U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Innovative Building Materials

Life-Cycle Energy & Related Impacts of Buildings Webinar Series

November 12, 2020

Agenda

I. **Opening Remarks**
   Sven Mumme –Technology Manager, U.S. DOE Building Technologies Office

II. **Introduction to Life Cycle Carbon**
   Lyla Fadali – AAAS Policy Fellow, U.S. DOE Building Technologies Office

III. **Low-Carbon and Carbon-Storing Materials for the Built Environment**
   Wil Srubar – Associate Professor, CU Boulder

IV. **Reducing the Carbon Footprint of Concrete**
   Christie Gamble – Sustainability Director, CarbonCure

V. **Advanced, Multifunctional Wood-Based Structural Materials for Green, Energy Efficient Buildings**
   Liangbing Hu – Professor, University of Maryland; Co-Founder, Inventwood

VI. **Life Cycle Climate Potential of Cooling/Heating Systems for Buildings**
   Yunho Hwang – Professor, University of Maryland

VII. **Q&A Session**
   Carl Shapiro– AAAS Policy Fellow, U.S. DOE Building Technologies Office

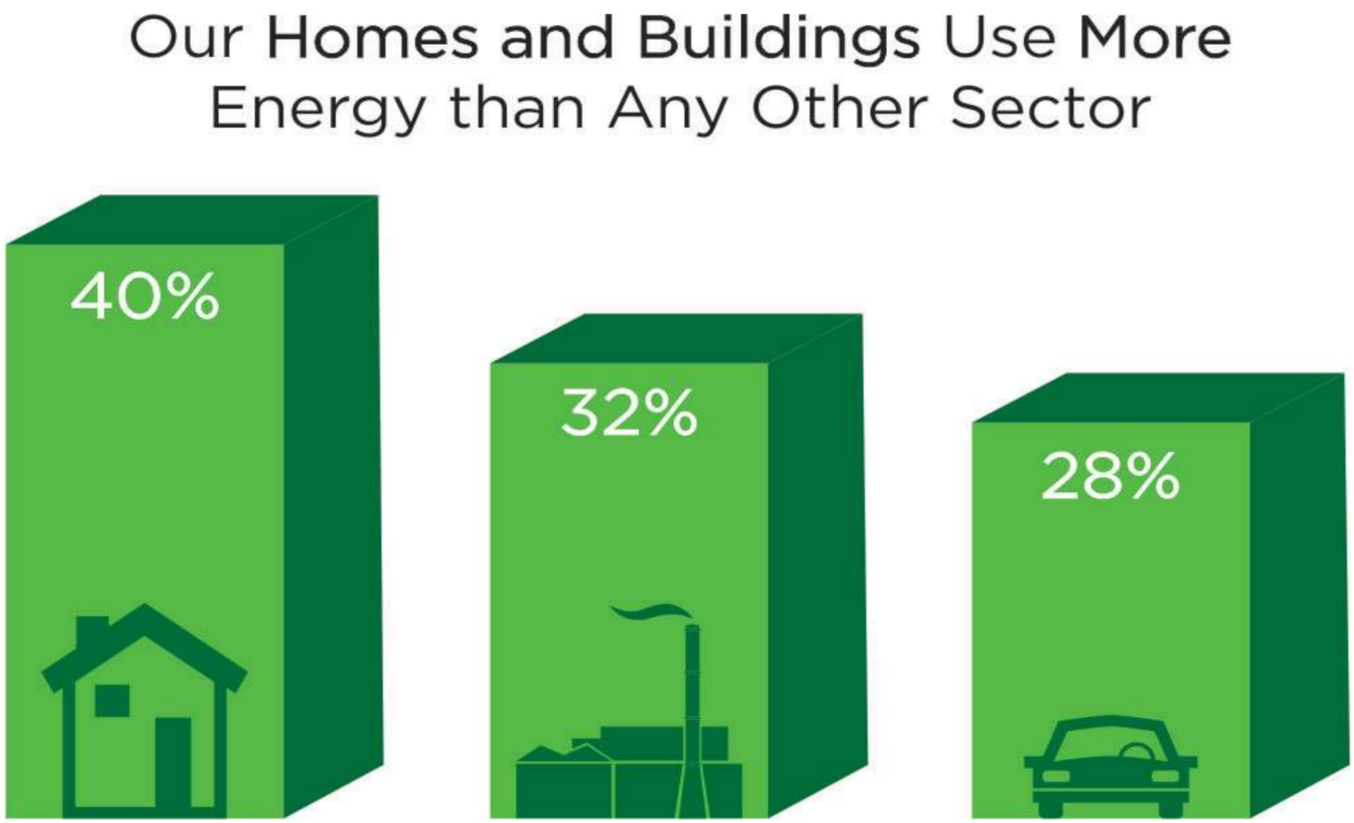
Building Life Cycle Impacts DOE Webinar Series

Topic	Date	Time
Overview of life cycle impacts of buildings	Oct. 16	12:00pm – 1:00pm ET
Challenges of assessing life cycle impacts of buildings	Oct. 29	12:00pm – 1:00pm ET
➡ Innovative building materials	Nov. 12	12:00pm – 1:00pm ET
"Real Life" buildings striving to minimize life cycle impacts	Dec. 3	12:00pm – 1:00pm ET
Intersection of life cycle impacts & circular economy potential for the building sector	Dec. 17	12:00pm – 1:00pm ET

Poll Questions

- What industry are you from?

Efficiency is key to meeting U.S. energy goals



Residential & Commercial | Industrial | Transportation

Source: EIA Monthly Energy Review

Building Technologies Office

BTO invests in energy efficiency & related technologies that make homes and buildings more affordable and comfortable, and make the US more sustainable, secure and prosperous.

Budget ~US$285M/year; activities include:

R&D
Pre-competitive, early-stage investment in next-generation technologies

Integration
Technology validation, field & lab testing, metrics, market integration

Codes & Standards
Whole building & equipment standards technical analysis, test procedures, regulations

DOE research has saved energy and saved consumers money

FOR EXAMPLE:

Past

Units **half** the price, almost 20% bigger, and **75% less energy** to operate – AND have more features!

Present

- $550 purchase
- $50/year to operate
- 22 cubic feet

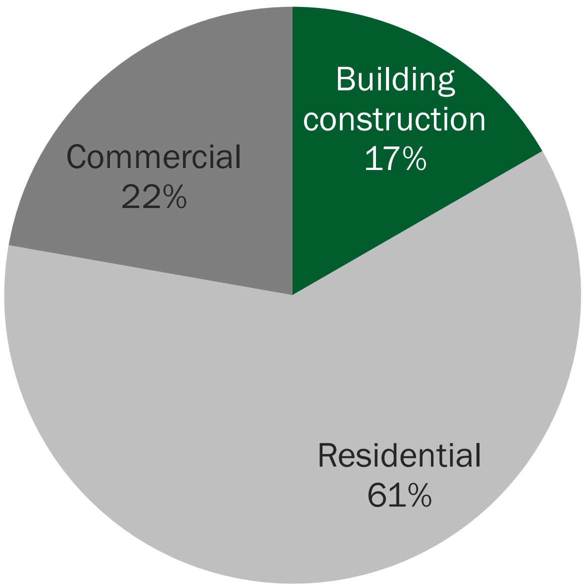
Our impact on a national scale

Energy efficiency standards completed through 2016 are expected to save **142 quadrillion Btu through 2030** — more energy than the entire nation consumes in one year.

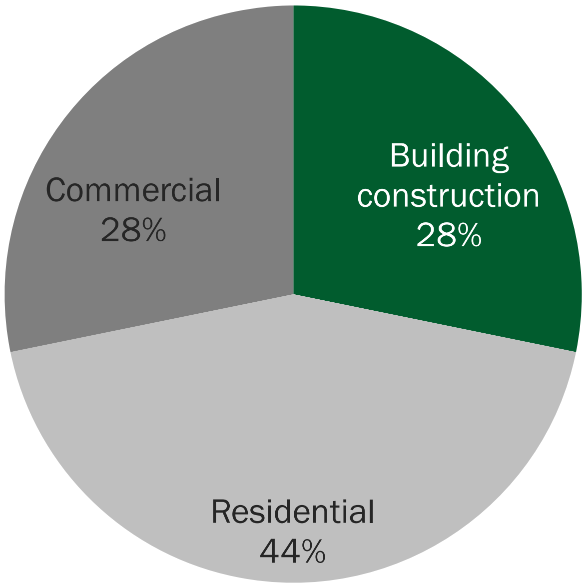
BTO's work is making a difference, but we're missing part of the picture.

Historically, BTO has focused on operating buildings.

Global energy use in buildings

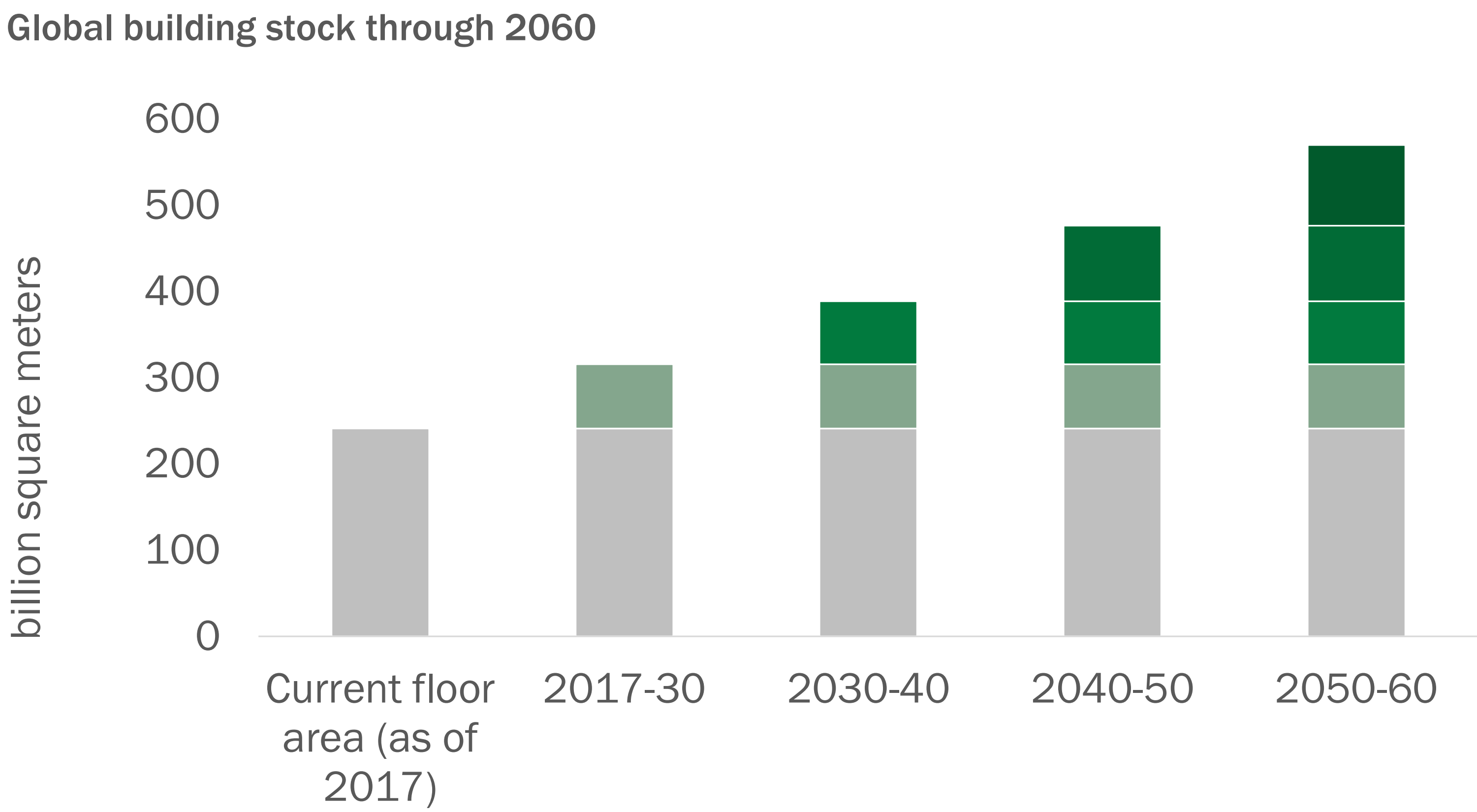


Global emissions from buildings



2018 Global Status Report. United Nations Environment Programme.
International Energy Agency for the Global Alliance for Building and Construction (GlobalABC)

Global building stock expected to more than double, making embodied carbon increasingly important.

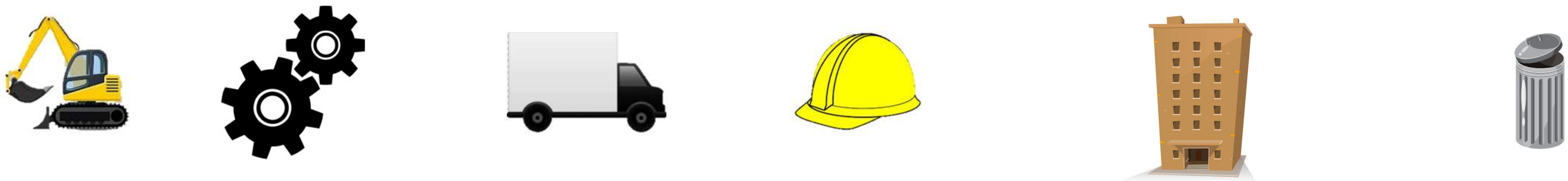


Source data from GlobalABC Status Report in 2017

Let’s look at the whole picture:

Lifecycle carbon refers to carbon emissions associated with all stages of a building’s life

Resource extraction | Manufacturing | Transportation | Construction/ Installation | Equipment Replacement/ Maintenance | Demolition/ End of life



Operations

Embodied carbon is the carbon associated with all stages of a building’s life cycle not including operating the building

Operational carbon is the carbon associated with operating the building

Where are the biggest opportunities? Where is BTO needed?

What types of buildings?

Residential or commercial?

New construction or retrofits?

What types of materials in the building?

Envelope? Lighting? HVAC?

What parts of the life cycle?

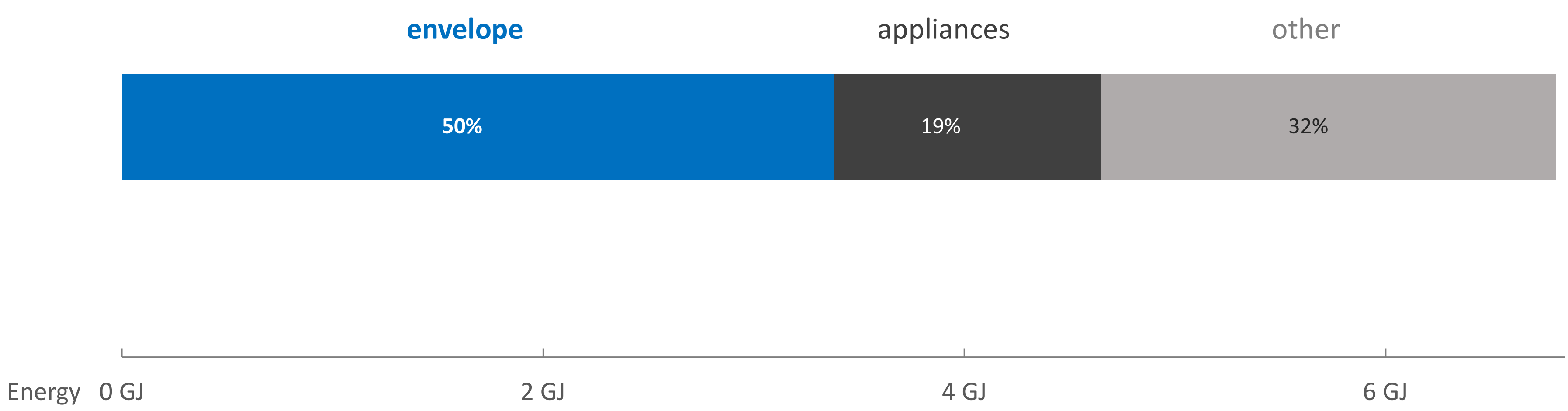
Transportation?

Material extraction?

End of life?

Envelope and appliances account for 70% of lifecycle energy.

Lifecycle energy in superinsulated multifamily residential buildings



Other includes joinery, electrical work, plumbing, foundation, furniture, and site & transport
Data from N. Mithraratne, B. Vale/Building and Environment 39 (2004) 483-492

Reducing the Carbon Footprint of Concrete

CHRISTIE GAMBLE
Senior Director Sustainability
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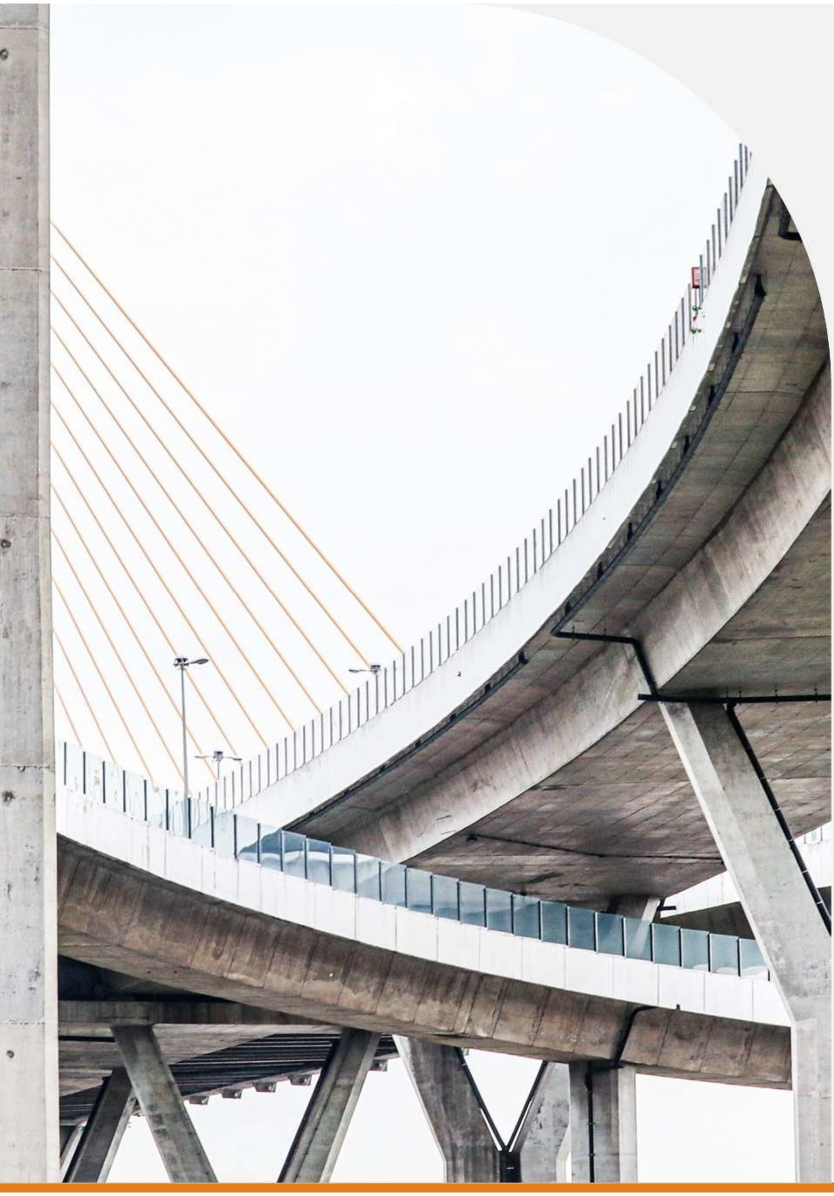
CARBON CURE™
Simply better concrete.

Did you know?

Embodied carbon is expected to account for nearly 50% of the total carbon emissions from new construction over the next 40 years.



Concrete is the most abundant man-made material in the world.

As a result, cement production creates **~7%** of the world's CO_2 emissions and is the **largest contributor** to embodied carbon in the built environment.

What is CarbonCure?

CO_2 Utilization in Concrete

CarbonCure's technology beneficially repurposes carbon dioxide (CO_2) to reduce the carbon footprint of concrete without compromising concrete performance.

CarbonCure Concrete Producers

Nearly 300 plants worldwide using the technology.

CO_2 Supply

CO_2 is captured and distributed to concrete plants by industrial gas suppliers.

Collection

CO_2 is collected from large emitters

Purification

The gas is purified by industrial suppliers

Delivery

The CO_2 is delivered to concrete plants by industrial gas suppliers

Storage

The CO_2 is stored at concrete plants in pressurized tanks

How it Works: Technology

Seamless retrofit technology that operates with no disruption to normal batching procedures

Installation

- CarbonCure engineers install the proprietary equipment into existing concrete plans

Integration

- The CarbonCure software integrates seamlessly with the plant's existing batching software

Injection

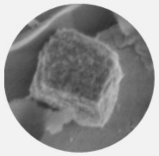
- The equipment injects a precise automated dosage of CO_2 snow into concrete as it mixes

What Happens When CO_2 is Injected?

Cement + H_2O → Ca^{2+} Calcium

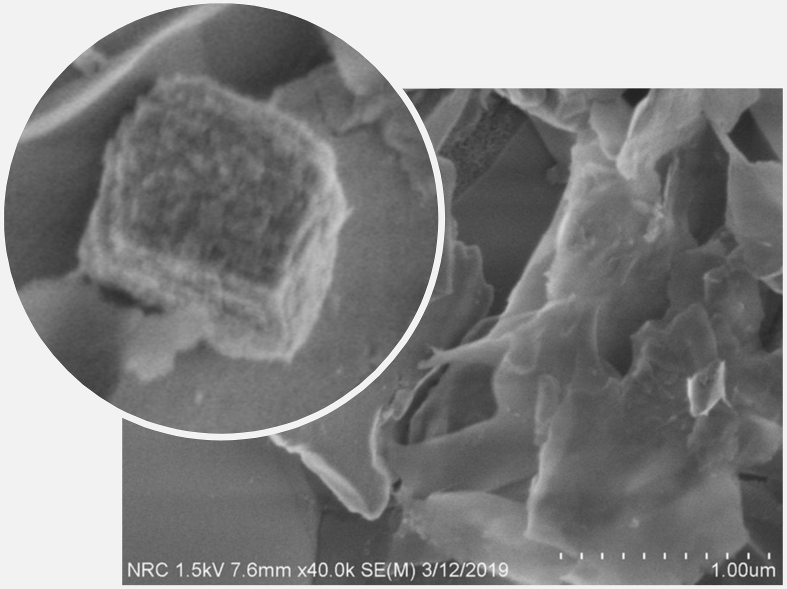
CO_2 + → CO_3^{2-} Carbonate

Ca^{2+} (Calcium) + CO_3^{2-} (Carbonate) = $CaCO_3$ (Calcium Carbonate)



- Reverse calcination reaction occurs
- CO_2 converts into $CaCO_3$ (solid limestone)

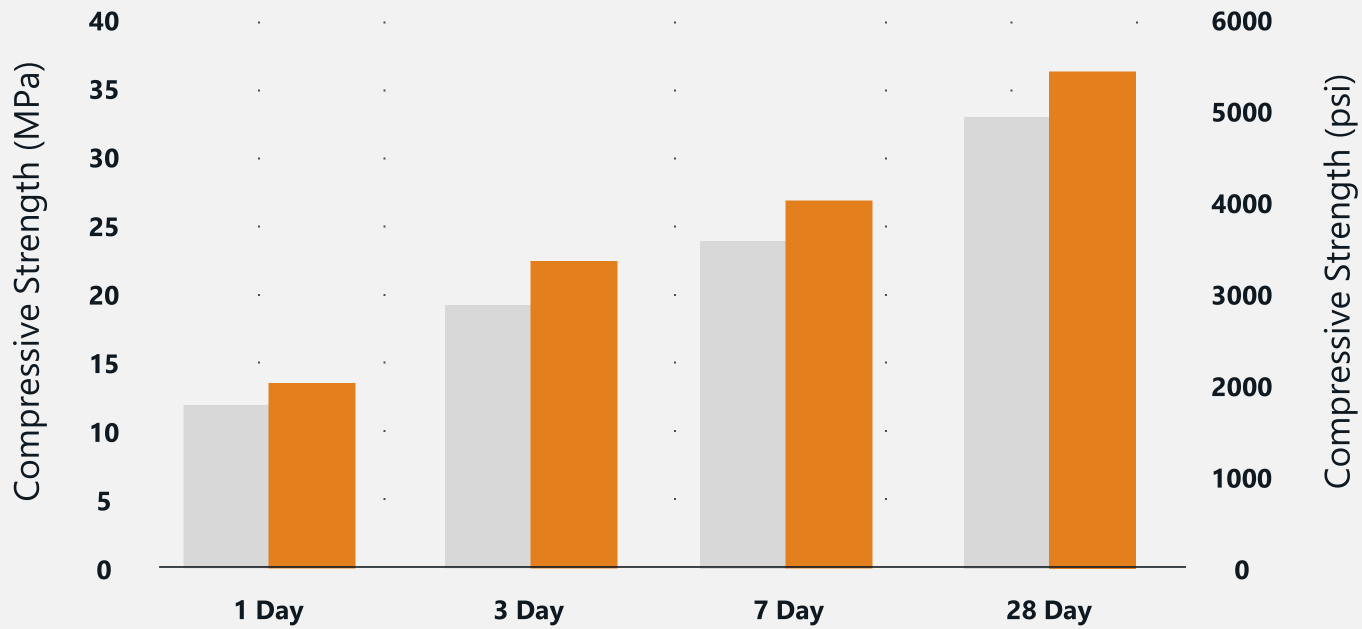
Converting CO_2 to a Mineral



Carbonate product formed about 400 nm dimension

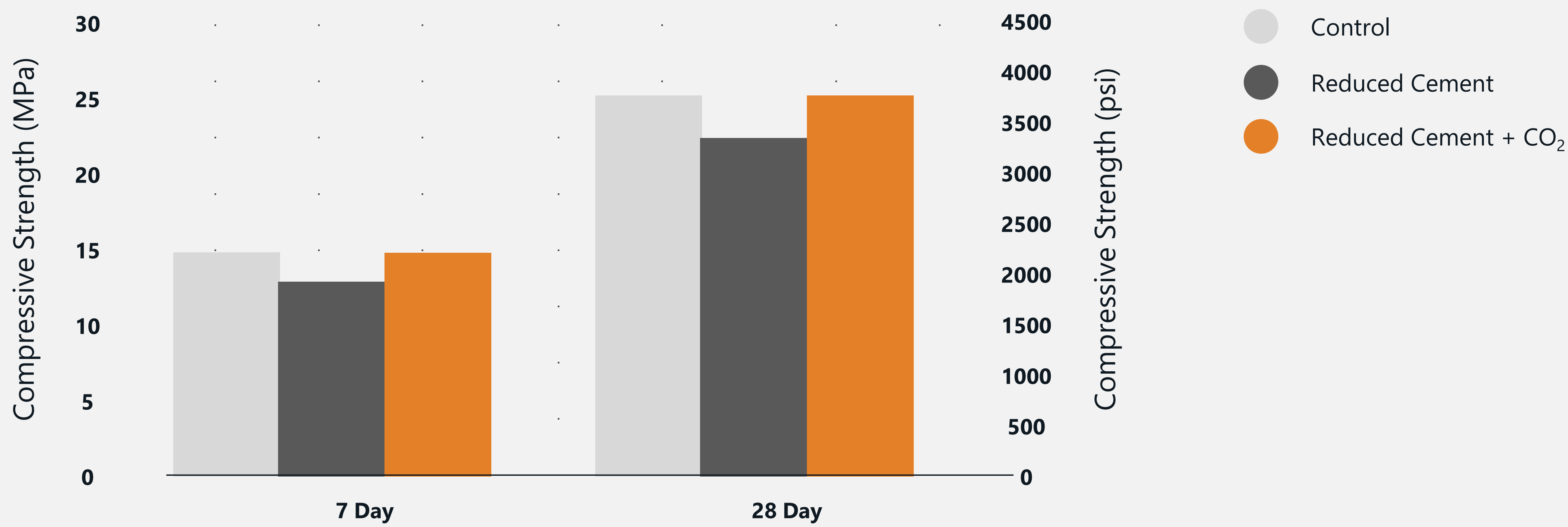
Nano-calcium carbonate particles act as nucleation sites for hydration. Compressive strength benefits arise from this interaction of up to 10% at 28 days.

Compressive Strength Effect



Conclusion: *The formation of a calcium carbonate nanomaterial* ***improves the compressive strength*** *of ready mix concrete.*

Mix Adjustment Potential



Conclusion: *CarbonCure enables concrete producers to* ***reduce cement content*** *without sacrificing strength.*

CO_2 has a Neutral Impact on…

Fresh Properties

- Setting time
- Workability/slump
- Concrete pumping
- Air content
- Temperature
- Finishing

Hardened Properties

- Freeze-thaw
- pH
- Density
- Durability
- Color
- Texture

Note: Peer reviewed papers are available to support the above information at carboncure.com.

CarbonCure for Ready Mix

How Much CO_2 Can Be Saved?

~25 lbs CO_2 saved per yd^3

CO_2 saved = CO_2 mineralized + CO_2 avoided by reducing cement

Reference Project:

725 Ponce

360,000 sq ft commercial office in Atlanta, GA

"Uzun+Case, with input from Thomas Concrete, specified the CarbonCure Technology to reduce the carbon footprint of 725 Ponce. We're proud to have saved 1.5 million pounds of CO_2 while maintaining our high-quality standards for concrete."

Rob Weilacher
Engineer of Record, Uzun+Case

Supplier:
Thomas Concrete

Concrete Usage:
48,000 cy of concrete made with CarbonCure

CO_2 Savings:
1.5 million lbs

CO_2 Savings Equivalent:
888 acres of forest absorbing CO_2 for a year

Reference Projects

Atlanta, GA – Mixed-Use High-Rise
Concrete Producer: Thomas Concrete
CO_2 Saved: 750 tons (1.5M lbs)

San Francisco, CA – LinkedIn Campus
Concrete Producer: Central Concrete
CO_2 Saved: 240,000 lbs

Indianapolis, IN – IUPUI
Concrete Producer: Irving Materials
CO_2 Saved: 180,000 lbs

Halifax, NS – RBC Centre
Concrete Producer: Quality Concrete
CO_2 Saved: 200,000 lbs

Chicago, IL - McDonald's Flagship
Concrete Producer: Ozinga
CO_2 Saved: 30,000 lbs

Atlanta, GA – Georgia Aquarium
Concrete Producer: Thomas Concrete
CO_2 Saved: 330,000 lbs

Calgary, AB – YYC International Airport
Concrete Producer: Dufferin Concrete
CO_2 Saved: 350,000 lbs

Washington DC – The Wharf
Concrete Producer: Vulcan Materials

Early DOT/Municipal Acceptance

CarbonCure is gaining traction for acceptance with various government procurement agencies, including Chicago Department of Transportation, Hawaii Department of Transportation and City of Honolulu.

CDOT
Chicago Department of Transportation

DEPARTMENT OF TRANSPORTATION • STATE OF HAWAII •

CITY AND COUNTY OF HONOLULU • STATE OF HAWAII

How can you help reduce concrete's carbon impact?

- **Communicate** your commitment to embodied carbon reduction throughout the supply chain *early* and *often*
- Design strengths for what you **need**
- Use **supplementary cementitious materials** and/or **low-carbon cement**
- **Remove** unnecessary prescriptive concrete specs
- Consider **performance**-based concrete specs
- Specify and/or approve **CO_2 mineralized concrete**

Build for the Future.
Build with CarbonCure.

A building or infrastructure project may save as much CO_2 as 100s if not 1000s of acres of trees absorb over a year.

Who knew that building with concrete could be like planting trees?

Christie Gamble
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@CarbonCure
CarbonCure Technologies
CarbonCure.Technologies

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Simply better concrete.

Advanced, Multifunctional Wood-Based Structural Materials for Green, Energy Efficient Buildings

Presentation for Alfred P. Sloan Proposal

Proposal Team:

Liangbing Hu, University of Maryland, College Park

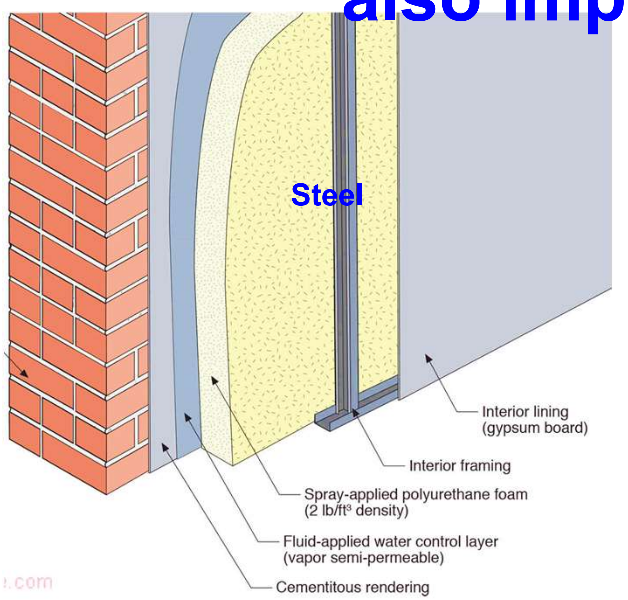
Liangbing Hu
UMD, MSE
Advanced wood

Building Energy Use and Materials

- **Total building energy-use ~$220 billion/year (~50% total energy)**
- **Heating/cooling ~50-70% of energy used in the average American home**
- **~35% of energy leaks through walls**

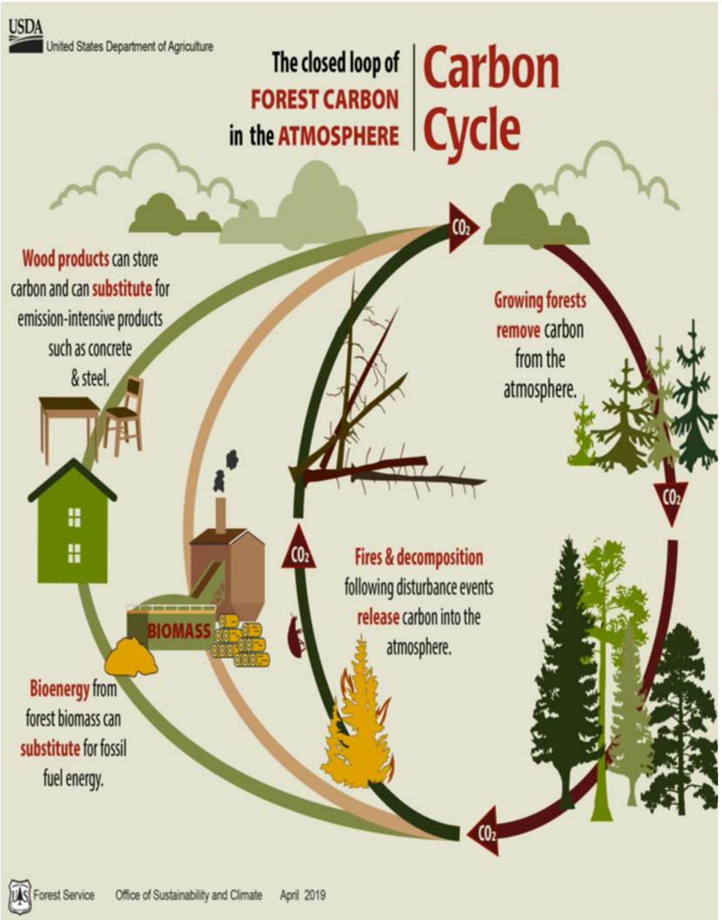
Energy Efficiency Trends in Residential and Commercial Buildings, DOE EERE

Future buildings need more sustainable materials that can also improve building energy efficiency.



- Non-sustainable materials (plastic foam, glass, steel) are heavily used in buildings.
- Energy intensive processes/CO_2 emission problem for steel and glass production.
- Plastic foam is harmful for the environment.
- Wood is used in many buildings, but:
  - Poor mechanical properties that limit its use (tall buildings, structural components);
  - Poor energy efficiency (e.g., poor thermal insulation ~0.1 W/mK)

Carbon Cycle in Forests



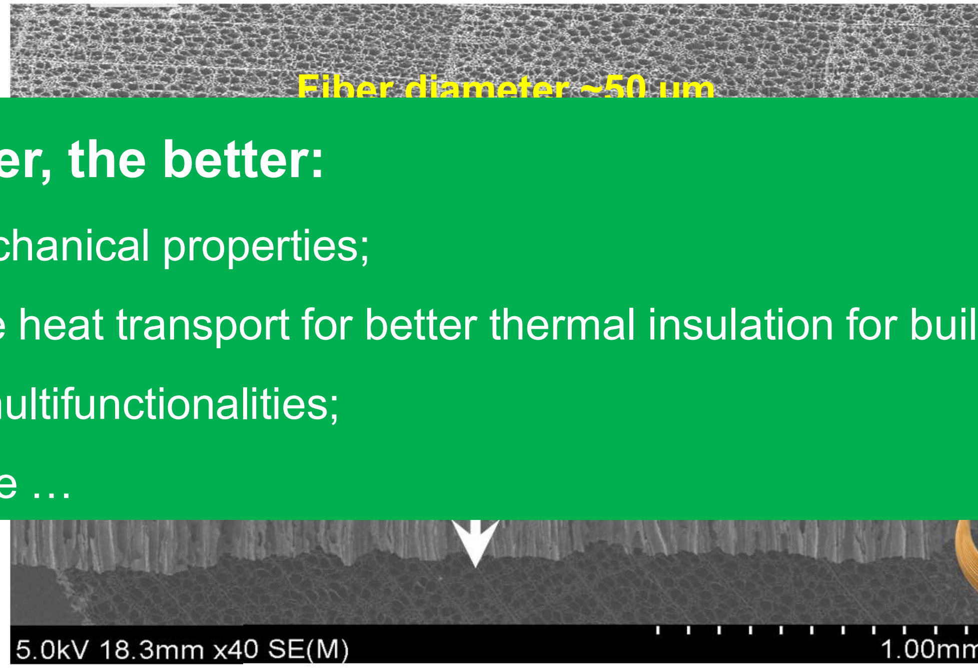
- U.S. forest is a carbon sink – sequestrates more carbon than it releases.*

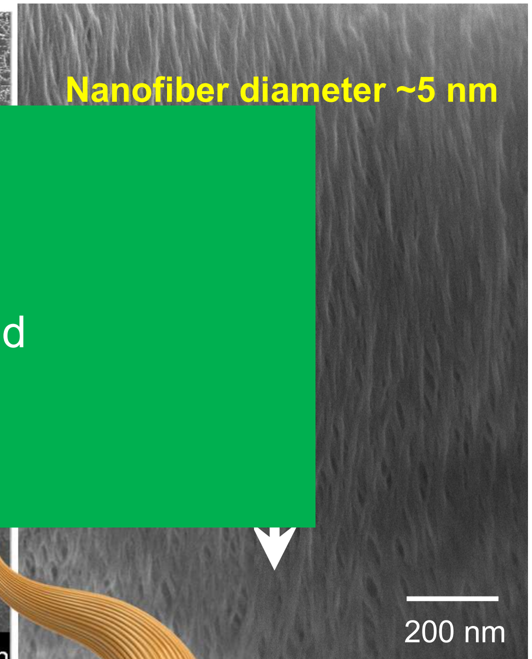
Carbon is stored in wood products. The longer, the better.

Building material, an excellent example of long lived wood product, serves as a prolonged carbon storage.

** Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2018. U.S. Environmental Protection Agency. Washington, DC. 2020.*

Advanced Wood Technology Through Nanoscience



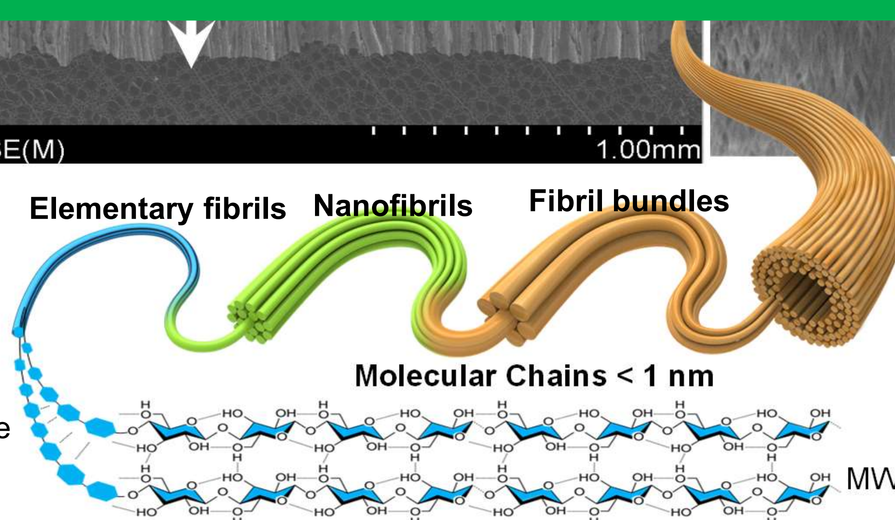


The smaller, the better:

- Better mechanical properties;
- Nanoscale heat transport for better thermal insulation for build
- Tunable multifunctionalities;
- Much more …

Cellulose is the most abundant biomaterial.

Scientists estimate that plants worldwide synthesize up to one trillion metric tons of cellulose annually, from www.encyclopedia.com.



Cellulose (40-50%)
DP: 7000-15000
MW: 50,000-2500,000 g/mol

Hu, L. et al. Nature Review Materials, 2020, 5, 642-666.

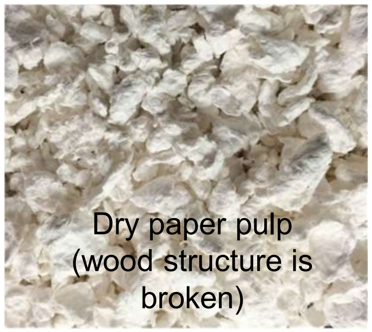
Cellulose nanofiber is the most abundant nanomaterial.

Bottom Up vs. Top Down for Cellulose Nanostructures

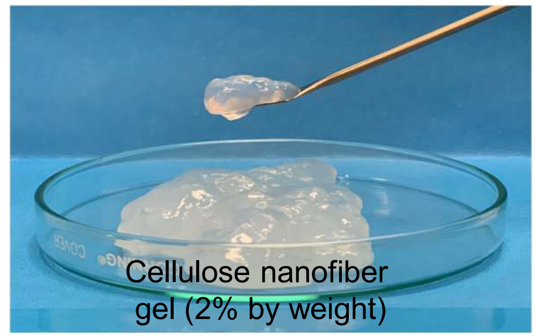
Traditional Approaches: Bottom up

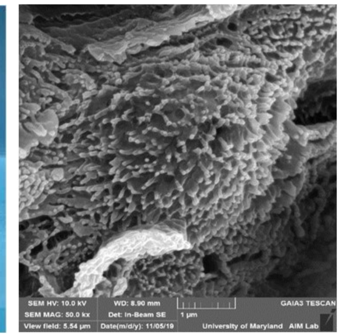
- Energy intensive processes;
- ~98% is water;
- Limited scalability (especially for dry product).

Wood



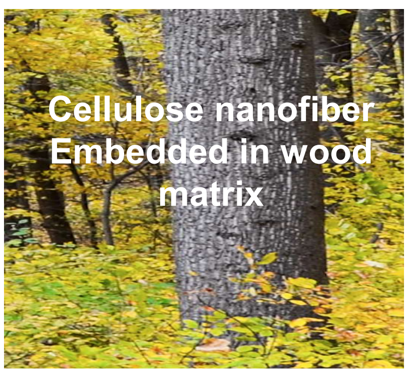
1. Chemical
2. Mechanical





Our Approaches: Top Down

- Much less intensive processes (energy, water use).
- Scalable nanotechnologies.



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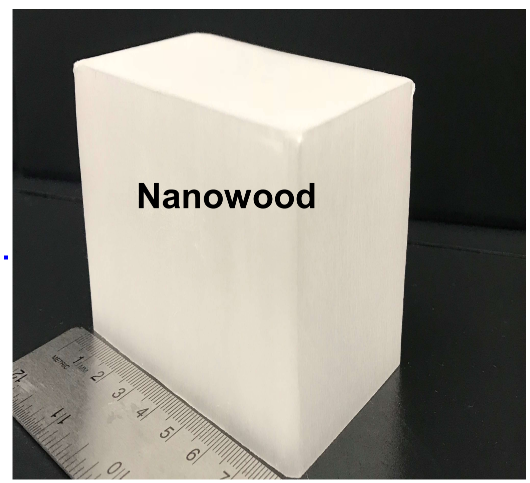
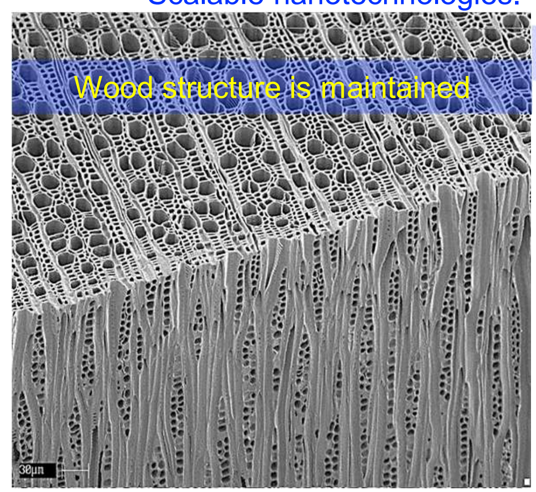
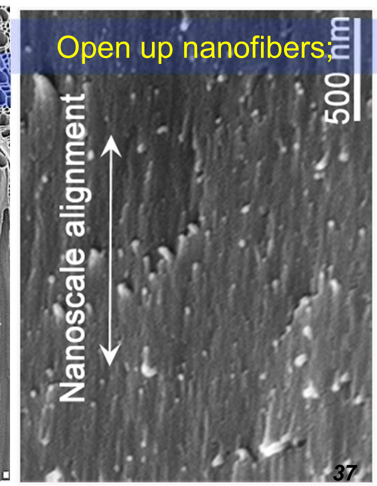
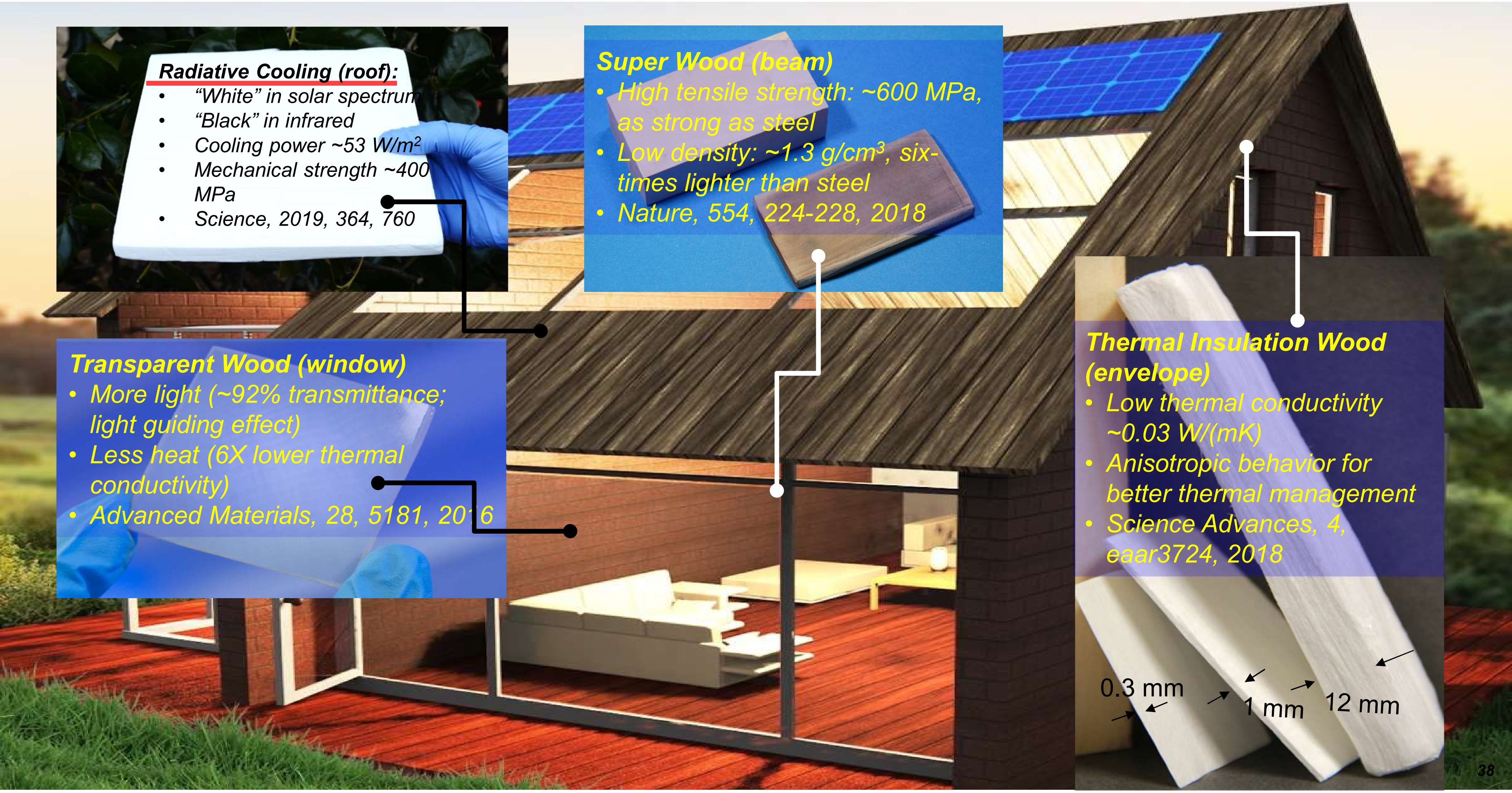






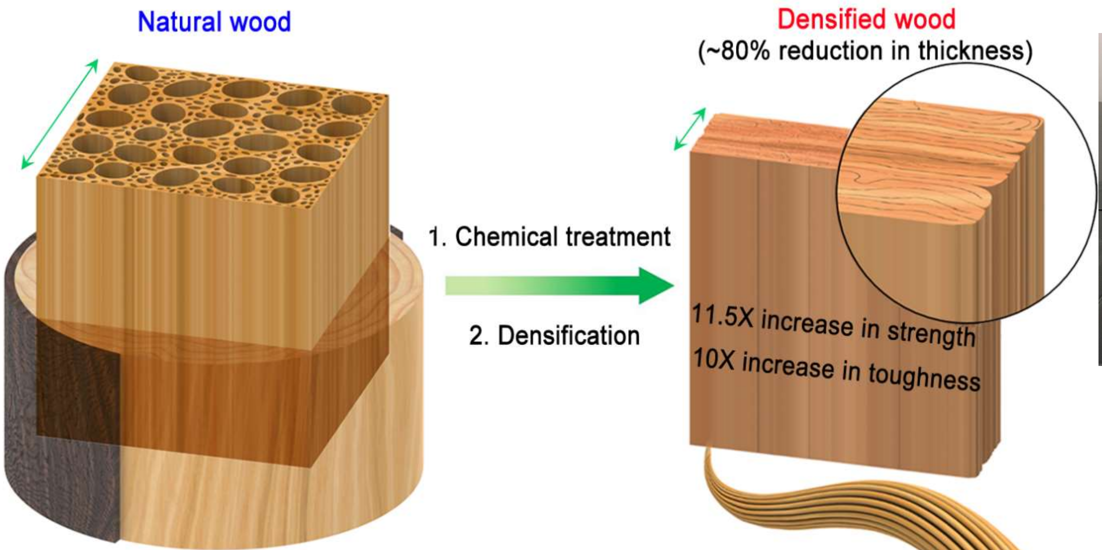
Patent: 62/559,147 15.09.2017, Hu et al.

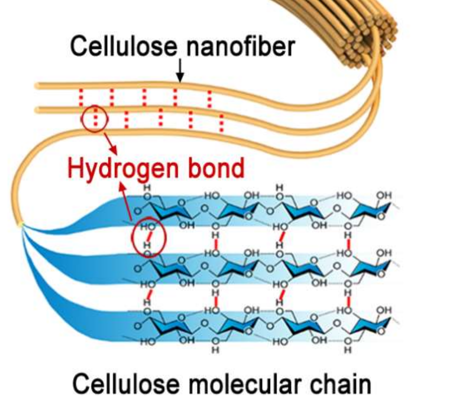
Innovations by the PIs: Advanced Wood for Building Energy Efficiency



1. *Engineering Wood for Lightweight (Mechanics)*

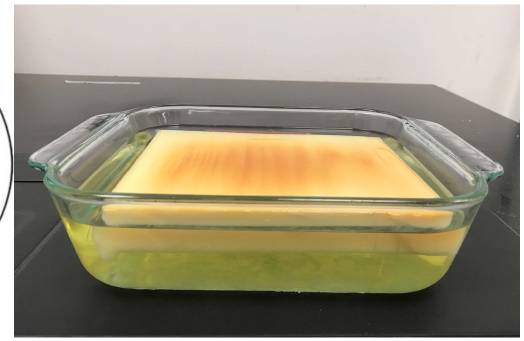
Densified Superwood (with Naturally Aligned Nanofibers)





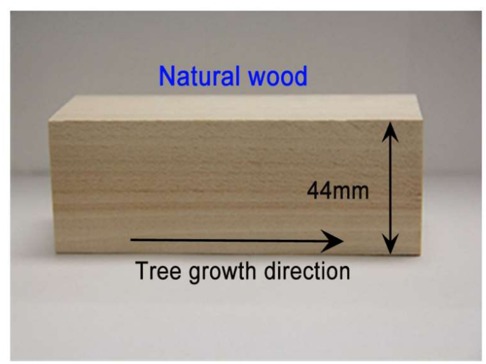
- **Partial lignin removal allows complete densification**
- **Remaining lignin as a "glue"**
- **Strength is ~600 Mpa (then) and 1000 Mpa (now)**
- **Similar strength to steel with 1/6 density**

Nature, 2018, 554, 224-228

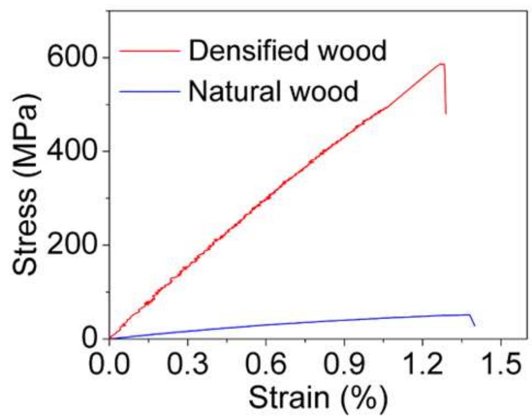


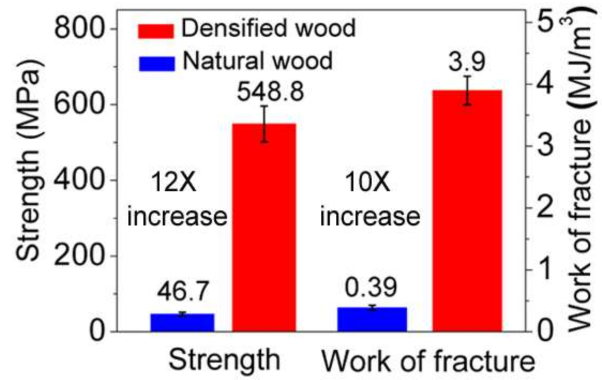
Delignification methods:
- *NaOH*
- *NaOH + H_2O_2*
- *NaOH + Na_2SO_3*

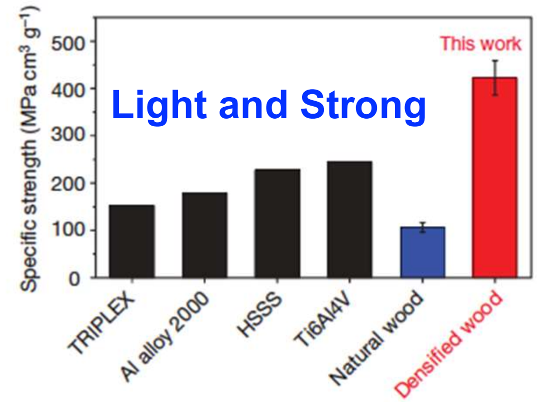
Pressure ~5 MPa

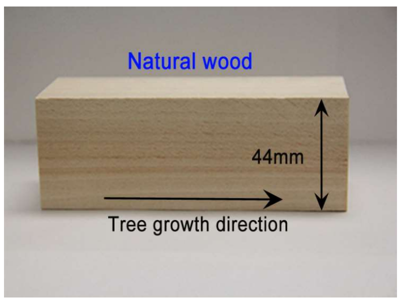


Superb Mechanical Properties of Densified Wood









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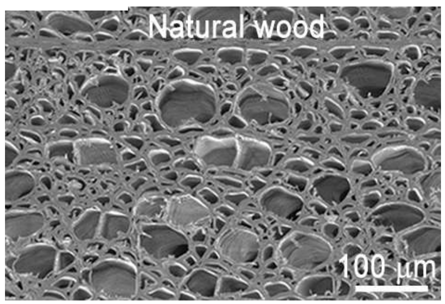

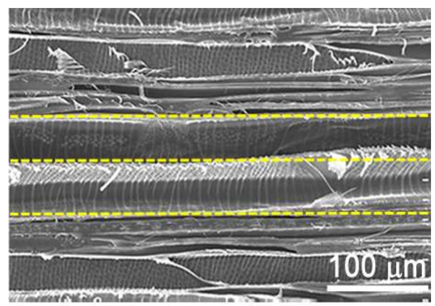

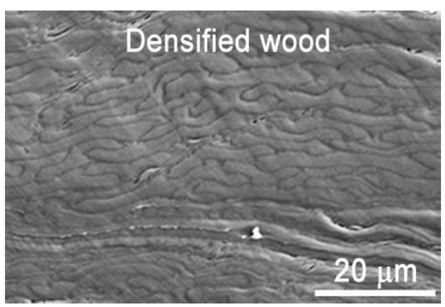

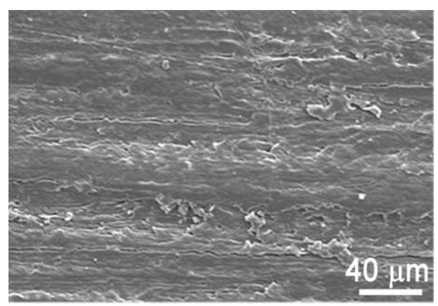

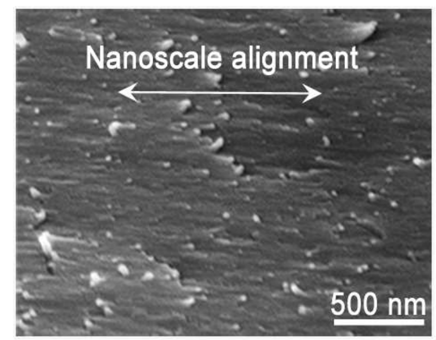

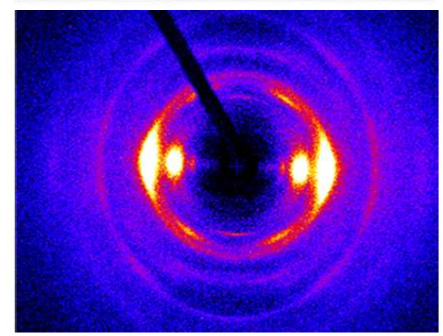

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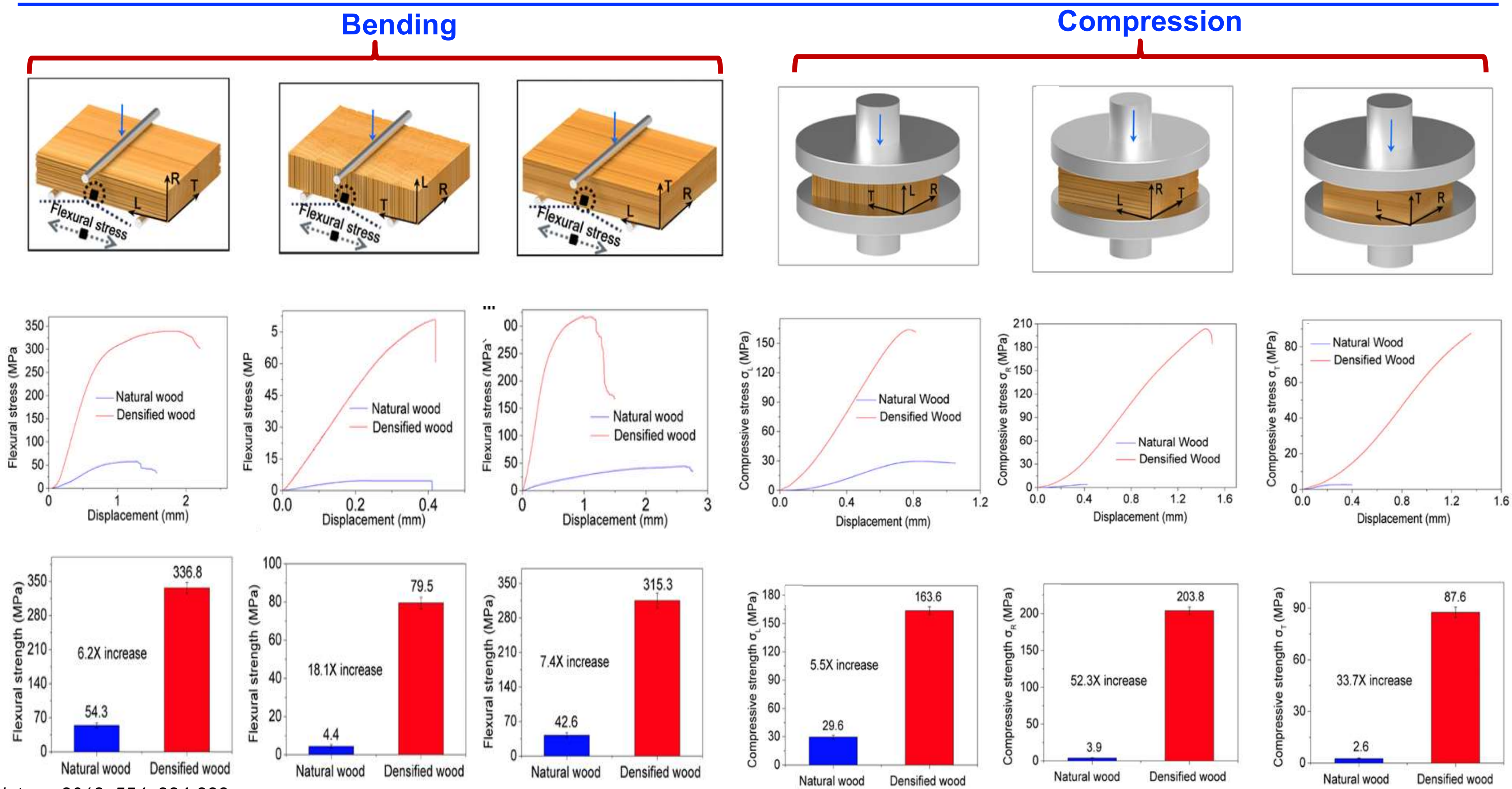
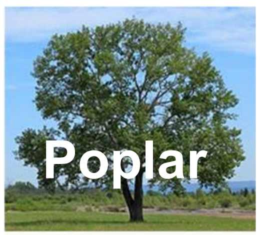


Nature, 2018, 554, 224-228

A Universal Process for Various Wood Species



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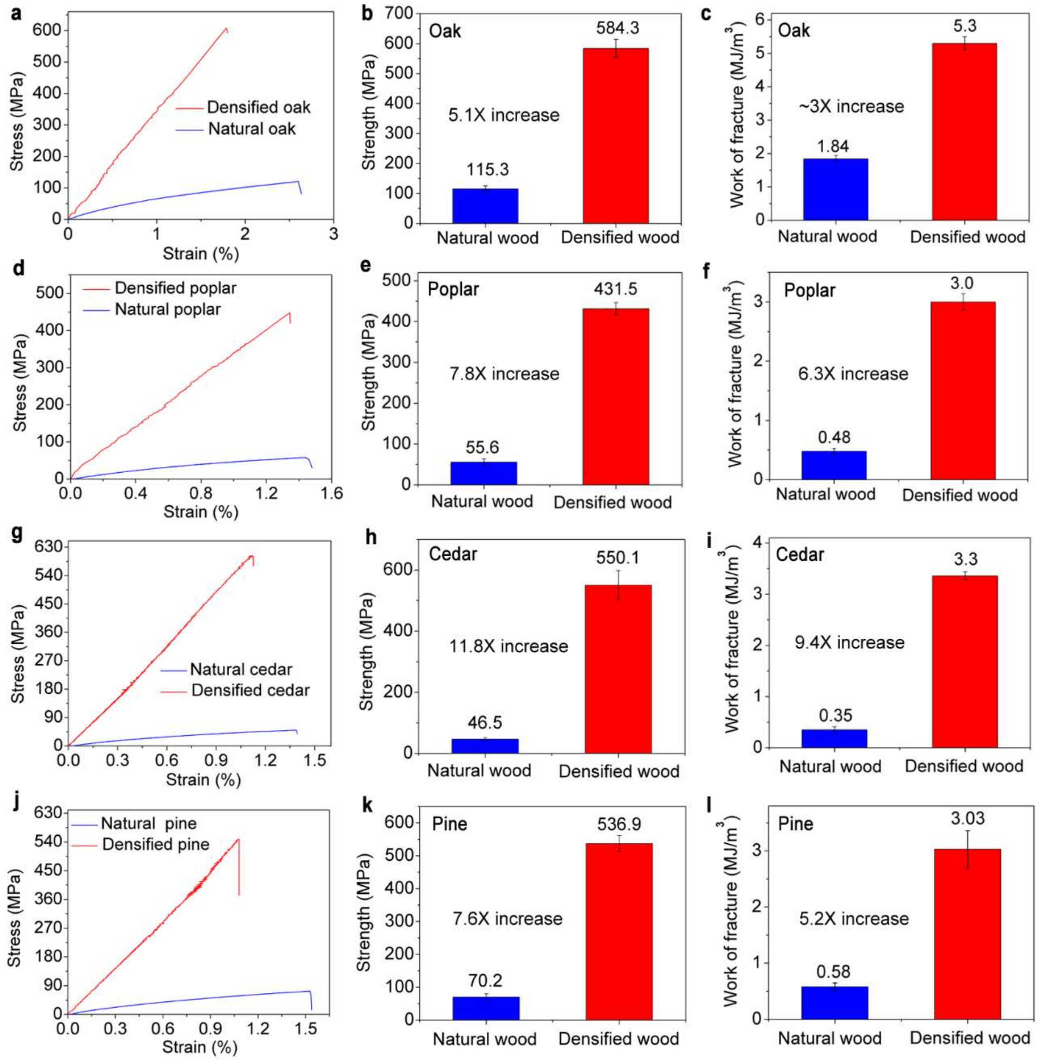
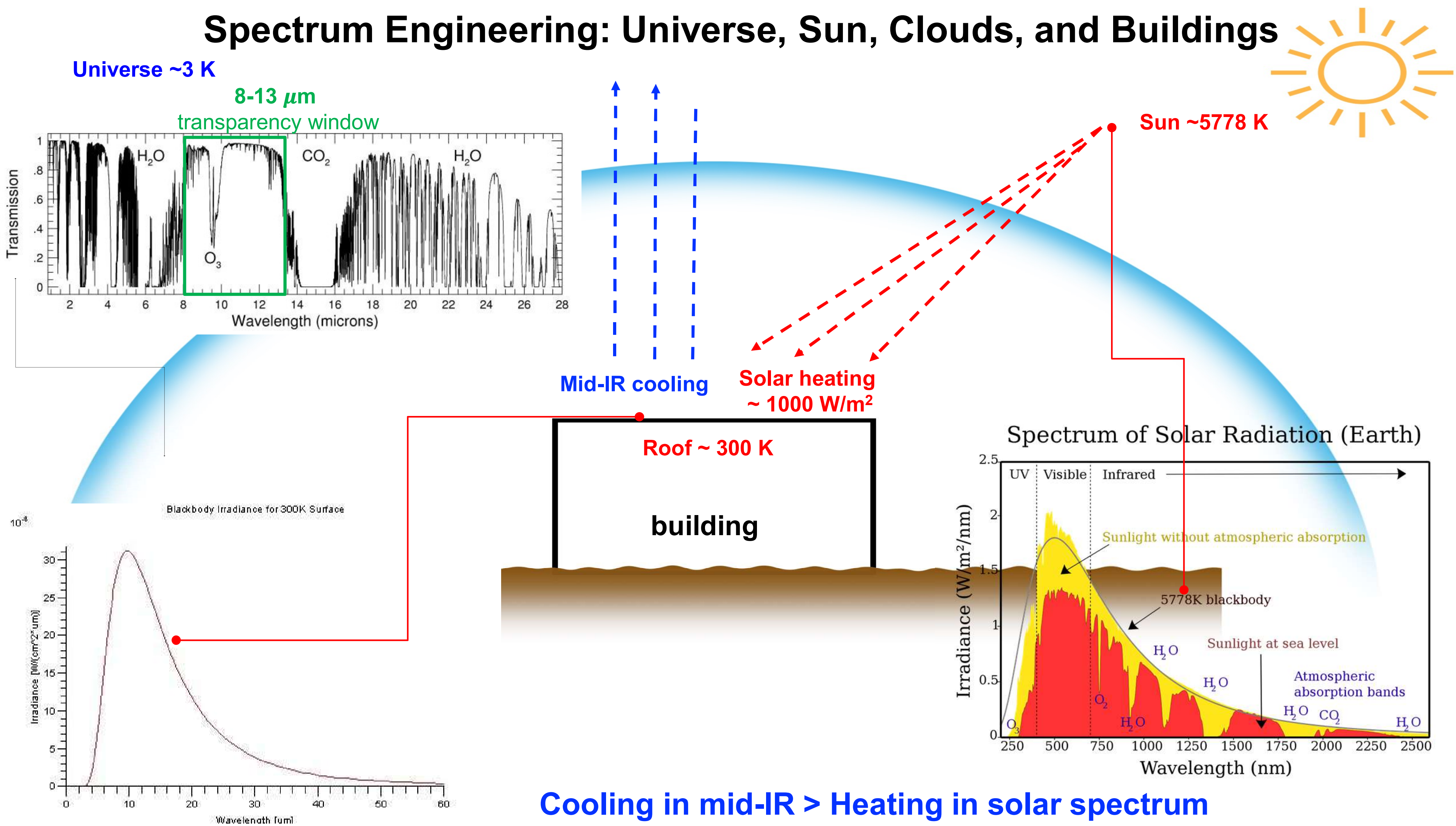


2. Optical and Thermal Engineering with Wood Materials

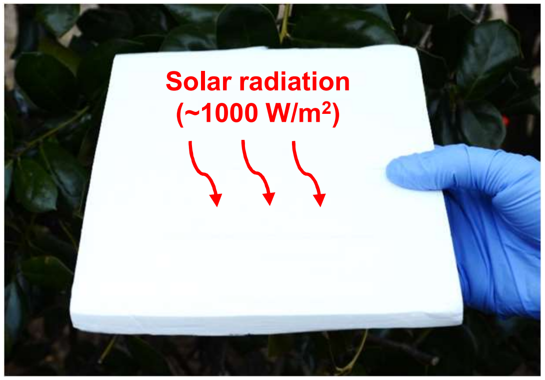
(for building energy efficiency)

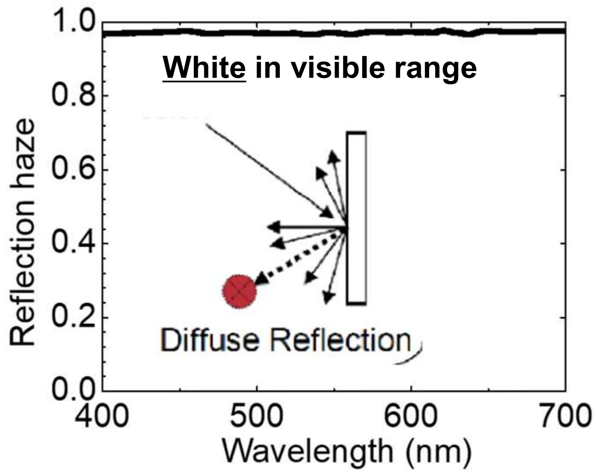
Spectrum Engineering: Universe, Sun, Clouds, and Buildings

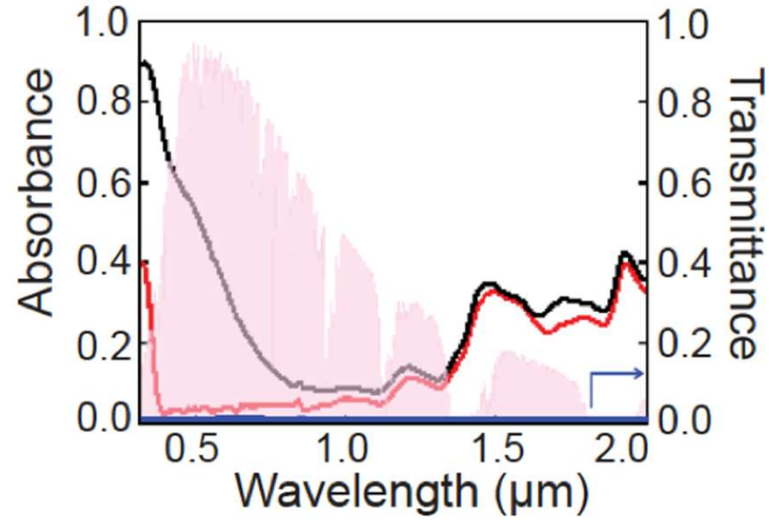


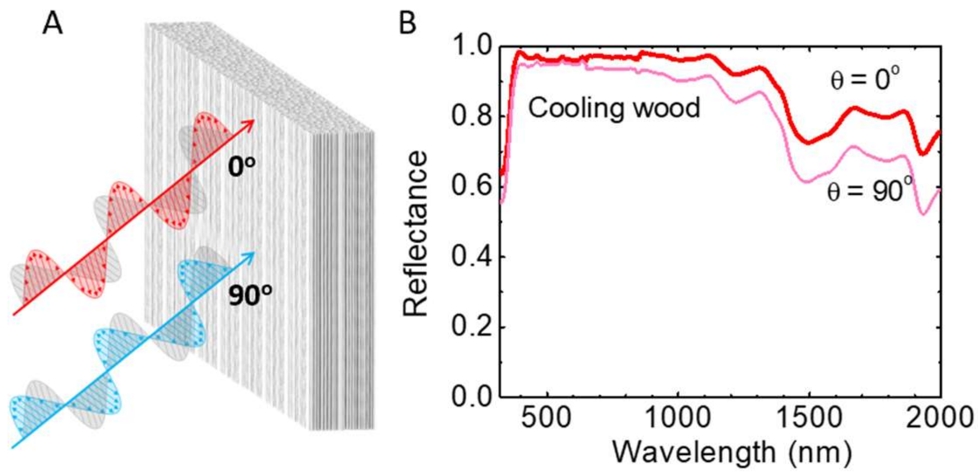
Cooling in mid-IR > Heating in solar spectrum

Cooling Wood in Solar Spectrum: Integrated Heating Power





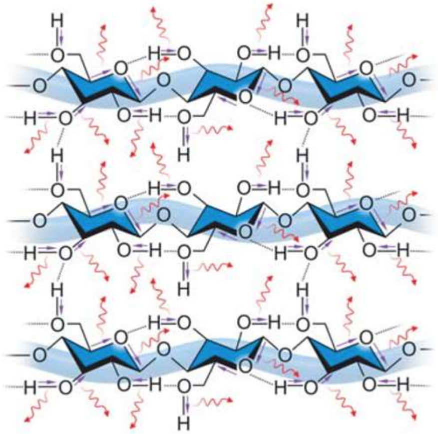




Science, 2019, 364, 760

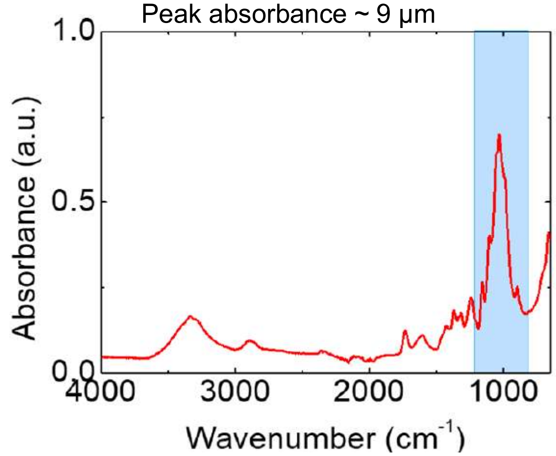
- Energy density of solar radiation ~1000 W/m^2 at the Earth's surface
- Highly reflective (~96%) in visible region (majority of solar energy)
- Absorption happens mainly in the near infrared of solar spectrum (weak solar radiation)
- Integrated solar adsorption P_{solar} ~ 53 W/m^2.

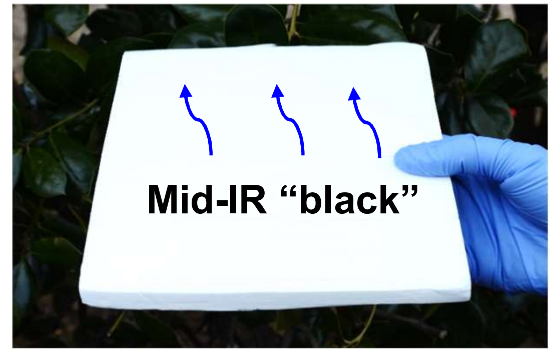
Mid-Infrared Spectrum: High Emissivity (Black)

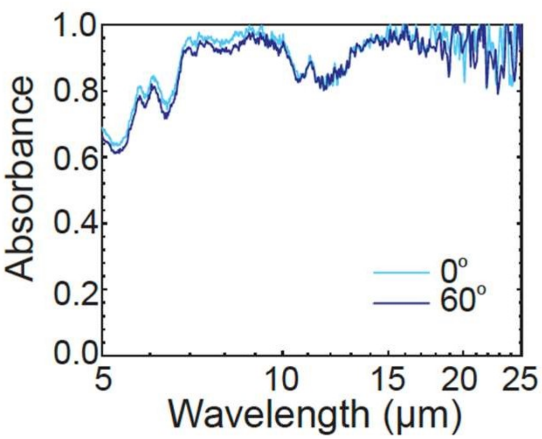


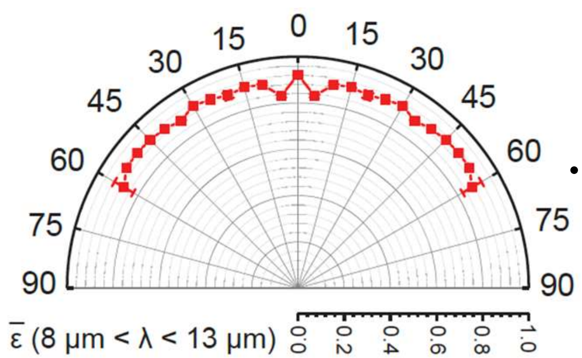
8 µm to 13 µm = 770 cm^{-1} to 1250 cm^{-1}

Peak absorbance ~ 9 µm









- **Total outgoing radiative cooling power density:**
- $P_{rad}(T)$ is the emitted heat of the surface (mainly at mid-infrared)

$$P_{rad}(T) = 2\pi \int_0^{\pi/2} sin\theta cos\theta d\theta \int_{0.3\ \mu m}^{25\ \mu m} \epsilon(\lambda) I_{b\lambda}(T) d\lambda = 358\ W$$

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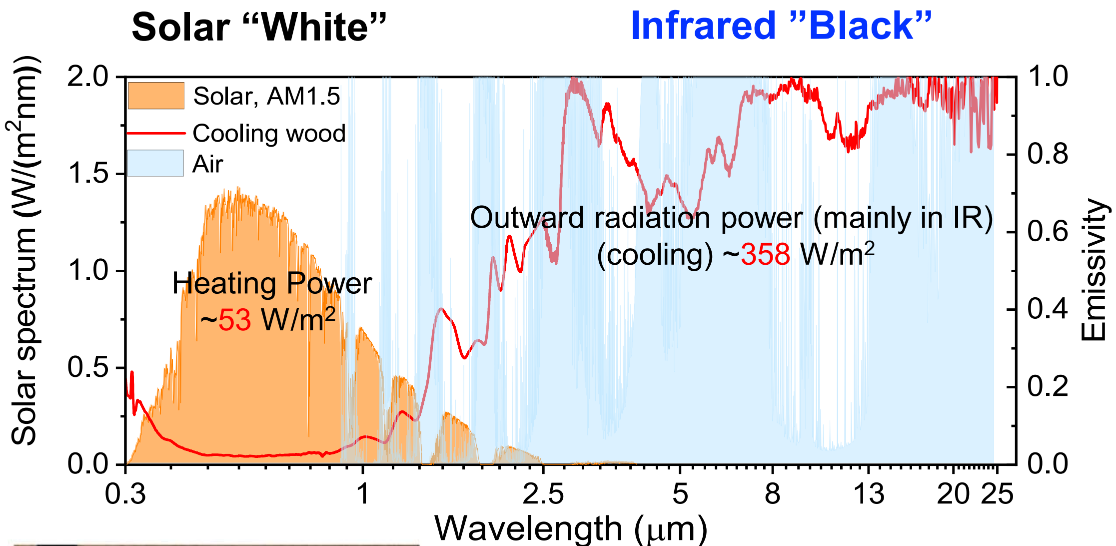
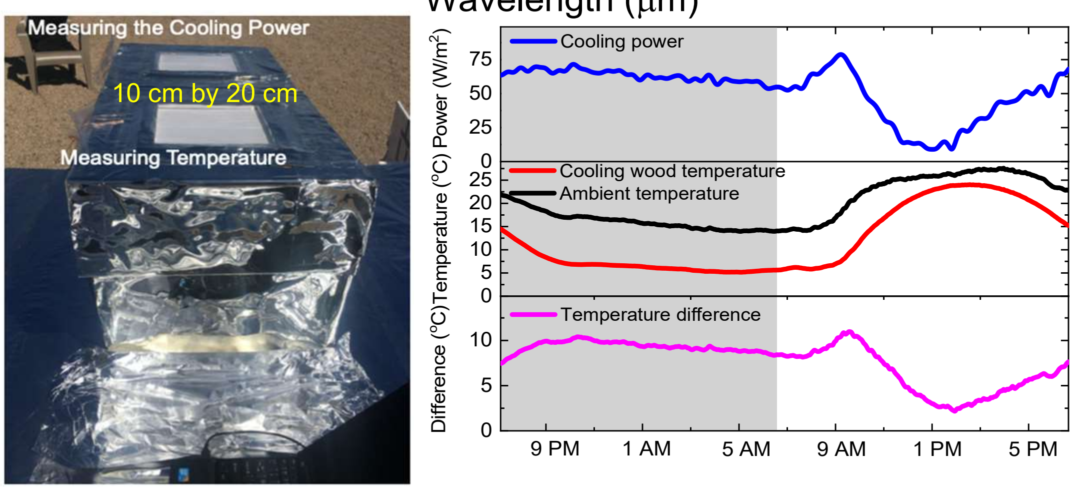
- Mid-Infrared wavelengths: 5-25 µm = Temperature 140-740 K.
- Building temperature ~ 300 K.
- High absorptivity α = High emissivity ε .

Overall Daytime Radiative Cooling





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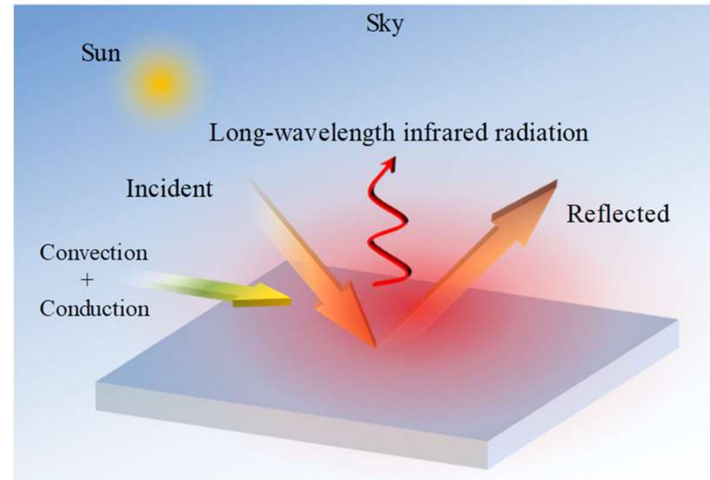


Ambient temperature

$P_{atm}(T_{amb}) =$

$2\pi \int_0^{\pi/2} sin\theta cos\theta d\theta \int_{0.3\ \mu m}^{25\ \mu m} \epsilon(\lambda)\epsilon_{atm}(\lambda) I_{b\lambda}(T_{amb}) d\lambda = 227\ W$

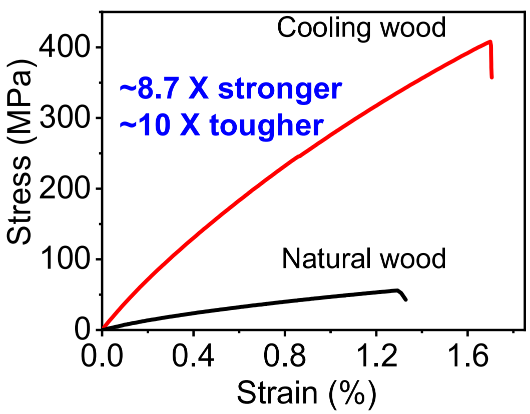
$P_{conv+cond}(T, T_{amb}) = 20\text{W}$, based on wind speed $\sim 2\frac{\text{m}}{\text{s}}$.

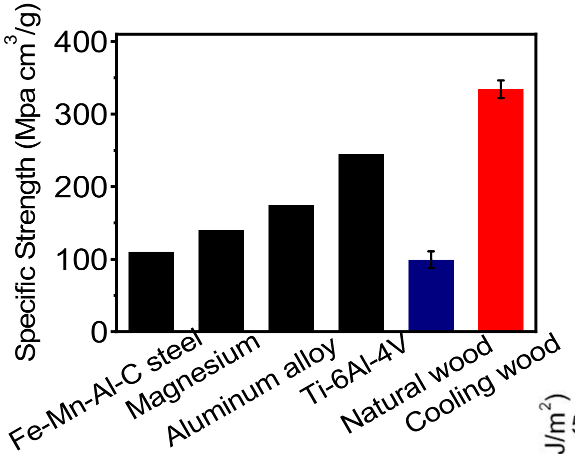
$P_{net}(T)$

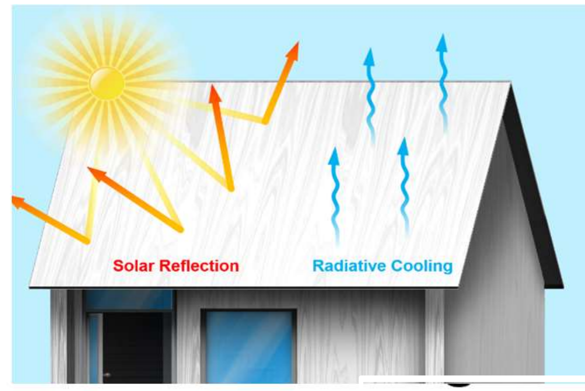
$= P_{rad}(T) - P_{solar} - P_{conv+cond}(T, T_{amb}) - P_{atm}(T_{amb})$

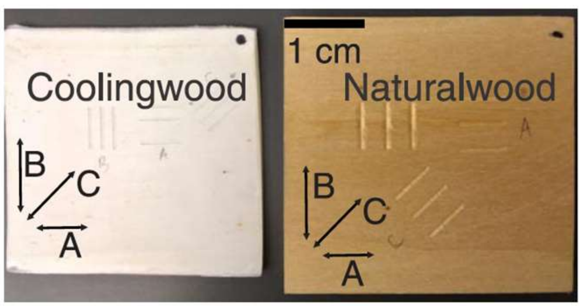
= 58W

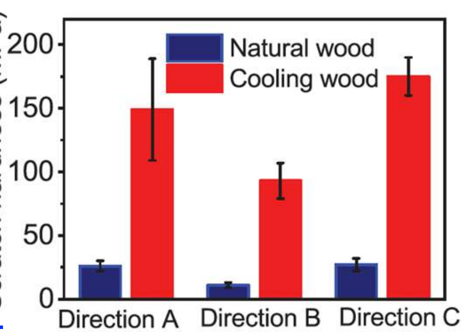
Cooling Wood: A Structural Material for Building

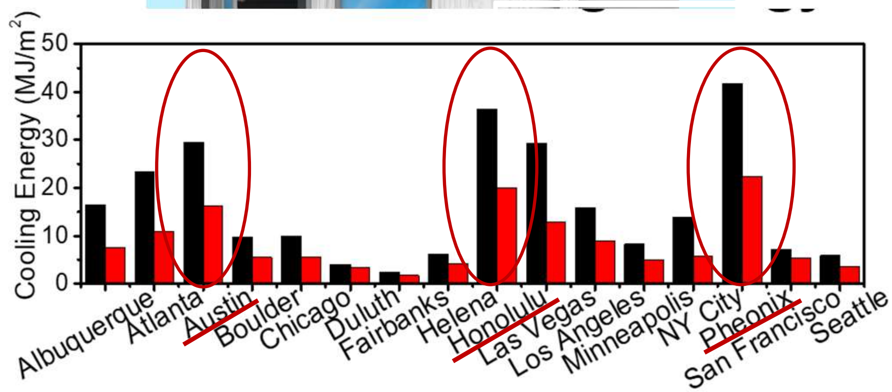




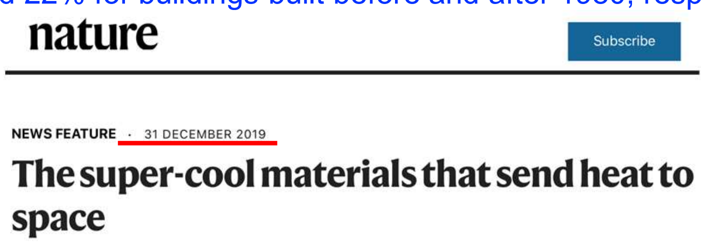








- More effective radiation cooling in dry areas.
- Cooling savings of 35% and 22% for buildings built before and after 1980, respectively.



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NEWS FEATURE · 31 DECEMBER 2019

The super-cool materials that send heat to space

Science, 2019, 364, 760

Modeling:

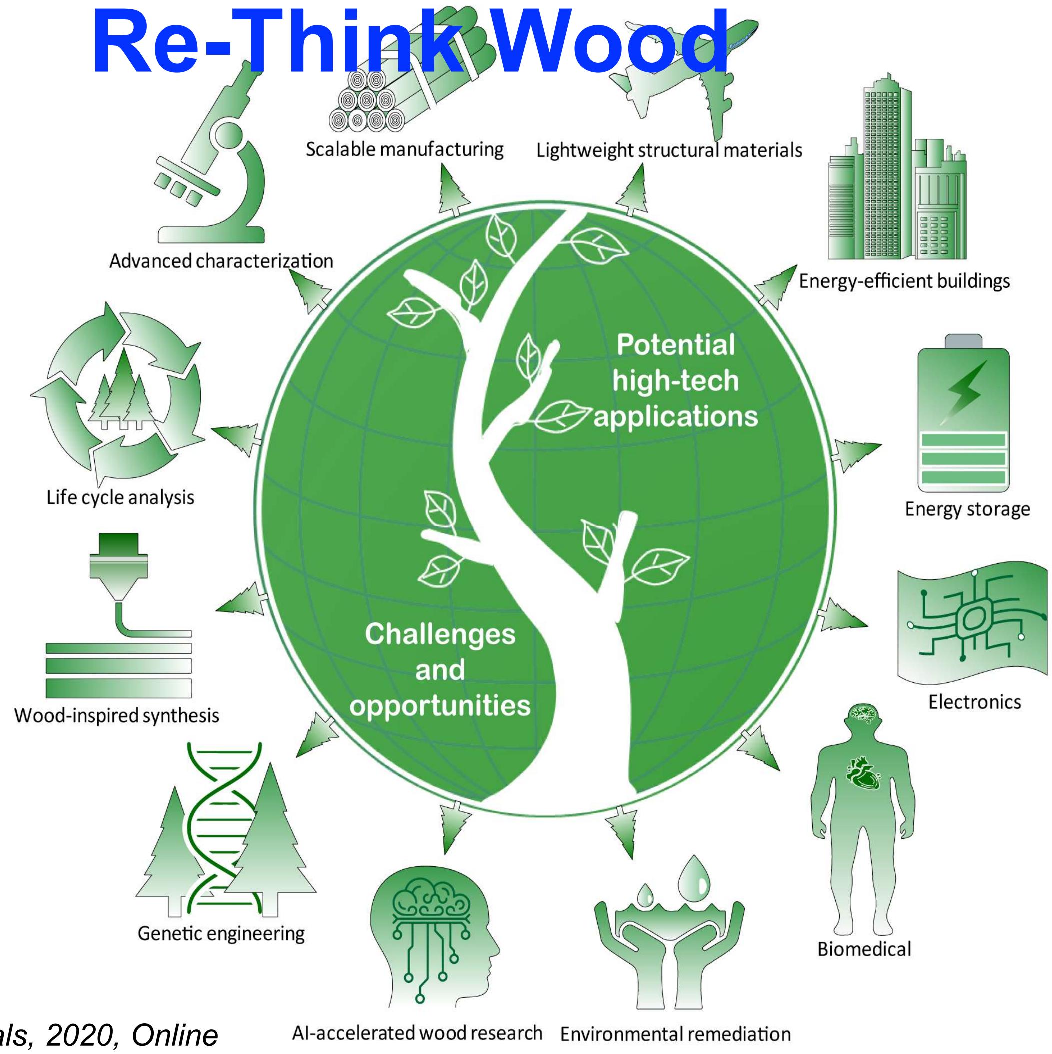
- Through collaboration with Prof. Jelena Srebric
- EnergyPlus version 8
- Midrise apartment buildings across the United States, based on data from old (built before 1980) and new (built after 2004) structures provided by the U.S. Department of Energy Commercial Reference Buildings

Integration with Existing Wood/Paper Manufacturing Infrastructure

Weyerhaeuser

INTERNATIONAL PAPER

Re-Think Wood



Nature Review Materials, 2020, Online

CEEE CENTER *for* ENVIRONMENTAL ENERGY ENGINEERING

Life Cycle Climate Potential of Cooling/Heating Systems for Buildings

November 2020

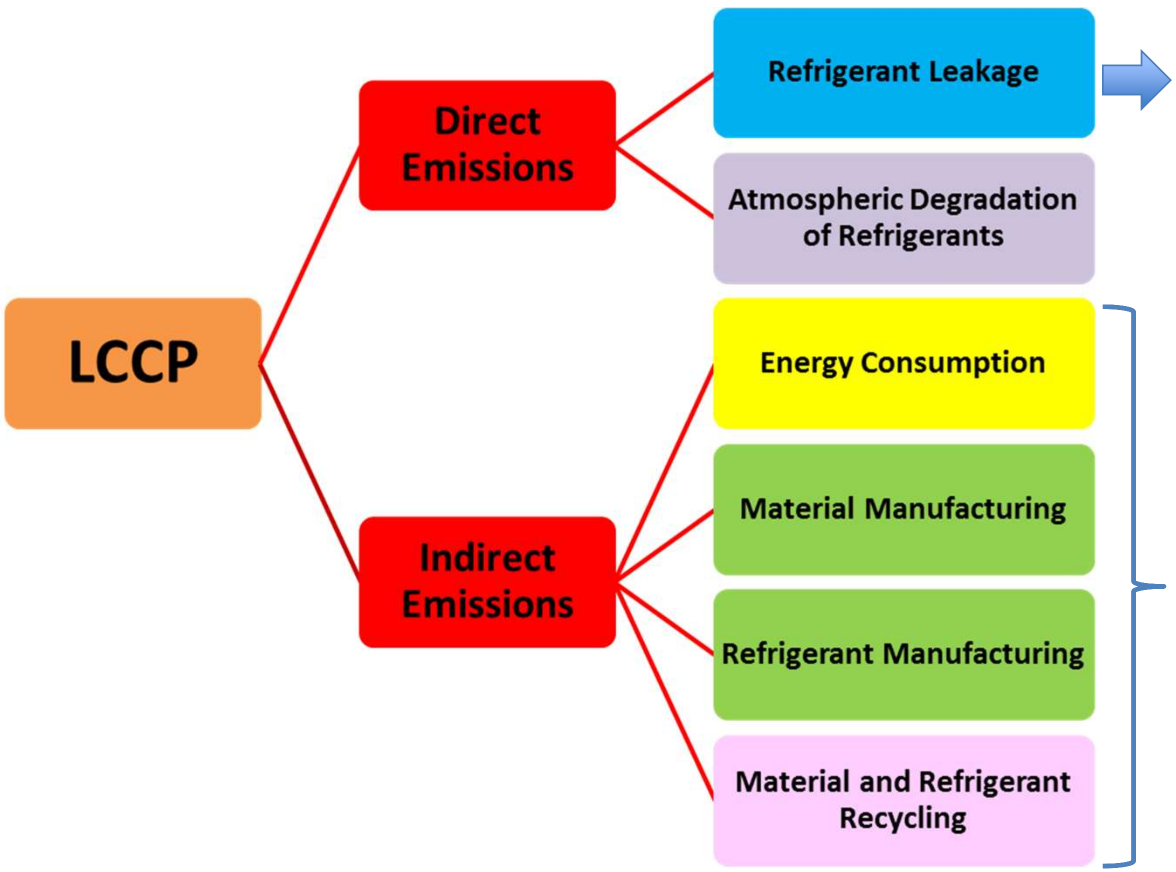
Yunho Hwang, Ph.D., FASME, FASHRAE

Center for Environmental Energy Engineering
Department of Mechanical Engineering
University of Maryland
College Park, MD 20742-3035

BTO Webinar Series on the Life-Cycle Energy

UNIVERSITY OF MARYLAND CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING

Life Cycle Climate Performance



- Regular emissions
- Irregular emissions
- Service emissions
- End-of-life emission
- Leakage during production & transport

- Energy consumption of the system
- Energy to make system/components
- Energy to produce refrigerant
- Energy to transport
- Energy for end-of-life, recycling/recovery of system and refrigerant

LCCP IIR Excel Tool (2012-2016) for Residential Heat Pumps – User Inputs

INSTITUT INTERNATIONAL DU FROID
INTERNATIONAL INSTITUTE OF REFRIGERATION

- Single Speed Compressor, Single Speed Fan
- 8 Refrigerants built in
  - HFC-32, HFC-1234yf, HFC-134a, R-290, HFC-404A, HFC-410A, L-41b, DR-5
- 5 Locations (Miami FL, Phoenix AZ, Atlanta GA, Chicago IL, Seattle WA)
  - Each location in a different climate zone
- Inputs and results in SI units

IIR LCCP Working Group Residential Heat Pump Excel Tool

System	System A		User Input:
Refrigerant	HFC-410A		Energy Calculation is perform
Charge (kg)	6		
Unit Weight (kg)	115		INSTRUCTIONS
Annual Refrigerant Leakage (% per year)	4.00%		1. Select the refrigerant from
EOL Leakage	15.00%		2. Enter the charge, unit wei
Lifetime (years)	15		3. Select "Virgin" or "Mixed"
Manufacturing Emissions Type	Virgin		4. Enter the Cut Off Temperat
Cut Off Temperature (°C)	-17.78		5. Enter the AHRI Standard 21
T_{on} (°C)	-12.22		6. Select the electricity gener
			Refrigerant Options: HFC-32, I

AHRI Std 210/240 Performance Data			
Cooling or Heating	Test Number	Capacity (W)	Total Power (W)
Single speed unit - Fixed Fan Speed			
Cooling	A Test	10,140	2,550
Cooling	B Test	10,474	2,378
Heating	H1 Test	10,082	2,500
Heating	H2 Test	8,382	2,370
Heating	H3 Test	6,154	2,310

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LCCP IIR Excel Tool (2012-2016) for Residential Heat Pumps – Outputs

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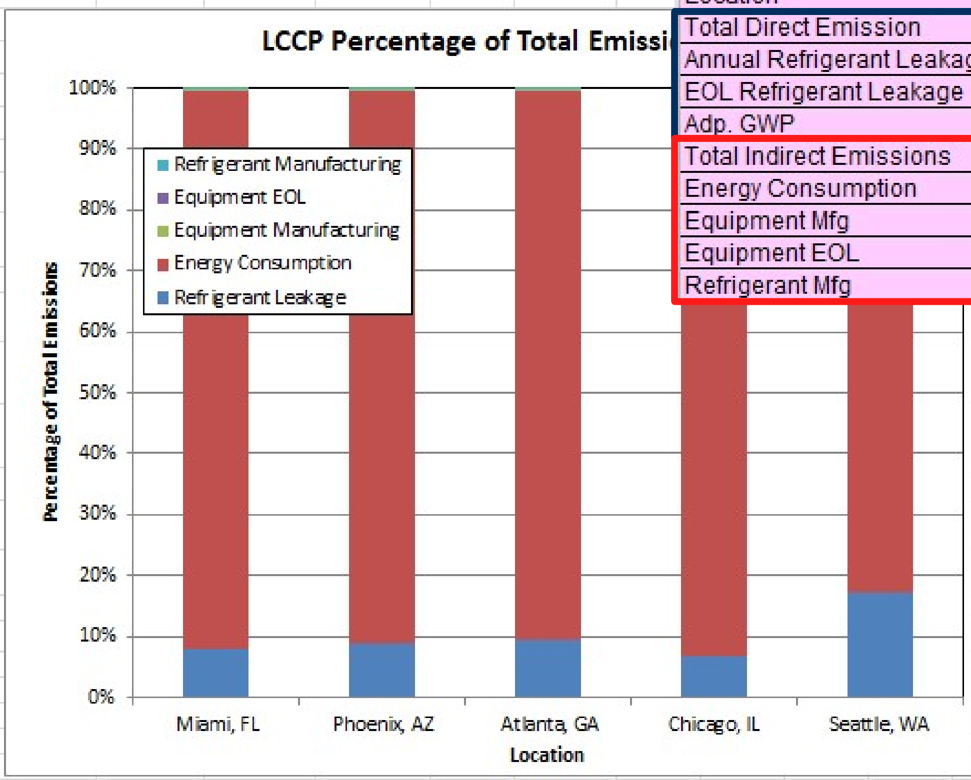

Percentage of Composition

Location	Miami, FL	Phoenix, AZ	Atlanta, GA	Chicago, IL	Seattle, WA
Total Direct Emission	7.96%	8.75%	9.37%	6.67%	17.19%
Annual Refrigerant Leakage	6.37%	7.00%	7.49%	5.34%	13.75%
EOL Refrigerant Leakage	1.59%	1.75%	1.87%	1.33%	3.44%
Adp. GWP	-	-	-	-	-
Total Indirect Emissions	92.04%	91.25%	90.63%	93.33%	82.81%
Energy Consumption	91.66%	90.83%	90.18%	93.01%	81.98%
Equipment Mfg	0.38%	0.41%	0.44%	0.31%	0.81%
Equipment EOL	0.01%	0.01%	0.01%	0.00%	0.01%
Refrigerant Mfg	0.09%	0.10%	0.11%	0.08%	0.20%

Table 3: Material Information

Material	Virgin Manufacturing Emissions (kg CO_{2e}/kg)	Mixed Manufacturing Emissions (kg CO_{2e}/kg)
Steel	1.8[29]	1.43[37]
Aluminum	12.6[30-32]	4.5[31]
Copper	3.0[33]	1.64[33]
Plastics	2.8[34]	2.61[35],[36]

Table 4: Recycling Information

Material	Recycling Emissions (kg CO_{2e}/kg)
Metal[5, 37, 38]	0.07
Plastics[5, 35, 36]	0.01

Equipment manuf. Emission < 1%

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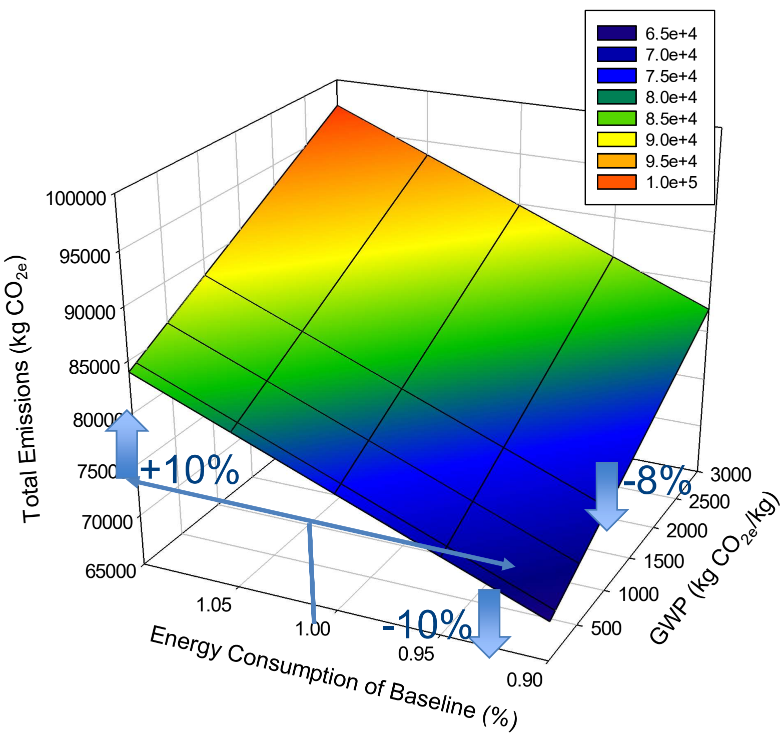
BTO Webinar Series on the Life-Cycle Energy

Sensitivity Study



Energy Consumption & GWP

Refrigerant	Constituent	Mass fraction	Classification	GWP	LCCP
R410A	R32/R125	50/50	A1	2,088	100%
ARM70a	R32/R134a/R1234yf	50/10/40	A2L	482	96%
D2Y60	R32/R1234yf	40/60	A2L	272	96%
DR5	R32/R1234yf	72.5/27.5	A2L	490	95%
L41b	R32/R1234ze	73/27	A2L	494	95%
R32	R32	100	A2L	675	94%
Propane	R290	100	A3	3	88%

- Reducing GWP to around 500 decreases direct emission by 71% but total LCCP by 11%
- Reducing energy consumption by 10% lowers total LCCP near to 10%.
- The most effective way to reduce equipment emissions is to increase the energy efficiency of the equipment (or building envelop performance).

Enhanced & Localized LCCP (2017-2019)

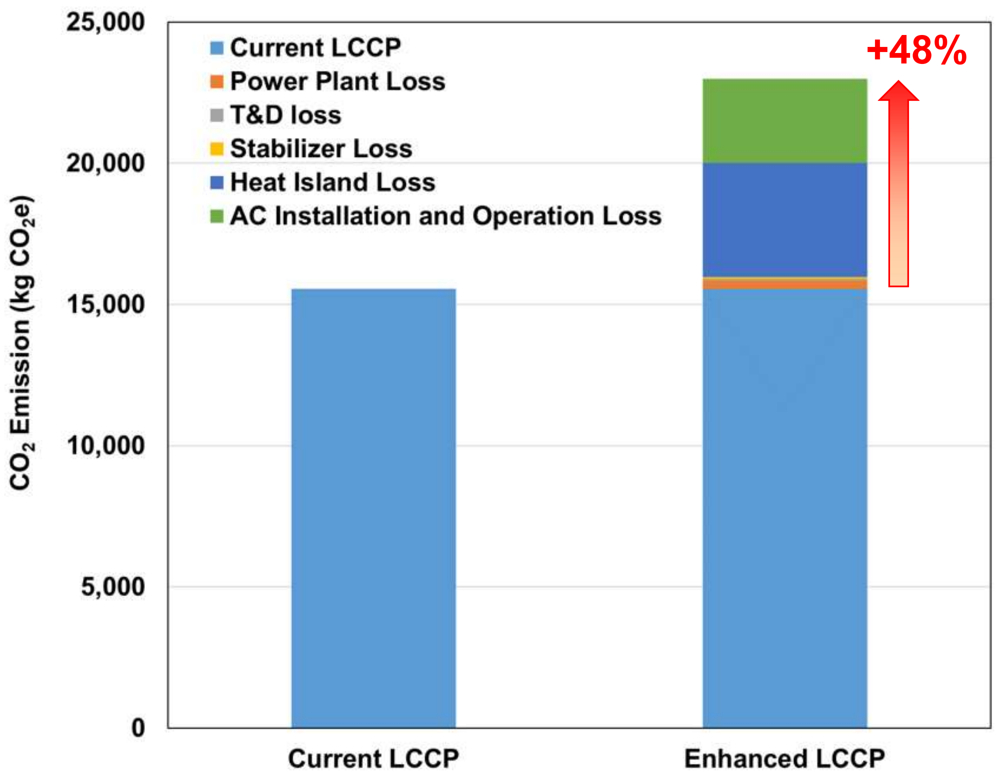


Figure 1. Extra carbon emissions due to various losses

Dr. Stephen Andersen (IGSD) and expert members suggested to consider enhanced and localized circumstances

Additional degradation factors	Impact
Power plant efficiency by ambient temperature	Power plant efficiency reduced by 2% (from 36% to 34%)
T&D loss by ambient temperature	Loss increases by 0.5% (from 5% to 5.5%)
T&D loss by infrastructure	<5% modern grids; >50% obsolete grids
Voltage stabilizer	Adds additional 5% loss
Heat island impact	Reduces AC COP by 27%
Stacked condenser impact	Reduces AC COP by 20%

Life-Cycle Climate Performance Metrics and Room AC Carbon Footprint

BY STEPHEN O. ANDERSEN; JAMES WOLF, PRESIDENTIAL/LIFE MEMBER ASHRAE; YUNHO HWANG, MEMBER ASHRAE; JIAZHEN LING, ASSOCIATE MEMBER ASHRAE

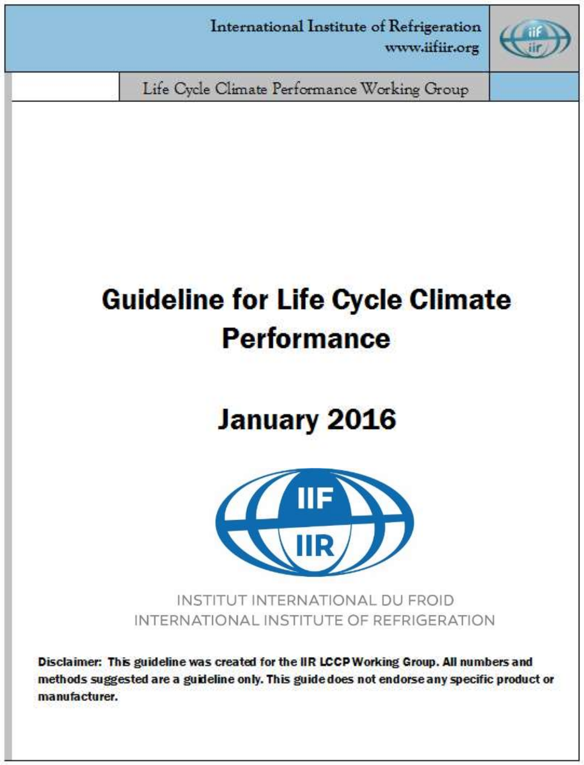
ASHRAE JOURNAL ashrae.org NOVEMBER 2018

CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING

Summary

- IIR LCCP Guideline (2016) recommends how to perform the LCCP calculation for heat pump systems and provide data sources for the individual components.
- Energy consumption is the main contributor to the LCCP followed by annual refrigerant leakage.
- EL-LCCP considers practical localized installation factors.
- Low-GWP refrigerant will be applied globally and using low-GWP refrigerant (GWP=10) is equivalent to improving energy efficiency by 8% in Miami, US.
- Improving building material performance directly improves on equipment LCCP.

IIR Guideline for LCCP Performance



- Guideline for Life Cycle Climate Performance published in January 2016.
  - Detailed explanation of calculation process
  - Recommended traceable data sources for GWP values, leakage rates, manufacturing emissions rates, recycling emissions rates
  - Recommended traceable data sources for weather data, electricity generation rates
  - Recommended standards for energy consumption calculation
  - Comparison to TEWI
  - Available LCCP calculation tools
  - Residential heat pump sample problem

LCCP Publications

INTERNATIONAL JOURNAL OF REFRIGERATION 70 (2016) 128–137

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refrigeration

LCCP evaluation on various vapor compression cycle options and low GWP refrigerants

CrossMark

Hoseong Lee [a,b], *Sarah Troch* [a], *Yunho Hwang* [a,*], *Reinhard Radermacher* [a]

[a] *Center for Environmental Energy Engineering (CEEE), Department of Mechanical Engineering, University of Maryland, 3157 Glenn L. Martin Hall Bldg., College Park, MD 20742, USA*

[b] *Department of Mechanical Engineering, Korea University, 409 Innovation Hall Bldg., Anam-Dong, Sungbuk-Gu, Seoul, Republic of Korea*

- **Published *"Harmonization of Life Cycle Climate Performance"* at 16th Int. RAC conference at Purdue, Paper No. 2382.**
- **Published *"LCCP evaluation on various vapor compression cycle options and low GWP refrigerants"*, Int. J. of Refrigeration, 2016, V 70, pp. 128-137.**

Q&A Session

- **Use the Q&A feature to ask a question**
- **Panelists**
  - Wil Srubar – Associate Professor, CU Boulder
  - Christie Gamble – Sustainability Director, CarbonCure
  - Liangbing Hu – Professor, University of Maryland; Co-Founder, Inventwood
  - Yunho Hwang – Professor, University of Maryland

Building Life Cycle Impacts DOE Webinar Series

Topic	Date	Time
Overview of life cycle impacts of buildings	Oct. 16	12:00pm – 1:00pm ET
Challenges of assessing life cycle impacts of buildings	Oct. 29	12:00pm – 1:00pm ET
Innovative building materials	Nov. 12	12:00pm – 1:00pm ET
"Real Life" buildings striving to minimize life cycle impacts	Dec. 3	12:00pm – 1:00pm ET
Intersection of life cycle impacts & circular economy potential for the building sector	Dec. 17	12:00pm – 1:00pm ET