Decentralized Coordination of Inverter Air-Conditioners for Virtual Energy Storage

State-of-the-Art Seminar

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Contents

Background and Focus of the Research

Renewable Energy Generation

- Share of renewable and nuclear energy globally expected to reach 50% by 2030[1]
- India achieved its 50% non-fossil fuel installed power capacity target in November 2025[2]

Solar and wind are intermittent energy sources[3]
(Time-varying and Uncertain)

1) IEA (2026), Electricity 2026, IEA, Paris https://www.iea.org/reports/electricity-2026, Licence: CC BY 4.0
2) 2025 marks Highest-Ever renewable Energy expansion in India's energy transition journey. https://www.pib.gov.in/PressReleasePage.aspx?PRID=2209478®=3&lang=1
3) G. Notton *et al.*, "Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting," *Renewable and Sustainable Energy Reviews*, vol. 87, pp. 96–105, Feb. 2018.

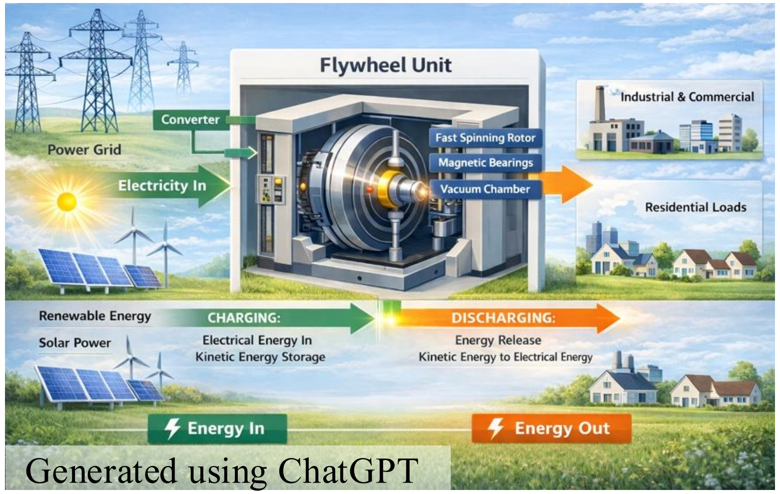
Solutions to Intermittency of Renewables

Batteries


Edwards & Sanborn Solar + Energy Storage
Source: www.mortenson.com

- Fast response
- High capital cost

Flywheel Energy Storage



Generated using ChatGPT

- Very fast response
- High capital cost

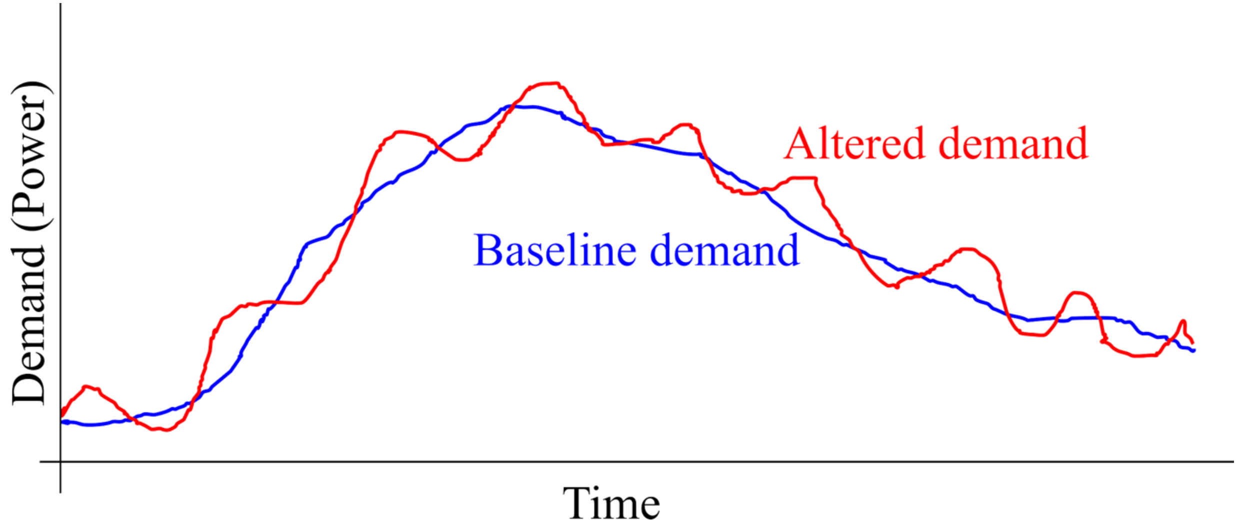
Pumped Hydro Storage


Source: www.drax.com

- Large energy capacity
- High capital cost

An Alternative Solution to Intermittency

Virtual Energy Storage (VES)

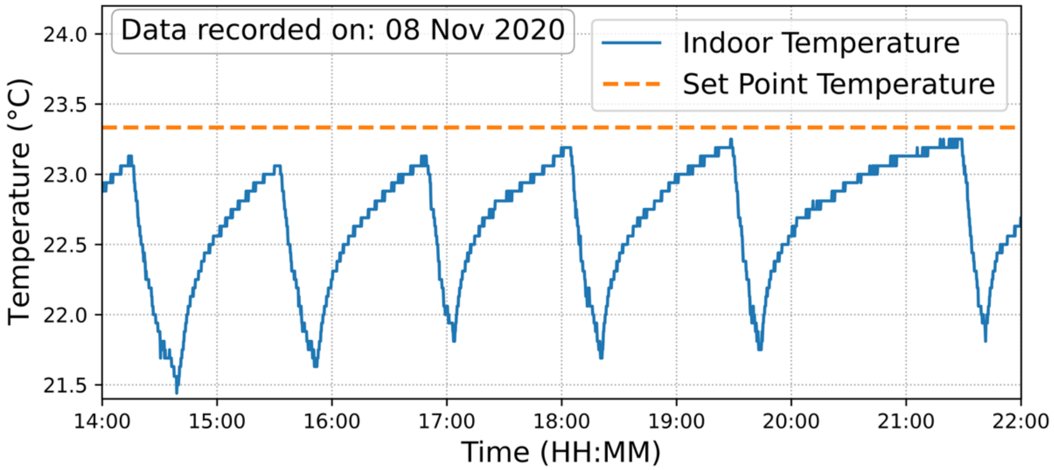


- Uses existing flexibility of demand
- Air-conditioners, room heaters, refrigerators, etc., are flexible loads
- Low cost

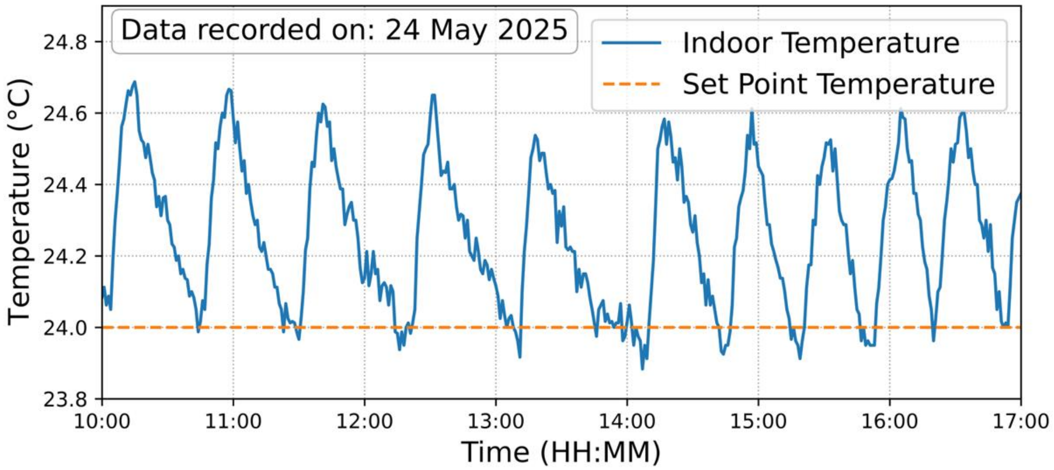
Requirements

- *For Power Grid:* Ensure total demand equals total generation
- *For Consumers:* Maintain Quality of Service (QoS)

Demand Flexibility of an Air Conditioner



ON/OFF AC (Data from a single-family home in Gainesville, FL, USA)



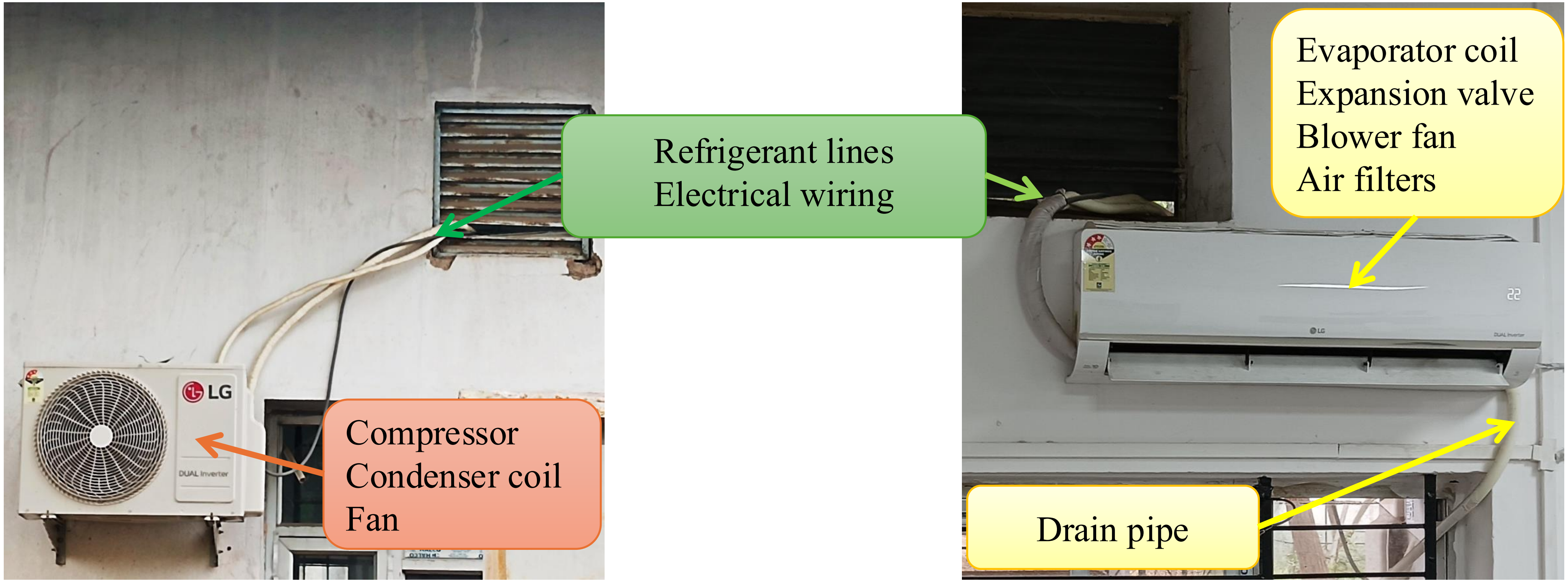
Inverter AC (Data from an office room at IIT Guwahati)

- As long as the temperature remains in the band, consumers won't feel any discomfort.
- The power consumption can be changed without making temperature go out of the bands.

1) Fanger, P. O. (1973). Assessment of man’s thermal comfort in practice. Occupational and Environmental Medicine, 30(4), 313–324.
2) Fanger, P. (1988). FUNDAMENTALS OF THERMAL COMFORT. In Elsevier eBooks (pp. 3056–3061).

Split Air Conditioner

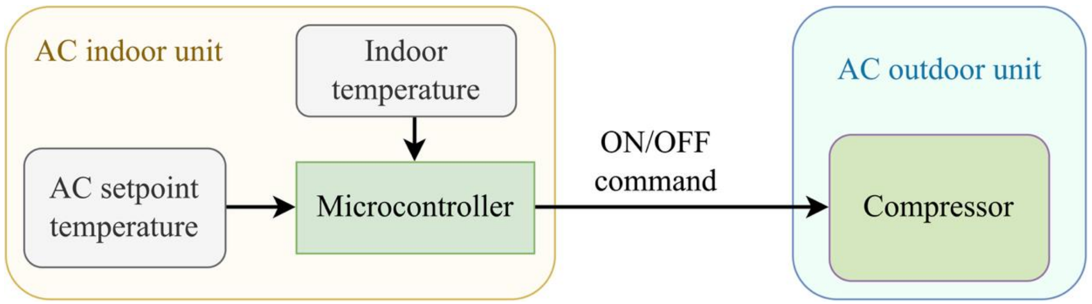
Outdoor Unit **Indoor Unit**



ON/OFF vs Inverter Air-Conditioners

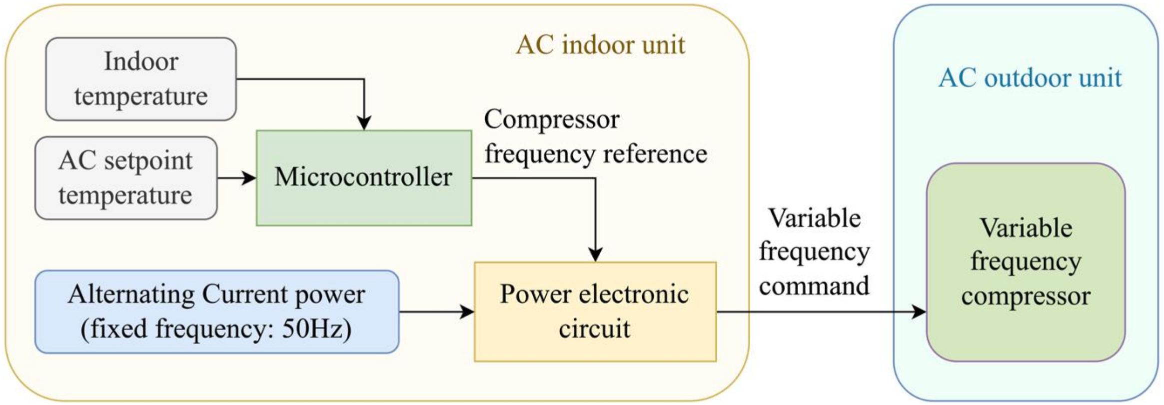
ON/OFF AC

- Fixed compressor speed
- ON state: Rated power
  OFF state: 0



Inverter AC

- Variable speed compressor
- Power varies continuously between 0 and the rated power



Load Coordination: Need and Method

Single Air Conditioner

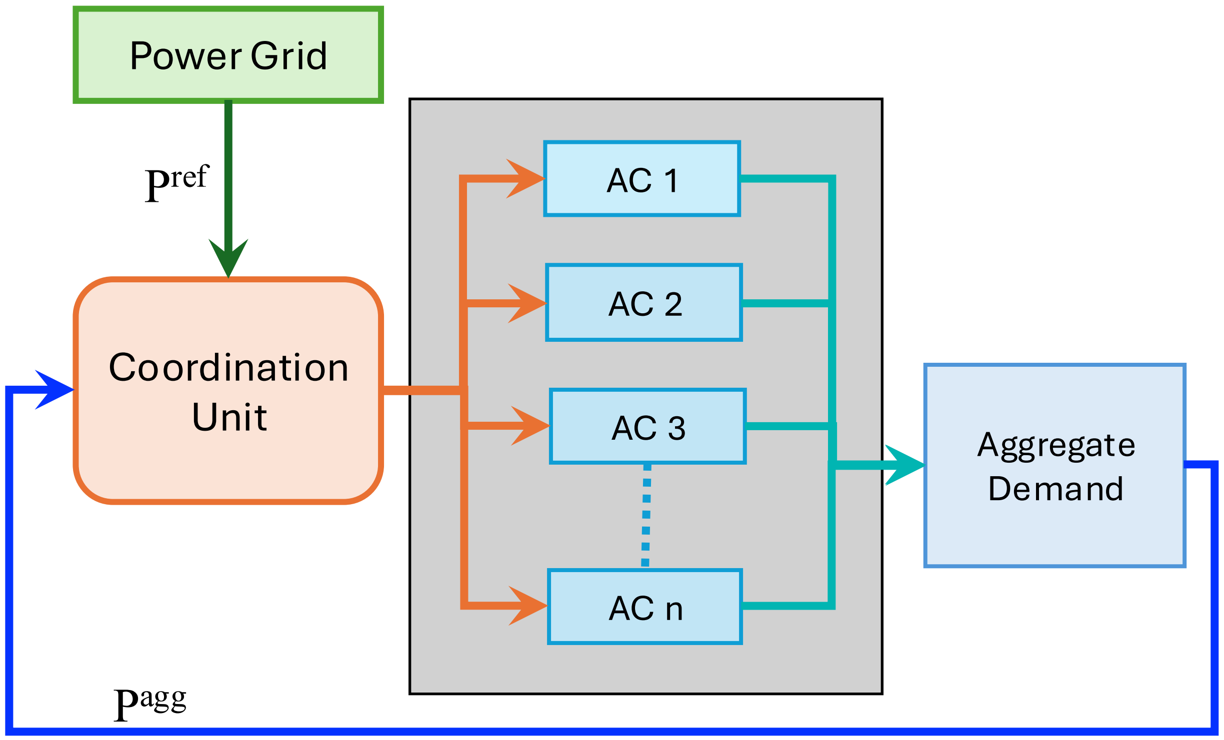
Small Power Consumption

Many Air Conditioners

Large Aggregated Power Consumption

Need Coordinated Control

- Centralized
- Non-centralized
  - Distributed
  - Decentralized



Decentralized Coordination Architecture

Focus of My Research

Virtual Energy Storage (VES)

Inverter Air Conditioners

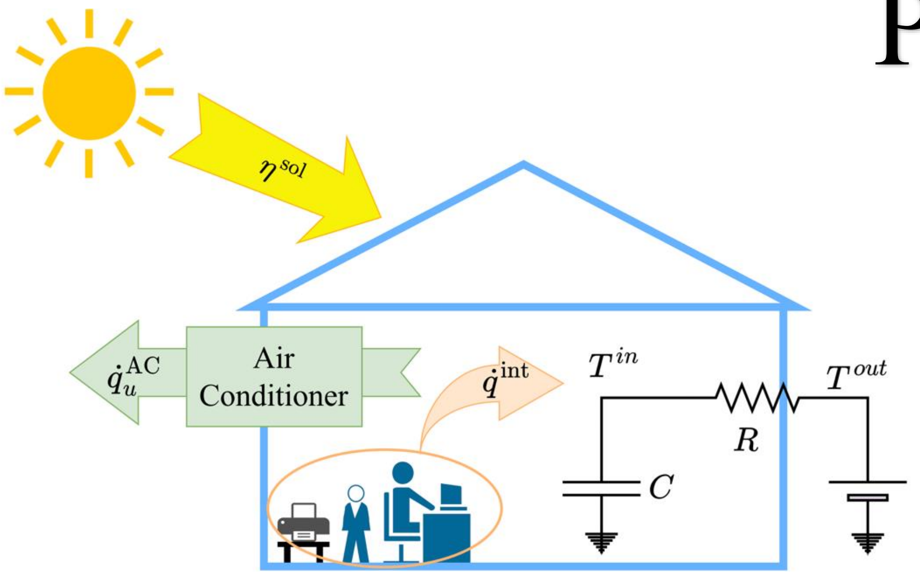
Decentralized Coordination

Model Free

Most of the previous papers focus on ON/OFF ACs, and their coordination algorithm is model-based

Background: Room Thermal Model

$P^{AC} \rightarrow T^{in}$



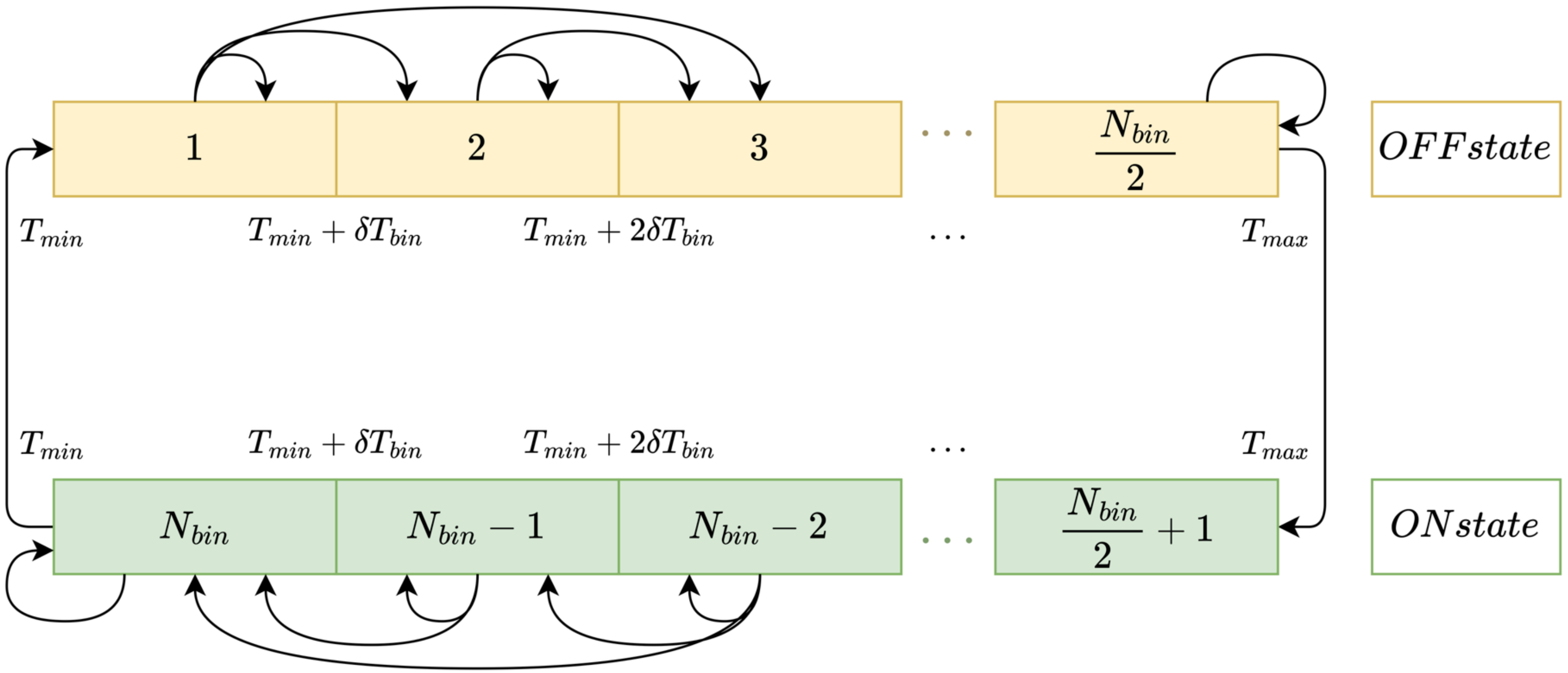
A very widely used model for building thermal dynamics since the 1960s

$$C\dot{T}^{\text{in}} = \frac{T^{\text{out}}(t) - T^{\text{in}}(t)}{R} + A^{\text{eff}}\eta^{\text{sol}}(t) - COP \times P_u^{\text{AC}}(t) + \dot{q}^{\text{int}}(t)$$

1) G. Burnand, "The study of the thermal behaviour of structures by electrical analogy," British Journal of Applied Physics, vol. 3, no. 2, pp. 50–53, Feb. 1952.
2) J. D. Balcomb, J. C. Hedstrom, and R. D. McFarland, "Simulation analysis of passive solar heated buildings—Preliminary results," *Solar Energy*, vol. 19, no. 3, pp. 277–282, Jan. 1977.
3) S. Hassid, "A linear model for passive solar calculations: Evaluation of performance," Building and Environment, vol. 20, no. 1, pp. 53–59, Jan. 1985.
. . . .

Background: Markov Chain Formulation for a Collection of ACs

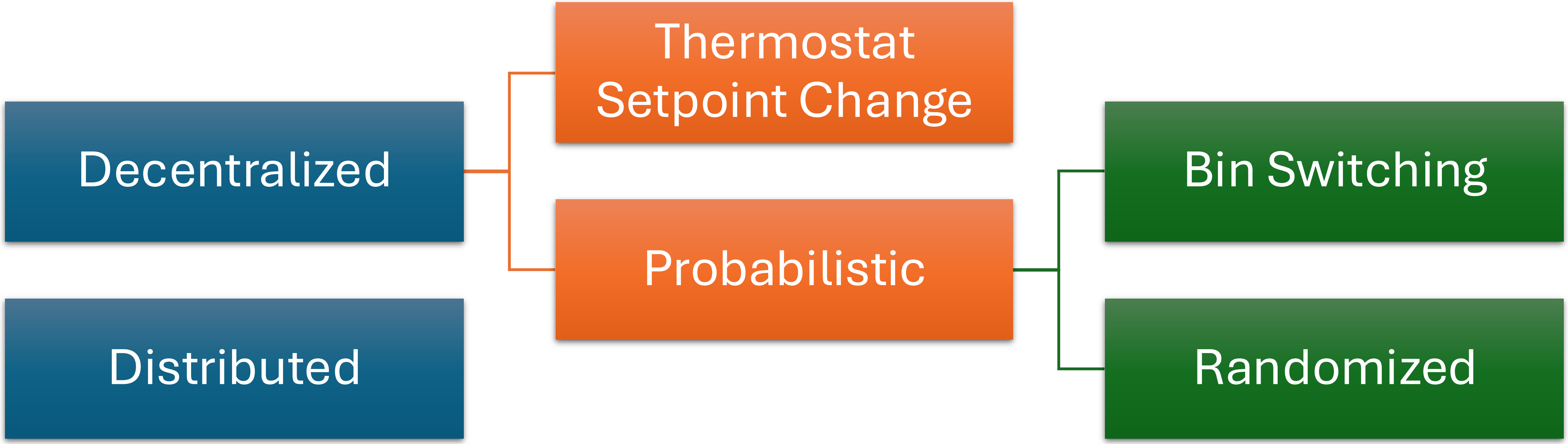
Transition probabilities with thermostat control



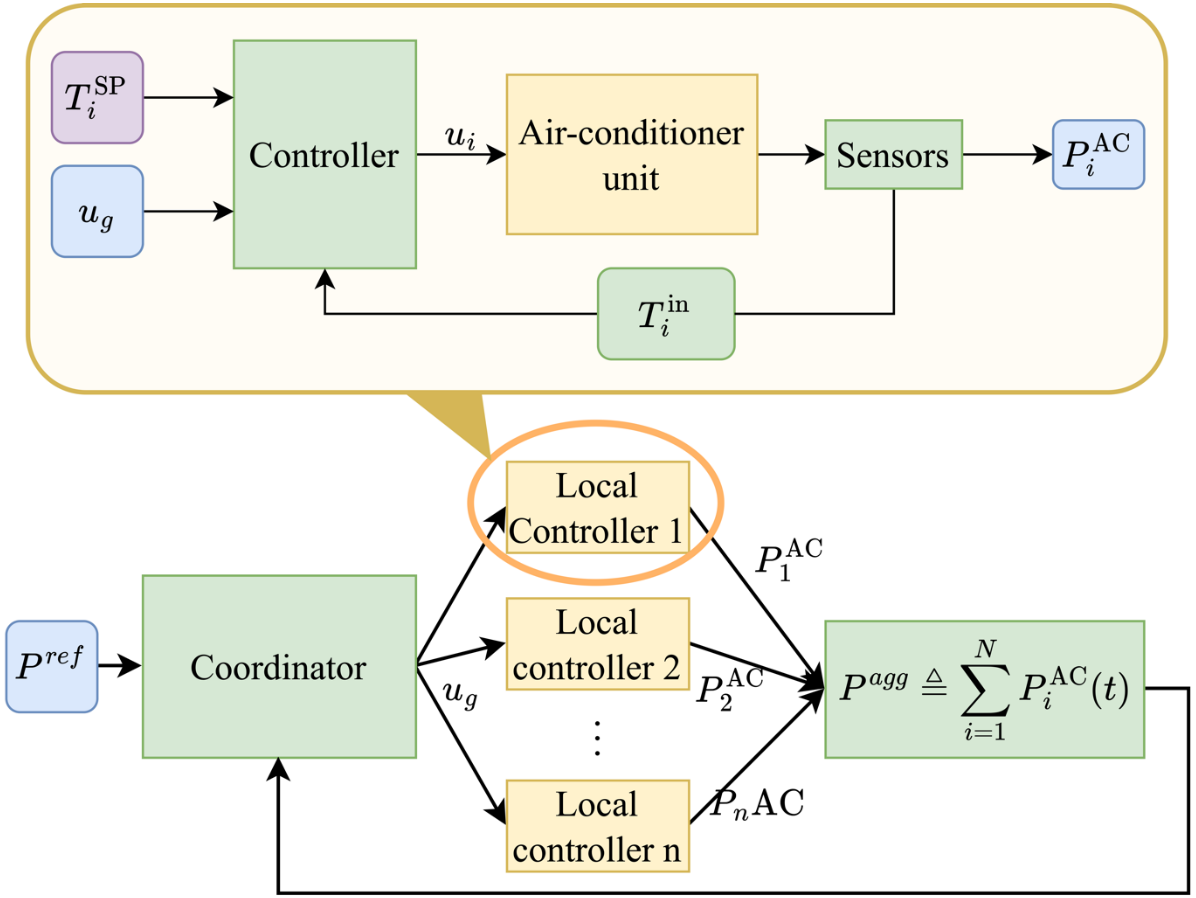
- Divide the temperature range into bins
- X_i = fraction of ACs in the i^{th} bin ≈ an AC in the i^{th} bin
- The evolution of the temperature of all ACs can be modeled as a probabilistic transition among bins of the Markov chain

Literature Review

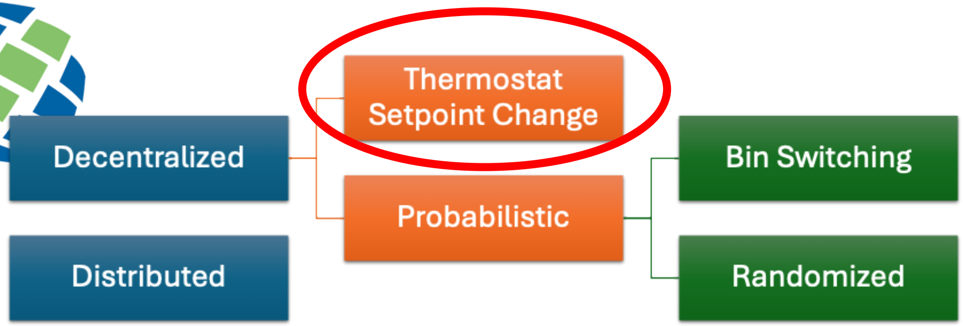
Coordination of ON/OFF ACs for VES



Decentralized Coordination Architecture (ON/OFF ACs)



- *Coordinator*: Compute broadcast signal (u_g) for all loads to ensure aggregated demand (P^{agg}) tracks reference signal (P^{ref}).
- *Local controller:* uses the broadcast signal and local information to compute ON/OFF control for the AC.

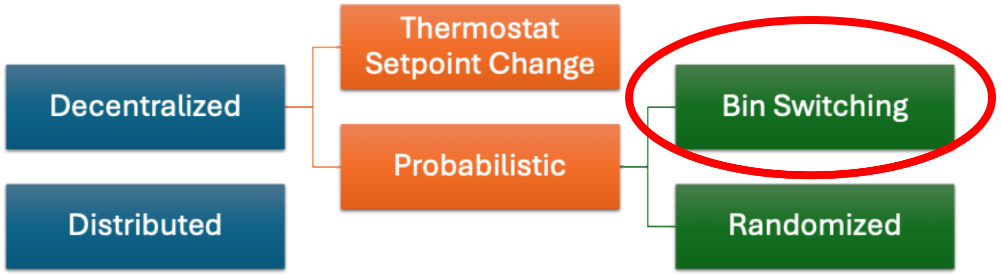


Thermostat Setpoint Change

- The coordinator sends the temperature set-point or change in set-point to all AC units
- Local AC controllers update the set-point in AC
- The coordinator calculates the set-point based on the current & the desired demand

- ACs accept discrete set-points only, so small or precise adjustments may not be possible
- Large set-point deviations from the user's preference may reduce occupant comfort
- No performance guarantee

1) D. Callaway and I. Hiskens, "Achieving controllability of electric loads," Proceedings of the IEEE, vol. 99, no. 1, pp. 184–199, 2011.
2) S. Bashash and H. K. Fathy, "Modeling and control of aggregate air conditioning loads for robust renewable power management," IEEE Transactions on Control Systems Technology, vol. 21, no. 4, pp. 1318–1327, 2013.
3) N. Mahdavi, J. H. Braslavsky, M. M. Seron, and S. R. West, "Model predictive control of distributed air-conditioning loads to compensate fluctuations in solar power," IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 3055–3065, 2017.
4) Z. E. Lee and K. M. Zhang, "Scalable identification and control of residential heat pumps: A minimal hardware approach," Applied Energy, vol. 286, p. 116544, 2021.
5) …



Bin Switching

- The Markov chain model is used
- The temperature is divided into bins

$$P^{agg} \triangleq \sum_{i=1}^{N} P_i^{\mathrm{AC}}(t)$$

- The coordinator computes the broadcast signal based on $(P^{ref} - P^{agg})$
- Broadcast signal contains switching probabilities for the i^{th} bin for $i = 1, 2, \ldots, N_{bin}$

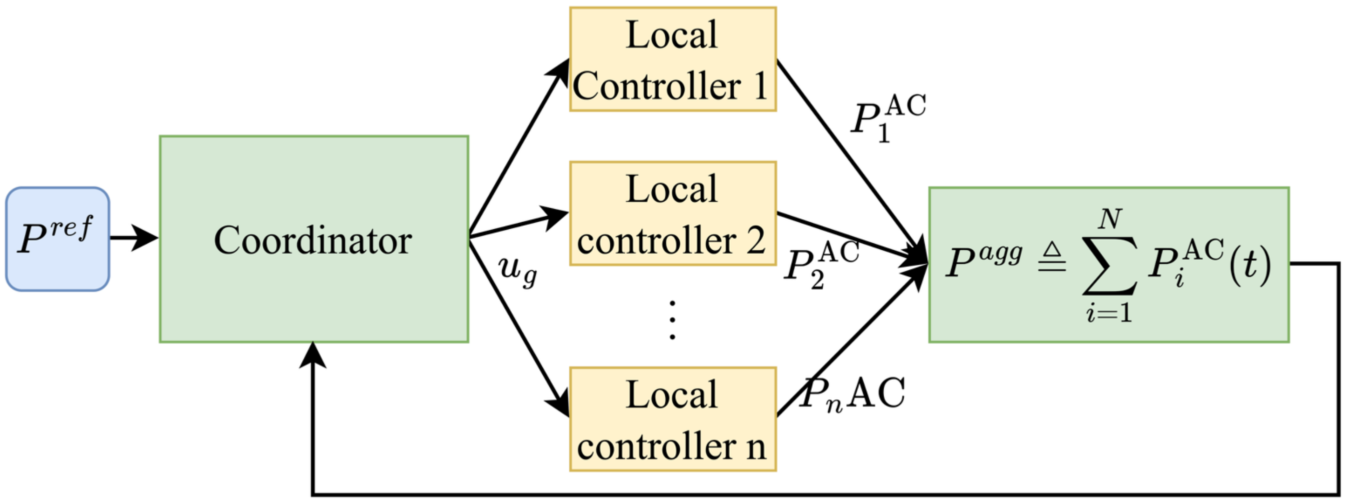
1) A. Coffman, A. Buˇsi´c, and P. Barooah, "Virtual energy storage from TCLs using QoS preserving local randomized control," in 5th ACM International Conference on Systems for Built Environments (BuildSys), November 2018, p. 10.
2) J. L. Mathieu, S. Koch, and D. S. Callaway, "State estimation and control of electric loads to manage real-time energy imbalance," IEEE Transactions on Power Systems, vol. 28, pp. 430–440, 2013.
3) M. Liu, Y. Shi, and X. Liu, "Distributed MPC of aggregated heterogeneous thermostatically controlled loads in smart grid," IEEE Transactions on Industrial Electronics, vol. 63, no. 2, pp. 1120–1129, 2016.
4) M. Liu and Y. Shi, "Model predictive control of aggregated heterogeneous second-order thermostatically controlled loads for ancillary services," IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 1963–1971, May 2016.
5) L. C. Totu, R. Wisniewski, and J. Leth, "Demand response of a TCL population using switching-rate actuation," IEEE Transactions on Control Systems Technology, vol. 25, no. 5, pp. 1537–1551, 2017.
6) …

Example: Mathieu *et al.*'s method

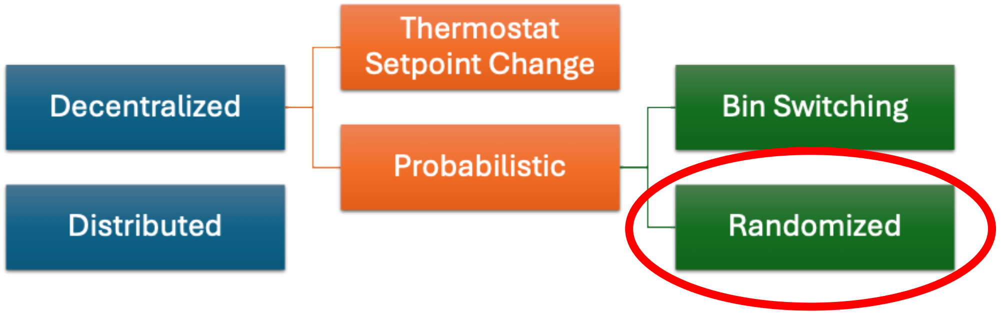
- u (scalar) = P × (P^{ref} – P^{agg}) (Proportional controller)
- Convert u to a vector of switching probability (u_g) using a heuristic and broadcast it.
- Local controller turns on or off based on $u_g(i)$ received, i is its own bin

u_g is a ($N_{bin}/2$) dimensional vector

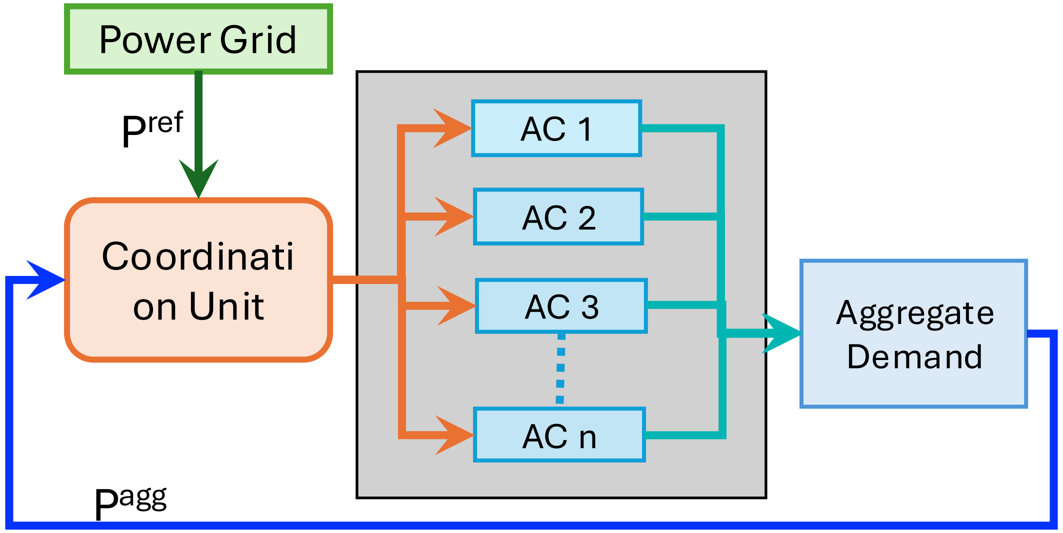
There is no performance guarantee



1) J. L. Mathieu, S. Koch, and D. S. Callaway, "State estimation and control of electric loads to manage real-time energy imbalance," IEEE Transactions on Power Systems, vol. 28, pp. 430–440, 2013.



Randomized



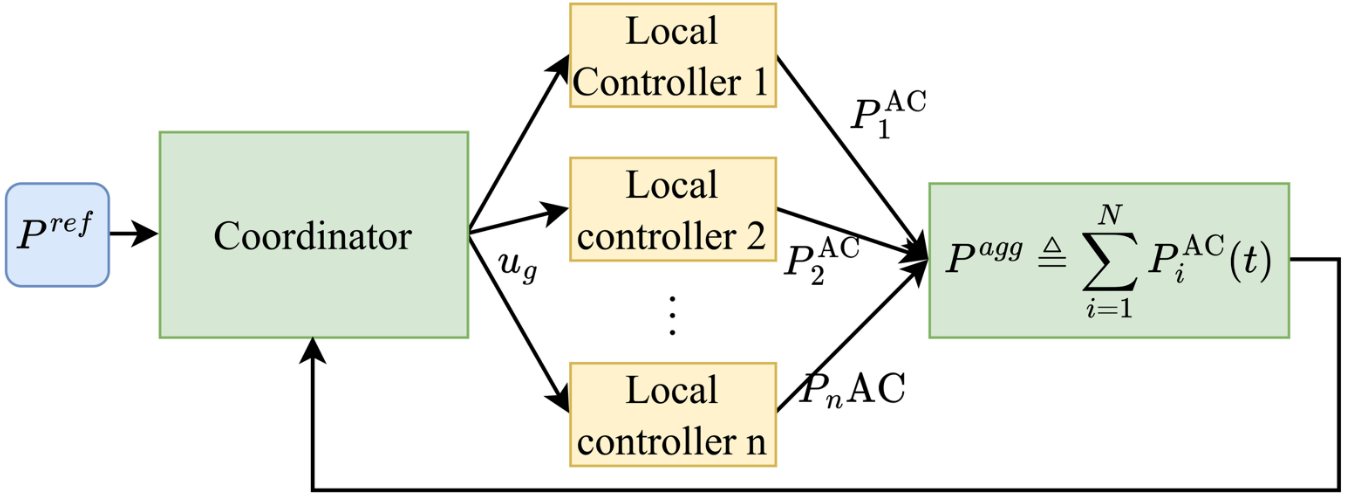
- The coordinator sends the conditional probability (u_g) of switching ON/OFF, given the current Markov state
- Each AC makes a local ON/OFF decision in accordance with the received u_g

1) A. R. Coffman, A. Bu˘si´c, and P. Barooah, "A unified framework for coordination of thermostatically controlled loads," Automatica, vol. 153, p. 111002, 2023.
2) A. Bu˘si´c and S. Meyn, "Distributed randomized control for demand dispatch," in IEEE conference on decision and control, 2016, pp. 6964–6971.
3) S. Meyn, P. Barooah, A. Bu˘si´c, Y. Chen, and J. Ehren, "Ancillary service to the grid from intelligent deferrable loads," IEEE Transactions on Automatic Control, vol. 60, pp. 2847 – 2862, March 2015.
4) Y. Chen, M. U. Hashmi, J. Mathias, A. Bu˘si´c, and S. Meyn, "Distributed control design for balancing the grid using flexible loads," in IMA Volume on the Control of Energy Markets and Grids, 2017, pp. 1–26.

Coffman *et al.*'s method

$$\min_{u_g} \sum_{k=1}^{T} \left(P_k^{\mathrm{ref}} - P_k^{\mathrm{agg}}\right)^2$$

s.t. Markov Model(QoS constraints)



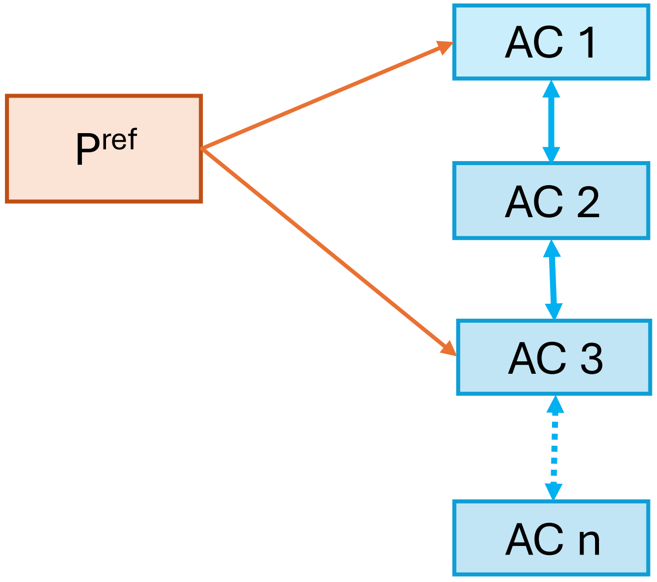
- Provides the best feasible aggregate demand without violating QoS
- u_g is a scaler signal
- Requires broadcast of about 17 numbers to each AC every 1 minute, independent of number of ACs

Assumes all AC's are approximately homogeneous

1) A. R. Coffman, A. Bu˘si´c, and P. Barooah, "A unified framework for coordination of thermostatically controlled loads," Automatica, vol. 153, p. 111002, 2023.

Distributed Coordination of ON/OFF ACs

- A coordinator does not directly communicate with all ACs
- Coordination is formulated as an optimization problem, solved using local and shared information between neighbors
- Solutions converge to an optimal point under certain assumptions



1) S. Kim and G. Giannakis, "Scalable and robust demand response with mixed-integer constraints," IEEE Transactions on Smart Grid, vol. 4, no. 4, pp. 2089–2099, December 2013.
2) E. M. Burger and S. J. Moura, "Generation following with thermostatically controlled loads via alternating direction method of multipliers sharing algorithm," Electric Power Systems Research, vol. 146, pp. 141–160, 2017.
3) M. Franceschelli, A. Pilloni, and A. Gasparri, "Multi-agent coordination of thermostatically controlled loads by smart power sockets for electric demand side management," IEEE Transactions on Control Systems Technology, vol. 29, no. 2, pp. 731–743, 2021.

Inverter AC

- Power varies continuously
- Control of individual AC is not simply ON/OFF
- More control over the power consumption of AC
- Coordination: more complex than ON/OFF ACs

- Control
  - Direct Compressor Frequency Control (DCFC)
  - High Level Variable Control (HLVC)
- Coordination
  - Centralized
  - Non-centralized

Direct Compressor Frequency Control (DCFC)

- Assume compressor speed is controllable
- Uses a thermal model to compute compressor speed

- Requires access to the AC's internal controller.
- All ACs do not behave the same way due to different makes, models, and building parameters.
- Practical implementation is challenging

1) L. Zhu, J. Hong, S. Yang, Z. Hu, Y. Shao, C. Wu, and G. He, "Online modeling of virtual energy storage for inverter air conditioning clusters in CDL-based demand response," Energy Reports, vol. 9, pp. 2024–2034, 2023.
2) C. Wang, B. Wang, M. Cui, and F. Wei, "Cooling seasonal performance of inverter air conditioner using model prediction control for demand response," Energy and Buildings, vol. 256, p. 111708, 2022.
3) Q. Li, Y. Zhao, Y. Yang, L. Zhang, and C. Ju, "Demand-response-oriented load aggregation scheduling optimization strategy for inverter air conditioner," Energies, vol. 16, no. 1, p. 337, 2022.

…

High Level Variable Control (HLVC)

- Changes temperature set-points, temperature band, duty cycles or ON/OFF states
- Compatible with existing commercial AC systems
- No need for low-level compressor access

1) A. Burgio, D. Cimmino, M. Dolatabadi, M. Jasinski, Z. Leonowicz, and P. Siano, “Virtual energy storage system for peak shaving and power balancing the generation of a mw photovoltaic plant,” Journal of Energy Storage, vol. 71, p. 108204, 2023.
2) M. Song, C. Gao, H. Yan, and J. Yang, “Thermal battery modeling of inverter air conditioning for demand response,” IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 5522–5534, 2017.
3) W. Liu, G. He, Y. Shen, Z. Wang, Q. Wu, and Y. Zhang, “Implementing demand response in the park: leveraging specialized agents for large-scale inverter air conditioners,” International Journal of Electrical Power & Energy Systems, vol. 172, p. 111130, 2025.
4) Z. Li, Z. Sun, Q. Meng, Y. Wang, and Y. Li, “Reinforcement learning of room temperature set-point of thermal storage air-conditioning system with demand response,” Energy and Buildings, vol. 259, p. 111903, 2022.
5) T. Jiang, P. Ju, C. Wang, H. Li, and J. Liu, “Coordinated control of air-conditioning loads for system frequency regulation,” IEEE Transactions on Smart Grid, vol. 12, no. 1, pp. 548–560, 2021.

…

Centralized Coordination of Inverter ACs

A centralized optimization-based method to calculate the control commands for all the ACs

$$\min_{u_1(k),u_2(k),\ldots,u_N(k);\ k=1,\ldots,T} \quad \sum_{k=1}^{T}\left(P^{\text{ref}}(k)-\sum_{i=1}^{N}P_i u_i(k)\right)^2$$

$$\begin{aligned}\text{s.t.}\quad & T_i(k+1)=(1-a_i)T_i(k)+a_iT_i^{\text{out}}-b_iu_i(k), \quad \forall i,k\\ & T_i^{\min}\le T_i(k)\le T_i^{\max}, \quad \forall i,k\\ & u_i(k)\in[0,P_i^{\text{rated}}], \quad \forall i,k\end{aligned}$$

1) Y. Che, J. Yang, Y. Zhou, Y. Zhao, W. He, and J. Wu, "Demand response from the control of aggregated inverter air conditioners," IEEE Access, vol. 7, pp. 88 163–88 173, 2019.
2) Y. Che, J. Yang, Y. Zhao, and S. Xue, "Control strategy for inverter air conditioners under demand response," Processes, vol. 7, no. 7, p. 407, 2019.
3) Q. Li, Y. Zhao, Y. Yang, L. Zhang, and C. Ju, "Demand-response-oriented load aggregation scheduling optimization strategy for inverter air conditioner," Energies, vol. 16, no. 1, p. 337, 2022.
4) A. Burgio, D. Cimmino, M. Dolatabadi, M. Jasinski, Z. Leonowicz, and P. Siano, "Virtual energy storage system for peak shaving and power balancing the generation of a mw photovoltaic plant," Journal of Energy Storage, vol. 71, p. 108204, 2023.
5) M. Song, C. Gao, H. Yan, and J. Yang, "Thermal battery modeling of inverter air conditioning for demand response," IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 5522–5534, 2017.
6) …

Distributed Coordination of Inverter ACs

ACs coordinate using local information + limited communication with neighbors

1) J. Hong, H. Hui, H. Zhang, N. Dai, and Y. Song, "Event-triggered consensus control of large-scale inverter air conditioners for demand response," IEEE Transactions on Power Systems, vol. 37, no. 6, pp. 4954–4957, 2022.
2) B. Wang, T. Zhang, X. Hu, Y. Bao, and H. Su, "Consensus control strategy of an inverter air conditioning group for renewable energy integration based on the demand response," IET Renewable Power Generation, vol. 12, no. 14, pp. 1633–1639, 2018.
3) Z.-W. Yu, L. Ding, Z.-M. Kong, Z.-W. Liu, P. Hu, and Y. Xiao, "A distributed coordinated framework with fair comfort level sharing for inverter air conditioner in auxiliary services," IEEE Transactions on Smart Grid, vol. 15, no. 3, pp. 2776–2790, 2024.

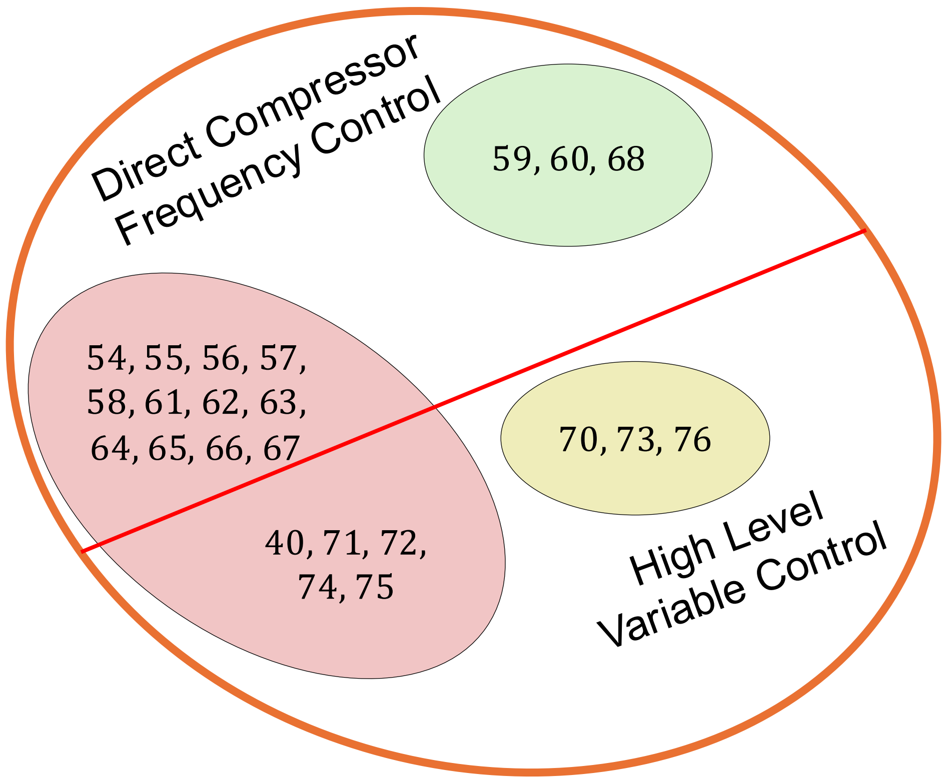
Decentralized Coordination of Inverter ACs

- Similar to setpoint change coordination with ON/OFF AC
- No performance guarantee

1) L. Dong, Q. Wu, J. Hong, Z. Wang, S. Fan, and G. He, “An adaptive decentralized regulation strategy for the cluster with massive inverter air conditionings,” Applied Energy, vol. 330, p. 120304, 2023.
2) W. Liu, G. He, Y. Shen, Z. Wang, Q. Wu, and Y. Zhang, “Implementing demand response in the park: leveraging specialized agents for large-scale inverter air conditioners,” International Journal of Electrical Power & Energy Systems, vol. 172, p. 111130, 2025.
3) T. Jiang, P. Ju, C. Wang, H. Li, and J. Liu, “Coordinated control of air-conditioning loads for system frequency regulation,” IEEE Transactions on Smart Grid, vol. 12, no. 1, pp. 548–560, 2021.

VES literature review

	ON/OFF AC	Inverter AC
Centralized	39, 40	54, 55, 56, 57, 58, 66, 67, 69, 71, 72
Decentralized	41, 42, 43, 44, 45, 20, 38, 46, 48, 49, 23, 25, 47	70, 73, 76
Distributed	51, 52, 53	59, 60, 68



Inverter AC literature

Research Gaps and Objectives

Research Gaps and Objectives

Research Gaps	Objectives
Most works focus on ON/OFF ACs	Inverter ACs
Inverter ACs: mostly centralized coordination	Decentralized coordination
Inverter ACs: mostly direct compressor frequency control	High-level variable control
Rely on a thermal model of a building, which is hard to obtain	Model free
Inverter ACs: experimental verification of decentralized coordination is rare	Experimental verification

Additional Goals

Analyze the available storage capacity in a cluster of ACs

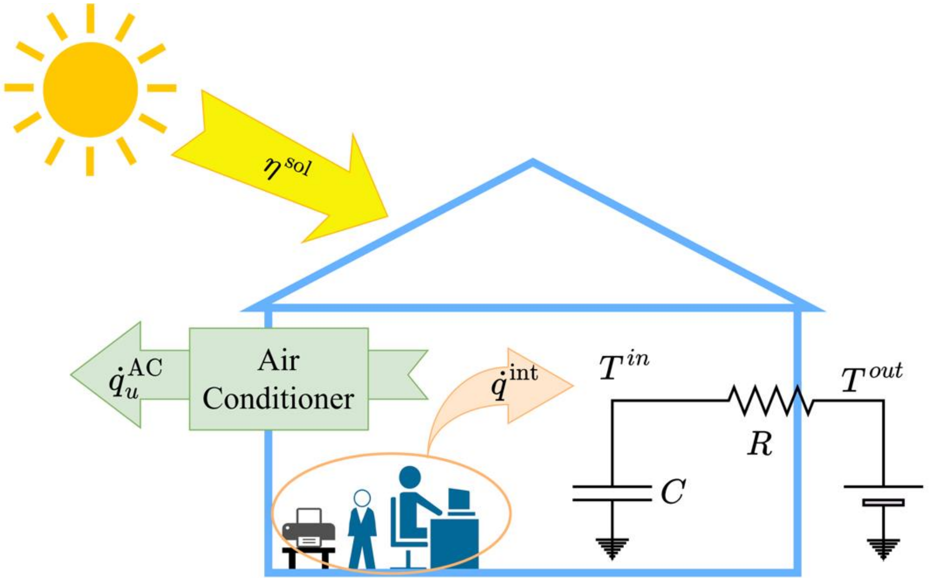
- f(number of ACs, ...)
- Similar to batteries, VES also has a storage limit, which might be dynamic, unlike batteries

The effect of humidity on power consumption will be studied

- The humidity effect might be significant in a humid climate

Preliminary Work

Model of a building with an inverter AC

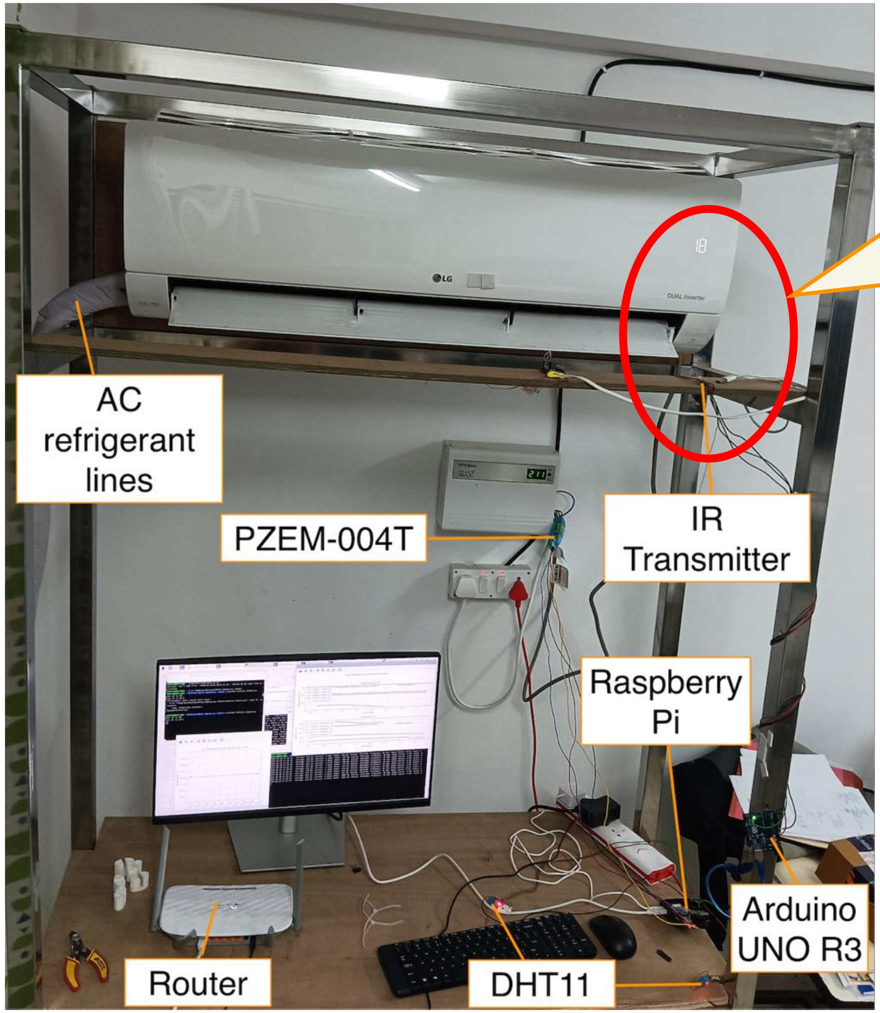


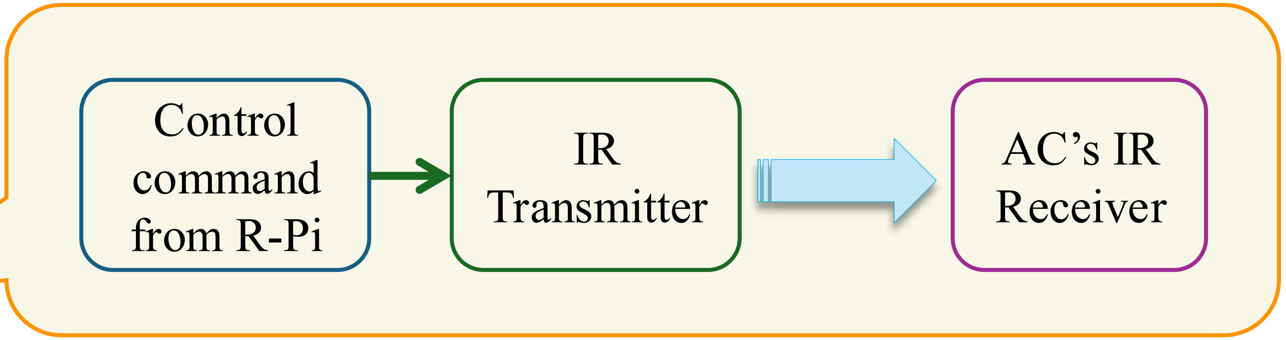
- Developed a thermal model of a room with an inverter AC and unknown disturbances
- Developed a power consumption model of the inverter AC
- Data-driven estimation of the model parameters

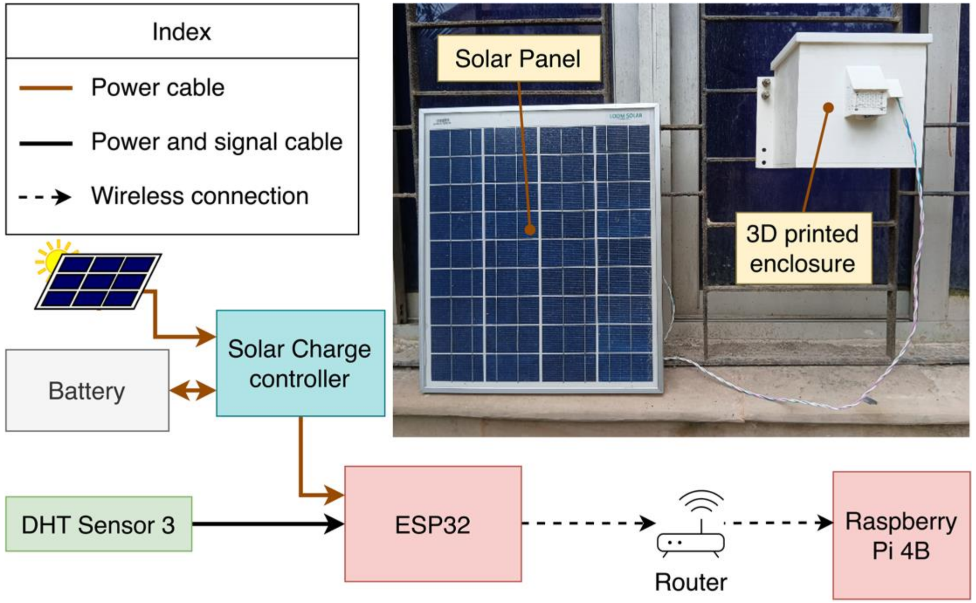
$$C\dot{T}^{\text{in}} = \frac{T^{\text{out}}(t) - T^{\text{in}}(t)}{R} + A^{\text{eff}}\eta^{\text{sol}}(t) - \dot{q}_u^{\text{AC}}(t) + \dot{q}^{\text{int}}(t)$$

1) S. Paul and P. Barooah, "A data-driven thermal model of a building with an inverter-based air-conditioner for demand dispatch," in 2025 Eleventh Indian Control Conference (ICC). IEEE, 2025, pp. 684–689.

Experimental Setup







Method to Estimate Thermal Parameters

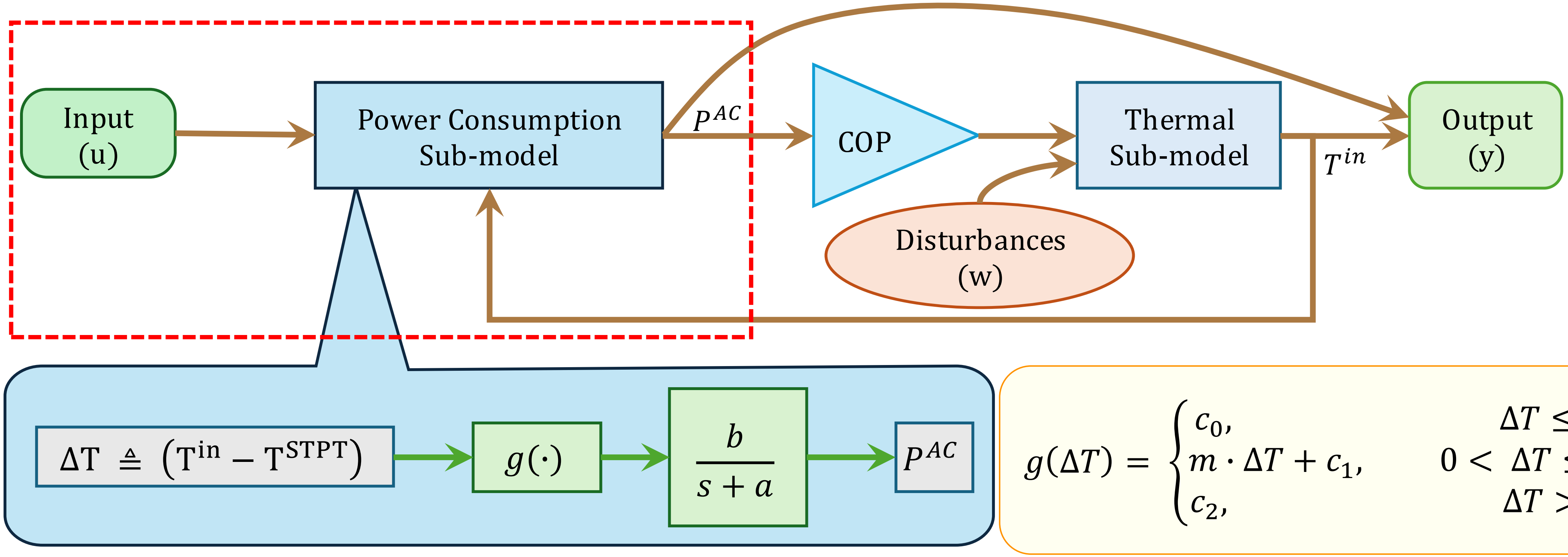
$$\theta^* = \min_{\theta} \; J(\theta)$$

$$\text{s.t.} \quad \theta \geq 0, \theta \in \mathbb{R}^{N+3}$$

Objective Function

$$J(\theta) \triangleq \left\| T^{\text{in}}(\theta) - T^{\text{in,m}} \right\|_2 + \lambda \sum_k \left| \dot{q}_k^{\text{int}}(\theta) - \dot{q}_{k+1}^{\text{int}}(\theta) \right| + \alpha \left\| \dot{q}^{\text{int}}(\theta) \right\|_2$$

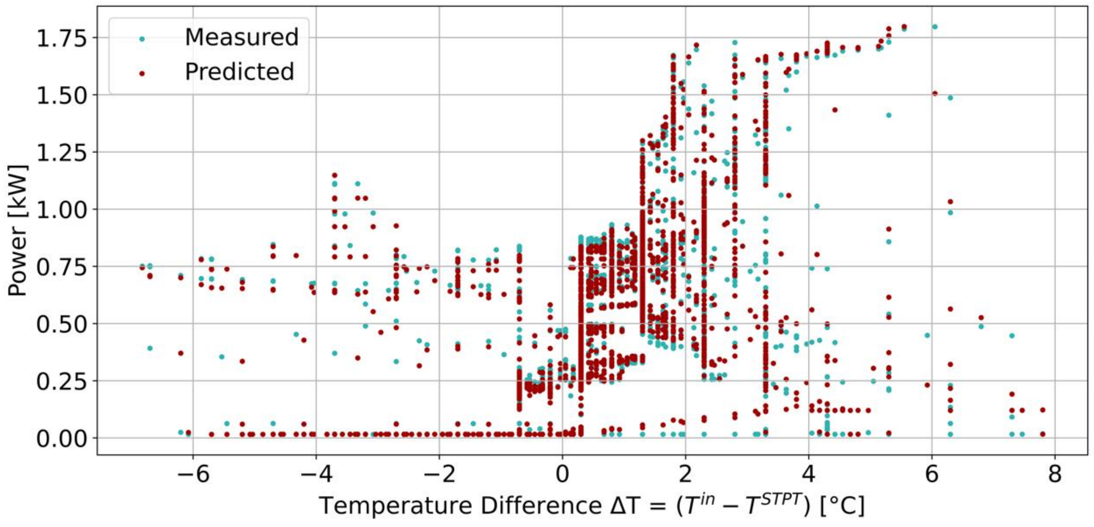
Power Consumption Sub-model



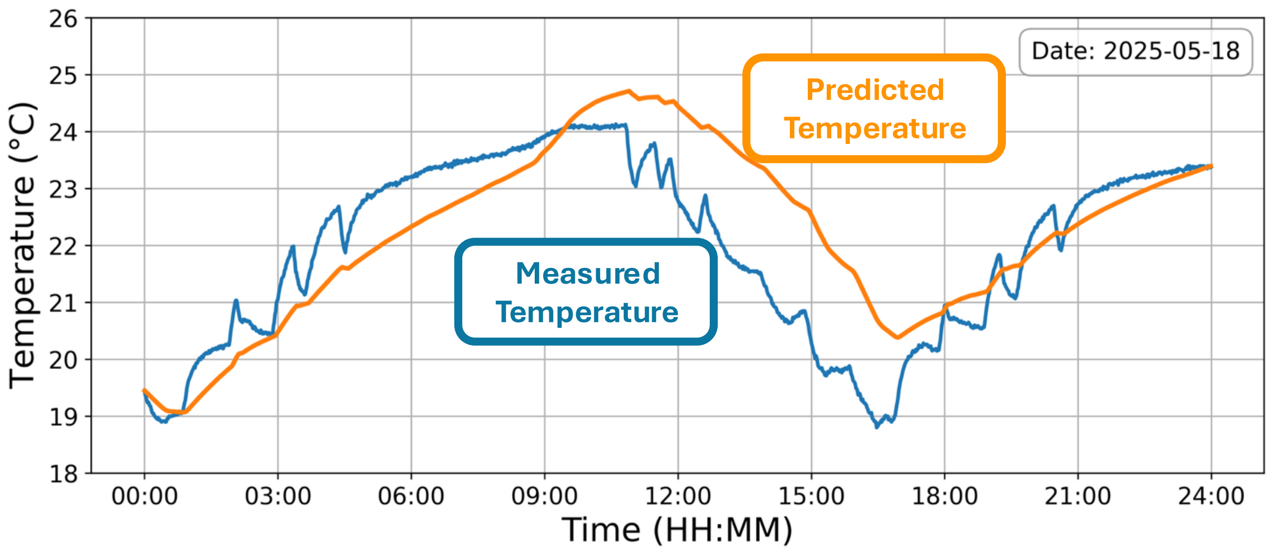
$$g(\Delta T) = \begin{cases} c_0, & \Delta T \leq 0.0 \\ m \cdot \Delta T + c_1, & 0 < \Delta T \leq 3.3 \\ c_2, & \Delta T > 3.3 \end{cases}$$

Results of Thermal Modeling

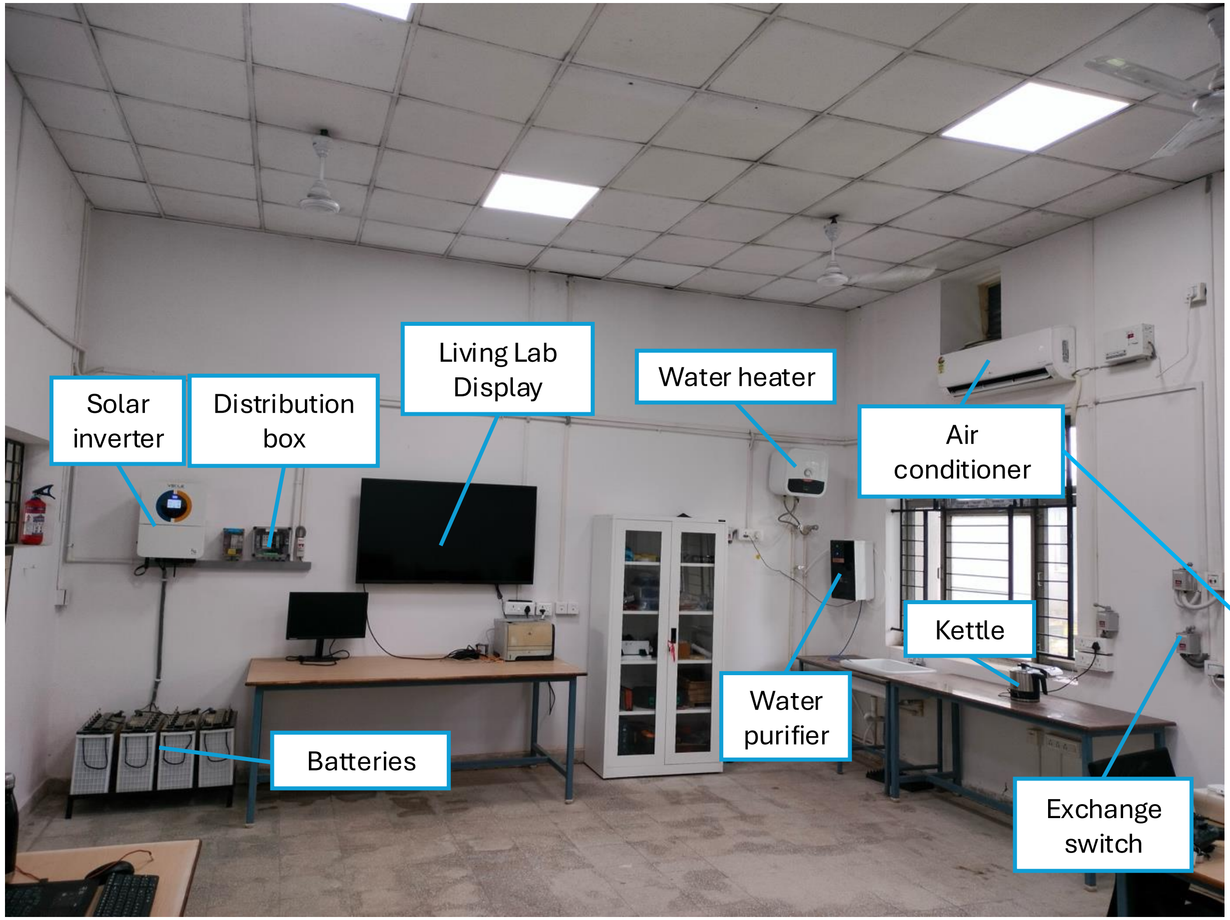
Power Consumption Sub-model



Thermal Sub-model



Experimental Facility



Tentative Timeline

Objectives	Semester-wise Timeline						
	Sem 4	Sem 5	Sem 6	Sem 7	Sem 8	Sem 9	Sem 10
Coordination Architecture							
Control Mechanism							
Simulating Platform							
Experimental Evaluation							
Analysis of Storage Capacity							
Effect of Humidity							
Synopsis							
Thesis Writing							
Thesis Defense							

Publication

1) S. Paul and P. Barooah, "A Data-Driven Thermal Model of a Building with an Inverter-Based Air-Conditioner for Demand Dispatch," *2025 Eleventh Indian Control Conference (ICC)*, Bangalore, India, 2025, pp. 684-689, doi: 10.1109/ICC69100.2025.11372385.

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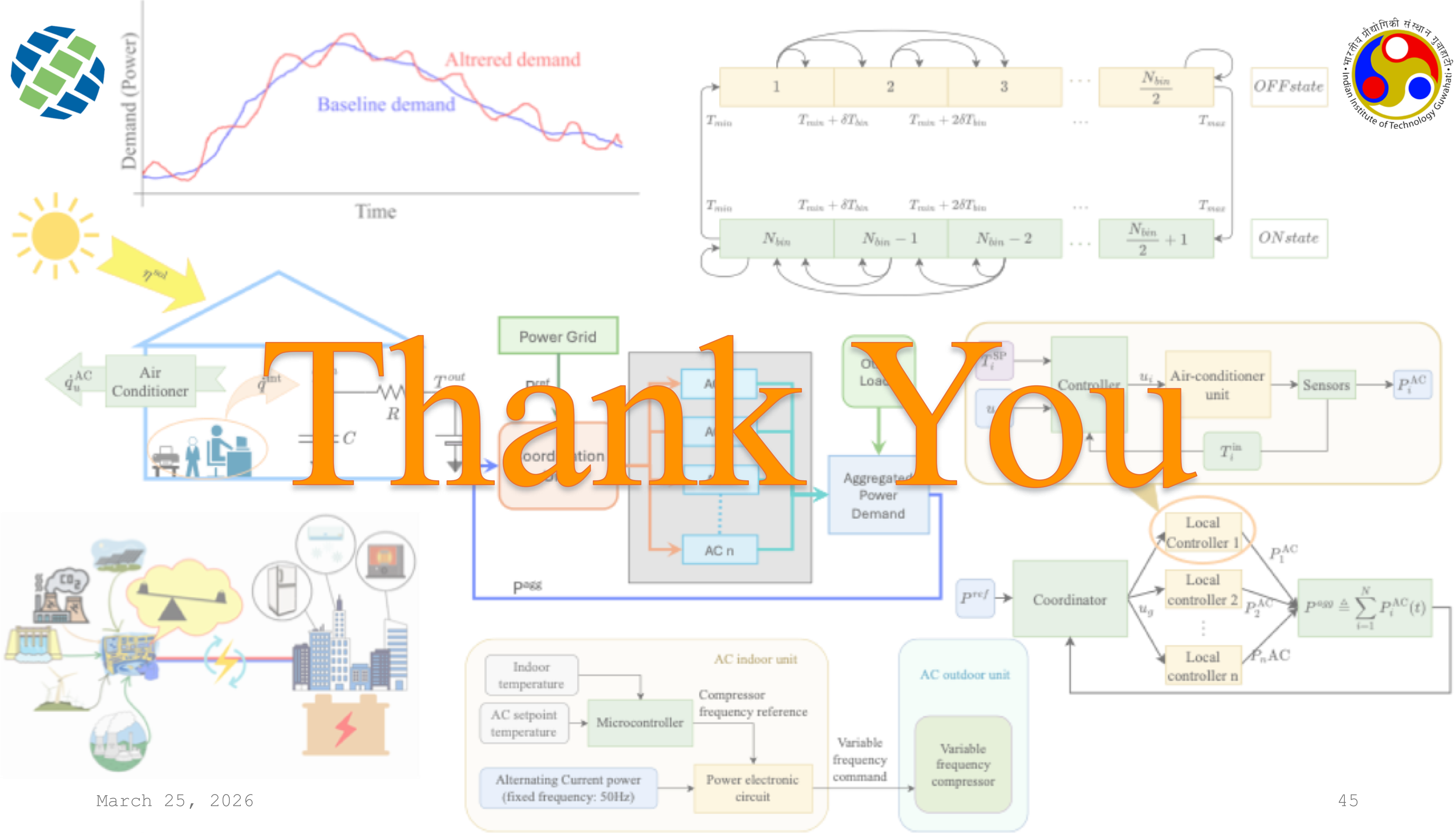
Thank You



Altrered demand
Baseline demand
Demand (Power)
Time
OFFstate
ONstate
Air Conditioner
Power Grid
AC n
Aggregated Power Demand
Air-conditioner unit
Sensors
Controller
Local Controller 1
Local controller 2
Local controller n
Coordinator
AC indoor unit
AC outdoor unit
Indoor temperature
AC setpoint temperature
Microcontroller
Compressor frequency reference
Alternating Current power (fixed frequency: 50Hz)
Power electronic circuit
Variable frequency command
Variable frequency compressor