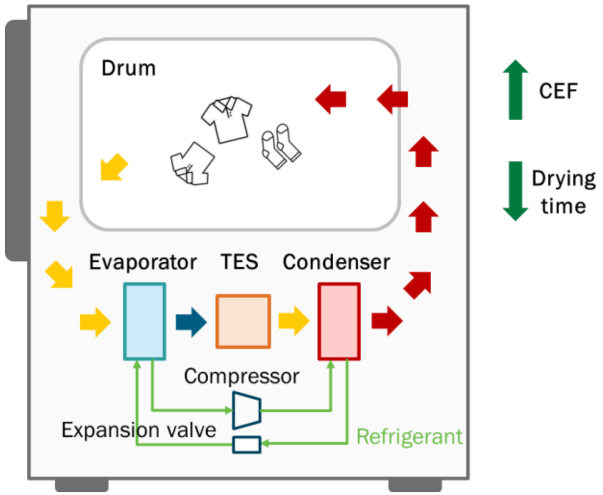
CWD: Next-Gen Combined Washer and Dryer Platform for Higher Efficiency and Fast Operation



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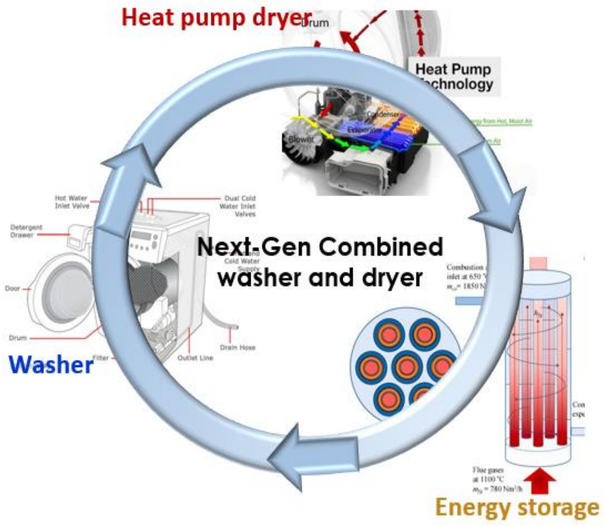
WBS #03.02.02.48.

Project Summary

Objective and outcome

Development of a combined washer and heat pump dryer platform with a higher combined energy factor, CEF (>25% improvement), compared to existing electric resistance dryers and with faster operation (>20% reduction in overall operating time) compared to state-of-the-art dryers.



Team and Partners

Kashif Nawaz, Pengtao Wang, Xiaoli Liu, Cheng-Min Yang, Chris Harnett

Stats

Performance Period: Jan 2023 –Dec 2025

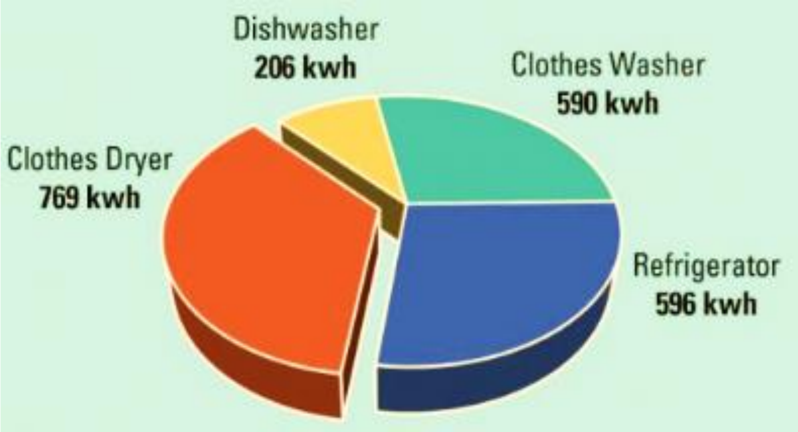
DOE budget: $900k, Cost Share: $300k

Milestone 1: Completion of thermodynamic analysis
Milestone 2: Development of prototype incorporating washer, dryer and energy storage

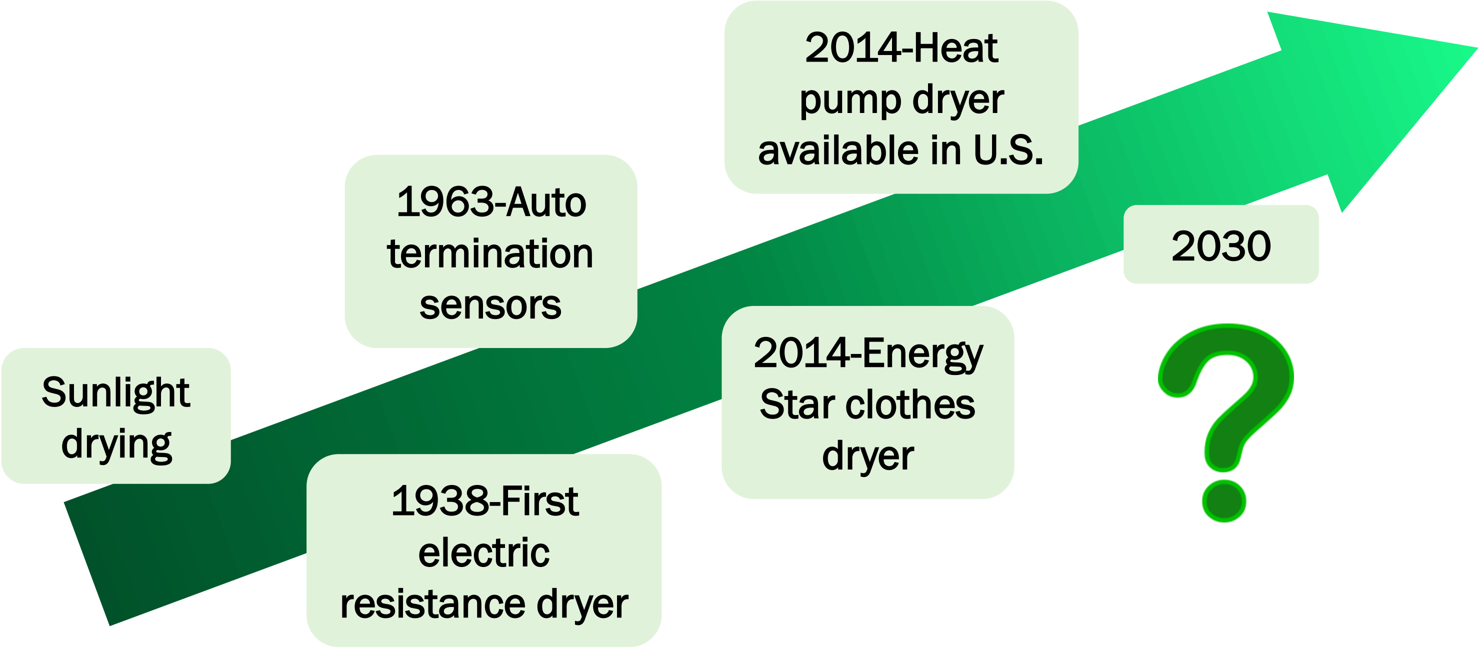
Milestone 3: Demonstration of CEF>25%

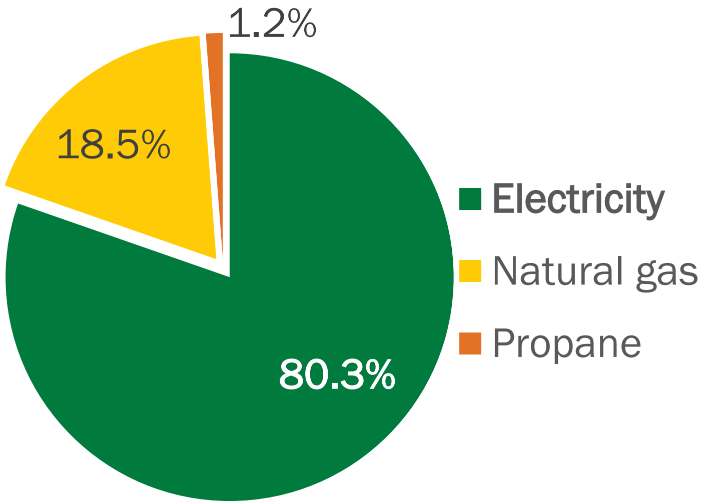
Problem

- Drying is <u>energy intensive process</u>, consuming on average 290,200 Btu (85 kWh) of heat for each 1,000 lb of wet laundry
- Laundry consumes 0.42 Quads of primary energy annually in commercial sector and 5% of electricity in residential sector
- Near 80% of the total U.S. households have a clothes dryer at home. Heat pump dryers take less than 1% of the market



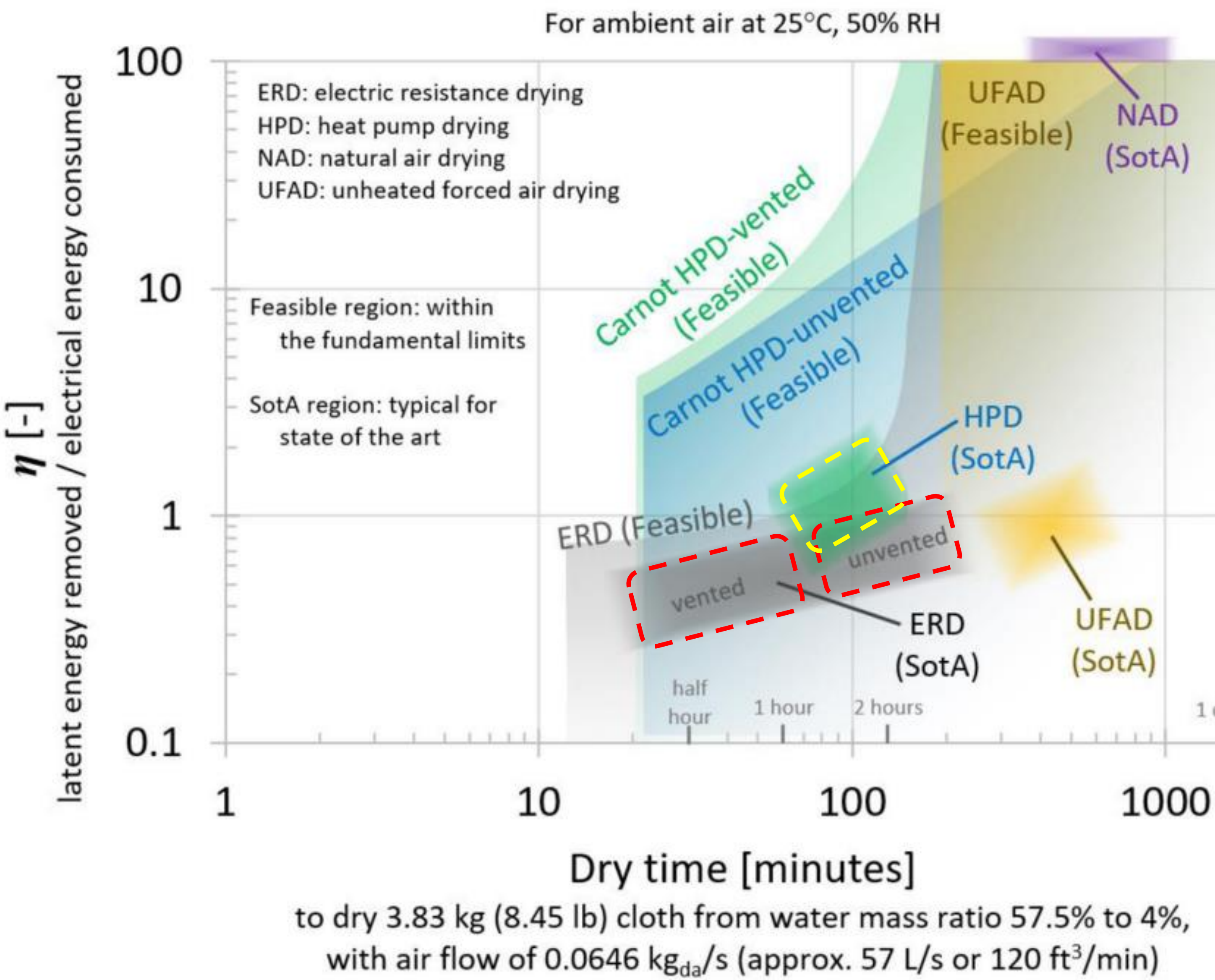
Energy consumption of standard household appliances (source: U.S. EPA)





Percentage of Total CD Household Owners

Problem



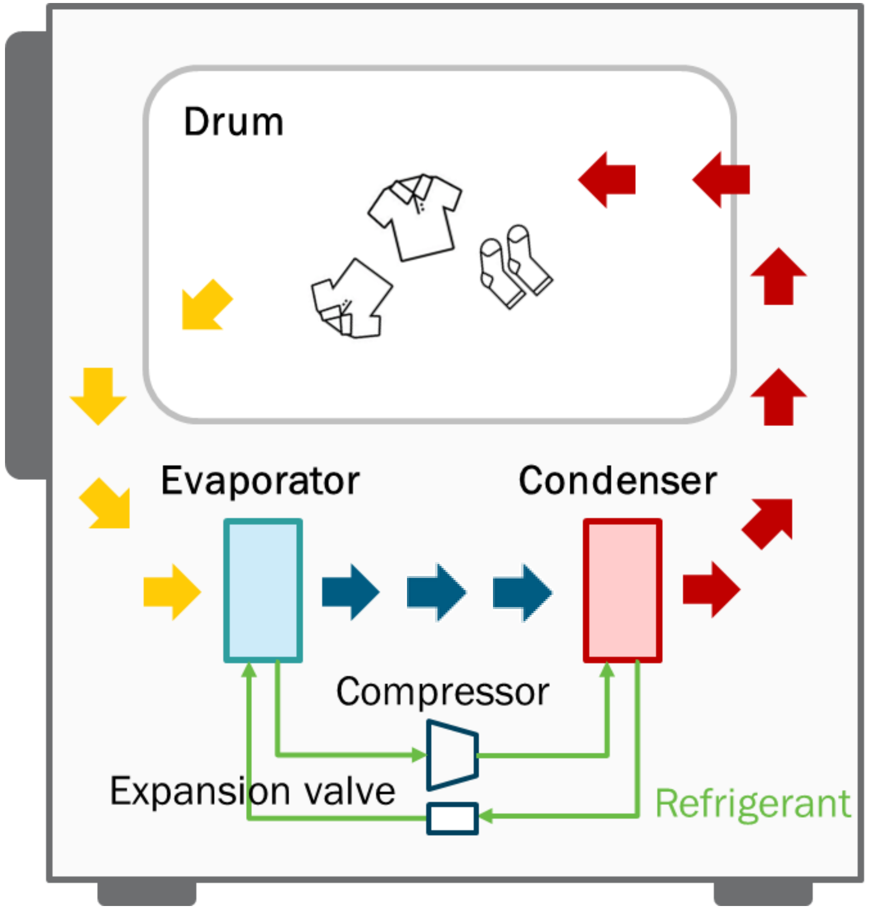
- An energy-efficient cost-effective process will transform the market
- Ventless design alleviates the impact of laundry on indoor thermal comfort and HAVC load.
- Extended drying time for heat pump dryers have been a major technological challenge

Source: Kyle R. Gluesenkamp, Viral K. Patel & Ayyoub M. Momen (2020) Efficiency limits of evaporative fabric drying methods, Drying Technology, 39:1, 104-124

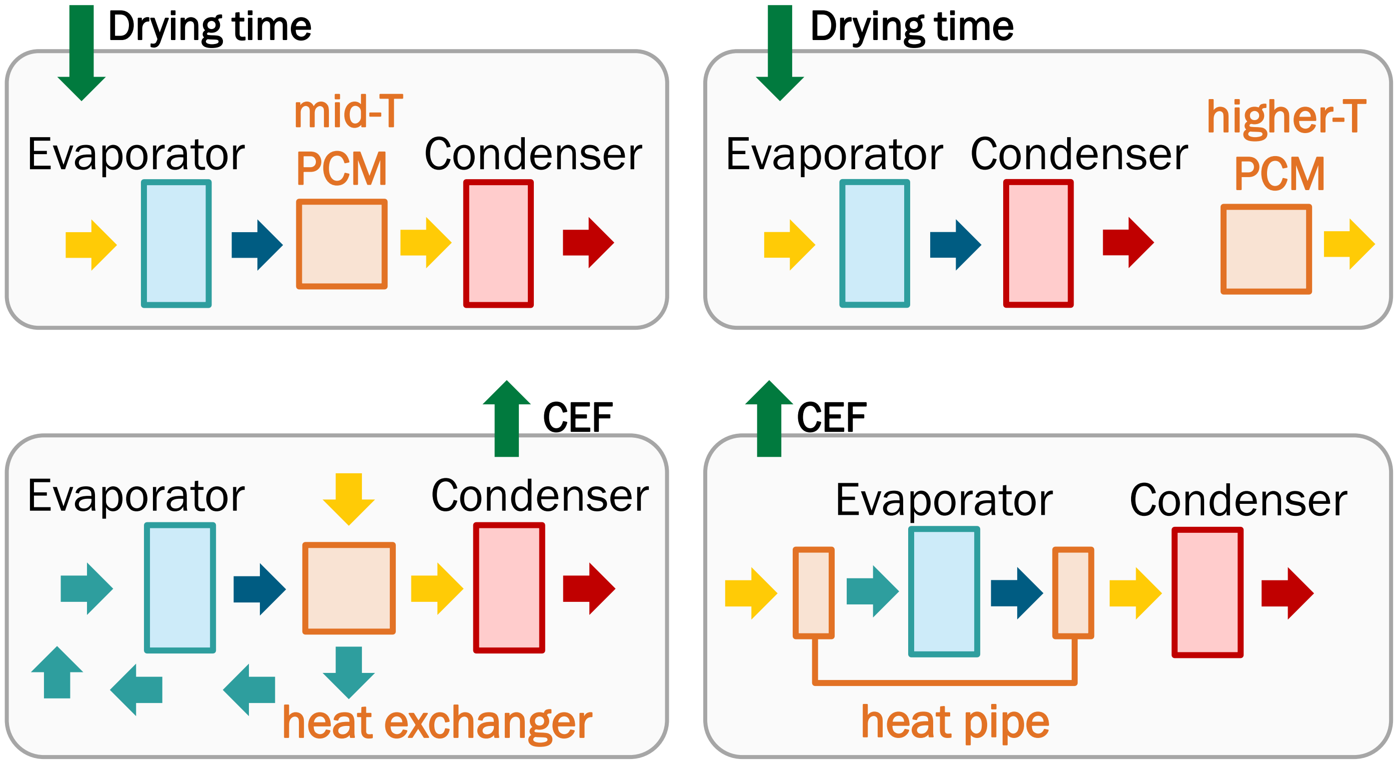
Approach

All-in-one unit

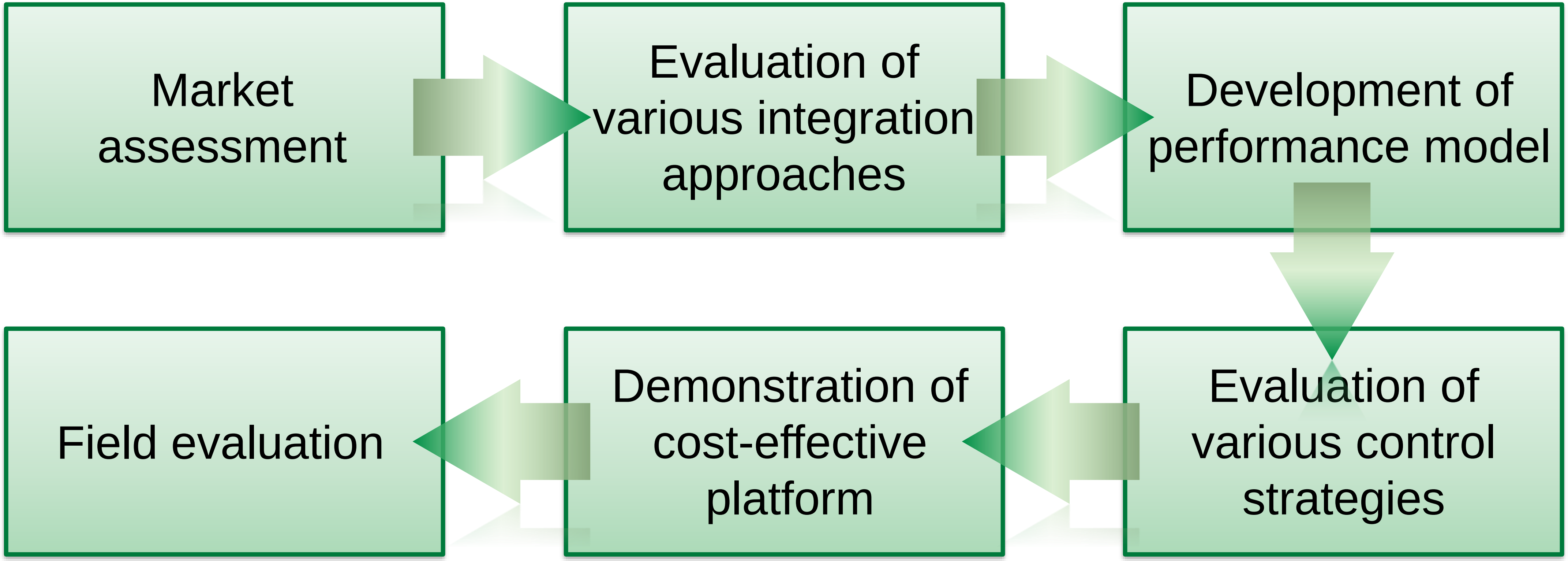
Combined Washer and Dryer (CWD)



Evaluation of various technology and system integration approaches for next-gen CWD



Approach


Market assessment
Evaluation of various integration approaches
Development of performance model
Evaluation of various control strategies
Demonstration of cost-effective platform
Field evaluation

Project Impact

- At least 0.2 Quad/year energy savings
- Aligned with BTO goal to develop energy-efficient technology to effect 45% energy savings by 2030 compared with 2010 technologies
- Lower costs to increase deployment at scale and make decarbonization available to lower income households
- 1.25-1.5 times higher combined energy factor (CEF) and reduced drying time
- Reduced footprint, simplified design, improved reliability and durability, and easy retrofits
- The project will demonstrate a first-of-its-kind combined washer and dryer with thermal energy storage integrate, through both numerical investigation and experimental prototype.

Performance Goals

Type	CEF	Dry time (minutes)	Cost (USD)
Electric resistance dryer	3.7-4.0	20-40	300-1200
Hybrid heat pump dryer	4.5-7	70-120	1400-2000
CWD	>6	<45	1000-1100

Risk

Potential risks	Mitigation strategy
Higher cost	• Low-cost TES material • Optimized design, sizing, and control

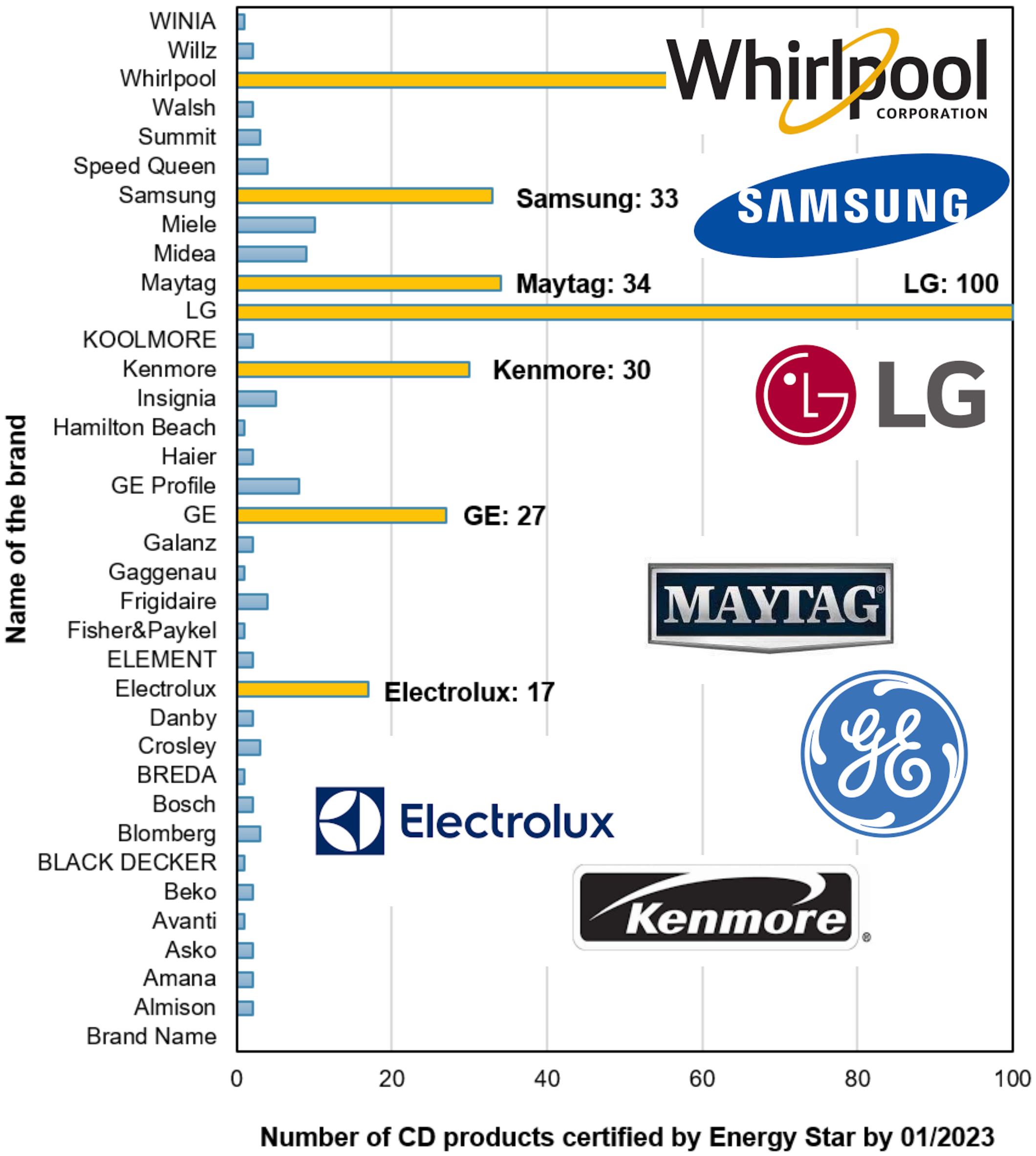
Longer operation time	• Heat recovery technologies for pre-cooling and pre-heating
	  • Heat pipe
	  • Heat exchanger

Increased system complexity	• Compact system design through valuation of various integration approaches

Market Assessment

- By January 2023, over 40 residential heat pump dryer models from 13 different manufacturers were labeled as Energy Star in the U.S. market.

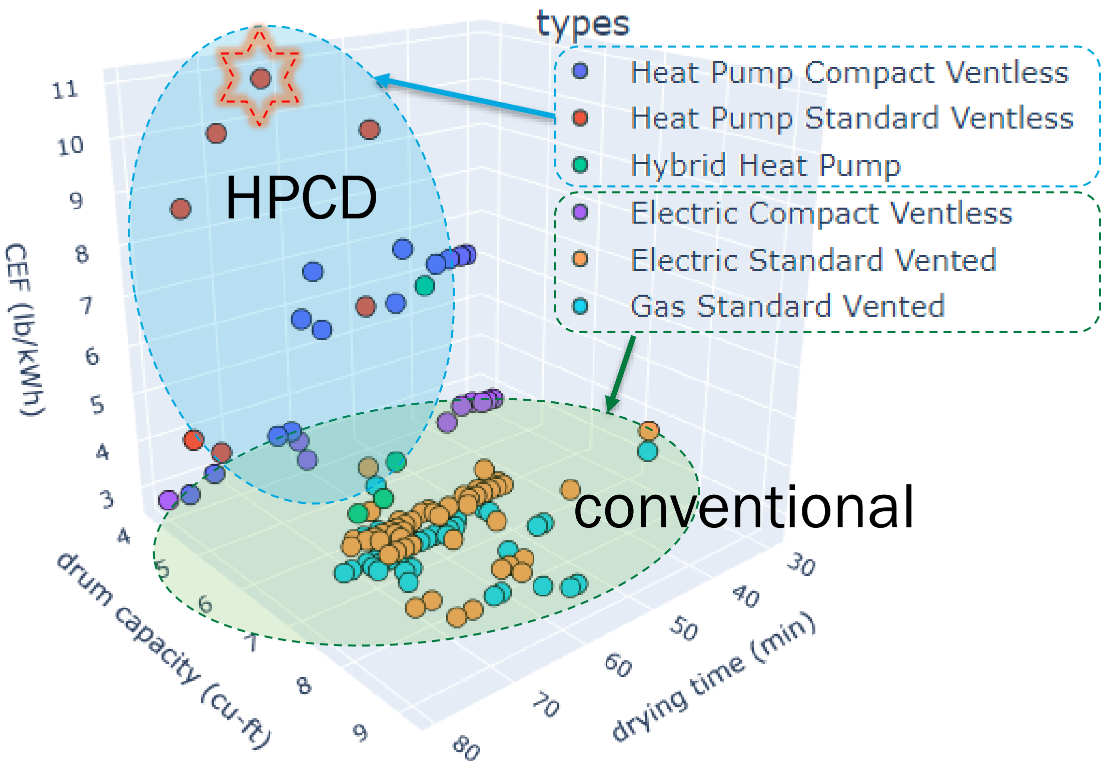
- In 2013 and 2014, EPA elected advanced Clothes Dryers as the ENERGY STAR Emerging Technology award winner.
- In 2015, Northwest Energy Efficiency Alliance (NEEA) Launches super-efficiency dryer initiative (SEDI).
- In 2023, the High-Efficiency Electric Homes and Rebates Act (HEEHRA) was created. Qualifying households can use up to $840 in HEEHRA rebates for the heat pump dryers.



State-of-the-art Technology

CFR 430 Subpart B Appendix D/D1/D2 defines the combined energy factor (CEF) in pounds per kilowatt-hour as a rating metric.

$$CEF = \frac{m_{dry}}{E_{CC}}$$



Type \ Mean value	Drum capacity (ft^3)	CEF	Annual energy use (kWh)	Cycle time (min)	DOE min CEF	ENERGY STAR min CEF
HPCD-compact (ventless)	**4.1**	5.46	169	51	2.55	2.68
HPCD-standard (Excluding hybrid)	**4.78**	7.75	372	72		
HPCD-hybrid (ventless)	**7.44**	5.27	475	72	3.73	**3.93**
ERCD-standard (vented)	7.58	3.94	607	65		
ERCD-compact (ventless)	4.00	2.74	311	52	2.55	2.68
GCD-standard (vented)	7.55	3.49	686	66	3.30	3.48
Combined washer and dryer	4.50	3.93	139	-	2.08	-

Data is obtained on Energy Star Database

Model Development

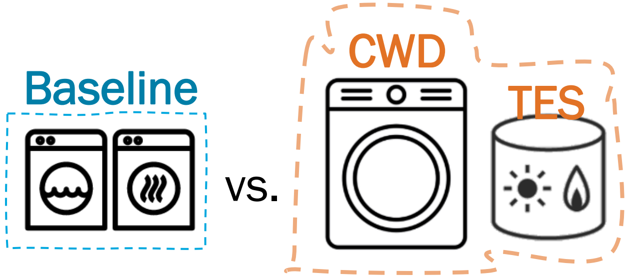
Inputs

Operating conditions
- Ambient condition
- Initial clothes temperature and moisture content
- Air flow rate
- Mass of clothes

Design parameters
- Heat pump design
- Drum capacity
- TES design

Numerical models

Heat & mass transfer models
- 1D & transient (+dynamic)



Outputs

Performance
- Air status
- Drying curve (RMC)
- Power input vs. time

Derived metrics
- CEF
- COP
- SMER

To guide the sizing and design optimization

Highlights:
- First prototype, first numerical and experimental study on CWD with TES.

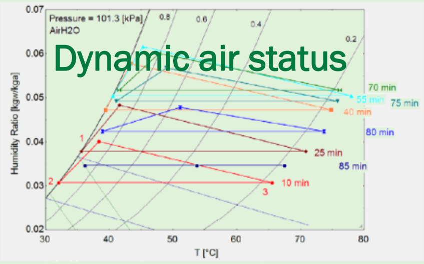
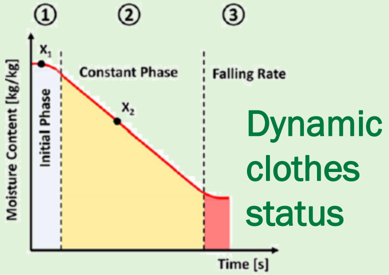
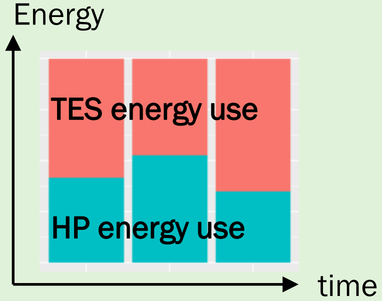


Figure 63: Progress of psychrometric process



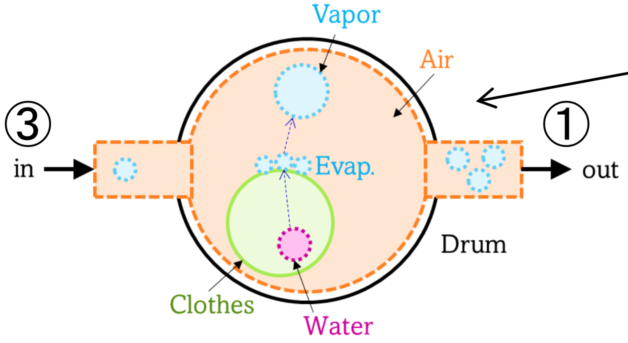


Model Development

$$\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da,3} = \dot{m}_{da}$$

$$\frac{\partial m_{da}\bar{h}_{da}}{\partial t} + \frac{\partial m_{da} x_a \bar{h}_v}{\partial t} + \frac{\partial m_{clo}\bar{h}_{clo}}{\partial t} + \frac{\partial m_w \bar{h}_w}{\partial t} = \dot{m}_a h_{a3} - \dot{m}_a h_{a1}$$

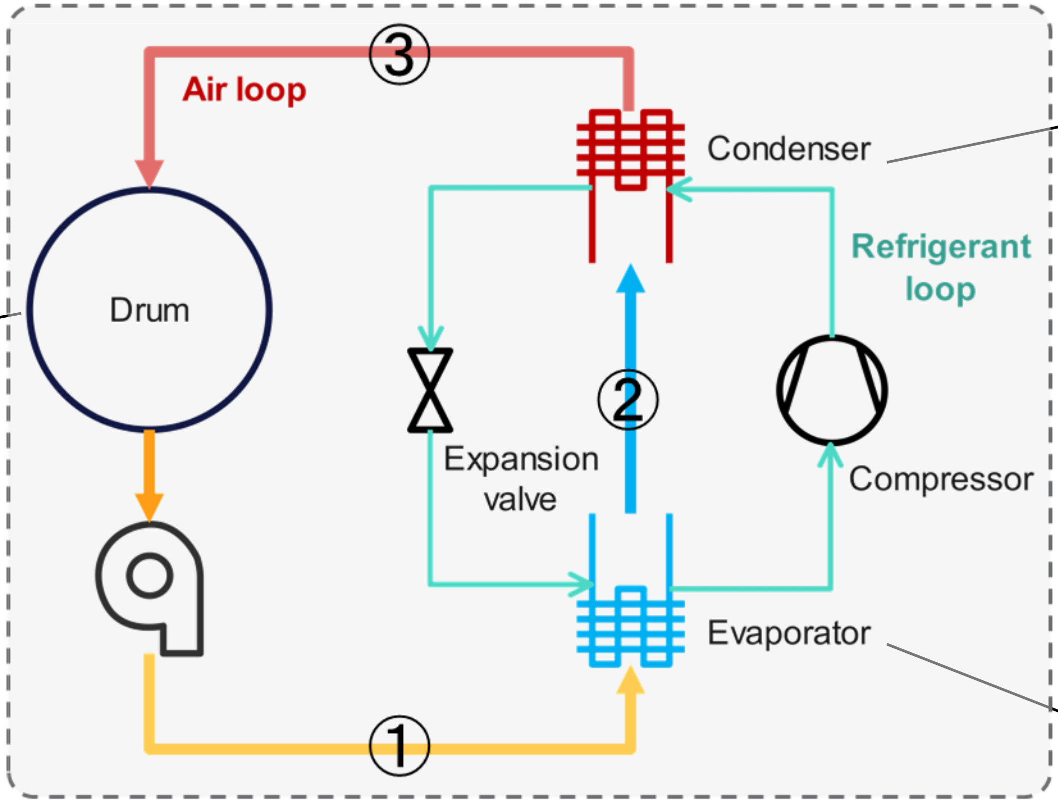
$$\dot{m}_{v,out} - \dot{m}_{v,in} = -\frac{\partial m_{w,clo}}{\partial t}$$



$$-\dot{m}_{w,clo} = h_m A\left(a x_{surf} - \frac{x_{a3} + x_{a1}}{2}\right)$$

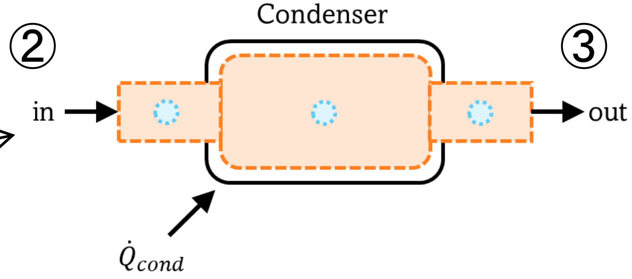
$$\frac{\partial m_{clo}\bar{h}_{clo}}{\partial t} = hA(T_a - T_{clo}) + \dot{m}_{w,clo}\bar{h}_v$$

Thermodynamic analysis for the closed air loop



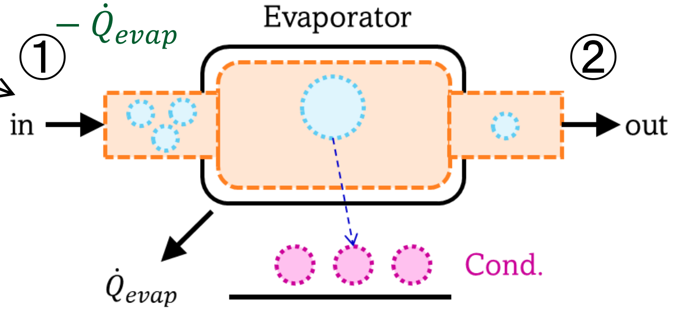
$$\dot{m}_{v,2} = \dot{m}_{v,3}$$

$$m_{da}\frac{\partial \bar{h}_a}{\partial t} = \dot{m}_{da}(h_{a2} - h_{a3}) + \dot{Q}_{cond}$$



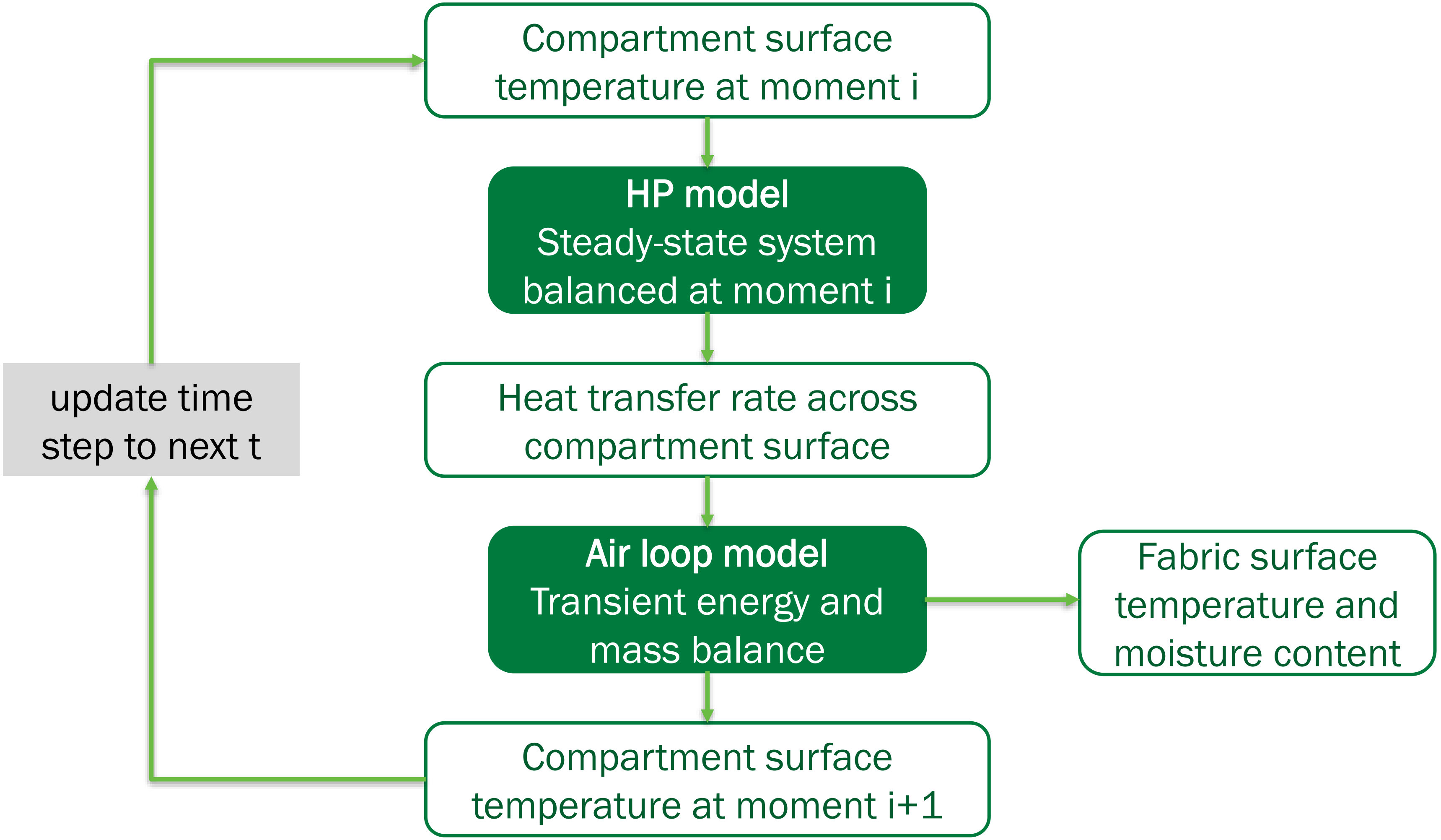
$$\dot{m}_{v,1} = \dot{m}_{v,2} + \frac{\partial m_{w,cond}}{\partial t}$$

$$m_{da}\frac{\partial \bar{h}_a}{\partial t} + \frac{\partial m_{w,cond}\bar{h}_w}{\partial t} = \dot{m}_{da}(h_{a1} - h_{a2}) + \dot{m}_{da}(x_1 - x_2)h_w - \dot{Q}_{evap}$$

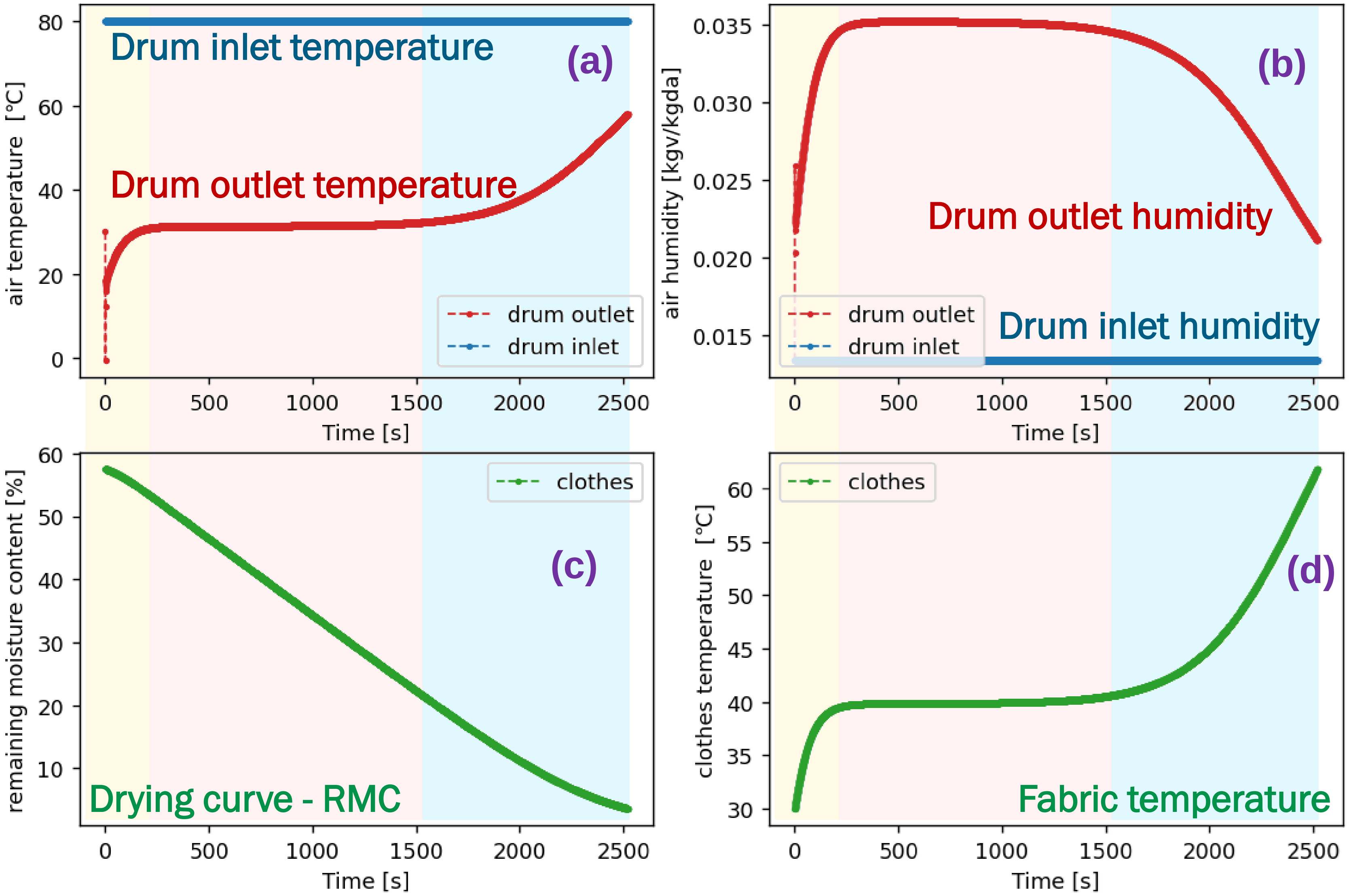


Model Development

Heat pump model and a quasi-steady-state system model



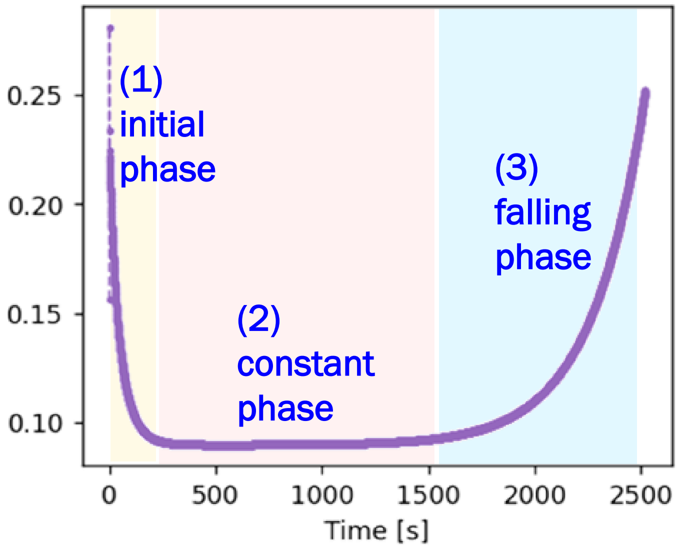
Preliminary Modeling Result



Drying involves the internal migration of moisture to the surface and the evaporation and removal of water from the surface.

Phase 1 and phase 3 are the most energy intensive processes.

(e) SMER kWh/kg v.



Facility Design, Development, and Future Plan

Phase i:
- Market assessment

Phase ii:
- Model-based TES and prototype design
  - Sensible TES
  - Latent TES
  - Combined

Phase iii:
- Baseline test
- Prototype development

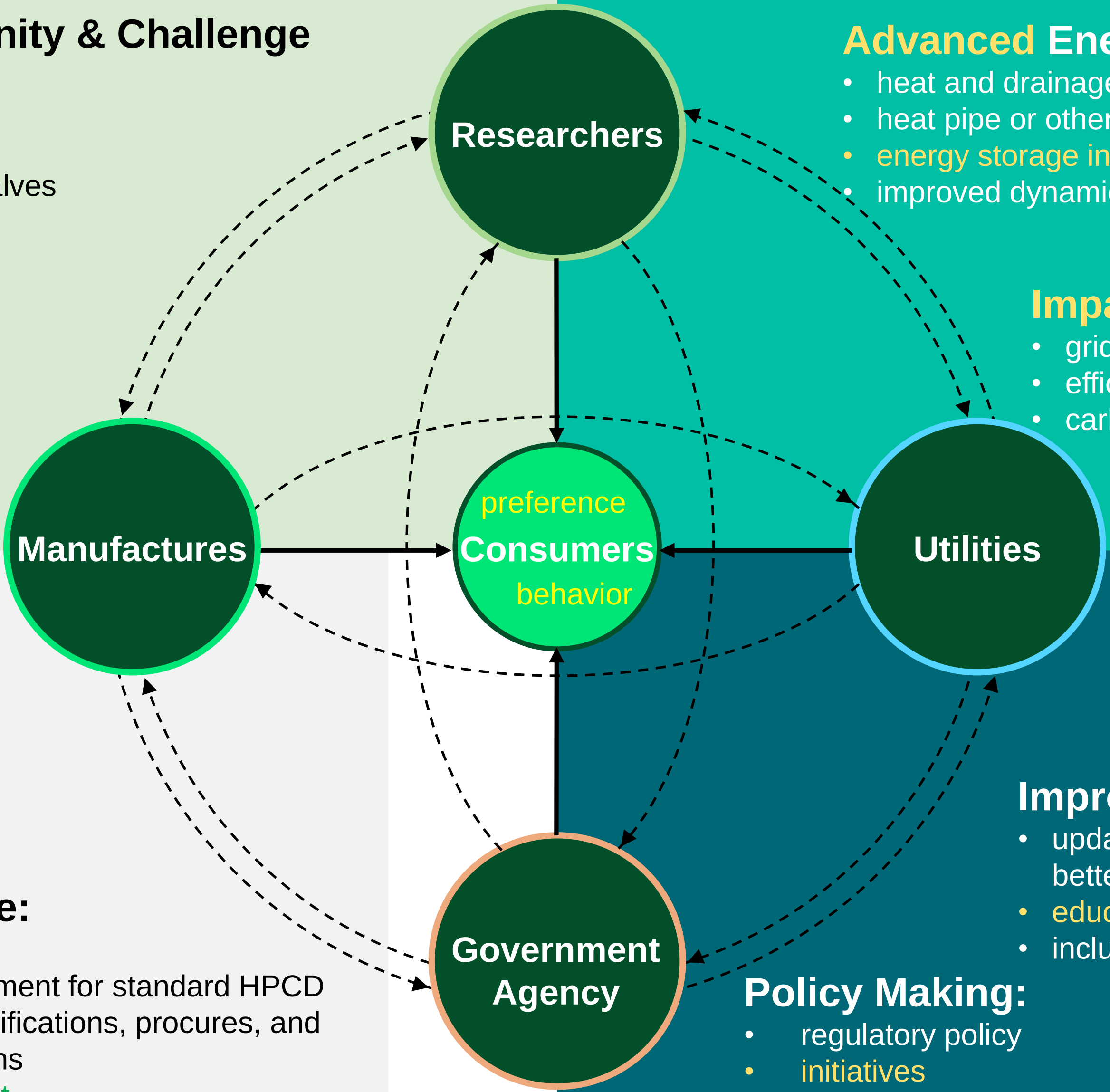
Phase iv:
- Prototype evaluation

Challenges and Opportunities

Energy-saving Opportunity & Challenge
- variable capacity compressors
- multistage compression
- vapor injection technique
- electronic/thermal expansion valves
- alternative working fluids
- suction line heat exchanger
- heat exchanger optimization
- control strategy & optimization
- lint control
- drum design

Technology Advancement :
- bring new technology into market
- improve the availability and reliability of HPCD
- market-development activities
- test and certify more models using automatic termination
- ensure dryers provide efficiency settings

Standard & Rating Procedure:
- publish test data
- publish CEF and drying time requirement for standard HPCD
- regular update ENERGY STAR specifications, procures, and metrics to reflect real-world operations
- set achievable and competitive target



Advanced Energy Efficiency
- heat and drainage recovery
- heat pipe or other heating and drying technologies integration
- energy storage integration
- improved dynamic models for performance prediction and control

Impact
- grid-interactive buildings
- efficient electrification
- carbon reduction

Reward:
- conduct field studies to study real-world saving potentials.
- provide rebates for most-efficient dryers
- establish even higher rebates for HPCD that can dry more quickly

Improving Awareness:
- update state technical reference manual (TRM) to better reflect HPCD benefits and savings
- educate employees on the HPCD benefits
- include dryers in energy efficiency programs

Policy Making:
- regulatory policy
- initiatives
- incentives & rebates

Thank you

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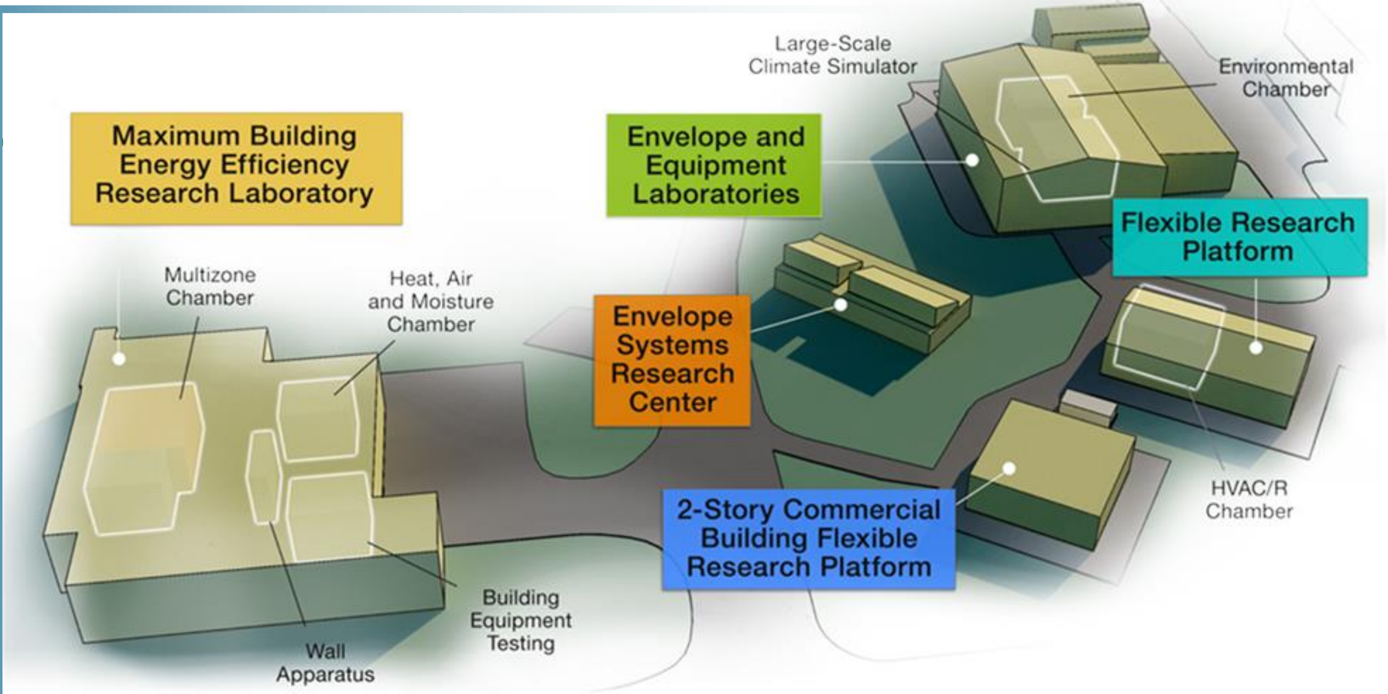

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

Task No.	Task Name
1	Market assessment and state-of-the-art technology
2	System performance modeling and design optimization
3	Evaluation of thermal energy storage (TES) systems
4	System analysis using simulation tools
5	Development of appropriate control strategies
6	Design and fabrication of alpha prototype
7	Performance analysis of alpha prototype
8	System integration and development of packaged beta prototype
9	Performance analysis of beta prototype
10	Performance evaluation- beta prototype
11	Final report and development of deployment strategy