AEEM HVAC ENERGY VALVE

Master Prototype Build Package

Disconnect-adjacent HVAC energy intelligence, adaptive supervisory control, equipment-health analytics, and an optional separately engineered surge-protection layer.

Package section	Included
V0 sensing/logger	Architecture, BOM, sensor placement, calibration, data schema
V1 adaptive control	Low-voltage supervisory logic, heat-pump rules, fail-safe behavior
Diagnostics	Fault taxonomy, confidence scoring, health score, service triggers
Validation	A/B protocol, normalization, field trial, go/no-go metrics
Economics	Savings model, payback, consumer positioning
V2 productization	SPD integration, production roadmap, IP/disclosure framework

1. Product Definition and Safety Boundary

The AEEM HVAC Energy Valve is a measurement-first residential HVAC intelligence platform. Its first job is to quantify how much electrical energy an HVAC system consumes for a given thermal result under comparable conditions. Only after the model is trustworthy does the prototype supervise normal low-voltage HVAC calls.

Prototype boundary: the V0/V1 prototype does not use homebuilt electronics as the normal 240-V compressor disconnect. The existing disconnect remains the service disconnect. Any line-voltage measurement, branch-circuit modification, or surge-protection installation should use appropriately rated hardware and qualified electrical/HVAC practices.

Current NEC development text for 440.14 states that the disconnecting means for air-conditioning or refrigerating equipment is to be within sight from and readily accessible from the equipment. The prototype layout therefore preserves the local disconnect rather than hiding service isolation inside software.

2. V0 Hardware Architecture

```
PANEL / BRANCH CIRCUIT | v EXISTING HVAC DISCONNECT | +---- split-core CT, L1 +---- split-core CT, L2 | v OUTDOOR CONDENSER / HEAT PUMP AEEM V0 ENCLOSURE (adjacent) +---- isolated power metering +---- ESP32-class controller +---- SD / local data storage +---- outdoor + line temperature sensors +---- indoor sensor link +---- thermostat-call sensing +---- optional commercial SPD status input
```

Subsystem	Prototype target	Reason
Controller	ESP32-S3 or similar	Cheap, local compute, Wi-Fi/BLE, sufficient ADC/I/O
Current sensing	2 split-core CTs	Non-invasive branch-current measurement
Voltage / real power	Isolated rated energy meter	Real watts, PF, kWh; avoids inference from amps alone
Thermal sensing	4-6 temperature channels	Air and refrigerant-line trend data
Humidity	Indoor RH sensor	Latent-load normalization
HVAC calls	Isolated 24-VAC input channels	Correlate electrical behavior with Y/G/W/O-B commands
Storage	MicroSD or flash	Preserve raw evidence for validation
Enclosure	Outdoor rated, DIN rail	Field-serviceable prototype

Prototype BOM target

Item	Allowance
Controller / radio	$10-$25
Two CTs	$20-$60
Isolated real-power meter	$25-$80
Temperature + RH sensing	$25-$60
Isolated HVAC-call inputs	$15-$40
Storage + low-voltage PSU	$20-$45
Enclosure / terminals / glands / DIN hardware	$40-$100
Commercial SPD status interface (optional V0)	$10-$30
Estimated V0 prototype total	~$165-$440 before labor

3. Installation Maps

3.1 Straight air conditioner + furnace / air handler

```
OUTDOOR: Existing disconnect -> CTs -> condenser AEEM enclosure beside disconnect T_outdoor at shaded air inlet T_suction on insulated large refrigerant line T_liquid on small refrigerant line INDOOR: T_return / RH in return-air stream T_supply in supply-air stream Y + G + W call-state sensing optional blower-current CT
```

3.2 Heat pump

```
OUTDOOR: Same electrical sensing as AC Add O/B call-state context Track defrost-state signatures Track line-temperature reversals / mode changes INDOOR: Return / supply temperature + RH Y / G / O-B / AUX-W call-state sensing optional auxiliary-heat current sensing at indoor equipment
```

Temperature sensors should be used for repeatable trending, not as a substitute for technician refrigeration measurements. Line-temperature abnormalities should trigger a confidence-weighted service recommendation rather than an automatic refrigerant diagnosis.

4. Commissioning and Calibration

Step	Procedure	Acceptance
1. Electrical reference	Compare voltage, watts and kWh to a known reference meter over multiple operating states	Target within about +/-2% for prototype
2. CT polarity / phase	Verify positive power and consistent L1/L2 relationship	No negative or phase-inverted readings
3. Temperature	Place probes together for 10-15 min before installation	Offsets characterized; repeatability about +/-0.5 F desirable
4. Call-state inputs	Command fan/cool/heat/aux individually	Each state logged correctly
5. Clock	Sync local time and preserve timezone	No timestamp jumps during tests
6. Idle baseline	Record system off for 30+ min	Noise floor and parasitic draw characterized
7. One complete cycle	Capture start -> steady -> shutdown	State machine labels cycle correctly

Calibration values and sensor offsets should be stored separately from raw observations so the original measurements remain auditable.

5. Data Schema and State Machine

```
timestamp_local timestamp_utc firmware_version sensor_calibration_version voltage L1_current L2_current
real_watts apparent_va power_factor cumulative_kWh outdoor_temp indoor_temp indoor_RH return_temp supply_temp
suction_line_temp liquid_line_temp Y_call G_call W_or_AUX_call OB_call operating_state cycle_id
cycle_runtime_sec time_since_last_cycle_sec comfort_setpoint user_override fault_flags health_score
model_confidence
```

State	Definition
OFF	No active HVAC load beyond characterized standby
FAN_ONLY	Indoor airflow without outdoor compressor state
COMPRESSOR_START	Transient start signature
COOLING_STEADY	Stable cooling electrical + control-state signature
HEATING_STEADY	Stable heat-pump heating signature
DEFROST	Heat-pump defrost pattern inferred from controls + temperatures + power
AUX_HEAT	Auxiliary / resistance heat active
RECOVERY	System actively recovering from setback or disturbance
ABNORMAL	Observed behavior exceeds confidence-weighted learned bounds

6. Performance, Health and Confidence Scores

Energy Performance Index (EPI): a weather- and condition-normalized measure of useful thermal response per electrical energy consumed. It is deliberately a relative performance metric for the same system, not a laboratory SEER/COP certification measurement.

Health Score (0-100): weighted combination of energy-per-result deviation, cycling behavior, start signature, thermal response, temperature spread, and sensor integrity.

Model Confidence (0-100%): rises with sample count, coverage of outdoor conditions, stable sensor agreement, and repeated comparable cycles. Low confidence suppresses diagnostic language.

Health score	Consumer message
90-100	Normal
75-89	Watch - mild deviation
60-74	Service may improve efficiency
<60	Service recommended; show evidence and confidence

A service alert should require both a meaningful deviation and sufficient model confidence. The product should prefer 'possible airflow restriction' over asserting a specific fault when the measurements cannot isolate the root cause.

7. Fault Taxonomy

Fault / condition	Signals used	Prototype response
Short cycling	cycles/hour, runtime, thermostat calls	Immediate alert; suppress adaptive actions that worsen cycling
Long runtime / poor recovery	kWh/cycle, indoor response, outdoor temp	Efficiency-deviation alert
Airflow restriction candidate	supply-return response, runtime, blower state, trend	Service recommendation with moderate confidence
Dirty condenser / heat rejection candidate	outdoor temp, line temps, power, runtime trend	Maintenance recommendation; no refrigerant claim
Start-component degradation candidate	start-current/time signature drift	Electrical-service alert
Condenser fan degradation candidate	power/state signature + line-temp trend	Service alert
Possible refrigerant-side degradation	line-temp trend + thermal result + energy trend	Low-to-moderate confidence service recommendation
Aux heat overuse	AUX runtime and outdoor conditions	High-priority cost alert
Sensor fault	stuck/outlier/impossible rate of change	Ignore bad channel, lower confidence, service sensor
Control fault	call state inconsistent with equipment state	Fail-safe / bypass adaptive control

DOE describes automated fault detection and diagnostics as using operational data to identify faults and, in some cases, isolate root causes. That supports the general product direction, but consumer diagnostic wording should remain proportional to what the installed sensors can actually distinguish.

8. Fail-Safe Logic

Failure	Required behavior
Wi-Fi / internet loss	Continue local measurement and safe local control; never require cloud to heat/cool
MCU reset	Default to transparent/bypass HVAC control path
Sensor failure	Drop failed channel, reduce confidence, avoid aggressive optimization
Corrupt model	Revert to conservative static rules and relearn
User override	Immediate user command wins; log override
Extreme weather	Relax cost optimization; prioritize comfort/equipment protection
Stuck low-voltage relay	Hardware bypass / watchdog architecture in production design
Bad clock / tariff feed	Disable tariff optimization; preserve normal HVAC operation
SPD status lost	Report surge-protection status unknown; do not infer protection

9. Heat-Pump-Specific Logic

Heat pumps require a separate operating model because heating, cooling, defrost and auxiliary resistance heat can have very different power signatures.

Feature	Rule
O/B state	Use only as context; support both energize-in-cooling and energize-in-heating configurations
Defrost	Do not flag expected defrost power/temperature reversals as faults
Aux heat	Track separately because electric resistance heat can dominate cost
Recovery	Avoid setbacks that provoke unnecessary auxiliary heat
Low outdoor temperature	Use equipment-specific limits; do not invent universal lockout temperatures
Compressor protection	Honor manufacturer minimum off/run constraints
Dual-fuel systems	Treat furnace staging and heat-pump staging as separate modes

ENERGY STAR smart-thermostat criteria explicitly track heating/cooling runtime and electric resistance heat use for heat pumps, which makes auxiliary-heat accounting a particularly important validation metric.

10. Adaptive Learning Timeline

Elapsed time	Phase	Allowed actions
0-3 days	Fingerprinting	Observe only
4-7 days	Environmental normalization	Alerts only; no claimed savings
7-14 days	Useful personalized model	Conservative recommendations; optional low-risk control
14-30 days	Active learning control	Recovery, scheduling and cycle optimization
30-60 days	Stable personalized model	Full normal adaptive feature set
90+ days	Seasonal refinement	Improved weather and seasonal diagnostics

ENERGY STAR reports approximately 8% average heating/cooling bill savings for certified smart thermostats. AEEM should treat that as a benchmark, not a guaranteed claim. Its differentiation is electrical measurement + thermal-response modeling + equipment-health analytics.

11. A/B Validation Protocol

Mode A - Observe: AEEM records but does not change HVAC operation. **Mode B - Optimize:** AEEM applies the learned supervisory strategy.

Control variable	Requirement
Indoor comfort	Comparable occupied temperature and humidity
Weather	Normalize by outdoor temperature / humidity or pair comparable intervals
Occupancy	Exclude materially different occupancy periods or model them separately
Equipment state	Exclude service/repair transition windows from simple A/B comparison
Energy	Use measured real kWh, not amp-hours
Duration	Use enough cycles to avoid single-day weather noise
Savings claim	Credit only statistically/operationally repeatable normalized reduction

Primary prototype pass condition: >=5% normalized HVAC kWh reduction with negligible comfort degradation. Stretch target: 8-12% in suitable homes. Fault-mediated savings after a repair are reported separately as maintenance recovery.

12. Field-Trial Protocol

Stage	Sample	Purpose
Alpha	1-3 homes	Instrumentation reliability and state-machine debugging
Pilot	5-20 homes	Baseline learning, false-alert rate, initial A/B control
Beta	50-100 homes	Savings distribution by climate/equipment/home type
Pre-commercial	250+ homes	Payback, installer burden, retention, support, failure rates

Recommended stratification

• Straight AC + gas furnace

• Single-stage heat pump

• Two-stage / variable-capacity equipment

• Heat pump with electric auxiliary heat

• Different home ages / insulation levels

• Flat-rate vs time-of-use pricing where available

13. Savings and Consumer Payback Model

Monthly HVAC spend	5%	8%	12%
$100	$5	$8	$12
$200	$10	$16	$24
$350	$17.50	$28	$42
$500	$25	$40	$60
Installed price	**$10/mo saved**	**$20/mo saved**	**$30/mo saved**
$250	25 mo	12.5 mo	8.3 mo
$400	40 mo	20 mo	13.3 mo
$600	60 mo	30 mo	20 mo

The consumer case improves when surge protection and equipment-health detection are included because those benefits exist even during mild-weather months when energy savings are small. The product should therefore be sold as HVAC protection + intelligence + adaptive efficiency, not solely as a bill-reduction gadget.

14. Consumer and Technician Interfaces

Consumer view

Field	Example
System health	94 / 100 - Normal
Model confidence	87%
HVAC cost this month	$146
AEEM-estimated savings	$13.40
Surge protection	Healthy / Unknown / Service
Action	No service needed

Technician view

Voltage, real watts, PF, start signature, cycle histogram, runtime by mode, aux-heat runtime, supply-return temperature spread, line-temperature trends, energy-per-result trend, fault evidence, confidence and raw-data export.

15. Production Roadmap

Version	Deliverable	Commercial gate
V0	Logger + health model	Accurate measurement and reliable diagnostics
V1	Isolated supervisory control	A/B proof of >=5% normalized savings
V1.5	Installer tooling + consumer app	Fast commissioning and low support burden
V2	Integrated outdoor product + SPD function	Safety/listing path and strong payback
V3	Utility / tariff integration	Additional bill optimization
V4	Future AEEM wireless node functions	Only if separately proven efficient and safe

16. Surge-Protection Integration

The product can legitimately include surge protection only when a dedicated surge-protective function is intentionally designed, validated and certified. UL Solutions identifies UL 1449 as the principal standard used for surge protective devices. A controller or power monitor alone is not an SPD.

```
PANEL / BRANCH CIRCUIT | v AEEM V2 +-- dedicated SPD stage +-- power metering +-- controller +-- HVAC isolated
I/O +-- SPD health/status monitoring | v EXISTING / LISTED LOCAL DISCONNECT | v HVAC EQUIPMENT
```

Prototype rule	Production rule
Use a commercially rated HVAC SPD as the reference module	Integrate only after SPD engineering/listing work
Read status/alarm contacts when available	Report protection health to consumer
Do not bench-test loose MOV networks on a live home circuit	Validate VPR, SCCR, nominal discharge and thermal behavior in certification path

17. Patent / Invention Disclosure Framework

Potentially protectable value is more likely to reside in the combined sensing/control method than in common components such as CTs, thermistors or relays.

Candidate inventive element	Disclosure focus
Weather-normalized HVAC fingerprint	Electrical + thermal response model tied to local equipment
Energy-per-result degradation detection	Detect performance drift before simple amperage alarms would
Confidence-gated consumer diagnostics	Diagnostic wording changes with sensor sufficiency and model confidence
Adaptive supervisory control	Uses learned building/equipment response to minimize kWh/cost subject to comfort and equipment cons
Integrated protection intelligence	Combines SPD health, equipment health and energy performance in one node
Dual-mode validation	Built-in observe/optimize alternation to continuously verify savings

Before filing, conduct a dedicated prior-art search covering smart thermostats, HVAC fault detection, disconnect-mounted monitors, compressor protection devices, surge protectors with telemetry, and energy-performance normalization. This document is an engineering disclosure framework, not a patentability opinion.

18. V0/V1 Harness and Connector Specification

The prototype harness should be modular so every sensor can be replaced without changing the controller PCB. Use keyed low-voltage connectors and label both enclosure and cable ends.

Port	Signals	Suggested connector class
J1 - Power	isolated low-voltage DC only	locking 2-pin
J2 - CT1	CT pair / shield if required	locking 2-3 pin
J3 - CT2	CT pair / shield if required	locking 2-3 pin
J4 - Temperature bus	multiple digital temp sensors	locking 3-pin bus
J5 - Indoor RH / temp	power, ground, data	locking 4-pin
J6 - HVAC calls IN	Y, G, W/AUX, O/B through isolation board	multi-pin pluggable terminal
J7 - HVAC supervisory OUT (V1)	isolated control contacts only	multi-pin pluggable terminal
J8 - SPD status	dry contact / rated status output only	locking 2-pin
J9 - Service	USB/UART, local only	service connector

The mains-voltage measurement subsystem should remain a separately rated/isolated module in the prototype. This package intentionally does not provide DIY conductor termination instructions for live 240-V HVAC circuits.

19. Firmware State Machine

```
BOOT | +--> SELF TEST | +--> sensor fault? --> SAFE OBSERVE | +--> LOAD CALIBRATION | +--> OBSERVE MODE | +-->
classify HVAC state +--> update cycle metrics +--> update confidence +--> run fault checks | +--> if V1 enabled
AND confidence sufficient | +--> SUPERVISORY MODE | +--> apply hard safety constraints +--> calculate candidate
action +--> comfort check +--> equipment-protection check +--> execute or reject | +--> fault / override /
watchdog --> BYPASS / SAFE OBSERVE
```

Non-negotiable firmware rules

• Never depend on internet connectivity for basic heating/cooling availability.

• User override wins immediately.

• Hard compressor anti-short-cycle constraints outrank optimization.

• Low model confidence disables aggressive control.

• Every control decision is logged with reason and pre/post state.

• Firmware update rollback path is required before field beta.

20. Prototype Completion Checklist

Area	Completion requirement
Mechanical	Outdoor enclosure, strain relief, labels, replaceable sensor harness
Electrical sensing	CTs + isolated real-power reference validated
Thermal sensing	Outdoor, supply, return, RH and line-temperature channels calibrated
HVAC calls	Y/G/W/O-B inputs correctly classified
Logging	Raw data + versioning + calibration metadata preserved
State machine	>=99% cycle/state detection target
Model	Useful confidence within <=14 days; stable by <=60 days target
Diagnostics	Confidence-gated alert taxonomy implemented
Control	V1 fail-safe bypass and hard compressor constraints
Validation	Observe/Optimize A/B protocol implemented
Commercial gate	>=5% normalized savings with negligible comfort penalty
SPD	Commercial reference status only until dedicated certification path

21. Current Reference Basis

• ENERGY STAR, Smart Thermostats FAQs: approximately 8% average heating/cooling bill savings for certified smart thermostats.

• ENERGY STAR, Smart Thermostats Key Product Criteria: certified devices must meet runtime-reduction criteria and report electric resistance heat use for heat pumps.

• U.S. Department of Energy, Fault Detection and Diagnostics: operational-data algorithms can identify faults and sometimes isolate root causes.

• U.S. Department of Energy, Optimizing Residential HVAC Systems (2026): digital installation-quality and fault-detection tools are being evaluated for residential HVAC.

• UL Solutions, Surge Protection Device Testing and Certification Services: UL 1449 is the principal SPD certification framework.

• NFPA NEC development materials, Article 440.14: HVAC disconnect location is within sight and readily accessible from the equipment.

Final engineering note: this package is sufficient to begin a safe V0 sensor/logger prototype and V1 low-voltage-control software architecture. A production device that interfaces with branch-circuit conductors, replaces a disconnect, or claims surge protection requires final electrical design, applicable code review, and product-safety/listing work.