Methodology
PV Self-Sufficiency for Heating Energy

How much of the electricity for heating is covered by the photovoltaic system (including battery)?

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1. Problem Statement

A household uses two split-unit heat pump systems for heating. Electricity is supplied from three sources: a photovoltaic (PV) generator, a battery storage system, and the public grid. All energy flows are measured at a consistent time resolution (e.g., 15-minute or hourly intervals). The goal is to determine what fraction — and what absolute amount — of the heating electricity is covered by the local PV system (including battery) over the course of the heating period.

2. Known Time-Resolved Data

The following quantities are available for each timestep t of the heating period:

Symbol	Description	Unit
PV(t)	PV production	kWh / interval
BAT_in(t)	Energy flowing into the battery (charging)	kWh / interval
BAT_out(t)	Energy flowing out of the battery (discharging)	kWh / interval
GRID_in(t)	Energy imported from the public grid	kWh / interval
GRID_out(t)	Energy exported to the public grid	kWh / interval
HEAT(t)	Electricity consumed by heating systems	kWh / interval
OTHER(t)	All other household consumption	kWh / interval

OTHER(t) may be known directly or derived from the energy balance (Section 3).

3. Energy Balance Verification

At every timestep the following balance must hold — a useful consistency check before any attribution calculation:

```
PV(t) + GRID_in(t) + BAT_out(t)  =  HEAT(t) + OTHER(t) + GRID_out(t) + BAT_in(t)
  (all sources)                         (all sinks)
```

If OTHER(t) is not directly measured:

```
OTHER(t) = PV(t) + GRID_in(t) + BAT_out(t) - HEAT(t) - GRID_out(t) - BAT_in(t)
```

Note: In typical home systems import and export do not occur simultaneously within the same interval (GRID_in > 0 implies GRID_out ≈ 0, and vice versa). The same applies to battery charge and discharge. If the data shows simultaneous flows, net them before proceeding.

4. The Battery's Role — and a Critical Subtlety

The battery shifts solar energy in time: it absorbs excess PV production during the day and releases it at night. This creates a temporal dependency between daytime and nighttime flows. If the heating system uses solar energy during the day, the battery charges less. Later, when the battery discharges less at night, the grid must make up the difference. So while heating may appear 100% solar-powered at noon, it has indirectly caused grid consumption at night.

Two distinct questions arise:

- **Flow attribution (Method A):** At each moment, what fraction of the energy flowing to the heating system came from local sources? This is a symmetric, instantaneous question.
- **Causal / marginal attribution (Method B):** How much additional grid energy did the heating system cause the household to consume — taking the battery opportunity cost into account? This is a counterfactual question.

These two questions have different answers and require different methods, as detailed in Sections 5 and 7.

5. Method A — Proportional Flow Attribution

Step 1 — Local (PV + Battery) Supply at Each Timestep

```
LOCAL(t) = PV(t) - GRID_out(t) - BAT_in(t) + BAT_out(t)
```

Interpretation of each term:

- PV(t): total solar generation
- - GRID_out(t): subtract the portion exported (leaves the home)
- - BAT_in(t): subtract the portion stored in the battery (not yet consumed)
- + BAT_out(t): add back energy the battery releases to loads now

From the energy balance it follows that LOCAL(t) + GRID_in(t) = LOAD(t) exactly, so the split is well-defined and self-consistent.

Step 2 — Local Self-Supply Fraction

```
LOAD(t)    = HEAT(t) + OTHER(t)
f_local(t) = LOCAL(t) / LOAD(t)       [ranges 0 … 1]
```

Proportionality assumption: All loads within a timestep draw from local and grid sources in the same proportion. This is physically appropriate for a standard home without smart load-routing controls.

Step 3 — Attribute Heating Consumption

```
HEAT_local(t) = HEAT(t) x f_local(t)
```

Step 4 — Sum Over the Heating Period

```
E_heat_total = SUM  HEAT(t)
E_heat_local = SUM  HEAT_local(t)

SSR_heat = E_heat_local / E_heat_total x 100 %
```

Summary Formula

```
             SUM [ HEAT(t) x LOCAL(t) / LOAD(t) ]
SSR_heat  =  ■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■  x 100 %
                        SUM  HEAT(t)

where  LOCAL(t) = PV(t) - GRID_out(t) - BAT_in(t) + BAT_out(t)
```

```
         LOAD(t)  = HEAT(t) + OTHER(t)
```

6. Does Method A Capture the Battery Opportunity Cost?

Yes — correctly, provided the calculation is done at fine time resolution. The concern is: 'if I use solar for heating during the day, the battery charges less, so the grid must supply more at night.' This is correct, and the proportional method does reflect it:

- At noon: heating uses solar → BAT_in(t) is smaller → battery charges less.
- At night: less stored energy → BAT_out(t) is smaller → LOCAL(t) is smaller → f_local(t) is lower → a larger fraction of nighttime heating is attributed to the grid.

> **Critical requirement:** This only works if the calculation is performed at the original fine time resolution (15-minute or hourly data). If you aggregate to daily totals first, you lose all temporal information.

Rule: always calculate at the finest available time resolution, then sum.

7. Method B — Counterfactual (Marginal) Attribution

Concept

Method B answers: 'How much extra grid energy did the heating system cause, considering that using solar for heating reduces how much the battery can store?' The approach is to simulate what the system would have done without any heating load, then compare total grid imports:

```
Extra grid due to heating = SUM GRID_in_actual(t) - SUM GRID_in_counterfactual(t)

Solar fraction (marginal) = 1 - Extra grid / Total heating energy
```

How to Run the Counterfactual Simulation

Without a heating load, the battery would have charged more during the day (limited only by battery capacity and PV surplus). A simplified greedy maximum-self-consumption battery dispatch model simulates this:

- Net surplus = PV(t) - OTHER(t)
- If surplus > 0: charge battery up to available capacity; export remainder.
- If surplus < 0: discharge battery to cover deficit; import remainder from grid.

The simulated grid import series from this model gives GRID_in_counterfactual(t).

What the Counterfactual Method Adds

Method B assigns the full nighttime grid shortfall (caused by incomplete daytime battery charging) to the heating load. Method A allocates the same shortfall proportionally between heating and other nighttime loads. In practice the difference is modest for systems with adequate battery capacity and grows larger when heating significantly competes with battery charging.

8. Illustrative Numerical Example

A simplified day with two timesteps (noon and night). At noon, heating uses 1.0 kWh of solar that would otherwise have gone into the battery — so the battery charges 1.5 kWh instead of 2.5 kWh. At night the battery runs short and 0.5 kWh of grid import is needed.

Input data:

Timestep	PV	BAT_in	BAT_out	GRID_in	GRID_out	HEAT	OTHER
Noon	3.0	1.5	0	0	0	1.0	0.5
Night	0	0	1.5	0.5	0	1.5	0.5

Method A — Proportional:

Timestep	LOCAL	LOAD	f_local	HEAT_local
Noon	3.0-0-1.5+0 = 1.5	1.5	100%	1.000 kWh
Night	0-0-0+1.5 = 1.5	2.0	75%	1.125 kWh
Total				2.125 kWh

Solar fraction = 2.125 / 2.5 = **85%**

Method B — Counterfactual:

Without heating: battery charges 2.5 kWh at noon → fully covers night load → GRID_in = 0 at night.

```
Extra grid due to heating = 0.5 kWh (actual) - 0.0 kWh (counterfactual) = 0.5 kWh
Solar fraction = 1 - 0.5 / 2.5 = 80%
```

Interpretation of the difference (85% vs. 80%): Method A allocates the 0.5 kWh of nighttime grid import proportionally across heating and other loads (assigns 0.375 kWh grid to heating). Method B recognises that all 0.5 kWh was caused by heating displacing battery charging during the day, and assigns the full 0.5 kWh to heating.

9. Which Method to Use?

	Method A (Proportional)	Method B (Counterfactual)
Question answered	What fraction of heating energy was locally sourced at the moment of consumption?	How much extra grid energy did the heating system cause?
Data required	Measured flows only	Measured flows + battery dispatch simulation
Captures battery temporal effects?	Yes, via measured flows at fine resolution	Yes, fully and causally
Complexity	Low	Moderate
Standard in practice?	Yes (industry standard)	Niche / research use
Typical result	Slightly higher solar fraction	Slightly lower solar fraction

For most purposes — assessing how well the PV system covers heating, comparing heating seasons, reporting — **Method A at fine time resolution** is the correct and standard approach.

Method B is valuable when you want to answer a causal question: 'What would my grid bill look like if I didn't heat at all?' or when optimising heating schedules to maximise solar self-sufficiency. It requires building a battery simulation model, but gives a more rigorous causal attribution.

10. Practical Implementation Notes

Time resolution: Always compute at the finest available resolution (15-minute data preferred). Never aggregate to daily totals before computing the ratio.

Battery charged from grid: If the battery is sometimes charged from the grid, the origin of battery energy must be tracked using a state-of-charge fraction method. Define SOC_PV(t) as the fraction of battery charge of solar origin, and apply it to BAT_out(t) to separate solar vs. grid contributions.

Edge cases:

- If LOAD(t) = 0: skip the timestep.
- If LOCAL(t) < 0 due to data noise: clamp to zero.
- If f_local(t) > 1 due to measurement error: clamp to 1.

Heating period definition: Restrict the analysis to months/hours where the heating system is actually active, to avoid diluting the result with summer or shoulder-season data where HEAT(t) = 0.

11. Relevant Publications

The following peer-reviewed papers provide the theoretical foundation for the methods described above. Availability was verified at time of writing (April 2026).

Weniger, J., Tjaden, T., & Quaschning, V. (2014). Sizing of residential PV battery systems. *Energy Procedia*, 46, 78–87. DOI: 10.1016/j.egypro.2014.01.160. — Defines the greedy maximum-self-consumption battery dispatch algorithm used in Method B's counterfactual simulation. 320+ citations.

Quoilin, S., Kavvadias, K., Mercier, A., Pappone, I., & Zucker, A. (2016). Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Applied Energy*, 182, 58–67. DOI: 10.1016/j.apenergy.2016.08.077. — Methodological reference for SSR/SCR calculation with timestep-level battery simulation. Open GitHub repository available.

Sun, S.I., Kiaee, M., Norman, S., & Wills, R.G.A. (2018). Self-sufficiency ratio: an insufficient metric for domestic PV-battery systems? *Energy Procedia*, 151, 150–157. DOI: 10.1016/j.egypro.2018.09.040. — Argues that SSR (Method A) does not fully capture system-level consequences; advocates for comprehensive modelling. Open-access PDF at eprints.soton.ac.uk.

Yu, H.J.J. (2021). System contributions of residential battery systems: New perspectives on PV self-consumption. *Energy Economics*, 96, 105151. DOI: 10.1016/j.eneco.2021.105151. — Explores battery system contributions beyond standard SSR, aligned with the causal thinking behind Method B.

Wang, Z., Luther, M.B., Horan, P., et al. (2023). On-site solar PV generation and use: Self-consumption and self-sufficiency. *Building Simulation*, 16, 1835–1849. DOI: 10.1007/s12273-023-1007-3. — Covers the combination of PV, battery, and heat pump for heating and cooling using TRNSYS simulation — closest in setup to the system described in this document.

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