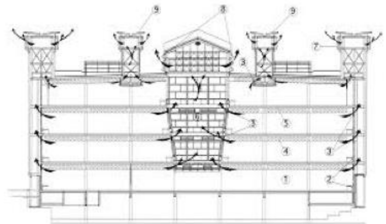
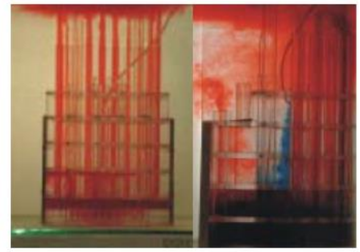
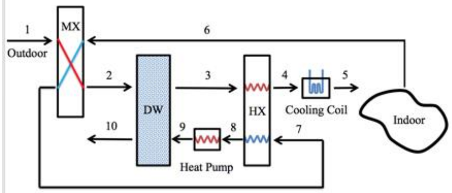
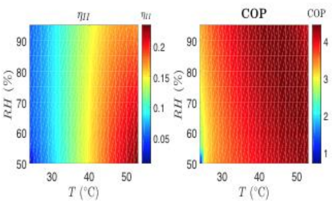
Space-Conditioning Systems for Low-Carbon Buildings
4.421 Department of Architecture Spring 2023



Images: UCL, BPI Cambridge, MIT and NUS

Instructor: Les Norford lnorford@mit.edu Teaching Assistant: Ramon Weber reweber@mit.edu
Lectures Monday and Wednesday, 2:00-3:30, Room 5-415; Lab Monday 3:30-5, Room 5-415;
In-person teaching; lectures will be Zoom-recorded as needed for academic continuity
Units: 3-2-7; 3-2-4 available. Class is open to students in all degree programs

Consensus understanding of climate change identifies a need to drastically reduce anthropogenic emissions of greenhouse gases in coming decades, including those associated with buildings. In this course, we seek a thermofluids understanding of the basics of natural and mechanical systems for conditioning high-performance buildings and will develop and assess systems based on this understanding. We will consider options for new and existing buildings. Can these and other buildings, large or small, meet municipal and global goals for decarbonization? Should they simply depend on a decarbonized grid or can energy consumption be substantially reduced relative to current practice? Can they be maintained at a comfortable temperature with little or no use of mechanical systems? ? Can waste heat at building or community scale be effectively captured and reused – or, at last resort, transferred to the environment with minimal environmental and financial cost?

We will investigate natural ventilation in detail, including the thermal and fluid dynamics of airflow in buildings, application to multi-zone wind- and buoyancy-driven airflows, and adjustments in urban areas to account for reduced wind speeds. Performance assessments will be based on analyses and simulations that couple airflow and energy analysis programs. Building cooling strategies will be motivated by mapping conventional and innovative cooling systems on the psychrometric chart. First-principles analysis and simulations with an equation-based language, Modelica, and with EnergyPlus will be used to quantify the performance of energy-recovery systems, membrane- and desiccant-based dehumidification, evaporative cooling, thermal storage at diurnal (building materials) and annual (ground-coupled heat pumps) scales and radiant cooling and heat-rejection systems. System design at building and district scale in leading commercial practice will be presented and critiqued. Current-practice and advanced district heating and cooling systems will be explored. Working in groups and making use of design workflows under development at MIT and Harvard, we will assess climate- and building-specific systems based on thermal comfort, energy consumption, carbon emissions and resilience to climate change. Project-based testing of speculative proposals, based on natural or man-made systems, will be encouraged.

Learning objectives

The objectives of the course are to help students:

- Understand the societal and environmental context of building energy consumption;
- Understand and apply the scientific principles underlying the thermal and fluid dynamic characteristics of buildings and building conditioning systems, and apply these fundamentals to practical design problems;
- Recognize design opportunities to use natural ventilation;
- Develop an ability to use contemporary component and whole-building simulation programs to analyze building performance;
- Learn to evaluate a range of technologies for creating comfortable indoor environments and
- Demonstrate an ability to critically discuss and present the environmental concept of low-energy and low-carbon building systems integrated into a building.

Requirements

This course requires the following:

- Attendance of bi-weekly lectures;
- Timely completion of assignments that involve analytic and computational assessment of system performance;
- Completion of a group course project;
- Active participation in class discussions.

Course grading

60% homework assignments (all but the first in teams of 2-3)
10% project proposal
20% project presentation
10% class participation

Please familiarize yourself with MIT's Academic Integrity Expectations at http://web.mit.edu/academicintegrity/. We will largely work in groups; information shared from other groups should be acknowledged.

Assistance with writing

The MIT Writing and Communications Center (WCC) offers free professional advice. Appointments may be made at https://mit.mywconline.com.

Required text

None. Readings will be assigned from multiple sources.

Office hours

Weekly office hours will be set to accommodate all schedules.

Student support

As a graduate student, a variety of issues may impact your academic career including faculty/student relationships, funding, and interpersonal concerns. In the Office of Graduate Education (OGE), GradSupport provides consultation, coaching, and advocacy to graduate students on matters related to academic and life challenges. If you are dealing with an issue that is impacting your ability to attend class, complete work, or take an exam, you may contact GradSupport by email at gradsupport@mit.edu or via phone at (617) 253-4860.

Software

We'll use many but not all of the following programs:

- **Rhino 7** (https://www.rhino3d.com/download) is the 3D modeler we will use to represent buildings in a form that can be linked to performance analysis tools through the Grasshopper visual scripting program, which comes with the Rhino download. We'll use the Windows version, for compatibility with other software (Climate Studio).
- **Ladybug Tools** (https://www.ladybug.tools) make building performance analysis available in Grasshopper. MIT Department of Architecture alumnus Chris Mackey (M.Arch and SMBT 2015) and colleagues hav developed four insects:
  - Ladybug can perform user-defined climate analyses, such as 3-D plots of temperature as a function of date and time and wind roses limited to specific outdoor temperatures.
  - Honeybee links to EnergyPlus for energy analysis and to Radiance and Daysim for daylighting analysis, OpenStudio for HVAC system templates for EnergyPlus and THERM for thermal analysis of walls and windows. The installation instructions with the download provides the necessary URLs.
  - Dragonfly provides a means to estimate energy consumption at neighborhood scale by accessing NREL's URBANopt and the impact of urban development on the urban climate, through the Urban Weather Generator developed at MIT.
  - Butterfly links to a Windows-based version of OpenFOAM, for CFD analyses. Those seeking to do CFD in the course project can proceed largely on their own or use another CFD program; the course will not require it.
- **Climate Studio** (https://www.solemma.com/climatestudio version 1.4 is the latest. https://www.climatestudiodocs.com/Installers/download.php?software=cs&version=networked) is a comprehensive climate analysis, daylighting and energy analysis package that runs under Rhino or Grasshopper. Windows only.
- **EnergyPlus** (https://energyplus.net) is the whole-building energy simulation program we will use to generate heating and cooling loads that must be met by space-conditioning equipment we will define and represent by seasonal efficiency metrics.
- **CC WorldWeatherGen** (http://www.energy.soton.ac.uk/ccworldweathergen/) morphs weather files to account for projected regional climate change.

- **CBE Thermal Comfort Tool** (http://comfort.cbe.berkeley.edu) is an interactive psychrometric chart developed by the Center for the Built Environment at UC Berkeley that will conditions that are acceptable thermal acceptable to humans.
- **CBE Clima Tool** (https://clima.cbe.berkeley.edu) is an online climate analysis and thermal comfort tool.
- **Psycho about Psychro** (http://www.comfortch.art), developed at Princeton University, encourages thinking outside the comfort box.
- **Climate Consultant** (http://www.energy-design-tools.aud.ucla.edu) is a freely downloadable tool that runs under Windows or Mac OS and provides a relatively comprehensive set of graphical presentations of data from standard weather files. We prefer Climate Studio and Ladybug Tools and the CBE and Princeton thermal comfort tools but acknowledge that Climate Consultant is easy to use for standard climate information.
- **OpenModelica** is a free interface for the Modelica equation-based systems analysis program. We will use it in conjunction with Python to analyze advanced systems for drying air brought into buildings.
- **Dymola** is another interface for Modelica. Download and installation instructions have been established by the SA+P IT service, STOA, and will be provided at the appropriate time. We will use it for analysis of district heating and cooling systems. Windows only.
- **CoolVent** (http://coolvent.mit.edu) is a freely downloadable tool developed at MIT for analyzing airflows and indoor temperatures associated with naturally ventilated buildings. Windows only.

Schedule as of 20230205

W1	2/6	L1	Climate change, urban heat island, buildings
		Lab	personal carbon budget, national and global carbon emissions, with attention to HVAC; offsets; MIT and SA+P carbon budgets
		A1	National and personal carbon budgets, including role for offsets (due 2/20)
	2/8	L2	Economics of building electrification
W2	2/13	L3	Low-energy building standards, practices and examples: Passive House, LEED, Living Building Challenge, etc.; energy and carbon emissions
		Lab	Exploration of carbon emissions data and options for reducing emissions (Leela Velautham, MIT Energy Initiative; Passive House in practice: Deborah Moelis, Handel Associates, NYC (previously recorded).
	2/15	L4	Indoor and outdoor thermal comfort. Implications for design, including air movement and cooling at the skin.
W3	2/20		Presidents' Day holiday; Tuesday has Monday class schedule
	2/21	L5, L6	Natural ventilation toolkit (recorded lecture); Buoyancy- and wind-driven airflow; two-way airflows through single openings; steady-state mass and energy balances
		Lab	Thermal comfort metrics and calculations, including UTCI, CBE and Psycho about Psychro.

	2/22	L7	Mass and energy balances for multiple zones in series and for wind and buoyancy flows; advanced analytic flows
W4	2/27	L8	Buoyancy-induced cooling
		Lab	Analytic solutions for mass and energy balances; exploration of the Torrent Research Center in Ahmedabad, India and the UCL School of East European and Slavic Studies (SSESS)
		A2	buoyancy-driven airflows: up and down! (due 3/13)
	3/1	L9	Building thermal dynamics, including night flush; African termite mounds
W5	3/6	L10	ground coupling: earth tubes, boreholes
		Lab	EnergyPlus via grasshopper and EP-Launch; LB intro. CoolVent for multizone flow and temperature calculations, with emphasis on chimneys
	3/8	L11	ground heat storage
	3/10		Add date
W6	3/13	L12	Radiant heat rejection: device-scale performance
		Lab	Design at urban scale to promote passive heat rejection (Edu Gascon, MIT BT PhD student)
		A3	Climate-specific urban design exploration to minimize need for active cooling (due 4/3)
	3/15	L13	Radiant heat rejection at urban scale
W7	3/20	L14	Introduction to Modelica – (Dave Blum, Lawrence Berkeley National Lab)
		Lab	Modeling with Modelica
	3/22	L15	Moist-air processes
		P1	Project proposal (due 4/10)
	3/27-31		Spring break!
W8	4/3	L16	Outdoor-air systems, heat and enthalpy recovery; membranes and desiccants for dehumidification
		Lab	project development
	4/5	L17	Heat pump fundamentals, including refrigerants and their environmental impact
W9	4/10	L18	Heat pump part-load models and efficiency metrics; low-lift options; ground-coupled heat pumps,
		Lab	Modelica modeling of vacuum membrane dehumidification Manideep Rebbagondla, MIT CSE); grand cooling challenge (Ross Bonner, Transaera)
		A4	Modelica modeling of vacuum membrane dehumidification; passive chilled beam and ground heat exchange (due 4/24)
	4/12	L19	Radiant cooling systems
W10	4/17		Patriots’ Day -holiday

	4/19	L20	Water use for cooling and production of electricity; comparison with direct and indirect evaporative cooling
W11	4/24	L21	District heating and cooling systems. Stanford vs. MIT: heat recovery, co- and tri-generation
		L22	Waste heat recovery at neighborhood scale; data center heat recovery
	4/26	Lab	Tour of MIT Central Utility Plant
W12	5/1	L23	Modelica modeling of DHC
		Lab	Modelica and Dragonfly modeling of DHC
		A5	Modeling of district heating and cooling system to maximize heat recovery (due 5/15)
	5/3		working session: Modelica modeling of DHC and/or project time
W13	5/8	L24	Sustainable HVAC systems in practice; Jacob Knowles, Director of Sustainable Design, BR+A Consulting Engineers (recorded); room-level systems design
		Lab	Optimization of temperature set points for carbon and energy savings and heat resilience – Daisy Green and You Lin (MIT EECS and LIDS)
	5/10	L25	hydrogen economy, fuel cells
W14	5/15		preparation for project presentations
	5/16		Last day of classes
	5/19-24		Final presentations to be scheduled by the MIT registrar in the exam period