Grid-Responsive HVAC Flexible Measures – Annual Energy Simulations

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Content

- New and modified E+ modules
- Equipment performance Curves from HPDM
- HVAC Flexible Measures – Heating
- HVAC Flexible Measures – Cooling
- Recommendations

New and Modified E+ Modules

- Modified E+ features

1. Modulating cooling coil: Coil:Cooling:DX:VariableSpeed (responding to grid signal)
2. Modulating heating coil: Coil:Heating:DX:VariableSpeed (responding to grid signal)
3. Modulating water heating coil: Coil:WaterHeating:AirToWaterHeatPump:VariableSpeed (responding to grid signal)
4. Multi-mode coil system: CoilSystem:IntegratedHeatPump:AirSource (holder and controller of grid responsive cooling and heating coils, ice storage + supplemental cooling coil)
5. AirLoopHVAC:UnitaryHeatPump:AirToAir containing VS and IHP coils in air loop
6. CoilSystem:Cooling:DX and CoilSystem:Heating:DX containing VS and IHP coils

New E+ features

1. PCM storage: ThermalStorage:Pcm:Simple
2. Liquid desiccant heat&mass exchanger: Coil:LiquidDesiccant:Simple
3. Modulating air source chiller: Coil:Chiller:AirSource:VariableSpeed (responding to grid signal)
4. liquid desiccant storage heat pump: CoilSystem:DesiccantStorageHeatPump:AirSource
5. Heat storage sizing pair: ThermalStorage:Heating:Pair
6. Cool storage sizing pair: ThermalStorage:Cooling:Pair

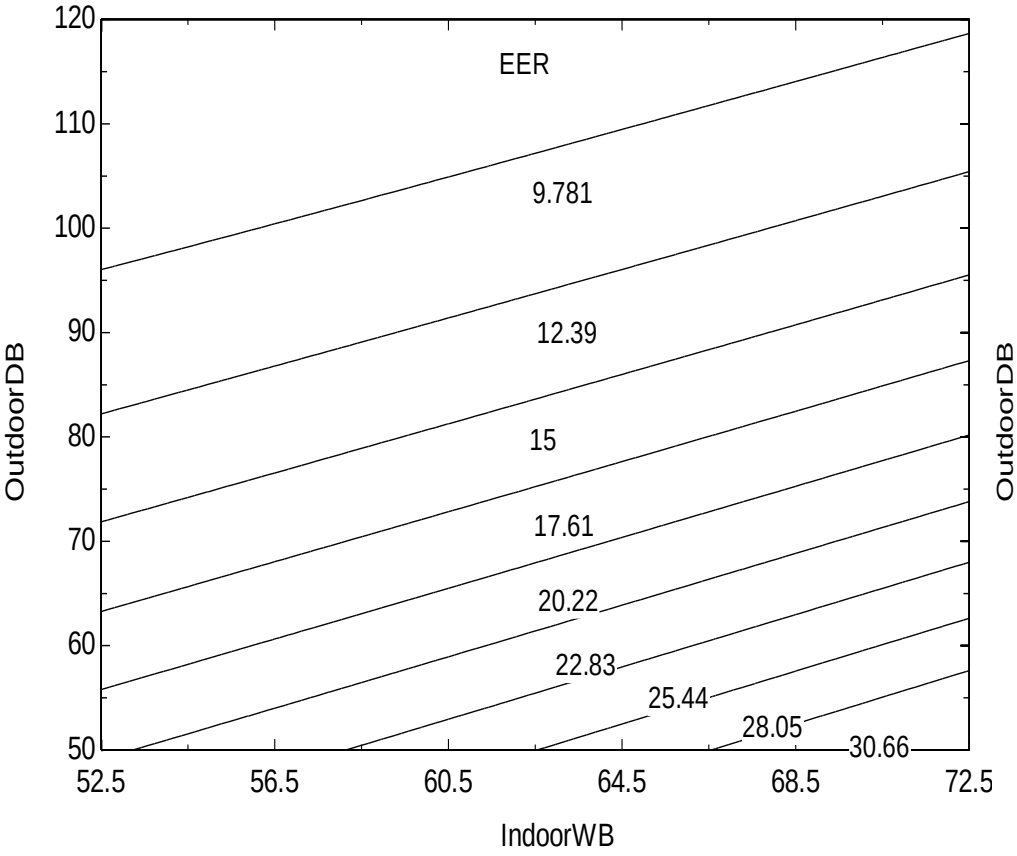
https://github.com/NREL/EnergyPlus/tree/HVACFlexMeasures

Equipment Performance Curves

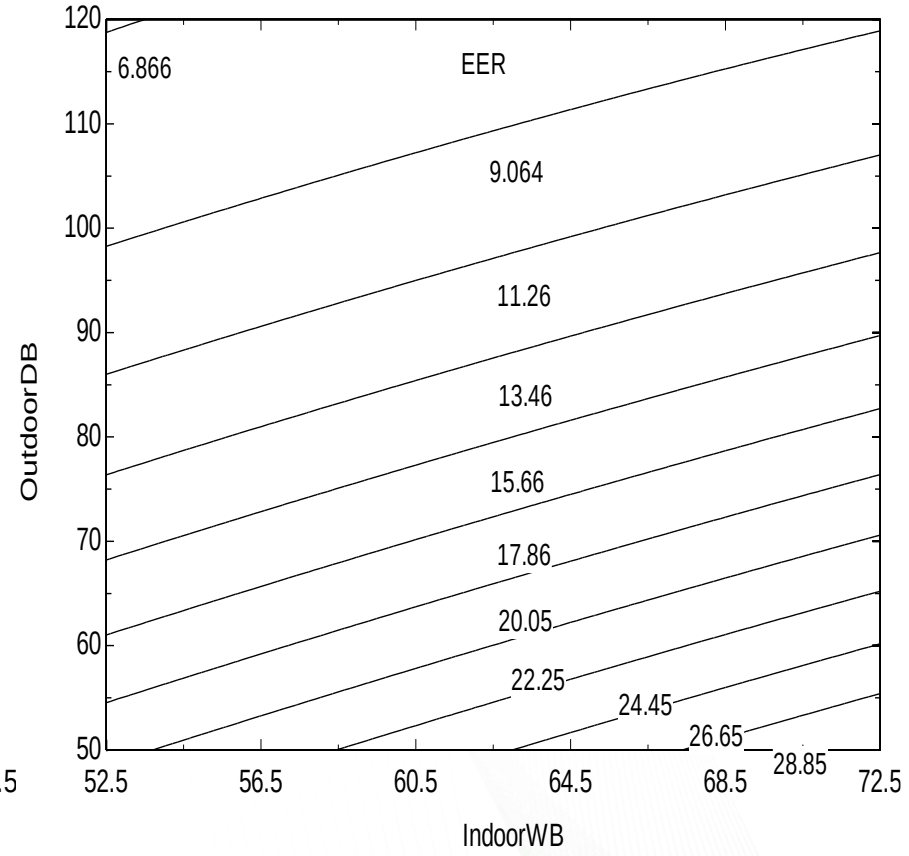
- Base unit is a 3-stage heat pump, i.e. the compressor runs at low (50% capacity); middle (67% capacity) and high (100% capacity)
- The high compressor capacity is locked for cooling mode, but allowed for enhanced heating at low ambient temperatures
- The rated SEER is 16.0 and HSPF (Region IV) is 12.0.
- The unit is autosized at the middle compressor capacity to meet the building design cooling load

→performance verified in laboratory

Temperature Performance Curves – Cooling EERs



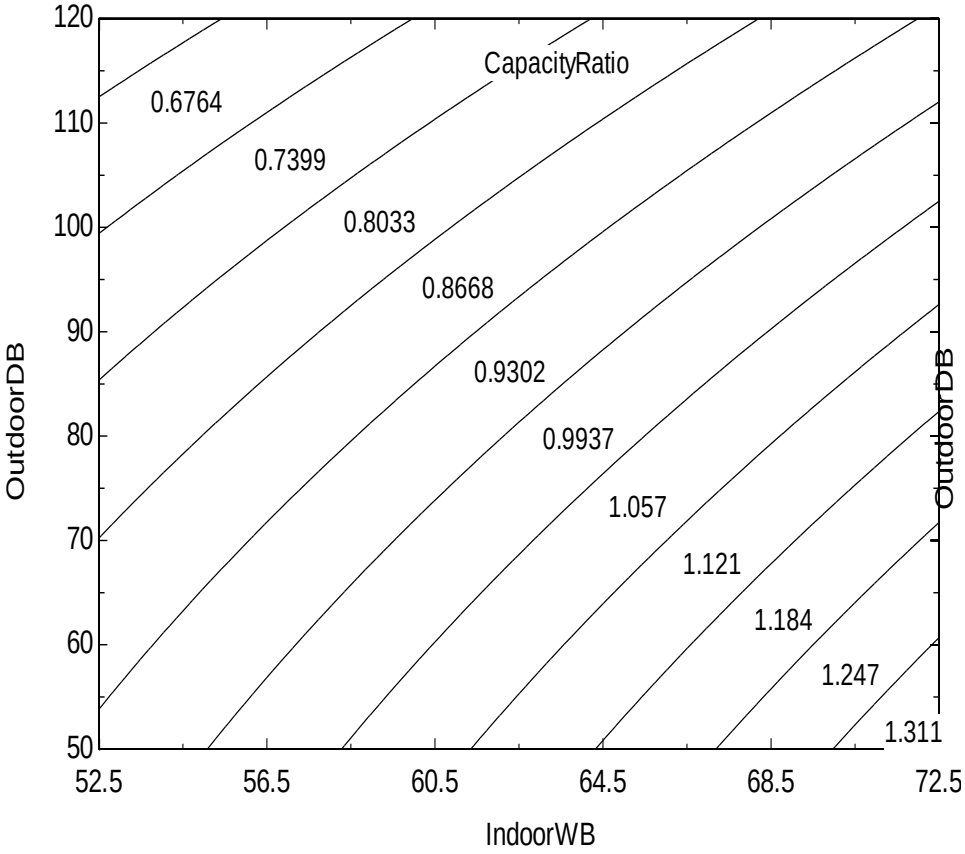
Low Cooling Stage



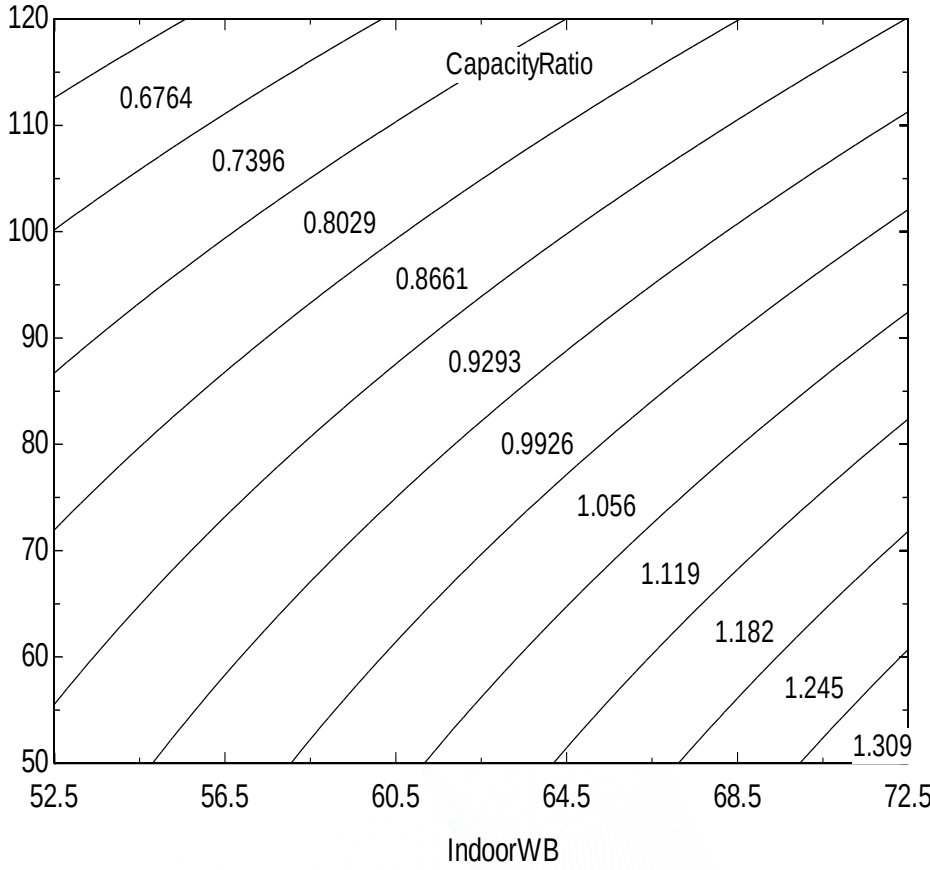
High Cooling Stage

Low cooling Stage is 5% to 7% more efficient than the high cooling stage
Air flow rate scales down with the compressor capacity (normal air flow rate)

Capacity Modification Ratios



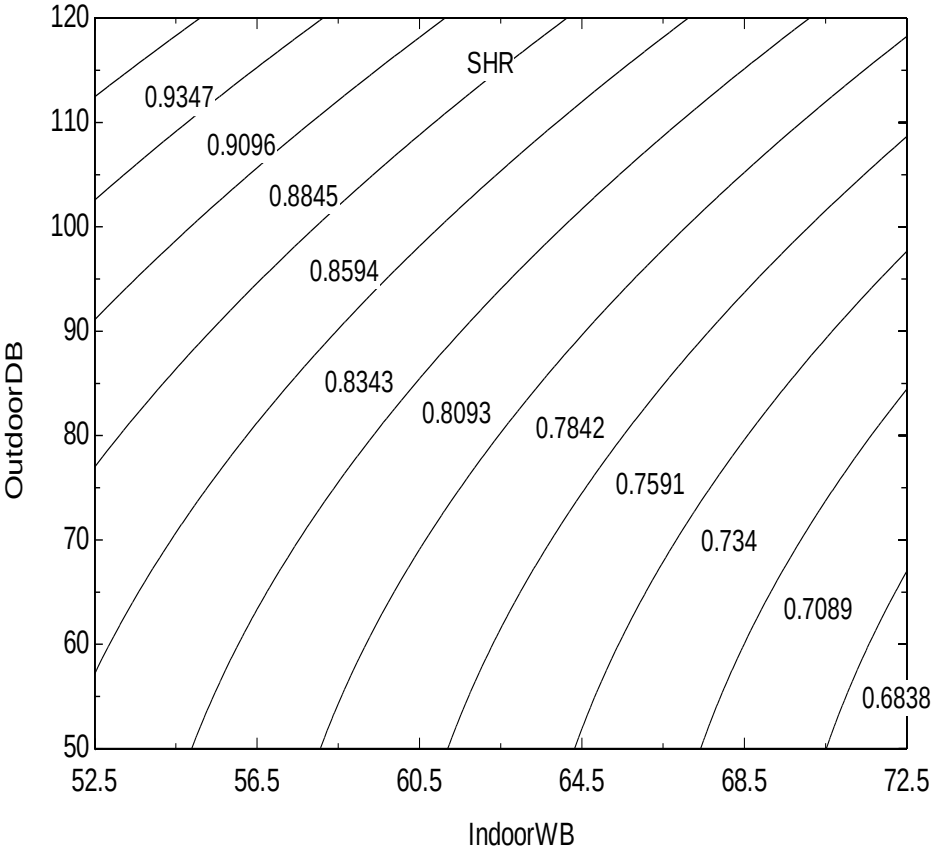
Low Cooling Stage



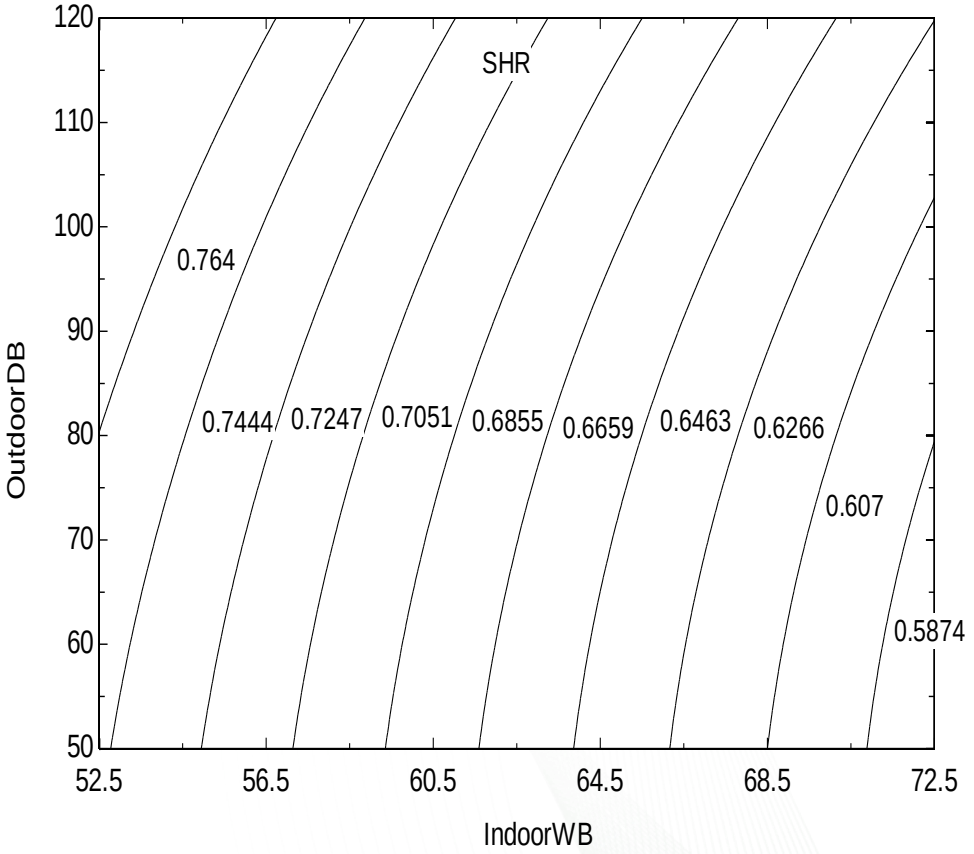
High Cooling Stage

Functions of capacity modification ratios versus temperatures are similar at different stages.

Enhanced Dehumidification at Low Stage (Reduce Indoor Air Flow to 50% of normal low stage) – sensible heat ratio



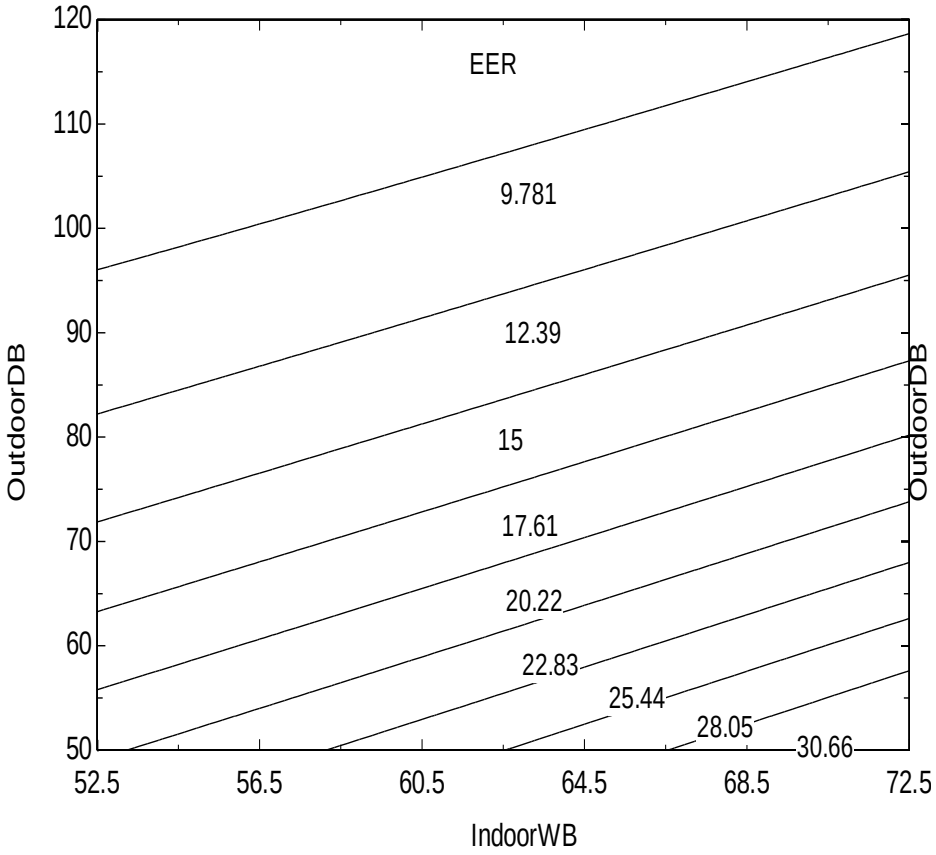
Normal Low Stage



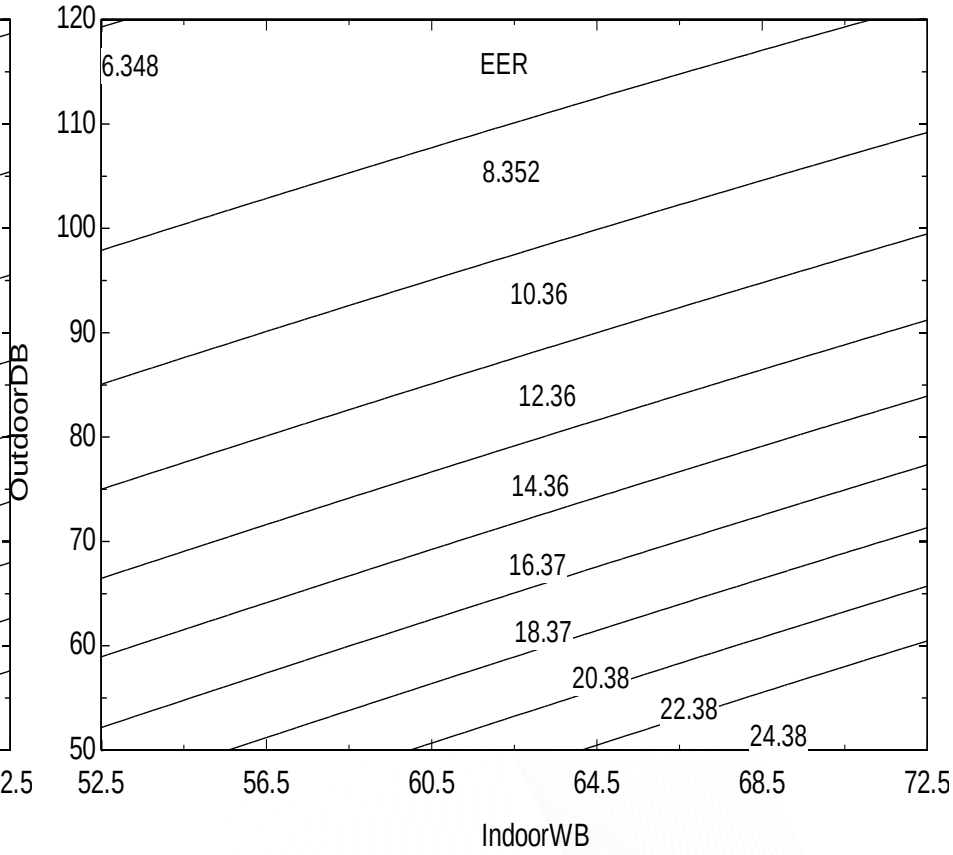
Enhanced Dehumidification Low Stage

Reduced indoor air flow increases moisture removal capability.

Enhanced Dehumidification versus Normal Mode - Efficiency



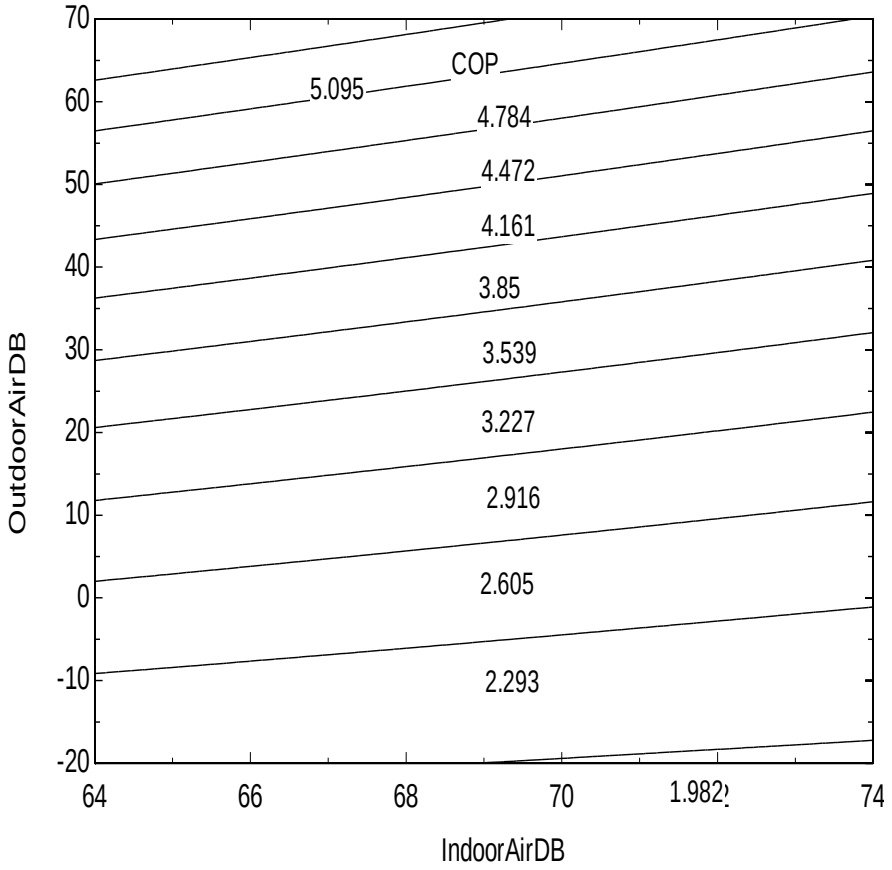
Normal Low Stage



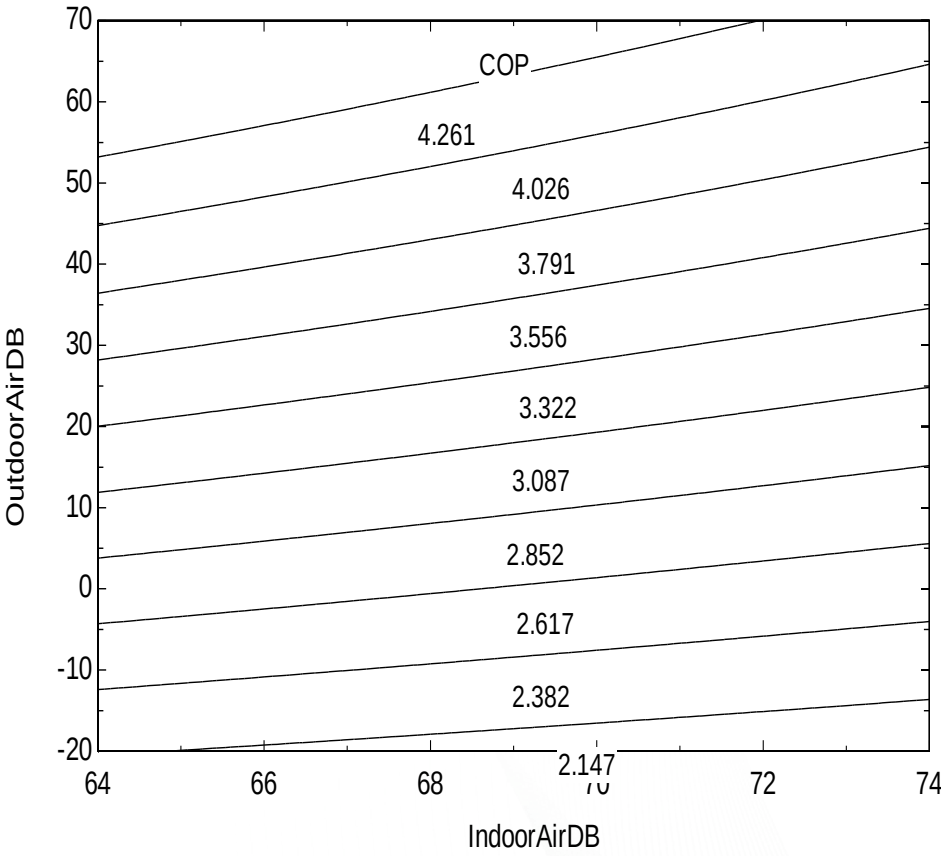
Enhanced Dehumidification Low Stage

Enhanced dehumidification causes 10% to 20% efficiency degradations.
Enhanced DH causes lower cooling capacity than the normal low stage.

Space Heating COPs



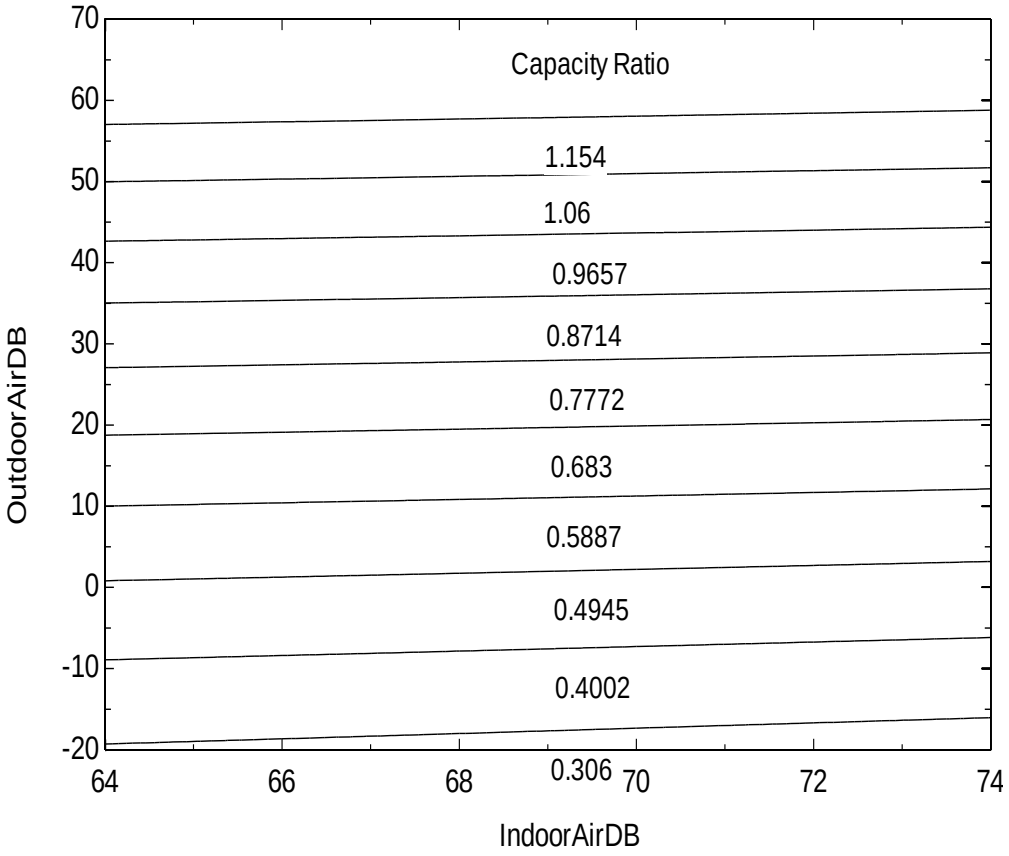
Middle Heating Stage



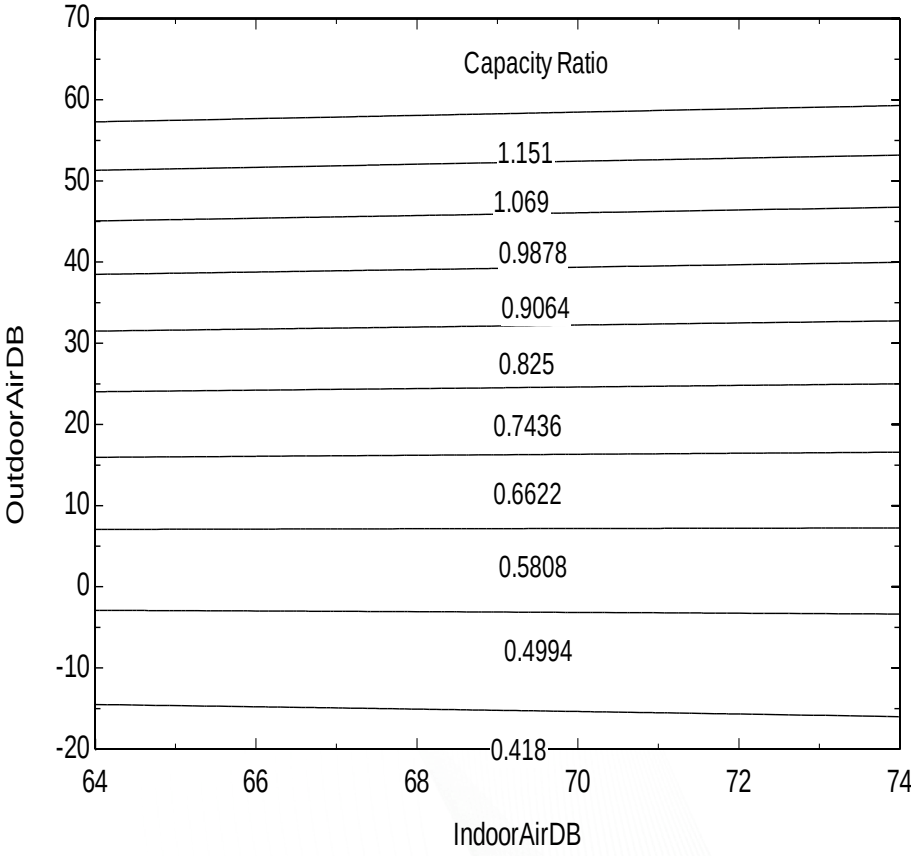
High Heating Stage

Lower heating capacity results in higher heating COPs.

Heating Capacity Degradation



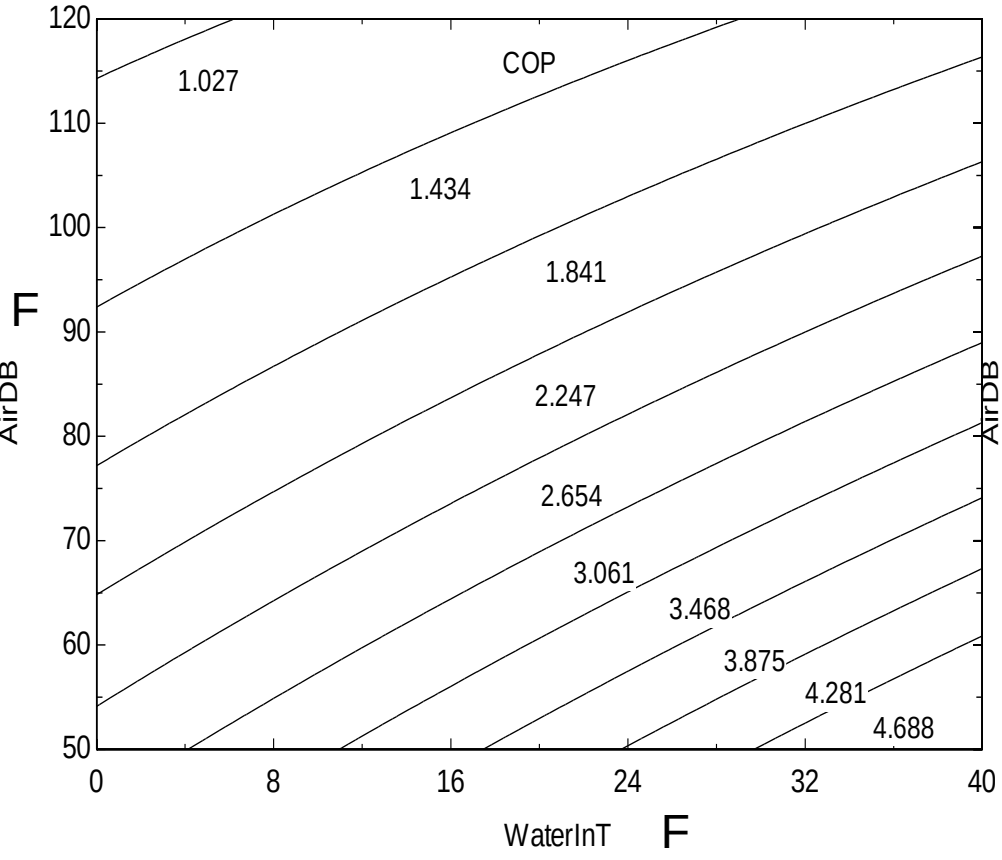
Middle Heating Stage

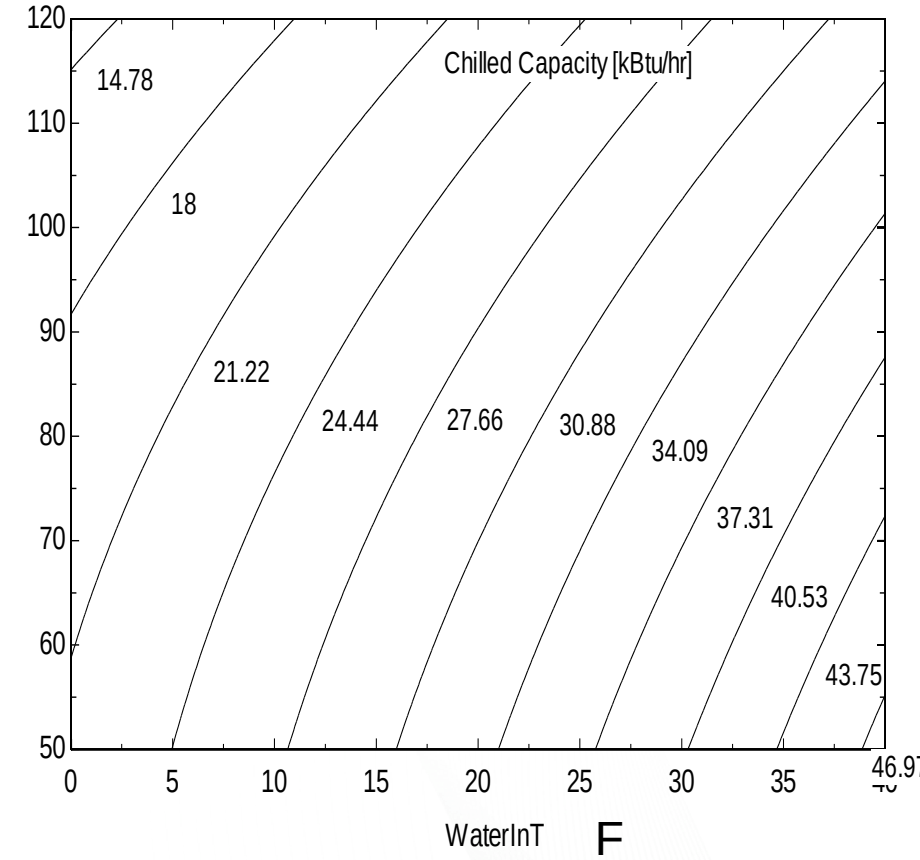


High Heating Stage

Heating capacity reduces to 50% if operating in sub-zero environment.

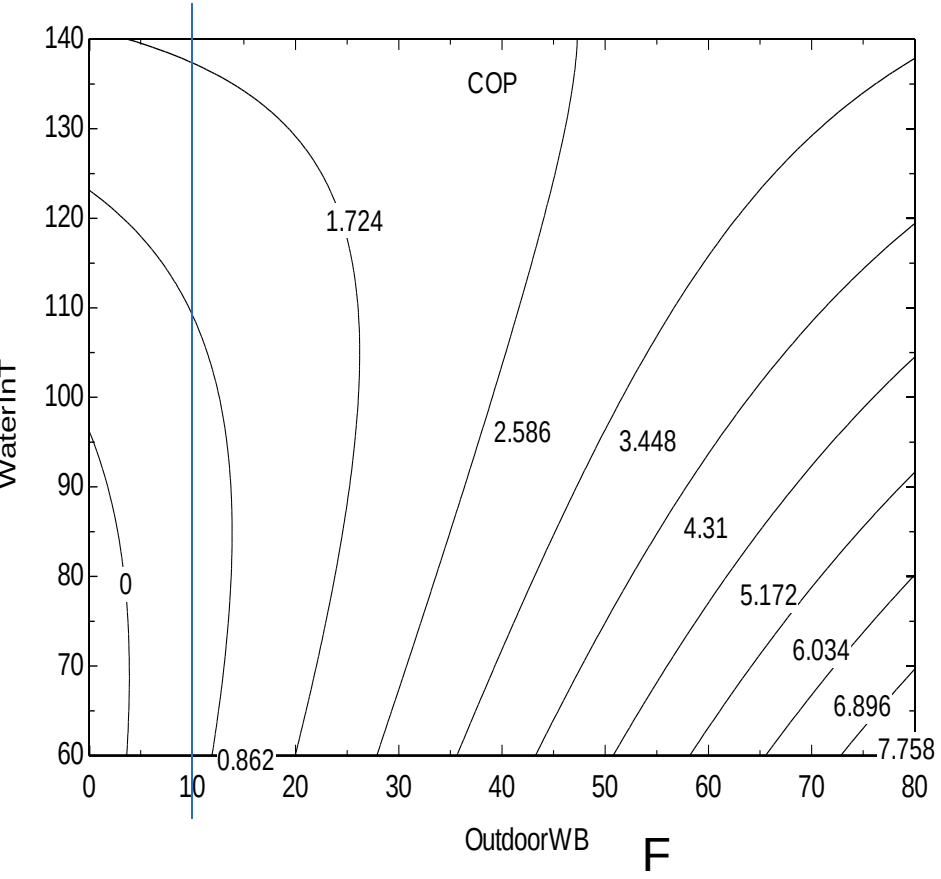
Ice Making Air-Source Chiller Performance

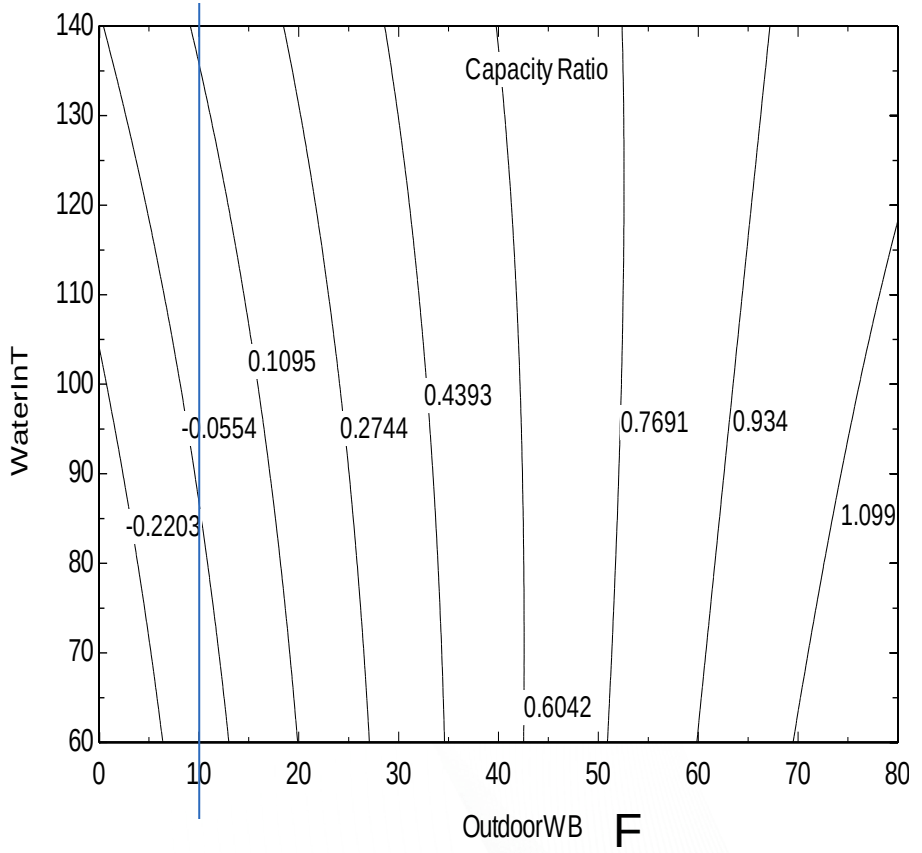




Higher ice/pcm phase change temperature boosts the chiller performance

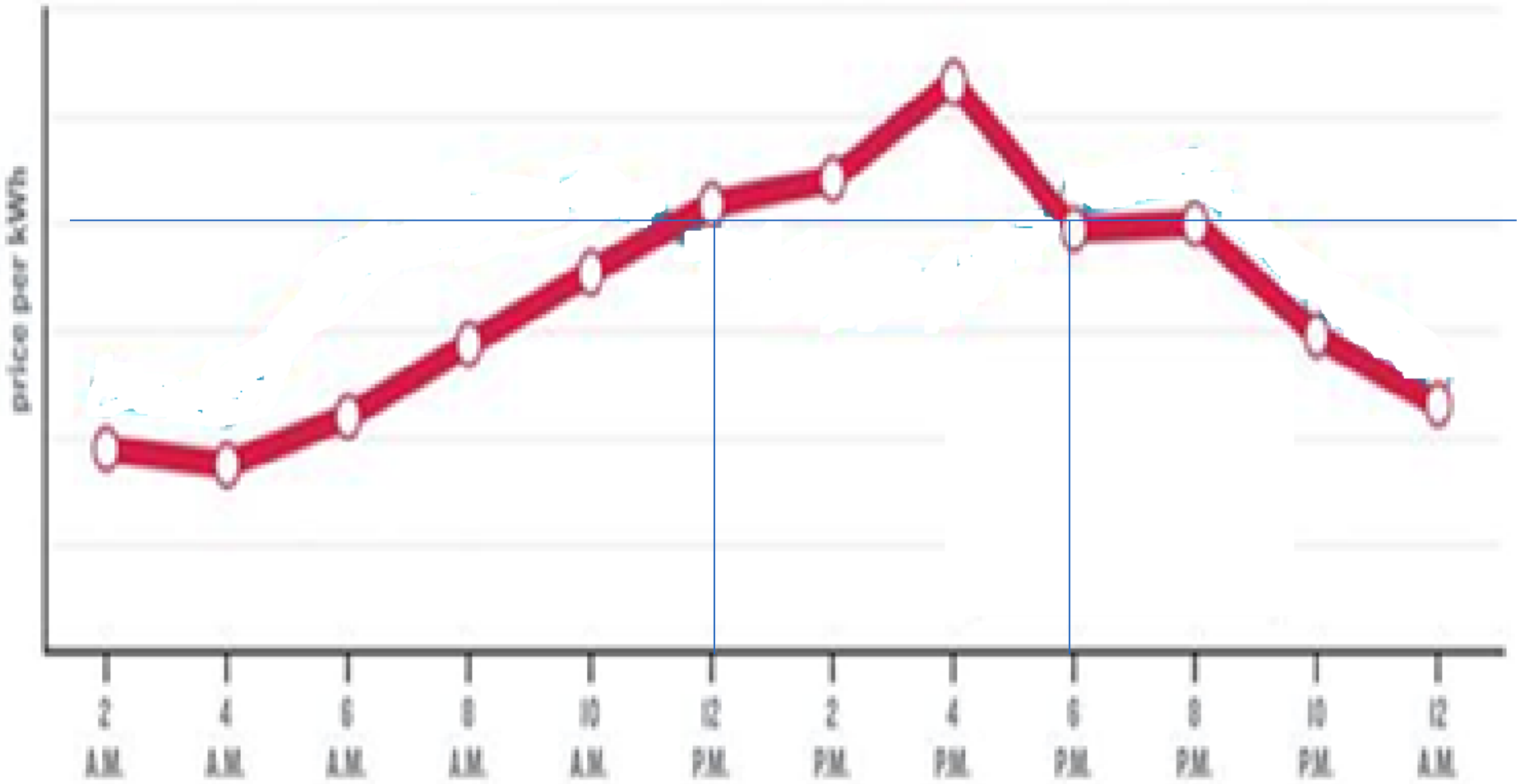
Regular Heat Pump Water Heater Performance





HPWHs have lower efficiency than air-to-air heat pumps because of the higher hot water supply temperature
the performances degrade drastically when reducing the ambient temperature and increase the hot water inlet temperature

Grid Signal – Hourly Electricity Price



Apply grid-responsive control when the electricity price is > 10 cents/ kwh, from 12:00P to 18:00P – turn off or limit the top speed of electric units.

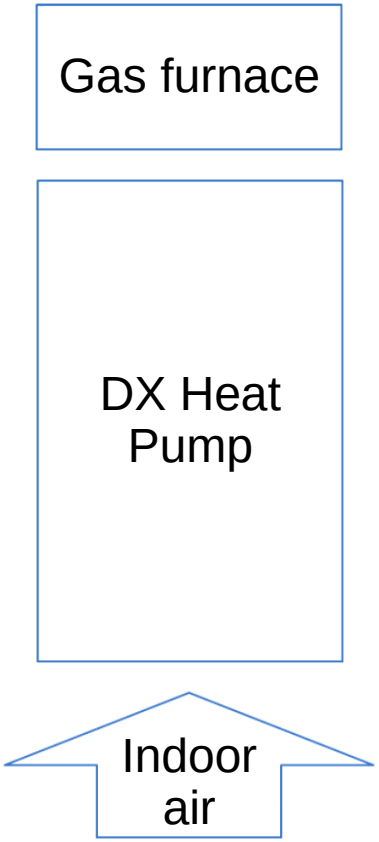
Residential Template House

- Single-family homes with slab foundations
- AirLoopHVAC:UnitaryHeatPump:AirToAir containing VS and IHP coils in air loop
- Two climate zones: Atlanta and Indianapolis
- Built according to IECC 2006 (The International Energy Conservation Code)
- DX cooling coil is autosized, and heating coil has the same rated capacity
- Cooling set point is 23.3 C (75 F); heating set point is 21.1 C (70 F) through the year.

Commercial Template Building

- Middle Office Building having three floors
- CoilSystem:Cooling:DX and CoilSystem:Heating:DX containing IHP coils
- One climate zone: Atlanta
- Built according to IECC 2006
- DX cooling coil is autosized, and heating coil has the same rated capacity
- Heating and cooling set points have set-back schedules
- Run Flexible Measures for the HVACs at the bottom floor

HVAC Flexible Heating Measures



Dual source heat pump

- Use gas supplemental heating when the heat pump is off or can't meet the heating demand
- Dual heating sources provide adequate heating capacity to maintain good comfort
- Run two cases: baseline (never shut-off compressor) versus grid-responsive control (Shut-off the compressor when the grid electricity price is above 10 cents)

Dual Source Heat Pump (Residential)

Atlanta – Heating Season

	HP_deliver	HP_Power	Gas_deliv	HP_COP	total_deliver	Price_Elec
	kwh	kwh	kwh	W/W	kwh	dollar
Baseline	11678	3499	270	3.338	11948	273
Grid-Res	9046	2708	2694	3.341	11740	181
Grid/Base	77%	77%	N/A	100%	98%	66%

Indianapolis – Heating Season

	HP_deliver	HP_Power	Gas_deliv	HP_COP	total_deliver	Price_Elec
	kwh	kwh	kwh	W/W	kwh	dollar
Baseline	17145	5658	2631	3.030	19776	481
Grid-Res	11279	3709	8396	3.041	19675	252
Grid/Base	66%	66%	320%	100%	99.5%	52%

- For the baseline cases, Indy requires more supplemental heating because it is colder
- Total delivered capacities (baseline versus grid-response) are close.

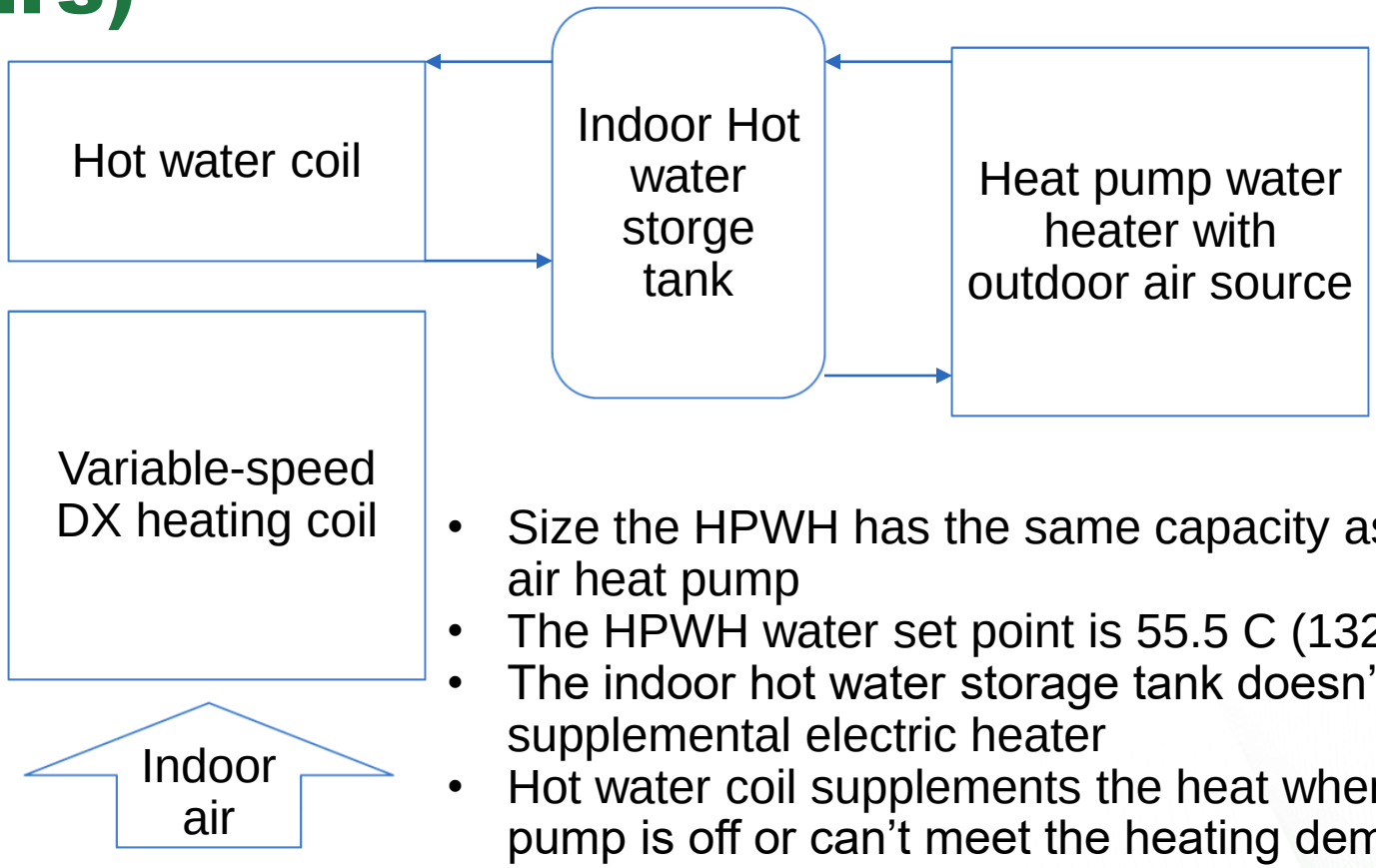
Dual Source Heat Pump (Commercial)

Atlanta – Heating Season

	HP_deliver	HP_Power	Gas_deliv	HP_COP	total_deliver	Price_Elec
	kwh	kwh	kwh	W/W	kwh	dollar
Baseline	9888	3318	0	2.980	9888	302
Grid-Res	6084	2061	3804	2.951	9888	157
Grid/Base	62%	62%	N/A	99%	100%	52%

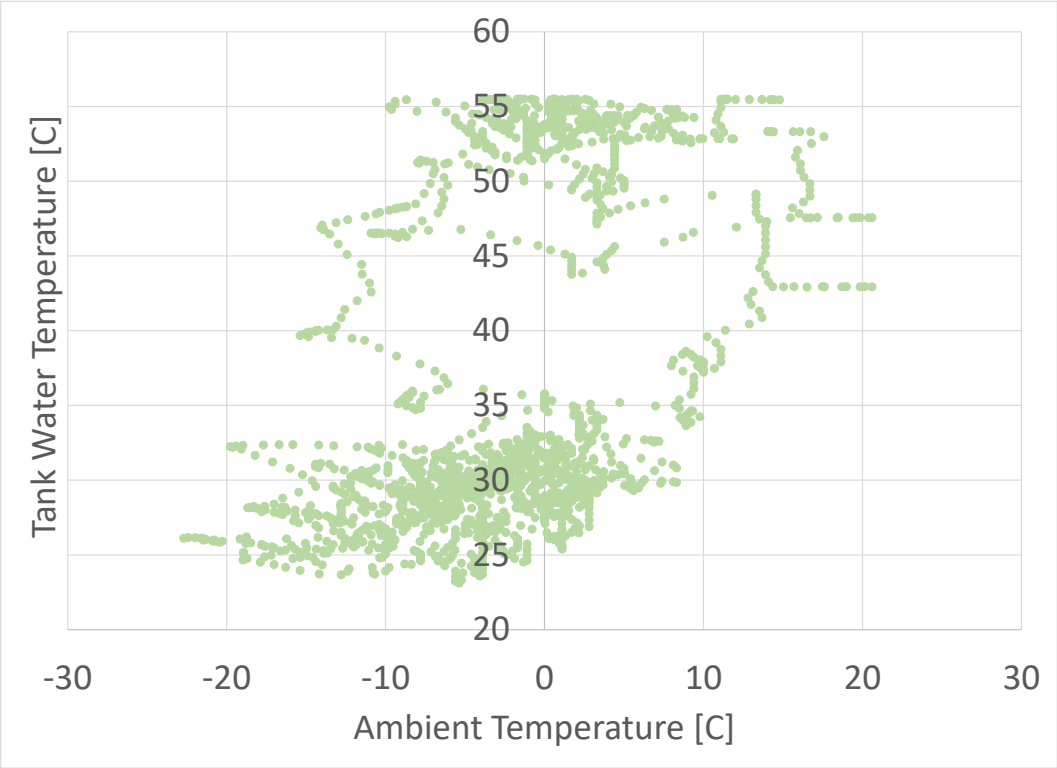
- Commercial buildings have no occupancies during night time, with lower setting temperature.
- Grid-responsive controls during day time have relatively larger impact on commercial buildings than residential buildings.

HVAC Flexible Measure – Hot Water Storage (HPWH runs during off-peak hours)



- Size the HPWH has the same capacity as the air-to-air heat pump
- The HPWH water set point is 55.5 C (132F)
- The indoor hot water storage tank doesn't have a supplemental electric heater
- Hot water coil supplements the heat when the heat pump is off or can't meet the heating demand
- Hot water tank is sized to match the heat pump capacity for 24 hour with 15 K temperature drop, i.e. from 40 K to 55 K → a 1-ton heat pump will require 4.8 m^3 storage tank

Water tank temperature change in Indianapolis



- The HPWH can't maintain tank water temperature at low ambient temperatures, because it has minimal efficiency and capacity below -10 C.

Seasonal Simulation of Hot Water Storage and Supplemental Heat (residential)

Atlanta – Heating Season

	HP_deliver	HP_Elec	HP_COP	WH_deliver	WH_Elec	WH_COP	total_deliver	Elec_cost	Tmin	uncomfort
	kwh	kwh	W/W	kwh	kwh	W/W	kwh	dollar	C	Hours < 15 C
base	11445.20	3438.56	3.33	251.01	334.86	0.75	11696.22	298.76	21.11	0
grid	8877.69	2664.67	3.33	2631.84	1516.67	1.74	11509.53	282.22	17.13	0

Indy – Heating Season

	HP_deliver	HP_Elec	HP_COP	WH_deliver	WH_Elec	WH_COP	total_deliver	Elec_cost	Tmin	uncomfort
	kwh	kwh	W/W	kwh	kwh	W/W	kwh	dollar	C	Hours < 15 C
base	16941.49	5606.10	3.02	2510.82	1537.41	1.63	19452.31	616.53	19.08	0
grid	11319.81	3662.60	3.09	5865.65	2786.29	2.11	17185.46	440.99	10.38	261

- Hot water storage can reduce the total electric cost in mild climate zones.
- Hot water storage is not practical in cold climate zones

→require very large storage tank and HPWH unit

→It is more challenging to operate HPWHs in cold climate zones than air-to-air heat pumps

HVAC Flexible Cooling Measures

- Modulating – Lock high capacity, only operate 75% sized capacity during grid-responsive hours

→run normal air flow

→run reduced air flow (enhanced dehumidification)

- Phase change material storages

→ice storage

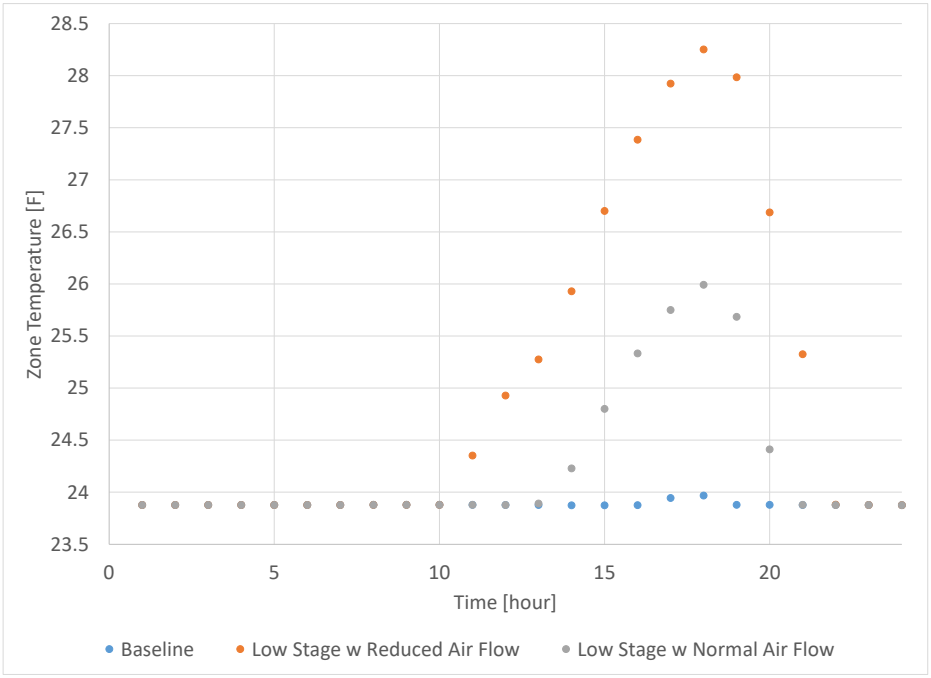
→pcm storage

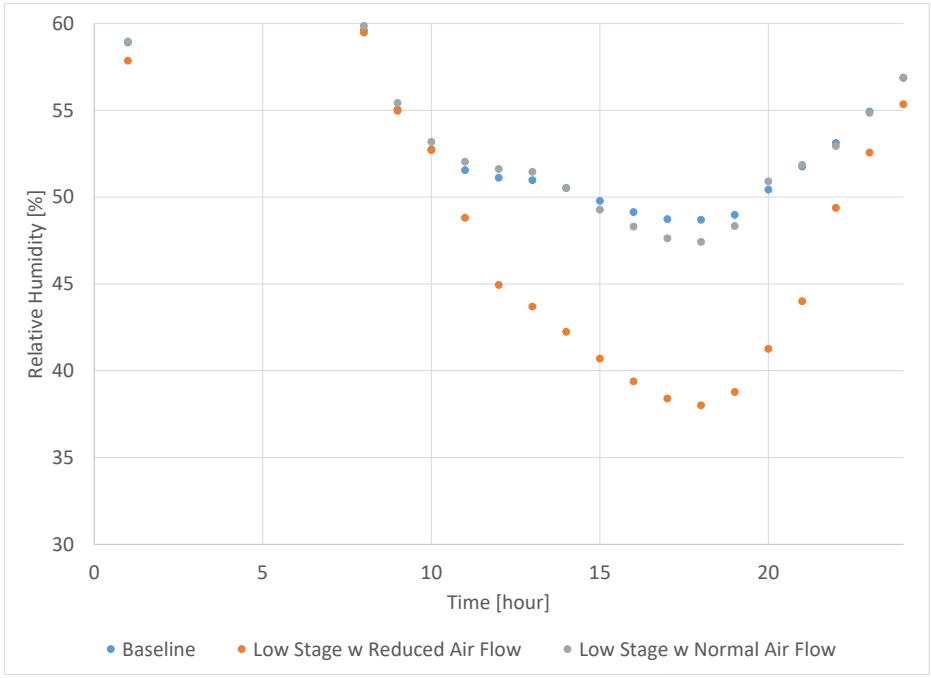
- Liquid desiccant storages

→desiccant dehumidification + indirect evaporative cooling

→desiccant dehumidification + DX cooling

Modulating Cooling Unit





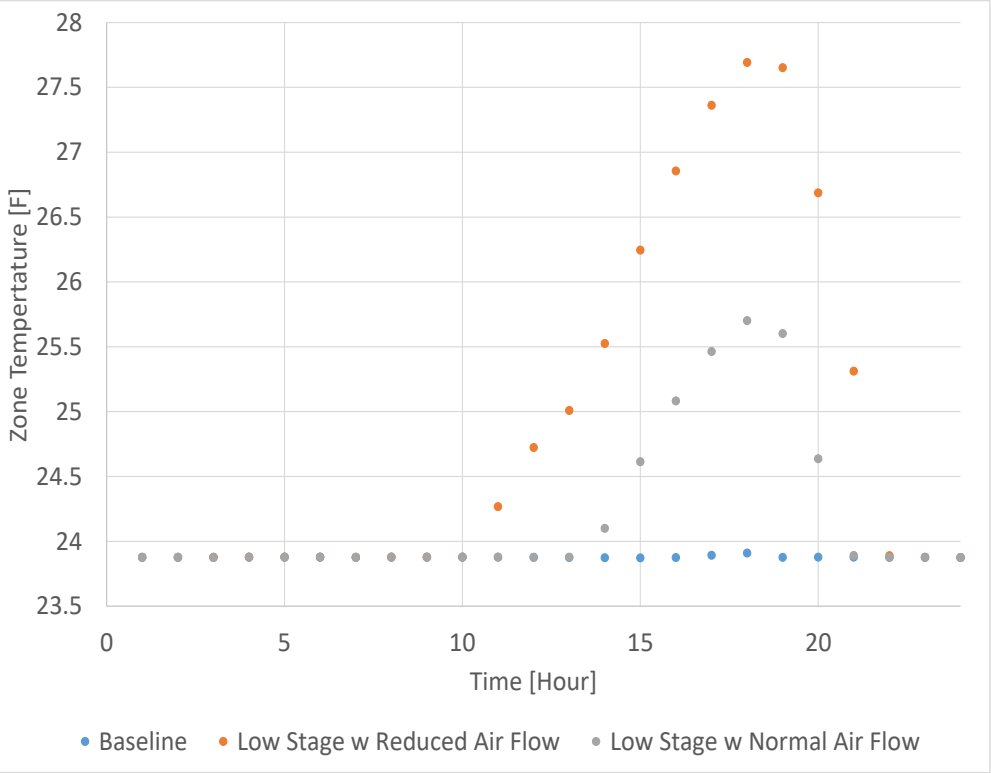
Zone Temperature

Zone Relative Humidity

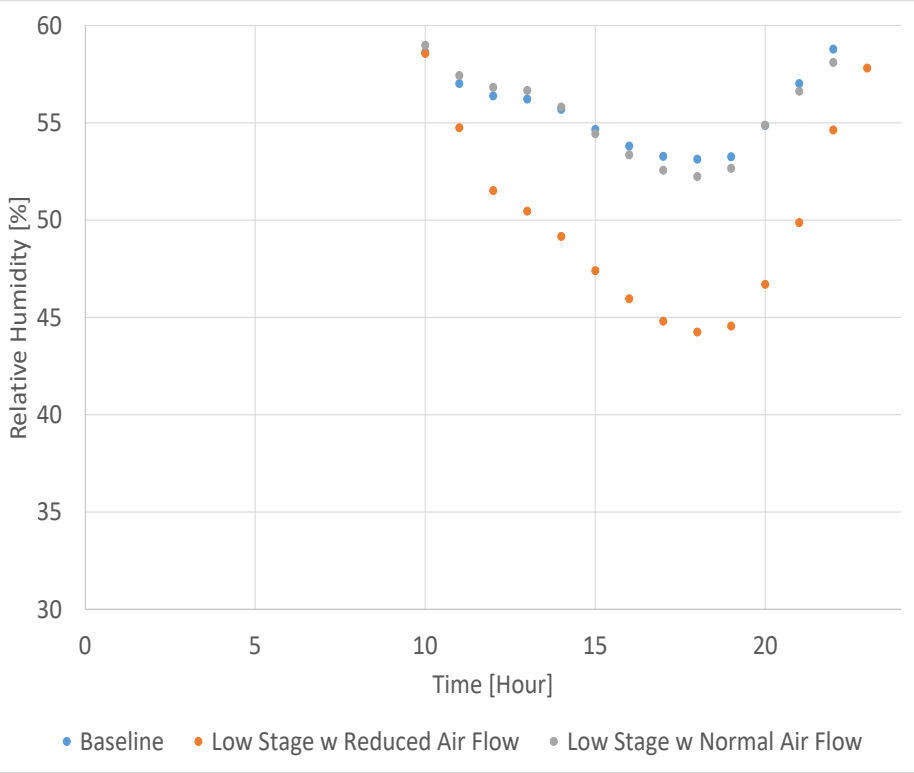
Atlanta

- Enhanced dehumidification at low stage controls lower indoor relative humidity down to 35%
- It loses control of the zone temperature, i.e. sensible load due to its smaller capacity and lower SHR at reduced air flow rate.

Indianapolis



Zone Temperature



Zone Relative Humidity

Seasonal Simulations of Modulating Units (residential)

Atlanta – Cooling Season

	CoolingDeliver	CoolingElec	SEER	Price	uncomfort	PeakReduction
	kwh	kwh	Btu/hr/w	dollar	hour > 27 C	%
base	11069.8	2423.0	15.6	251.1	0	0
modulating w Normal flow	10957.1	2381.1	15.7	246.1	0	26%
enhancedDH	11187.2	2691.2	14.2	281.9	0	28%

Indianapolis – Cooling Season

	CoolingDeliver	CoolingElec	SEER	Price	uncomfort	PeakReduction
	kwh	kwh	Btu/hr/w	dollar	hour > 27 C	%
base	8351.5	1797.5	15.9	191.7	0.0	0%
modulating w Normal flow	8205.3	1741.8	16.1	184.7	6.0	27%
enhancedDH	8346.4	1954.5	14.6	209.0	12.0	28%

- Enhanced dehumidification has more peak power reduction due to its lower capacity and power consumption
- Enhanced DH may increase the electricity bill because it causes lower overall cooling efficiency

Seasonal Simulations of Modulating Units (commercial)

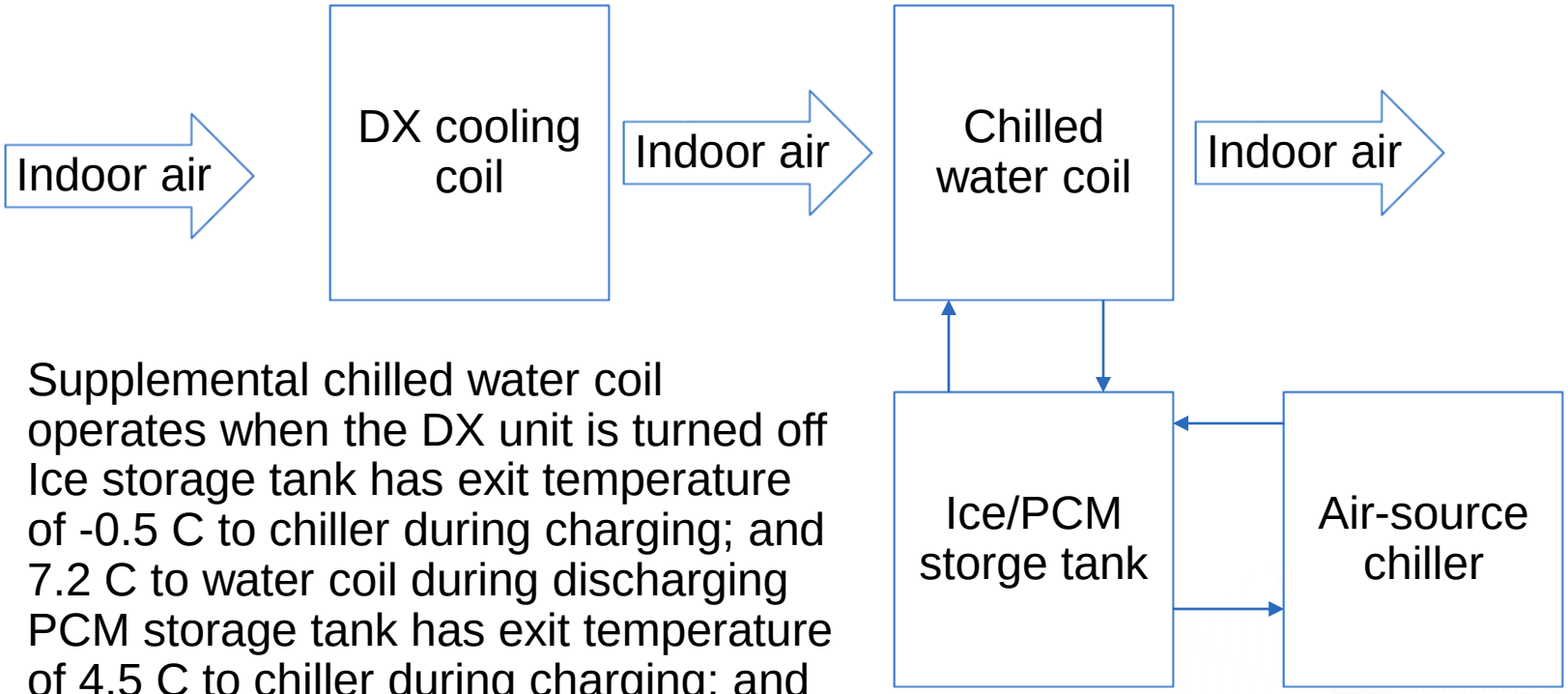
Atlanta – Cooling Season

	Cool_deliver	Cool_Power	SEER	Price_Elec	MaxCoolPower
	kwh	kwh	Btu/hr/W	dollar	kW
Baseline	153498	32565	16.1	3686	34
Modulating	152950	32175	16.2	3635	25
enhancedDH	152926	32172	16.2	3634	25

Difference to baseline	PeakPowerReduction	MaxZoneT_Diff	MaxRH_Diff
	[%]	[C]	[%]
Modulating	26.58%	1.96	11.71%
EnhancedDehum	26.58%	1.96	11.71%

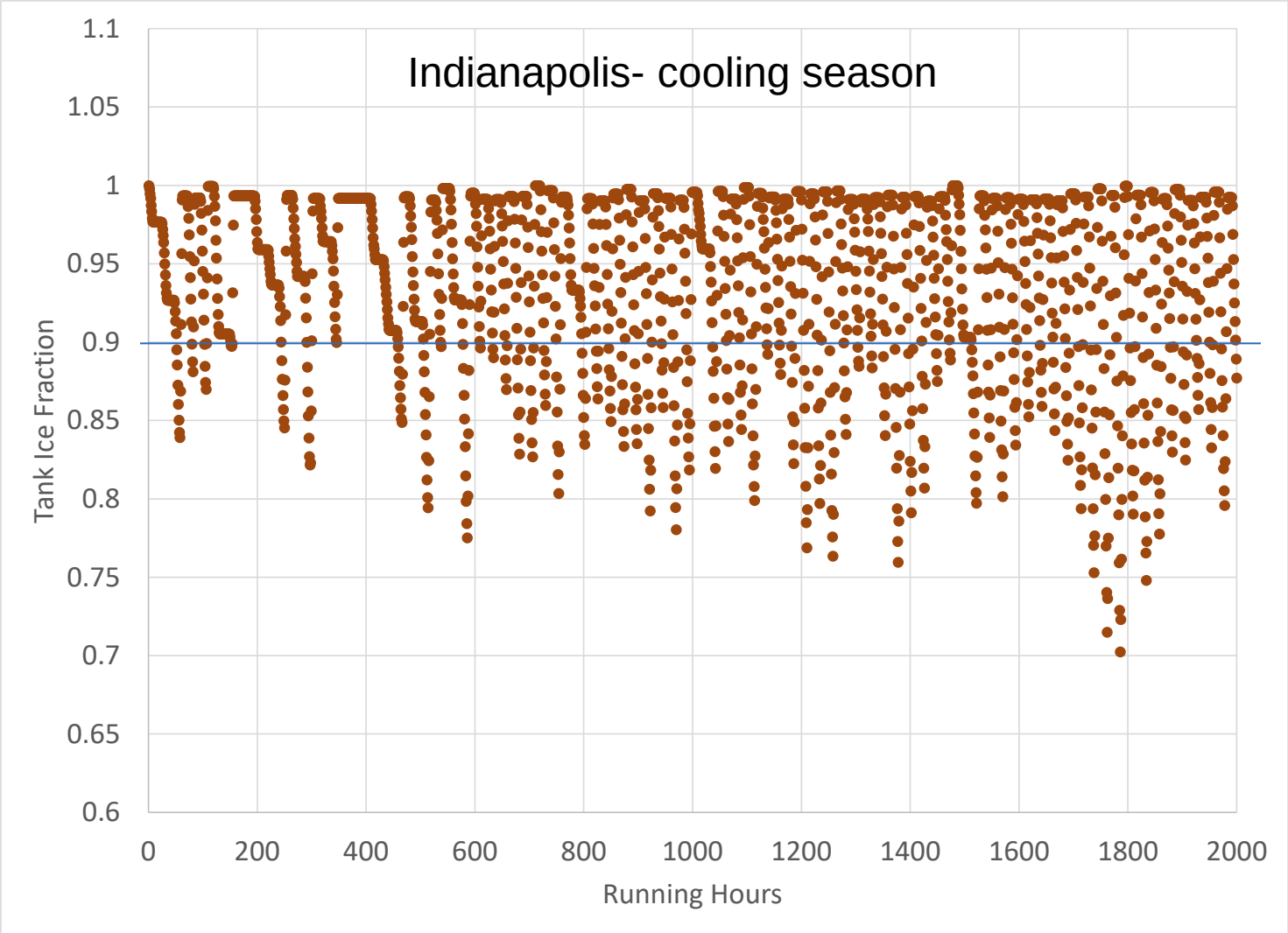
- CoilSystem:Cooling:DX (in middle office building template) can't represent enhanced dehumidification with reduced indoor air flow rate, due to its air flow control logic to match the load.
- Modulatign DX coils lead to minor comfort difference from the baseline, but noticeable peak power reduction.

Ice/PCM storage



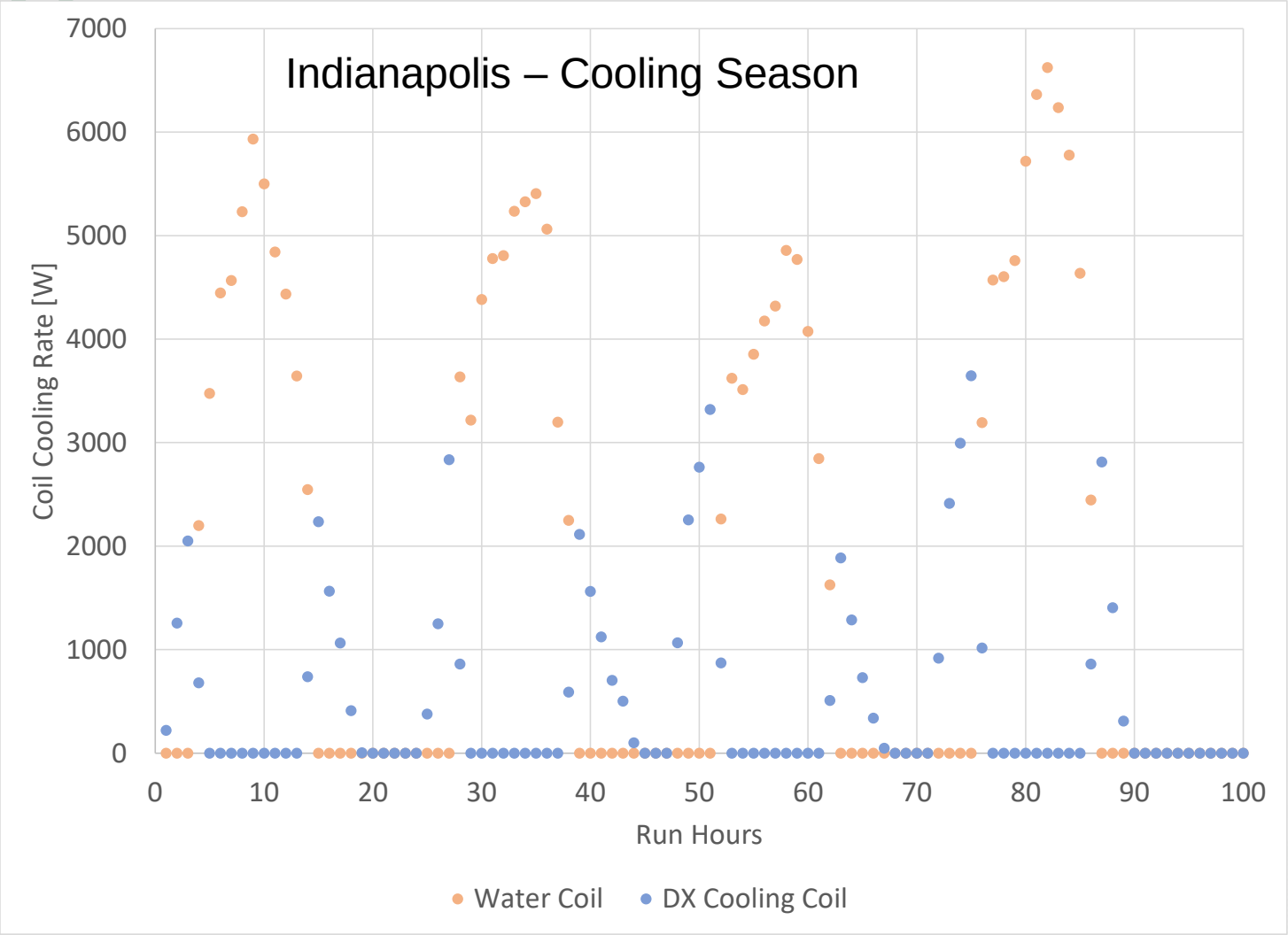
- Supplemental chilled water coil operates when the DX unit is turned off
- Ice storage tank has exit temperature of -0.5 C to chiller during charging; and 7.2 C to water coil during discharging
- PCM storage tank has exit temperature of 4.5 C to chiller during charging; and 10.0 C to water coil during discharging

Seasonal Ice Tank Fraction Variation



single-speed chiller turned on during off-peak hours; tank set fraction is 90% (charge to 100%)

Cooling Rates of DX Coil and Supplemental Chilled Water Coil



Water coil has larger cooling rate (size) due to operating in peak hours.

Annual Simulation of Ice/PCM Storage-Atlanta (residential)

	TotCoolingDeliv	TotCoolingElec	Tot_SEER	Price	uncomfort
	kwh	kwh	Btu/H/W	dollar	hours>28C
base	11069.8	2423.0	15.6	251.1	0
icestorage	10357.9	2637.1	13.4	179.8	14
pcmstorage	9546.1	2191.2	14.9	154.4	14

	WaterCoil_deliver	Chiller_deliv	chillerElec	chillerCOP
	kwh	kwh	kwh	W/W
icestorage	7140.6	7138.9	1987.7	3.6
pcmstorage	6200.5	6202.8	1521.9	4.1

- Ice/PCM storage actually leads to smaller electricity bills
- PCM results in higher chiller efficiency due to the elevated (5 K) phase change temperature; but it requires larger water coil due to the reduced heat transfer temperature difference

Annual Simulation of Ice/PCM Storage-Indianapolis (residential)

	TotCoolingDeliv	TotCoolingEle	Tot_SEER	Price	uncomfort
	kwh	kwh	Btu/H/W	dollar	hours>28C
base	8351.6	1797.6	15.9	191.7	0.0
icestorage	7971.7	2038.8	13.3	145.3	2.0
pcmstorage	7506.5	1704.8	15.0	126.1	2.0

	WaterCoil_deliver	Chiller_deliv	chillerElec	chillerCOP
	kwh	kwh	kwh	W/W
icestorage	5747.8	5849.1	1591.5	3.7
pcmstorage	5154.6	5156.0	1242.7	4.1

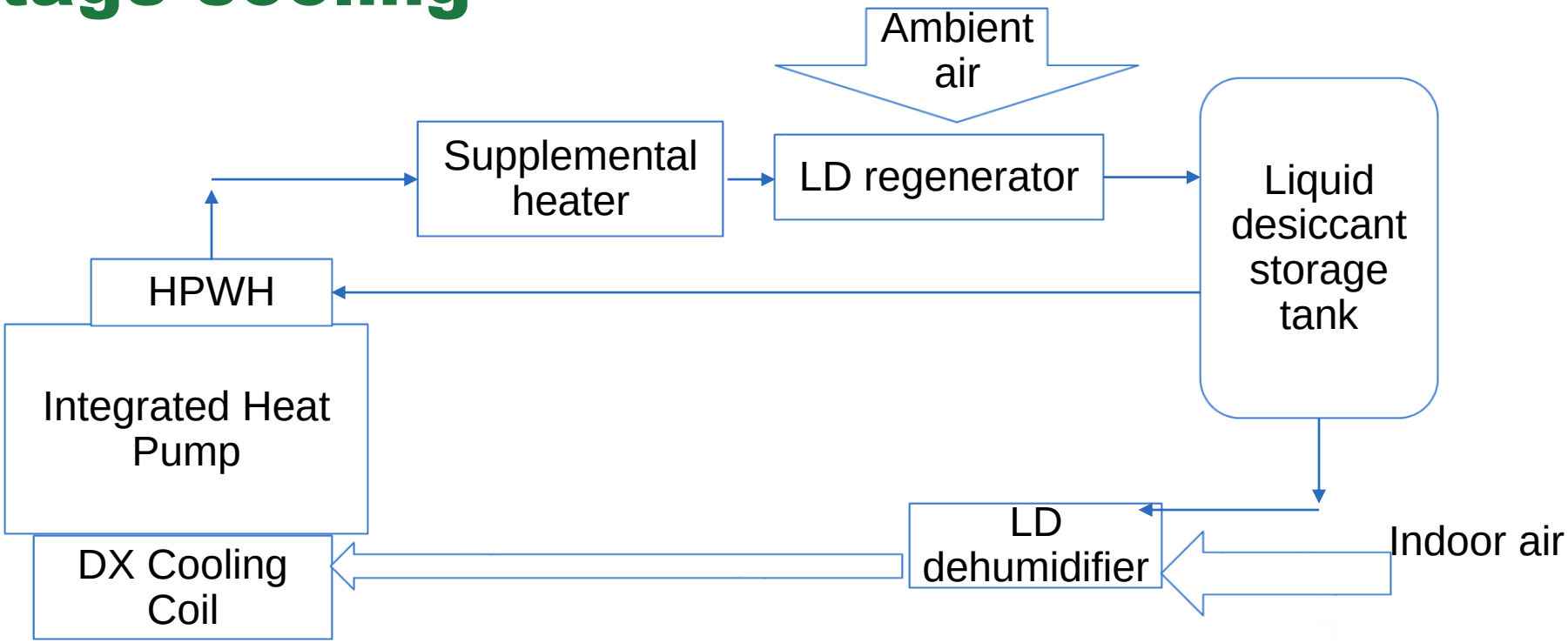
Annual Simulation of Ice/PCM Storage-Atlanta (commercial)

	TotCoolingDeliv	TotCoolingElec	Tot_SEER	Price
	kwh	kwh	Btu/H/W	dollar
base	153498	32565	16.083	3686
icestorage	147940	33762	14.951	2491
pcmstorage	144935	30168	16	2291

	Chiller_deliv	chillerElec	chillerCOP
	kwh	kwh	W/W
icestorage	96393	27266	3.53
pcmstorage	95117	23569	4.04

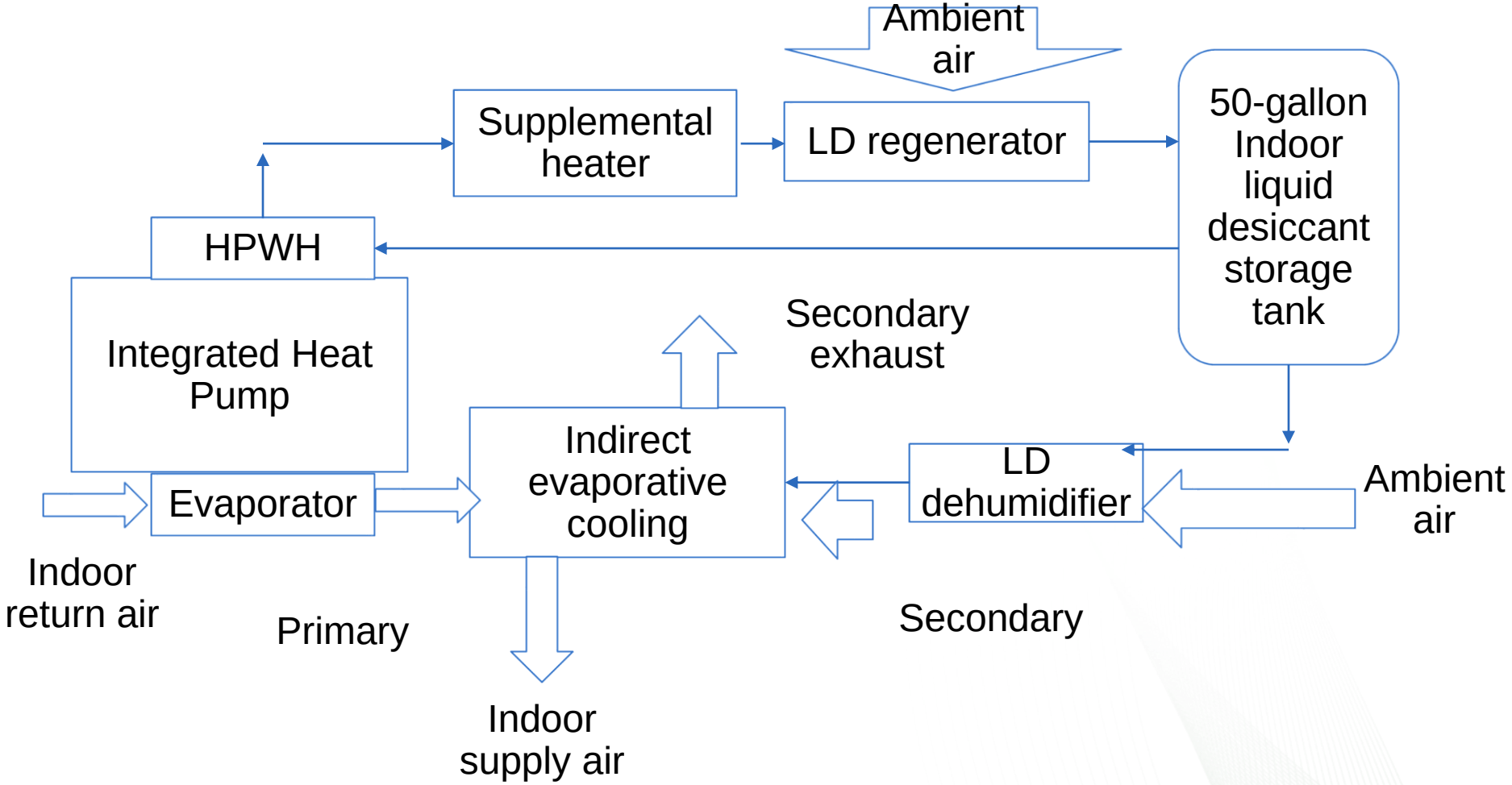
- Trends in the commercial building is similar to the residential house in the same climate zone.

Liquid Desiccant Storage + DX low stage cooling



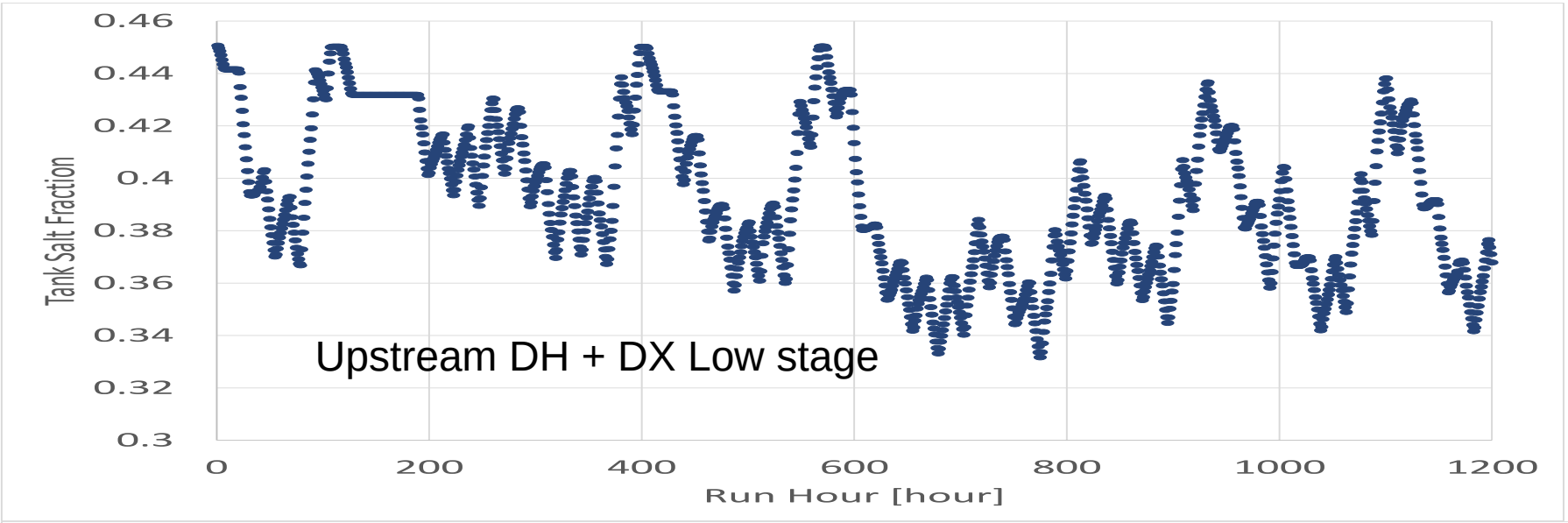
- Liquid desiccant is LiCl
- Dedicated HPWH to heat LD when the LD salt concentration < 43% (off at 45%)
- Supplemental heater to increase the LD temperature to 45C
- During peak hours, run DX coil at low stage and turn on the upstream LD dehumidifier

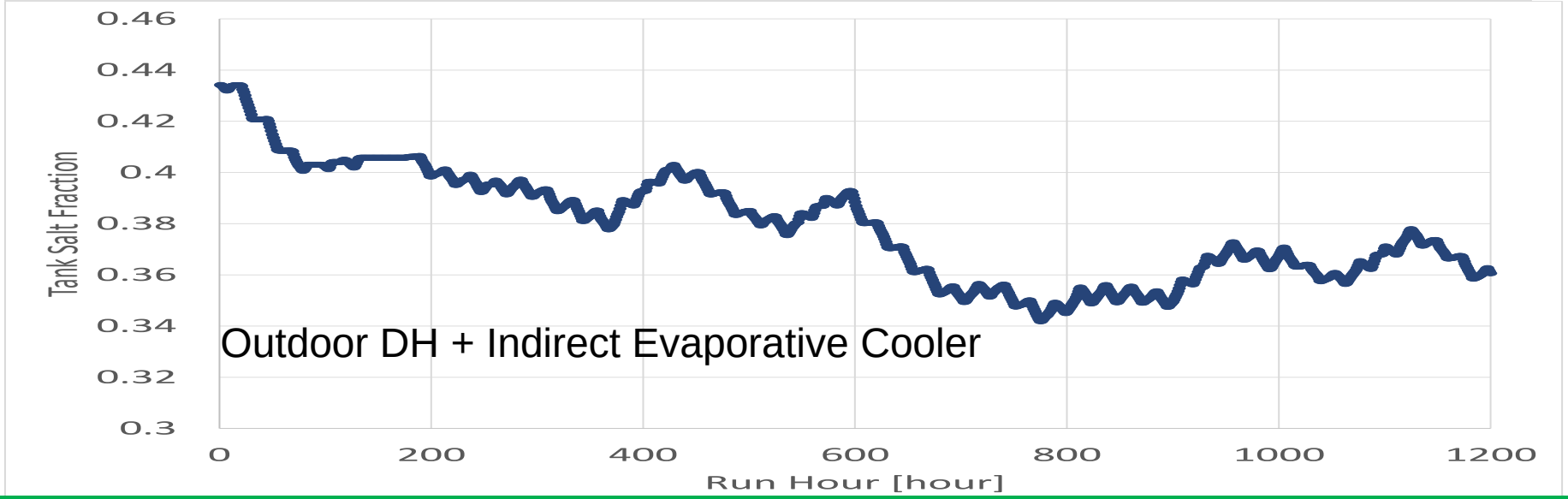
Liquid Desiccant Storage + Evaporative Cooling



- LD dehumidifier treats outdoor air before entering an indirect evaporative-cooler to replace the DX coil during peak hours

Variation of Salt Concentration





- Require larger units to recover the LD tank when integrated with evaporative cooler

Annual Simulation of Liquid Desiccant Cooling (residential)

Atlanta

	TotCoolingDeliv	TotCoolingE	TotSEER	Price	uncomfort
	kwh	kwh	Btu/h/W	dollar	hours>28C
base	10832.19	2482.06	14.89	261.27	0.00
upstreamDH	13198.96	51011.01	0.88	3637.75	0.00
DH+EvapCool	N/A	35105.46	0.35	2377.56	486

Indianapolis

	TotCoolingDeliv	TotCoolingE	TotSEER	Price	uncomfort
	kwh	kwh	Btu/h/W	dollar	hours>28C
base	8214.94	1853.54	15.12	199.18	0
upstreamDH	10336.31	42046.55	0.84	3001.15	0
DH+EvapCool	N/A	33378.72	0.29	2333.77	423

- Desiccant dehumidification introduces 30% more cooling load
- 10 times more energy is required to regenerate the liquid desiccant – must use free solar heat
- Liquid DH + EvapCool can't meet the cooling load if the ambient WB is high.

Recommendations

- Dual source (electric + gas) HP works
- Hot water storage may reduce electricity bill in mild climate zones; it is difficult to apply in cold climate zones due to the size and cost of storage tank and cold climate HPWHs.
- Modulated cooling (limited the top capacity) w/wo enhanced dehumidification reduced peak power consumption up to 30%.
- Ice/PCM storage can reduce the electricity bills and eliminate > 90% peak power; PCM results a bit larger saving due to its enhanced chiller efficiency.
- Current configurations of liquid desiccant storage not useful for grid flexibilities, except desert zones.