Space-conditioning systems for very-low-energy buildings

Les Norford

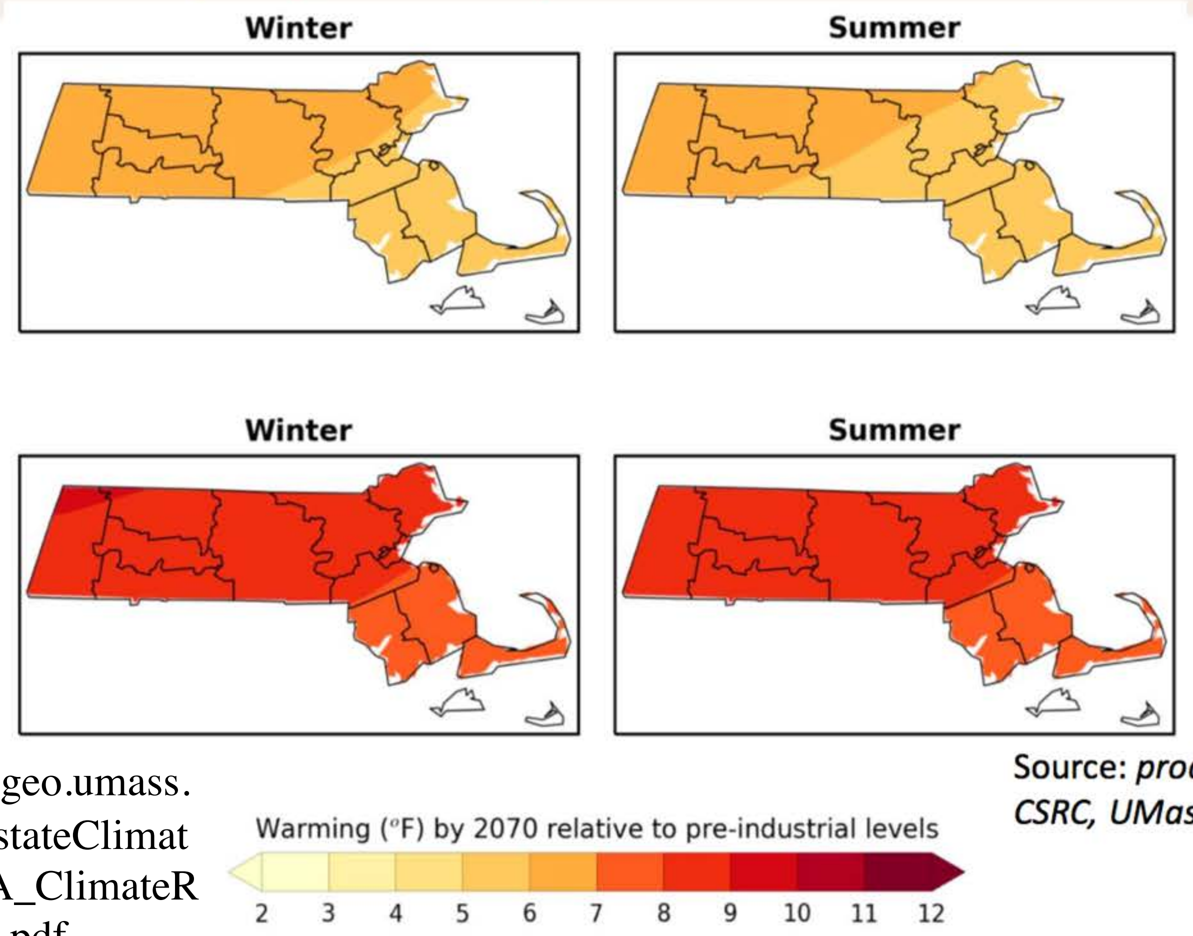
Building Technology Program
Department of Architecture
Massachusetts Institute of Technology

13th Annual North American
Passive House Conference, September 21-22, 2018 Boston, MA

Image from Rocky Mountain Institute: Boulder Commons Net Zero leased-space building

Warming in Massachusetts

PROJECTIONS In the next 50-60 years, when global warming crosses the 2°C threshold, MA average summer and winter temperatures are projected to increase by over 6°F (3.3°C) relative to pre-industrial levels.



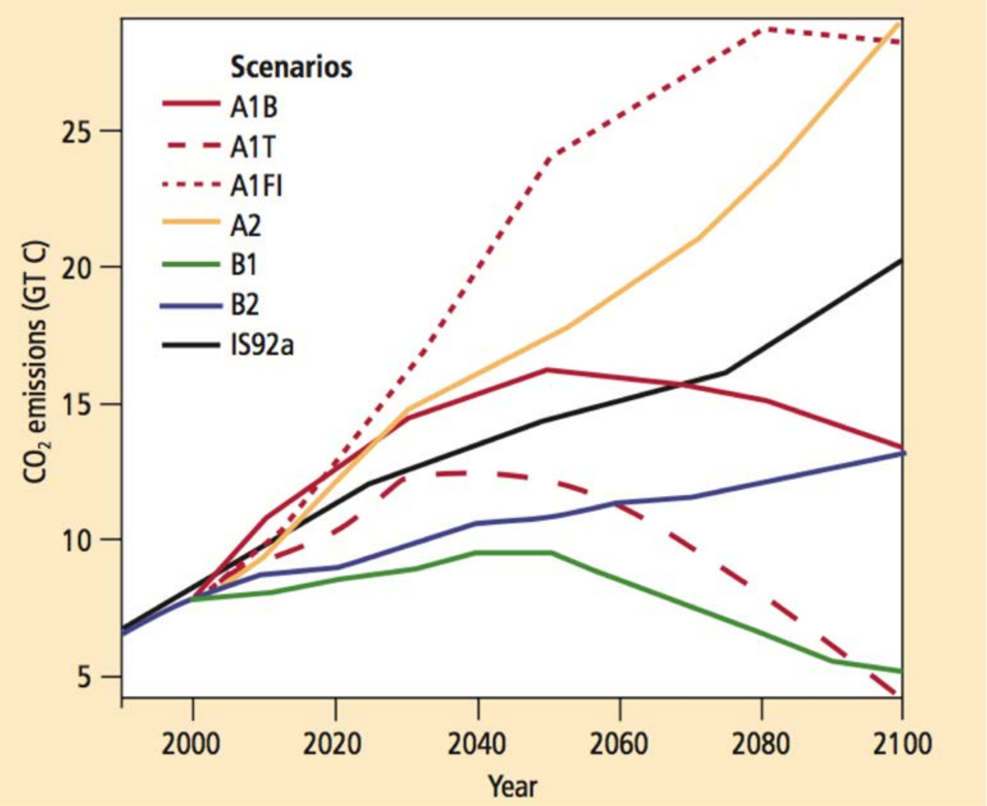
Lower Emissions

Higher Emissions

https://www.geo.umass.edu/climate/stateClimateReports/MA_ClimateReport_CSRC.pdf

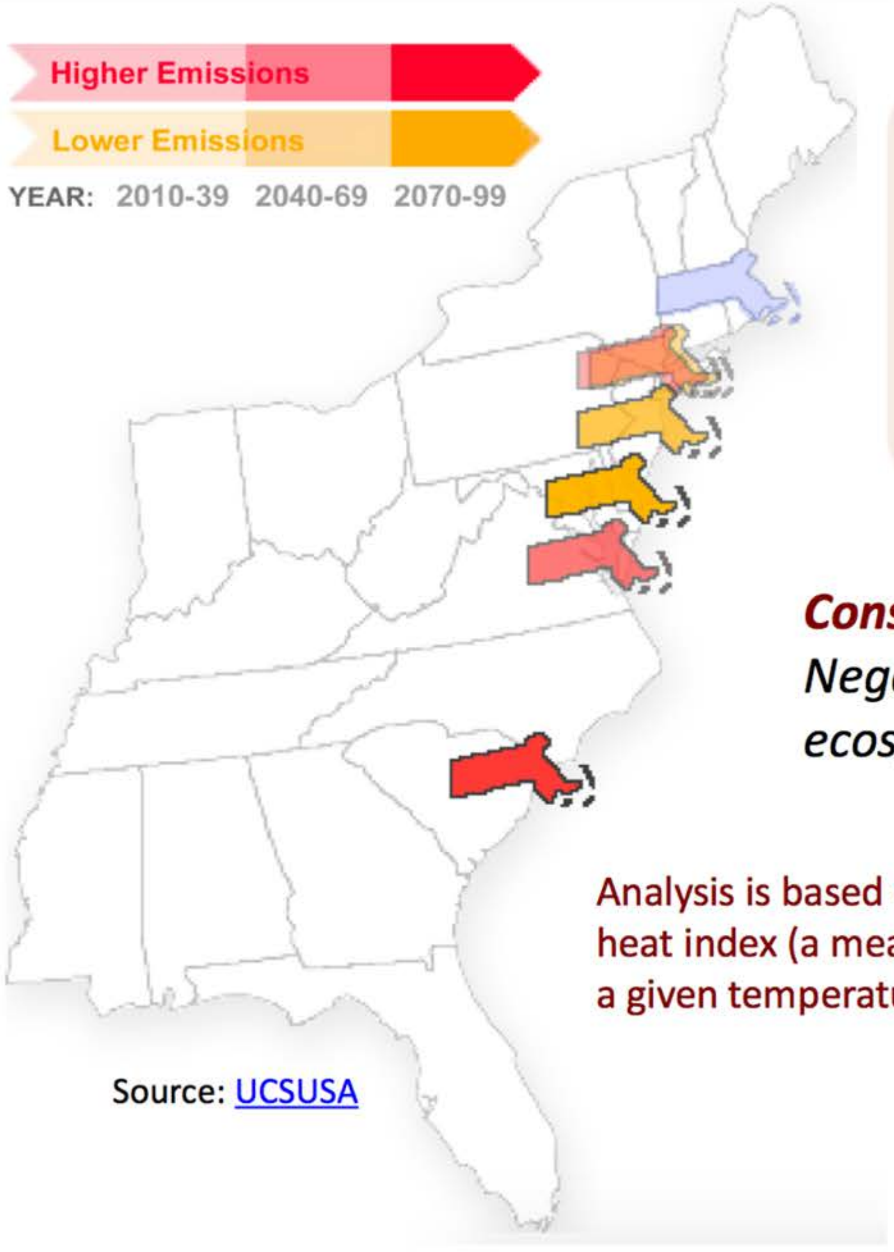
Source: *produced by CSRC, UMass Amherst*

Emissions scenarios:
high = A1Fi   low = B1



https://www.ipcc.ch/ipccreports/tar/wg1/figts-17.htm

Migrating Massachusetts Climate



Source: UCSUSA

PROJECTIONS

Summer in Massachusetts by the end of this century could feel like a present-day typical summer in South Carolina.

Consequences:

Negative impacts on human health, ecosystems, and the economy.

Analysis is based on changes in average summer heat index (a measure of how it actually feels for a given temperature and humidity).

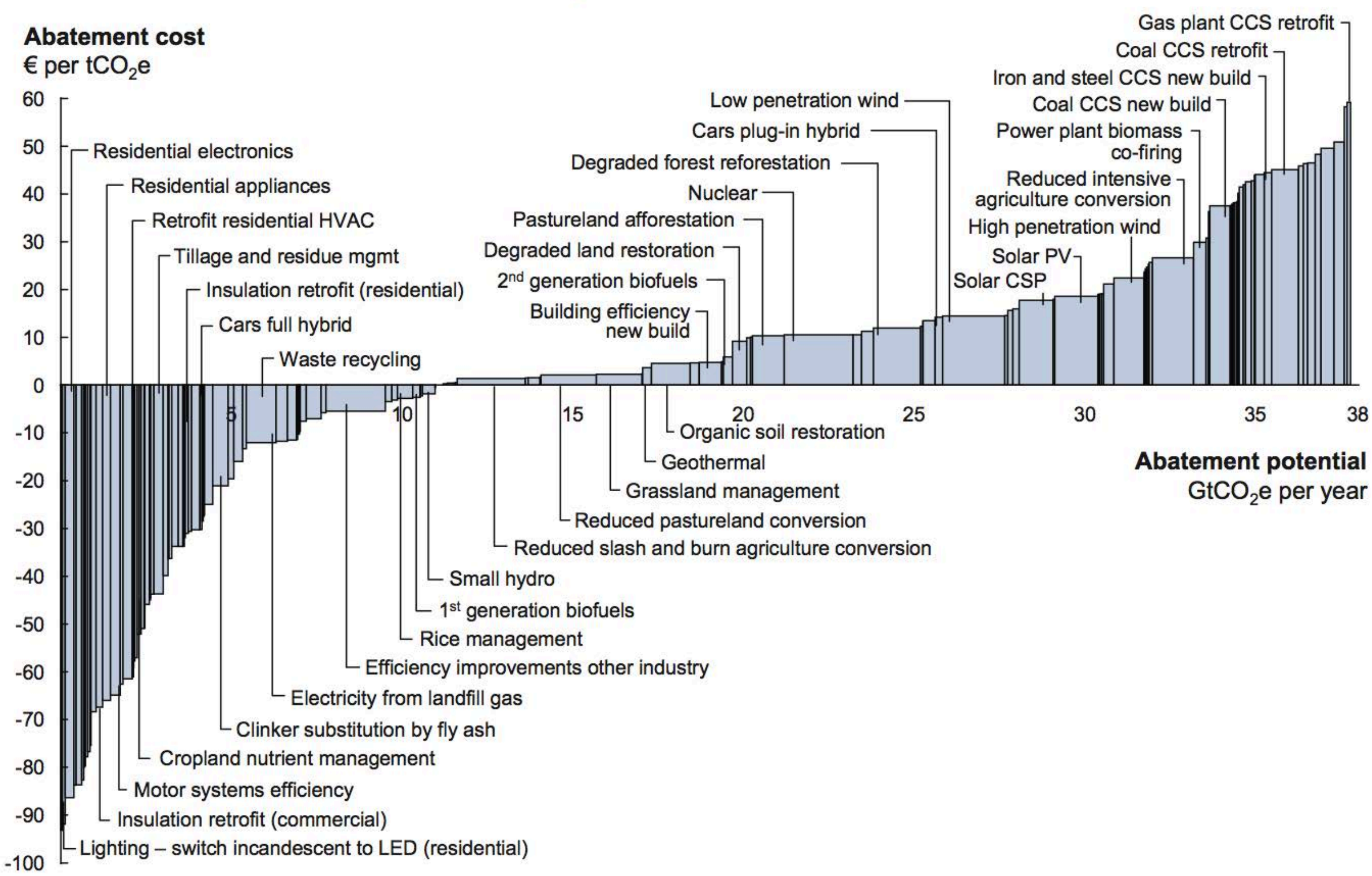
CLIMATE SYSTEM RESEARCH CENTER

Solar option decarbonizes energy

Source: Nathan Lewis, Caltech

Is solar PV or wind the best low-carbon investment?

Global GHG abatement cost curve beyond business-as-usual – 2030

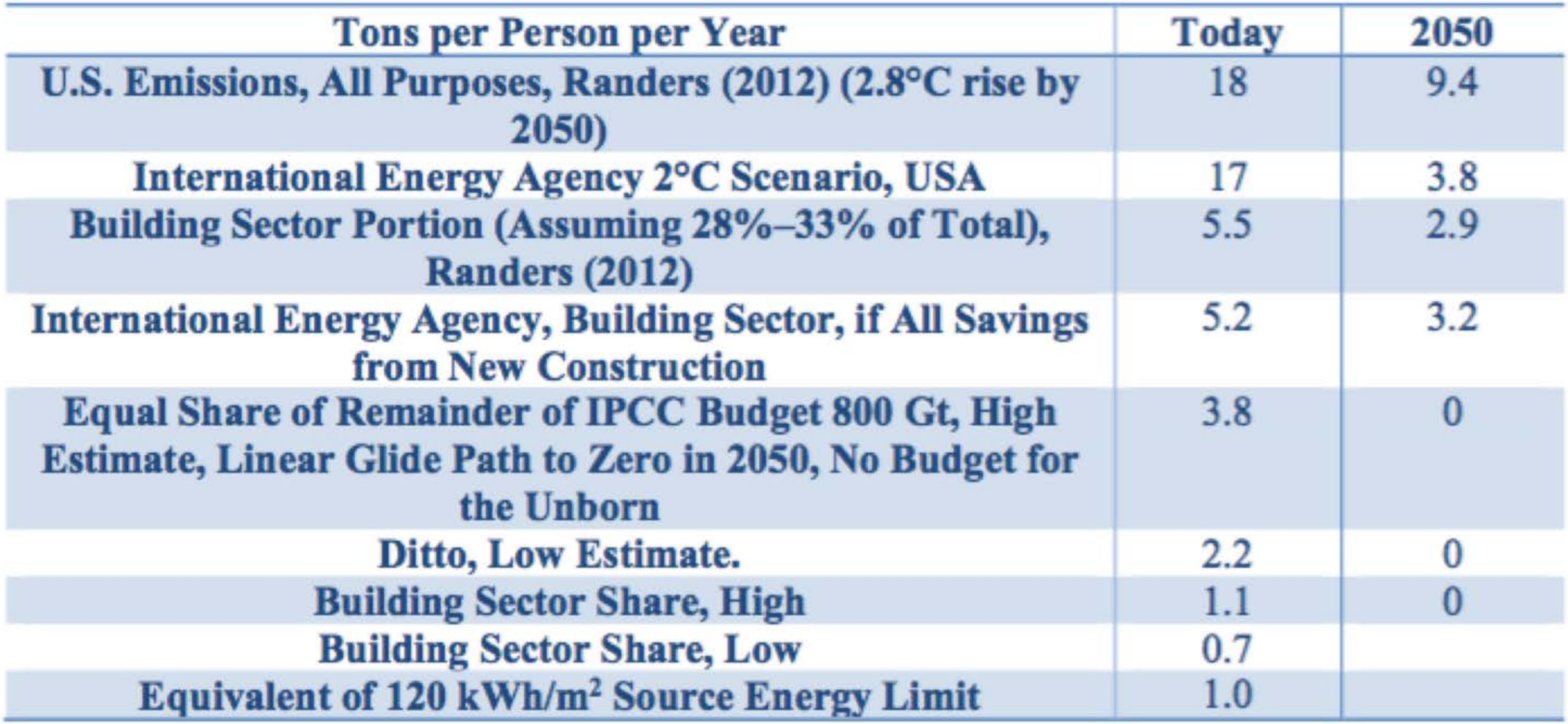


Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

PHIUS 2015 standard source energy criterion

- IPCC says we can emit about another 800 Gigatons for a 60% chance of < 2C temperature rise
- There are about 8 Gigapeople
- Atmosphere is the ultimate commons, so about 100 tons/person share.
- Current US rate ~17 tons/person.yr

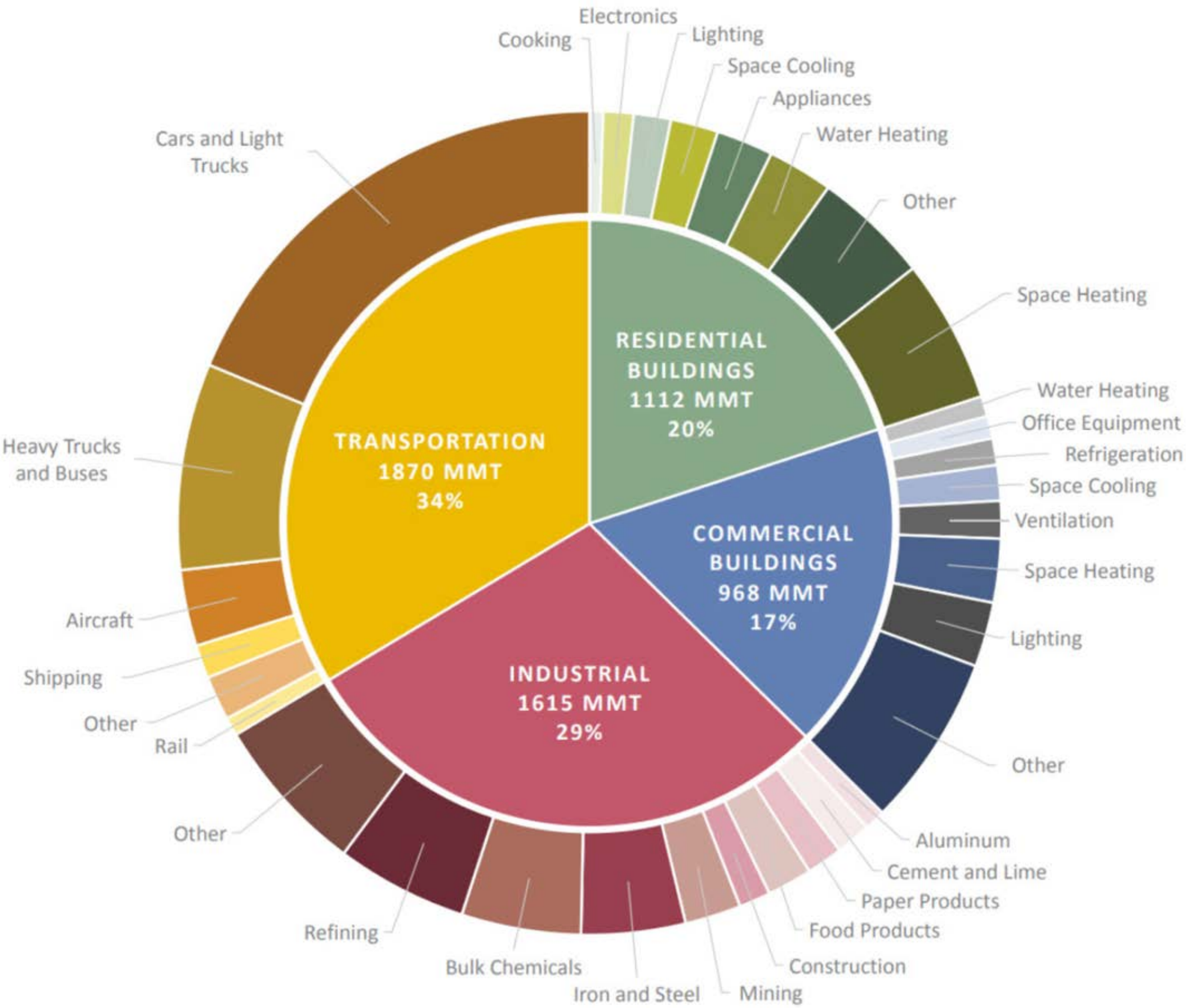
Source energy criterion



Tons per Person per Year	Today	2050
U.S. Emissions, All Purposes, Randers (2012) (2.8°C rise by 2050)	18	9.4
International Energy Agency 2°C Scenario, USA	17	3.8
Building Sector Portion (Assuming 28%–33% of Total), Randers (2012)	5.5	2.9
International Energy Agency, Building Sector, if All Savings from New Construction	5.2	3.2
Equal Share of Remainder of IPCC Budget 800 Gt, High Estimate, Linear Glide Path to Zero in 2050, No Budget for the Unborn	3.8	0
Ditto, Low Estimate.	2.2	0
Building Sector Share, High	1.1	0
Building Sector Share, Low	0.7	
Equivalent of 120 kWh/m^2 Source Energy Limit	1.0	

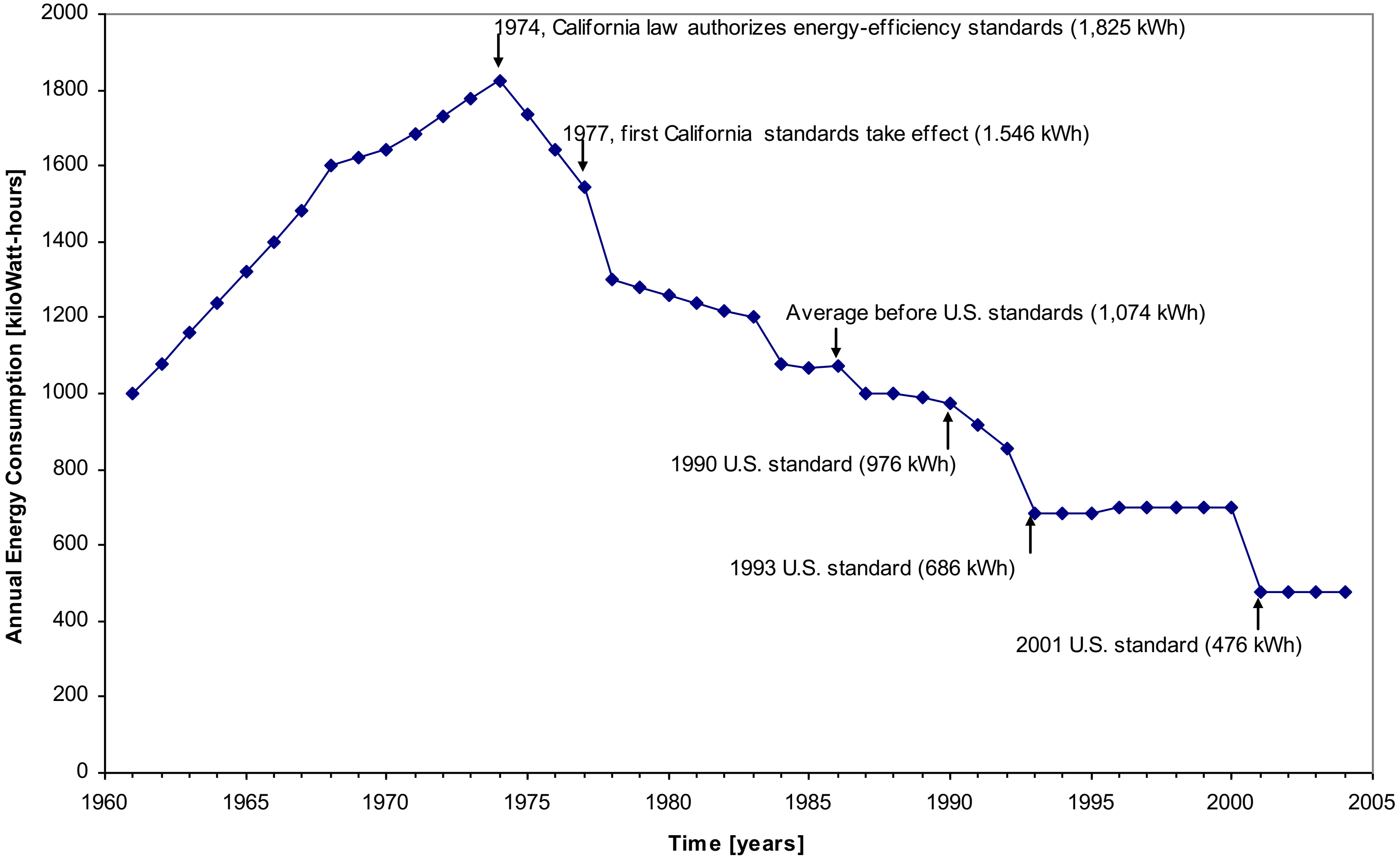
Wright, G.S. and K. Klingenberg. 2015. Climate-specific passive building standards.
U.S. Dept of Energy, Energy Efficiency and Renewable Energy (EERE)

2014 US end-use CO_2 emissions



4.) Obama Whitehouse

Refrigerators – good progress



Source: Collaborative Labeling and Appliance Standards Program

Super-insulated house in Illinois built to German Passivhaus guidelines

2-3 times as much insulation as a normal house, best-available windows and very tight construction

Heat-recovery ventilator with a single 1,000 W heater

January electricity bill: $35!!!

https://www.treehugger.com/sustainable-product-design/a-passiv-haus-in-urbana-illinois.html

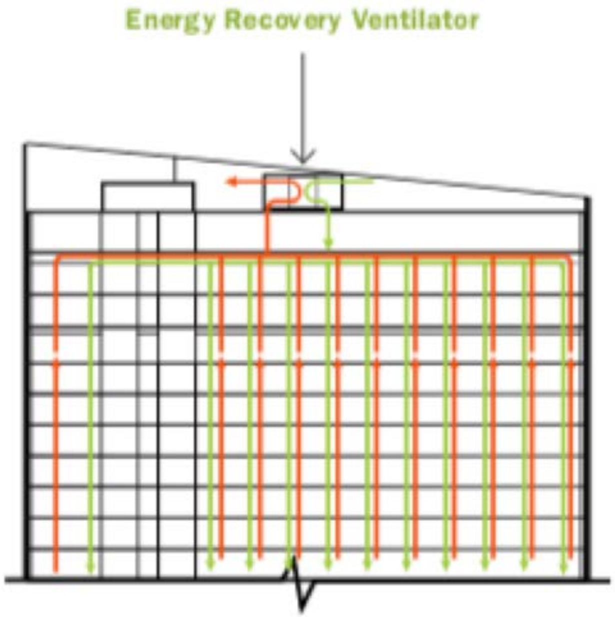
Zehnder Heat Recovery Ventilators

- Zehnder Novus 300 has 95% heat-recovery efficiency
- Air movement up to 177 cfm or 84 L/s (for reference, ASHRAE requires 29 L/s for a three-bedroom house)
- Separate supply and exhaust fans can be tuned to adjust airflows in 1% increments from 29-177 cfm (14-84 L/s)
- Low fan power: 0.23 Wh/m^3 = 0.83 W/L/s

https://zehnderamerica.com/wp-content/uploads/2014/02/Zehnder-Novus-300.pdf

World’s largest Passive House building

ny.curbed.com



←

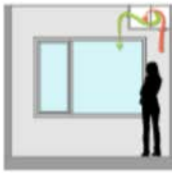
Bathrooms / Kitchens

Exhaust air exits the building at the roof after passing through the ERV so heat energy can be captured

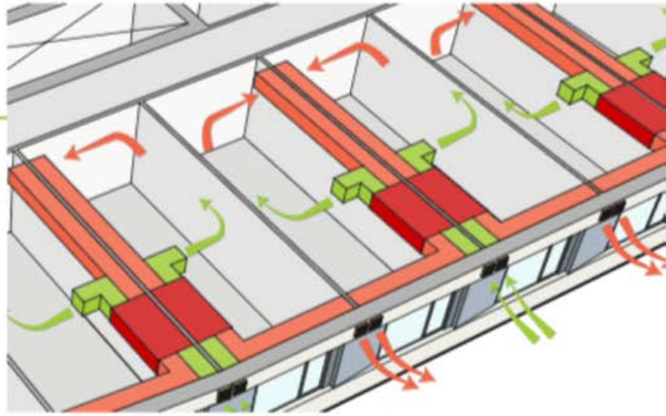
→

Fresh Air

Tempered supply air provided to all bedrooms and living rooms in separate supply risers

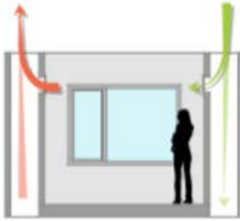


Unitized Ventilation System

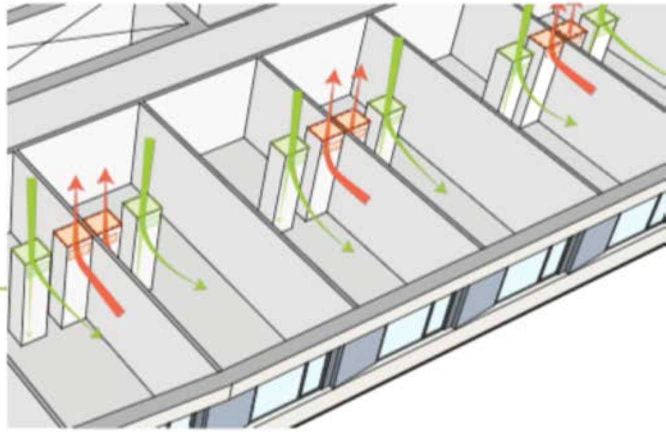


Many Passive House projects in the US and Europe employ "through-wall" ERVs, which take up very little space and provide the ventilation system for an apartment or home. However, each unit requires an air filter that needs to be changed regularly. In a 26-story high-rise, with more than 500 occupants and irregular tenancies, the maintenance costs for changing that many individual filters would have been prohibitive.

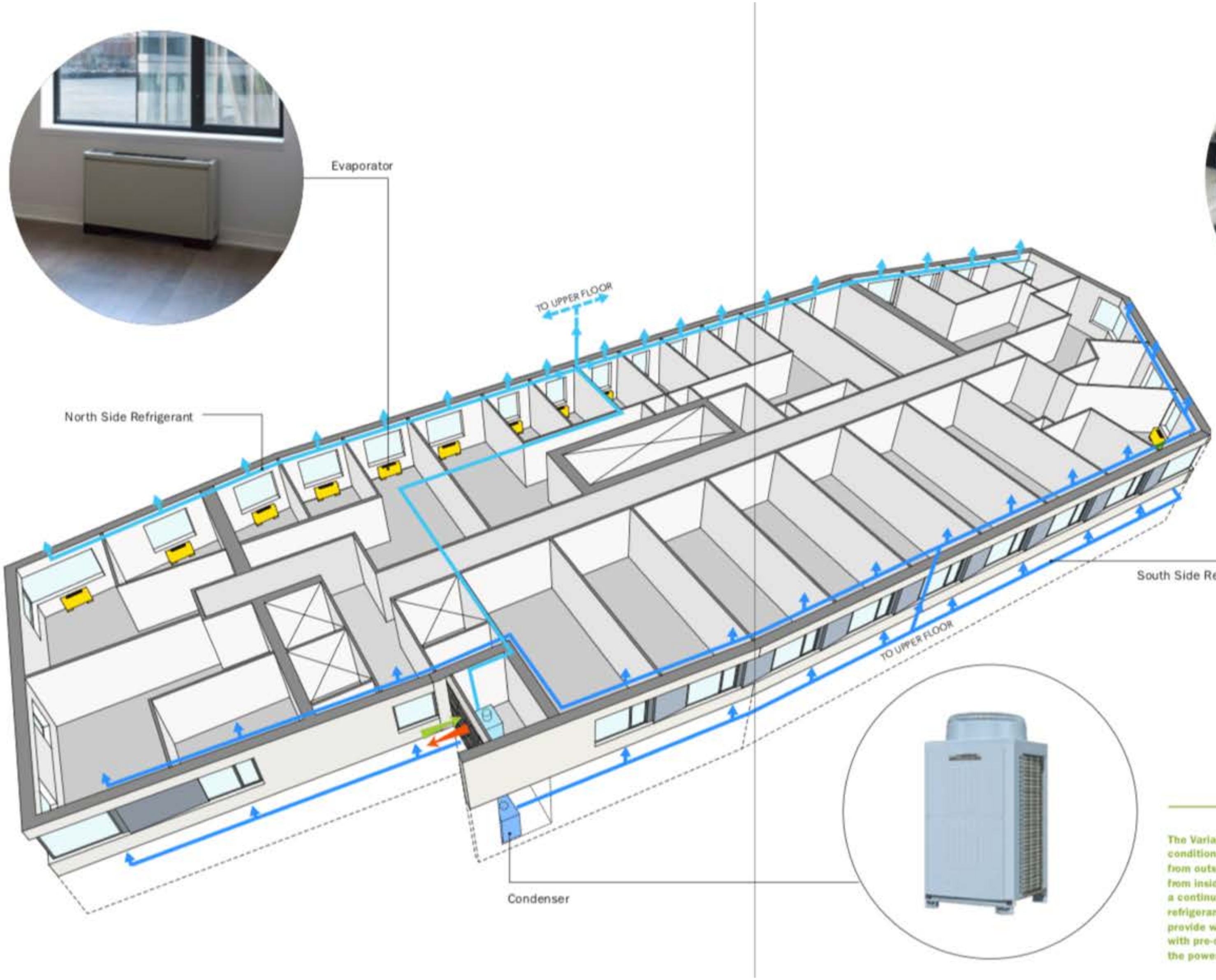
🟥	ERV
🟧	Exhaust Air
🟩	Fresh Air



Central Ventilation System



The central air distribution system at The House at Cornell Tech has only a small number of air filters in the rooftop ERVs: easy to maintain without disturbing tenants.



The Variable Refrigerant Flow (VRF) system is like a typical air conditioner, but works in both directions: It can extract heat from outside air to provide heat in cool months, or extract heat from inside air in warm months. Via an outdoor condenser in a continuous loop around the perimeter of the building, the refrigerant fluid is delivered to apartment evaporators that provide warm or cool air to each room. The spaces are filled with pre-conditioned fresh air from the ERV, thus minimizing the power needed to heat or cool individual rooms.

Handel Architects TheHouse_pamphlet_17092.pdf

No heating in the 1980s? Yes! Massachusetts State Transportation Building, Boston

Heat recovery from building core and storage in water tanks

Successful without A/C: Harare, Zimbabwe

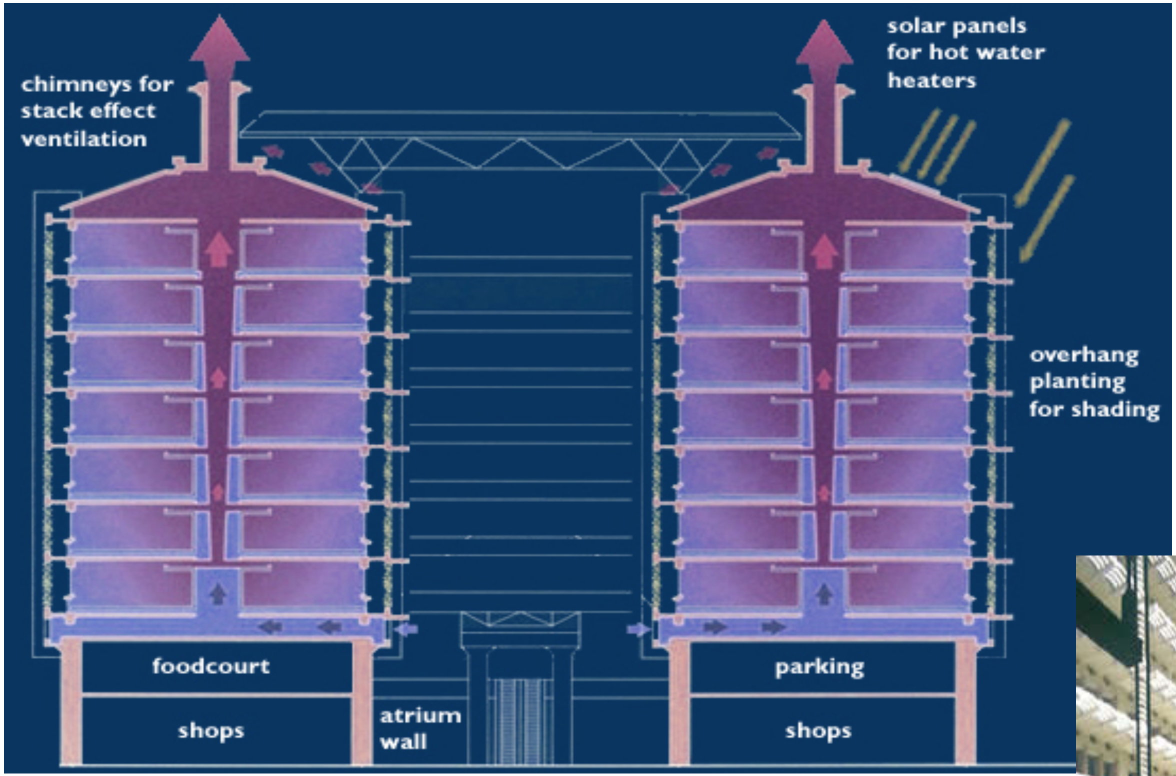
Zimbabwe's largest office + retail development

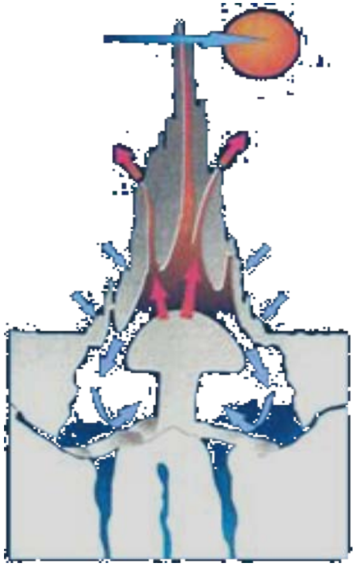
Relatively low cost

At the time of construction (1996), Africa's most advanced integrated, low-energy building

Images: Melissa Edmands

Ventilation strategy

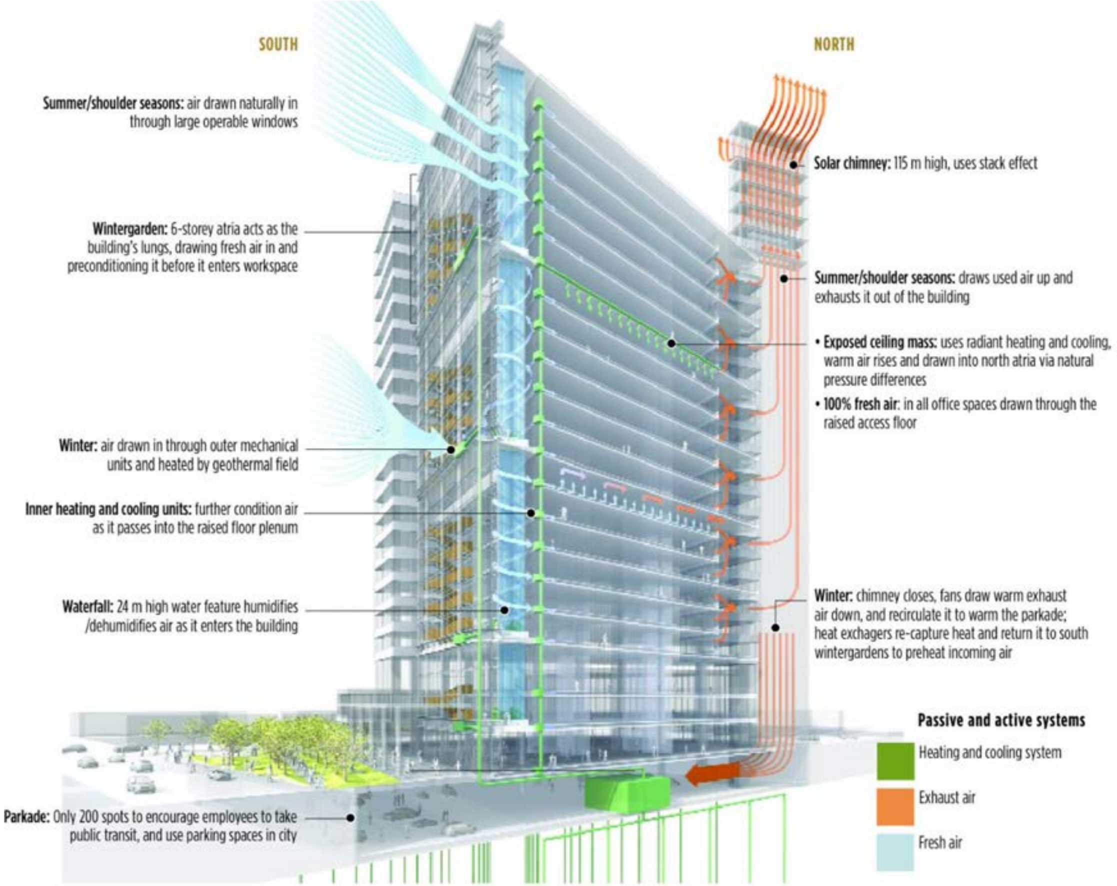




- thermal massing and natural ventilation scheme based on termite mounds
- simplicity of design facilitates cost restraint

http://www.mickpearce.com/Eastgate.html; https://inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/

Buoyancy-induced upward flow of cooled outdoor air



Summer/shoulder seasons: air drawn naturally in through large operable windows

Wintergarden: 6-storey atria acts as the building's lungs, drawing fresh air in and preconditioning it before it enters workspace

Winter: air drawn in through outer mechanical units and heated by geothermal field

Inner heating and cooling units: further condition air as it passes into the raised floor plenum

Waterfall: 24 m high water feature humidifies /dehumidifies air as it enters the building

Parkade: Only 200 spots to encourage employees to take public transit, and use parking spaces in city

Solar chimney: 115 m high, uses stack effect

Summer/shoulder seasons: draws used air up and exhausts it out of the building

- **Exposed ceiling mass:** uses radiant heating and cooling, warm air rises and drawn into north atria via natural pressure differences
- **100% fresh air**: in all office spaces drawn through the raised access floor

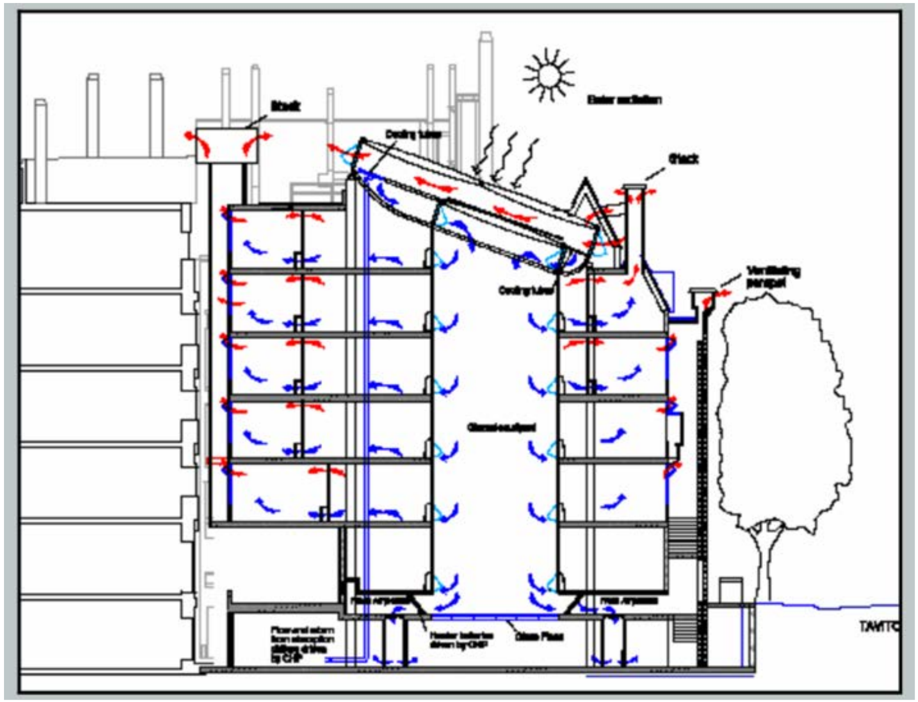
Winter: chimney closes, fans draw warm exhaust air down, and recirculate it to warm the parkade; heat exchagers re-capture heat and return it to south wintergardens to preheat incoming air

Passive and active systems

🟩 Heating and cooling system
🟧 Exhaust air
🟦 Fresh air

wikipedia.com, Manitoba Hydro

Buoyancy-induced downward and upward flow of cooled outdoor air
School of Slavonic and East European Studies, University College, London
Alan Short, Architect



K. Lomas, M. Cook and D. Fiala. Passive Downdraught cooling for non-domestic buildings. http://www.iesd.dmu.ac.uk/posters/kevin2.pdf

HVAC improvements needed if ZNE is to be achieved, in Masdar City and elsewhere

Annual solar radiation	7700 MJ/m^2
Annual electricity (15% efficiency)	330 kWh/m^2
Building energy use intensity (5 story)	66 kWh/m^2

Foster and Partners, carboun.com,

Doing less: reduce pressure “lift” across HVAC refrigerant compressor

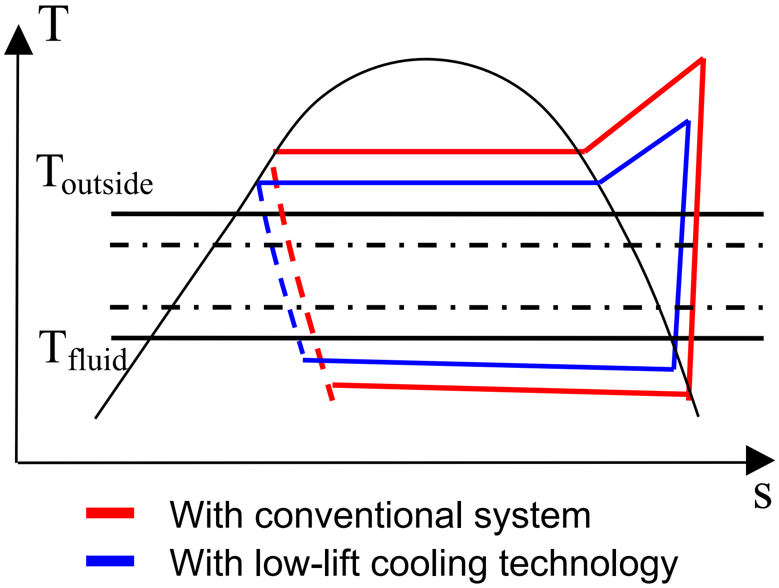
Thermally Activated Building Surface (TABS) - radiant cooling increases evaporating temperature and reduces transport power.

Thermal storage – reduces condensing temperature, peak loads and daytime loads. Use building as thermal storage saves useful building space.

Dedicated Outdoor Air System (DOAS) – provides better ventilation and humidity control.

Model Predictive Control (MPC) – enables strategic cooling, shifting cooling toward night time.

Cooling cycle in T-s diagram

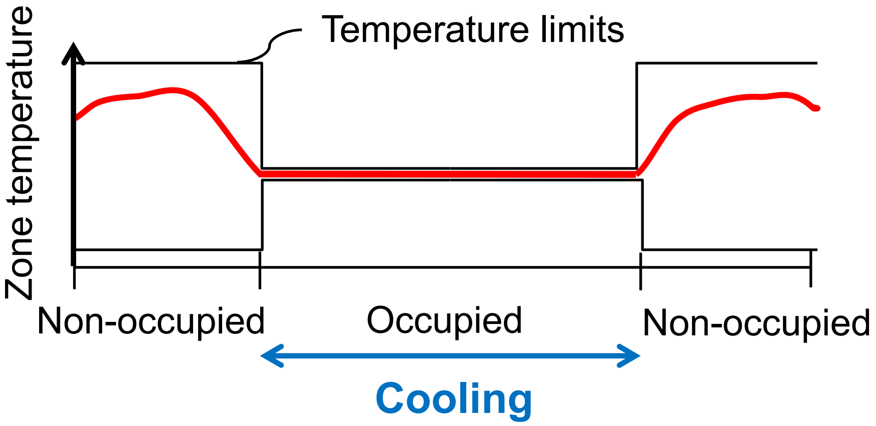


Low-lift cooling (slides 22-34) from MIT research of Nick Gayeski (now KGS Buildings) and Tea Zakula (now U. Zagreb), especially Dr. Zakula’s 2013 PhD thesis, Model predictive control for energy efficient cooling and dehumidification.

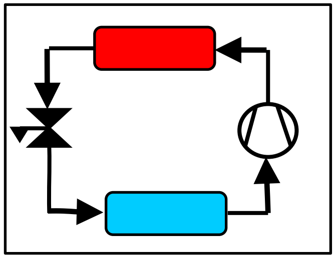
Conventional control of a conventional cooling system

Variable-Air-Volume system (VAV) used by majority of buildings delivers air to maintain constant temperature during occupied hours.

Conventional control



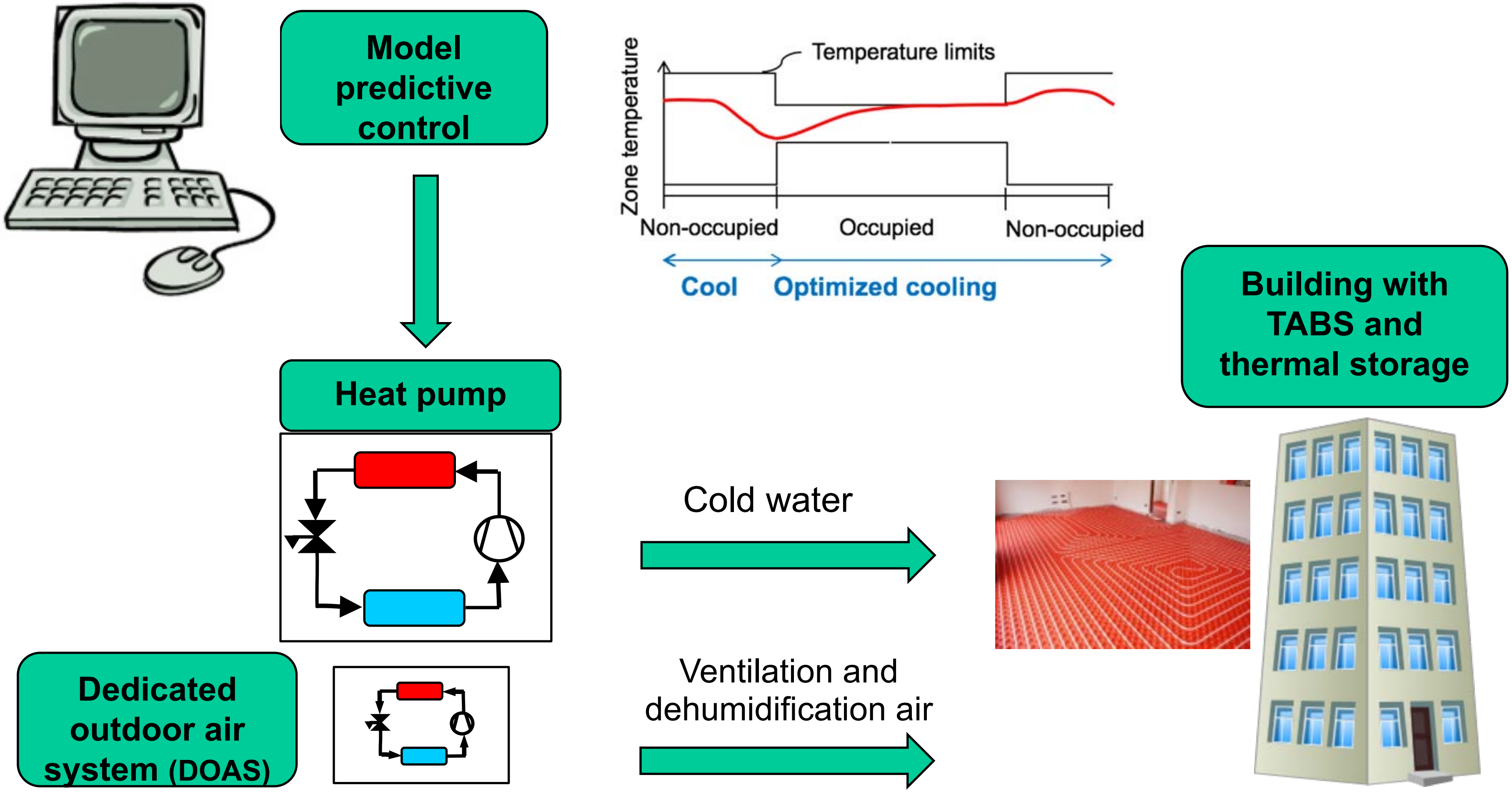
Heat pump



Cold air for cooling, ventilation and dehumidification

Model predictive control of a low-lift cooling system

Low-Lift Cooling System (LLCS) delivers cold water to Thermally Activated Building Surfaces (TABS). Cooling is optimized by the Model Predictive Control (MPC) algorithm.



Model predictive control

Heat pump

Dedicated outdoor air system (DOAS)

Building with TABS and thermal storage

Cold water

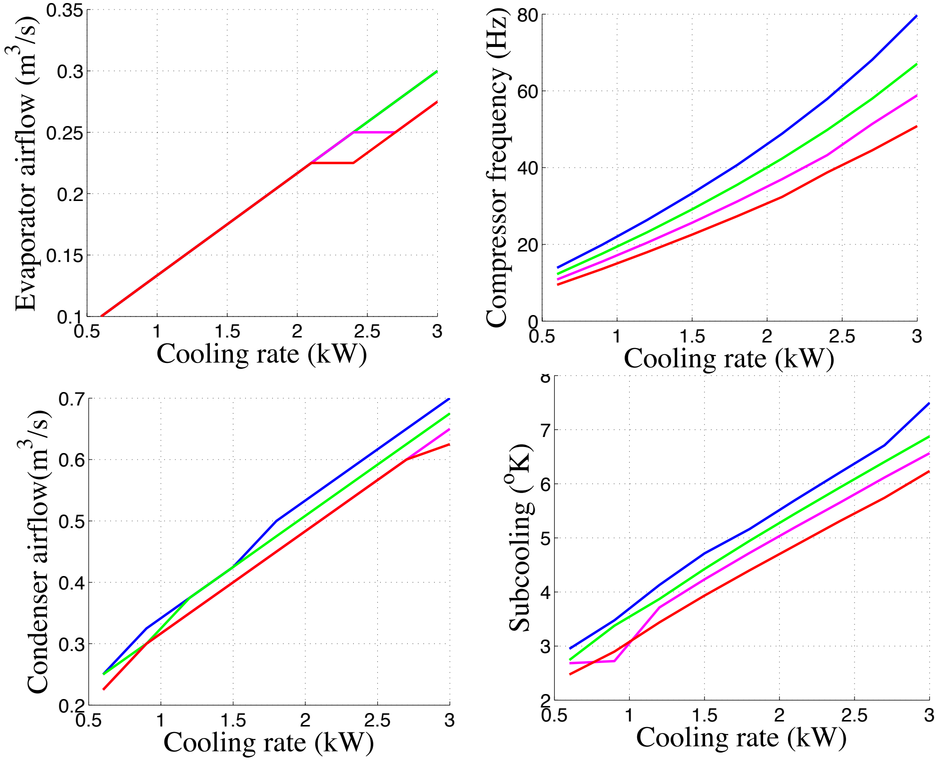
Ventilation and dehumidification air

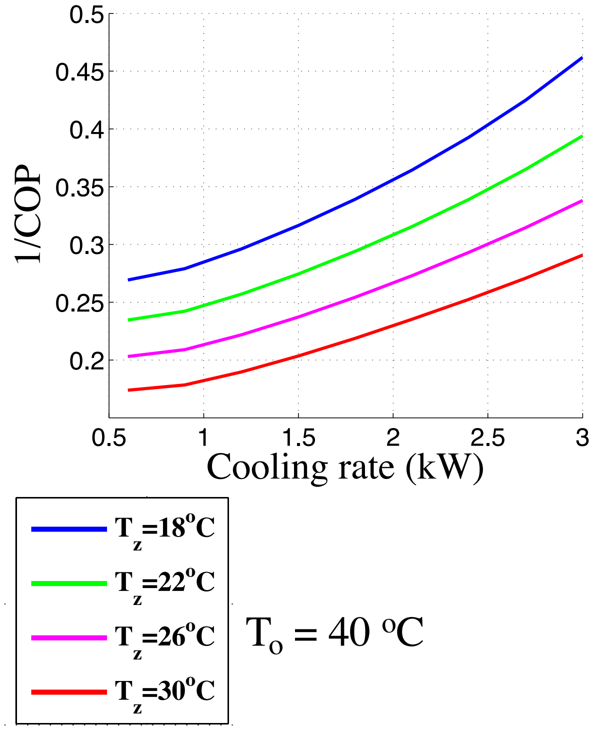
Heat pump maps

The results of heat pump optimization, developed from first-principles component models, for a range of cooling conditions.

Optimal parameters

Power consumption

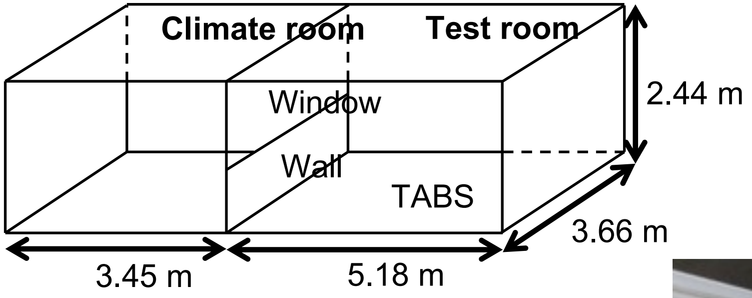


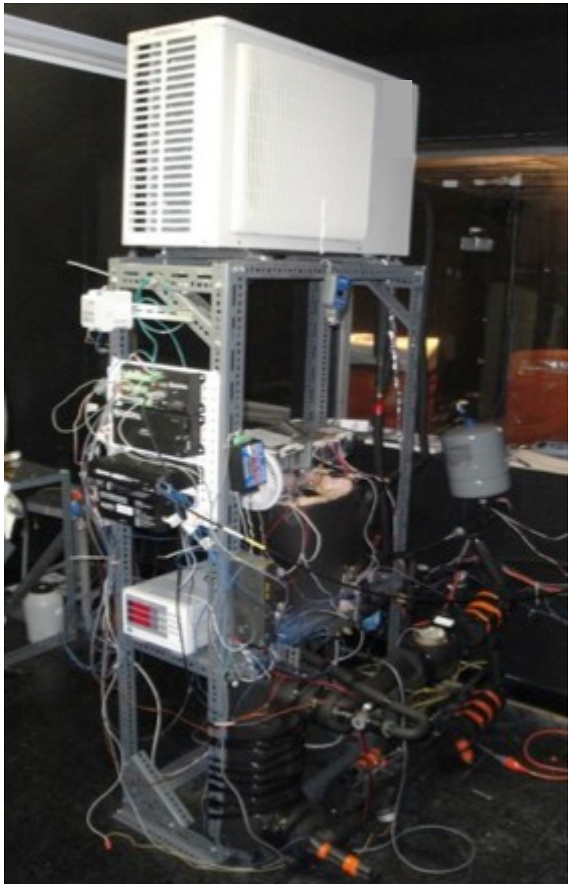


T_o = 40 °C

Experimental evaluation of control strategy in MIT test chamber

- 25% cooling energy savings for Atlanta typical summer week
- 19% cooling energy savings for Phoenix typical summer week

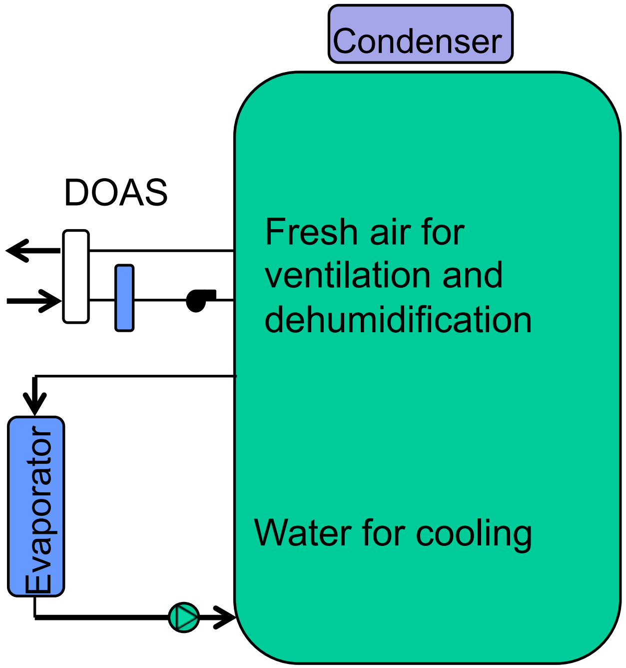




LLCS vs. conventional VAV

Simulating a typical summer week and 22-week period across 16 climates assuming standard internal loads (from people and equipment) for an office.

LLCS



Condenser

DOAS

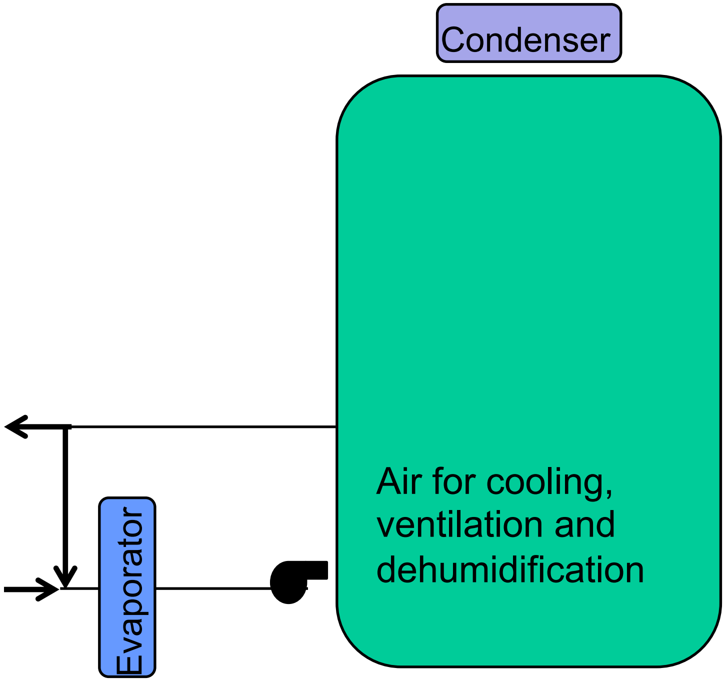
Fresh air for ventilation and dehumidification

Evaporator

Water for cooling

Operated under MPC
with temperatures allowed to float
between 20 and 25°C during occupied hours

VAV



Condenser

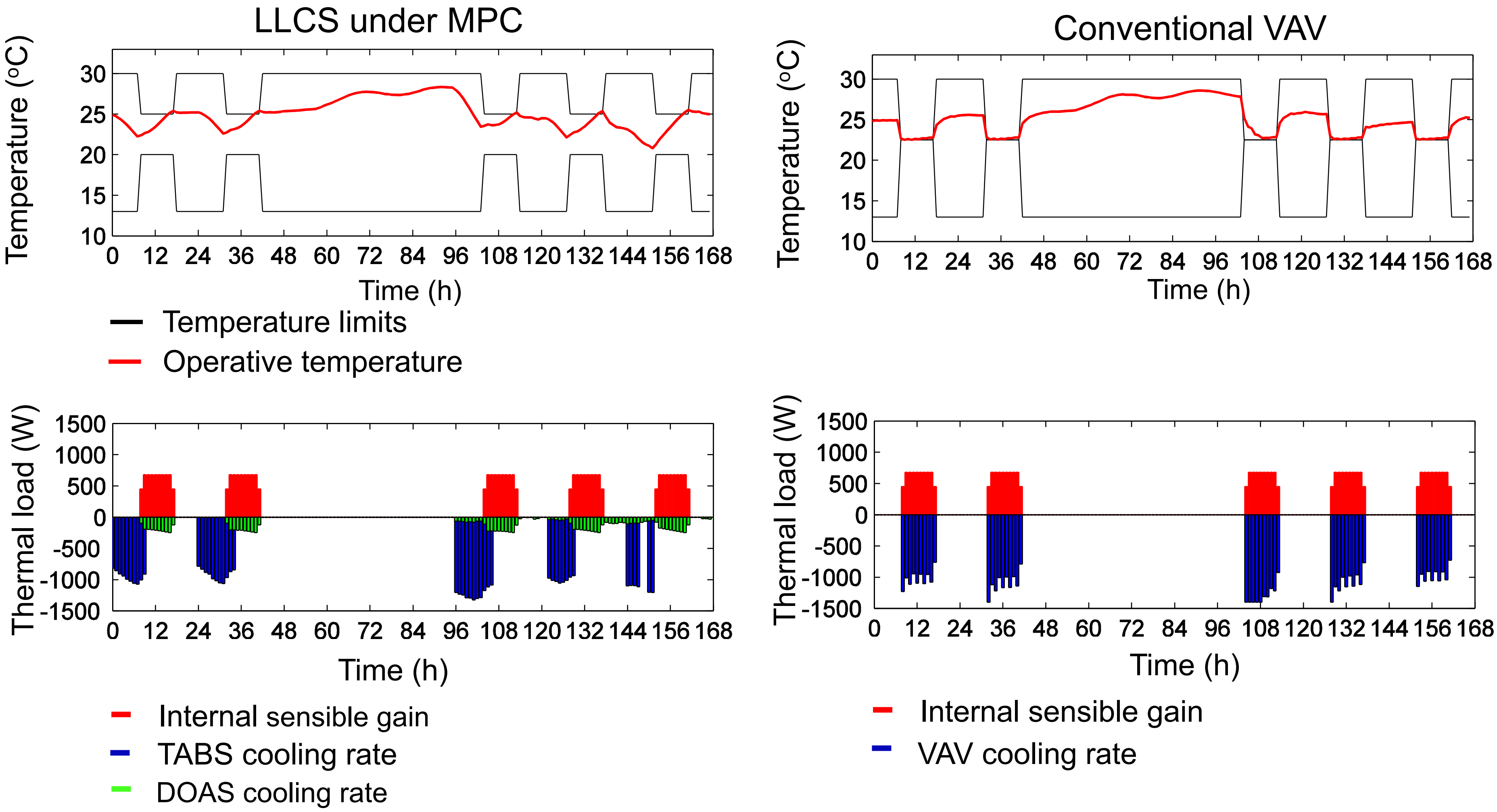
Evaporator

Air for cooling, ventilation and dehumidification

Operated under conventional control
(only during the operating hours to
maintain constant temperature of 22.5°C)

LLCS vs conventional VAV

Results: zone temperatures and cooling rates for Phoenix climate

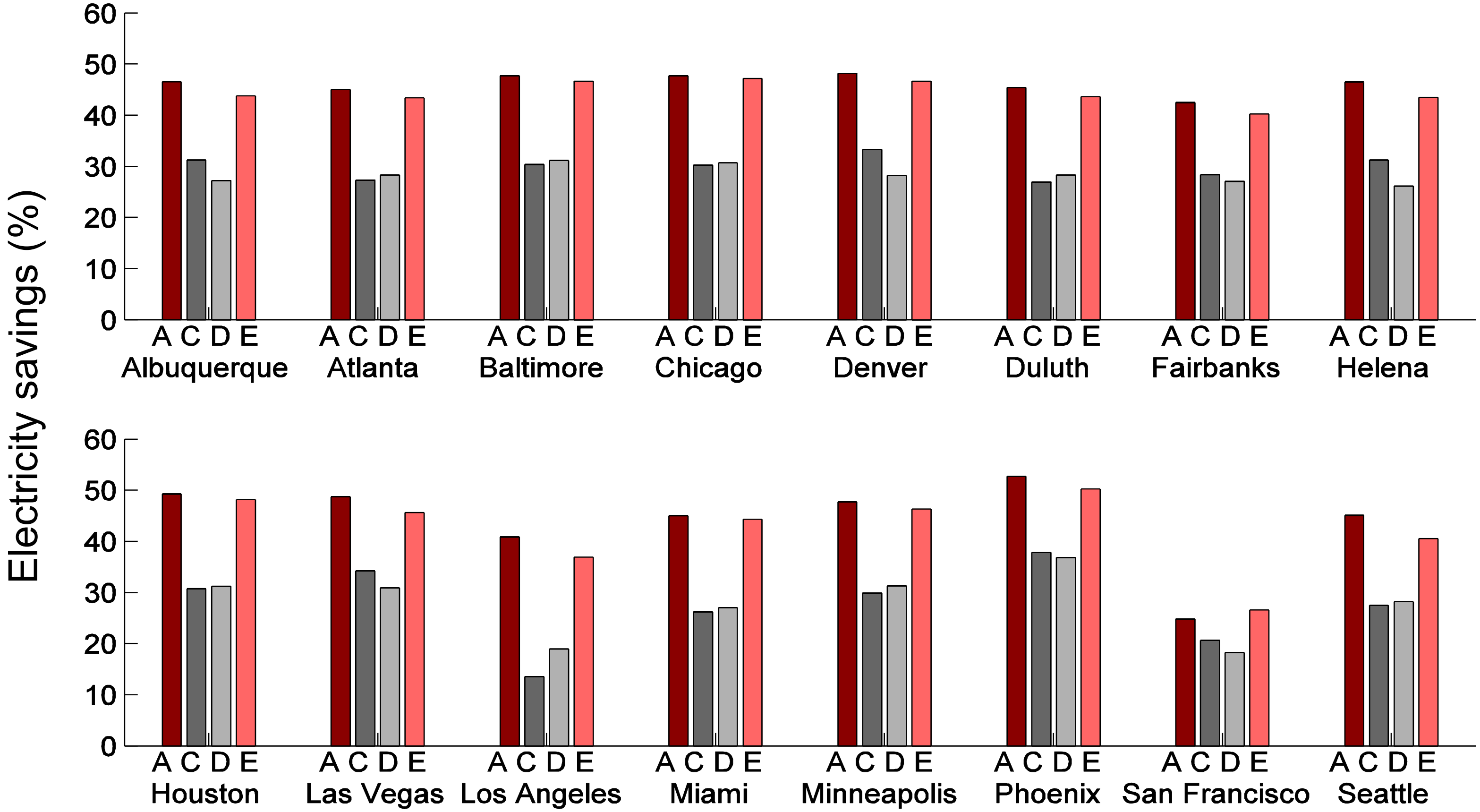


LLCS under MPC

Conventional VAV

LLCS vs conventional VAV

Results: LLCS electricity savings for a typical summer week



🟦 A LLCS with condenser placed outside → **typical and best performing**

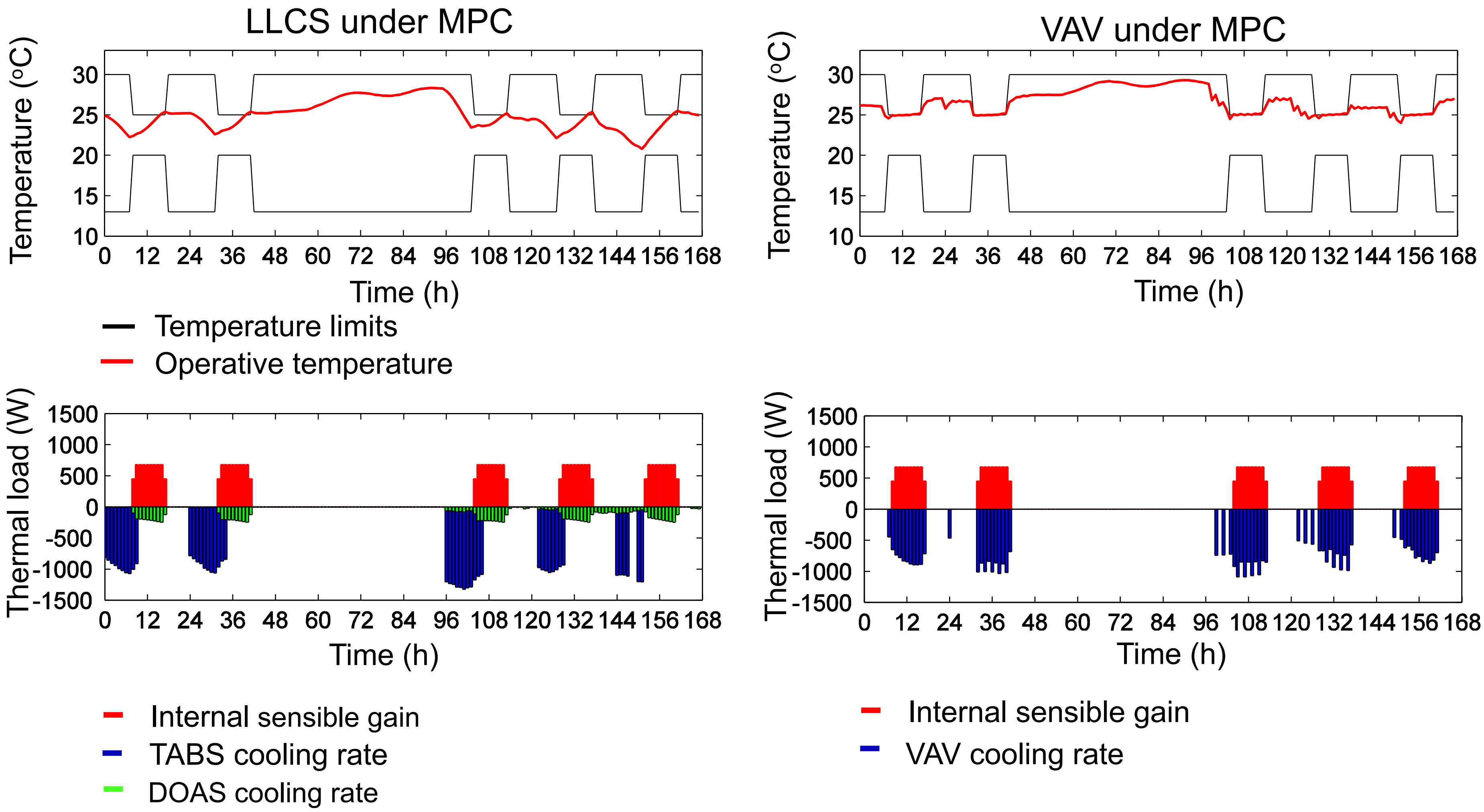
C LLCS with parallel condensers, one in supply, the other in return stream

D LLCS with parallel condensers, one in supply stream, the other outside

🟦 E LLCS with condenser placed outside and run-round heat pipe → **second best performing**

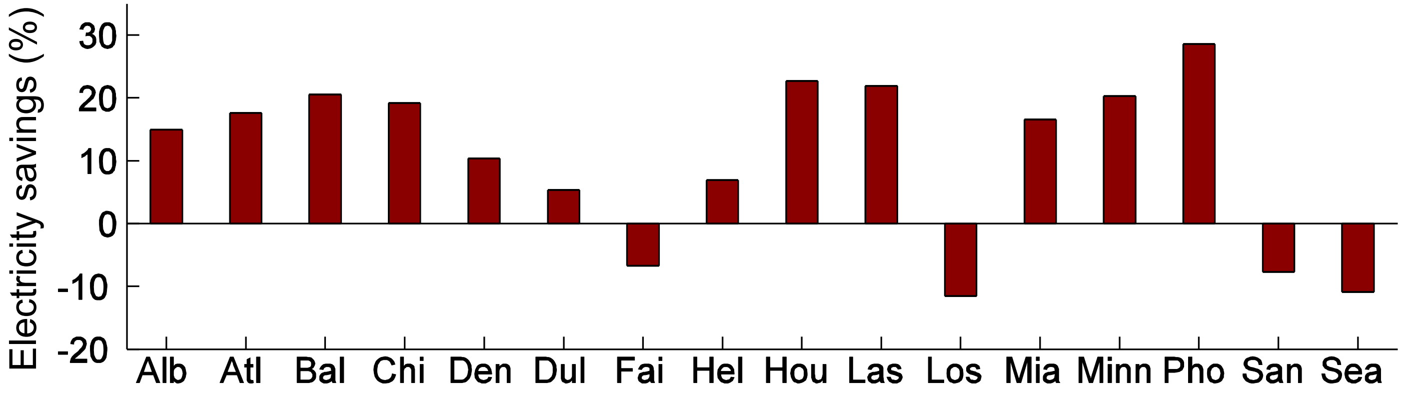
LLCS vs VAV under MPC

Results: zone temperatures and cooling rates for Phoenix climate

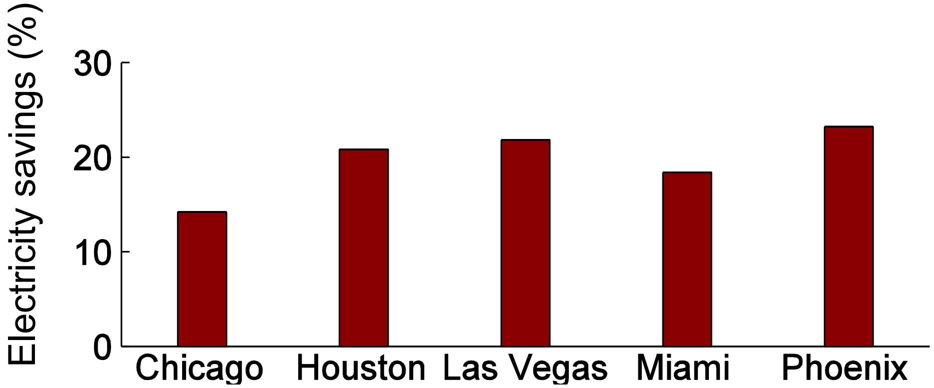


LLCS vs VAV under MPC

Results: LLCS electricity savings for a typical summer week*



Results: LLCS electricity savings from May 1st – September 30th*



*LLCS assumes simple DOAS (system A)

Ductless heating and cooling systems (also known as split systems)

Indoor units

Refrigerant lines (not ducts)

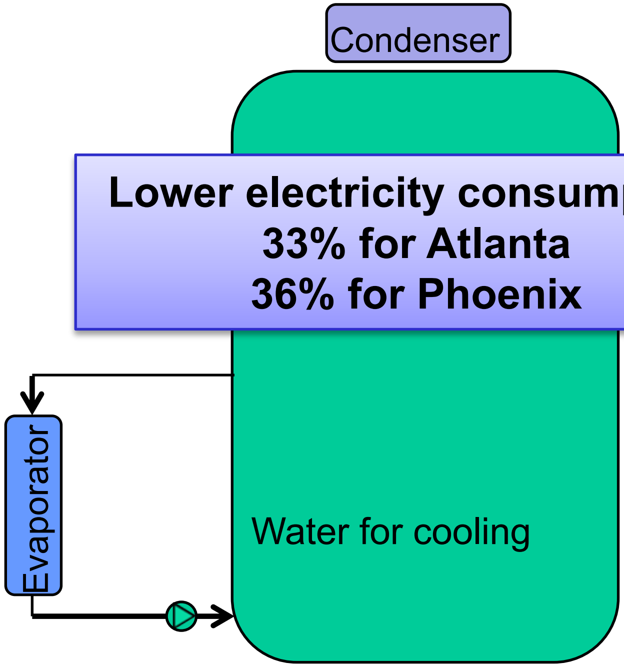
Outdoor unit

nisair.com

LLCS vs conventional split-system

Simulating a typical summer week in Atlanta and Phoenix, and taking into account only sensible cooling (no ventilation and dehumidification system).

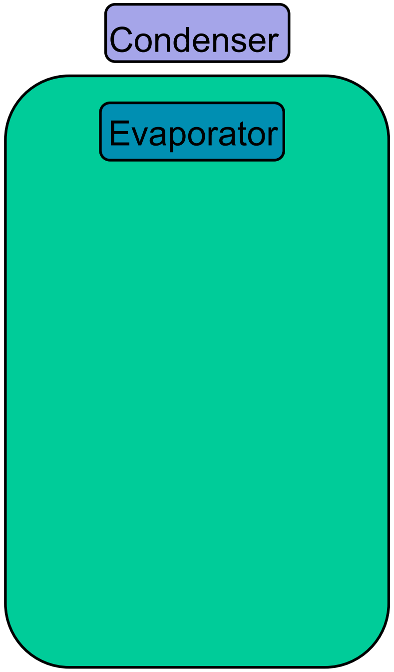
LLCS



Lower electricity consumption
33% for Atlanta
36% for Phoenix

Operated under MPC
with temperatures allowed to float
between 20 and 25^{o}C during occupied hours

Split-system

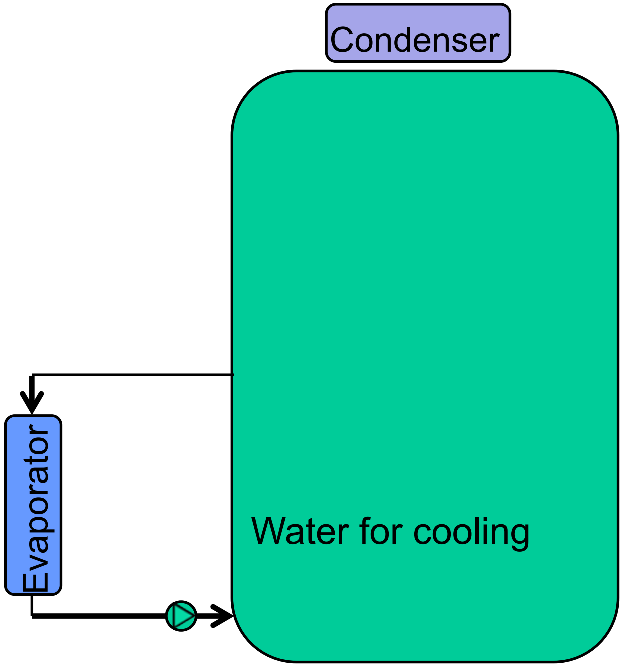


Operated under conventional control
(only during the operating hours to
maintain constant temperature of 22.5^{o}C)

LLCS vs split-system under MPC

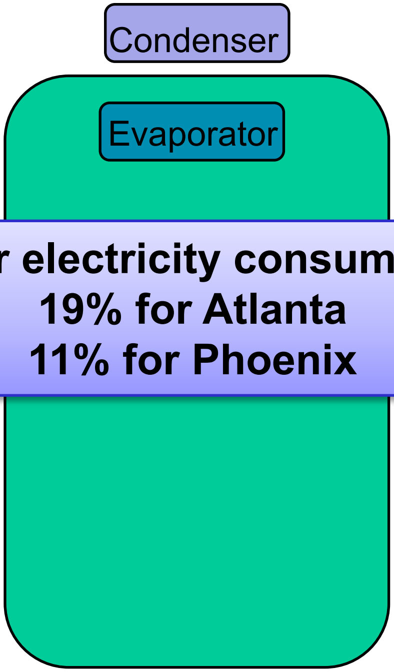
Simulating a typical summer week in Atlanta and Phoenix, and taking into account only sensible cooling (no ventilation and dehumidification system).

LLCS



Operated under MPC
with temperatures allowed to float
between 20 and 25^{o}C during occupied hours

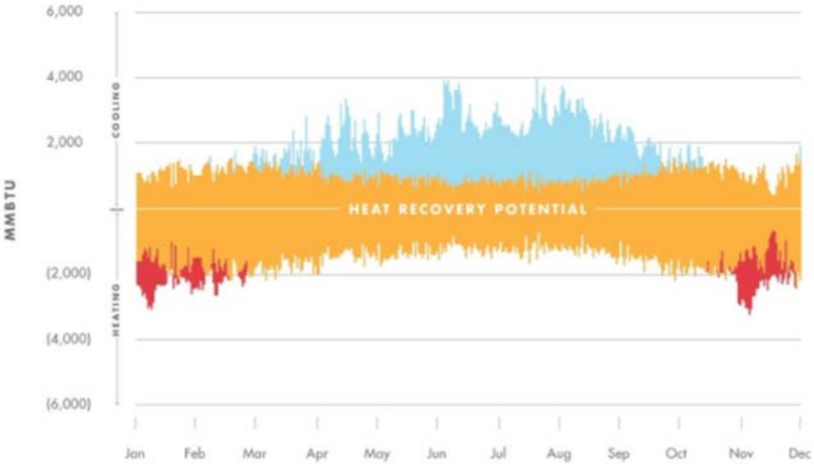
Split-system



Lower electricity consumption
19% for Atlanta
11% for Phoenix

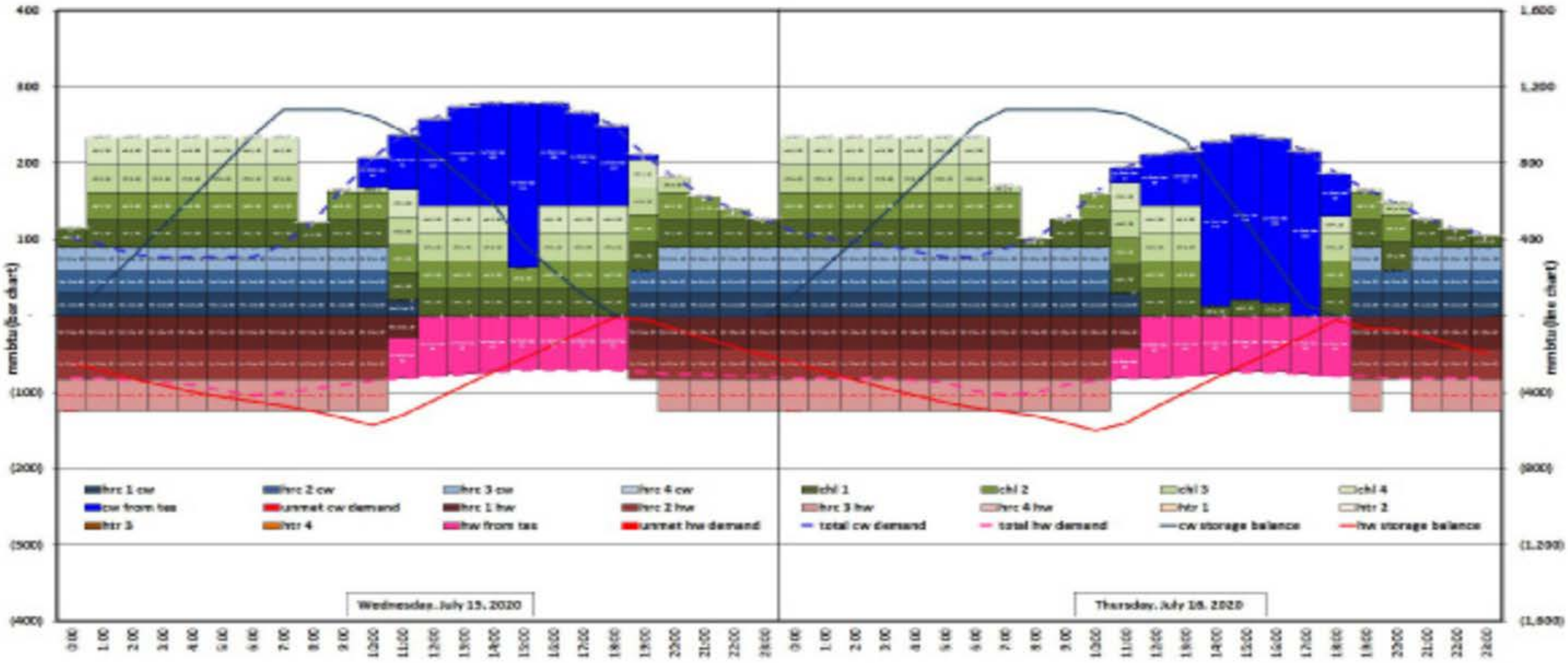
Operated under MPC
with temperatures allowed to float
between 20 and 25^{o}C during occupied hours

Stanford Central Energy Facility: heat recovery from buildings and a path to decarbonization



archdaily.com, inhabit.com, ZGF Architects

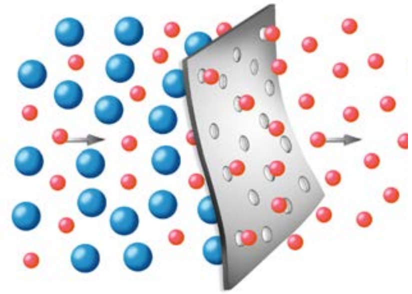
Model Predictive Control at large scale!

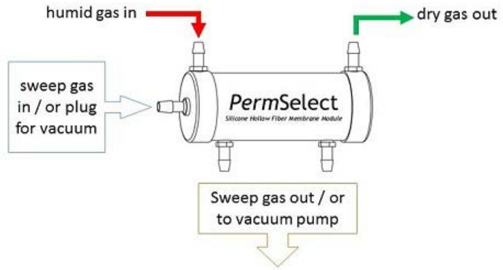


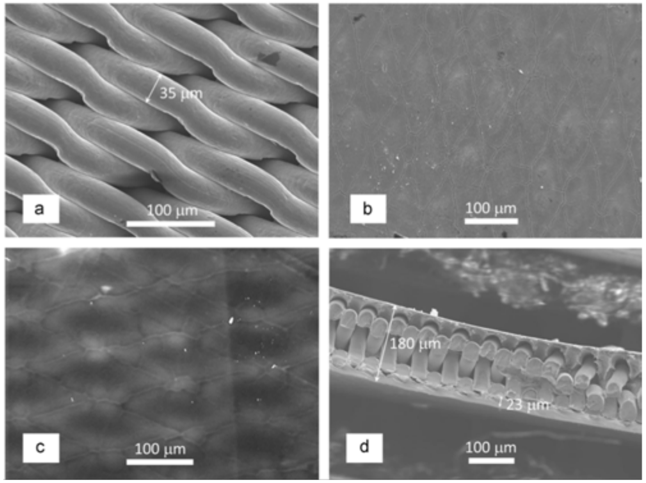
Sample optimal CEF dispatch plan generated through CEPOM

Desiccants and membranes for latent cooling

- **Current approach has VERY low second-law efficiency, in large part because removal of water vapor by condensation on cooling coils is very energy intensive**
- **Desiccants are attractive, with attention to low temperatures for regeneration that facilitate the use of waste heat from air-conditioner or chiller condensers**
- **Membranes can act as molecular sieves, with vapor drawn out by a vacuum pump or equivalent and condensed**
- **By separating latent and sensible cooling, chilled water supply temperatures can be raised from 7 to 13 °C.**







a) Wiremesh scaffold; b) TiO_2 layer; c) top polymer layer; d) membrane cross section

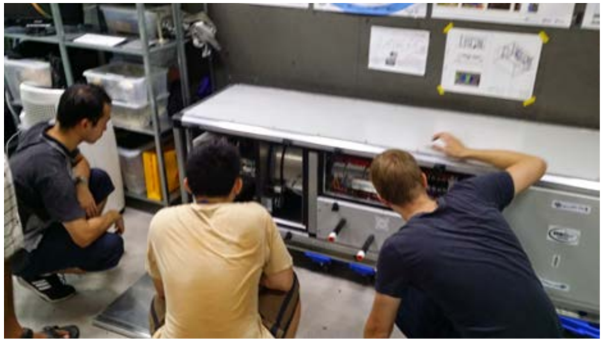
Condensing water vapor, chiller COP 3.0 ~200 kWh/m^3
Thermal desalination 10-14
Theoretical minimum 1

medaad.com, www.permaselect.com,
Bui et al. JMS 2016

Singapore-ETH Center's 3for2 technology (no ducts or suspended ceilings)

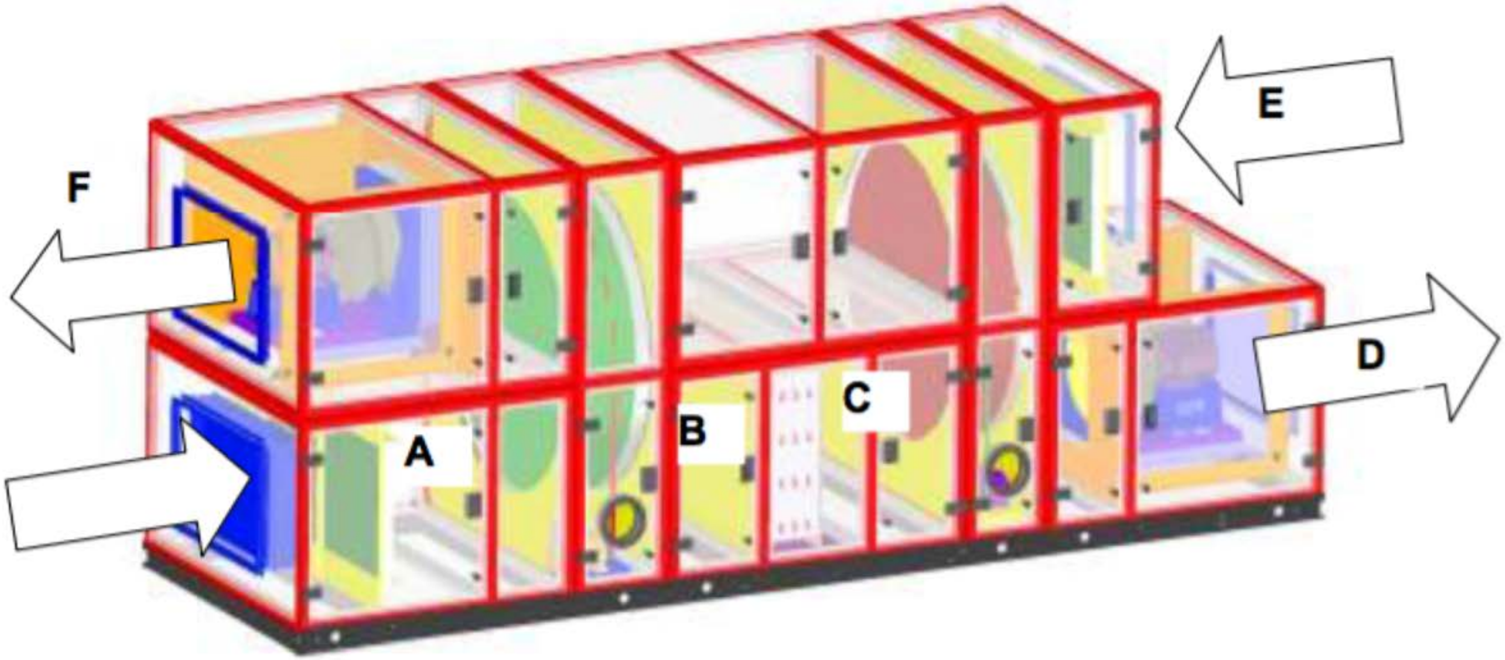
- Gypsum / plaster conduits hide mechanical and electrical distribution fittings (e.g., pipework, connections, wiring, etc.)
- Passive chilled beams are implemented in lieu of radiant chilled panels for sensible cooling
- Raised floor system installed in lieu of void-form concrete slab

- Dedicated outdoor air system (DOAS) with built-in energy recovery devices provide latent cooling
- Sloped façade implemented with integrated plenum area for mounting ventilation units
- Fresh air supplied through underfloor air distribution (UFAD) network



ura.gov.sg/uol/urbanlab/visit-exhibition/current/FCL/Events/~/media/User%20Defined/URA%20Online/urban-lab/Past-events/3for2_ARysanek.ashx

DRI dedicated outdoor air system (DOAS)



A – Hot & Humid outside Air Inter in to the System

B – Fresh Air Leaving the Ecofresh Rotor after recovering return air energy & Entering in to the cooling coil for further cooling

C – Fresh Air leaving the Cooling Coil after cooling & dehumidifying

D – Supply Air Leaving the Passive Desiccant Wheel & enter to the building after removing the Moisture

E – Cool & Dry Return Air coming from Room

F – Hot & Humid air exhausted to the Atmosphere.

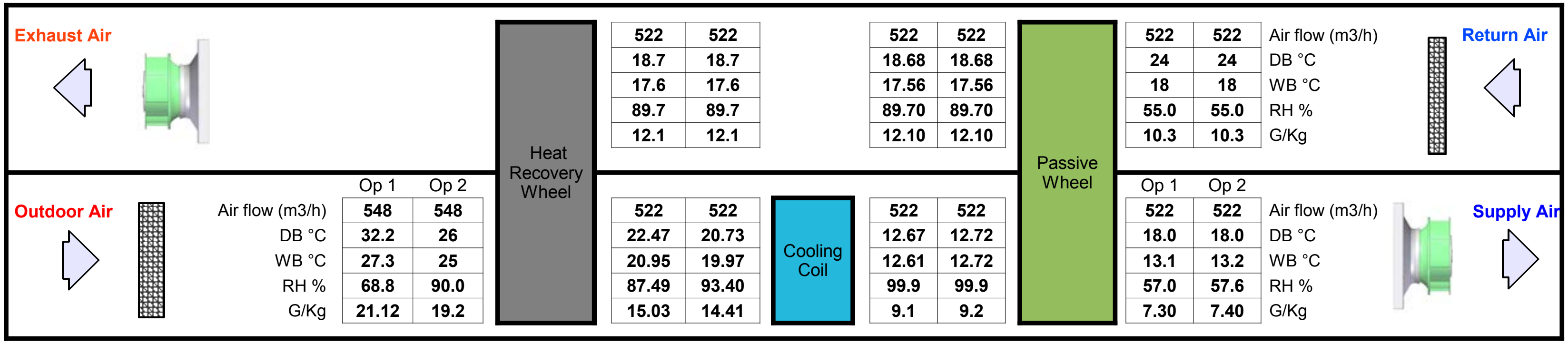
Desiccant Rotors Intl ERV-500 DOAS
DRI DOAS Manual 141001.pdf

Original manufacturer specifications of ‘3for2’ Dedicated Outdoor Air System (DOAS)

Project : FCL Project / UWC Building

Date : July 10,2014

Configuration of DOAS (MS200+CC+PDHC200)



Exhaust side (Exhaust Air ← Heat Recovery Wheel ← Passive Wheel ← Return Air):

	After Heat Recovery Wheel Op 1	After Heat Recovery Wheel Op 2	Before Heat Recovery Wheel Op 1	Before Heat Recovery Wheel Op 2	Return Air Op 1	Return Air Op 2
Air flow (m3/h)	522	522	522	522	522	522
DB °C	18.7	18.7	18.68	18.68	24	24
WB °C	17.6	17.6	17.56	17.56	18	18
RH %	89.7	89.7	89.70	89.70	55.0	55.0
G/Kg	12.1	12.1	12.10	12.10	10.3	10.3

Supply side (Outdoor Air → Heat Recovery Wheel → Cooling Coil → Passive Wheel → Supply Air):

	Outdoor Air Op 1	Outdoor Air Op 2	After Heat Recovery Wheel Op 1	After Heat Recovery Wheel Op 2	After Cooling Coil Op 1	After Cooling Coil Op 2	Supply Air Op 1	Supply Air Op 2
Air flow (m3/h)	548	548	522	522	522	522	522	522
DB °C	32.2	26	22.47	20.73	12.67	12.72	18.0	18.0
WB °C	27.3	25	20.95	19.97	12.61	12.72	13.1	13.2
RH %	68.8	90.0	87.49	93.40	99.9	99.9	57.0	57.6
G/Kg	21.12	19.2	15.03	14.41	9.1	9.2	7.30	7.40

Cooling Capacity		Water flow
Option 1	4.2 kW	0.1988 l/s
Option 2	3.7 kW	0.1759 l/s

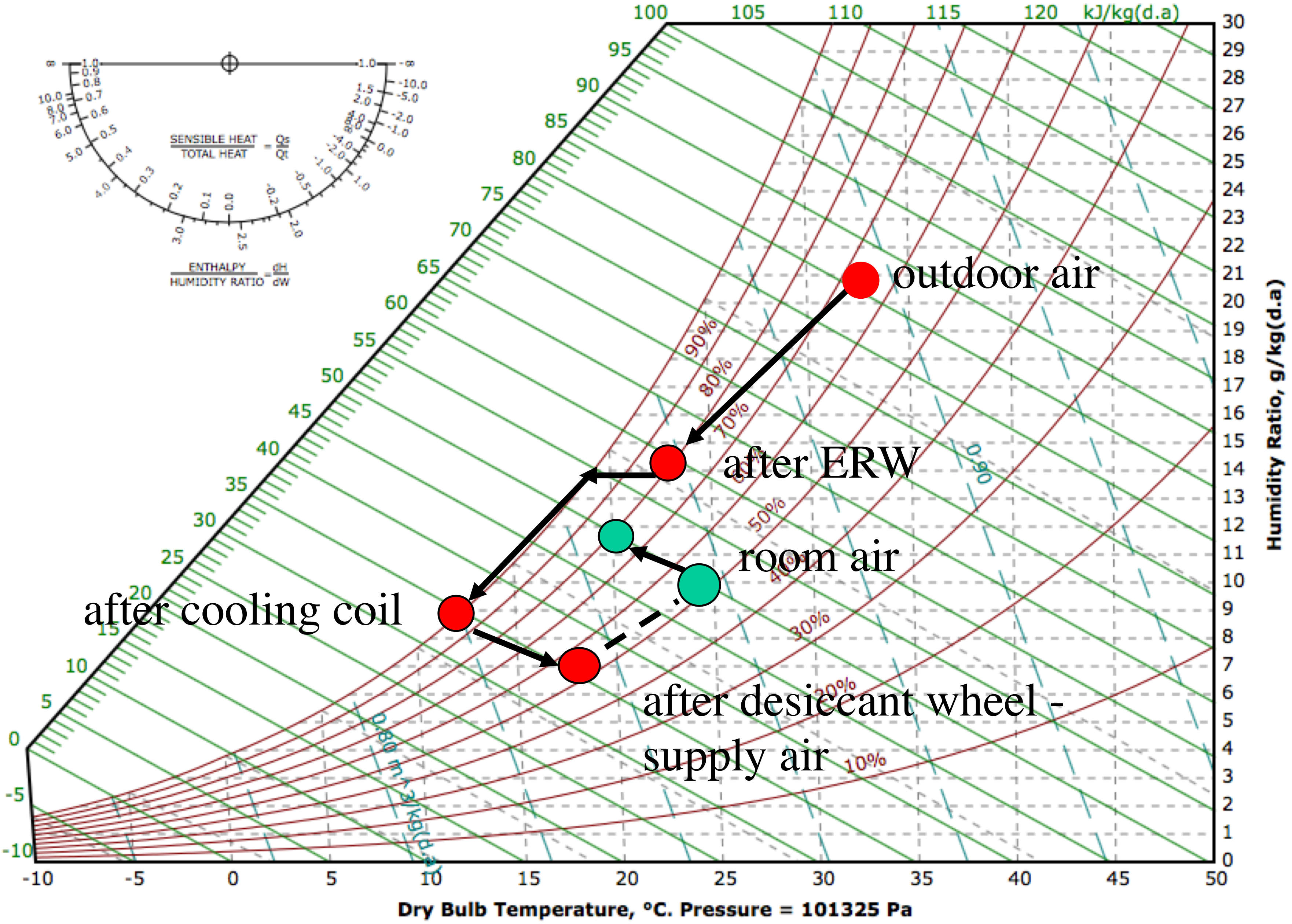
Chilled Water	
In	6.8 °C
Out	11.8 °C

$$Q_{ER} = Q_{coil} - \dot{m}_{supply\ air}(h_{outdoor} - h_{supply\ air})$$

Nominal cooling coil capacity: 3.7-4.7 kW

Nominal additional cooling provided by energy recovery: 3.1-4.0 kW

DRI DOAS air paths



outdoor air

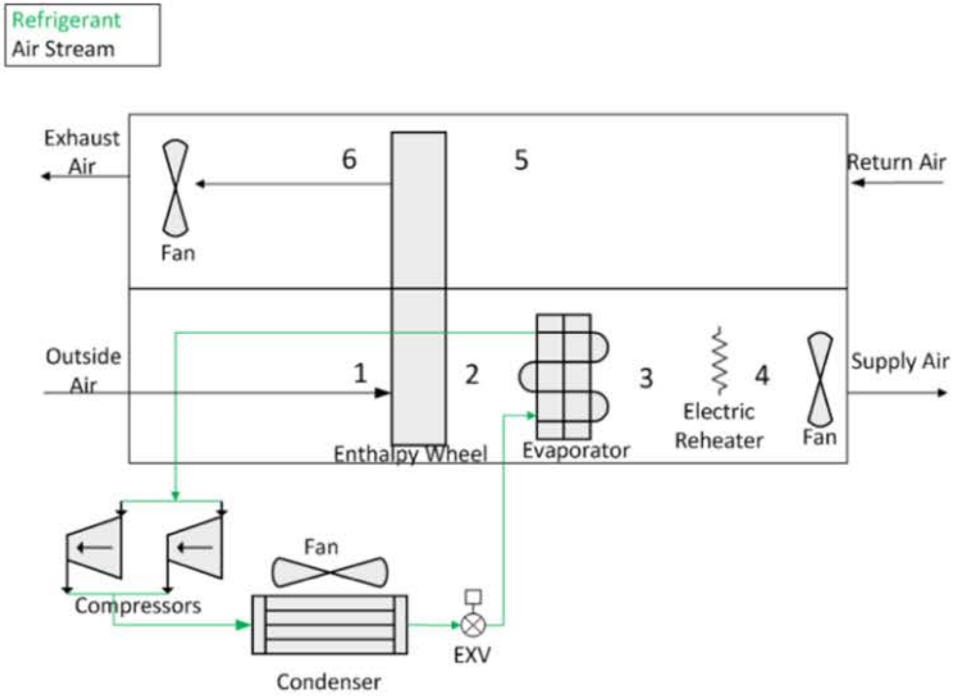
after ERW

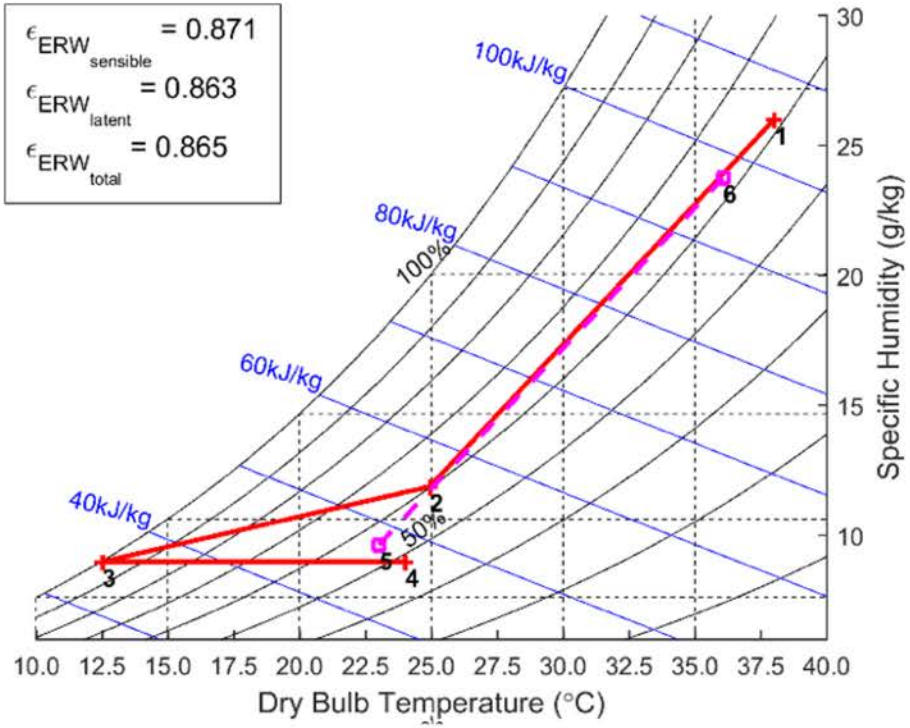
room air

after cooling coil

after desiccant wheel - supply air

Performance of DOAS in Abu Dhabi
DOAS with ERW and DX coil





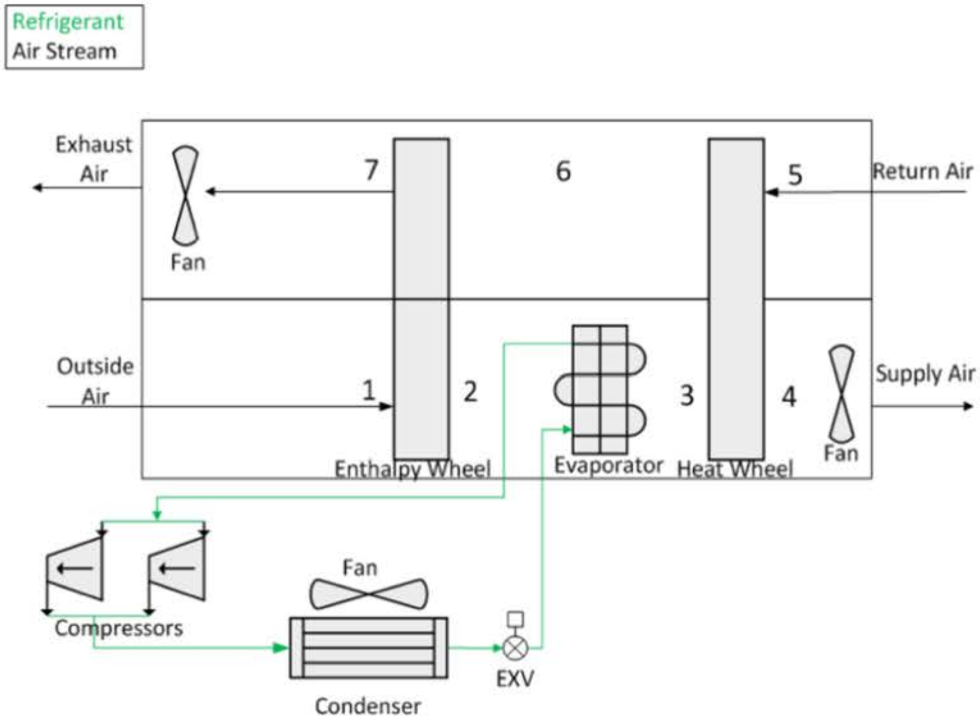
$\epsilon_{ERW_{sensible}} = 0.871$

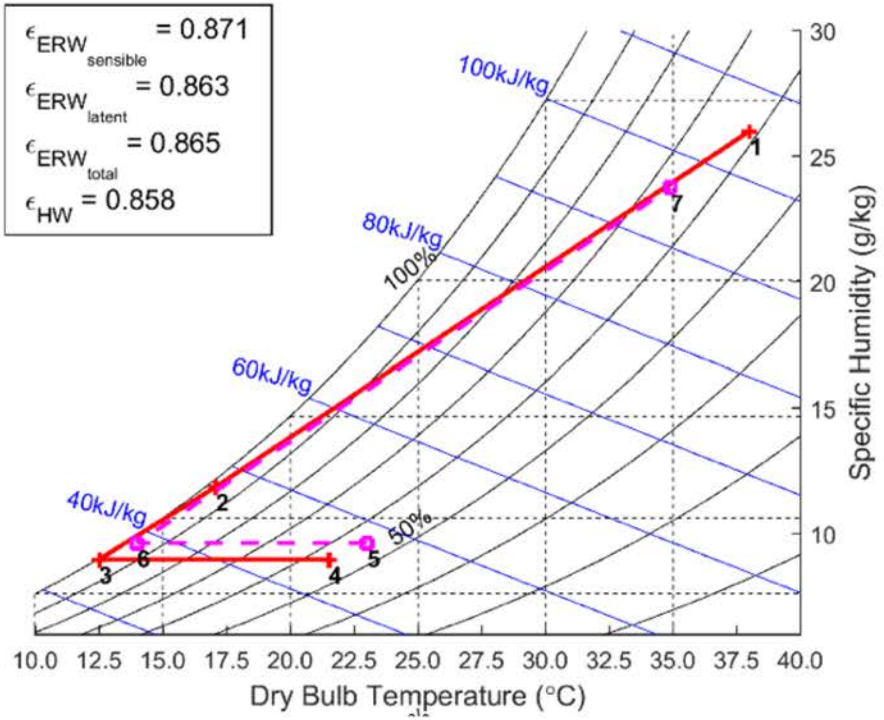
$\epsilon_{ERW_{latent}} = 0.863$

$\epsilon_{ERW_{total}} = 0.865$

M.T. Ali, O. Sarfraz and P.R. Armstrong. Energy performance of GCC-specification LCC optimized dedicated outdoor air system configurations coupled to an air-cooled outdoor unit. Energy and Buildings 158 (2018) 417-430.

DOAS with ERW, DX coil and HW between SA and RA



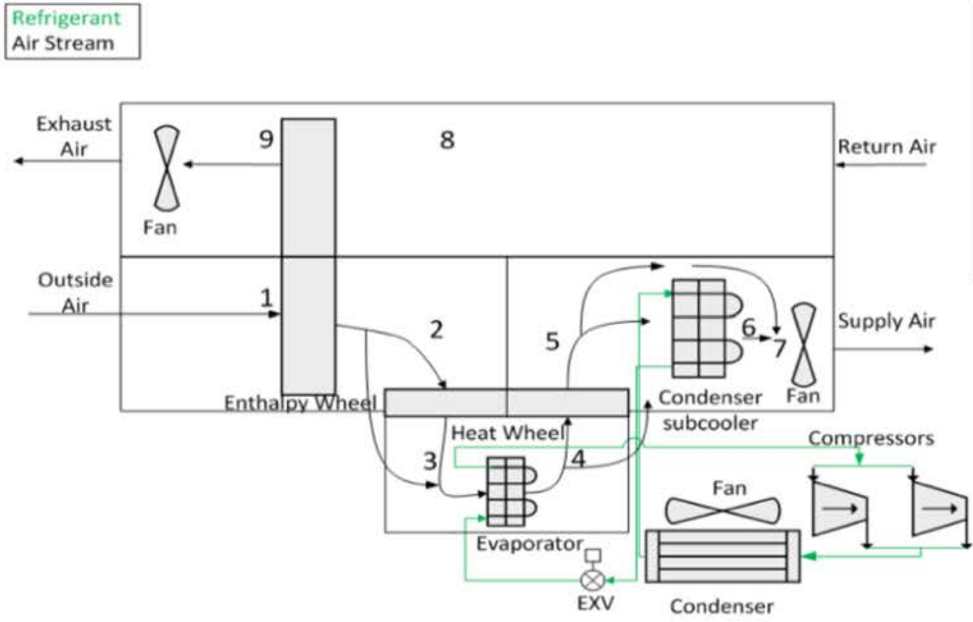

$\epsilon_{ERW_{sensible}} = 0.871$

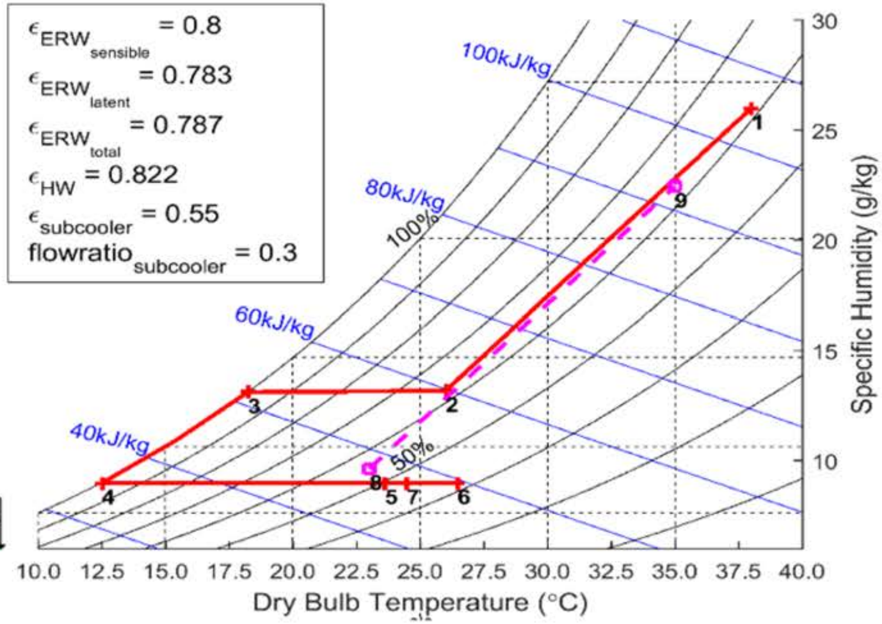
$\epsilon_{ERW_{latent}} = 0.863$

$\epsilon_{ERW_{total}} = 0.865$

$\epsilon_{HW} = 0.858$

DOAS with ERW, DX coil and air-subcooling/reheating coil in series with HW




$\epsilon_{ERW_{sensible}} = 0.8$

$\epsilon_{ERW_{latent}} = 0.783$

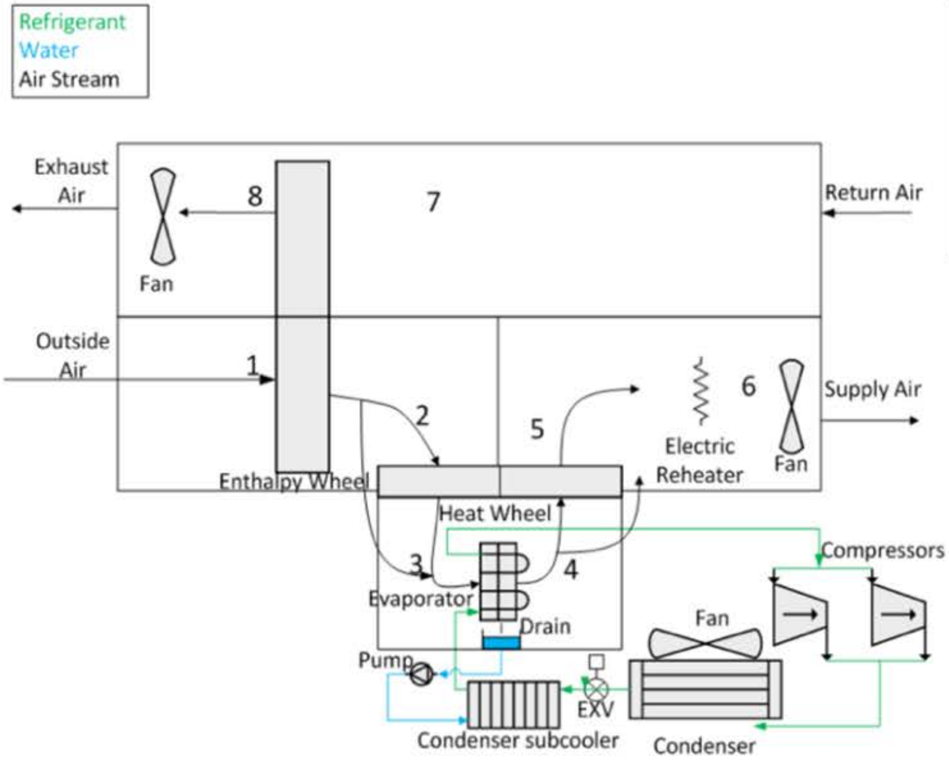
$\epsilon_{ERW_{total}} = 0.787$

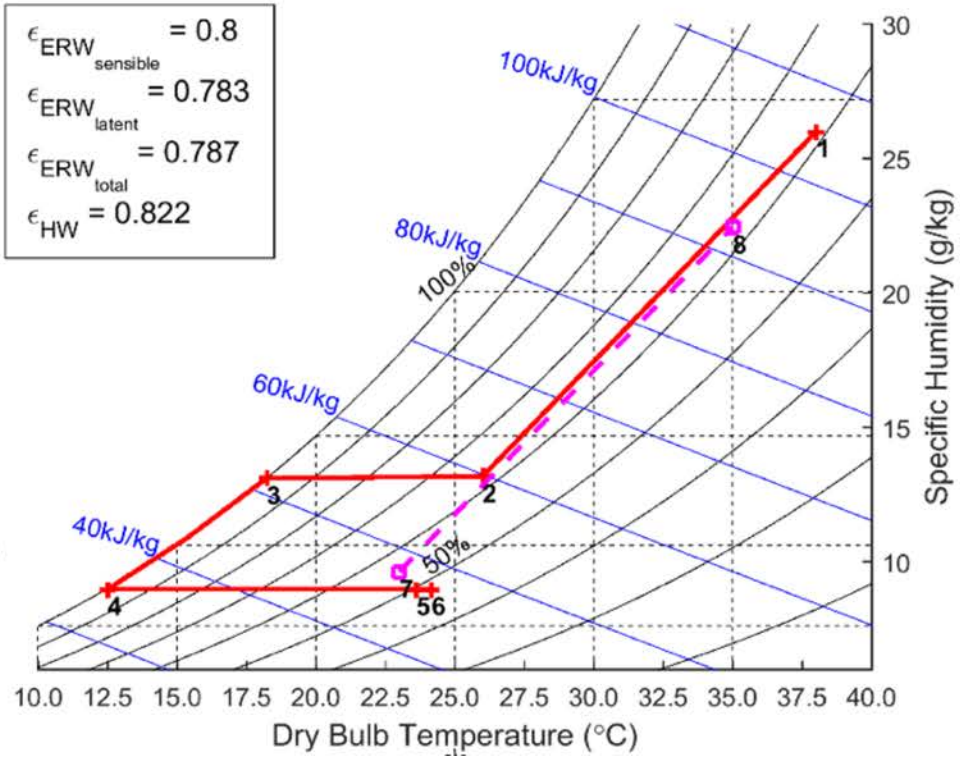
$\epsilon_{HW} = 0.822$

$\epsilon_{subcooler} = 0.55$

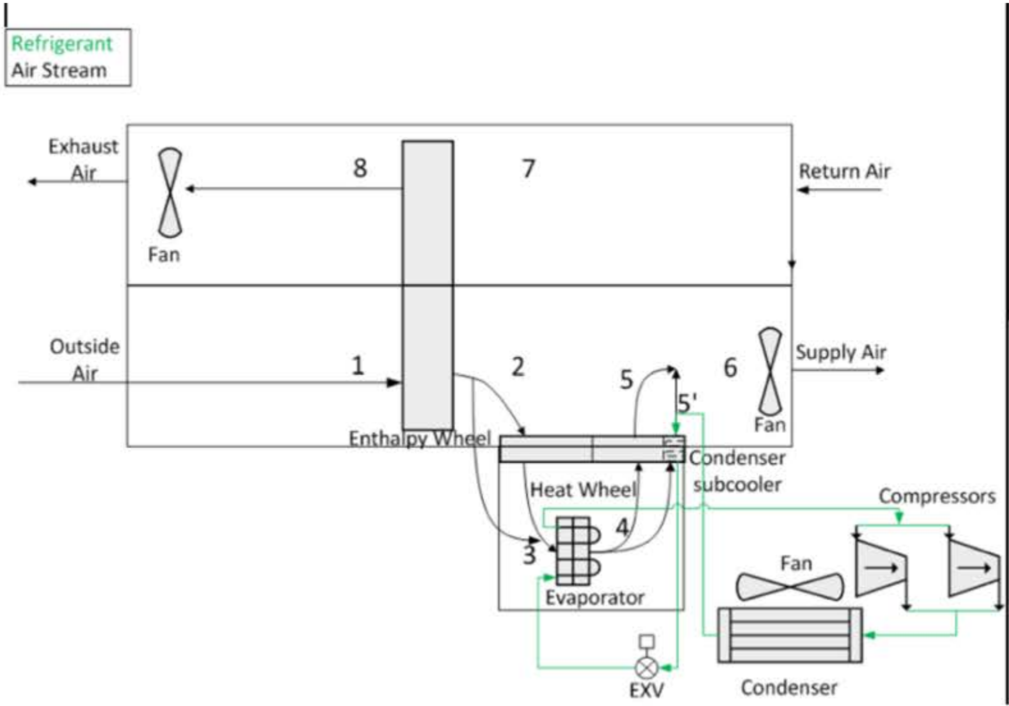
$flowratio_{subcooler} = 0.3$

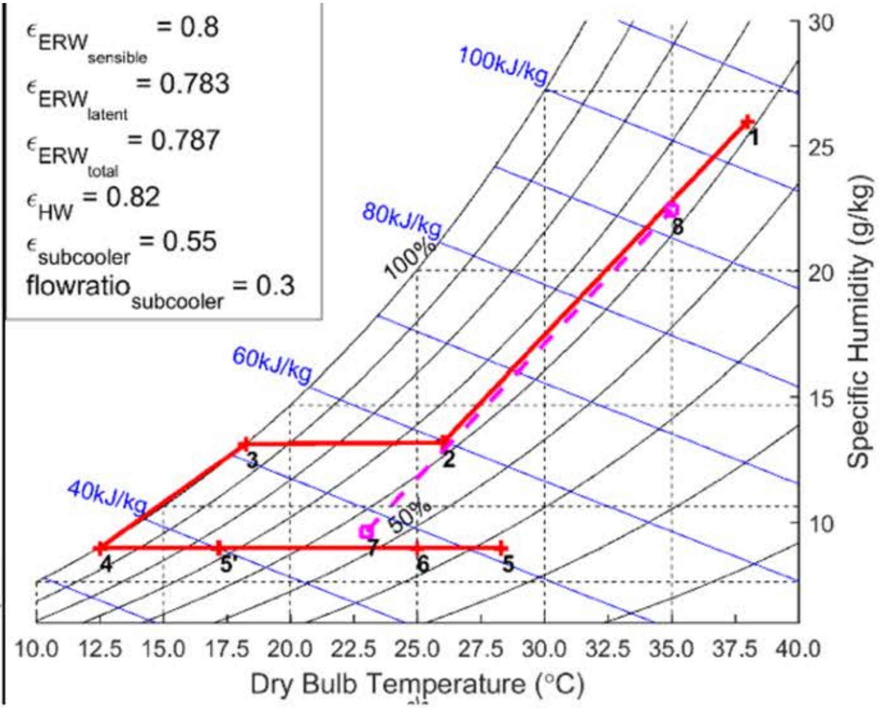
DOAS with ERW, DX coil and water-subcooling HX





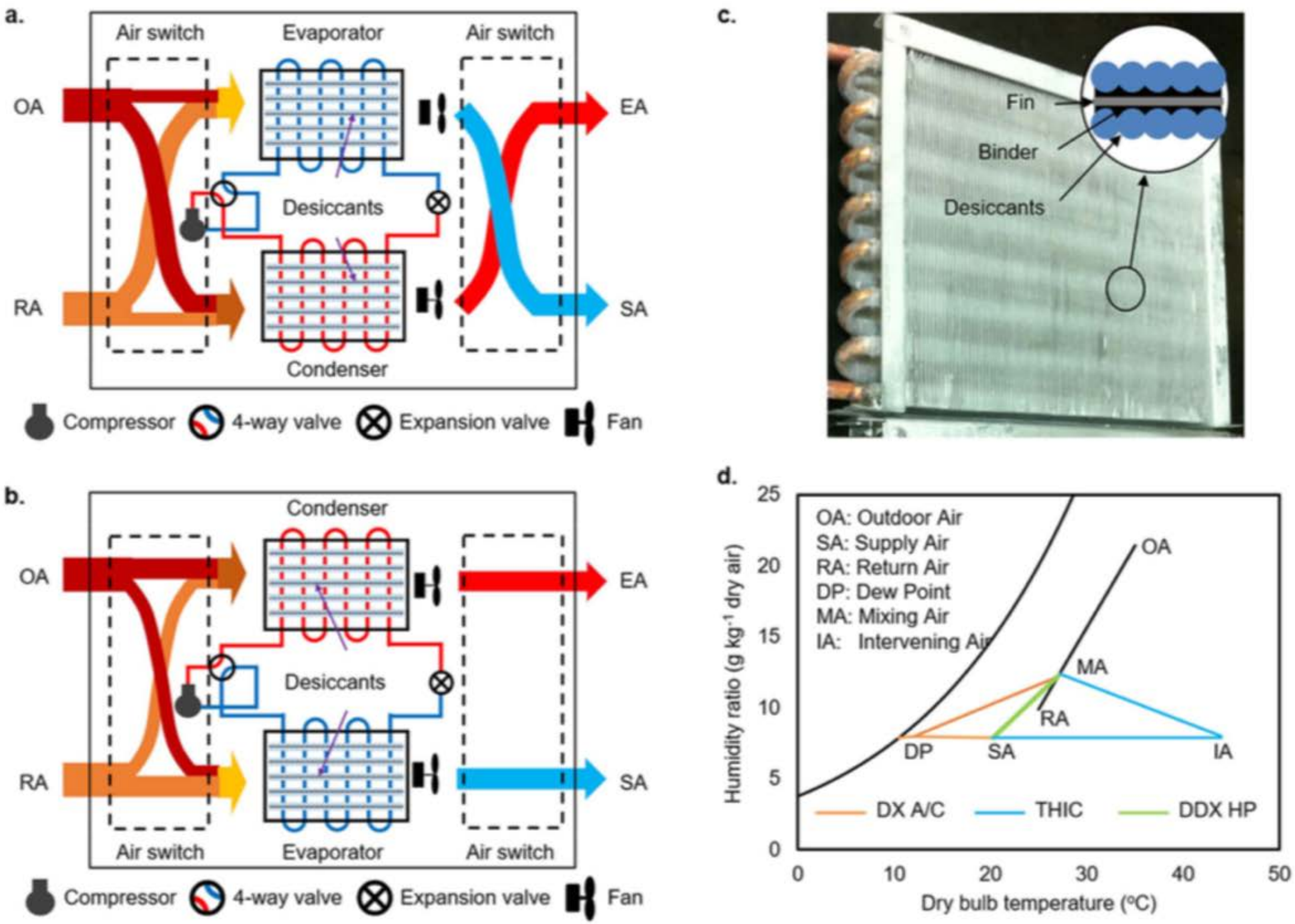
DOAS with ERW, an un-balanced run-around HW, DX coil and air-subcooling/reheating coil in parallel with HW





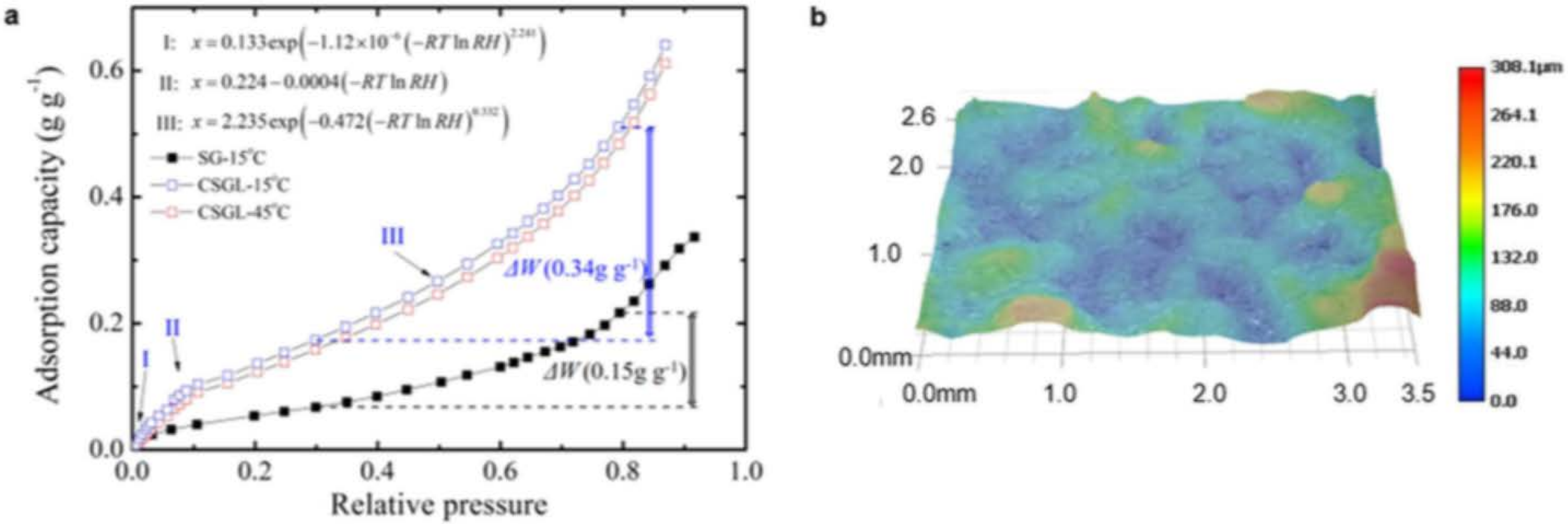
Annual Energy End Use	Cooling Energy (kWh)	DX Unit Energy (kWh)	SCOP	NPV ($)	Energy Savings/Year @0.089¢/kWh ($)	NPV with reheat ($)
DOAS with only DX coil	12538.5	4285.5	2.93	10505.5	--	20630.6
Case (a): DOAS with ERW	12538.5	2506.5	5.00	6544.6	158.3	17055.0
Case (b): DOAS with ERW and HW in SA and RA	12538.5	1140.5	10.99	4846.3	279.9	6240.1
Case (c): DOAS with ERW, HW across evaporator and air subcooler/reheater in series to HW	12538.5	986.2	12.71	4357.3	293.64	5621.0
Case (d): DOAS with ERW, HW across evaporator and water subcooler	12538.5	1018.8	12.31	4400.7	290.74	6221.2
Case (e): DOAS with ERW, HW across evaporator and air subcooler/reheater in parallel to HW	12538.5	1075.8	11.66	4476.7	285.66	5447.6

Desiccant-enhanced DX heat pump, doubling COP of conventional DX units



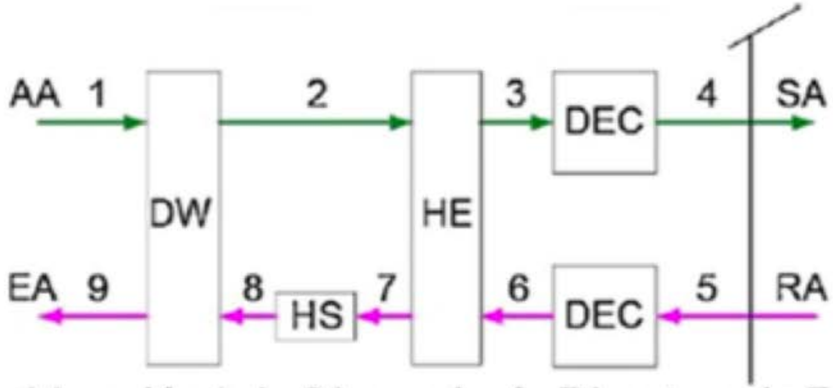
Tu, Y.D., R.Z. Wang, T.S. Ge and X. Zheng. Comfortable, high-efficiency heat pump with desiccant-coated, water-sorbing heat exchangers. Scientific Reports 7:40427 DOE:10.1038/srep40437

Performance of silica-gel-supported lithium chloride (CSGL)

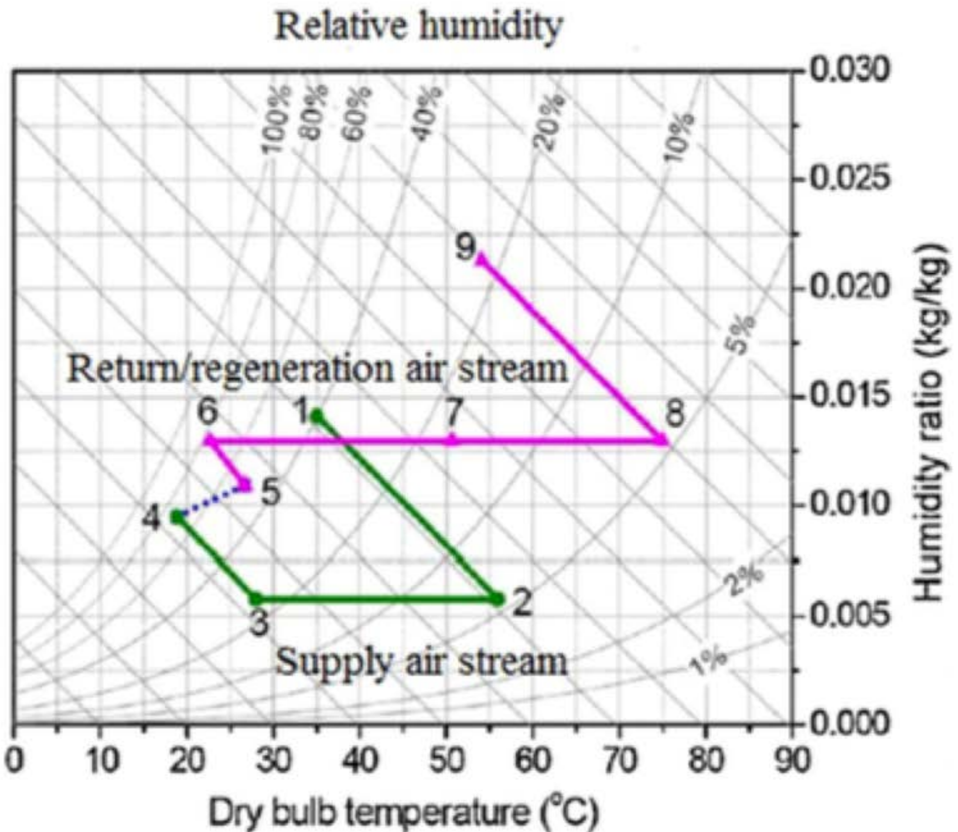


Tu, Y.D., R.Z. Wang, T.S. Ge and X. Zheng. Comfortable, high-efficiency heat pump with desiccant-coated, water-sorbing heat exchangers. Scientific Reports 7:40427 DOE:10.1038/srep40437

Desiccant system with direct evaporative cooler – no vapor compression

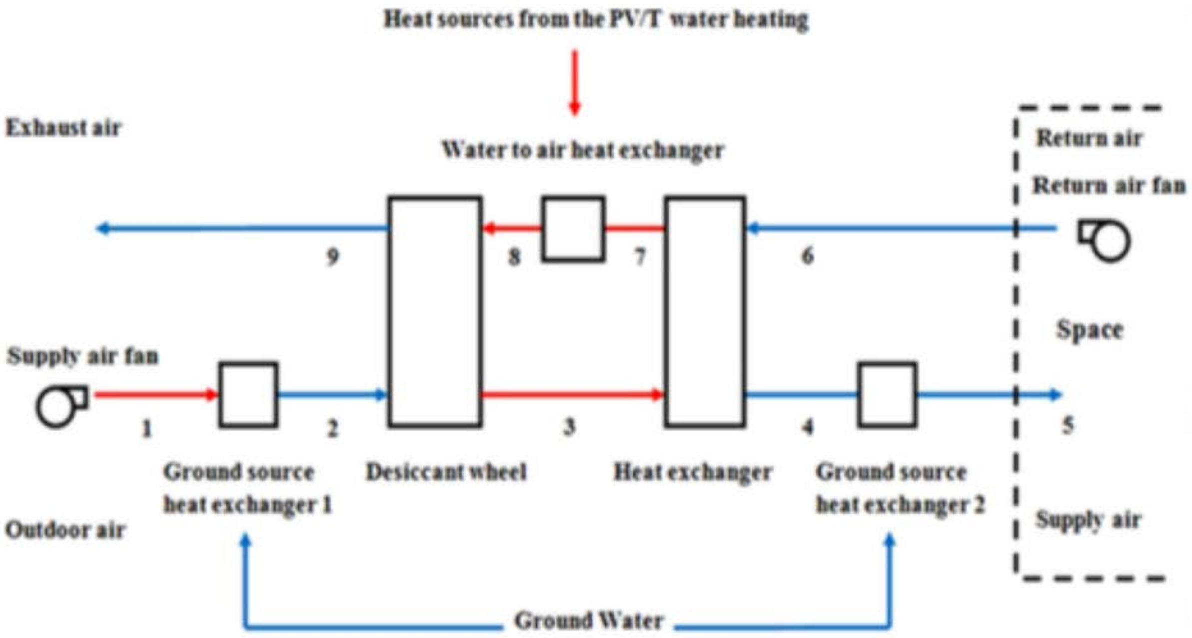


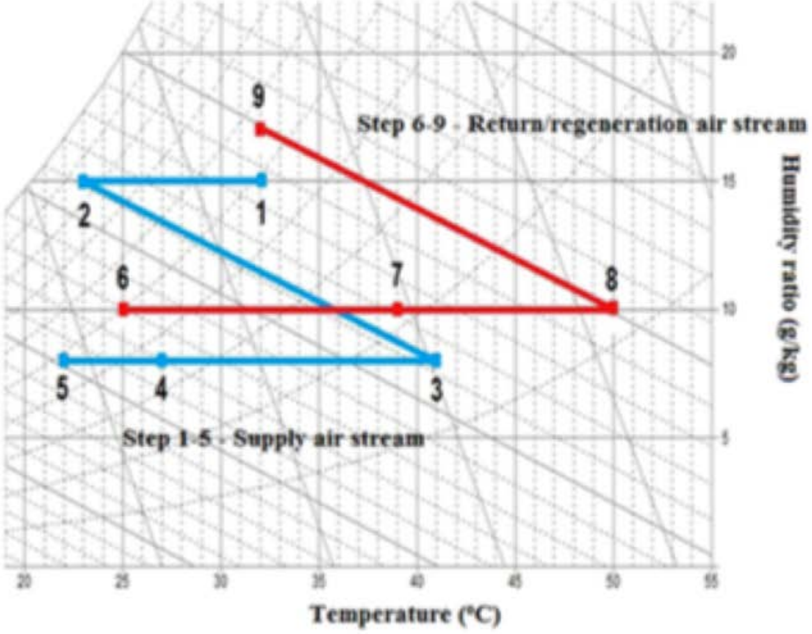
AA: ambient air; SA: supply air; RA: return air; EA: exhaust air; DW: desiccant wheel; HE: heat exchanger; HS: heat source; DEC: direct evaporative cooler



Guo, J. et al. A review of photovoltaic thermal (PV/T) heat utilization with low temperature desiccant cooling and dehumidification. *Renewable and Sustainable Energy Reviews* 67 (2017) 1-14

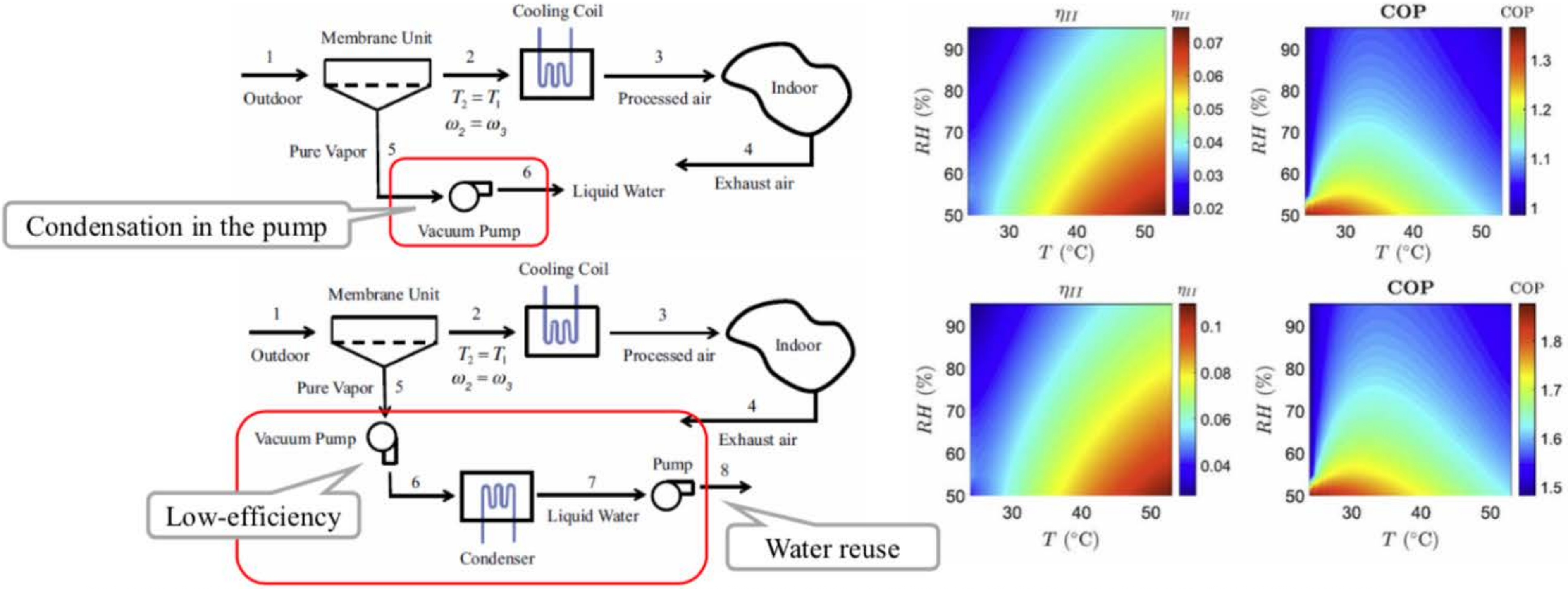
Desiccant system with ground-sourced pre-cooling





Guo et al., Ground coupled photovoltaic thermal (PV/T) driven desiccant air cooling. 2004 Asia-Pacific Solar Research Conference

Membrane dehumidification and cooling systems



Condensation in the pump

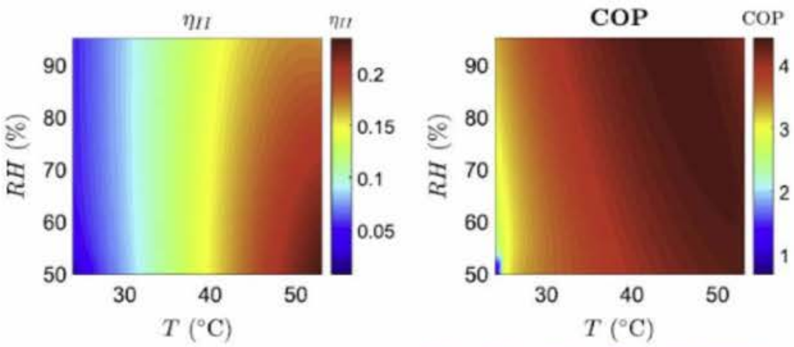
Low-efficiency

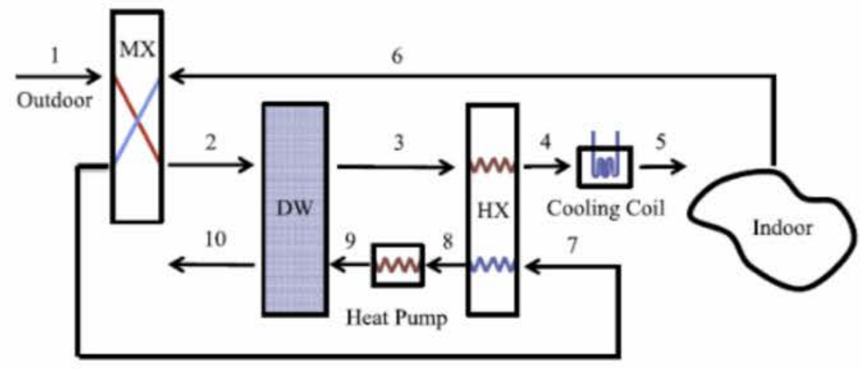
Water reuse

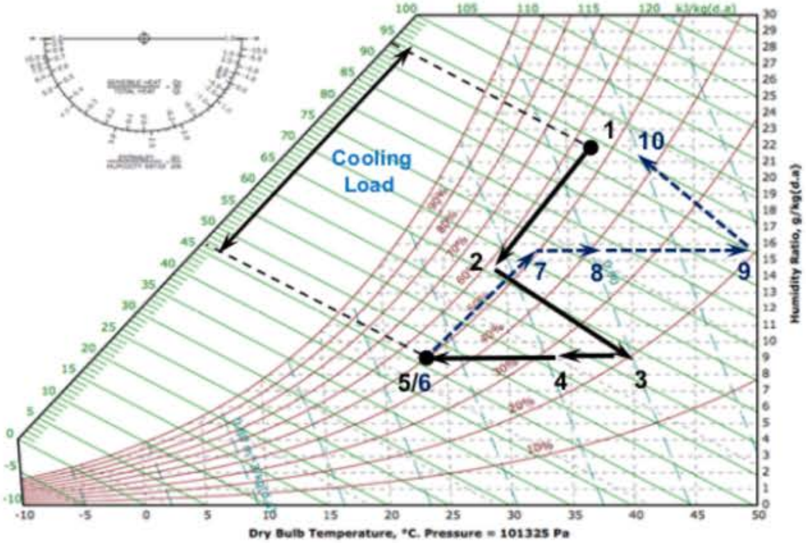
Source: Labban, Omar, Tianyi Chen, et al. "Next-generation HVAC: Prospects for and limitations of desiccant and membrane-based dehumidification and cooling." *Applied Energy* 200 (2017): 330-346.

Membrane Dehumidification & Cooling System (Cont'd)

- System Integration
    - Enthalpy Recovery Wheel (ERW)
    - DW

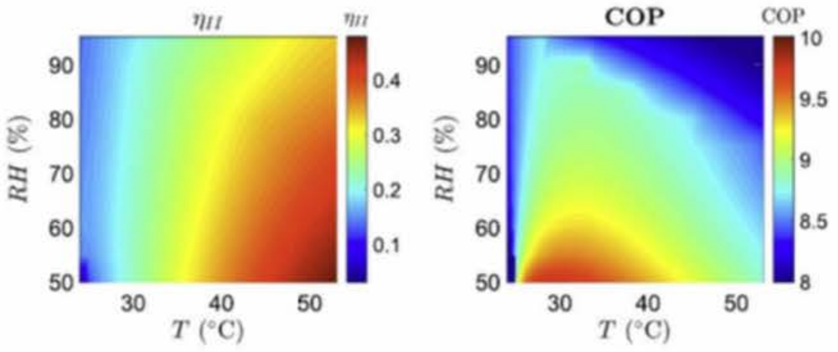




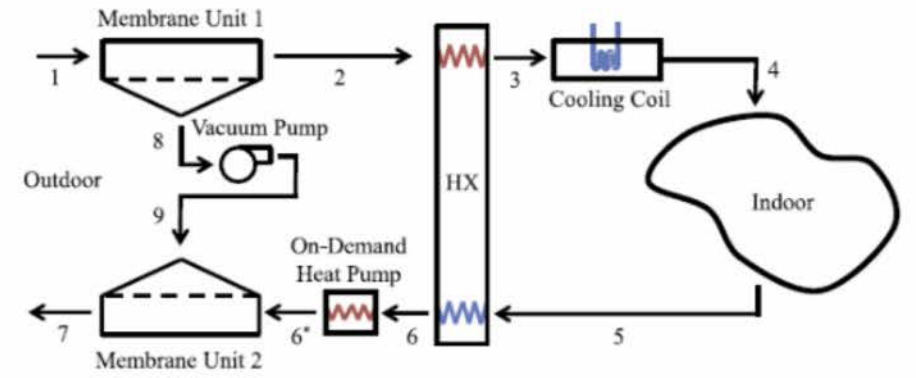


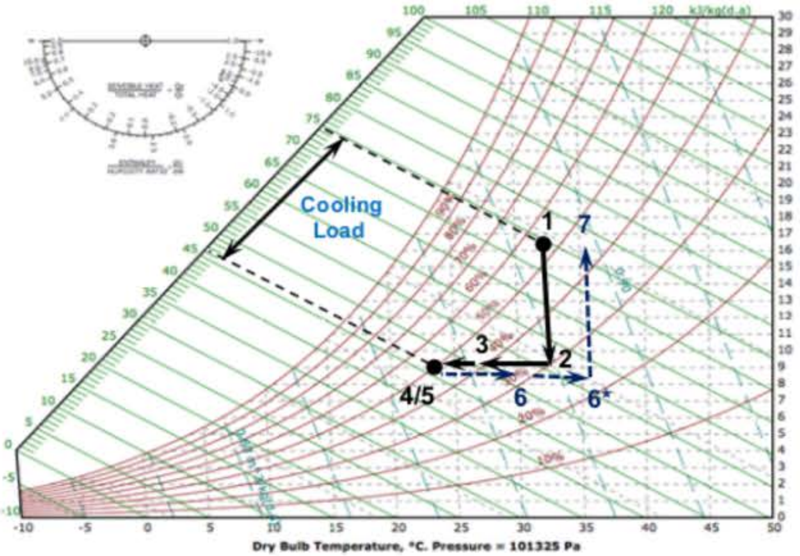
Source: Labban, Omar, Tianyi Chen, et al. "Next-generation HVAC: Prospects for and limitations of desiccant and membrane-based dehumidification and cooling." *Applied Energy* 200 (2017): 330-346.

Membrane Dehumidification & Cooling System (Cont'd)



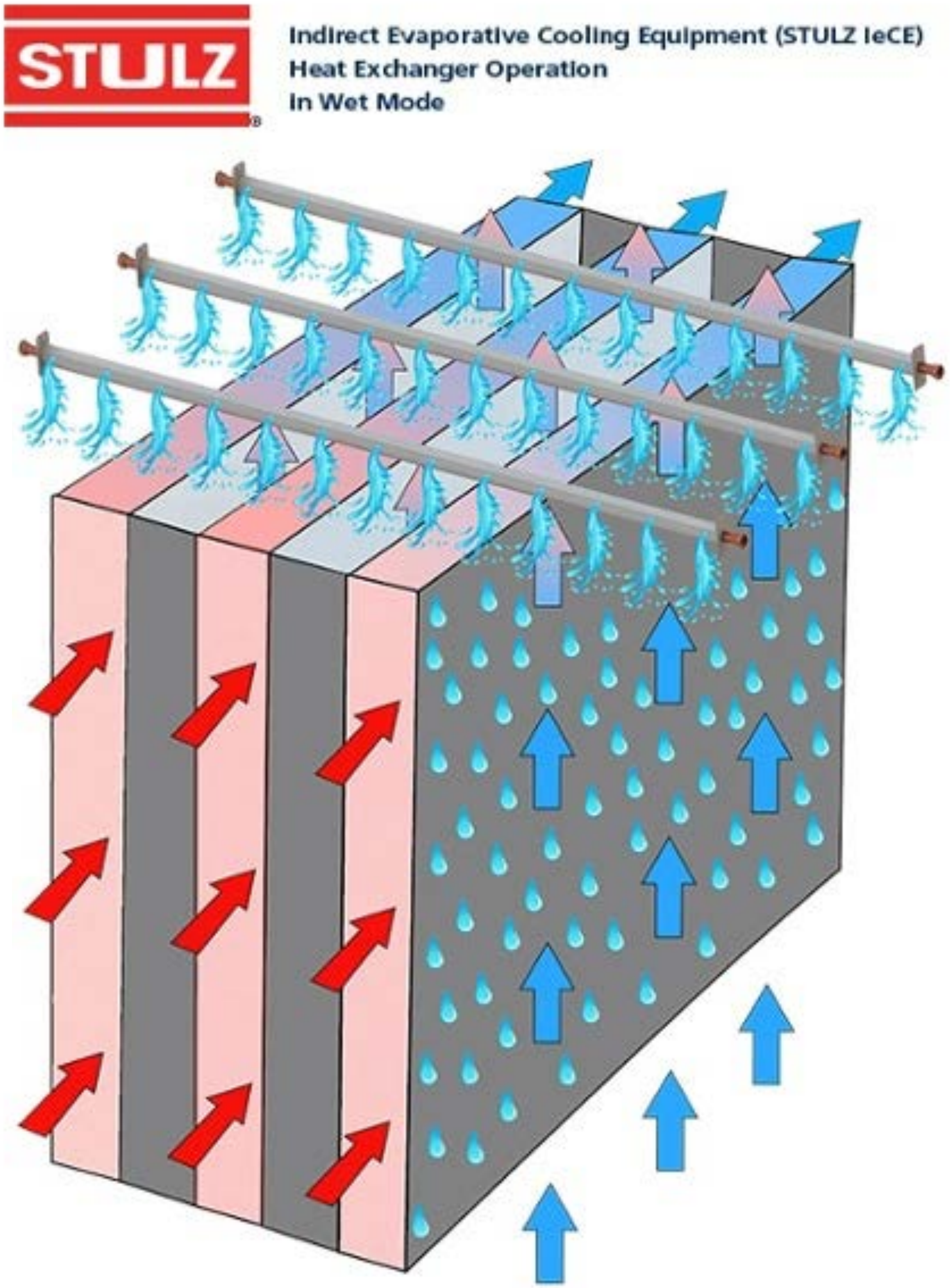
- System Integration
  - Two-membrane system
    - $P_{6^*w} < P_{7w} < P_9 \le P_{7sat}$, $P_8 < P_{1w} \le P_{1sat}$
    - $P_8 < P_9$
    - $P_1 - P_8 = P_9 - P_{6^*}$





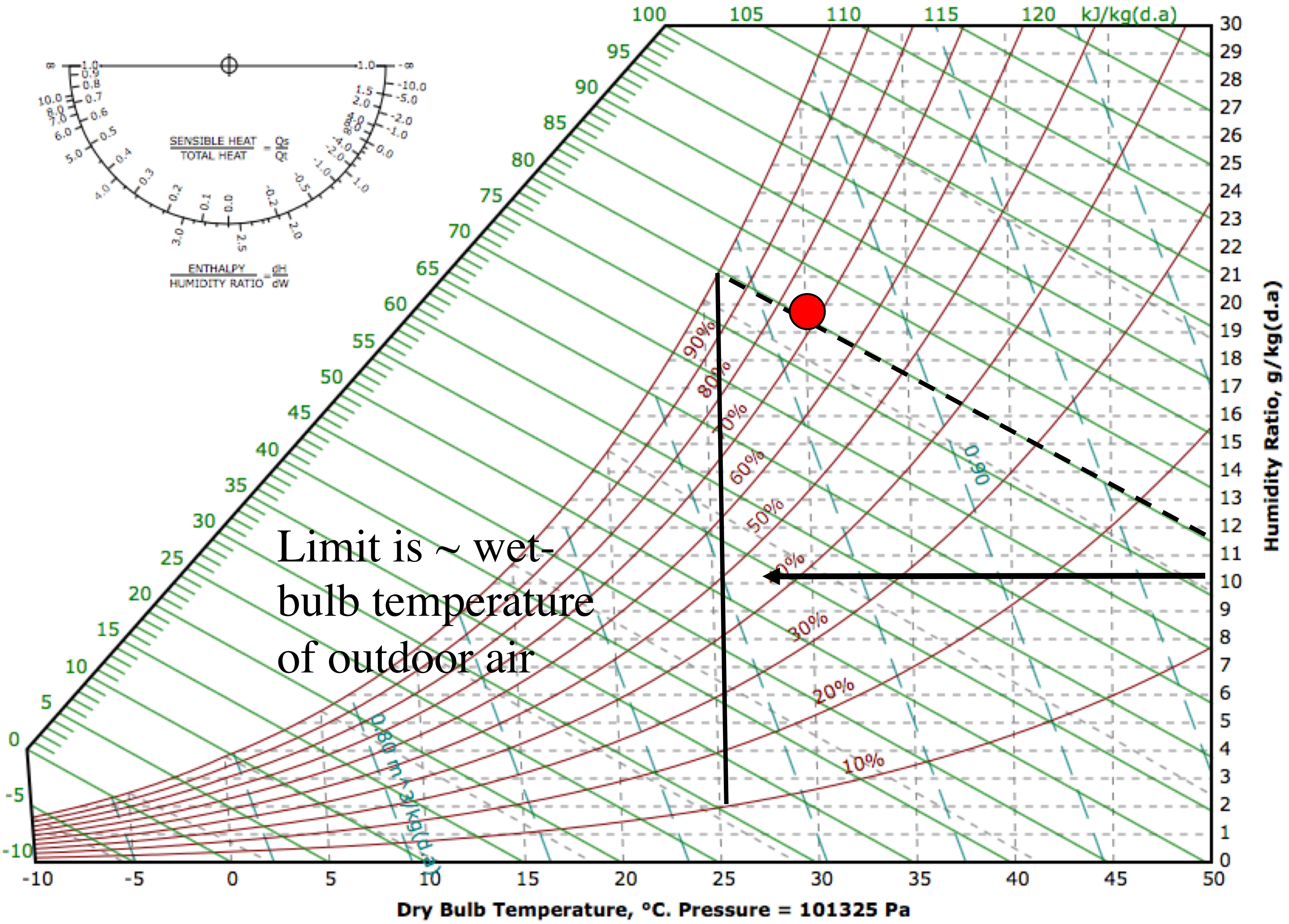
Source: Labban, Omar, Tianyi Chen, et al. "Next-generation HVAC: Prospects for and limitations of desiccant and membrane-based dehumidification and cooling." *Applied Energy* 200 (2017): 330-346.

Indirect evaporative cooling



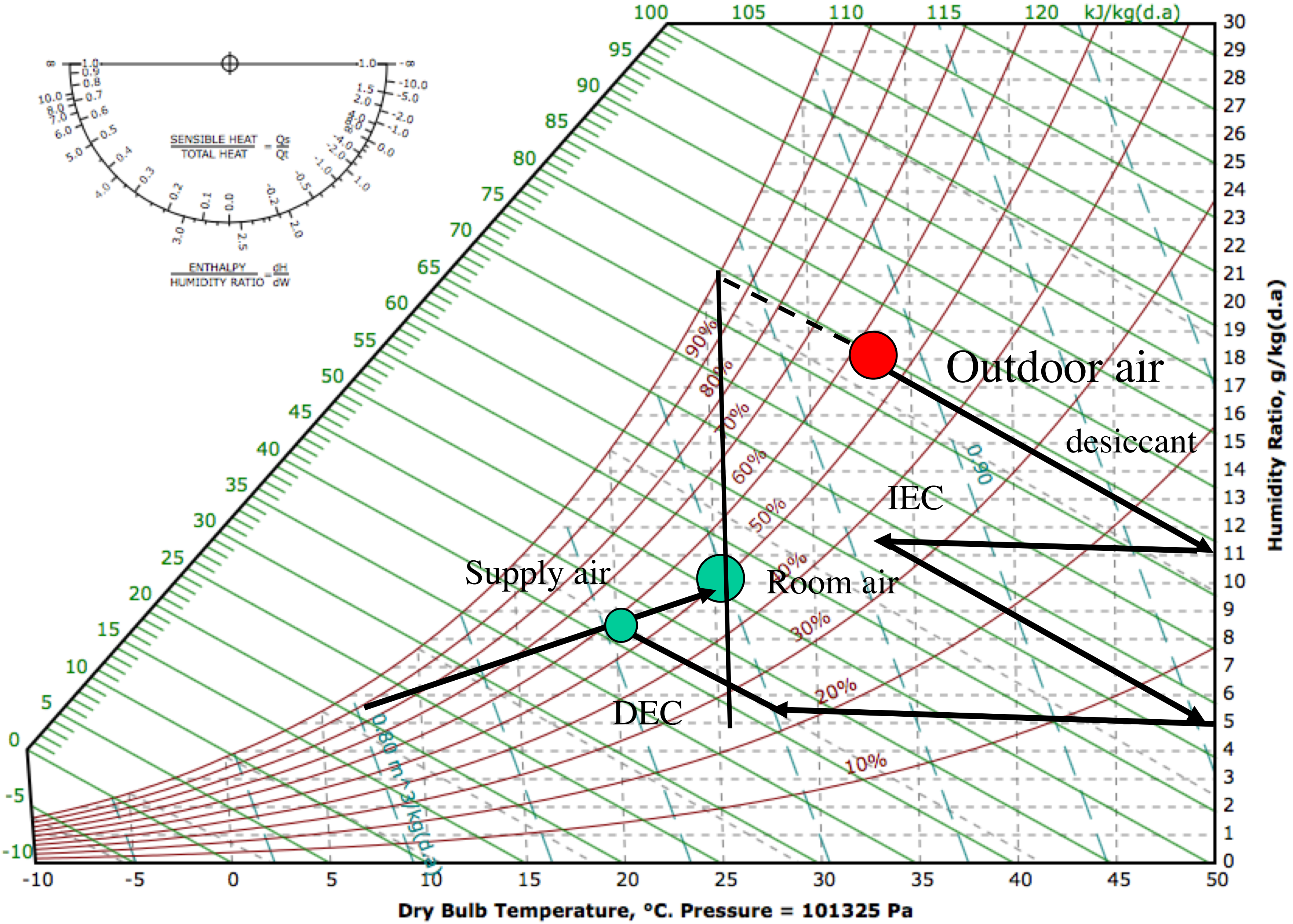
https://blog.stulz-usa.com/idec-indirect-evaporative-cooling-equipment-iece

Indirect evaporative cooling

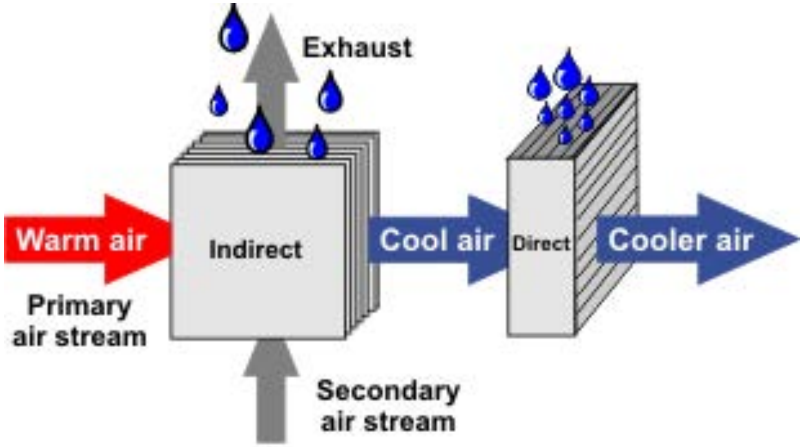


Limit is ~ wet-bulb temperature of outdoor air

An evaporative cooling pathway



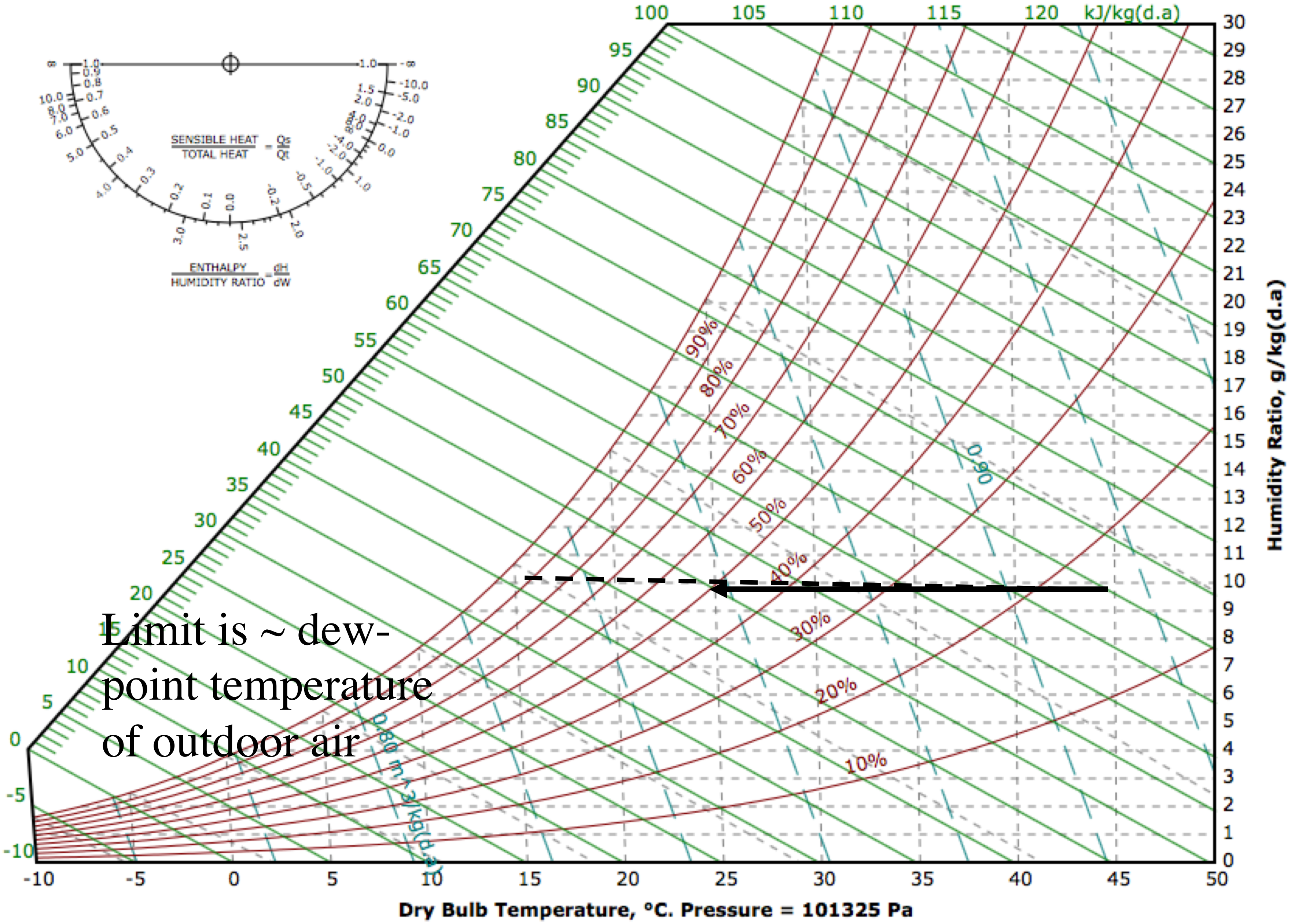
Indirect/direct evaporative coolers



http://www.wescorhvac.com/IndirectDirect.png

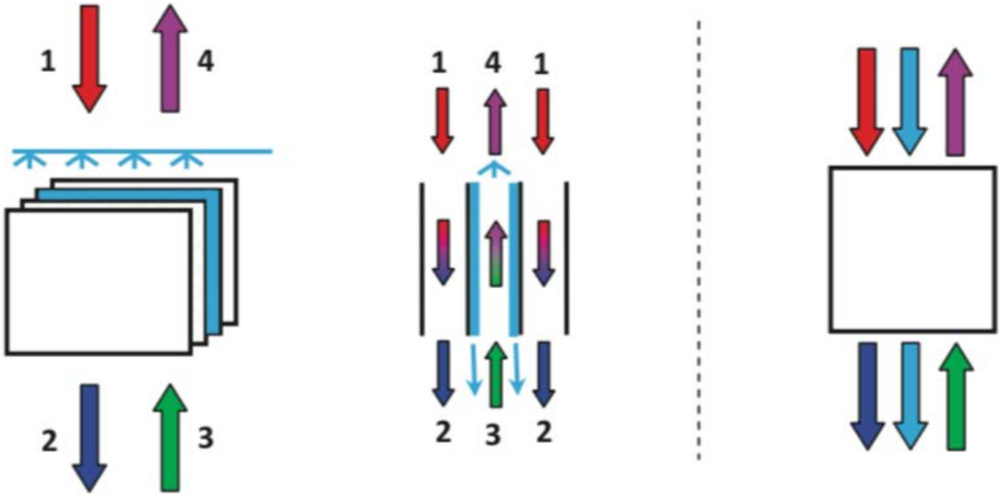
http://www.unitedmetal.com/our-products/indirect-direct-unit/

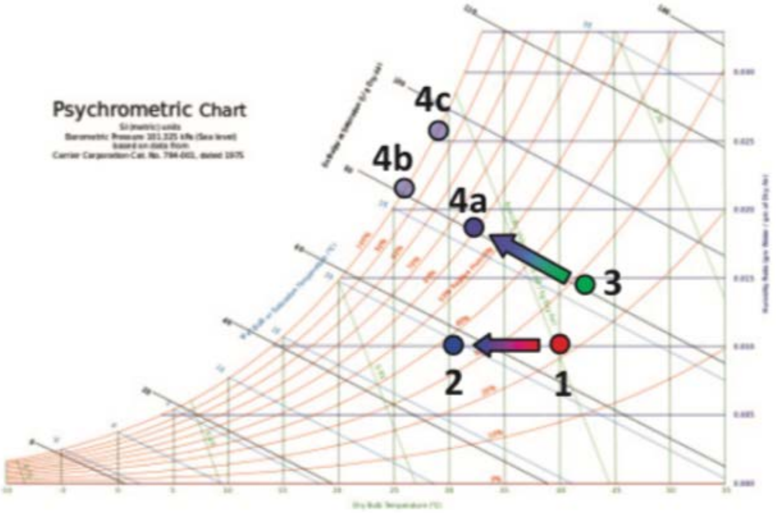
Dew-point indirect evaporative cooling



Limit is ~ dew-point temperature of outdoor air

Indirect evaporative cooler, revisited

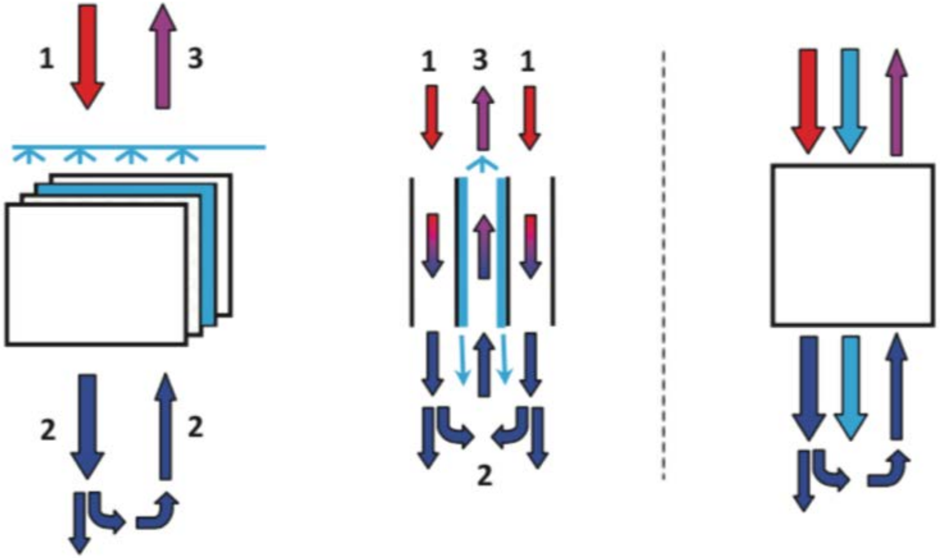


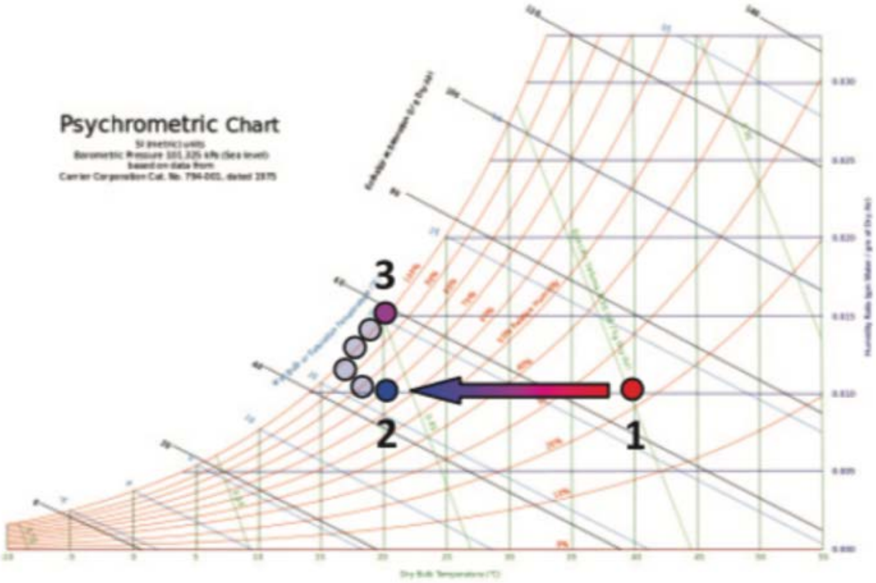


Porumb, B. et al. A review of indirect evaporative cooling technology. Energy Procedia 85 (2016) 461-471 (four slides)

Regenerative indirect evaporative cooler

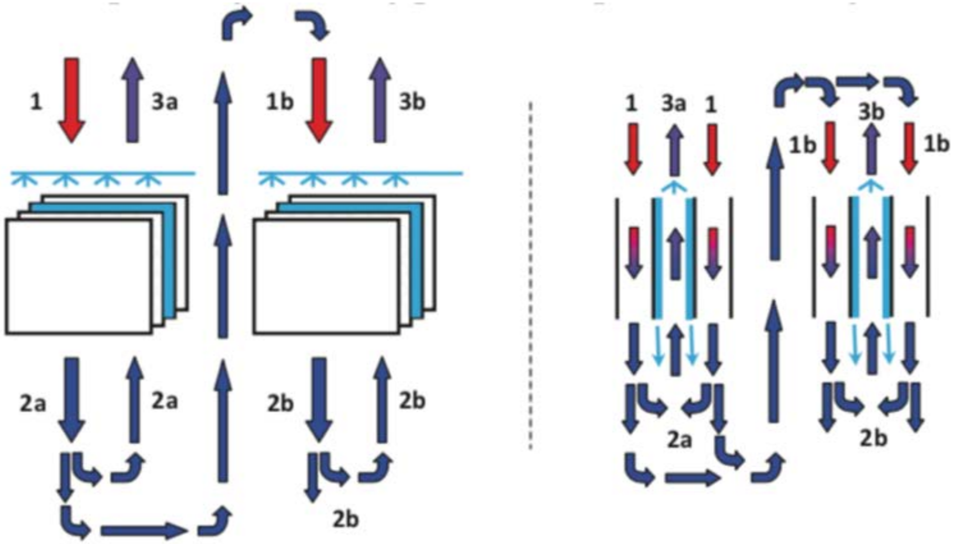
A portion of primary air is extracted at its outlet and used as secondary air.

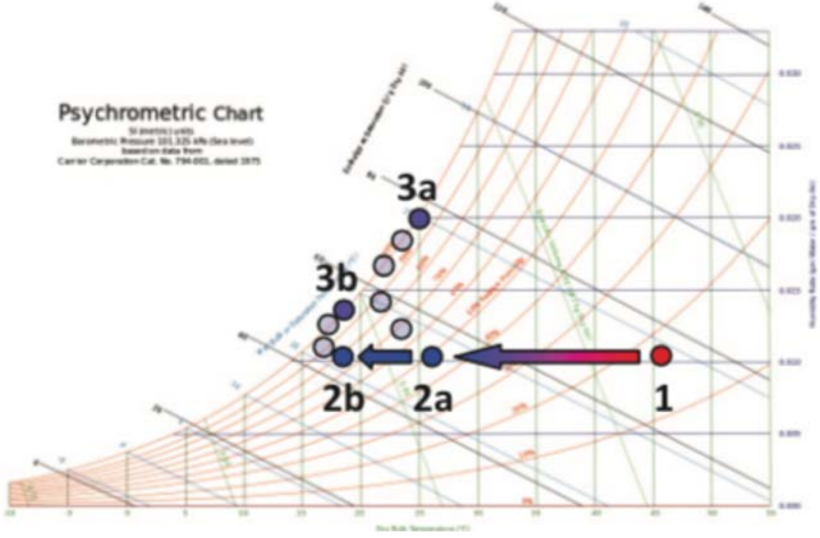




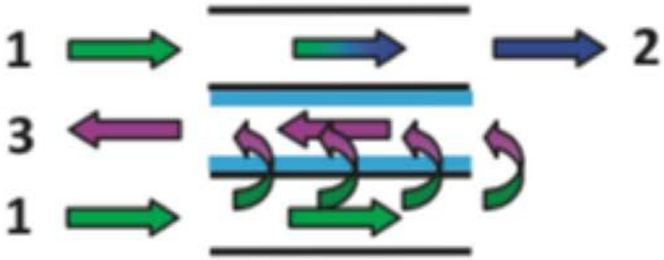
Dew-point indirect evaporative cooler

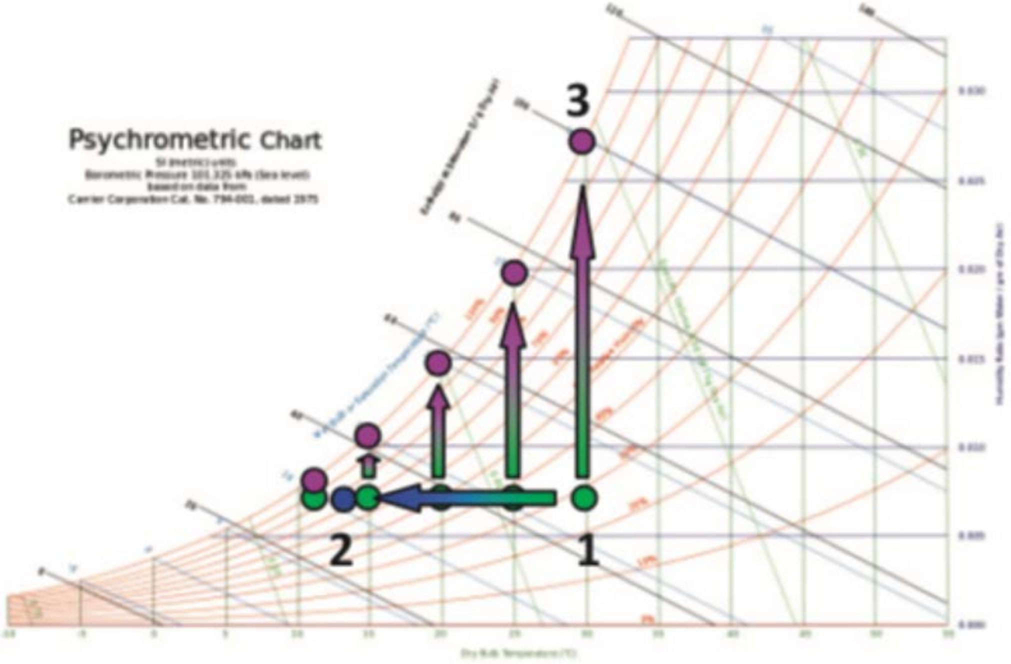
Multiple stages of R-IEC equipment



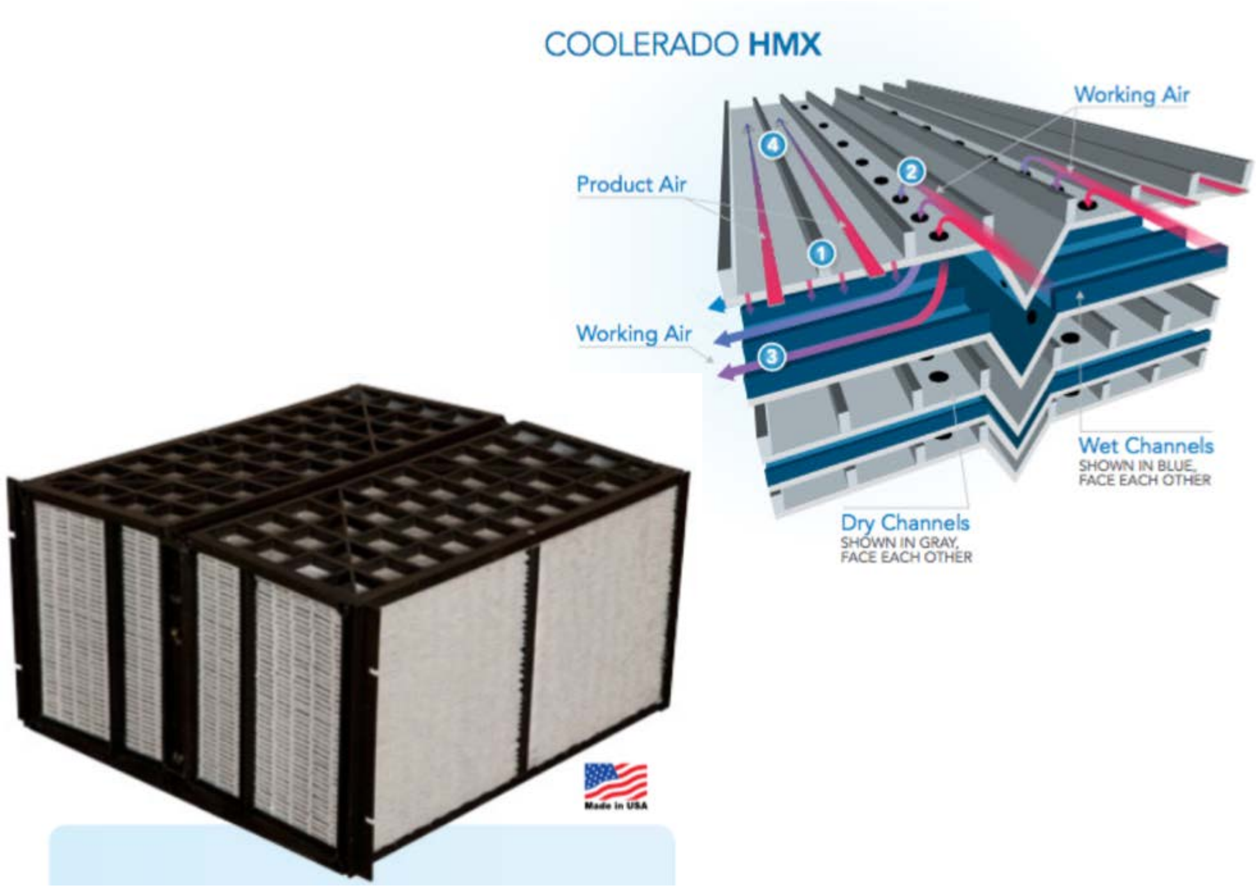


Maisotsenko indirect evaporative cooler





Coolerado dew point indirect evaporative cooler based on Maisotsenko cycle



① Product air and working air enter the dry side of the HMX.

② Cooled working air is fractioned off into wet channels throughout the exchanger.

③ Heat from the product air is transferred into the working air through evaporation and is rejected as exhaust.

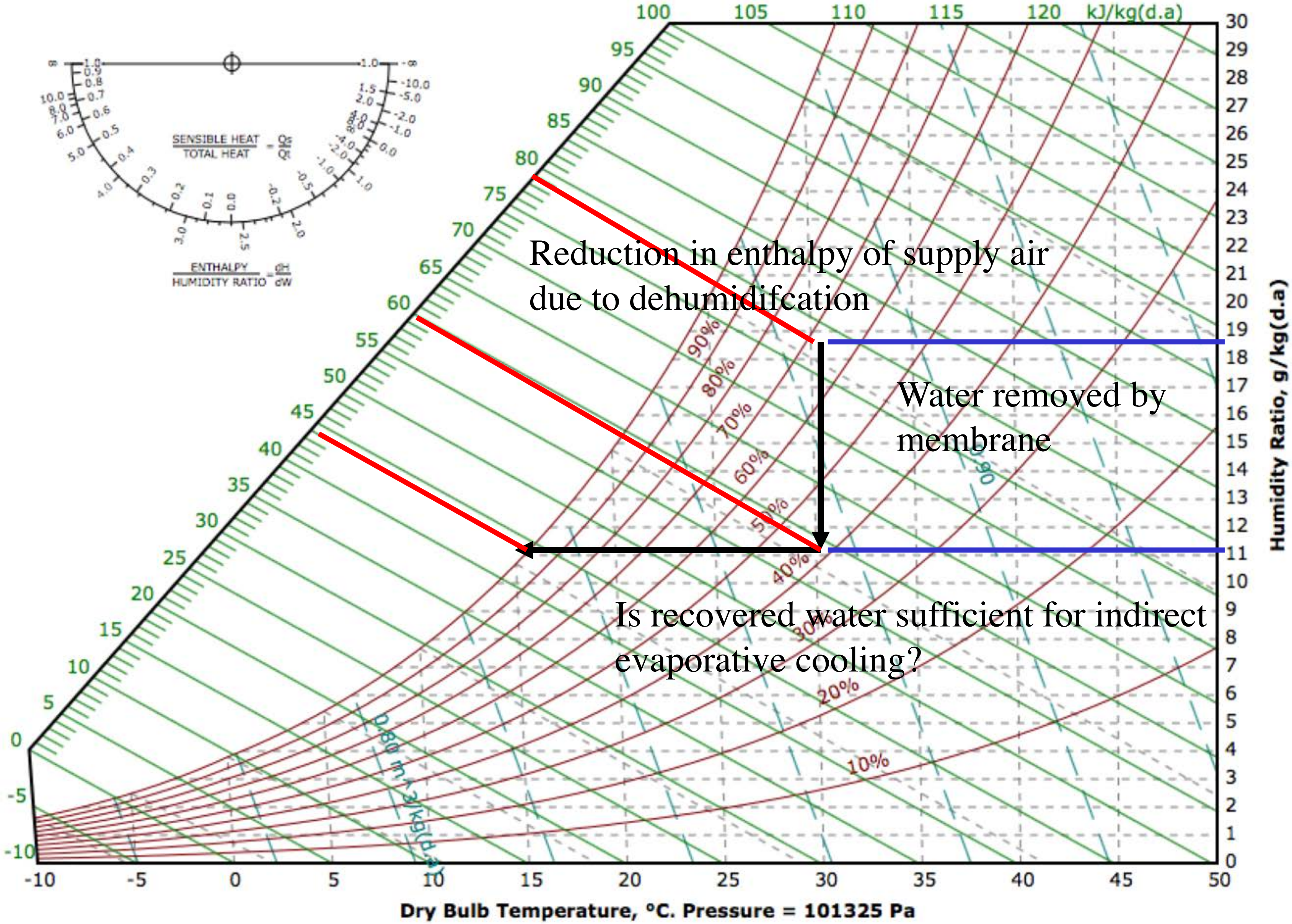
④ The product air travels the length of the dry channels, while transferring its heat to the working air in the wet channels above and below. As a result, the product air cools down and remains dry as it enters the building.

http://www.coolerado.com/hmx/

The Coolerado units demonstrated the ability to operate with an average seasonal efficiency as low as 0.157 kW/ton (energy efficiency ratio [EER] = 76.4) when calculated as a function of the total cooling provided by the unit and as low as 0.262 kW/ton (EER = 45.8) when calculated as a function of building cooling, which is considerably better than the specified performance metric. The total installed costs, seasonal energy efficiency, energy use, and projected water consumption of the Coolerado units were used to compare the economics and performance to a code-minimum packaged rooftop unit (RTU) with an integrated energy efficiency ratio (IEER) of 12. Given the measured performance of the Coolerado units during the 2011 cooling season, the annual energy savings were estimated at 63.3% compared to a code-minimum RTU. The estimated simple payback was 7.62-41.8 years, depending on the facility that the unit was installed in when the maintenance costs were assumed to be equivalent to a packaged RTU.

NREL report TP-7A40-56256-1 November 2012 https://www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/Energy/Conservation-and-Efficiency/EW-200821

Membrane + dew-point indirect evaporative cooling: cooling in the tropics without refrigerants

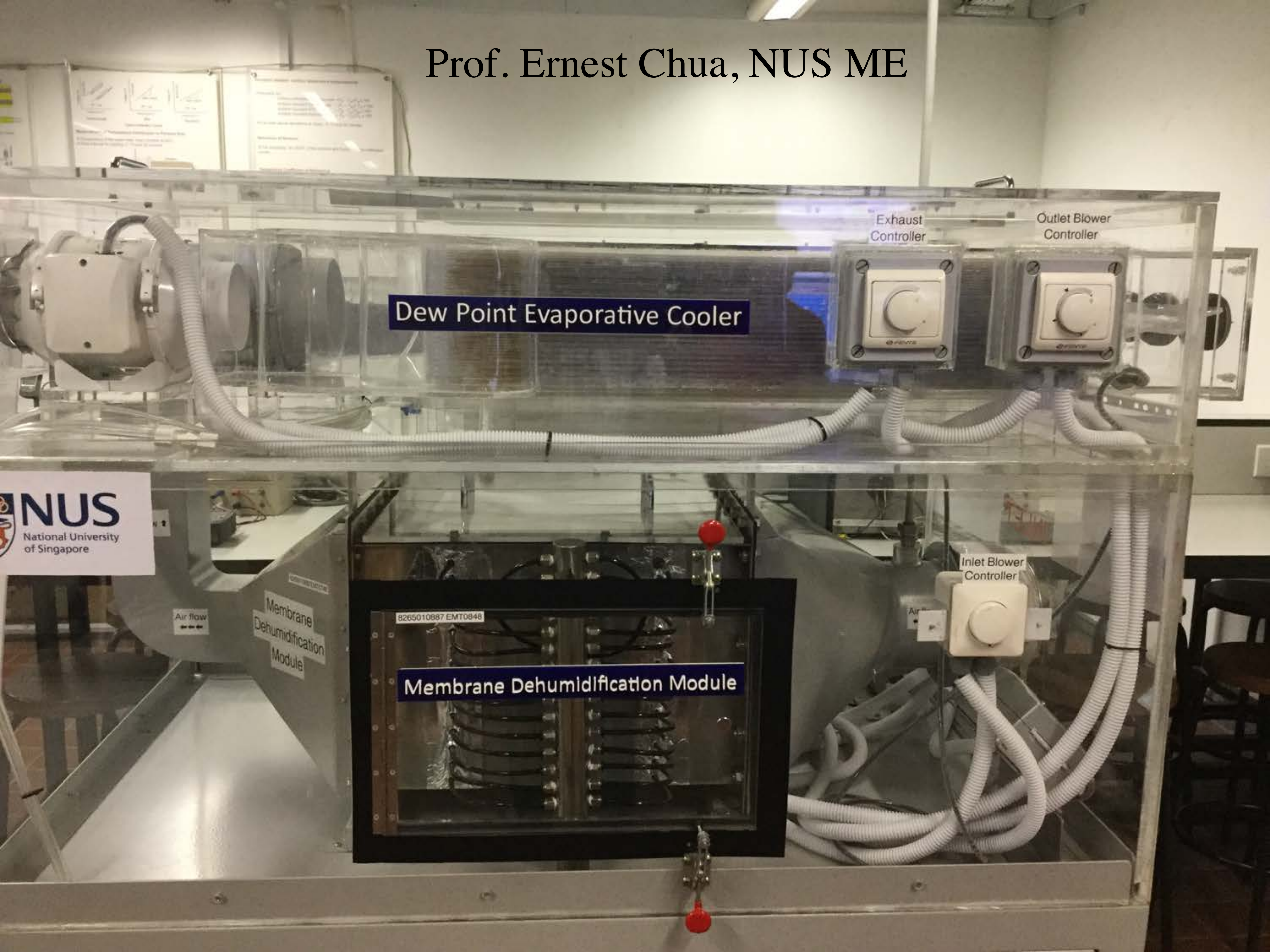


Reduction in enthalpy of supply air due to dehumidifcation

Water removed by membrane

Is recovered water sufficient for indirect evaporative cooling?

Prof. Ernest Chua, NUS ME



Parting perspective: the many innovative systems are cause for optimism, particularly as industry evolves more of them into economically viable products

Thank you! Any questions? If later, lnorford@mit.edu