OpenADR 3.0 Demand Flexibility for Heat Pump Water Heaters

IEA EBC Annex 96 — Activity A3

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Outline

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2. **Background** — OpenADR 3.0, demand flexibility, HPWHs
3. **Use Case** — Price-responsive HPWH control through OpenADR
4. **Software Architecture** — Components and data flow
5. **Implementation** — LP/heuristic schedulers and CTA-2045 integration
6. **How to Use** — Setup, run, and extend

1. Introduction

Water Heaters for Demand Flexibility

- Grid decarbonization requires flexible loads that can **shift consumption**
- Water heating accounts for **~18% of residential energy use**[1] (and up to ~40% in multifamily) in the US
- Field pilots show that water-heating load can be shifted or avoided during peak/price events [2]
- Heat pump water heaters (HPWHs) with storage tanks are ideal candidates:
  - Thermal storage enables **load shifting** without impacting comfort
  - Can pre-heat during cheap/clean hours, coast during expensive/dirty hours
- **Challenge:** How do we communicate price signals to devices at scale?

[1] https://www.energy.gov/energysaver/water-heating
[2] https://www.energy.gov/eere/buildings/articles/heat-pump-water-heaters-achieve-significant-peak-reduction-and-energy

Project Goals

Develop an **open-source software toolkit** so that researchers and practitioners can:

1. Set up an OpenADR 3.0 communication infrastructure (VTN + VEN)
2. Fetch dynamic electricity prices and publish it as OpenADR events
3. Run a control algorithm that converts price signals into HPWH schedules (triggering a change in operation of the HPWH)
4. Generate CTA-2045 demand response commands for water heaters
5. Test the full pipeline end-to-end on their own machines

> All code, documentation, and quickstart notebooks are publicly available.

2. Background

OpenADR 3.0

Open Automated Demand Response — an protocol for communicating DR signals.

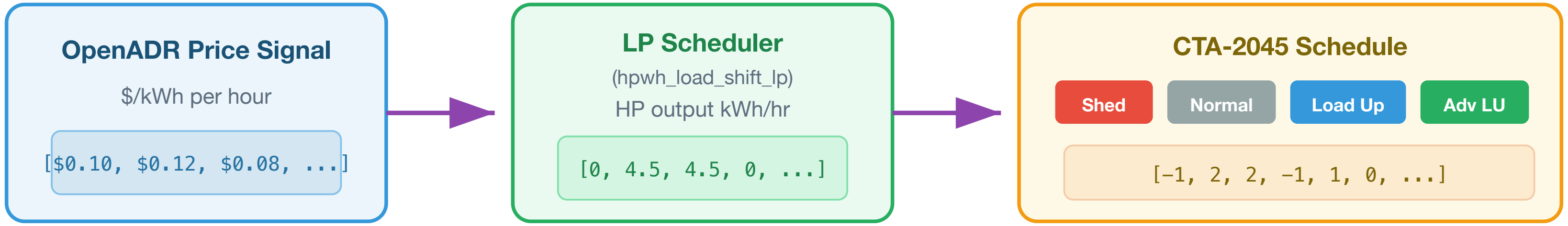
Concept	Description
VTN (Virtual Top Node)	Server — publishes programs, events, price signals
VEN (Virtual End Node)	Client — receives signals, controls devices
Program	Defines a demand response program (e.g., dynamic pricing)
Event	Time-based signal with payload (e.g., hourly prices)
Report	Telemetry data sent from VEN back to VTN

REST API (JSON over HTTP) with OAuth 2.0 authentication

CTA-2045 and Device Communication

CTA-2045 is a modular communications interface for energy devices, providing standardized demand response commands for water heaters:

Signal	DR Mode	Water Heater Action
Shed	-1	Lower setpoint, disable HP — coast on stored energy
Normal	0	Default operation
Load Up	1	Raise setpoint, pre-heat the tank
Adv. Load Up	2	Max setpoint, tight deadband

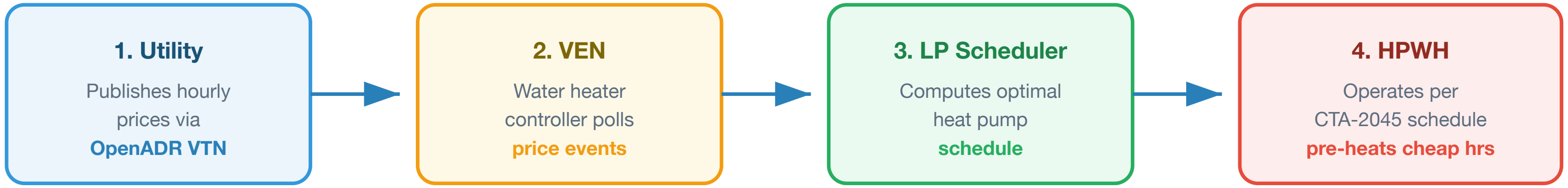


Full pipeline: OpenADR price signal → LP-optimal schedule → CTA-2045 commands

3. Use Case

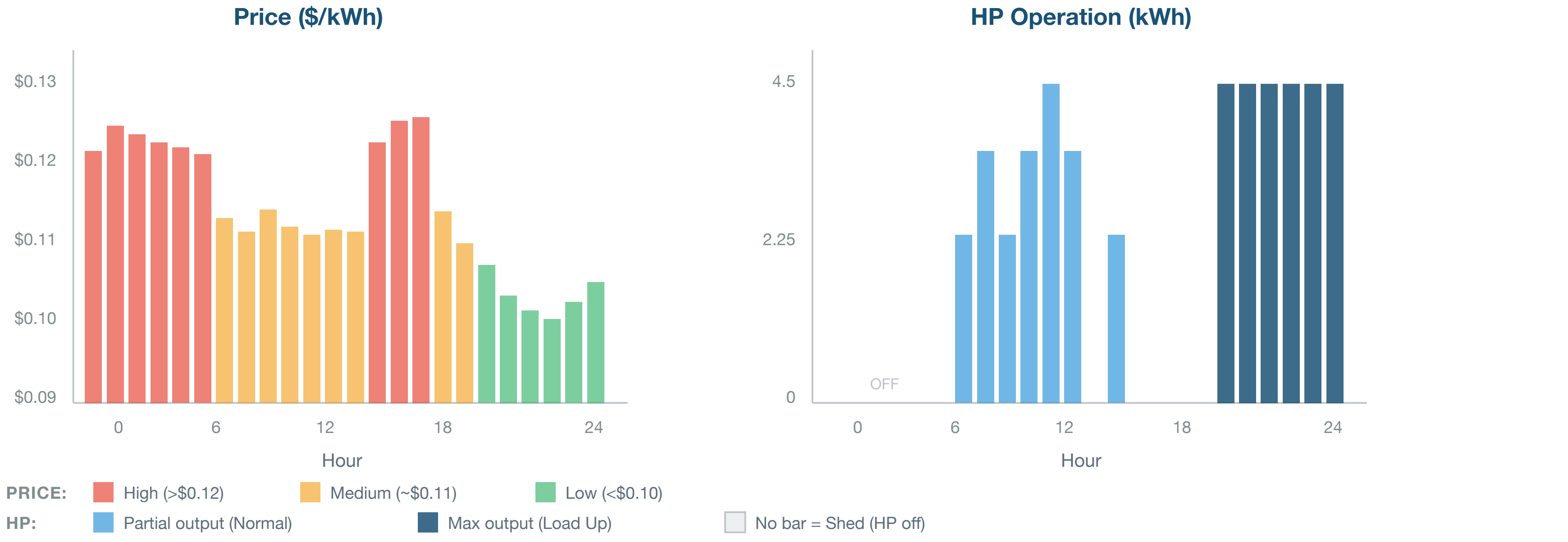
Price-Responsive HPWH Control Through OpenADR

Scenario: A utility publishes dynamic electricity prices. A water heater controller receives these prices and optimizes its operation schedule.



OpenADR 3.0 Price Signal → LP Scheduler → CTA-2045 Commands → Device Action

Example: 24-Hour Price Signal and Response



Result: Same hot water delivered at lower cost by shifting to cheap hours.

Assumptions

Parameter	Typical Value
Tank capacity	80 gallons
HP max output	4.5 kW thermal
COP	3 (constant)
Thermal storage	12 kWh
Minimum thermal storage	1 kWh
Average water draw	1.5 kWh per hour

These assumptions allow for the implementation of a simple *linear programming* controller.

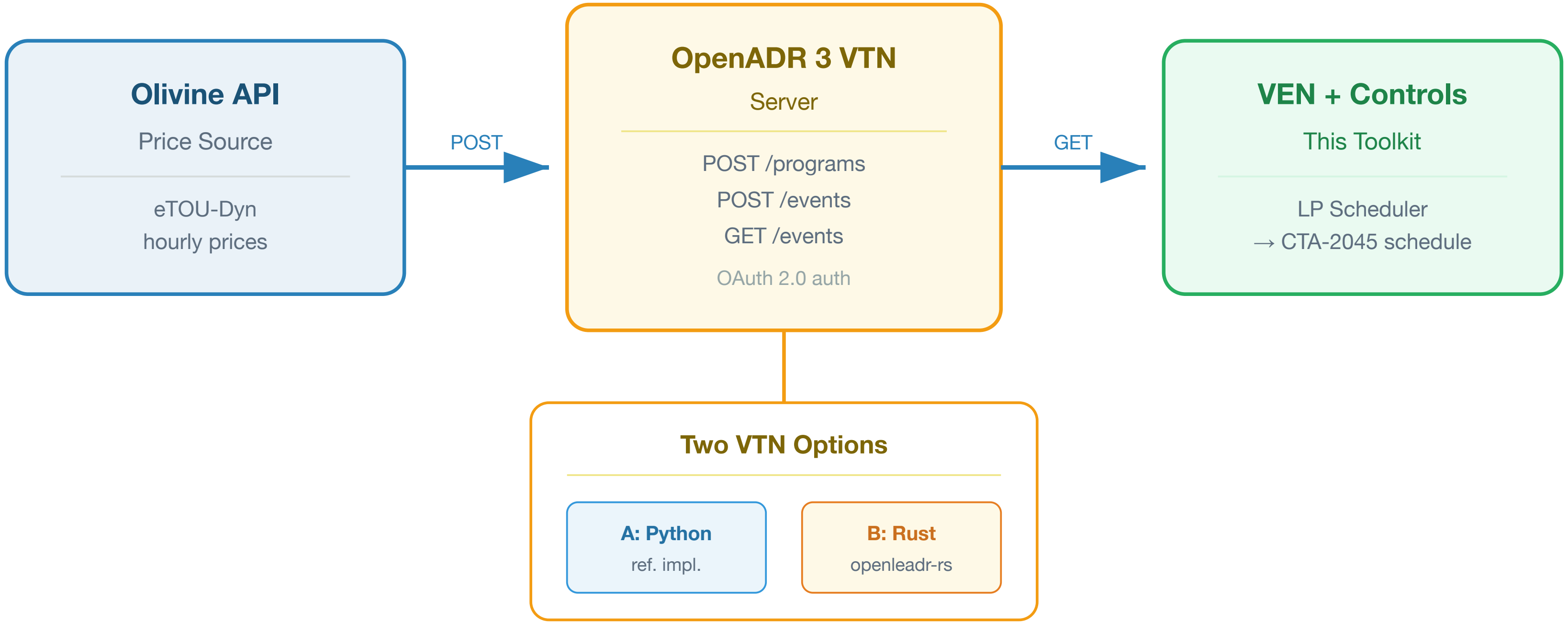
No reporting capability from the HPWH to the utiltiy has been configured in this demonstration.

4. Implementation

Repository Structure

```
annex96-a3-hotwater/
├── README.md                          # Project overview
├── requirements.txt                   # Python dependencies
├── instructions.ipynb                 # Setup: Python VTN
├── instructions-openleadr.ipynb       # Setup: openleadr-rs VTN
├── quickstart.ipynb                   # Demo: Python VTN
├── quickstart-openleadr.ipynb         # Demo: openleadr-rs VTN
├── controls/                          # Control algorithms
│   ├── hpwh_load_shift_lp.py          # LP scheduler (globally optimal)
│   ├── hpwh_load_shift_heuristic.py   # Heuristic scheduler (greedy)
│   └── cta2045.py                     # CTA-2045 schedule generation
├── sample_data/                       # Example JSON payloads
└── presentation/                      # This presentation
```

System Architecture



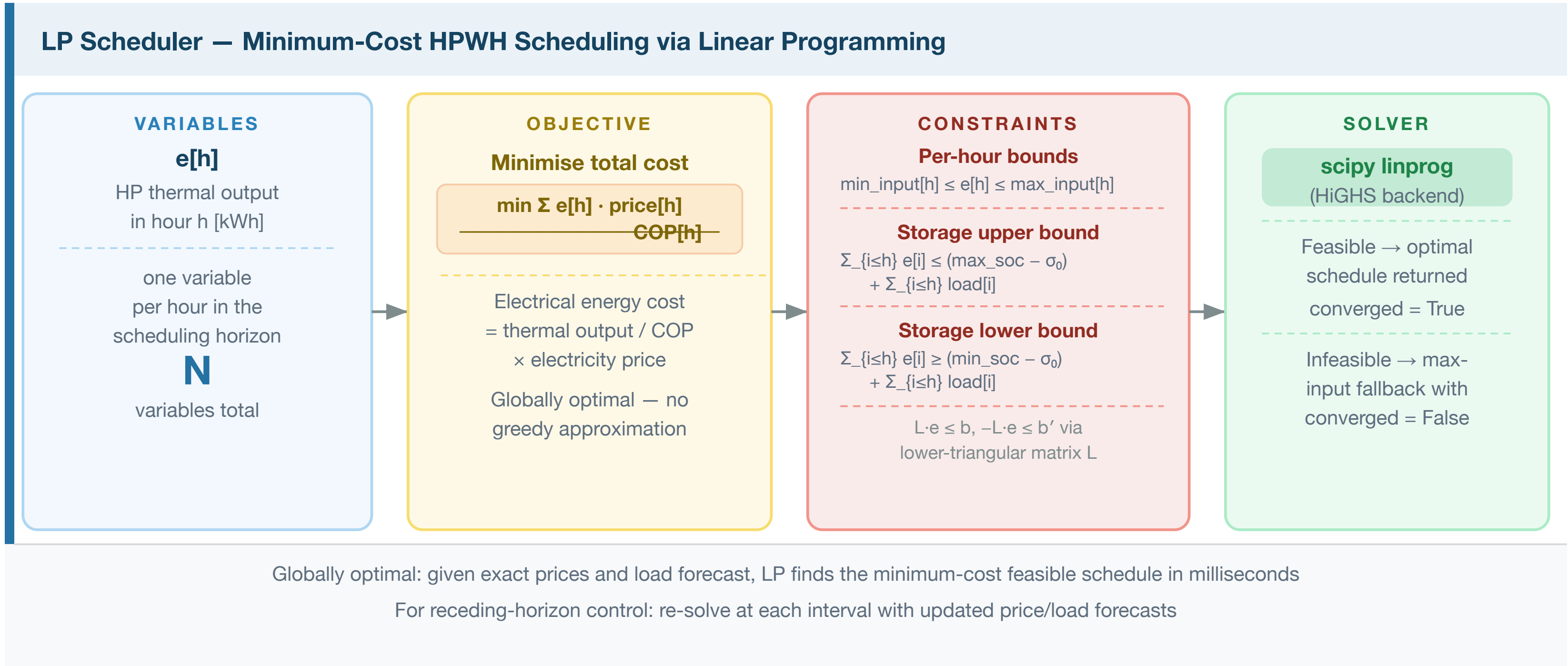
Two VTN Options

	Python VTN Ref. Impl.	openleadr-rs (Rust)
Language	Python (Flask)	Rust (Axum)
Database	In-memory	PostgreSQL (Docker)
Auth	`bl_client/1001`	`any-business`
Base URL	`localhost:8080/openadr3/3.0.1`	`localhost:3000`
Access	Contact for access	Open source
Best for	Quick local testing	Production-like setup

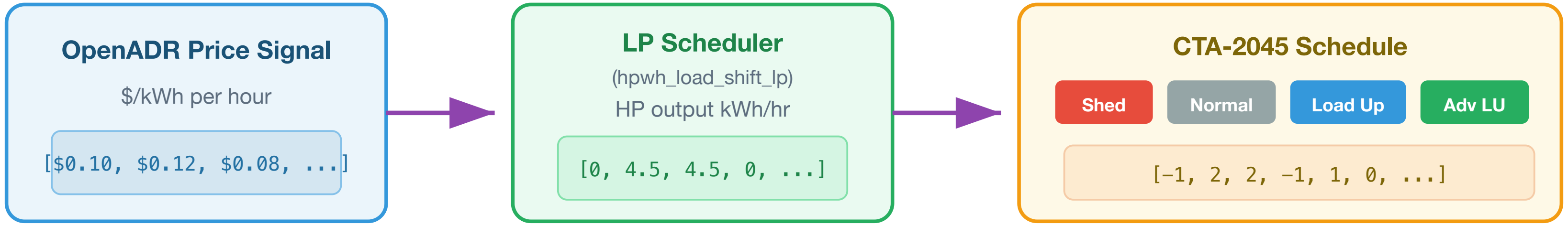
HPWH Load Shift Scheduler

Two interchangeable implementations in `controls/`: 1) **LP Scheduler** (`hpwh_load_shift_lp`) and 2) **Heuristic** (`hpwh_load_shift_heuristic`)

LP formulation: min Σ e[h]·price[h]/COP[h] subject to storage bounds and HP capacity bounds.



CTA-2045 Schedule Generation



Full pipeline: OpenADR price signal → LP-optimal schedule → CTA-2045 commands

Quickstart Demo Pipeline

```
# Step 1: Authenticate with VTN
token = get_token("bl_client", "1001")

# Step 2: Fetch prices from Olivine API
olivine_data = requests.get(OLIVINE_PRICING_URL).json()

# Step 3: Create pricing program on VTN
requests.post(f"{VTN}/programs", json=program_data, headers=auth)

# Step 4: Publish price event
requests.post(f"{VTN}/events", json=event_data, headers=auth)

# Step 5: Read events as VEN
events = requests.get(f"{VTN}/events", headers=ven_auth).json()

# Step 6: Run LP Scheduler → Step 7: Generate CTA-2045 schedule
schedule, converged = hpwh_load_shift(params)
cta_schedule = hpwh_load_shift_to_cta2045(schedule, params)
```

Example Output

```
LP status: Optimization terminated successfully (HiGHS Status 7: Optimal)

Hourly schedule (kWh):
  Hour  0: OFF   0.00 kWh  @ $0.12052/kWh   →  Shed
  Hour  1: OFF   0.00 kWh  @ $0.12227/kWh   →  Shed
  ...
  Hour 18:  ON   1.50 kWh  @ $0.11120/kWh   →  Normal
  Hour 19:  ON   1.50 kWh  @ $0.10689/kWh   →  Normal
  Hour 20:  ON   1.50 kWh  @ $0.10519/kWh   →  Normal
  Hour 21:  ON   1.50 kWh  @ $0.10300/kWh   →  Normal
  Hour 22:  ON   1.50 kWh  @ $0.10620/kWh   →  Normal
  Hour 23:  ON   1.50 kWh  @ $0.10930/kWh   →  Normal

Total electricity cost: $0.28741
```

LP finds the globally optimal allocation — charges exactly what is needed at the cheapest hours.

Quickstart: Step by Step

Each step — inputs, what it does, outputs, and what to change for your implementation

Example notebook: https://github.com/anandkp92/annex96-a3-hotwater

Step 1: Setup & Verify VTN Connection

1

Setup & Verify VTN Connection

Exchange credentials for an OAuth token; confirm the VTN is reachable

INPUTS

- **VTN_BASE_URL**
  localhost:8080/openadr3/3.0.1
- **BL_CLIENT_ID / SECRET**
  Business Logic credentials
- **VEN_CLIENT_ID / SECRET**
  VEN read-only credentials

WHAT IT DOES

POST /auth/token

grant_type: client_credentials
→ returns JWT Bearer token

GET /programs

Confirm VTN returns HTTP 200
(raises exception if offline)

OUTPUTS

- **access_token**
  Bearer JWT for API headers
- **bl_headers() helper**
  Authorization header for BL calls
- **ven_headers() helper**
  Authorization header for VEN calls
- **Confirmed VTN is live**
  exception raised if not running

CUSTOMIZE

→ VTN implementation: change VTN_BASE_URL to localhost:3000 (no path prefix) for openleadr-rs
→ Credentials: update CLIENT_ID / SECRET to match your VTN's user fixture (see instructions.ipynb)
→ Token caching: get_token() is called per request; cache the token for higher-throughput use
→ TLS: replace http:// with https:// and pass verify= cert path for non-local deployments

Step 2: Fetch Dynamic Prices from Olivine

2

Fetch Dynamic Prices from Olivine

Fetch eTOU-Dyn dynamic electricity prices from the Olivine API

INPUTS

- **OLIVINE_PRICING_URL**
  api.olivineinc.com/…/etou-dyn
- **Accept: application/json**
  HTTP request header

WHAT IT DOES

GET OLIVINE_PRICING_URL

Parse vtnComment → metadata dict

Parse dtstart → start_time

Extract eiEventSignals intervals

```
price = interval["streamPayloadBase"]
[0]["item"]["value"]
```

Repeats for each interval (N hours)

OUTPUTS

- **prices [$/kWh] × N hrs**
  one price per scheduling hour
- **start_time (datetime)**
  pricing window start (ISO 8601)
- **intervals (raw list)**
  full API response for reference
- **metadata (dict)**
  retailer, rate name, date range

CUSTOMIZE

→ Price source: replace OLIVINE_PRICING_URL with any hourly price feed, RTO/ISO API, or local file

→ Load from file: read a CSV/JSON with [hour, price_$/kWh] columns instead of a live API call

→ Horizon: N = len(intervals); slice to a shorter window for faster re-runs or sub-day scheduling

→ Units: algorithm assumes $/kWh — convert if your data source uses ¢/kWh, mills, or other units

Step 3: Create Pricing Program on VTN

3

Create Pricing Program on VTN

Register a program definition that groups related price events on the VTN

INPUTS

- **OAuth token (Step 1)**
  via bl_headers()
- **programName**
  "etou-dynamic-pricing"
- **payloadDescriptors**
  [{payloadType: PRICE, units: KWH}]

WHAT IT DOES

POST /programs

Register program definition on VTN
VTN assigns a unique program_id

program_id links all future events
to this program (Step 4)
VENs can filter events by program_id
to subscribe to specific tariffs

OUTPUTS

- **program_id**
  "0" (Python VTN) or
  UUID (openleadr-rs)
- **Stored program record**
  persists on VTN until deleted
- **Confirmed HTTP 201**
  creation verified via raise_for_status()

CUSTOMIZE

→ programName: any descriptive string matching your tariff (e.g. "eTOU-Dynamic", "real-time-pricing")
→ Payload type: PRICE (absolute $/kWh) or PRICE_RELATIVE (delta from a baseline price)
→ openleadr-rs extras: add programType, retailerName, country, principalSubdivision fields
→ Reuse: query GET /programs first and skip creation if a matching program already exists

Step 4: Publish Price Signal as an Event

4

Publish Price Signal as an Event

Package the fetched prices as an OpenADR 3 event and post it to the VTN

INPUTS

- **prices + start_time (Step 2)**
  hourly prices and window start
- **program_id (Step 3)**
  links event to program
- **OAuth token (Step 1)**
  via bl_headers()

WHAT IT DOES

Format each hour as an interval:

```
{id: hour, payloads: [{type:
"PRICE", values: [price]}]}
```

POST /events

Event stored on VTN server

Any auth'd VEN can now read it

via GET /events (Step 5)

OUTPUTS

- **event_id**
  stored event identifier on VTN
- **N intervals on VTN**
  queryable by all VENs
- **Linked to program_id**
  VENs can filter by program
- **HTTP 201 confirmed**
  raised if creation fails

CUSTOMIZE

→ Interval duration: "PT1H" (1 hr default) — OpenADR 3 also supports "PT15M" for 15-minute intervals
→ Price rounding: round(price, 5) — adjust decimal places to match utility data precision requirements
→ Multiple events: publish separate events per tariff zone, VEN group, or building type
→ Event expiry: set intervalPeriod.duration to automatically expire stale events on the VTN

Step 5: Read Events as a VEN

5

Read Events as a VEN

Simulate the water heater controller reading price signals from the VTN

INPUTS

- **VEN_CLIENT_ID / SECRET**
  VEN credentials (Step 1)
- **VTN_BASE_URL**
  same server as Steps 3–4
- **(Optional) programID**
  filter events by program

WHAT IT DOES

GET /events (as VEN)

Sort intervals by interval id
for each payload where
payload["type"] == "PRICE":
prices.append(values[0])

Prices now ready for the
LP Scheduler (Step 6)

OUTPUTS

- **prices [$/kWh] × N hrs**
  same prices, from VEN perspective
- **events[] (raw list)**
  full event objects from VTN
- **event metadata**
  eventName, intervalPeriod.start

CUSTOMIZE

→ Filter by program: append ?programID=X to GET /events to subscribe to a specific tariff
→ Multiple programs: loop events[] and select by evt["programID"] for multi-tariff deployments
→ Real deployment: replace this notebook GET with a persistent VEN client process (e.g. openleadr-python)
→ Report-back: POST /reports to send HPWH telemetry (SOC, temperatures, energy use) to the VTN

Step 6: Run LP Scheduler

6

Run LP Scheduler

Solve for the globally optimal HP schedule that minimises cost while meeting load

INPUTS

- **price [$/kWh] × N hrs**
  from Step 5 — prices list
- **max_input / min_input [kWh]**
  HP thermal capacity bounds
- **max/min_storage_capacity**
  tank bounds + initial_soc [kWh]
- **load [kWh/hr] × N hrs**
  hot-water draw profile
- **cop [list, per hour]**
  heat pump efficiency profile

WHAT IT DOES

hpwh_load_shift(params)

① Build LP objective: min Σ e[h]·price[h]/COP[h]
② Per-hour bounds: min_input ≤ e[h] ≤ max_input
③ SOC upper bound via L·e ≤ b_max
④ SOC lower bound via −L·e ≤ b_min
⑤ Solve with scipy linprog (HiGHS)

Infeasible → max-input fallback
converged = False

OUTPUTS

- **control[h] [kWh/hr]**
  optimal HP thermal output per hour
- **cost[h] [$/hr]**
  electricity cost per hour
- **converged (bool)**
  True = optimal found
  False = fallback to max-input

CUSTOMIZE

→ HP capacity: set max_input to your HPWH spec in kW (= kWh at hourly time steps)
→ Tank size: max_storage_capacity ≈ 12 kWh per 80-gal tank; min_storage_capacity = reserve
→ Draw profile: replace [avg_draw]*N with a measured or simulated hourly hot-water draw schedule
→ Swap solver: replace with hpwh_load_shift_heuristic for a greedy alternative (no scipy needed)

Step 7: Generate CTA-2045 Schedule

7 Generate CTA-2045 Schedule

Map the HP schedule to discrete demand-response commands for the water heater

INPUTS

- **schedule dict (Step 6)**
  schedule["control"] per hour
- **params (Step 6)**
  params["max_input"] per hour

WHAT IT DOES

hpwh_load_shift_to_cta2045(sched, params)

fraction = control[h] / max_input[h]

fraction = 0%	Shed (–1)
0% – 30%	Normal (0)
30% – 80%	Load Up (1)
≥ 80%	Adv LU (2)

Repeat for every hour in horizon

OUTPUTS

- **signals per hour**
  list of [-1, 0, 1, 2] values
- **signal_names per hour**
  ["Shed", "Normal", ...]
- **Formatted schedule string**
  via format_schedule() for logging
- **plot_schedule() figure**
  bar chart of signals over time

CUSTOMIZE

→ Thresholds: change 30% and 80% in hpwh_load_shift_to_cta2045() to match your device's response curve
→ Price-based mapping: use prices_to_cta2045(prices) instead — assigns signals by price percentile
→ Physical control: replace format_schedule() print with an API call to your HPWH hardware
→ Fleet deployment: loop over units and call hpwh_load_shift() + hpwh_load_shift_to_cta2045() per device

5. How to Use This Software

Quick Setup

1. Clone and install

```
git clone <repository-url>
cd annex96-a3-hotwater
pip install -r requirements.txt
```

2. Start a VTN (choose one)

Option A: Python VTN (contact anandkrp@andrew.cmu.edu for access)

```
cd openadr3-vtn-reference-implementation
virtualenv venv && source venv/bin/activate
pip install -r requirements.txt && python -m swagger_server
```

Option B: openleadr-rs (open source — see `instructions-openleadr.ipynb`)

Run the Quickstart

3. Launch the notebook

```
jupyter notebook quickstart.ipynb           # for Python VTN
jupyter notebook quickstart-openleadr.ipynb  # for openleadr-rs
```

4. What the notebook does

Step	Action
1–2	Connect to VTN, fetch dynamic prices from Olivine API
3–4	Create pricing program, publish hourly price event
5	Read events as a VEN
6	Run LP Scheduler and plot optimal schedule
7	Generate CTA-2045 command schedule

Extending the Software

- **Customize HPWH parameters** — Edit Step 6: tank size, HP capacity, COP, draw profile
- **Use your own price data** — Replace Olivine API with your own source
- **Swap the scheduler** — `hpwh_load_shift_lp` (optimal) ↔️ `hpwh_load_shift_heuristic` (no scipy needed)
- **Integrate with CTA-2045 hardware** — Connect generated schedules to physical devices
- **Connect to a real VEN** — Replace notebook HTTP calls with a persistent VEN client

Resources and References

- **Repository:** `annex96-a3-hotwater/`
- **OpenADR 3.0.1 Spec:** included in repo, or openadr.org
- **openleadr-rs:** github.com/OpenLEADR/openleadr-rs
- **Olivine API:** `api.olivineinc.com/i/oe/pricing/signal/paced/etou-dyn`
- **scipy linprog / HiGHS:** scipy.org — LP solver used by the scheduler

Thank You

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All source code and documentation available in the `annex96-a3-hotwater` *repository*