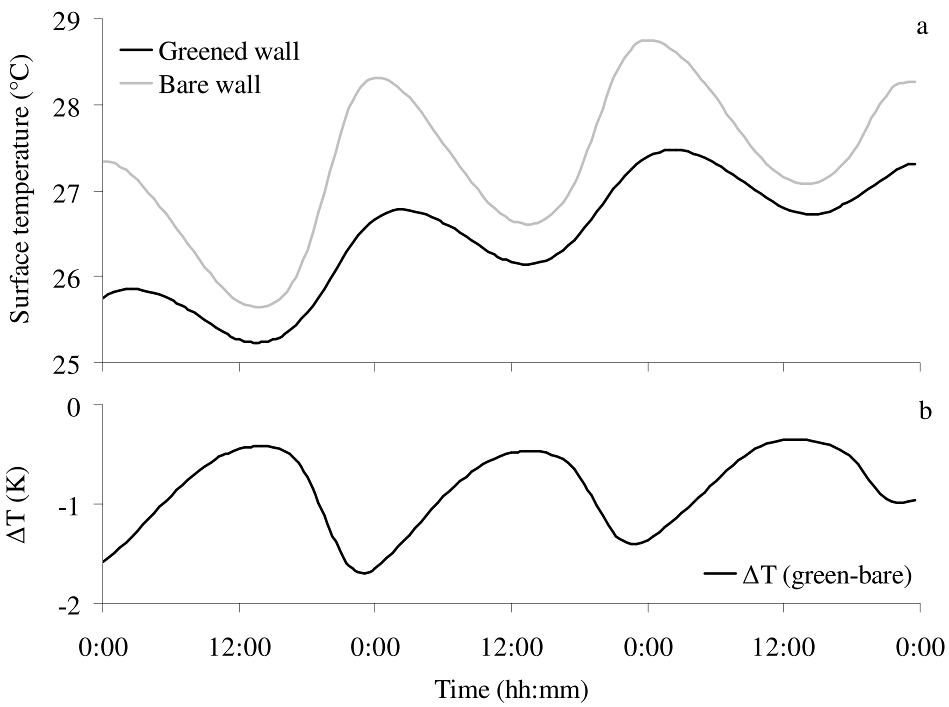


- insulation effect weak due air gap
- greened wall can cool down much better

Hoelscher et al, 2016, Energy & Buildings

Measuring cooling effects – Results

indirect greening, mean $T_{surface}$, interior wall, hot days 2014

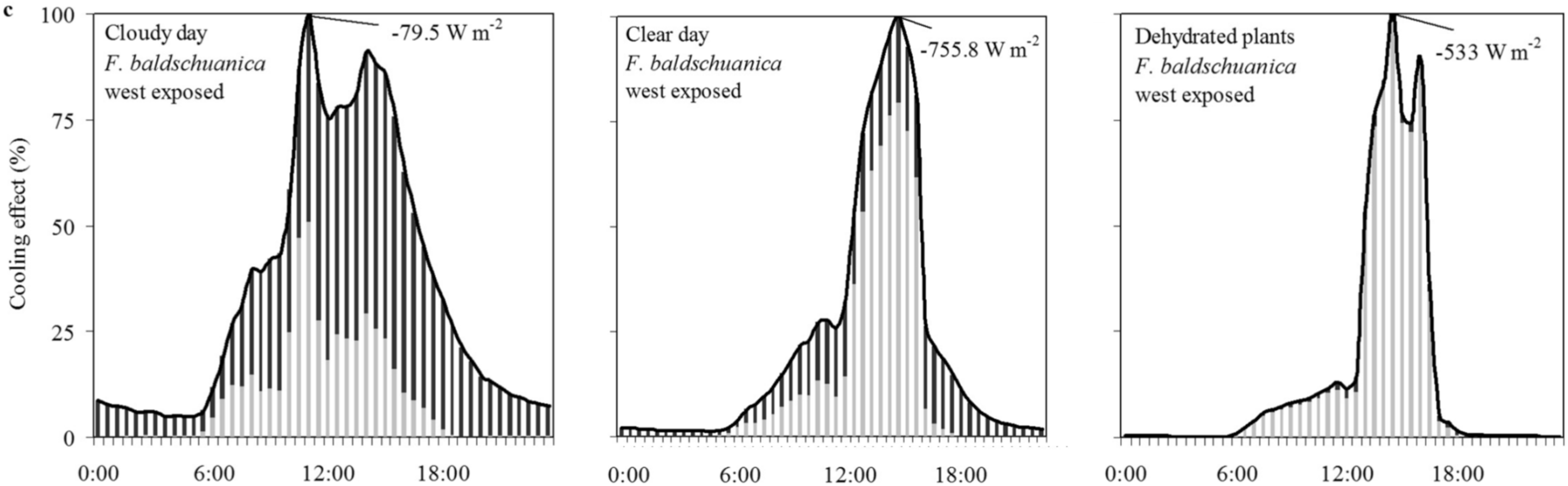


- max. ΔT = -1.7 K , min. ΔT = - 0.4 K
- cooling effect for the indoor wall clear
- time shift & cooling effect depend on wall construction?

Hoelscher et al, 2016, Energy & Buildings

Measuring cooling effects – Results

transpiration vs. shading

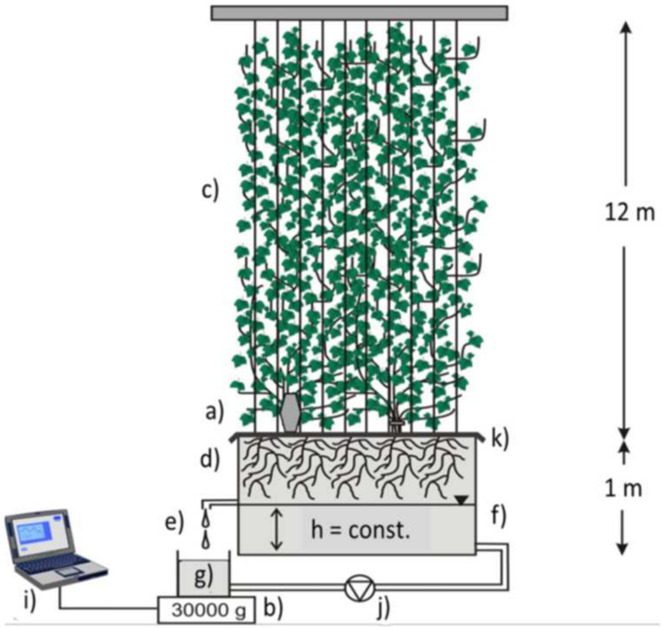


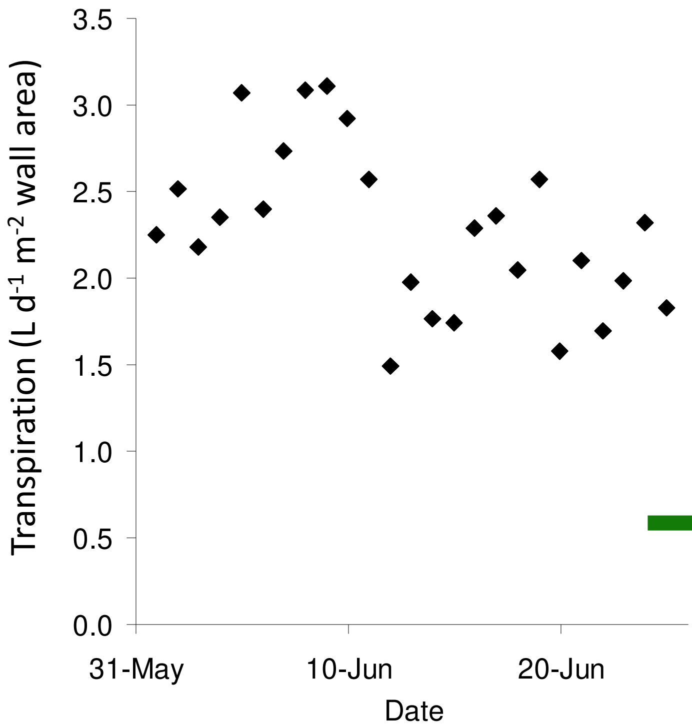
cloudy day, 12.09.2014	hot, sunny day, 03.09.2014	drought simulation, 18.09.2014
27% shading	79% shading	94% shading
73% transpiration	21% transpiration	6% transpiration

Hoelscher et al, 2016, Energy & Buildings

Measuring cooling effects – Results

Transpiration (measured), water demand





Mean daily sums of water uptake:

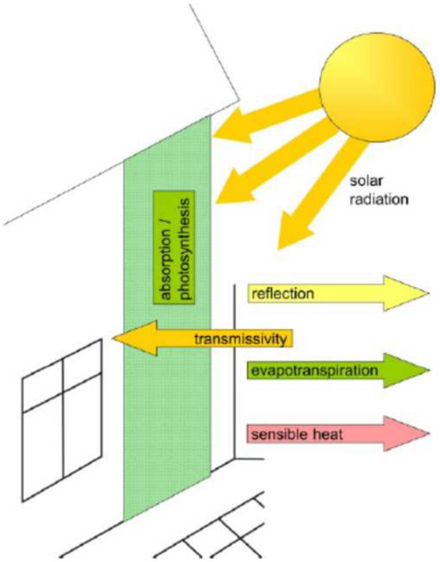
2.3 L d^{-1} m^{-2} wall area

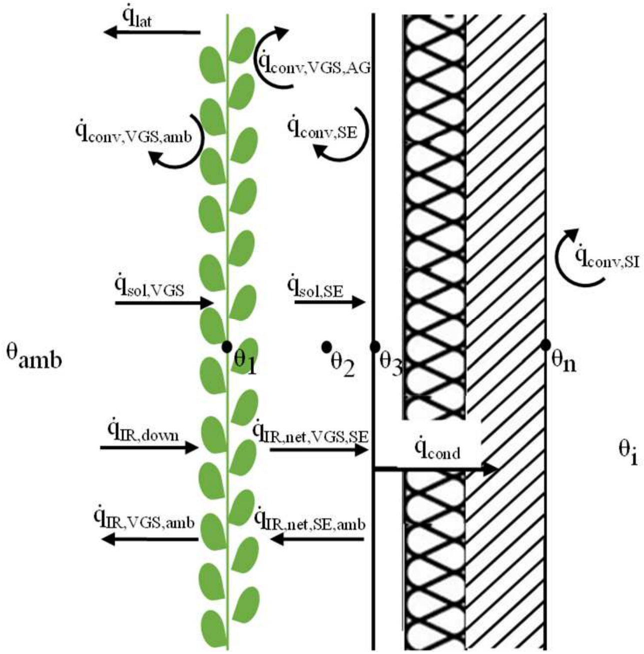
up to 3.2 L d^{-1} m^{-2} wall area

→ Predict the need for irrigation water!

Hoelscher et al, 2018, Agricultural and Forest meteorology

Predicting the cooling energy saving potential of facade greening – Introduction





Heat transfer:

- radiation, convection, conduction

- facade greening shades the builiding, transpiration cools it

- **What is the impact of the building?**

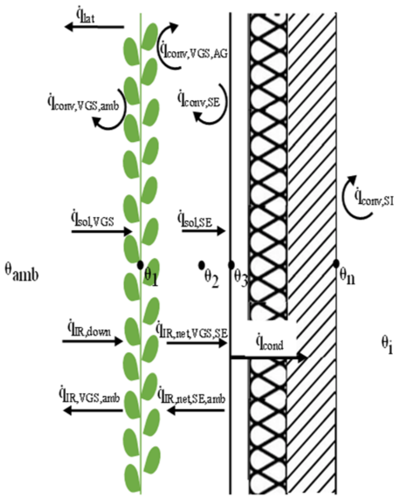
- Wall construction? Insulated? Exposition?

- Berlin vs. Ljubljana vs. …?

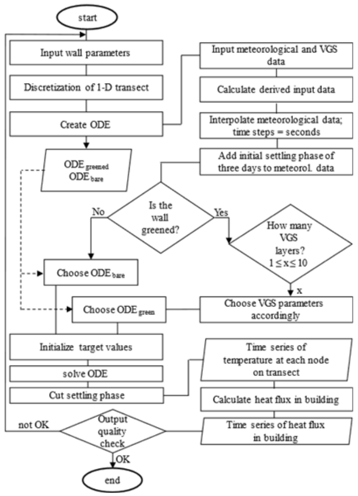
Hoffmann et al, 2021, Energy and Buildings

Predicting the cooling energy saving potential of facade greening – Introduction

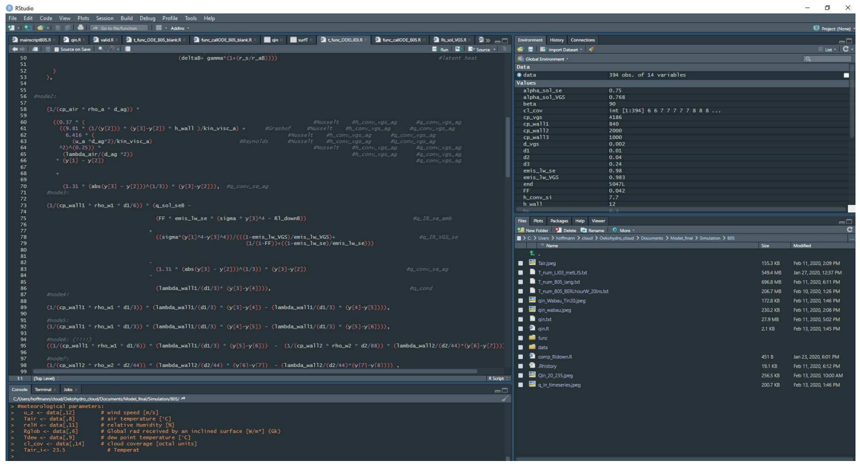
Model



Flowchart



Code (*R*)



one-layer bean plant

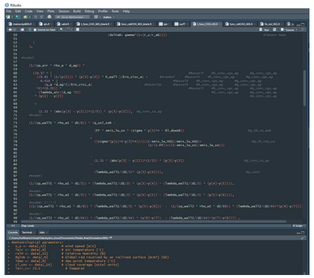
Open Access, Open source:
http://dx.doi.org/10.14279/depositonce-10512

use it! And tell us your results!

Šuklje et al. 2016, Energy; Hoffmann et al., 2021, Energy and Buildings

Predicting the cooling energy saving potential of facade greening – Material & Methods

Code (*R*)



+ Scenarios

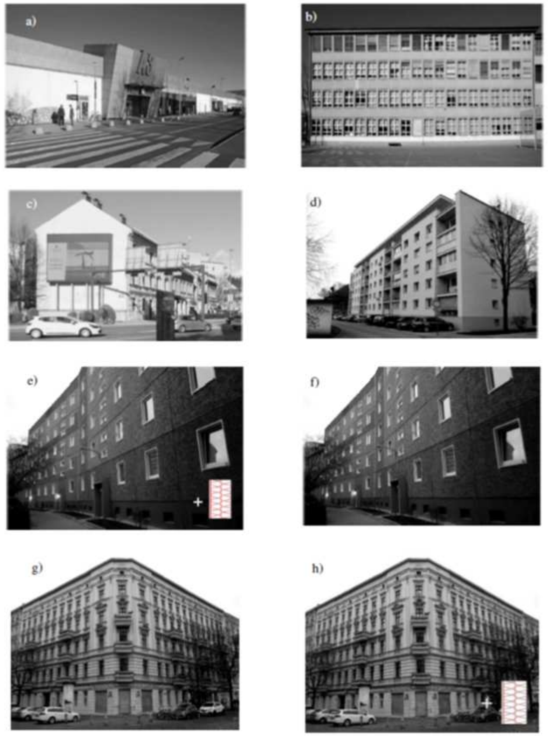


Figure 4: a) BTC hala A; b) Elementary school R. Jakopic; c) residential building at crossroads; d) residential block, Prule; e) Prefabricated panel building with added insulation; f) Prefabricated panel building; g) Wilhelmine building; h) Wilhelmine building with added insulation; i) University test hall; Fotographers: J. Kozamernik (a-d), K. Hoffmann (e-i)

+ Parameters

#	Building (year of constr.)	Material	d [m]		ρ [kg m^{-3}]	λ [W m^{-1} K^{-1}]	c_p [J kg^{-1} K^{-1}]	[V
1	BTC hala A (1954)	Acrylic smooth plaster	0.002	0.285	1600	0.66	1000	
		Thin-layer reinforced plaster	0.003		1800	1	1000	
		Styrofoam board	0.06		70	0.04	1260	
		reinforced concrete	0.2		2400	2.04	960	
		Extended lime mortar	0.02		1600	0.81	1050	
2	Elementary school Rihard Jakopic (1965)	Lime scratched plaster, terranova	0.03	0.43	1600	0.81	1050	
		Solid brick	0.38		1600	0.64	920	
		Extended limestone mortar	0.02		1600	0.81	1050	
3	residential building at crossroads (1932)	Lime plaster	0.03	0.66	1600	0.81	1050	
		Solid brick	0.61		1800	0.76	920	
		Extended limestone mortar	0.02		1600	0.81	1050	
4	residential block, Prule (1963)	Silicone or acrylic smooth plaster	0.002	0.575	1600	0.66	1000	
		Thin-layer reinforced plaster	0.003		1800	1	1000	
		Graphite Styrofoam plates	0.14		20	0.032	1260	
		Modular brick blocks	0.41		1400	0.61	920	
		Extended limestone mortar	0.02		1600	0.81	1050	
5	Prefabricated panel building / added insulation (since 1950)	Composite insulation system	0.12	0.38	30	0.035	1030	
		Weather shell (concrete)	0.06		1800	1.15	1000	
		Thermal insulation	0.06		150	0.0407	1030	
		Load-bearing wall (concrete)	0.14		1800	1.15	1000	
6	Prefabricated panel building (since 1950)	Weather shell (concrete)	0.06	0.26	1800	1.15	1000	
		Thermal insulation	0.06		150	0.0407	1030	
		Load-bearing wall (concrete)	0.14		1800	1.15	1000	
7	Wilhelmine building (1871-1918)	Exterior plaster	0.02	0.42	2000	0.96	840	
		Solid brick	0.37		2000	0.96	840	
		Mortar	0.01		2000	0.96	840	
		Exterior plaster	0.02		2000	0.96	840	

+ Meteorological input

Meteonorm data base

- 20 years mean
- hourly data
- 1st June – 30th September
- θi = const. 26 °C

(DIN EN ISO 4108-2: 2013-2: Thermal protection and energy economy in buildings)

Šuklje et al. 2016, Energy; Hoffmann et al., 2021, Energy and Buildings

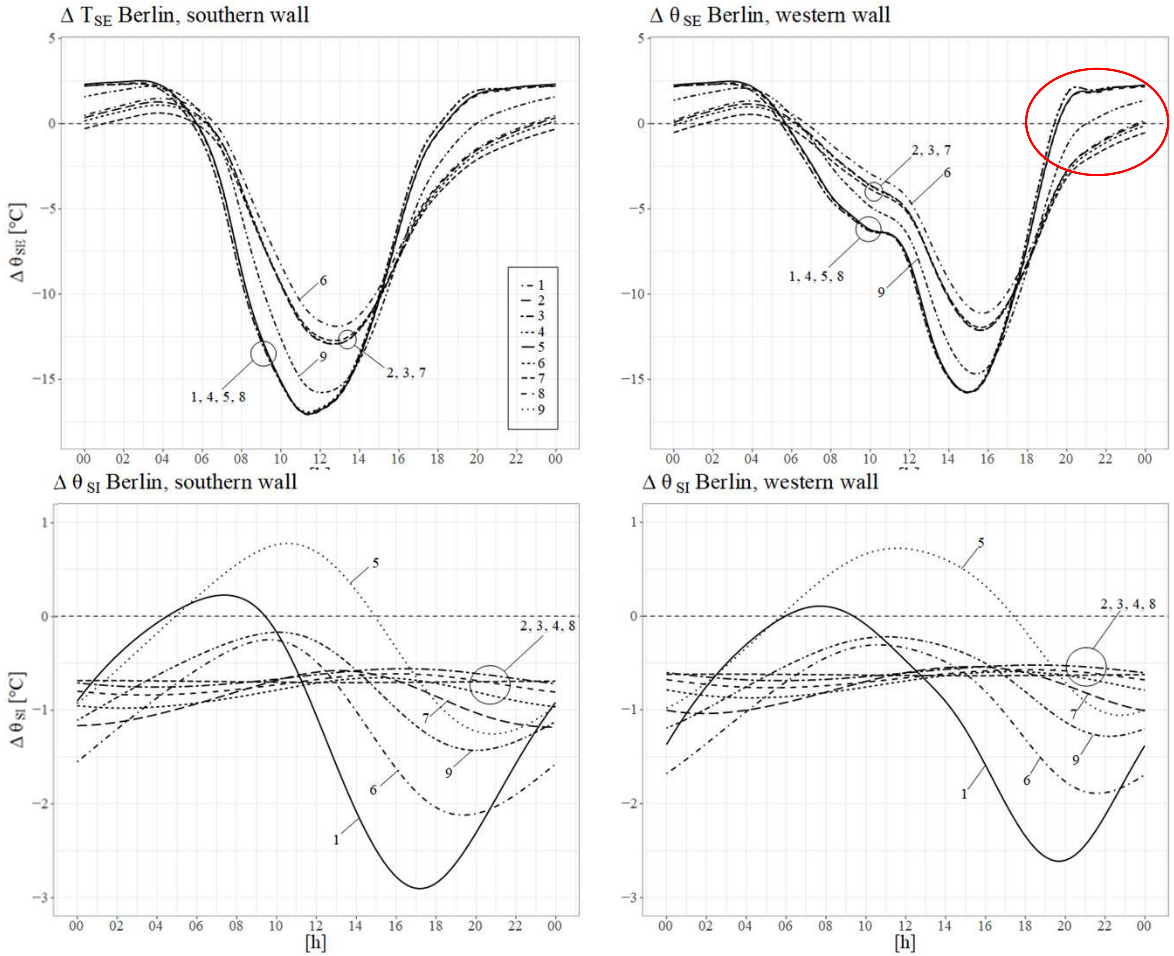
Predicting the cooling energy saving potential of facade greening – Results

South-oriented

West-oriented

exterior

interior

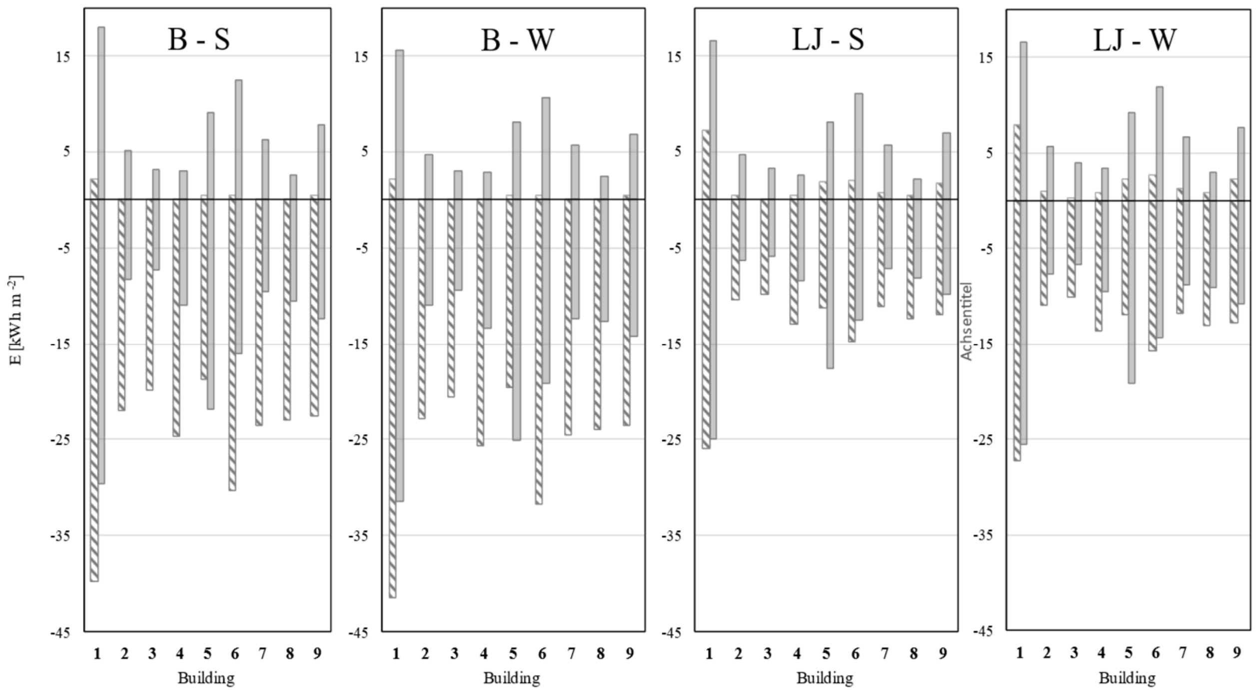


- θ_{SE}: most effective on insulated buildings
- insulation effect visible

- θ_{SI}: most effective on non-insulated pre-fabricated houses
- least T-fluctuation: non-insulated, high thermal inertia

Hoffmann et al., 2021, Energy and Buildings

Predicting the cooling energy saving potential of facade greening – Results



Integrated Energy [kWh m^{-2}] through the bare (grey) and greened (striped) wall:
Inflow (+) and outflow (-) for the set of nine wall compositions between 1 June and 30 September. Meteorological input data from left to right: Southern and western wall in Berlin; southern and western wall in Ljubljana

Hoffmann et al., 2021, Energy and Buildings

Water demand, water availability, transpiration performance

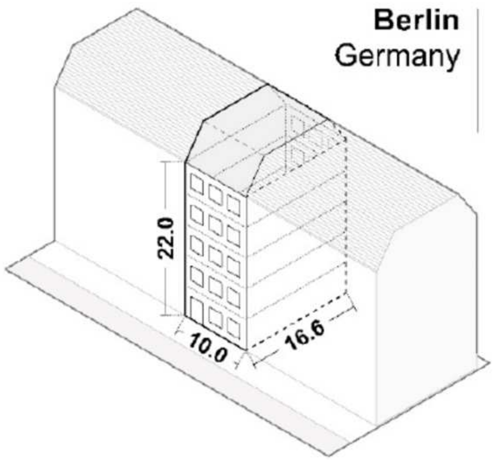


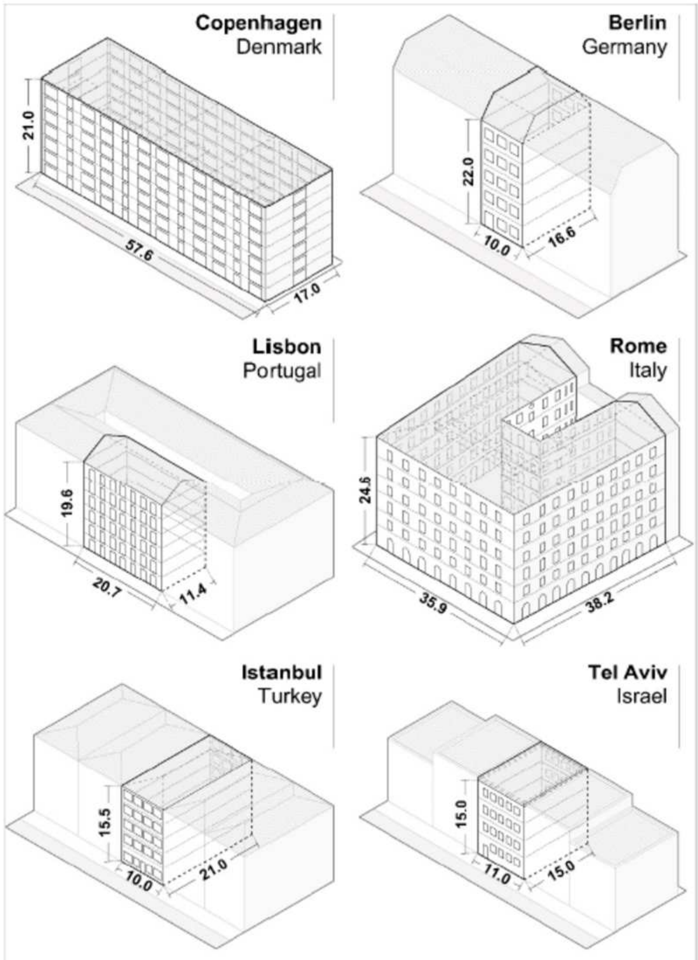
Table 1. Parameters describing the climatic, architectural, and hydrological characteristics of the case studies. The presented data included precipitation (P), temperature (T), evapotranspiration (ET), greywater (GW) production per inhabitant, occupancy (O) and run-off (RO) generation.

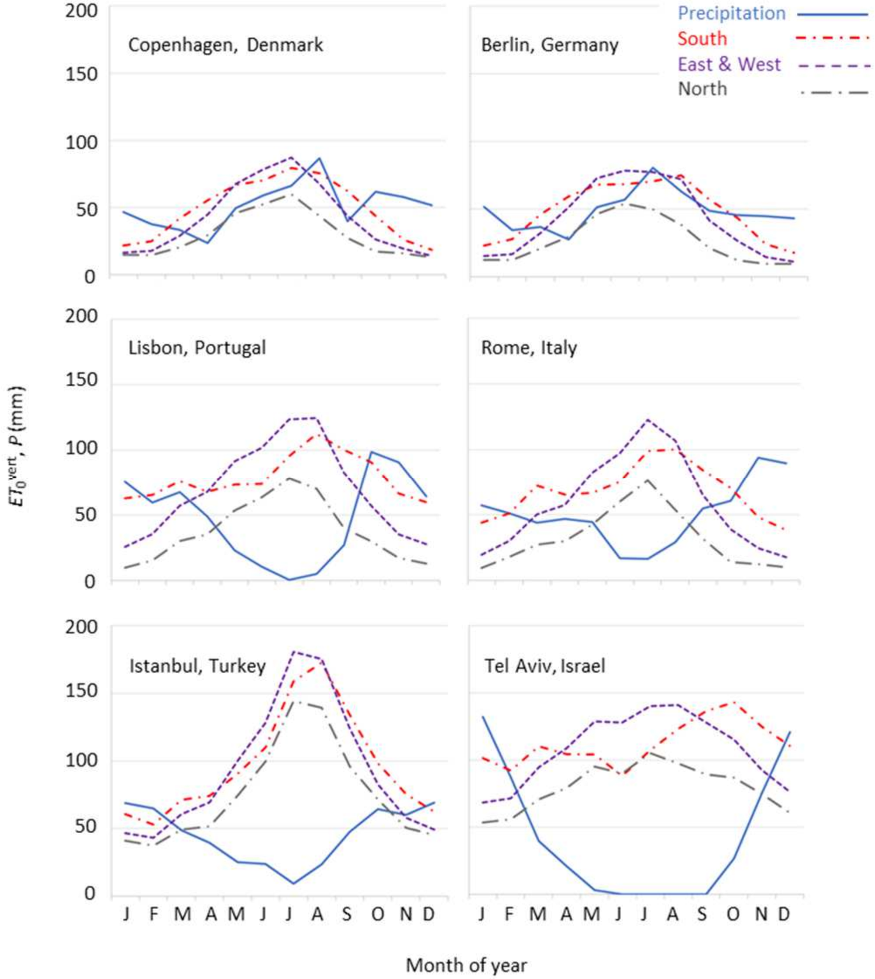
City	Climate [2]					Typical Building					Water Availability		
	Class [1]	*P*	*T*	*P-ET* Oct-Mar	*P-ET* Apr-Sep	Ground	Facade	Window	v/h	*O*	*GW* Capita	*GW* Facade	*RO* Facade
		mm/a	°C	mm		—m²—			(-)	inh/m²	L/inh d	—L/m² d—	
Copenhagen	Dfb	614	9.4	151	−206	980	3206	1408	3.27	0.044	51	0.69	0.37
Berlin	Dfb	585	10.3	118	−238	166	440	132	2.65	0.065	63	1.54	0.43
Rome	Csa	605	17.8	135	−644	1302	3996	813	3.07	0.029	90	0.85	0.41
Lisbon	Csa	571	17.4	126	−791	237	407	142	1.72	0.021	81	0.99	0.71
Istanbul	Csa	546	16.0	−18	−840	231	310	132	1.34	0.170	58	7.35	0.82
Tel-Aviv	Csa	506	21.5	−171	−1090	165	330	66	2.00	0.040	58	1.16	0.57

[1] acc. to Köppen-Geiger, [2] acc. to Meteonorm 8, Meteotest Bern, Switzerland 2000–2019.

Pearlmutter et al. , 2021

Water demand, water availability, transpiration performance





Pearlmutter et al. , 2021

Water demand, water availability, transpiration performance

Rainwater

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Berlin	0.8	0.5	0.3	0.1	0.2	0.2	0.3	0.3	0.3	0.5	0.8	0.9
Copenhagen	0.6	0.4	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.5	0.6	0.7
Istanbul	0.8	0.8	0.4	0.3	0.1	0.1	0.0	0.1	0.2	0.5	0.6	0.7
Rome	0.6	0.4	0.2	0.2	0.2	0.0	0.0	0.1	0.2	0.4	0.9	1.1
Lisbon	1.1	0.7	0.6	0.4	0.1	0.1	0.0	0.0	0.2	0.8	1.1	0.9
Tel Aviv	0.7	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.6

Greywater

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Istanbul	4.5	4.5	3.7	3.2	2.4	1.8	1.3	1.3	1.8	2.6	3.5	4.3
Berlin	2.8	2.2	1.4	0.9	0.7	0.6	0.7	0.7	1.1	1.8	2.9	3.7
Copenhagen	1.2	1.0	0.7	0.5	0.3	0.3	0.3	0.3	0.5	0.7	1.0	1.4
Lisbon	1.0	0.7	0.5	0.5	0.4	0.3	0.3	0.3	0.4	0.5	0.8	0.9
Rome	1.1	0.7	0.5	0.5	0.4	0.3	0.2	0.3	0.4	0.6	0.9	1.2
Tel Aviv	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4

Fraction of facade that can be irrigated sufficiently

Pearlmutter et al. , 2021

Water demand, water availability, cisterns

City	Water Management Potential							
	(a) Solely RO Irrigation		(b) Optimized RO Irrigation			(c) Full RO + GW Irrigation		
	Facade Greened	Evaporated RO	Facade Greened	Evaporated RO	Evaporated GW	Facade Greened	Evaporated RO	Evaporated GW
	%		%			%		
Copenhagen	10	35	26	79	11	46	92	41
Berlin	13	39	64	95	29	87	100	47
Rome	4	17	24	64	21	28	67	27
Lisbon	-	-	28	44	28	28	44	28
Istanbul	3	9	100	100	30	136	100	45
Tel-Aviv	-	-	28	60	53	28	60	53

Pearlmutter et al. , 2021

- Rainwater is sufficient for approx. 13% of the facade areas in the center of Berlin *(Pearlmutter et al., 2021)*

- Use of gray water would enable 64% to 87% greening, windows approx. 30%- Management of 39 to 100% of the rainwater possible, up to 47% GW

- Monument protection “prohibits” greening of approx. 30% of the facades *(Rösch et al., 2023)*

→ Cross-building, district-oriented rainwater management necessary and enabled by plants

Conclusions

- facade greenery is a systemic solution for a systemic failure (UHI-realted heat hazard and heat stress)

- cooling effect is caused by shading and transpiration → passive building cooling

- effective for all (investigated) building types, as long as green and transpiring (provide ≈5 L/m² greened wall)

- performance depends on site specific conditions

- design of greening system should avoid insulation, especially during night time

- reduced reflection and $T_{surface}$ is of advantage for street canyon

- watering with rainwater and grey water recommended

Conclusions

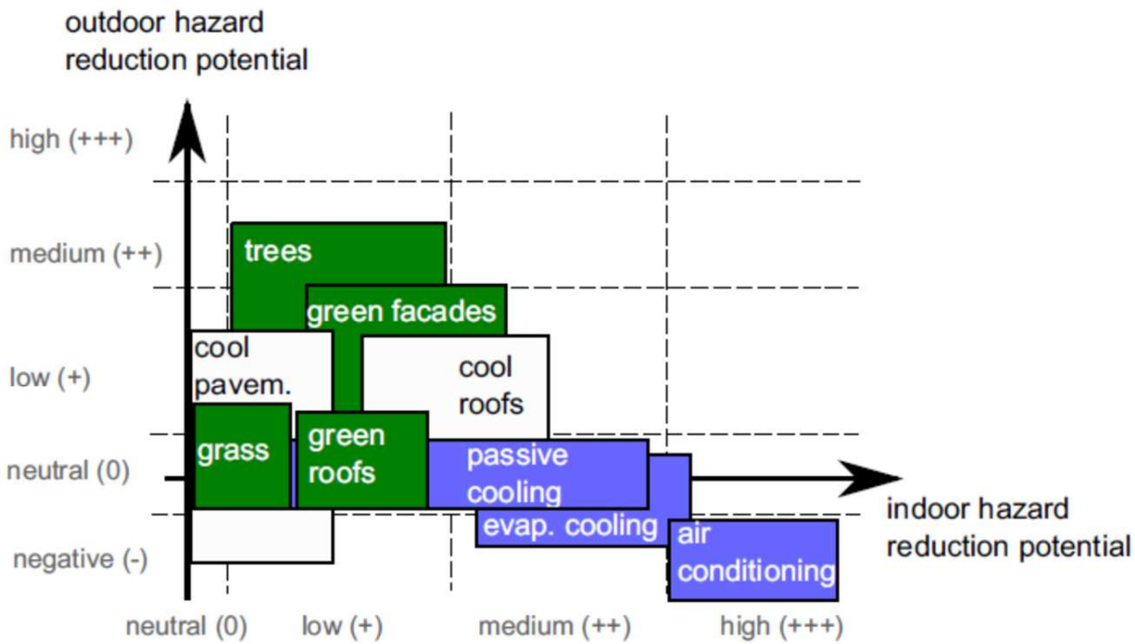


Fig. 7. Hazard reduction potential of countermeasures to UHI and active and passive cooling measures on the room scale.

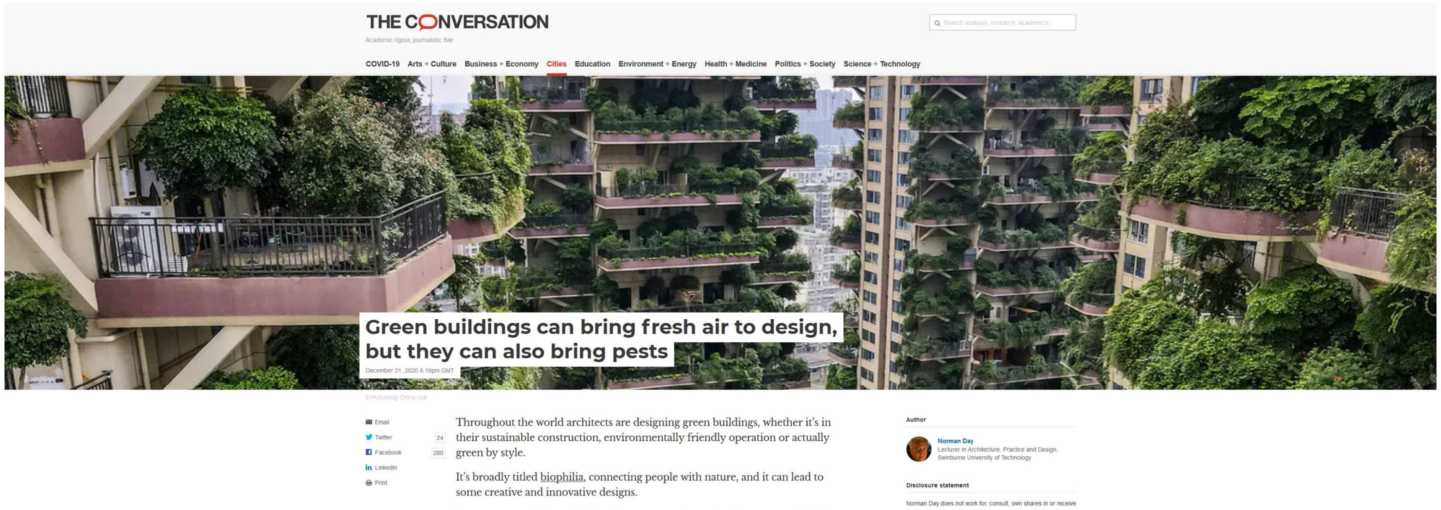
Buchin et al. 2015 Energy and Buildings

Outlook

- facade greenery is not recognized as a part of the building (no standard performance values available, e.g. U-value)

- impact on „soft“ factors like biodiversity, well being, etc. not comparably studied yet

- Acceptance by city-zens depends on maintenance, costs, and annoyances



https://theconversation.com/green-buildings-can-bring-fresh-air-to-design-but-they-can-also-bring-pests-147838

Thanks

Prof. Gerd Wessolek, Marie Hölscher, Karin Hoffmann, Oliver Buchin, Tomaz Suklje, Prof. Eva Paton, Nikola Schwarzer, Björn Kluge

The team of Urban Vertical Green 2.0 (www.verticalgreen2dot0.eu)
The team of Urban Climate and Heat Stress (www.ucahs.org)
The team of COST Circular City
The Technische Universität Berlin

Literature

Buchin, O, Hoelscher, M.-T., Meier, F., Nehls, T. and Ziegler, F. (2016) Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. Energy and Buildings, 114: 27–37, https://doi.org/10.1016/j.enbuild.2015.06.038

Hoelscher, M.-T., Nehls, T., Jaenicke, B. and Wessolek, G. (2016) Quantifying cooling effects of facade greening: shading, transpiration and insulation. Energy and Buildings, 114, 283–290, https://doi.org/10.1016/j.enbuild.2015.06.047

Hoelscher, M.-T., Kern, M.A., Wessolek, G. and Nehls, T. (2018) A new consistent sap flow baseline-correction approach for the stem heat balance method using nocturnal water vapour pressure deficits and its application in the measurements of urban climbing plant transpiration, Agricultural and Forest Meteorology, 248: 169-176, https://doi.org/10.1016/j.agrformet.2017.09.014

Hoffmann, K. Sukle, T., Kozamernik, J. and Nehls, T. (2021) Modelling the cooling energy saving potential of facade greening in summer for a set of building typologies in mid-latitudes. Energy and Buildings, https://doi.org/10.1016/j.enbuild.2021.110816

Pearlmutter et al. (2021) Closing water cycles in the built environment through nature-based solutions: The contribution of building greening with vegetated roofs and façades vertical greening systems and green roofs. Water, 13(16), 2165 https://doi.org/10.3390/w13162165

Roesch, E.J., Hoffmann, K.A. & Nehls, T. Monument protection as a limiting factor for large scale vertical greening system implementation to counteract indoor heat stress – a GIS-based analysis for Berlin, Germany. Urban Ecosyst 26, 821–829 (2023). https://doi.org/10.1007/s11252-023-01333-z