Buildings as Thermal Batteries

Dynamic Programming Control of Danish Household Heating for Cost and Emission Reduction

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Master Thesis Presentation · 2025-2026

UNIVERSITY OF COPENHAGEN

“

What if your house could act as a battery?

The Challenge

70%

Denmark's CO_2 reduction target by 2030

40%

National energy consumed by buildings

Buildings have massive thermal storage capacity...
Yet they remain largely disconnected from grid flexibility services.

Renewable volatility

↓

Requires flexibility

↓

Buildings thermal mass

↓

Stores heat naturally

The Core Idea

THERMAL MASS

Buildings naturally store heat.
Walls, floors, and furniture absorb and release heat over hours to days.

TIME CONSTANT τ

20–70 hours for Danish homes.
Better insulation = longer τ = more flexibility.

Pre-heat
when electricity is cheap

↓

Coast
through price peaks

↓

Save Money
and reduce emissions

Three Questions to Answer

1. HOUSEHOLD SAVINGS

What cost savings can dynamic programming control achieve for electrically heated households?

2. NATIONAL IMPACT

What is the estimated national impact on peak electricity demand if widely adopted?

3. ENVIRONMENTAL BENEFIT

Does cost optimisation implicitly result in emission reduction through price-emission correlation?

Two Control Strategies

BASELINE: Hysteresis Control

- Simple on/off around $21\,^{\circ}\mathrm{C}$
- How most thermostats work
- No price awareness
- $T < T_{\text{target}} \Rightarrow$ Turn ON

OPTIMISED: Dynamic Programming

- 24-hour planning horizon
- Comfort bounds: $20\,^{\circ}\mathrm{C}$–$23\,^{\circ}\mathrm{C}$
- Cost optimisation with forecasts
- Complexity: $\mathcal{O}(S \times T)$
- Runs on Raspberry Pi

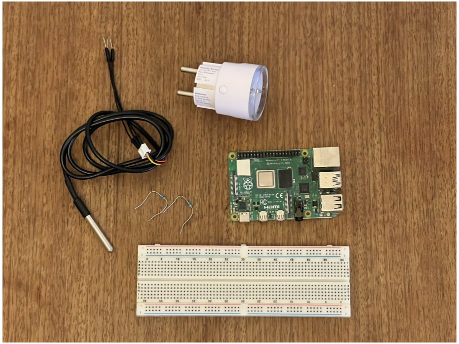
Field Experiment

Real-world validation in a Danish vacation home

Hardware Setup:

- **DS18B20 Thermometer**
  Indoor temperature every 15 min
- **Shelly Smart Plug**
  $500\,\mathrm{W}$ electric heater control
- **Raspberry Pi 3B+**
  Central controller running DP algorithm

Control Loop (every 15 min):
Measure → DP algorithm → Action → Log



Hardware setup

Hysteresis Control Results

Baseline experiment: Traditional thermostat behavior

Control Parameters:

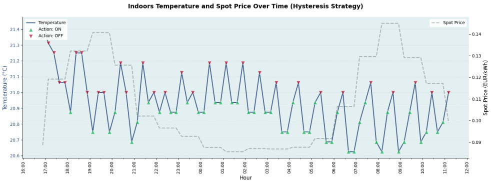
- Target temperature: $21\,^{\circ}\mathrm{C}$
- Simple on/off switching
- No price awareness

Results:

Total cost: **€0.339**

Cumulative price: €8.03

Heating activates reactively when temperature drops below target.



Hysteresis control: Temperature & heating

Dynamic Programming Results

Optimised experiment: Price-aware predictive control

Control Parameters:

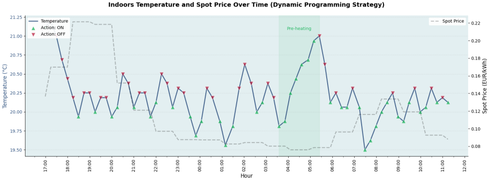
- Comfort bounds: $20\,^{\circ}\mathrm{C}$–$23\,^{\circ}\mathrm{C}$
- 24-hour planning horizon
- Price forecast integration

Results:

Total cost: **€0.309**

Cumulative price: €8.44

Pre-heated before morning peak (06:00–10:00) despite higher daily prices.



DP control: Temperature & heating

Experiment Results

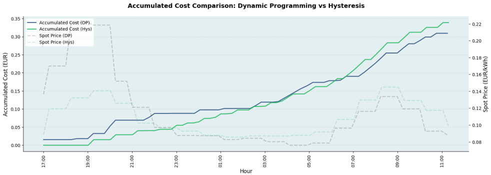
8.71%

Cost Reduction

(DP vs Hysteresis control)

Hysteresis: €0.339 total cost
DP Control: €0.309 total cost

Despite higher cumulative prices during DP day (€8.44 vs €8.03), DP pre-heated before morning peak (06:00–10:00).



Temperature & price comparison

Monte Carlo Validation

1,000 randomly sampled days from 3 years of data

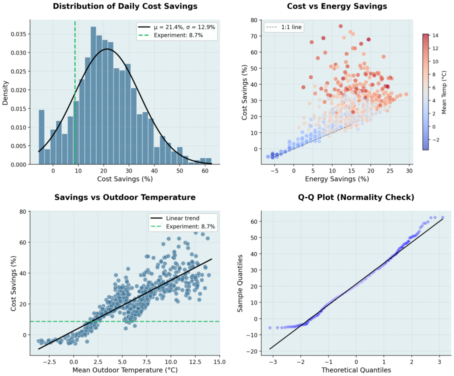
21.4%

Mean Cost Savings

$(\sigma = 12.89\%)$

Key Insights:

- Higher outdoor temps $\Rightarrow$ Greater savings
- Experiment (8.71%) in lower tail
- Room had $\tau = 13.1\,\mathrm{h}$ (below typical 20–70h)



Distribution of daily cost savings

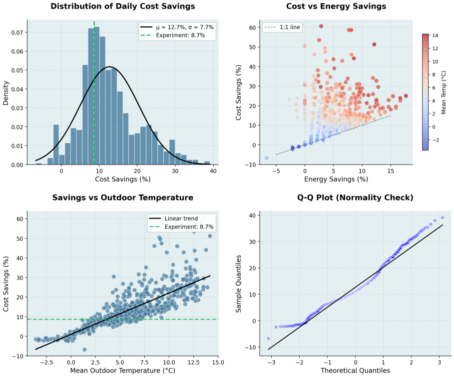
Monte Carlo Validation (Fixed)

1,000 randomly sampled days from 3 years of data

12.69%

Mean Cost Savings

($\sigma = 7.71\%$)



Distribution of daily cost savings

Key Insights:

- Higher outdoor temps $\Rightarrow$ Greater savings
- Experiment (8.71%) close to mean
- Room had $\tau = 13.1\,\mathrm{h}$ (below typical 20–70h)

National Simulation Setup

Methodology for scaling field experiment results

Simulation Parameters:

- Heater capacity: $5\,\mathrm{kW}$
- Heat pump COP: 3
- Electric heater COP: 1
- Heating season: Oct–Apr
- Control interval: 15 min

Control Strategies:

Hysteresis:
Target temperature: $21\,^{\circ}\mathrm{C}$

Dynamic Programming:
Comfort bounds: $20\,^{\circ}\mathrm{C}$–$23\,^{\circ}\mathrm{C}$
Planning horizon: 24h (96 steps)

765 complete days simulated from heating seasons 2021–2024

Danish Building Stock

216,791 electrically heated households analysed

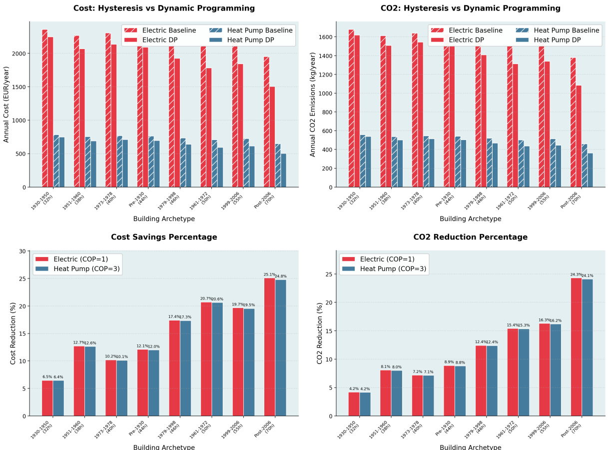
Construction Period	Time Constant τ	Electric	Heat Pumps
Pre-1930	44 hours	18,330	44,105
1930–1950†	32 hours	3,789	14,678
1951–1960	38 hours	2,440	9,301
1961–1972	50 hours	11,917	30,796
1973–1978	40 hours	11,127	8,896
1979–1998	46 hours	16,055	9,773
1999–2006†	55 hours	571	3,549
Post-2006†	70 hours	727	30,593

Time constants from Jensen et al. (2020). Newer buildings = better insulation = longer τ

Savings by Building Archetype

Key Insights:

- Electric heaters use 3x electricity
- Better insulation = More savings



Does Saving Money Also Save Emissions?

Statistical analysis: DK2 grid, 2021–2024

Pearson Correlation:

$$\rho = 0.379 \quad (p < 0.001)$$

Seasonal Patterns:

Winter: $\rho = 0.45–0.60$

July: $\rho \approx$ negative

✓ **Cost optimisation implicitly reduces emissions**

Pearson correlation heatmap (2021–2024)

Does Saving Money Also Save Emissions?

Statistical analysis: DK2 grid, 2021–2024

Spearman Correlation:

$$\rho = 0.464 \quad (p < 0.001)$$

Seasonal Patterns:

Winter: $\rho = 0.45–0.70$

July: $\rho \approx$ negative

✓ **Cost optimisation implicitly reduces emissions**

Spearman correlation heatmap (2021–2024)

National Impact: Denmark

216,791 electrically heated households

€34.5M
Annual Cost Savings

12,421t
CO_2 Avoided (13.99%)

9.88%
Peak Demand Reduction

Building Type	**Savings**	**Time Constant τ**
Older Buildings (1930–1950)	6.8%	32 hours
Average All Types	18.89%	—
New Buildings (Post-2006)	25.7%	70 hours

Better insulation = Longer time constant = Greater flexibility = More savings

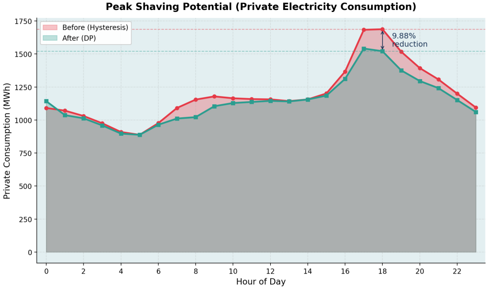
Peak Shifting: Grid Benefits

∼200 MWh
Shifted from peak hours

9.88%
Evening peak reduction

Cost optimisation naturally incentivises peak shifting.

Strategy: **Pre-heat before peak** hours when prices are low.



Peak shaving potential

VPP: Service Requirements

Aggregation thresholds for Danish system services

Service	Min. Bid	Response	Duration	Households
FCR-D (DK2)	0.1 MW	7.5 s	20 min	**20**
FCR-N (DK2)	0.1 MW	60 s	1 h	**20**
FFR (DK2)	0.3 MW	1.3 s	10 s	**60**
aFRR	1 MW	5 min	2 h	**200**
mFRR	1 MW	12.5 min	2 h	**200**

FCR-D (Frequency Containment Reserve - Disturbance) recommended:

- Asymmetric (matches heating system capabilities)
- Only 20 households needed for minimum bid

VPP: Revenue Potential

Based on 2024 FCR-D market prices (DK2)

Capacity Prices (2024 avg):

- FCR-D up: €11.63/MWh
- FCR-D down: €35.84/MWh

Per Household Revenue:

Strategy	EUR/year
FCR-D up only	€149
FCR-D down only	€458
Symmetric	€607
+ Spot savings	**€180–770**

Assumes 200 households (1 MW portfolio), 50% bid acceptance, heating season only.

Key Findings

1. **HOUSEHOLD SAVINGS** — **8.71%** (experiment) / **18.89%** (national avg)
   What cost savings can DP achieve?

2. **NATIONAL IMPACT** — **€34.5M** saved annually / **9.88%** peak reduction
   What is the impact if widely adopted?

3. **ENVIRONMENTAL BENEFIT** — $\rho = 0.464$ correlation / **13.99%** CO_2 reduction
   Does cost optimisation reduce emissions?

Limitations

Single-zone thermal model
Simplifies complex multi-room dynamics

Binary control (on/off)
Modern heat pumps allow continuous modulation

Experiment on different days
Introduces weather/price variation

$\tau = 13.1$ **hours (experiment room)**
Below typical household range (20–60h)

Assumes perfect price forecasts
Real forecasts introduce uncertainty

No interaction effects at scale
Mass adoption could affect prices/grid

These limitations suggest the results represent conservative estimates — better insulated buildings and continuous control could achieve higher savings.

Future Work

RESEARCH EXTENSIONS

- **Longer field experiments**
  Full heating season validation
- **Economic MPC**
  Continuous control for modern heat pumps
- **Emission-explicit optimisation**
  Maximise environmental benefit directly

COMMERCIAL APPLICATIONS

- **VPP pilot project**
  Real FCR-D market participation
- **Commercial buildings**
  Larger temperature flexibility potential
- **Smart plug integration**
  Consumer product development

Buildings Can Serve as Distributed Thermal Storage

Cost optimisation implicitly reduces emissions.

2026 tax reduction will strengthen the business case.

Scalable path to grid flexibility without new infrastructure.

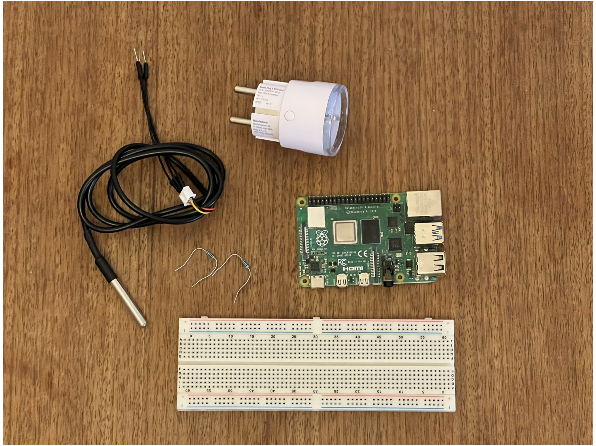
Thank You

Questions?

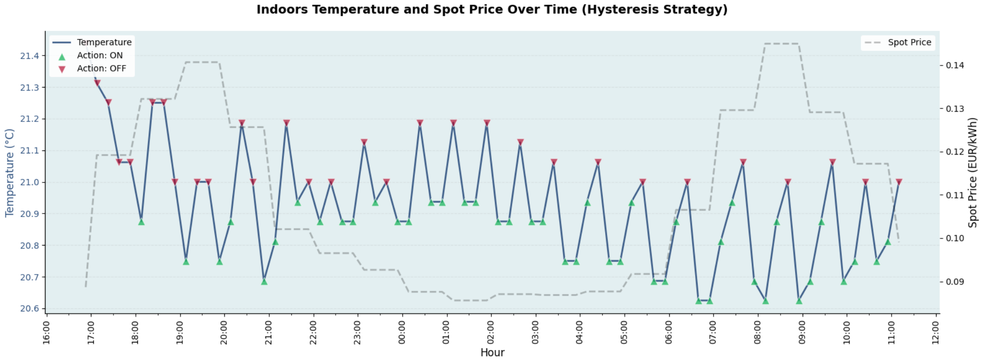
Code and data available at:
`github.com/KaffeDiem/buildings-as-thermal-batteries`

Kasper Munch Jensen
Advisor: Troels Christian Petersen
University of Copenhagen · December 2025

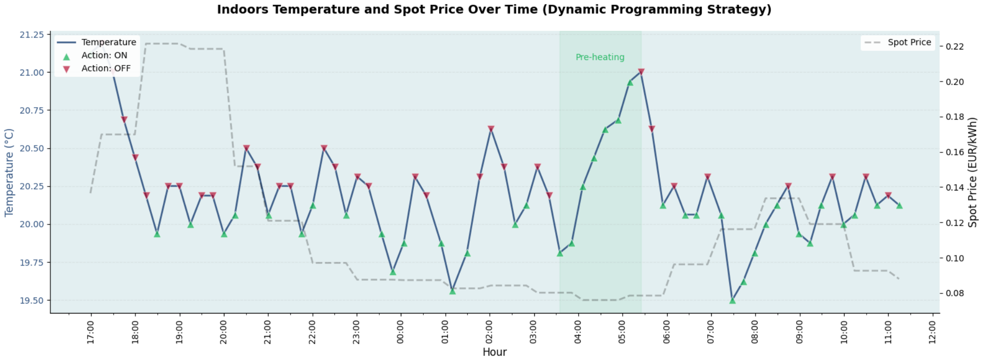
Hardware Setup



Hysteresis Control: Temperature & Heating



DP Control: Temperature & Heating



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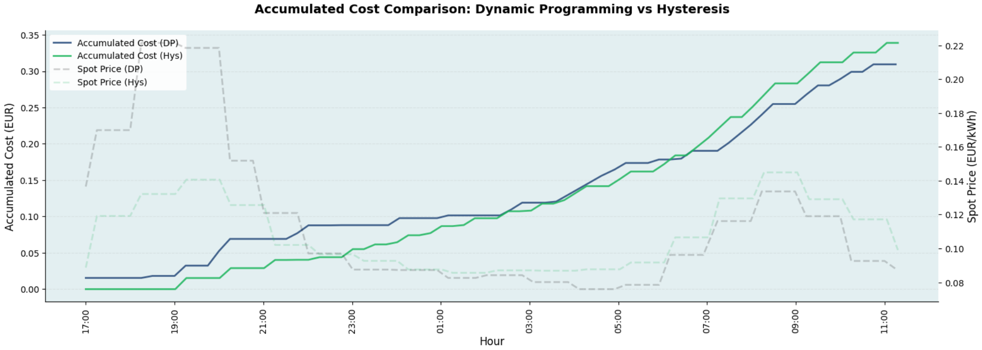
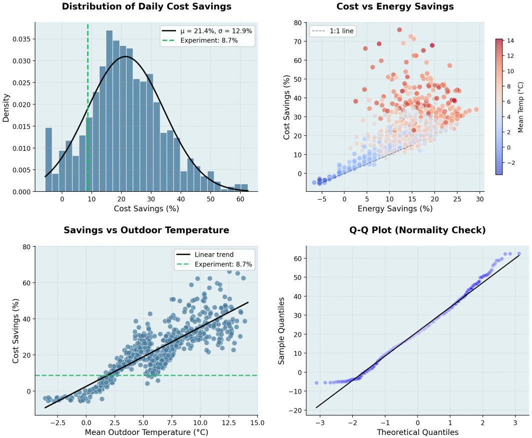
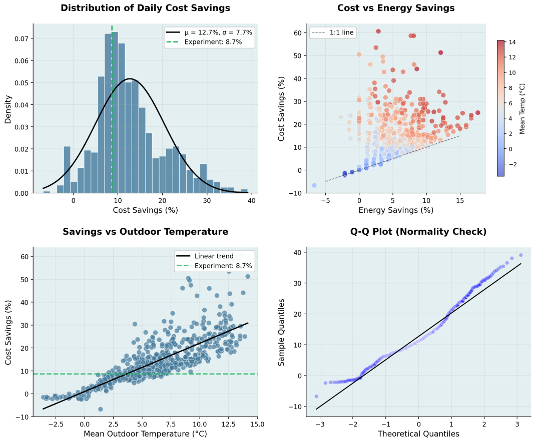


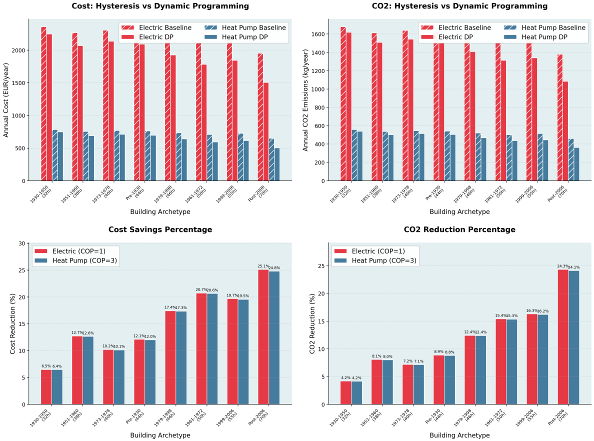
Monte Carlo Validation



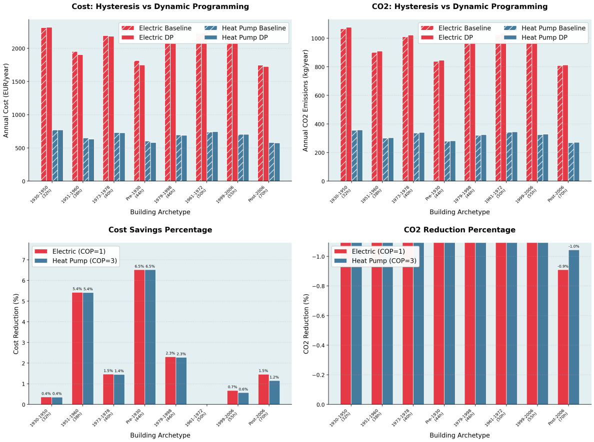
Monte Carlo Validation (Fixed)



National Scaling

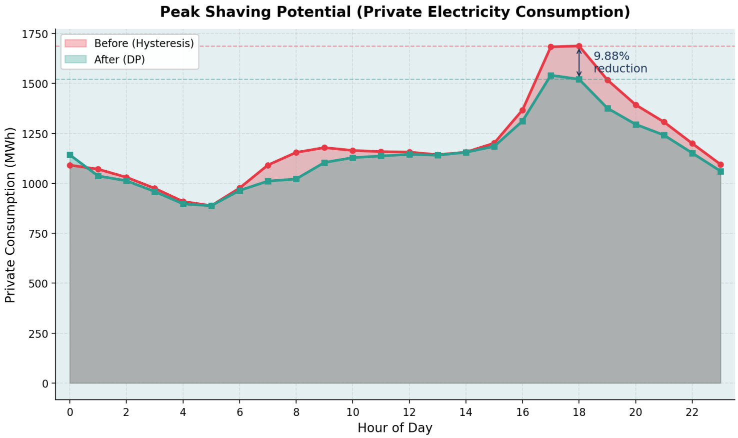


National Scaling (Hysteresis target: 20 °C)



Pearson Correlation Heatmap (2021–2024)

Peak Shaving Potential



Peak Shaving Potential (Hysteresis target: 20°C)