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Approaches to Energy Efficiency in Air Conditioning: Processes and Thermodynamics

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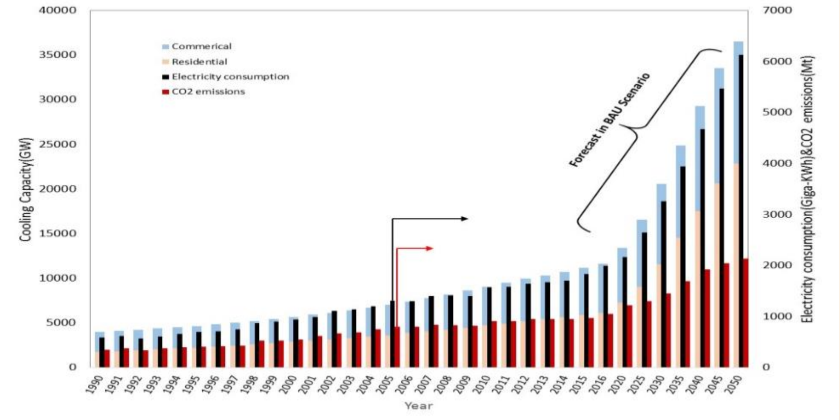
INTRODUCTION

- ➢ Increasing demand for air conditioning (AC) cooling - CAGR of 4.5% over past decades, particularly in China, South & South-East Asia:- driving factors: (i) Population growth rate and (ii) Increasing disposable income in many developing economies
- ➢ World electricity consumption for AC cooling increases by 3 folds since 2010,- In 2018, AC cooling in China exceeds that in US and whole Africa, AC units sold annually peaked at 50+ million,

IEA projection of Energy consumption by AC



Availability of AC versus Income (per month)

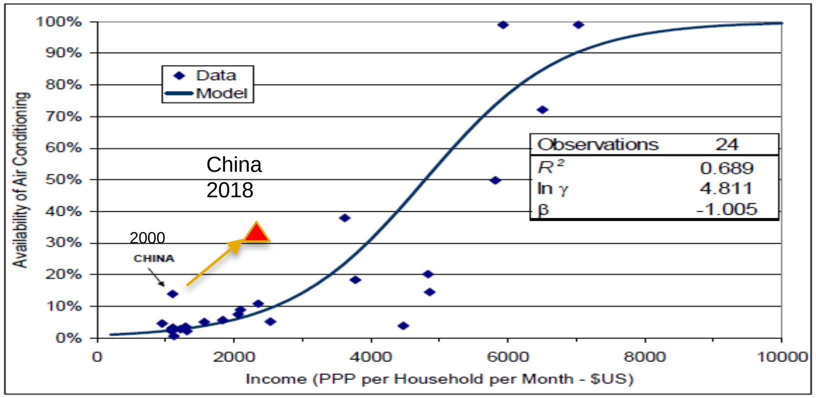


Figure 3 Air Conditioner Availability vs. Income

INTRODUCTION

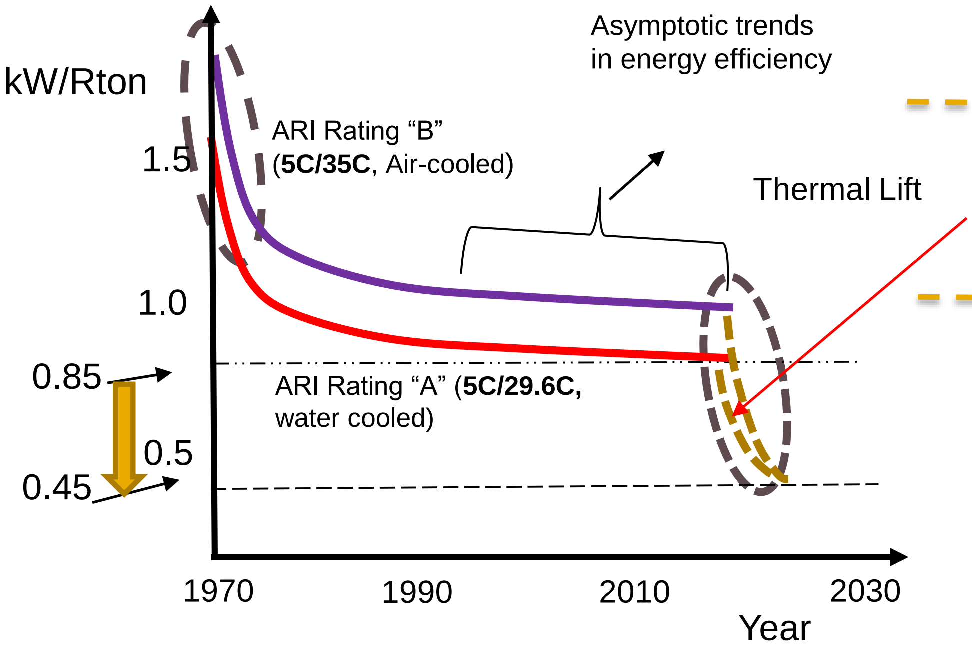
- Total AC cooling energy consumption is 37% in non-OECD countries, 35% in the Americas, 17% in Europe.
- Energy intensive refrigerant-based MVC cycle – **> 0.9 ±0.05** kW_$_{elec}$/Rton and it has stagnated at to 0.85±0.3 kW/Rton – only marginal improvements from heat exchangers and refrigerants.

Year	Electricity consumption for Cooling (TWh/yr)	No of folds (BAU)	World Annual Electricity consumption (TWh/yr)	Percentage of world consumption to cooling (%)	CO2 emission from cooling (Gton / year)
2000	**300**	**1**	**13,200**	**2.25**	**0.173**
2015	**815**	**2.71**	**21,240**	**6.8**	**0.479**
2050	**6200**	**20.6**	**31,440**	**19.7**	**4.022**
2100	**53,300**	**177**	**198,600**	**26.8**	**34.58**

- **Assumption: This is a Business-as-usual (BAU) scenario for energy consumption forecast. The efficiency of chillers remain unchanged over the forecast period.**

Improving Energy Efficacy requires a Paradigm Change

- Energy Efficiency (the kW/Rton) of MVCs have stagnated since, 0.85±0.05 kW/Rton,
- The “Thermal Lift” in treating the moist outdoor air (OA), i.e., operating between dew point of air (evaporator) and ambient temperatures in a single coil (condenser).



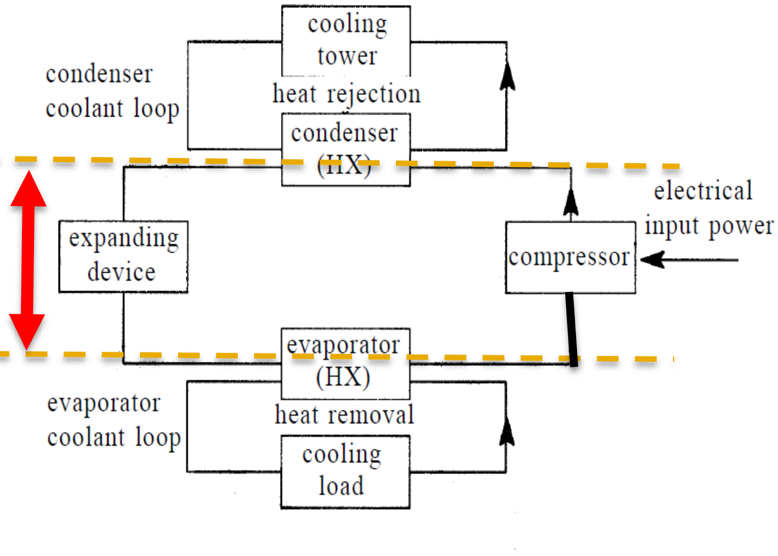


Figure 1.2: Schematic of a mechanical chiller. Heat transfers at the condenser and evaporator are effected through heat exchangers.

KAUST’s Cooling research for AC:-

Emulating nature’s evaporative cooling

- De-coupling of Q_{latent} to $Q_{sensible}$ in treating the moist air (previously performed at evaporator):
  - (i) moisture removal by sorption uptake of adsorbent,
  - (ii) cooling of warm but dry air by indirect evaporation of water films
- Minimized heat & mass transfer resistances across the thin-foil between the dry and wet channels,
- Exploiting the hydrophilic coatings on wall surfaces of wet sections and optimized the purged ratio of air to enhance COP_{IEC}.
- Scaled modularly dry & wet pairs to meet capacity design.

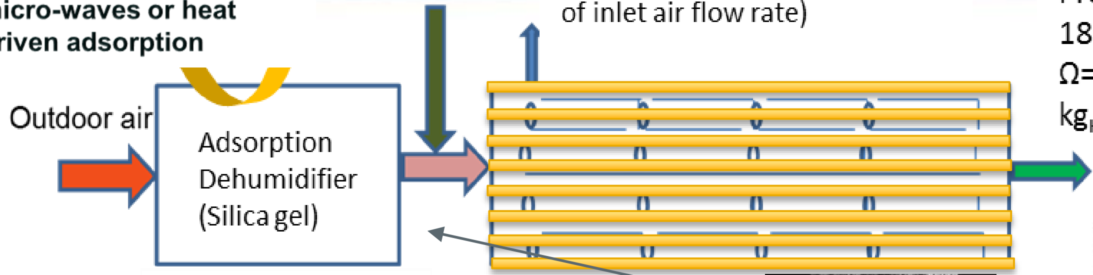
Proposed Innovative Low-Energy Cooling Technology:

Dehumidification by micro-waves or heat driven adsorption

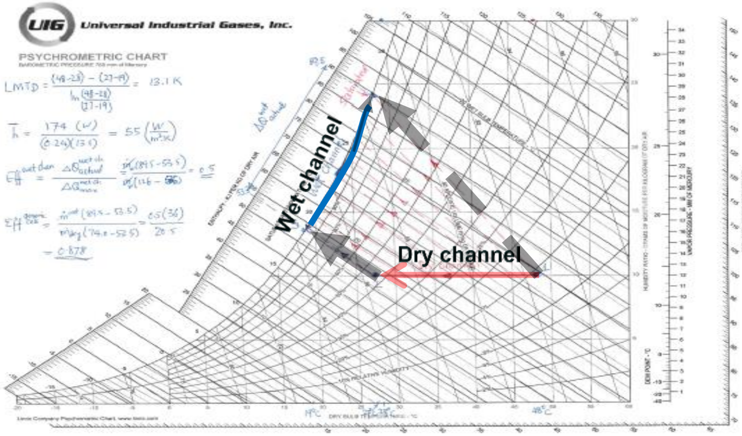
Return air

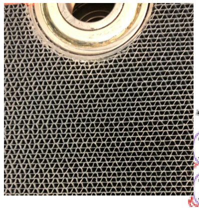
Purged saturated air (30 to 40% of inlet air flow rate)

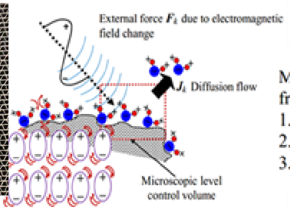
Product air at 18~20ºC and Ω=0.008~0.01 $kg_{H2O}/kg_{dry\ air}$



Psychrometric processes in the wet & dry channels

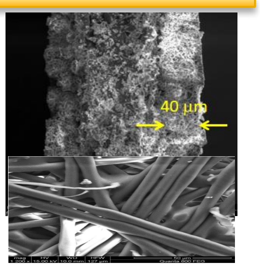






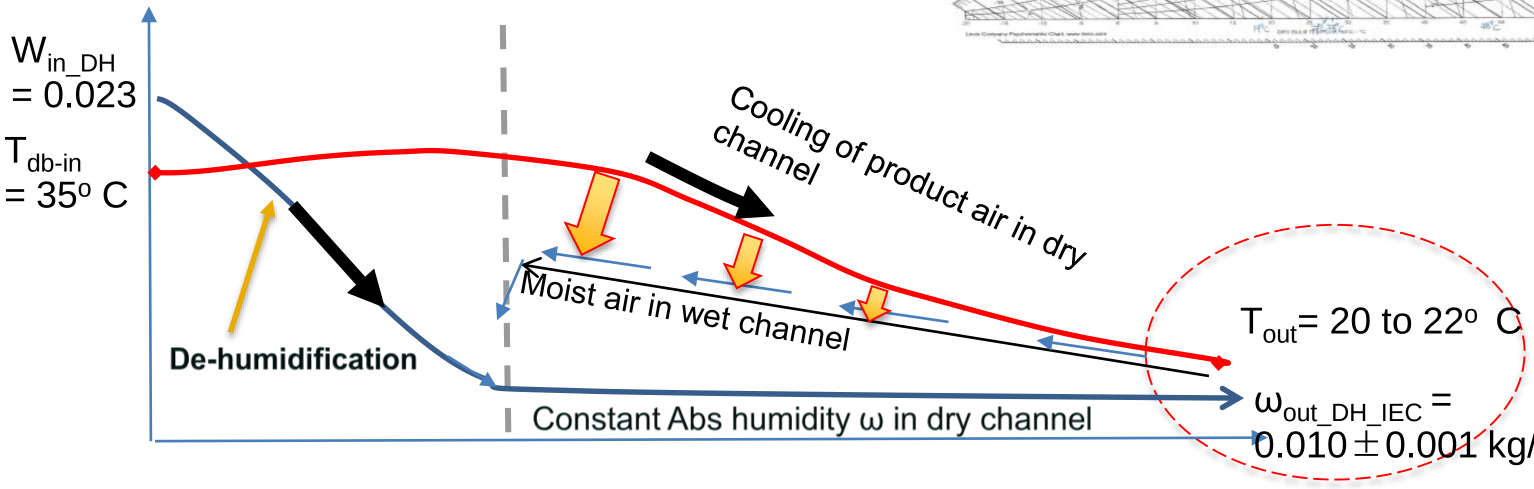
Microwave transfer to heat energy due to friction

1. Among adsorbents molecules
2. Adsorbent and adsorbate molecules
3. Among adsorbate molecules



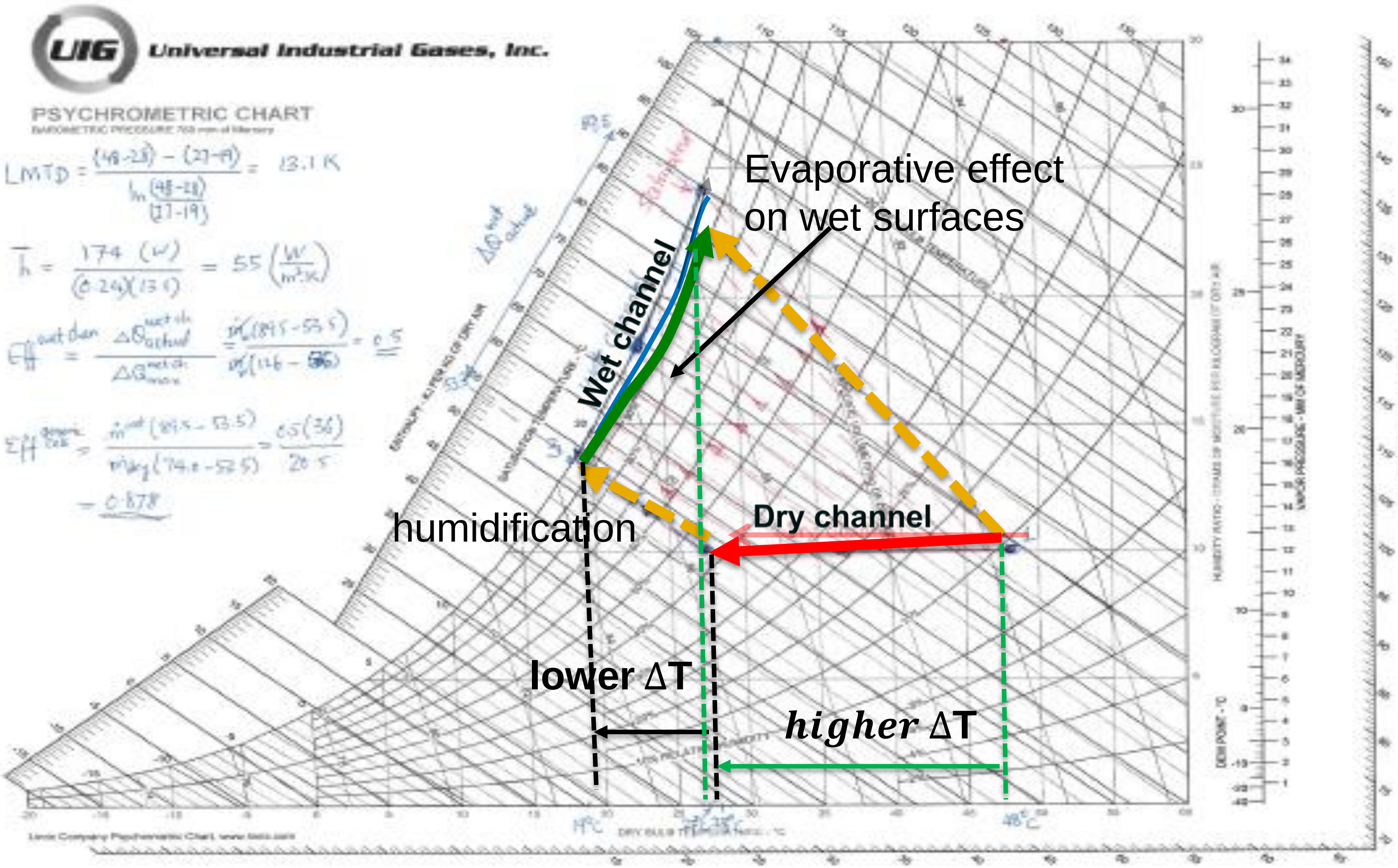
Purged air (30 to 50%) in wet channel

RH80%



RH50%

Psychrometric process paths



Evaporative effect on wet surfaces

Wet channel

Dry channel

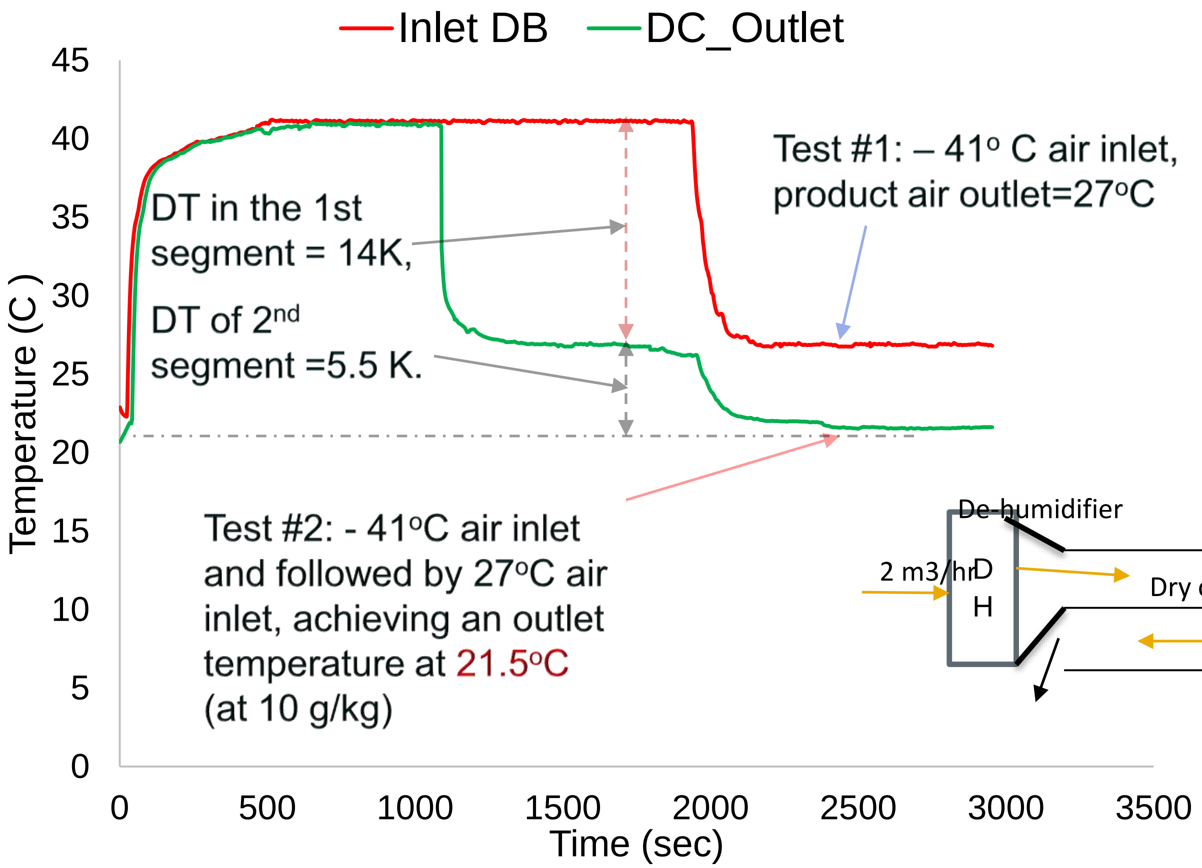
humidification

lower ΔT

higher ΔT

Temporal traces of a single generic IEC cell (T$_{in}$ = 41 °C, T$_{out}$ = 23 °C, Q = 185 W, U$_{IEC}$ = 100±5 W/m^2.K)

- “Tests conducted on a 0.8m length IEC

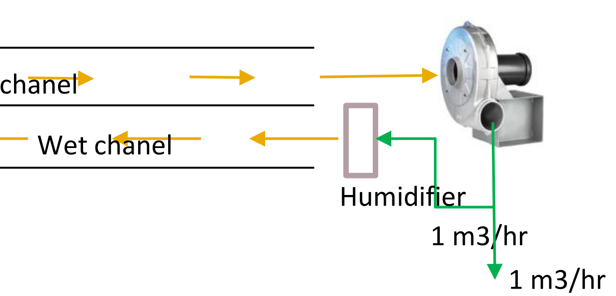


DT in the 1st segment = 14K,

DT of 2nd segment =5.5 K.

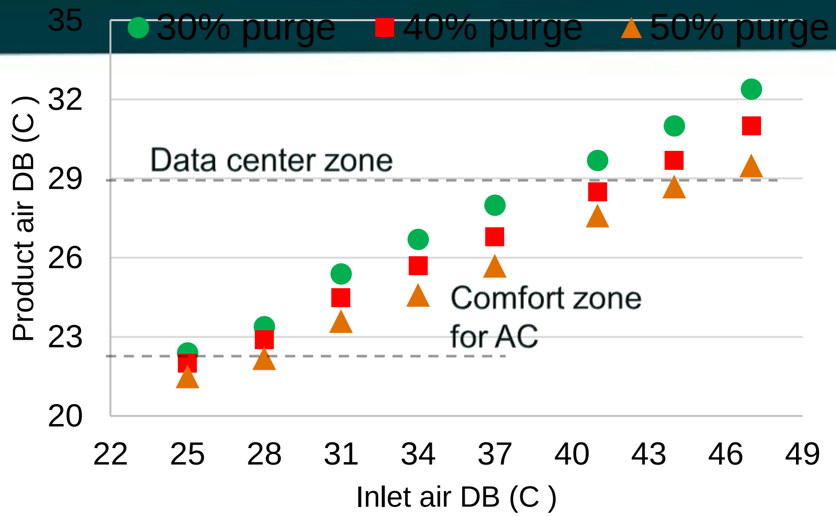
Test #1: – 41° C air inlet, product air outlet=27°C

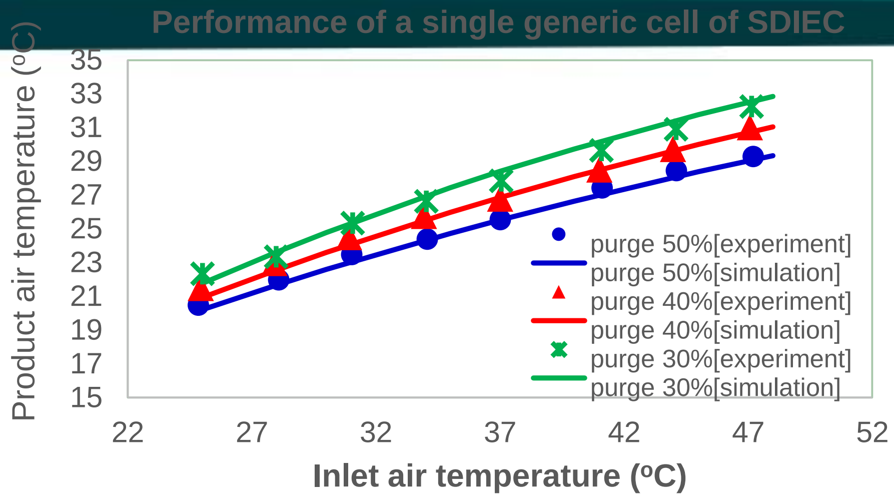
Test #2: - 41°C air inlet and followed by 27°C air inlet, achieving an outlet temperature at 21.5°C (at 10 g/kg)

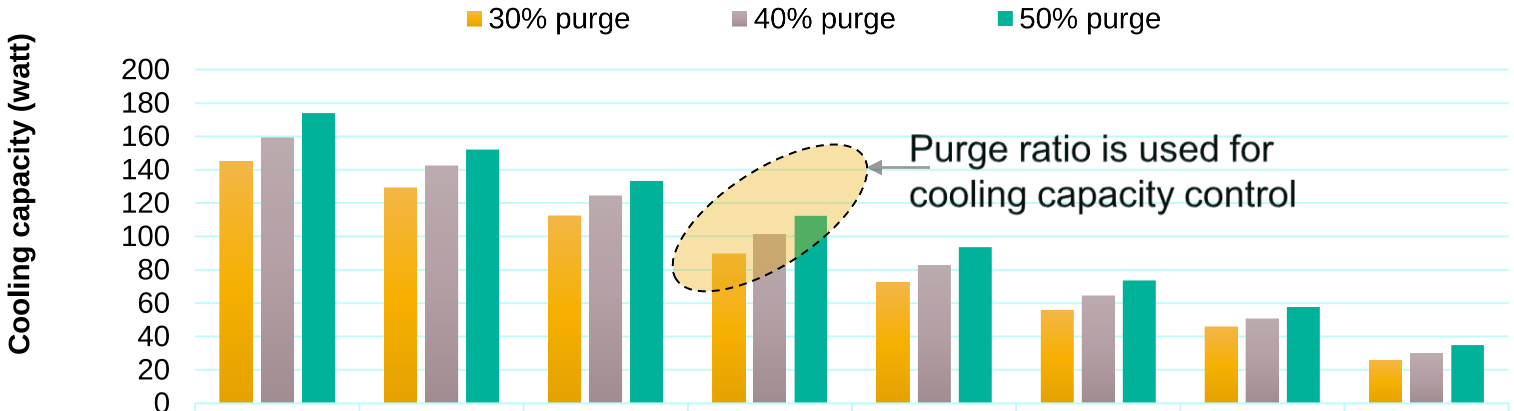


Experimental results of a generic cell

(absolute humidity = 10±0.2 g H_2O/kg of dry air), wet channel is laminar flow (Re=1000±70), dry channel is Turbulent (Re=4100±50)




Performance of a single generic cell of SDIEC

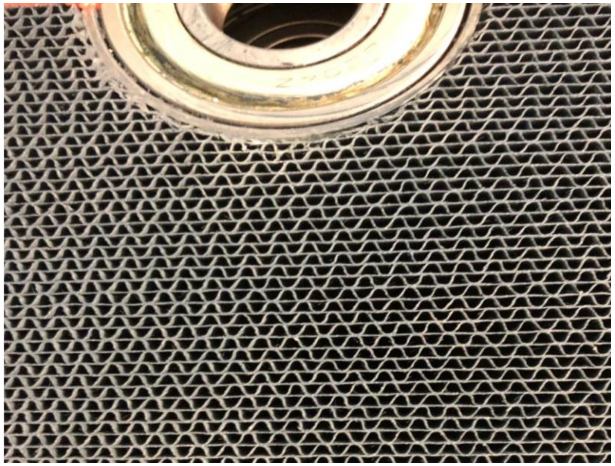


Purge ratio is used for cooling capacity control

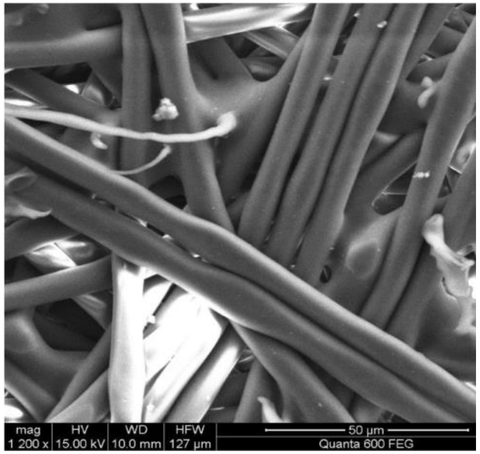
	47	44	41	37	34	31	28	25
30% purge	145.20	129.29	112.38	89.51	72.60	55.69	45.75	25.86
40% purge	159.12	142.22	124.32	101.44	82.55	64.64	50.72	29.84
50% purge	174.04	152.16	133.27	112.38	93.48	73.59	57.68	34.81

Dehumidification by adsorbent and regeneration of adsorbent

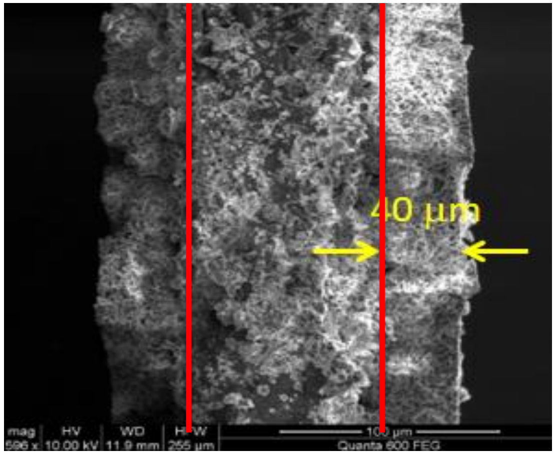
- Moisture removal from air stream by two major processes:
  - (i) liquid adsorbent such as LiCr solution with a heat source regeneration, CoP < 1.0 due to high energy of latent evaporation
  - (ii) Solid adsorbent such as $SiO_2.nH_2O$ (mesoporous at 700-800 m^2/g and pore diameters from 5 to 30 µm. Water vapor molecules are desorbed from pore surfaces by resonance of molecules at 2.45 GHz of µ-waves. CoP > 2.0 to 3.0



Honey-come coated adsorbent structure at 1.8 to 2 mm pitch

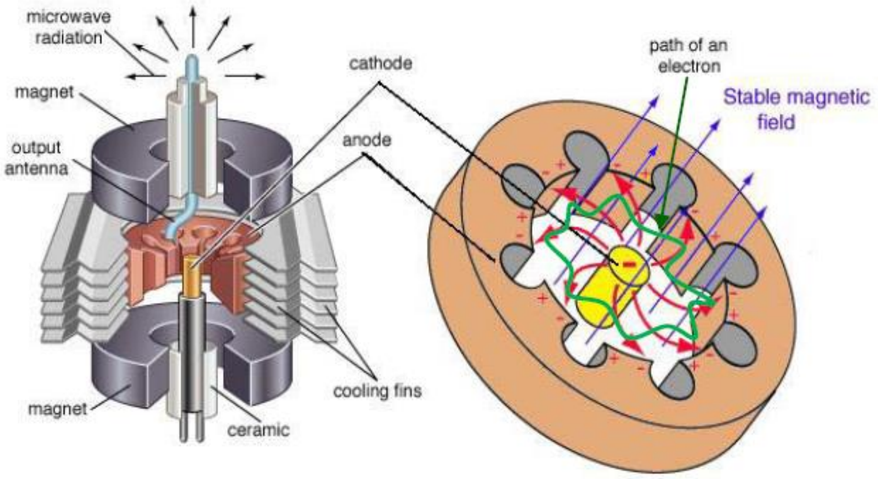


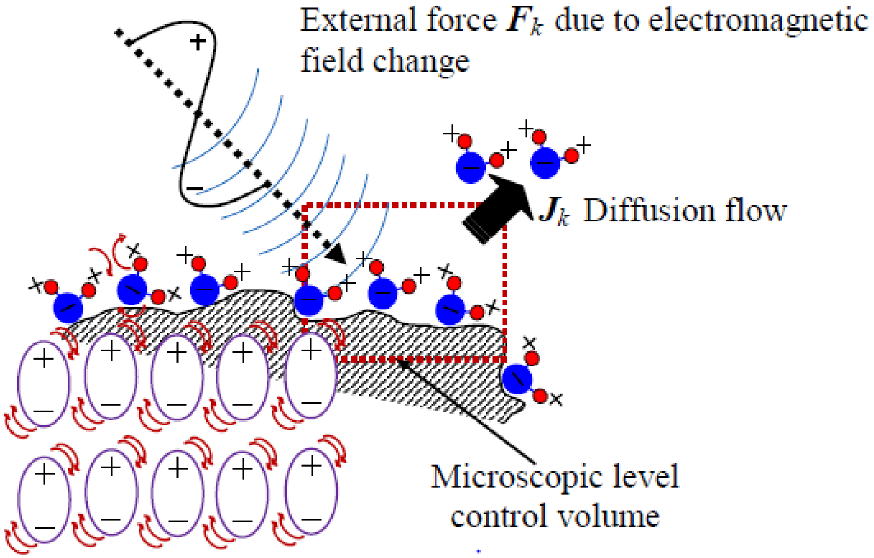
Base structure of polyester or paper structure up to 250 µm



Good adhersion of adsorbent onto substract up to 40 µm.

Microwave desorption





$$P_{avg} = 2V\pi f \epsilon_o \varepsilon'' E_{rms}^2$$

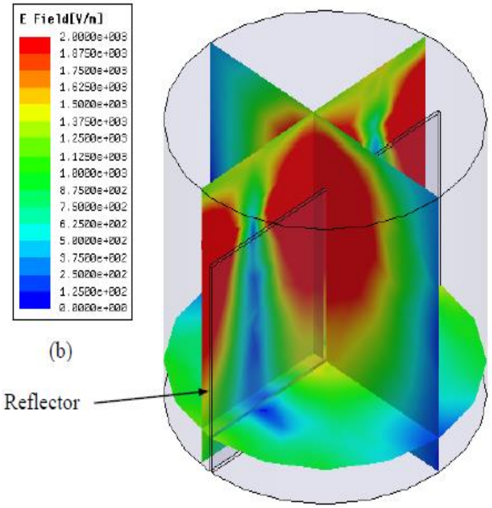
V	Volume of work load (m^3)
ϵ_o	free space or vacuum permittivity (F/m)
ε''	Permittivity loss factor (imaginary part)
E_{rms}^2	Average Electric Field Intensity (V/m)
f	Electromagnetic frequency (GHz)

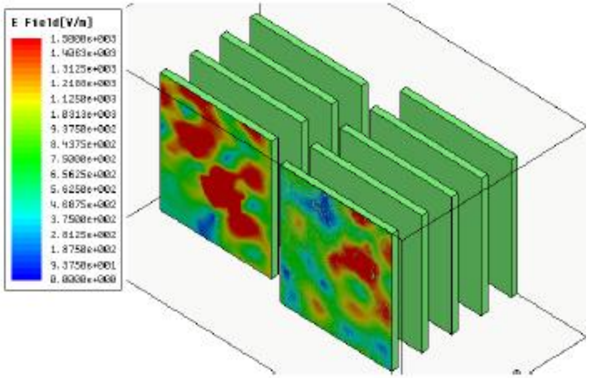
Microwave transfer to heat energy due to friction

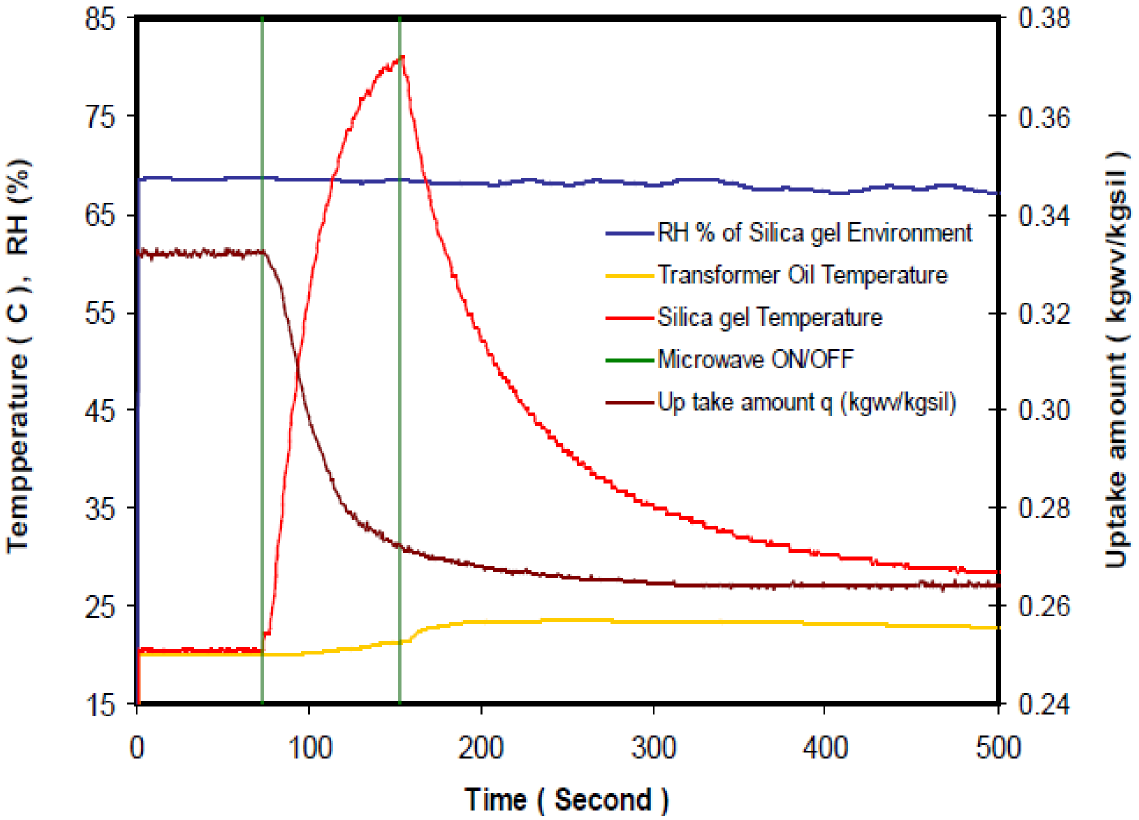
1. Among adsorbents molecules
2. Adsorbent and adsorbate molecules
3. Among adsorbate molecules

Microwaves desorption: - a challenge

Simulation of the electric field by magnetron

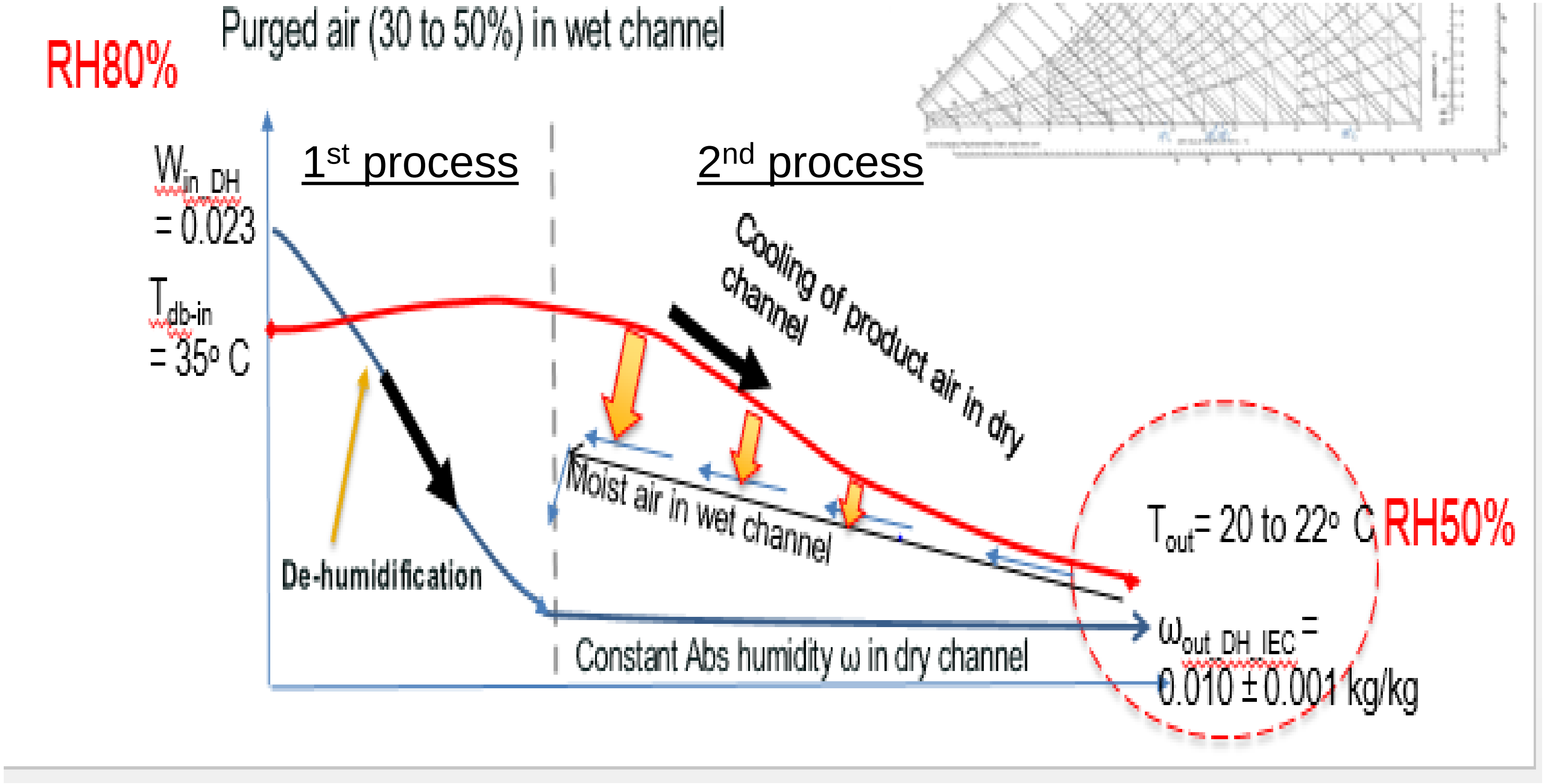




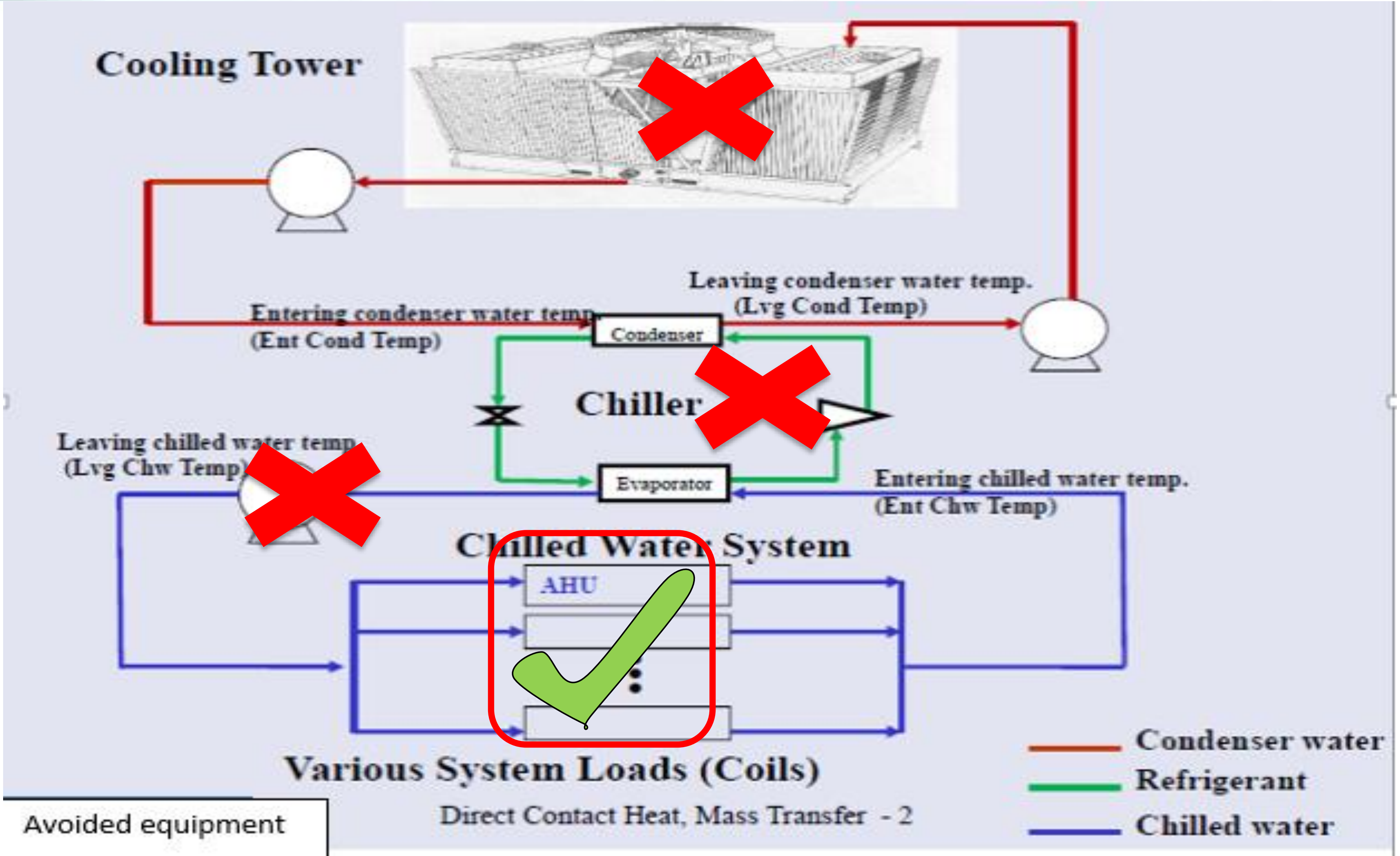


Temperature and mass transients under microwave irradiation (Silica RD)

De-coupled processes: (i) Dehumidification and (ii) sensible cooling



Avoided Equipment of AC Plant



Avoided equipment

Combined DH (COP=3) and IEC (COP=30)

Novel treatment Process for moist air ($Q_{total}=Q_{LAT}+Q_{sen}$, and $SHR=Q_{sen}/Q_{tot}$):

$$COP_{DH+Sensible\_cooling} = \frac{Q}{\left(\left\{\frac{(1-SHR)*Q}{COP_{DH}}\right\}+\left\{\frac{SHR*(Q)}{COP_{sensible\ cooler}}\right\}\right)}$$

Example: For a SHR in moist air = 0.7, $COP_{DH+Sensiblecooling} == \frac{1}{\left(\left\{\frac{0.3}{3}\right\}+\left\{\frac{0.7}{30}\right\}\right)} = 8.1$

Sensible Heat Ratio (SHR) of moist air	0.5	0.6	0.7	0.8	0.9
Combined COP	5.45	6.52	8.1	10.7	15.7

We have to perform better than the best available system of today (say the desiccant coated coils in MVCs). The bonus advantage is the lower capital cost due to avoided equipment as compared to existing MVCs.

An example to demonstract the efficacy of DH-IEC disruptive cooling technology

- We examine the cooling demand of an Island state, Singapore.
- Annual AC energy demand is about 37% of total electricity production
- Most AC chillers are of the MVC of assorted sizes and district cooling share is 4.5% of total cooling load
- Assume a realistic improvement to COP fro, 5 to 16

Case study of Singapore

Time series data for total gross floor area(GFA), total cooling load, total electricity consumption and electricity consumption for cooling of buildings in Singapore from 2002 -2017.

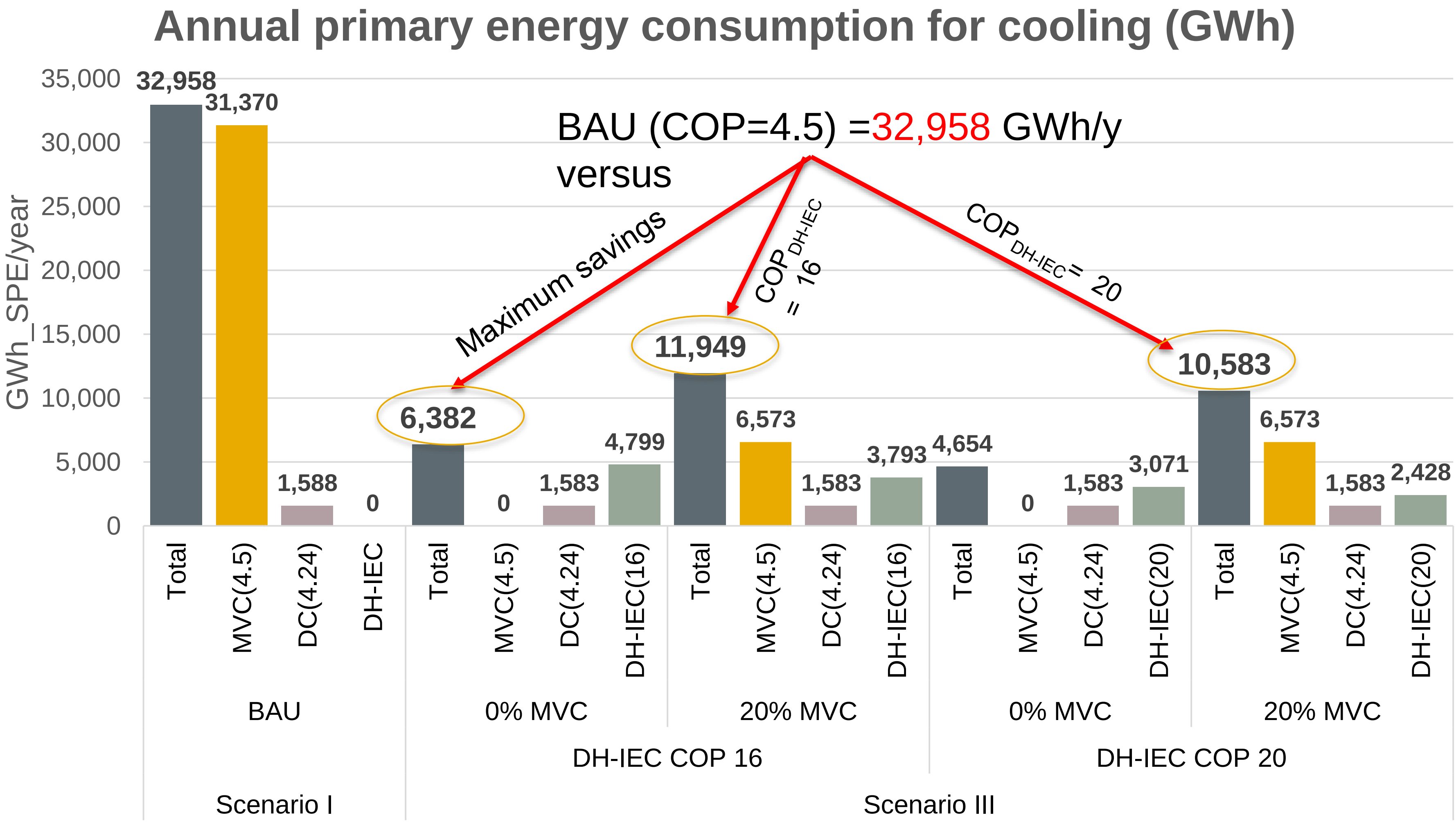
Year	Residence (DF=0.685)		Commerce and Service (DF=0.90)		Industry (DF=0.70)		Total				
	GFA (m^2) x10^6	CL (RTh/yr) x10^6	GFA (m^2) x10^6	CL (RTh/yr) x10^6	GFA (m^2) x10^6	CL (RT/yr) x10^6	GFA (m^2) x10^6	CL (RT/yr) x10^6	Total electricity consumption (GWh/yr)	Electricity demand for cooling (GWh/yr)	Fraction of Cooling Energy
2002	99.06	2,303.91	12.18	4,721.10	27.49	4,431.58	138.73	11,456.59	32,390	10,677.54	0.33
2003	100.18	2,580.42	12.05	4,672.45	28.43	4,583.43	140.67	11,836.30	33,386	11,019.59	0.33
2004	102.37	3,002.41	12.32	4,782.28	28.43	4,583.43	143.12	12,368.12	34,643	11,502.35	0.33
2005	103.48	3,628.97	12.64	4,899.14	29.20	4,706.26	145.31	13,234.37	36,290	12,307.97	0.34
2006	104.38	3,893.00	13.09	5,072.87	30.16	4,862.14	147.63	13,828.02	37,500	12,832.40	0.34
2007	104.69	4,200.52	13.35	5,159.53	31.49	5,075.41	149.52	14,435.46	39,066	13,381.67	0.34
2008	105.55	4,354.38	13.42	5,183.76	32.70	5,270.79	151.67	14,808.92	39,610	13,698.25	0.35
2009	106.67	3,668.60	13.58	5,267.28	33.74	5,438.92	153.98	14,374.81	38,853	13,296.69	0.34
2010	107.89	4,644.23	13.91	5,393.65	34.81	5,611.57	156.61	15,649.44	42,171	14,444.44	0.34
2011	109.07	4,951.33	13.94	5,400.61	35.13	5,662.83	158.14	16,014.76	43,007	14,749.60	0.34
2012	111.64	5,154.25	15.03	5,830.67	36.69	5,914.14	163.36	16,899.06	44,200	15,513.34	0.35
2013	113.01	5,656.69	15.45	6,002.74	37.32	6,015.54	165.78	17,674.96	44,923	16,084.21	0.36
2014	114.26	6,096.35	15.76	6,124.09	38.28	6,170.70	168.26	18,325.27	46,164	16,642.83	0.36
2015	115.52	6,570.19	16.08	6,247.89	39.27	6,329.86	170.77	18,999.50	47,440	17,220.85	0.36
2016	116.79	7,080.86	16.40	6,374.20	40.28	6,493.12	173.33	19,698.54	48,751	17,818.94	0.37
2017	118.08	7,631.22	16.73	6,503.06	41.32	6,660.60	175.92	20,423.30	50,098	18,437.81	0.37

Cooling Technology Perspective

- Base line year : 2016
- Annual total cooling load : 19,698.90 x 10^6 RT
- Comparison studies : 3 scenarios (BAU, MVC+DC(35% to 65%%), MVC(20%)+DG-IEC (COP =16, 20)
- Cost of electricity : 0.18 $
- COP of MVC: 3.91
- DC(District cooling) efficiency: 0.83 kW/RT
- Current annual throughput of DC in Singapore : 894,396,000 RT(4.54%)
- IPCC conversion factor : 0.54288 t/MWh

Annual Throughput of DC: 894,396,000 RT (4.54% of annual total cooling load)		
Installed capacity	Marina Bay Sands	25,600 RT
	Changi Business park	37,500 RT
	One-North: Biopolis, Mediapolis	28,0000 RT
	Woodland Wafer Fab Park	11,000 RT

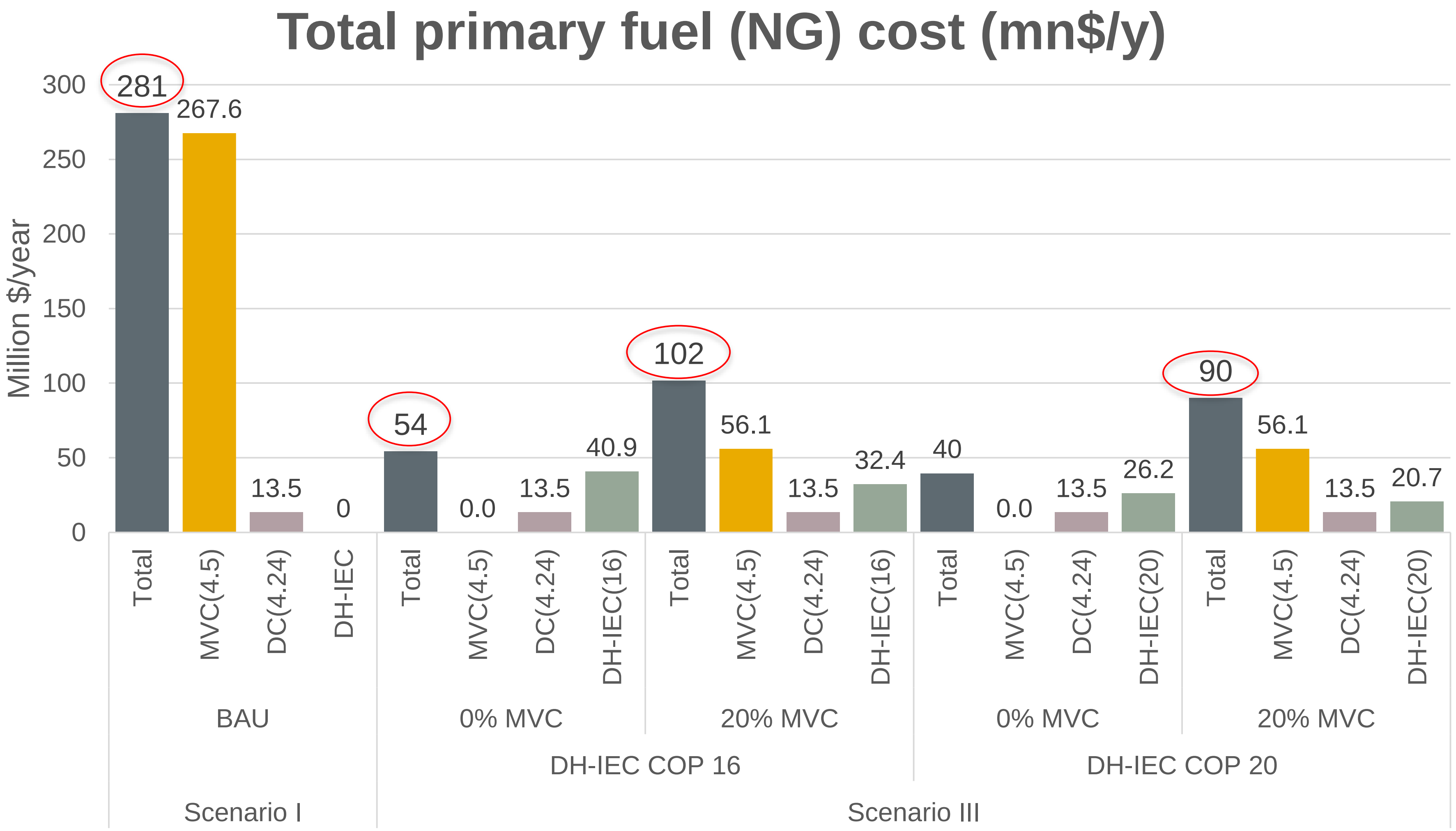
Energy scenario between BAU and DH-IEC for Singapore



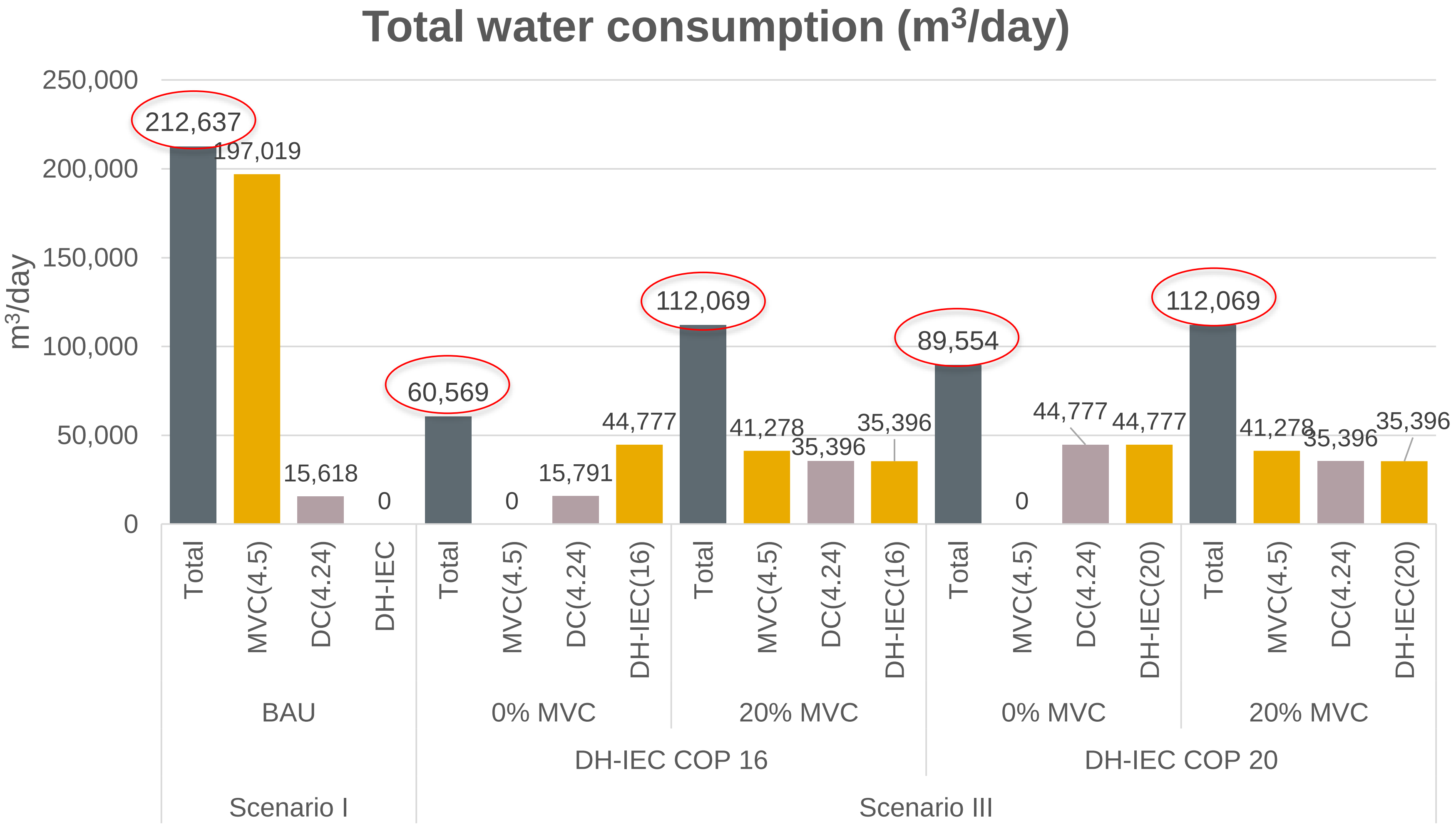
Annual primary energy consumption for cooling (GWh)

BAU (COP=4.5) =32,958 GWh/y
versus

Energy cost scenario between BAU and DH-IEC for Singapore (2)



Water scenario between BAU and DH-IEC for Singapore (3)



Conclusion

- A paradigm shift in AC technology is needed for achieving sustainable cooling future (with reduced CO2 and environment friendly cycle),
- DH-IEC is one of the most plausible ways to a quantum EE improvement, significant savings up to 50% of energy consumption;
- Other benefits include low capital cost, *avoided extensive infrastructure*,
- Caveat:- DH-IEC addresses only space comfort of AC not other aspects such as refrigeration or low temperature cryogenics, etc.