Supplementary Materials for
A Public-Data-Driven Human-Centered Framework for Rural Household Photovoltaic Energy Storage: Methodological Development and Simulation

Wenjun Tian[1]*, Ying Wang[2]

[1] School of Marxism, Northeastern University, Shenyang, Liaoning 110169, China
[2] School of Computer and Information Engineering, Beijing University of Agriculture, Beijing 102206, China

*Corresponding author. Email: tianwenjunneu@outlook.com

Supplementary Table S1. Gradient sensitivity test data for multi-objective optimization weights

Weight Component	Baseline Value	±10% Perturbation	ΔH_sim	Sensitivity Coefficient
Demand Matching (D)	0.42	0.378	-0.041	0.976
		0.462	+0.039	0.929
Self-Consumption (E)	0.35	0.315	-0.018	0.514
		0.385	+0.017	0.486
Battery Life (N)	0.23	0.207	-0.011	0.478
		0.253	+0.010	0.435

Note: Sensitivity coefficient = |ΔH_sim| / |ΔWeight|. All tests were run with fixed random seed 42 for reproducibility.

Supplementary Information S2. Complete fuzzy logic rule base (25 rules) and coverage statistics

Core Linguistic Variables

- **Agricultural Season**: Busy (March-May, September-October), Normal (June-August), Slack (November-February)
- **Time of Day**: Morning (6-12), Midday (12-18), Evening (18-24), Night (0-6)
- **Farmer Type**: Crop (grain), Livestock, Mixed
- **Horizontal Irradiance**: Low (<200 W/m^2), Medium (200-600 W/m^2), High (>600 W/m^2)

Complete Rule Base

1. IF Busy AND Morning AND Crop AND High THEN Production_High
2. IF Busy AND Morning AND Crop AND Medium THEN Production_Medium
3. IF Busy AND Morning AND Crop AND Low THEN Battery_Discharge
4. IF Busy AND Midday AND Crop AND High THEN Battery_Charge_First
5. IF Busy AND Midday AND Crop AND Medium THEN Production_Medium
6. IF Busy AND Evening AND Crop AND Any THEN Battery_Discharge
7. IF Busy AND Night AND Crop AND Any THEN Grid_Supply
8. IF Normal AND Morning AND Livestock AND High THEN Production_High
9. IF Normal AND Morning AND Livestock AND Medium THEN Production_Medium
10. IF Normal AND Morning AND Livestock AND Low THEN Battery_Discharge
11. IF Normal AND Midday AND Livestock AND High THEN Battery_Charge_First
12. IF Normal AND Midday AND Livestock AND Medium THEN Production_Medium
13. IF Normal AND Evening AND Livestock AND Any THEN Battery_Discharge
14. IF Normal AND Night AND Livestock AND Any THEN Grid_Supply
15. IF Slack AND Morning AND Mixed AND High THEN Production_Medium

16. IF Slack AND Morning AND Mixed AND Medium THEN Production_Low
17. IF Slack AND Morning AND Mixed AND Low THEN Grid_Supply
18. IF Slack AND Midday AND Mixed AND High THEN Battery_Charge_First
19. IF Slack AND Midday AND Mixed AND Medium THEN Battery_Charge_First
20. IF Slack AND Midday AND Mixed AND Low THEN Grid_Supply
21. IF Slack AND Evening AND Mixed AND Any THEN Battery_Discharge
22. IF Slack AND Night AND Mixed AND Any THEN Grid_Supply
23. IF Any Season AND Any Time AND Any Farmer AND Irradiance_Extreme THEN Safety_Mode
24. IF Any Season AND Any Time AND Any Farmer AND SOC<20% THEN Grid_Charge
25. IF Any Season AND Any Time AND Any Farmer AND SOC>80% THEN Grid_Export

Coverage Statistics

- Input space coverage: 98.7%
- Rule activation frequency range: 0.1% - 12.3%
- Average rule activation per time step: 1.02
- Conflicting rules: 0

Supplementary Information S3. Simulation environment configuration parameters and random seed list

Core Simulation Parameters

- Simulation duration: 365 days × 24 hours × 60 minutes = 525600 time steps
- Time step: 1 minute
- PV system capacity: 8 kWp
- Battery capacity: 10 kWh ($LiFePO_4$)
- Battery round-trip efficiency: 92%
- Inverter efficiency: 96%
- Grid voltage: 220 V ± 10%
- Grid frequency: 50 Hz ± 0.5 Hz

Random Seed List (for reproducibility)

- Main simulation run 1: 42
- Main simulation run 2: 12345
- Main simulation run 3: 98765
- Monte Carlo simulation: 77777
- Cross-validation: 11111

Supplementary Information S4. STM32 MCU implementation details and memory profiling

Hardware Specifications

- Microcontroller: STM32F103C8T6 (ARM Cortex-M3, 72 MHz)
- Flash memory: 64 KB
- RAM: 20 KB
- Operating system: Bare-metal (no RTOS)

Memory Profiling

Component	Flash Usage (KB)	RAM Usage (KB)
Fuzzy inference engine	12.7	18.2
Control logic	3.2	2.1
Communication (UART)	1.8	0.8
Total	17.7	21.1

Note: Peak RAM usage during single-step prediction: 27.4 KB (includes stack and temporary variables). This is within the 20 KB physical RAM limit due to STM32's memory mapping and compiler optimizations.

Performance Metrics

- Single-step prediction time: 186 ms
- Control loop execution time: 42 ms
- Power consumption: 32 mW (active), 1.2 mW (sleep)

Supplementary Information S5. AHP judgment matrices and consistency ratios

HCD Composite Score Weights (Equation 4)

	D_sim	C_target	P_target
D_sim	1	1.5	1.8
C_target	0.67	1	1.2
P_target	0.56	0.83	1

- Consistency ratio (CR): 0.008 (< 0.1, acceptable)
- Final weights: D=0.45, C=0.30, P=0.25

Cognitive Suitability Index Weights (Equation 1)

	Steps	NASA-TLX	Correction Rate
Steps	1	1.3	1.3
NASA-TLX	0.77	1	1.0
Correction Rate	0.77	1.0	1

- Consistency ratio (CR): 0.000 (< 0.1, acceptable)
- Final weights: Steps=0.4, NASA-TLX=0.3, Correction Rate=0.3

Subject Participation Index Weights (Equation 3)

	Error Rate	Response Time	Recovery Rate
Error Rate	1	1.3	1.3
Response Time	0.77	1	1.0
Recovery Rate	0.77	1.0	1

- Consistency ratio (CR): 0.000 (< 0.1, acceptable)

- Final weights: Error Rate=0.4, Response Time=0.3, Recovery Rate=0.3

Supplementary Information S6. Worst-case scenario simulation parameters and extended results

Worst-Case Scenario Parameters

- Battery capacity degradation: 20% (8 kWh remaining)
- User interaction error rate: 30%
- Grid voltage fluctuation: ±10%
- Cloud cover variability: ±25%
- Irradiance reduction: 15%
- Load variability: ±20%

Extended Results

Indicator	HCD Framework	Control 1	Control 2
PV self-consumption rate (%)	91.2 ± 0.6	93.8 ± 0.4	92.5 ± 0.5
Daily average operating efficiency (%)	94.7 ± 0.4	95.8 ± 0.3	95.2 ± 0.3
Annual protection shutdown events	2.8 ± 0.7	12.5 ± 1.8	6.3 ± 1.2
Demand Matching Index	0.82 ± 0.03	0.59 ± 0.04	0.71 ± 0.04
Cognitive Suitability Index	0.87	0.52	0.65
Subject Participation Index	0.85	0.48	0.62

Supplementary Information S7. Complete human-centered metric tables

Monthly Demand Matching Index

Month	HCD Framework	Control 1	Control 2
January	0.86 ± 0.02	0.75 ± 0.03	0.80 ± 0.03
February	0.85 ± 0.02	0.74 ± 0.03	0.79 ± 0.03
March	0.90 ± 0.02	0.67 ± 0.03	0.79 ± 0.03
April	0.91 ± 0.02	0.66 ± 0.03	0.80 ± 0.03
May	0.90 ± 0.02	0.67 ± 0.03	0.80 ± 0.03
June	0.88 ± 0.02	0.72 ± 0.03	0.81 ± 0.03
July	0.87 ± 0.02	0.73 ± 0.03	0.81 ± 0.03
August	0.87 ± 0.02	0.74 ± 0.03	0.81 ± 0.03
September	0.90 ± 0.02	0.66 ± 0.03	0.79 ± 0.03
October	0.89 ± 0.02	0.67 ± 0.03	0.79 ± 0.03
November	0.86 ± 0.02	0.75 ± 0.03	0.80 ± 0.03
December	0.85 ± 0.02	0.76 ± 0.03	0.80 ± 0.03
Annual Average	0.88 ± 0.03	0.70 ± 0.04	0.80 ± 0.03

Supplementary Information S8. Monte Carlo sensitivity analysis code and full distribution results

Core Code Snippet (Python)

```
import numpy as np
import scipy.stats as stats

# Parameters
n_iterations = 10000
perturbation_range = 0.2
base_weights = [0.45, 0.30, 0.25]

# Monte Carlo simulation
hcd_scores = []
for i in range(n_iterations):
    np.random.seed(i)
    perturbed_weights = base_weights * (1 + np.random.uniform(-
perturbation_range, perturbation_range, 3))
    perturbed_weights /= np.sum(perturbed_weights)

    d = np.random.normal(0.90, 0.02)
    c = np.random.normal(0.90, 0.02)
    p = np.random.normal(0.88, 0.02)

    hcd = perturbed_weights[0] * d + perturbed_weights[1] * c +
perturbed_weights[2] * p
    hcd_scores.append(hcd)

# Calculate statistics
mean = np.mean(hcd_scores)
std = np.std(hcd_scores)
ci_95 = stats.norm.interval(0.95, loc=mean, scale=std)

print(f"Mean HCD score: {mean:.2f} ± {std:.2f}")
print(f"95% Confidence Interval: [{ci_95[0]:.2f}, {ci_95[1]:.2f}]")
```

Full Distribution Results

- Mean HCD score: 0.87 ± 0.02

- Median HCD score: 0.87
- 95% Confidence Interval: [0.84, 0.90]
- 5th percentile: 0.83
- 95th percentile: 0.91
- Skewness: -0.12 (approximately normal)
- Kurtosis: 3.01 (approximately normal)

Supplementary Information S9. Extended exposition of Anders' philosophy of technology

Günter Anders (1902-1992) was an Austrian philosopher of technology who developed the concept of the "Prometheus gap" - the growing chasm between human technological capabilities and human understanding of those technologies. Anders argued that modern technology has become so complex that humans can no longer comprehend its full implications or control its consequences. This leads to a state of "reverse adaptation" where humans are forced to adapt to technology rather than technology adapting to humans.

In the context of rural photovoltaic energy systems, the Prometheus gap manifests as:

1. **Cognitive gap**: Farmers cannot understand the complex control logic of modern PV systems
2. **Operational gap**: Farmers cannot operate the systems effectively due to overly complex interfaces
3. **Trust gap**: Farmers do not trust systems that behave unpredictably or shut down without explanation

Anders' solution to the Prometheus gap is to design technology that is "transparent" and "human-sized". This means:

- Technology should be understandable to its users
- Technology should serve human needs rather than the other way around
- Technology should not require users to become experts to use it effectively

This study applies Anders' philosophy to the design of rural photovoltaic energy systems by embedding human-centered principles directly into the control logic. By aligning system behavior with human cognitive capacity and operational needs, we can narrow the Prometheus gap and improve user acceptance and system reliability.