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Research Article

Grid flex rhymes with derivatives trading: an observation

Damon Hart-Davis[1,*], Matthew Leach[1], Lirong Liu[1]

[1] Centre for Environment and Sustainability, University of Surrey, Guildford, UK
* Correspondence: d.hart-davis@surrey.ac.uk

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Abstract

Introduction: To eliminate the ~15% of UK greenhouse gas emissions due to home heating most will move to heat pumps by 2050. But electrifying heating will roughly double peak demand on the grid while green intermittent renewables such as wind and solar make available generation less predictable. Most of us will need to learn to flex our home space heat and hot water and other electricity demand else we will pay a high premium, but we do not all have to flex in the same ways at the same times to support the greening grid.

Materials and methods: This study synthesises existing literature and first-hand observations from investment banking derivatives and the energy system, along with primary data from one UK home enumerating a number of viable techniques.

Results: Static and dynamic demand-side flexibility responses, automated and manual, have visibly moved the case study home's load profile away from that of a typical Great Britain (GB) household on winter weekdays when national demand is highest.

Conclusions: A portfolio approach with a mixture of different grid flexibility responses across the housing stock, including those driven by Time-of-Use tariffs, can be a first-class contribution to Net Zero.

Keywords: grid; flexibility; renewables; demand-side response; fixed-income derivatives; distributed systems

1. Introduction

Residential heating is responsible for 10–20% of the UK's carbon footprint [1], mainly through tonnes of CO_2 leaving the flues of gas boilers each year in each of the ~20 million homes which are due to still be in use in 2050 [2–4]. Home heating must decarbonise as part of UK and global Net Zero goals to tackle climate change. To meet this existential imperative, we must *use less*, such as through the smarter direction of heat to where it is needed [5–7]. This will apply to cooling as domestic demand grows. Also, as we electrify everything, we must *better time* when we use that heating (and other) energy, in an interesting new interplay between habit and renewable generation availability and grid capacity. This paper observes one UK home and its heating energy data as a case study to explore how some different aspects can be improved and lessons can be learned from quite a different technical area.

1.1. The changing grid: supply and demand

Just before the turn of the century, the grid in Great Britain (GB)—there is no 'UK' grid, rather the GB grid and the Single Electricity Market for the island of Ireland, which Northern Ireland has been a part of since late 2007—had somewhere over 100 major coal, gas and nuclear generators [8]. A few years into this century, renewables (wind and solar) started to contribute significantly. The EC Large Combustion Plant Directive in 1988, though intended to combat acid rain, was the start of the phase-out of coal thermal generation, with the last shutdown in late 2024 [9]. The UK government's Clean Power 2030 Action Plan [10] aims to reduce GB grid carbon intensity from 171 gCO_2e/kWh in 2023 to "well under" 50 gCO_2e/kWh in 2030. As of 2026, along with large gas and nuclear generators, there are hundreds of utility-scale (multi-megawatt) solar and wind farms, tens of thousands of 'embedded' generators on the distribution network, over 1.6 million (mid-2026 [11]) embedded solar PV (PhotoVoltaic) microgeneration systems in UK homes, distributed battery storage at utility scale and "behind the meter" in tens of thousands of homes. This means that from a few centrally owned and managed generators that could have output called upon on demand, the GB grid has evolved to become a significantly renewable-supplied system with much generation available intermittently and with control distributed over millions of machines and the entire geography.

At the same time, patterns and habits of use, in part driven by office work changes such as working from home post-COVID-19; the shift in mass entertainment away from a few broadcast TV channels, blunting the very British grid demand "TV pick-ups" around popular programmes and major sporting fixtures as kettles were boiled to make tea [12]; and the starting of electrification for Net Zero [13], have made demand prediction harder [14], with real costs to the system and thus ultimately to energy users including householders.

What grid operators would like is steady demand and steady generation to match it, and transmission and distribution lines just big enough to meet that steady demand. But instead, both the supply and demand sides are becoming more complex to model and manage, though they still have to be balanced every second of every day, and the transmission and distribution lines have to be rated for maximum demand, if lights are to stay on. As one example, the lowest demand on the GB grid was until recently at night, ~4 am, but now, with significant solar PV generation, that minimum can be around solar noon. Indeed, NESO (the GB National Energy System Operator) reported on 24 May 2026 that the GB grid saw its lowest ever demand at solar noon on that bank holiday weekend.

1.2. Structure of this paper

This paper qualitatively introduces and extrapolates a method used in financial markets to divide ('slice-and-dice') bundles of behaviour unpalatable to any single market participant, including risk and stochastic unpredictability part-driven by external events, and to pass them on piece-wise to third parties that can handle them, and indeed that have a positive appetite for those individual pieces. This mode of operation of financial markets, the electricity grid, and other multi-million-participant systems such as the Internet—as huge distributed systems with shared control—is noted as a key part of their modern and fast-evolving incarnations.

A case-study London home's heat demands have been electrified and shaped to meet the overall goals of utility energy Net Zero while supporting the grid by reducing net imports at times of grid stress, with methods ranging from monitoring frequency to scheduling hot water production away from expected GB domestic demand peaks.

The Discussion considers trade-offs in managing intermittent generation and less predictable demand, solar and wind resources in GB, static vs. dynamic flexibility and how both are supported in existing GB retail electricity tariffs, and what services homes can provide to the grid.

1.3. Derivatives slice and dice

In the financial markets, "derivatives" trading desks are tasked with converting money or cash flows with one set of characteristics into another "derived" form that works better for a client or the market. This may be as simple as exchanging a stream of variable cash flows for known fixed flows, known as a "swap". "Securitisation" may support much more complex goals, such as increasing the diversity of funding sources and liquidity for sustainable development [15, 16].

Sometimes the task is to extract extra value from a pool of trades, such as chopping up a book of 1000 residential 20-year mortgages into parts more attractive than the original. Some mortgagors will pay the exact agreed monthly payment steadily until the end of the contract; pension funds would like to buy this slice of the flows to match long annuity liabilities. Some mortgagors will pay off quickly, for example to switch to a new deal or because they will receive a bonus or inheritance; there is lots of demand for this short-tenor (length) lending slice. Some mortgagors will pay irregularly or even default and there are buyers for this risky portion of the portfolio in return for a higher interest rate than the two previous slices. A consumer mortgagee bank or other originator (such as a UK building society) may sell off that 1000-strong portfolio to a 'structurer' who will slice and dice to create a CMO (Collateralised Mortgage Obligation) or similar; see **Figure 1**. The original bank now has a clean sheet without liabilities and liquid funds from the structurer (the Net Present Value) to go out and conduct new mortgage business. The structurer takes in all the mortgage repayments and issues the CMOs to those three (or more) third-party institutions and the cash flows that they imply. Consumers get easier and cheaper mortgages and the third parties get their cash flow needs fulfilled better. Sometimes these methods over-extend or go badly wrong in extreme circumstances and have to be pulled back [17, 18], rhyming with the constant refinements and retrenchments in the details of algorithms in other complex evolving distributed systems, such as TCP/IP (Transmission Control Protocol over Internet Protocol), which has carried much of the Internet's data, including email and web pages [19–21].

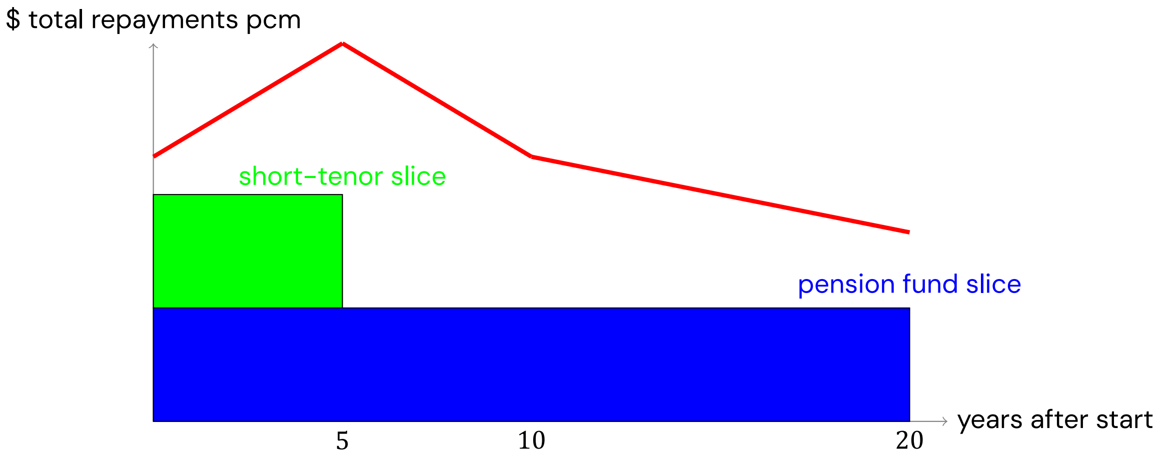


Figure 1. Simplified abstract CMO (Collateralised Mortgage Obligation) total repayment cash flow segmentation chart, with flows for two different tenors/lengths extracted. The remainder below the total-monthly-repayments red line carries more risk as it includes late and missed payments and defaults.

The fixed-income derivatives market has learned that outsourcing the sliced-and-diced curve simplifies the bank's books and has the bank able to do more business sooner. The differing flexibilities and appetites of other financial institutions can match the stochastic behaviour of the mortgagors over time, even the parts that go wrong. The same is true of many millions of grid-connected consumers and generators, as described below. The electricity system has not been sleeping and fits generation to demand better with 'flexibility': incentivising the slicing and dicing and morphing of demand in various ways [22–24].

In GB retail energy supply tariffs (**Table 1**), an analogue to the first two CMO slices in **Figure 1** is buying short- or longer-term fixed-price energy deals with a fixed single rate per kWh for their duration from months through to years; the retailer will embed a premium to absorb the prediction risk of wholesale supply and inflation, amongst other factors. The nearest comparison to the final slice currently may be the Octopus Agile tariff, exposing the user to a (capped) simple linear formula over day-ahead wholesale prices in each of 48 half-hour periods, passing through risk- and event-driven changes; the retail customer immediately shares some costs with Octopus during generation shortages, but may also receive low or negative pricing during periods of oversupply. The retail energy supplier is in each case slicing and dicing to extract these distinct tariffs from the wholesale market and other operational parameters.

Table 1. A brief description of GB retail electricity tariffs mentioned in this paper.

Name	Description
Single rate	Same unit (kWh) price for electricity throughout the day.
Economy 7	Differential/ToU tariff since 1978 featuring a low night unit rate for 7 h, possibly not continuous.
EDF Energy FreePhase	ToU domestic electricity tariff with three price bands: red: 4 pm–7 pm (peak, expensive); amber: 6 am–4 pm and 7 pm–11 pm; green: 11 pm–6 am (off-peak). The dynamic version unit rates change daily, while static fixes rates over 24 months.
Octopus Agile	Beta 'smart' ToU domestic tariff. "Between 4–8 pm every day (usually nearer 4 pm), your unit rates are updated for the next 24 hours, based on the wholesale market rates." Separately for each half-hour slot in the day, the kWh price (in pence) formula as of is $min(D.W + P, 95)$, where D includes distribution costs (varies by UK region), W is the wholesale price in that half hour, P is a peak-time-only premium (varies by UK region) and 95 is the cap.
Octopus Cosy	ToU: "3 rate tariff with triple dip Cosy Hours every day: eight hours of super cheap electric to warm your home."
Octopus Intelligent Flux	ToU: "With solar & storage you could earn up to £300 more than you pay for electricity" … "pairs with your battery to optimise your charging and discharging to save you money and help balance the grid."

kWh: kiloWatt hour (energy); ToU: Time-of-Use.

1.4. Research question

The problem and the research question being explored here are: given that GB grid demand is growing fast with Net Zero electrification, that low-carbon renewable generation is largely not callable on demand, and that the shape of both demand and supply are becoming less predictable, can 'slice-and-dice' techniques learnt many years ago in quite unrelated areas be applied to home heating (and other) demand and meaningfully contribute to keeping the grid reliable and affordable?

GB electricity demand has long been about one-third domestic [25, 26] and roughly a tenth of that has also long been flexible heat load via off-peak ToU (Time-of-Use) tariffs such as Economy 7 (**Table 1**), so a flexible component has been a significant part of all electrified space and water heating historically. EV (electric vehicle) and widespread cooling demand are new, and in many cases are being placed on the market with flexibility features from the outset. With smart meters in over two-thirds of GB homes and Internet control adding new more nimble and palatable opportunities, there are significant and growing deployable resources. The referenced home case study is posited as a supporting example and an existence proof of this.

Conceptually the abstraction being examined for applicability to domestic electrification for Net Zero is the management of a complex demand and supply curve over various dimensions by segmentation and repackaging ('slice-and-dice') of such a curve into a diverse set of independent and/or co-operating subcomponents with differing complexity and other features, driven by the value that reflects the risk and agility of each subcomponent. A distributed solution-by-parts approach is first class here, not failure. An example of such a demand and supply curve segmentation can be seen in **Figure 1**.

1.5. Contribution of this paper

The first author observes, after many years working in investment banking and then thinking about smart grid interactions, that while the grid dynamics of electrifying heat are not exactly repeating derivatives history, the divide-and-conquer story rhymes sufficiently well to be a useful Net Zero tool.

2. Materials and methods

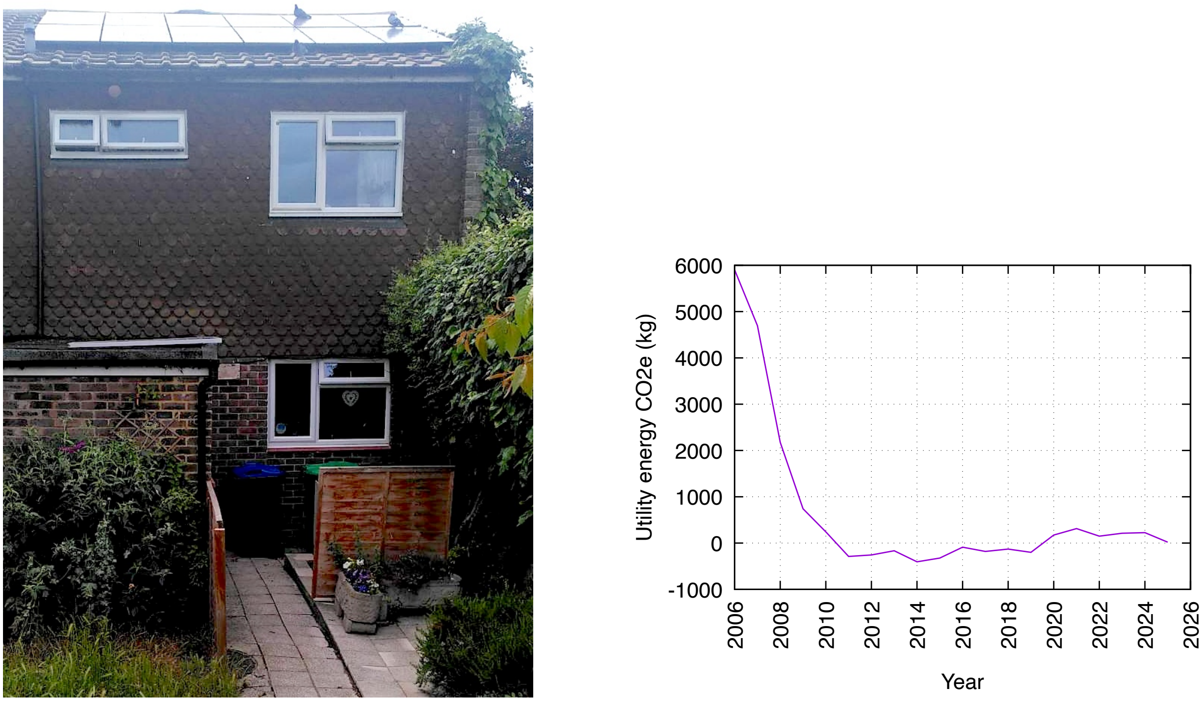
This study synthesises the existing literature and first-hand observations on the potential of bringing perspectives and techniques from investment banking derivatives to bear on supporting Net Zero through the electrification of heat with a rapidly rising fraction of grid renewable generation.

Primary data from one case study illustrates how one UK home contributes to these goals in multiple ways, and how others might, as none of the techniques employed are applicable only to that home.

2.1. 16WW home

"16WW" (**Figure 2**, 16 Willingham Way) is the first author's three-bedroom 76 m^2 end-of-terrace timber-frame house in a suburb of London, UK. It has been improved incrementally in terms of the fabric, such as through internal wall insulation, triple glazing and heat recovery (it is now EPC class A) and lights and appliances, over many years; has a single-rate—non-Time-of-Use (ToU)—'green' electricity supply; and has been approximately zero carbon for utility energy for several years. 16WW also has an entirely off-grid solar PV system covering some small loads.

As of 2026 the 16WW grid-connected energy systems (behind the meter) are: a 5.16 kWp solar PV system on east- and west-facing pitched roofs, a 6.2 kWh (1.3 kW) AC-coupled battery (connected to the Alternating Current mains, not the PV directly), a 4 kW_t air-to-water heat pump (ASHP) for DHW (Domestic Hot Water) with tank and space heat with smart radiator valves for automatic occupancy-driven microzoning, and a ~7 kWh_t phase-change DHW heat battery; see **Table 2** and **Figure 3**. The solar PV microgeneration was installed before the AC-coupled electrical battery system, and the two are entirely independent and autonomous (no run-time control is exercised over them by other systems). The A2W ASHP (Air-to-Water Air-Source Heat Pump) likewise has no external real-time control, but does have detailed static schedules programmed to keep demand away from expected grid demand peaks. The solar diverter is the main focus of the real-time reactive/dynamic grid response to frequency and voltage and carbon intensity, primarily through choosing whether to divert available solar PV generation to DHW and how much, but also when to boost from the grid for legionella control. The TMV (Thermostatic Mixing Valve) preferentially supplies DHW draw-off at the hot taps from the heat battery if hot enough, or else from the DHW cylinder, and also limits DHW temperature at the taps to ~50 °C for safety. The radiators' space-heat emitters are each managed by a smart occupancy-responsive and occupancy-predicting TRV (Thermostatic Radiator Valve) [7]. A newer installation should probably avoid the complexity of the heat battery and install a larger electric battery instead. The occupancy of the home is usually three. Energy consumption is extensively monitored at several levels from manually read calibrated supply and generation meters as the local root of 16WW's nominal calibration chain—such meters are required to be within ±1% (Class B) or sometimes ±2% (Class A) per UK Measuring Instruments Regulations (MIR)—through to per-minute PV generation and house and heat-pump consumption. Storage activity for both heat and electricity is also monitored and recorded. Static time-based and dynamic real-time responsive mechanisms are used together, some automated and some manual, to meet overall 16WW goals for carbon footprint reduction, grid support, and utility cost reduction. More details are provided below and are subject to some restrictions for privacy and security; the energy and related data is published per the Data availability statement. 16WW serves as proof of what *can* be done, but the high level of monitoring and direction conducted by the atypical first-author resident should be kept in mind, and the 16WW model cannot be directly generalised to most households.



(**a**) (**b**)

Figure 2. (**a**) The front view of 16WW with some roof-mounted solar panels visible. (**b**) 16WW utility energy carbon footprint ($kgCO_2e$) by year; the calculation methodology changed in 2020 to dynamic hour-by-hour imports/exports multiplied by the live GB carbon intensity implied by the Elexon FUELINST reported generation mix at [27]. CSV available per Data availability statement.

Table 2. 16WW grid-connected microgeneration and heating (space heat and DHW) that participate in grid demand response. Instantaneous maximum power and storage capacity are e electric or t thermal. Live grid-responsive control for the grid-based systems is primarily exercised via the MyEnergi diverter with a nominal 1 min or faster response, though storage state and grid carbon intensity are computed on 5 or 10 min cycles.

Subsystem	**Power (kW)**	**Capacity (kWh)**	**Grid response dynamic/static**	**Notes**
Solar PV	5.1_e	-	d: autonomous	Grid failure and voltage/frequency response per GB grid standard G83 (now G98). Sanyo HIT PV, SMA SunnyBoy 1100/1200 inverters.
Heat pump	4_t	-	s: scheduled DHW temperatures and space heat weather comp -ve delta	Schedule times avoid grid demand peaks, and half-hour price-change boundaries. Daikin Altherma 3 M, MPN EDLA04E2V3.
Radiators, TRVs	3.2_t	-	s: weather comp delta	Micro-zoned occupancy-responsive hydronic space heating; output power at design day conditions. Radbot (UK) TRVs, MPNs 2R and 1.
Diverter	3_e	-	d + s: grid frequency, voltage, carbon intensity; heat battery state	Modulated dual outputs, to DHW cylinder and heat battery. MyEnergi (UK) Eddi V1, MPN MYEN-EDDI-16A1P01.
Battery	1.3_e	6.2_e	d: autonomous	AC-coupled. Enphase MPN 800-00560-r03 + 4× equiv.
Heat battery	3_e	$\sim 7_t$	d + s: via diverter	Phase-change. ~30 kW_t to DHW. Sunamp (UK) Thermino 150ePV, MPN SKP-BAW-ATZ-1. Coupled to DHW cylinder via Intasol (UK) diverter/TMV, MPN 555CSD1.
DHW cylinder	3_e	$\sim 6_t$	d + s: via diverter	Primarily heated by the heat pump, but diversion/boost immersion heat used for anti-legionella pasteurisation at times of excess PV or grid low carbon intensity. Secon (UK) 180l, MPN TRSMVH-0180SFC.

None of these subsystems require day-to-day manual intervention after set-up; heat is available when needed. Subsystems without energy storage are marked '-' under Capacity. AC-coupled: connected to the Alternating Current mains, not directly to the Direct Current solar PhotoVoltaic microgeneration; DHW: Domestic Hot Water; kW: kiloWatt (power); kWh: kiloWatt hour (energy); MPN: Manufacturer Part Number; TMV: Thermostatic Mixing Valve; TRV: Thermostatic Radiator Valve.

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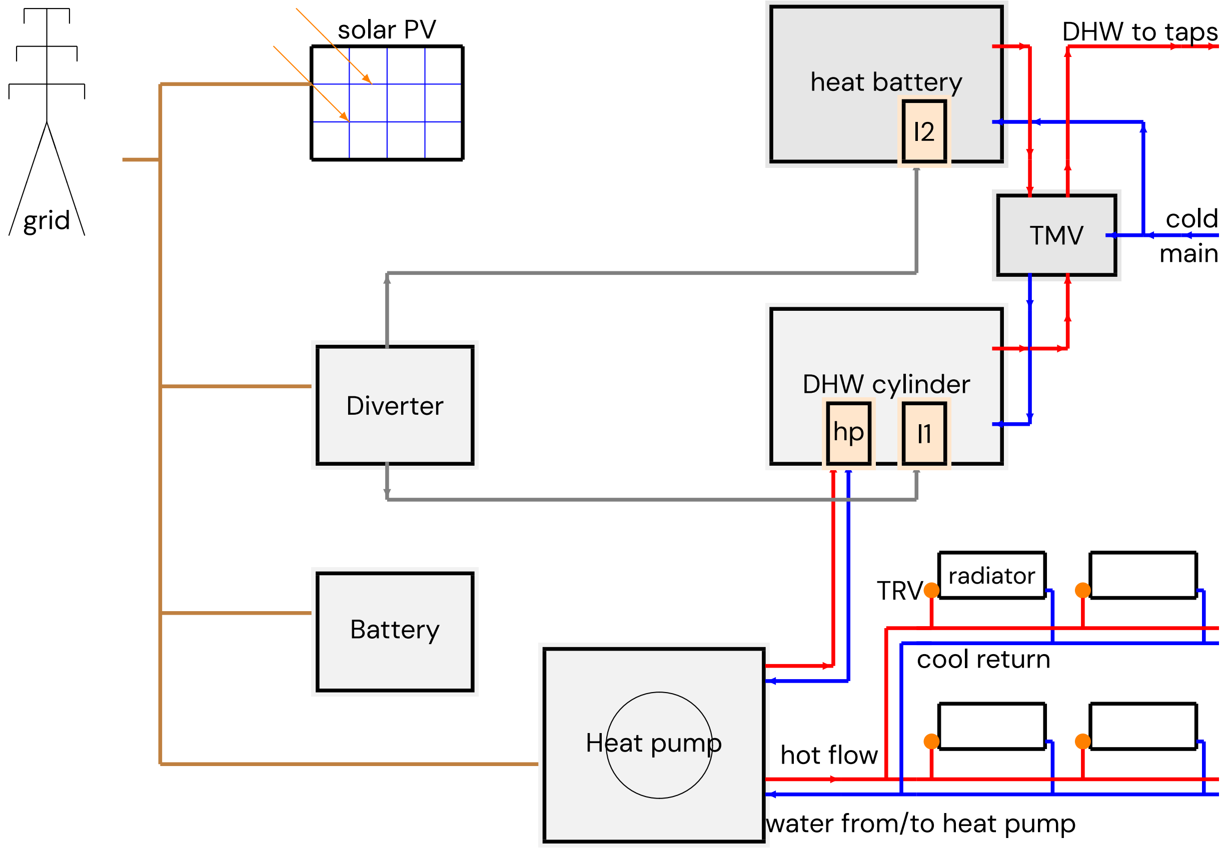

Figure 3. Simplified schematic of 16WW grid-connected heat equipment as of the start of 2026. The system consists of solar PV (PhotoVoltaic) microgeneration, a solar power diverter, an AC-coupled electric battery, a phase-change heat battery, a DHW (Domestic Hot Water) cylinder, a TMV (Thermostatic Mixing Valve), an A2W ASHP (Air-to-Water Air-Source Heat Pump) for DHW and space heating, and 'hydronic' radiator emitters to deliver space heating, with each radiator managed by (orange) TRV (Thermostatic Radiator Valve). Flows: red—hot water, blue—cold/return water, grey—modulated electricity, brown—mains electricity. I1 and I2 are electric immersion heaters.

2.2. 16WW merit order

A 'merit order' applies to the use of PV microgeneration at 16WW, which embodies some grid responsiveness. This scheme almost eliminates grid imports for half the year, shapes import and export profiles and provides dynamic and static support. A simplified summary, with the highest priority first, follows:

(1) Direct consumption in the house; minimised with efficient appliances and improved building fabric
(2) Absorption by the AC-coupled battery up to its kW/kWh capacity; dynamically reduces flow to and from the grid and increases self-consumption
(3) Power-limited spill to grid (max ~300 W); will be absorbed by a few neighbouring households so will not cause voltage-rise problems for the local network, and yields better carbon-reduction potential than conversion to heat
(4) Diversion to the DHW cylinder if a pasteurisation cycle is due or else to the heat battery to their kW/kWh capacities; dynamically reduces grid flow and in particular imports for heat
(5) Spill any remainder to the grid

Avoid diverting to DHW (usually the heat battery) or boosting when:

- Grid frequency drops below 49.9 Hz (~6% of the time); this dynamically provides support when demand outstrips generation

Also avoid diverting to DHW (usually the heat battery) when:

- Local grid voltage is low (<236 V); this dynamically provides support when local (or national) demand is high
- The grid 7-day carbon intensity is in the top quartile; this dynamically provides support when there is little low-carbon generation
- During grid predefined peak demand periods; this statically provides support at expected high-demand times
- The heat battery gets more full at a higher grid carbon intensity or before solar noon; this dynamically shapes and reduces exports at times when other solar generation is likely to be abundant

The responses to a combination of live grid carbon intensity and storage state help to minimise carbon emissions [28] and solar noon exports.

A snapshot of the `eddiFreqResponse` production diverter management script, which implements the merit order dynamic response, is included alongside the supporting data (see Data availability statement).

3. Results

In the first author's home, 16WW, static and dynamic ('demand-side') flexibility responses, both automated and manual, have visibly moved its load profile away from that of a typical GB household on winter weekdays when national demand is highest (Elexon reference) when compared with the 16WW weekday net load profile for Q4 (December 2025, i.e., mid-winter in the UK) in **Figure 4** (see also **Table 3**). The Elexon Class 1 typical GB home has a mean import power of ~541 W, full-day energy import of ~13 kWh, peak demand of 921 W in the interval starting at 18:00Z, and peak:mean ratio of ~1.7. Shown is 16WW's weekday net grid load profile in four seasons. Each trace is the average net load on the grid for the given interval UTC over the specified month, i.e., 16WW's 'load profile' or 'load curve'. In the winter plot (Q4, yellow curve) the initial (~06:15Z) and final (~20:15Z) peaks are water heating, and the second-last (~17:30Z) peak is preparation of an evening meal; all of these avoid the reference main morning and evening GB grid peaks to some degree. The morning DHW run timing was chosen after observing DHW draw-offs (inferred from temperature drops in the heat battery), indicating the majority of DHW demand to be in the hour from 07:00, and to avoid the ~07:00 DHW peak heating energy demand identified in [29] [Table 3]; see also [26] [§ 3.4.1] and [13]. The quarter curves have a 15 min resolution. For Q4, mean weekday (net) import power is ~385 W, full-day (net) import energy is ~9.2 kWh, peak (net) demand is ~2.5 kW in the interval starting 06:15Z, and peak:mean ratio is ~6.5, with (net) import power at a grid peak of 18:00Z at 491 W and so ~1.3× the mean (and lower absolute demand), thus easing peak grid strain compared to the Class 1 1.7× as well as with total daily import. Note how 16WW moves from importer in winter (Q4) to exporter in summer (Q2); year-round, 16WW is a small net exporter. The reshaping of these 16WW profiles is mainly the result of static scheduling of the heat pump away from peaks; unmanaged heat pumps might double peak GB grid demand [13, 30, 31]. Also contributing is the manual scheduling of loads, such as the dishwasher being timed to run in the early hours of the morning outside of summer, or else in sunny hours. The current mode of operation of the AC-coupled battery to locally minimise flows to and from the grid, and given its relatively low instantaneous power limit, brings the 16WW net grid demand curve towards zero rather than moving peaks; see **Figure 5**.

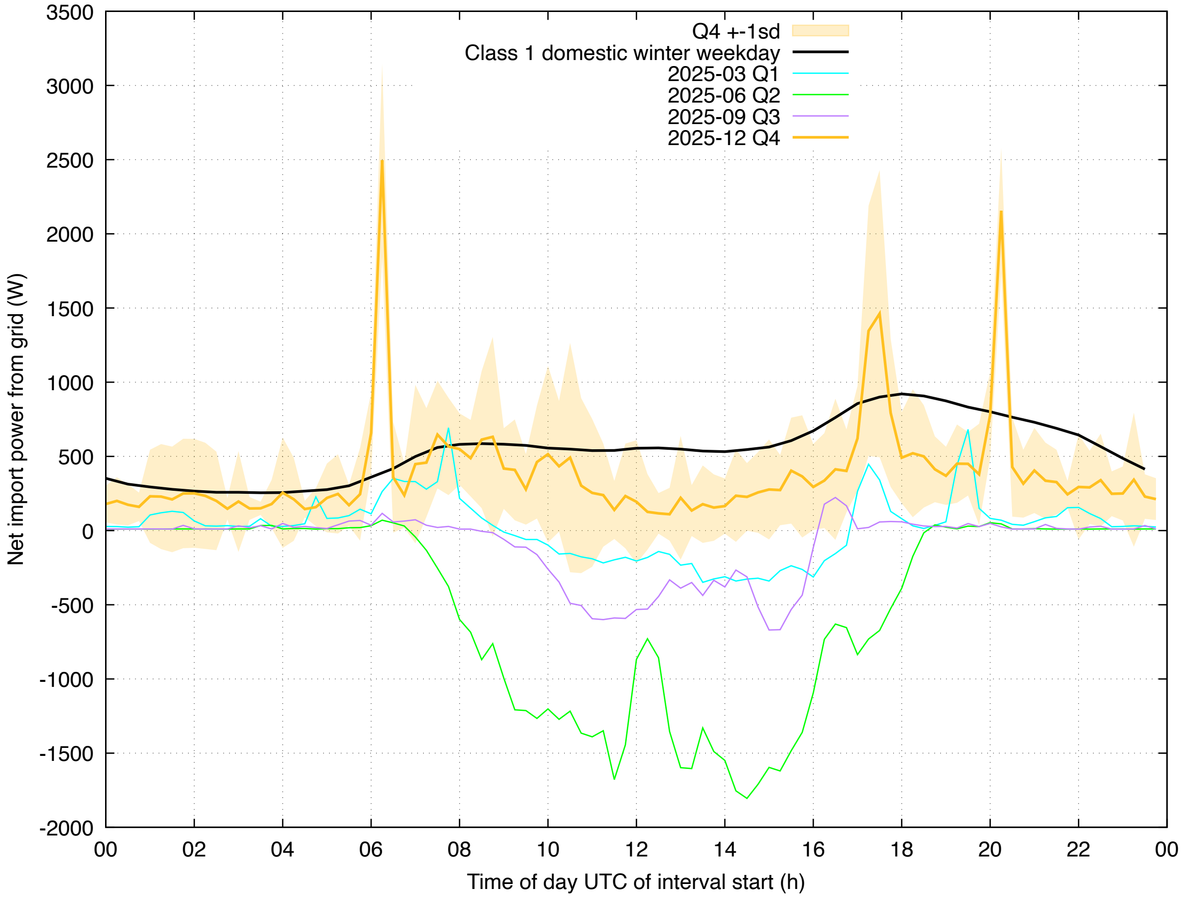

Figure 4. 16WW grid net load profile vs. GB (Great Britain) domestic reference. All times in UTC, with no daylight saving applied. The black curve is the reference Elexon Profile Class 1 Domestic Unrestricted Customers (excludes Economy 7) average winter weekday (Monday to Friday, excluding holidays) demand for a typical home on the GB grid. Overlaid is 16WW's weekday (Monday to Friday) net grid load profile for one month in each of the four quarters/seasons (Q1 spring cyan, Q2 summer green, Q3 autumn violet, Q4 winter yellow). Each trace is the average net load on the grid for the given interval over the specified month. A ± 1 standard-deviation dispersion band is shown for Q4. Data sources: Elexon (half-hourly, extracted from December 2020) and 16WW AC-coupled battery system (15 min). CSVs available per Data availability statement.

3.1. Static schedules

In **Figure 6**, underlying complexity in the provision of static response is visible, requiring three independent heat-pump schedules to achieve the desired result and move demand away from Smart Secure Electricity Systems (SSES [32]) and current GB grid peaks. DHW temperature scheduling and heat-pump power management by proxy through 'quiet' settings do most of the load curve shaping, with more in winter through a temperature delta on the space-heating weather compensation (WC) curve where lowering the radiator flow temperature reduces energy demand through improved efficiency but takes longer to get rooms warm. (With the previous gas boiler, the heating was set to be off from about 16:00–19:00 to avoid the relatively small load contribution of the circulation pump in that interval. A similar period of the heating being off around 18:00 would be something that any household still on gas heating might consider to help the energy transition by shaving peak demand a little.)

The DHW schedule with typical usage starts the heat pump at 06:10 (before morning peak) and at 20:10 (after evening core peak). The 16WW space heating receives a call for heat when any of the smart TRVs open up and call for heat; a WC delta during grid peaks reduces demand. The power schedule reduces maximum heat-pump power during the two usual DHW runs to enable the AC-coupled battery to carry all or most of the heat-pump demand. Timings of changes in the schedules are set to avoid hour and half-hour boundaries where pricing changes may induce synchronised 'herding' of demand changes across the GB grid. 16WW treats weekdays and weekends identically for most purposes, but grid peaks tend to be higher on weekdays and some households could respond to this better. There is currently no integrated dynamic management of the 16WW heat pump as part of the rest of the home energy system nor as part of any wider external VPP (Virtual Power Plant) scheme.

Table 3. Selected 16WW results including overall demand reduction vs. Ofgem 2023 TDCVs (Typical Domestic Consumption Values) [33]; 16WW has low demand even absent the benefit of its solar microgeneration. Winter load profile vs. typical home per **Figure 4**. Items marked '-' do not have a clear public comparator. See [34] for live 16WW energy time series. CSVs available per Data availability statement.

Metric	16WW value	Comparator	Comparator/value	Notes
Grid imports kWh (2025)	1303	TDCV class 1 low (medium)	1800 (2700)	Typically non-electric-heat homes.
	1303	TDCV class 2 low (medium)	2200 (3900)	Typically Economy-7.
Gross consumption kWh (2025)	3619	TDCV class 2 medium	3900	As if no solar microgeneration.
Net imports kWh (2025)	−328	-	-	Net exporter, 2026 est > 800 kWh/y.
Electricity bill GBP (2025)	620	UK 2025 average	1069	Excludes 16WW Feed-in-Tariff payment.
Winter import kWh/d (2025Q4)	9.2	Elexon class 1 domestic	13	Full day.
Winter weekday at peak demand W (2025Q4)	491	Elexon class 1 domestic	921	Half hour starting at 18:00Z, 1.3× mean for 16WW, and 1.7× for Class 1.
Summer all-days noon export avoidance W (2025Q2)	1151	diversion + export	2006	Automatically diverted 57% power fraction to DHW during hour starting 12:00Z.
Low-frequency response minutes (2025)	3566	-	-	Fast dynamic net export maximisation, primarily in summer daytime.

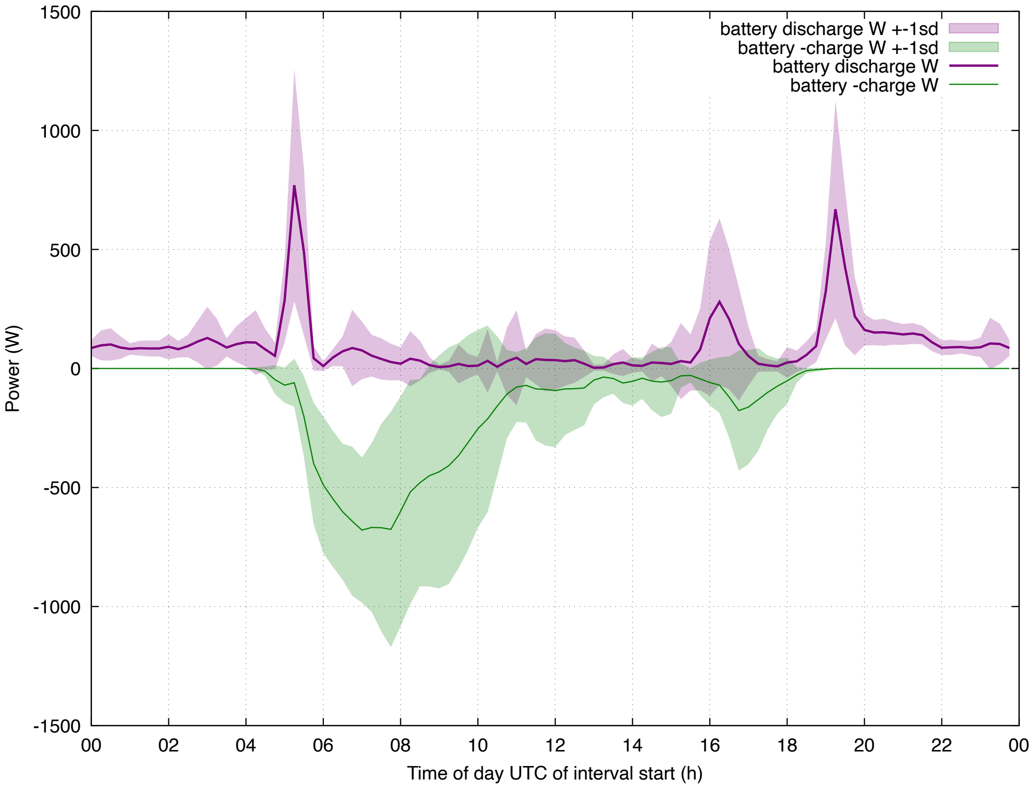

Figure 5. By-hour-of-day (UTC) AC-coupled battery discharge and charge profile for May 2026. The left-most and right-most peaks in discharge (violet, above zero) are consumption by the heat pump for DHW (Domestic Hot Water), and the next-to-right peak partially covers evening meal preparation. In the current scheme there is never any draw from the battery for DHW except during occasional pasteurisation cycles overnight in darker months when diversion cannot provide the ~3 kWh in one session that is required. A ± 1 standard-deviation dispersion band is shown. All-week 15 min granularity data captured via the Enphase AC-coupled battery system. CSVs available per Data availability statement.

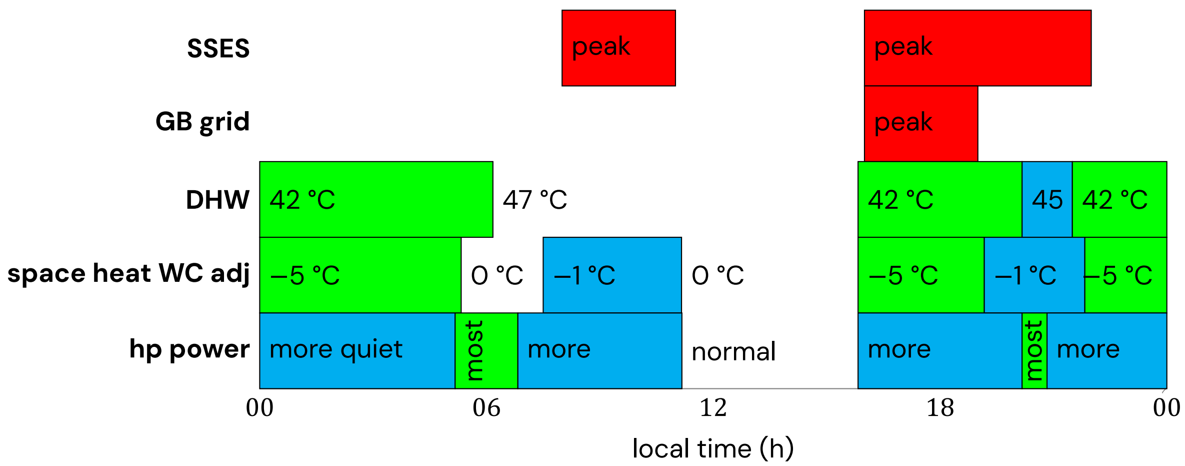

Figure 6. A by-hour-of-day (local time, i.e., following daylight saving) view of the grid notions of peak demand time (top two rows, primarily for weekdays) and the three separate heat-pump control schedules, with all days of the week the same, which are in use to statically schedule ('set and forget') heat-pump load away as far away as possible from grid peak demand; DHW (Domestic Hot Water), adjustment of the space-heat WC (weather compensation), and heat-pump power limitation achieved via quietness settings. Peak demand periods are shown in red; scheduled mild energy-saving periods in cyan; scheduled deep energy-saving periods in green.

3.2. Dynamic diversion

16WW also provides dynamic responses, such as regulating residual PV power spilled to the grid on the order of seconds, providing per-minute responses to low grid frequency and voltage, multi-day carrying of energy (and capacity to absorb energy) in the heat battery, to optimally support live grid stability and GB whole-system energy carbon emissions reduction. The notion of grid relative carbon intensity is measured against a one- and seven-day history and typically changes over the course of hours. How 16WW spills to the grid any PV generation beyond demand in the house is partly grid-interactive and stochastic, including randomisation of timings. The whole-month by-hour-of-day electric heating chart looks relatively simple and smooth in **Figure 7**, but is driven by many factors including local PV generation and instantaneous grid state. **Figure 8** reveals how much that varies by day given the various factors. **Figure 9** shows just how fast-changing and volatile solar PV generation can be, even on a reasonable generation day, not the commonly depicted repeating smooth curve peaking at noon. At 16WW the battery is able to store this highly variable output for when an appliance runs to improve household self-consumption. The solar diverter is able to direct excess that would flow back to the grid for heating water directly or via the heat battery. Both technologies as used in 16WW are autonomously able to accurately track and absorb generation as it rapidly changes over the course of fractions of a second to hours, and from a householder point of view are both simple, self-managing and extract more value from an installed PV system by reducing subsequent imports from the grid at full retail rates. From the grid viewpoint they reduce unnecessary flows in and out of the home and reduce load.

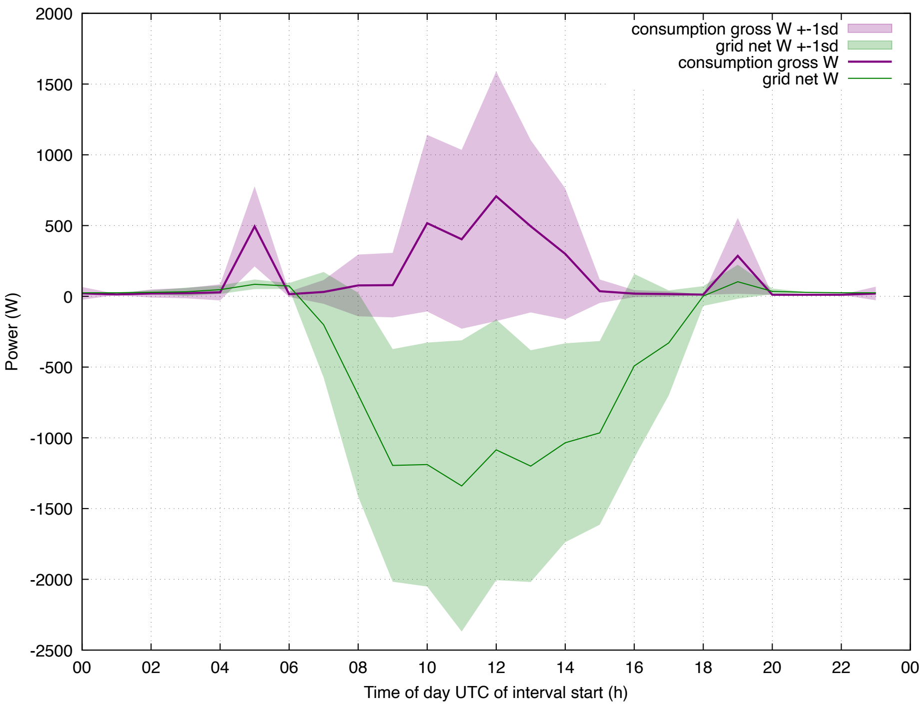

Figure 7. By-hour-of-day (UTC) electricity consumption for heating for May 2026 (violet line). The left-most and right-most peaks above the zero power line are consumption by the heat pump to make DHW (Domestic Hot Water) and are completely statically schedule-driven. The middle hump above the line is solar PV (PhotoVoltaic) diverted to immersion heating for the heat battery and DHW cylinder and depends on local PV generation, grid renewable abundance, grid health such as frequency, and local DHW demand. The green line largely below zero is net negative electricity import from the grid; i.e., 16WW is a net exporter this month. Diversion helps flatten the solar/UTC noon export peak. A ± 1 standard-deviation dispersion band is shown. All-week 1 h granularity data is captured via the MyEnergi Eddi diverter. CSVs available per Data availability statement.

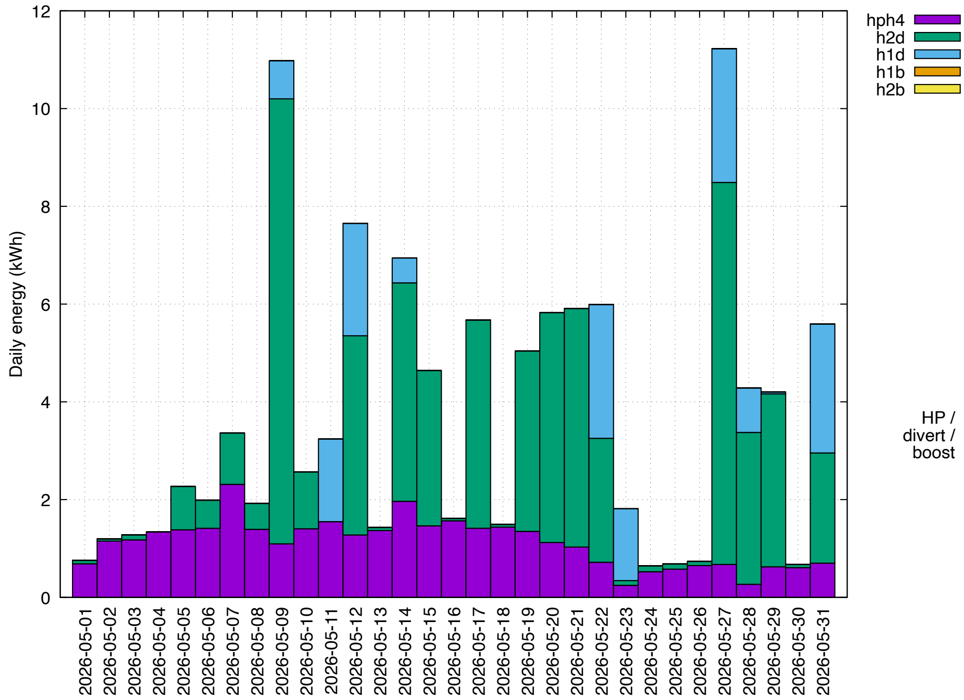

Figure 8. Electricity used for heat for DHW (Domestic Hot Water) by day during May 2026. There was no space heating during this month so all heat-pump consumption was nominally for DHW. hph4: Heat-pump energy consumption at the H4 boundary; h1d: diversion to the DHW cylinder; h2d: diversion to the heat battery; h1b and h2b: grid boost to cylinder and heat battery (both zero in this month). Data is collected per-day via the MyEnergi diverter. CSVs available per Data availability statement.

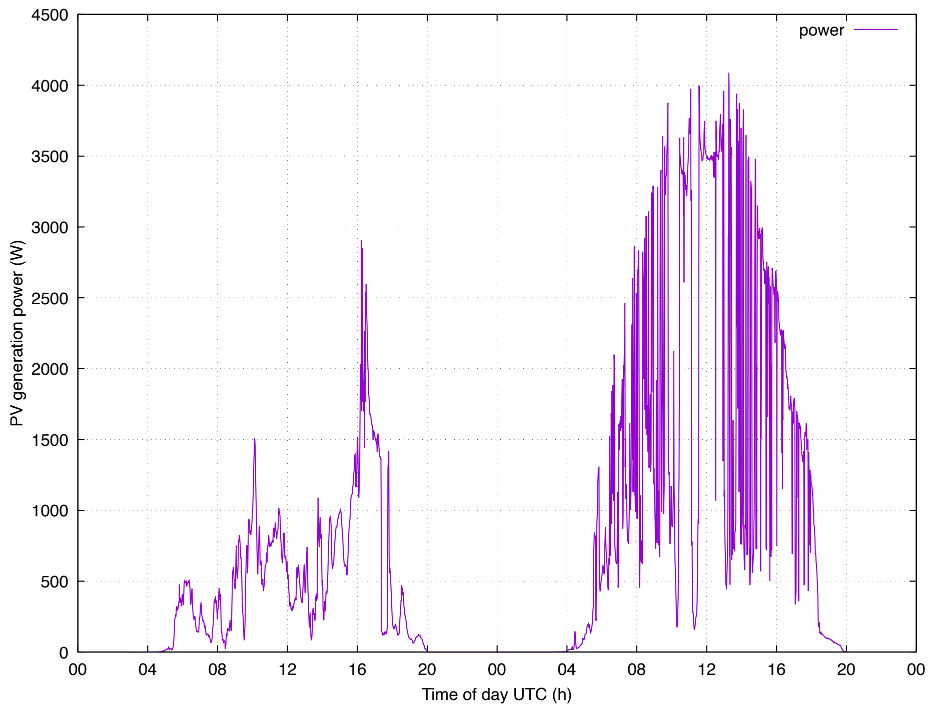

Figure 9. Two days' grid-tie solar PV (photovoltaic) generation with 1 min granularity at 16WW in early June 2026. CSVs available per Data availability statement.

In **Figure 8** the heat-pump energy use is relatively stable by day (hph4), but the diversion to the DHW cylinder (h1d) and the heat battery (h2d) is much more variable. Direct boosts from the grid to the DHW cylinder (h1b) only happen outside the summer/brighter months and are far less frequent and smaller in aggregate, and do not appear in this month; see the supplied December 2025 daily data for comparison. A merit order determines how solar generation is used: primarily household appliances first, then charging the AC-coupled battery, then the heat battery then the DHW cylinder. But diversion for DHW only happens when the grid is relatively 'green' and otherwise healthy. For May 2026 $eheat = h1d + h1b + h2d + h2b + hph4 = 16 + 0 + 63 + 0 + 34 = 113$ kWh, so h1d is 14%, h2d is 55% and hph4 is 31% of the DHW input electricity demand.

3.3. Availability

Static response can be especially easy to provide and thus available in practice to a large fraction of householders, usually requiring no additional hardware or software to significantly shift loads, and is able to reduce bills (or even earn an income) on the right Time-of-Use tariff. Hot water management is a fruitful area. A smaller group of householders will be able to add more dynamic elements right up to real-time responses to help make the generation/demand balancing whole. This paper adds to the evidence showing how relatively minor zero-cost effort can make a difference that is likely valuable to the whole grid. A typical household will likely have the agency to find 'slices' where it can contribute. To maximise participation and benefits, complexity will need to be managed for most.

3.4. 16WW out-turn

The results of 16WW energy management are summarised in **Table 3**, including the overall energy use vs. a typical GB home.

4. Discussion

This paper rests on the insight that much technical progress is made piece-wise and in small increments, and that when enabling the mass electrification of heat we should pay attention to examples (good and bad) from investment banking and other distributed algorithms over pooled resources.

No one participant, in this case with their heating system, needs to fix the balancing or peaking issue nor the entire load curve at once. Different participants can interact with separate parts of the curve simply and statically, or else dynamically (even stochastically). A more agile response comes with more risk and rewards. Neighbours may follow entirely independent strategies with their systems not directly interacting at all [31], or they may participate in a local energy club offering improved aggregate behaviour to the local DNO (Distribution Network Operator) that runs the lines to their homes to make better use of local line capacity [35]. Different grids will value different modes of flexibility, including heat, and together may offer global grid-upgrade savings of as much as USD1.8tn up to 2050 [36].

4.1. Bridging the gap: flex

There are two key goals to be met with energy demand for Net Zero: reduce then reschedule. These goals are not absolute, and often there are trade-offs. When renewables are generating near their peak, using *more* energy, possibly less efficiently, or discarding some putative energy, may be optimal for the system as a whole. For fuel-poor individuals, increasing their consumption to improve health is good. These methods can be combined. Solar PV systems from tiny 'plug-in' units up to utility farms tend to be 'overpanelled'—with more nominal panel generation capacity than the inverters can actually push into the grid—to maximise overall system returns, gaining the ability to export more throughout the day in return for clipping a little power at high noon when nearby PV would be exporting at maximum too and the energy less valuable.

The GB grid is having to be strengthened and reconfigured to bring in more power from new places, such as off-shore and Scottish wind, much as happened when big new coal-generating plants were built near coal fields [8]; this is another rhyme. The grid is also expanding to meet new demand to electrify everything, so an aim is to 'reduce' from what unrestricted demand might otherwise be through efficiency in new large appliances such as heat pumps and electric vehicles (EVs).

4.2. Solar and wind intermittency

Solar and wind are likely to be the key underpinnings of Net Zero, partly because solar output naturally matches humans' largely diurnal activity [37], and because wind generation is anticorrelated with that of solar [38]. The GB grid has a relatively expensive but still useful solar resource in terms of the area and capital expenditure required per unit of annual generation (about double that of Spain [39]), and in terms of there being a ~5:1 ratio between available energy from mid-summer to mid-winter. The GB grid has a relatively large available wind resource per capita compared to many other countries. Both solar and wind generation are intermittent and difficult to forecast precisely. There are other low-carbon sources available including mature less-intermittent hydro and nuclear, unproven-at-scale tidal and wave, and low-availability geothermal. Every grid has unique circumstances but GB seems technically able to electrify and decarbonise if willing, even with its relatively high population density and accustomed comforts.

4.3. Static vs. dynamic

'Flexibility', also known in the case of home energy use such as heating as 'demand-side response', is primarily the (re)scheduling of demand, and there is extensive literature studying the distinct facets according to [40], who propose a unified view: "Building demand flexibility is defined as the ability to manage a building's flexible resources in order to change its load profile to meet different requirements without sacrificing end-user interests." In part, rescheduling is in service of minimising peaks, and thus involves both how much new grid has to be built to avoid wires overloading [28] and how much expensive and usually fossil-fuelled 'peaker' generation plant is used to cover the crest of that maximum demand with its entrained carbon emission implications; see **Figure 10**. In part, such rescheduling is to absorb the huge influx of solar power now available on European grids near noon that might not otherwise be easy to handle or even export [22, 23]. Such flexible tariffs continue to emerge and develop at pace, and in the EU are driven by directives (EU) 2019/944 and 2012/27/EU. Wind generation is not so diurnal, but its equivalent of the noon solar surge is a storm passing over the UK from the Atlantic, which can drive output towards the maximum for much of the turbine fleet at the same time. Because it makes sense to overprovision renewables to minimise overall system costs, including storage, there will be other more variable times at which there will be excess power available for low or negative prices for those agile enough to respond to ToU (Time-of-Use) tariffs with day-ahead prices and to instantaneous emergent grid conditions. Those who can take more pricing and convenience risk are providing a function analogous to buying the risky residual CMO slice.

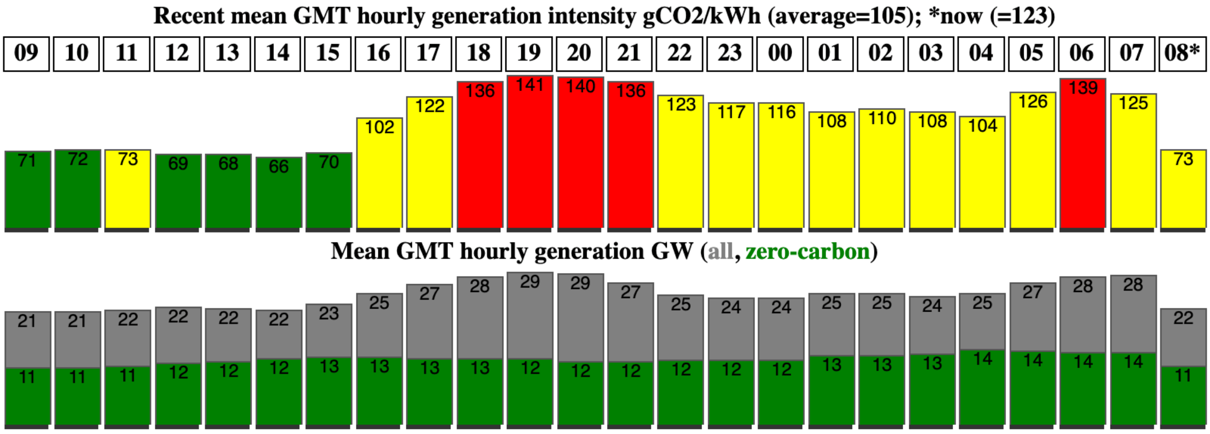

Figure 10. A 24 h snapshot of the GB (Great Britain) grid carbon intensity, demand, and (low-carbon) generation from the morning of 10 May 2026. The top bar-graph is colour-coded carbon intensity in gCO_2e/kWh (CO_2-equivalent emissions per kiloWatt hour generated), with red being the top quartile over 24 h, yellow the interquartile range, and green the bottom quartile. The * marks the current hour as the snapshot was taken. The lower graph shows the GWs (GigaWatts) of (green) low-carbon generation out of the total generation, with grey the residue. The figures apply to metered generation and demand on the transmission grid, and exclude generation such as home solar connected to the distribution system. Source: [27], based on live Elexon FUELINST data.

In this paper ‘static’ response describes pre-scheduled time-based behaviours, such as scheduling hot water or space heating to run other than at the usual grid peak demand hours. Such schedules may be the same for all days of the week (as for 16WW) or may differ between weekdays and weekends or in more complex ways, but are oblivious to the current live state of the grid. On Christmas Day or New Year’s Day with quite different patterns of grid demand, or during a partial eclipse which causes a dip in solar generation, the usual schedules may still be applied. This remains a reasonable ‘slice’ of response, so long as there is enough ‘dynamic’ response available in the system to deal with the unexpected and the untypical, and normal daily variation. In contrast, ‘dynamic’ responses react to the live grid state over timescales of fractions of a second (such as frequency and voltage) through to hours or days (such as relative wholesale cost and carbon intensity). Dynamic responses may be multi-input with complex calculations, possibly including forecasting of generation and demand, and may require live communication connectivity. These may require allowing a retail electricity supplier or aggregator to adjust the real-time behaviour of household devices such as thermostats, EV chargers and batteries. Static response has lower complexity and risk, but is typically also less rewarded.

As described in the Results, several measures have contributed to 16WW being able to significantly bend its net grid load curve in winter away from a typical domestic load curve, in particular avoiding contributing to the very top of the evening peak. The largest element of this has been the timing of DHW heating and DHW storage in a hot water cylinder ready for fast delivery when needed. In principle this level of static time-based control is within most householders’ agency in GB, and has been for some time. Tariffs such as Economy 7 (**Table 1**)—running since 1978 to soak up output at night from coal and nuclear generators that are hard to turn down—have recharged home storage heaters and DHW tanks cheaply overnight, absorbing about a tenth of all domestic electricity as flexible heat. The coming SSES rules for energy-hungry electricity appliances such as heating and mobility will assume and attempt to avoid peaks from 08:00 to 11:00 and 16:00 to 22:00, and that behaviour will have to be explicitly overridden if unwanted. Existing GB central heating and DHW systems—including gas boilers and heat pumps—within regulations should have at least a simple time-based control. So often no new equipment will be needed other than a possible free upgrade to a smart meter, and use of that in conjunction with a simple ToU tariff (such as EDF's FreePhase variants or Octopus' Cosy specifically for heat pumps—see **Table 1**) will likely save money and help toward achieving Net Zero. More vulnerable and less numerate householders can have a third party help with set-up.

It is possible as an 'early adopter' householder to glue together systems including software bridges to implement dynamic response, possibly being rewarded by a tariff such as Octopus' Agile (**Table 1**), but that requires a level of capital, skill and attention that most will not be able or willing to invest. Retail price capping to avoid extreme pass-through rates has been shown to be important [18] both to reduce bare risk but also simplify risk that might otherwise blindside even a professional trader, per the 2008 financial derivatives-driven crisis and the 2021 Texas winter electricity crisis. More simply, a tariff such as Octopus' Intelligent Flux (**Table 1**), which requires solar PV and a compatible battery to be installed, and which will remotely manage the battery, returned an operating profit to a significant fraction of customers as of 2025. There also exist schemes such as Axle Energy's payment offer of £1/kWh, with a minimum of £10/month, which is bolt-on to manage a home battery as part of a virtual power plant. Such a set-and-forget solution is likely to be acceptable to a wider audience, and can extend beyond the able-to-pay owner/occupier segment when (say) a social landlord installs PV and a battery and co-signs with the tenant to a similar tariff. Grid-wide programmes such as NESO's CrowdFlex [23] make it possible for householders to participate occasionally to save or be paid by adjusting their usage down or up when the grid is under high stress—as much as −23% was driven by ToU tariffs but +617%/−59% from one-off signals. This style of dynamic response may appeal to further demographics, though owners of batteries (stationary or in EVs) and other systems have to be convinced that when needed the resources will still be there for the owners' needs, e.g., a warm enough home and enough miles left in the EV, and not subject to excessive wear, so trust and other wider social issues enter the picture.

4.4. Grid slices

What 'slices' or services might a grid obtain from households? One example is "capacity limitation" [35], where a group of households cooperate to minimise peak demand on their part of the local electricity distribution network to avoid, postpone or minimise costly infrastructure upgrades. Like at 16WW, households could limit net imports near demand peaks and during periods of low frequency and voltage indicating grid stress, limit net exports during low demand and high renewable generation, and increase their imports when wholesale prices turn negative. In each case some of this can be done statically at fixed times when these events are likely to arrive, such as evening energy peak demand and summer solar noon peak PV generation, and some can respond dynamically and opportunistically to fill the gap between the static predictions and real-time actuality. See **Table 4** for a selection of slice types and features, including current active schemes providing measurable value to GB participants from the grid operator to householders, and expanding across Europe [22].

4.5. Limitations

16WW is one example of how heat for dwellings can support the grid, but is highly atypical in the degree of data analysis and tuning that has been applied to it. Extrapolating directly from it to all ~30 million UK households would be unwise, but the aim of this conceptual observation is to illustrate how even within one dwelling and across the housing stock, multiple approaches can and should be applied concurrently, such as static and dynamic for example, and this can meaningfully address the flexibility need. The presence of a variety of GB grid ToU tariffs of varying complexity illustrates how appropriate behaviour can be valued and incentivised in many distinct slices by timing and granularity.

Table 4. Example grid retail flexibility slice types and characteristics; all can reward users with reduced electricity costs. "Wet"/"white" goods/appliances involve water and heating/cooling and are therefore often heavy electricity consumers. More tariff information available in **Table 1**.

Description	Technical motivation	Timing	Interaction/ inconvenience	Notes
Static ToU tariffs: fixed price per hour of day for contract period	balance supply and demand	~HH ~year-ahead	setting of appliance schedules, manual scheduling of EV charge, wet goods	examples: Economy 7, Cosy, FreePhase static; 16WW uses static heat schedules and manually times wet goods
Dynamic ToU tariffs: variable price per hour of day	balance supply and demand	~HH ~day-ahead	automated integration plus manual scheduling per static ToU	examples: Agile, FreePhase dynamic; needs comms
TSO- and DNO-managed real-time interactive incentives	balance supply and transmission constraints in real time	~HH	includes real-time requests to manually raise/lower load	CrowdFlex and LCM [23, 24]; needs comms
Carbon intensity response	minimise carbon emissions	~HH	automated invisible	used at 16WW; needs comms and live grid metrics
Capacity limitation	minimise upgrades of distribution network	hourly	automated more volatile pricing	cooperating neighbours reduce infrastructure costs [35]; needs comms and shared computation
Retailer- or aggregator-managed appliances and battery	balance supply and demand in real time	≤HH	automated integration; adjustments of thermostat, EV charge, etc.	examples: Intelligent Flux; forms part of VPP; needs comms
Anti-herding	avoid synchronised fast demand slews	≤HH	automated barely visible	used at 16WW; randomising start and stop times and moving from HH boundaries [28]
Frequency and voltage response	balance supply and demand in real time	≪1 s–~1000 s	automated invisible	used at 16WW with 1 min latency; inputs measurable in home

DNO: Distribution Network Operator; EV: electric vehicle; LCM: Local Constraints Market; HH: half-hourly; ToU: Time-of-Use; TSO: Transmission System Operator; VPP: virtual power plant.

5. Conclusions

Solving the Net Zero grid problem of keeping GB demand and generation in balance at every second in the face of less predictable demand and largely non-callable zero-carbon generation spread over many millions of participants is being tackled with a segmentation approach that rhymes in some aspects with derivatives structuring, with no one participant seeing or addressing more than a relatively small part of the puzzle.

A portfolio approach must not be seen as some sort of failure; synergistic whole-system stability will emerge from householders making static load time shifting choices with their heating (and cooling) system in many cases, and dynamic day-ahead and real-time reactions in others. Behind-the-meter storage and microgeneration will be an increasing element. Flexibility in demand from all parts of the economy will be a necessary system component to handle the realities of intermittent generation. Success will be incentivised by Time-of-Use tariffs and orchestrated by a range of methods, from humble clocks and sophisticated Internet-based swarms to explicit retail consumer demand turn-up and turn-down requests from grid operators. This will have to be underpinned with evolving appropriate policy choices and market design, through working with different levels of individual interest and available capital, and working against resistance to change and even disinformation. Less engaged and inflexible households, including those without the ability to participate, will continue to be part of the consumption mix. Having fewer of them will help reduce costs across the whole system at times of low and high renewable generation. More sophisticated and attentive householders with the agency to pick their response slices can already make money from their utility energy supply, or at least pay significantly less than householders remaining on single-rate (non-ToU) tariffs; the derivatives do in fact rhyme.

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Author contributions

Conceptualisation, D.H.-D.; investigation, D.H.-D.; resources, D.H.-D.; writing—original draft preparation, D.H.-D.; writing—review and editing, M.L. and L.L.; supervision, M.L. and L.L. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that they have no competing interests.

Data availability statement

The data supporting the findings of this publication have been made available within a publicly accessible repository at https:zenodo.org/records/21948729. Further data for the 16WW home are available at https://zenodo.org/records/10206489. Slides for the Pint of Science 2026 public talk related to this paper are available at https://www.earth.org.uk/img/meet/2026-Pint-of-Science/20260518-PintOfScience.pdf. The live GB grid carbon intensity calculator is available at [27].

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