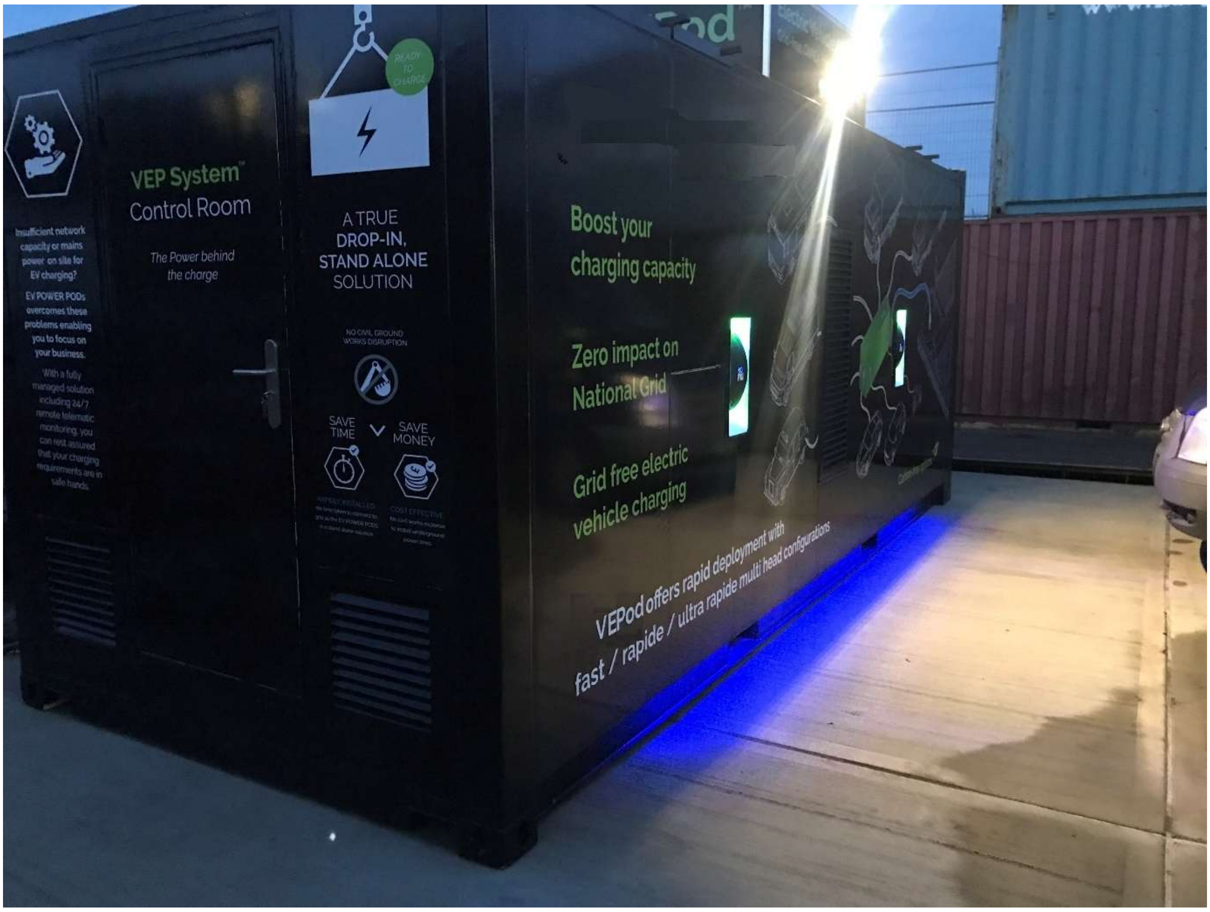
WPB1 D4 Report

Energy Centre design specification report for selected communities



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Executive Summary

- Two community energy groups were identified for further detailed analysis for a REACH energy centre in their respective location. These groups were Bigbury Net Zero (BNZ) and Amen Awel Tawe (AAT).
- The 11kV feeder lines for each community were analysed based on potential future loading demand to determine whether they may become constrained with high Low Carbon Technology (LCT) adoption above that forecast in the DFES 2024 data and under what network conditions.
- In both communities, the normal operation of the network indicated no (or very limited) constraints would be encountered.
- In fault conditions, where a feeder was compromised and power had to be back fed from an alternative feeder (so called N-1 conditions), some constraints appeared on some feeders in some scenarios.
- In BNZ, the Feeder 340040-0017 during abnormal Operation (N-1) has a constant export requirement from a REACH energy centre. With no co-ordination of heat pump demand the size of the genset is 833kW and the energy storage size is circa 2MWh. The inverter size is circa 0.5MW. These numbers drop slightly with a co-ordinated heat pump demand management.
- The sizing of the energy centre was calculated using a load levelling approach whereby the genset was sized based on the mean export requirement and the peaks and troughs of export demand were cushioned by a battery energy storage system (BESS). During a "Peak" additional power would be exported from the BESS and during a "trough", the BESS would be recharged by the genset.
- The indicative cost for the BNZ REACH energy centre is £890,000.
- In AAT, the feeder 502137-0782 during abnormal operations has an export requirement but benefits from the ability to also recharge its energy storage from the network. This means that it could be satisfied by a battery energy storage system (BESS) of circa 3MWh capacity. However, to provide greater resilience a hybrid solution has been modelled. In the most challenging scenario, a genset sized at 239kW (continuous) and a battery energy storage capacity of 1.1MWh with a 350kW bidirectional inverter is sufficient for peak shaving. Co-ordination of heat pump demand has a noticeable positive effect on the sizing.
- The indicative cost for the AAT REACH energy centre is circa £610k.
- In all scenarios, the co-ordination of heat pumps enabled a smaller energy centre size.

1. Introduction

1.1 Background on Project REACH

The Rural Energy and Community Heat (REACH) project recognises that addressing rural energy challenges requires innovative technical solutions and meaningful community partnerships. Throughout the Alpha phase, the project team engaged with seven diverse community groups before conducting detailed feasibility studies with two selected communities: Awel Aman Tawe, Wales, and Bigbury Net Zero, England.

This work Package (WPB1-D4) aims to validate the techno-economic viability of containerised hybrid energy centres that can defer rural network reinforcement by actively exporting/displacing power at constraint points.

1.2 Objectives

Deliver a Design Specification Report that:

- Analyses the network requirements for two edge-case communities.
- Sizes all REACH energy-centre components.
- Compares scenarios with and without heat-pump co-ordination.
- Provides cost ranges for the designs.
- Documents how the components will inter-operate

1.3 Scope

This document explains the methodology adopted and the results obtained for the sizing of a REACH energy centre for two selected communities as part of the Alpha phase of the REACH project. The first step of this analysis involved selecting appropriate forecast demand in relation to the corresponding 11kV feeder lines that serve the communities. NGED secondary system planning network engineers provided half-hourly forecast data of demand and a figure for the maximum feeder capacity (in MVA). Several alternative forecast datasets were provided.

In summary these can be summarised as follows for each feeder:

1. Normal operation of the feeder with no co-ordinated heat pump management.
2. Normal operation of the feeder with co-ordinated heat pump management.
3. Abnormal operation of the feeder (N-1) condition where the feeder is back fed from an alternative feeder line with no co-ordinated heat pump management.
4. Abnormal operation of the feeder (N-1) condition where the feeder is back fed from an alternative feeder line with co-ordinated heat pump management.

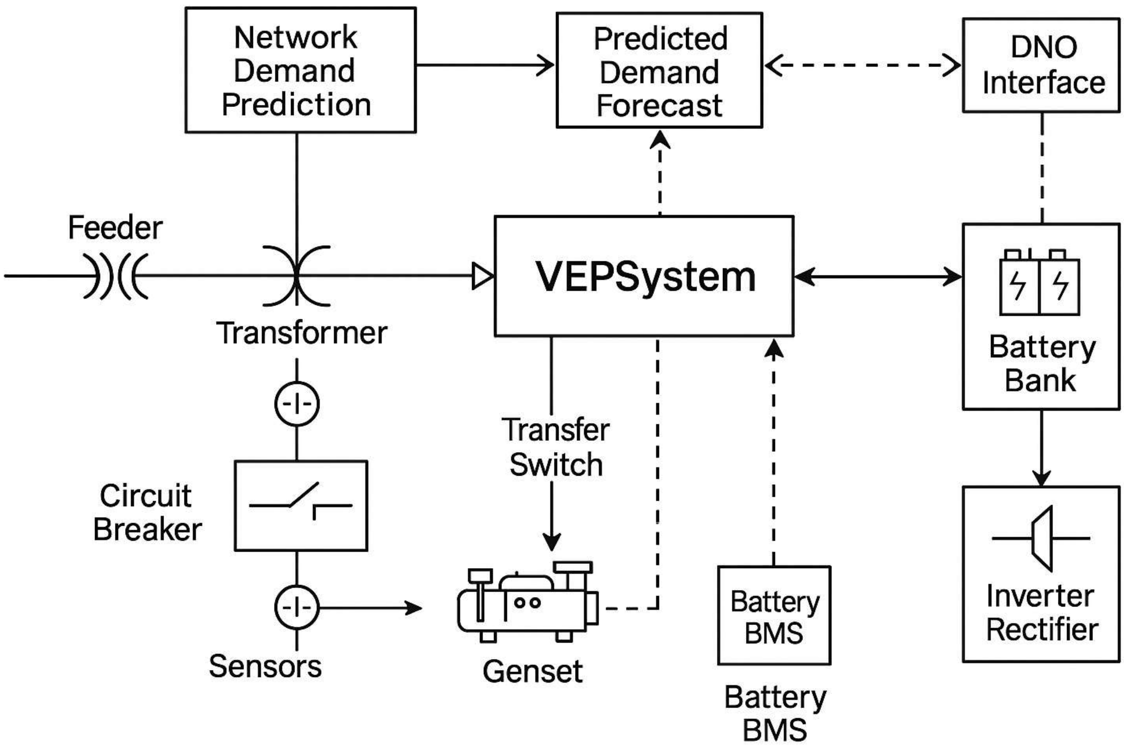
One key objective of the REACH project is to determine the viability of an energy centre to reduce the demand on the feeder in the edge case communities where Low Carbon Technologies (LCTs) are adopted at much faster rates than the standard DFES 2024 data suggest.

As such in creating the input forecast data the following assumptions were used:

Day	Year	Study	Community 2024 DFES Applied
1	Baseline	Baseline	Baseline
2	2026	Unabated Load Growth	2027
3	2027		2029
4	2028		2031
5	2029		2033
6	2030		2035
7	2026	Co-ordinated HP Controlled Load Growth	2027
8	2027		2029
9	2028		2031
10	2029		2033
11	2030		2035

2. System Architecture

The proposed REACH Energy Centre is a hybrid unit containing both an HVO powered genset and a Battery Energy Storage System (BESS) centrally managed by the smart VEPSystem control module.



2.1 Grid & Protection

- Feeder Line
  The NGED distribution feeder.

- Transformer
  Steps down medium voltage to the LV network feeding the REACH energy centre.

- CT/PT Sensors
  Current transformers (CTs) and potential transformers (PTs) provide voltage, current, and power measurements to the protection relay and VEPSystem.

- Circuit Breaker
  A rapid-trip device that can isolate the entire REACH centre from the grid under faults or maintenance.

2.2 VEPSystem (Smart control system)

- Core Brain
  High-performance industrial controller (Programmable Logic Controller (PLC) / Remote Terminal Unit (RTU)) with embedded forecasting and optimisation. A PLC is a type of industrial digital computer that is programmed to control machinery. It performs tasks based

on predefined conditions and inputs. An RTU is a microcontroller-based device used for remote monitoring and controlling field devices in industrial automation, particularly within Supervisory Control and Data Acquisition (SCADA) systems. SCADA is a computer-based system for gathering and analysing real-time data to monitor and control equipment that deals with critical and time-sensitive materials or events.

- Inputs
    - Real-time CT/PT measurements
    - Predicted Demand Forecast (cloud service feed)
    - DNO commands (Supervisory Control and Data Acquisition (SCADA) link).
    - Battery State of Charge (SoC) & health from Battery Management System (BMS).
- Outputs
    - Genset start/stop & power setpoint
    - Transfer-switch control
    - Inverter/rectifier charge/discharge setpoints
    - Alarms and status to DNO SCADA

2.3 Genset & Transfer Gear

- Genset
  HVO engine + alternator.
- Transfer Switch
  Solid-state or mechanical switch that connects/disconnects the genset to the LV bus.
- Genset Controller
  Manages engine speed, Automatic Voltage Regulator (AVR), and safety interlocks; accepts setpoints from VEPSystem.

2.4 Battery Energy Storage System (BESS)

- Battery Modules
  Lithium-ion racks.
- Battery Management System (BMS)
  Monitors individual cell voltages, temperatures, State of Charge (SoC), and State of Health (SoH); enforces safe operating limits.
- Communication
  BMS ↔ VEPSystem for SoC updates and health status.

2.5 Inverter / Rectifier

- Bidirectional Power Converter

- Rectifier Mode: draws excess genset or generator export to charge the battery at up to rated current.
- Inverter Mode: injects battery power back onto the LV bus to shave peaks.

- Control Interface
  Receives charge/discharge commands from VEPSystem; reports operating status and alarms.

2.6 Network Demand Prediction

- A cloud-based forecasting engine that uses Artificial Intelligence (AI) / Machine Learning (ML) to predict half-hourly feeder load up to several hours ahead.
- Feeds a Predicted Demand Forecast to VEPSystem for pre-emptive asset dispatch.

2.7 DNO Interface

- Supervisory Control and Data Acquisition (SCADA) / Human-Machine Interface (HMI) Gateway, where HMI is the user interface that allows operators to interact with machines and systems, providing a visual representation of data and controls.

  Allows the Distribution Network Operator to:

  - Monitor real-time flows, SoC, and genset status.
  - Issue remote commands or curtailment instructions.
  - Receive alarms and performance reports.

2.8 Operation Workflow

1. Data Acquisition
   - CT/PT sensors and BMS streams feed VEPSystem.
   - Forecast engine sends predicted demand profile.
2. Decision & Scheduling
   - VEPSystem calculates:
     - When to pre-start genset based on forecast.
     - How to split load between genset and battery.
     - Charging windows to restore SoC.
3. Dispatch
   - VEPSystem closes transfer switch, starts genset, sets its power to the continuous setpoint (e.g. 250 kW).
   - For any export above that, commands inverter to discharge from the Battery Energy Storage System (BESS).

- For export below that, commands inverter to charge BESS at available headroom.

4. DNO Coordination
   - If the DNO issues a command (e.g. reduce local injection), VEPSystem adjusts setpoints accordingly.
5. Protection & Fault Response
   - On any grid fault or overcurrent, the breaker trips, VEPSystem gracefully shuts down assets, and notifies DNO.

This detailed layout ensures robust, forecast-driven control of local generation and storage, seamless DNO integration, and full protection for reliable feeder support. The REACH energy centre is thus well placed to ensure accelerated low carbon technology adoption in rural areas whilst maintaining the stability of the network.

3. Technical Design

3.1 BNZ

BNZ Analysis

A visual review of the forecast demand data demonstrates that neither feeder is constrained under normal operation. Furthermore, feeder 340016-0015 is also not constrained during abnormal (N-1) operation. Based on the forecast data selected, the only candidate for a REACH energy centre at the BNZ location is this feeder 340016-0017 during abnormal (N-1) operation.

VEPOD Ltd calculated the 48 half-hour "peak shaving requirement" values in kWh (i.e., how many kWh must be supplied by the REACH energy centre in each 30-minute window to keep the feeder within its limit) based on feeder demand forecasts supplied by NGED and knowledge of the maximum feeder load (the upper limit of the amount of power that can be transmitted along the cable). The data was converted from kVA to kWh assuming a 0.95 power factor.

The data shown below is for the BNZ Feeder 340040-0017 during abnormal Operation (N-1) and under a non-coordinated heat pump scenario.

$E_1, E_2, \ldots, E_{48}$ are used for labelling each data point. For reference, here they are (48 intervals of 30 min each):

E_1	264.7488166	E_{13}	405.6940474	E_{25}	251.036461	E_{37}	535.511632
E_2	384.7978288	E_{14}	460.7838671	E_{26}	258.4216845	E_{38}	592.3191244
E_3	493.5433789	E_{15}	523.8534688	E_{27}	250.4438074	E_{39}	594.8511832
E_4	543.9368307	E_{16}	442.8251094	E_{28}	289.7402363	E_{40}	538.8441941
E_5	527.5079259	E_{17}	420.5491098	E_{29}	258.2687993	E_{41}	488.8629967
E_6	567.7693175	E_{18}	421.3040839	E_{30}	243.4443209	E_{42}	422.4652352
E_7	554.6237667	E_{19}	414.6154221	E_{31}	243.4423434	E_{43}	354.9438887
E_8	513.4087031	E_{20}	312.3361091	E_{32}	237.270732	E_{44}	307.7982642
E_9	444.1271998	E_{21}	265.0730989	E_{33}	265.6066024	E_{45}	267.9885658
E_{10}	392.2005081	E_{22}	317.9158437	E_{34}	325.9716526	E_{46}	201.3186845
E_{11}	395.9721269	E_{23}	262.1407119	E_{35}	396.4053535	E_{47}	195.9337425
E_{12}	426.1661546	E_{24}	219.8760918	E_{36}	459.2610189	E_{48}	218.2359517

Each value is the ***energy* in kWh** required in that half hour.

A visual inspection of the data indicated that the REACH energy centre would be required to continuously export power in the above fault condition scenario. There is thus no ability to recharge the batteries within the energy centre from the grid during the above referenced scenario.

The approach used a "peak shave" only case which assumes that the genset is always available running constantly at the average export value with the battery storage system supporting the peaks and troughs of demand from the mean. This approach sees the generator running constantly at its rated capacity which provides sufficient power to the network for the average of each of the half-hourly values. When the half-hourly demand is above the amount that is supplied from the generator, additional power is provided from the batteries. When the half-hourly demand is below the generator output, the excess power produced by the generator is used to top up the batteries.

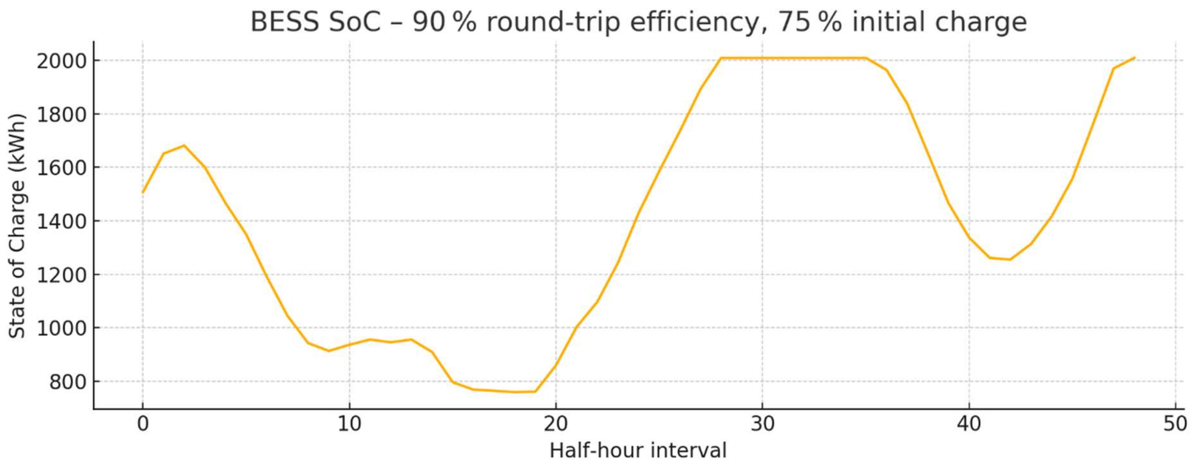
Sizing scenario - “Peak-shave only” case (genset always available)

In this scenario, we assume that the generator is always available and running constantly at its maximum rated power. The peaks and troughs of demand (above and below the amount of power supplied by the genset) are handled by a Battery Energy Storage System (BESS).

Scenario	Genset Size	Battery energy	Battery power inverter rating
Model with no co-ordinated heat pump demand	**833 kW**	**2.01 MWh**	**0.5 MW**

Analysis of the battery energy State of Charge (SoC)

The following graph shows the State of Charge (SoC) of the Battery Energy Storage System (BESS) throughout the day. The scale on the left shows the state of charge in kWh. In practice the minimum SoC should be no lower than 20% (0.4MWh). This has been modelled to account for the losses incurred when charging and discharging the battery, the so-called round-trip efficiency. In this example, the initial charge is set at 1.5MWh to account for the substantial initial draw from the network during the first phase of operation.



Metric	Results
Initial SoC	**1 508 kWh (75 %)**
Minimum SoC	**≈ 758 kWh (37.7 %)**
Intervals at 100 % SoC	**9 (28 → 36 & 48)**
Energy “spilled” while battery full	**≈ 285 kWh**

Key observations

1. Efficiency losses deepen every discharge & soften every charge.
   We modelled this by applying √0.90 ≈ 94.9 % efficiency on both charge and discharge legs, so a full round trip is 90 %.
2. Never empty - Even with losses, the battery bottomed at ~758 kWh—well clear of zero—thanks to the 75 % starting SoC.
3. Because we began three-quarters full, the mid-run surplus in intervals 22-36 pushes the battery to 100 % for nine consecutive half-hours. Any additional surplus during that plateau must be curtailed or diverted elsewhere.
4. Sizing remains adequate but could be optimised. If spilling ~285 kWh of potential storage is a concern, we could:
   - trim the genset set point slightly during the long charging stretch,
   - add a little more BESS capacity, or
   - export / curtail instead of charging once the battery hits its limit.
5. Round-trip losses cost about 93 kWh over the 48 intervals.
   (The sum of efficiency penalties applied during charge/discharge events.)

Effect of co-ordinating the heat pumps

Passiv Systems are one of the REACH project partners with expertise in heat pump control systems. Their analysis which can be found in their report demonstrates that a co-ordinated management approach has the potential to reduce the peaks in load demand which has a direct impact on the required sizing of the REACH energy centre.

Based on the revised input data provided by NGED which includes the effect of co-ordinated heat pump control, the calculation steps were repeated for the same feeder under abnormal load conditions to provide the following sizing result.

Scenario	Genset Size	Battery energy	Battery power inverter rating
Model with co-ordinated heat pump demand	**794.6 kW**	**2.03 MWh**	**0.5 MW**

Conclusion: What changed?

- **Generator**: sizing dropped from ~ 833 kW → ~ 795 kW (≈ 4.6 % lower).
- **Battery**: from ~2.01 MWh → ~2.03 MWh (≈ 1% higher).

3.2 AAT

AAT Analysis

A visual review of the forecast demand data demonstrates that the four feeders are not constrained under normal operation.

Under abnormal (N-1) operating conditions the following feeders are constrained depending on where they are back fed from:

- 520137-0778 when back fed from 520137-0782 (when no communities from 520137-0778 are connected but when all 520137-0782 communities are connected)
- 520137-0782 when back fed from EITHER 520137-0779 OR 520137-0291.

In each constraint scenario, there is an opportunity to import electricity from the network to recharge the REACH energy centre storage. Furthermore, the gross export requirement is lower than the available import capability. This means that there is more energy available to recharge batteries from the network than that required to be exported from the batteries to the network to shave the peaks of demand. As such an energy storage solution without a generator is viable as a battery working independently could be recharged sufficiently from the network and meet all export requirements.

VEPOD Ltd calculated the 48 half-hour “peak shaving requirement” values in kWh (i.e., how many kWh must be supplied by the REACH energy centre in each 30-minute window to keep the feeder within its limit) based on feeder demand forecasts supplied by NGED and knowledge of the maximum feeder load. The data was converted from kVA to kWh assuming a 0.95 power factor. The data shown below is for the AAT Feeder 520137-0782 during abnormal Operation (N-1) where the section is back fed from 52013-0778 and using no co-ordination of heat pump demand (Max Feeder Load: 3.289MVA)

E_1, E_2, ..., E_{48} are used for labelling each data point. For reference, here they are (48 intervals of 30 min each):

E_1	-99.28	E_{13}	-491.63	E_{25}	64.60	E_{37}	222.78
E_2	-137.28	E_{14}	-422.28	E_{26}	59.85	E_{38}	267.90
E_3	-162.45	E_{15}	-338.68	E_{27}	64.13	E_{39}	262.20
E_4	-189.05	E_{16}	-250.33	E_{28}	62.70	E_{40}	242.73
E_5	-239.88	E_{17}	-200.93	E_{29}	35.63	E_{41}	211.38
E_6	-295.93	E_{18}	-193.33	E_{30}	27.55	E_{42}	196.65
E_7	-355.78	E_{19}	-142.98	E_{31}	20.90	E_{43}	132.53
E_8	-405.18	E_{20}	-61.28	E_{32}	25.18	E_{44}	83.60
E_9	-425.60	E_{21}	-91.20	E_{33}	-59.38	E_{45}	73.63
E_{10}	-480.70	E_{22}	-28.03	E_{34}	36.57	E_{46}	57.00
E_{11}	-484.03	E_{23}	-24.70	E_{35}	146.78	E_{47}	-6.17
E_{12}	-449.83	E_{24}	7.60	E_{36}	196.65	E_{48}	0.95

Each value is the ***energy* in kWh** required in that half hour.

A visual inspection of the data indicated that the REACH energy centre can BOTH import and export electricity to the network even in the above fault condition scenario. The negative numbers indicate when the energy storage can be recharged from the network. There is thus an ability to recharge the batteries within the energy centre from the grid during the above referenced scenario. As the total energy that could be imported is higher than the amount of energy that needs to be exported a battery storage only solution could be deployed. However, the addition of a genset in a hybrid system provides greater resilience and enables the energy storage capacity to be reduced.

Two sizing approaches have been developed for this scenario:

1. Battery Energy Storage System (BESS) only solution
2. Hybrid (Genset + BESS) REACH energy solution (Load levelling approach)

Sizing scenario 1 – Battery Energy Storage Solution (BESS) only solution

In this scenario, no generator is considered, and the energy centre is sized based on only using a Battery Energy Storage Solution (BESS).

Objective

The design objective is to define the energy and power ratings of a Battery Energy Storage System (BESS) dedicated solely to peak-shaving, incorporating a 90 % round-trip efficiency and a 10 % design margin. The 90% round trip efficiency considers the losses that are incurred in moving energy between the BESS and the electricity network feeder line. The design margin considers a safety margin and the potential degradation of the batteries over time.

Summary of BESS Specification

Parameter	Calculation	Specification
Usable Energy Capacity	(2499.49/0.90) × 1.10	3.06 MWh
Discharge Power	2 × 267.90 × 1.102	0.59 MW
Charge Power	(2499.49/0.90)/8×1.10	0.38 MW

Note:

- Round final inverter sizes to industry-standard blocks (e.g. 0.6 MW discharge, 0.4 MW charge).
- The 10% safety margin should account for degradation, temperature effects and inverter efficiency.
- A BESS only approach provides an adequate solution and enables the peak shaving required.

Sizing scenario 2 – Sizing of Generator and Battery Storage for Load Levelling Using Export Demand Data

In this scenario a combination of a generator and a BESS system is considered. The generator sizing is calculated based on the mean export demand value. The peaks and troughs of demand (above and below the amount of power supplied by the genset) are handled by a Battery Energy Storage System (BESS).

Sizing summary

Scenario	Genset Size	Battery energy	Battery power inverter rating
Model with no co-ordinated heat pump demand	239 kW	1.10 MWh	350kW

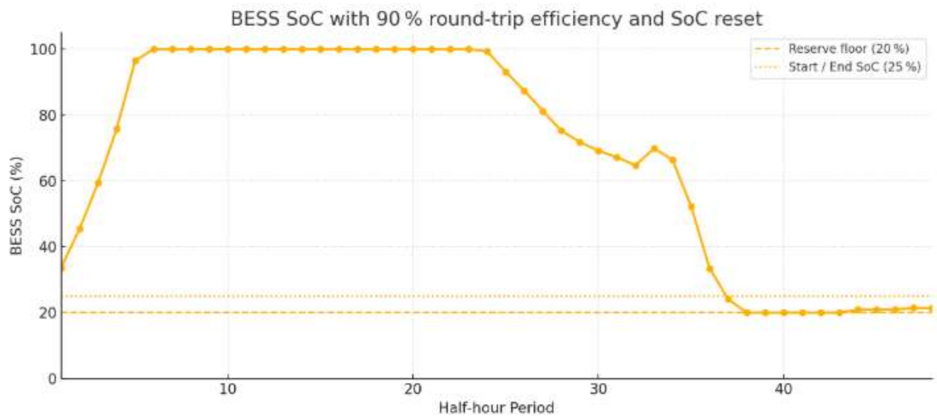
NB: All figures include the requested 90 % efficiency derating (for the battery) and 10 % safety margin.

Conclusion

The combination of a genset and BESS system enables a much smaller battery capacity to be deployed. The nameplate value of the genset is likely to be 250kW which would result in an even smaller amount of BESS storage.

Analysis of the battery energy State of Charge (SoC)

The following graph shows the State of Charge (SoC) of the Battery Energy Storage System (BESS) throughout the day. It is based on a 250kW genset being part of the hybrid solution. The scale on the left shows the percentage SoC with 100% representing fully charged and 0% representing entirely depleted of charge. In practice the minimum SoC should be no lower than 20%. This has been modelled to account for the losses incurred when charging and discharging the battery, the so-called round-trip efficiency and ensures that the SoC at the end of the day is equivalent to that of the start of the day.



Metric	Result
Genset energy	**1.100 MWh**
Slots genset runs	10
BESS min / max SoC	20 % / 100 % (unchanged)
SoC at end of day	**25 % (exactly start value)**

Explanation

1. **Efficiencies applied**
   Charge and discharge were both set to 94.9 % (√0.90), giving a 90 % round-trip.
2. **First pass (minimal-genset)** left the BESS at **20.4 %**—about **50 kWh short** of the 25 % starting level.
3. **Second pass (topping-up genset)** used spare head-room in periods 44 and 45—when the battery was already at its 20 % floor—to push an **extra 52.9 kWh** through the genset.
   Because net import flipped to a small export in those slots, the BESS soaked it up at 94.9 % efficiency and finished bang-on 25 %.

Effect of co-ordinating the heat pump demand on the sizing

Component	Non-co-ordinated	Co-ordinated	Δ
Genset	**239 kW**	**226 kW**	**–5 %**
Battery	**1.10 MWh**	**0.724 MWh**	**–34 %**
Inverter	**350 kW**	**279 kW**	**–20 %**

- The second dataset has **fewer** and **lower-magnitude** export spikes (17 vs. 23 positives, max ≈229 kWh vs. 268 kWh).
- That drives a slightly lower average export (102.8 vs. 108.7 kWh) and much less total “excess” energy to absorb, so the battery and inverter shrink disproportionately.
- The genset hardly changes, since it stays pegged to the **mean** export.

Overall, the second feeder profile which includes a co-ordinated control of heat pumps demands notably less storage and inverter capacity for peak shaving, though the genset rating remains in the same ballpark.

AAT Feeder 520137-0782 Abnormal Operation

Section Back fed from 520207/0291 (No co-ordination of heat pump demand)

Result

Component	Rated Power / Energy
Genset	185.4 kW (continuous)
Battery	0.268 MWh (usable)
Inverter/Rect.	143 kW (bidirectional)

By pegging the genset to 185.4 kW (92.7 kWh per interval), the REACH energy centre only needs to cover the five deeper export peaks. That reduces the battery size to just 0.27 MWh, and the inverter down to 143 kW.

Effect of co-ordinating the heat pump demand on the sizing

Component	Non co-ordinated	Co-ordinated	Δ
Genset	185.4 kW	167.7 kW	–10 %
Battery	0.268 MWh	0.218 MWh	–19 %
Inverter	143 kW	126.9 kW	–11 %

The data including the effect of the co-ordination of the heat pump demand has **lower and fewer** export spikes above the genset's output, so less stored energy is needed, and a smaller inverter can be used. The slightly smaller mean export also reduces the genset size.

4. Cost Analysis

4.1 BNZ

Indicative cost summary

Containerised 833 kW genset + 2 MWh BESS (0.5 MW PCS) ready for 11 kV grid connection (UK)

Cost element	Low (lean-spec)	Mid (typical C&I-spec)	High (premium / fast-track)	Notes & key drivers
833 kW diesel generator (Tier IIIa, open-skid → super-silent)	£90 k	**£130 k**	£180 k	Factory-gate pricing varies by engine brand, emissions tier, enclosure & warranty length.
2 MWh Li-ion battery racks incl. racks & BMS	£260 k	**£320 k**	£520 k	Uses (Perkins 800KVA Generators - Reliable Power Solutions - pricing ≈ $115 / kWh and UK turnkey uplifts (25–60 %).
0.5 MW bidirectional PCS	£17 k	**£25 k**	£45 k	ENF list (Lithium-ion battery pack prices fall 20% in 2024) or ATESS PCS500 gives ≈ £17 k; UK stock & grid-code firmware add margin.
EMS, SCADA & protection relays	£10 k	£15 k	£25 k	
1 MVA 11 kV/0.4 kV oil-filled transformer	£35 k	**£45 k**	£70 k	New Tier-2 Ecodesign unit; dry-type or ester-filled adds 15–30 %
11 kV RMU + metering panel	£30 k	**£37 k**	£45 k	National Grid budget price £25 k (RMU) + £12 k (metering).
Container fabrication (ISO 40 ft), HVAC, fire suppression, cabling, LV switchboard	£80 k	**£110 k**	£150 k	Dual-compartment design (diesel vs battery) & DSEAR zoning drive cost
Factory integration + FAT/SAT	£45 k	**£55 k**	£75 k	Mechanical fit-out, wiring looms, soak-testing
Site delivery, civils, commissioning & DNO witness	£70 k	**£90 k**	£160 k	Pad, crane lift, 11 kV cable tails (<50 m) and G99 paperwork

Ball-park totals (ex-VAT)

- Lean / minimum-spec: ≈ £620 k
- Typical commercial-industrial turnkey: ≈ £890 k
- Premium / accelerated schedule: ≈ £1.25–1.35 m

Why the spread is wide

Driver	Impact on cost
Specification choices	**Acoustic canopy vs. open skid (adds £20-40 k) – This would ensure a quieter operation which depending on location may be a key requirement; Tier 4-Final emissions kit (+10 %).**
Battery chemistry & warranty	**LFP vs NMC, 10- vs 15-year throughput guarantees can swing £80-150 k on a 2 MWh system.**
Container layout	**Single ISO 40 ft with fire wall is cheapest; two dedicated 20 ft modules or walk-in switch room add £40-60 k.**
Grid requirements	**DNO auxiliary supply, neutral-point earthing resistors or harmonic studies may add £20-40 k.**
Schedule & origin	**EU-built equipment shortens shipping time but lifts hardware 10-15 %; fast-track build slots add overtime premiums.**
Soft costs & risk	**EPC wrap, performance bonds and indexation allowances typically run 10-20 % of hardware but climb if finance parties require longer LD cover.**

- The central £890 k figure assumes mainstream brands (Cummins, CATL/LFP racks, ATESS PCS), 12-week lead, standard noise (75 dBA @ 1 m), and a single 40 ft container with internal fire partition.
- Grid connection fees, fuel system bund wall, standby fuel and land purchase are *excluded* as they depend heavily on-site specifics.
- Costs are referenced to Q2 2025, GBP terms, and should be uplifted by ~3-4 % / yr for budgeting beyond 2025 based on BEIS plant-cost indices.

These numbers are suitable for an early-stage feasibility analysis; expect ±20 % accuracy until supplier RFQs are obtained.

4.2 AAT

Indicative cost summary (BESS Only unit)

Bottom-up CAPEX build-up (central estimate)

Item	Basis	£ k
Battery modules & racks	£125 / kWh (BNEF £129 minus small-project premium) × 3 065 kWh	**383**
PCS & step-up transformer	15 % of system (high for small size)	**100**
Energy/SCADA/BMS software	~5 % of battery cost	**19**
Containerisation, cooling, fire suppression, marshalling kiosks	≈ 10 % of system	**40**
Civil works & installation	Foundations, cranage, cabling, labour	**60**
DNO connection & protection studies	10–15 % total ⇒ mid-point	**80**
Development, planning, legal	Land option, lease, planning fees, grid offer fees	**40**
Contingency (15 %)	Technology & connection risk	**108**
TOTAL EPC-level CAPEX		**≈ £830 k**

Final budget guidance (2025)

Line item	Low	Central	High
EPC turn-key (modules + PCS + BOP)	550 k	640 k	770 k
Grid connection & civils	60 k	140 k	210 k
Development, studies, legal	30 k	40 k	60 k
Contingency (10-20 %)	70 k	100 k	150 k
Total upfront	**≈ 700 k**	**≈ 830 k**	**≈ 1 050 k**

Given the 10% safety margin applied on the sizing, it is reasonable to suggest that circa £100k could be removed from the budgetary figures provided above.

Indicative cost summary (Hybrid unit)

Containerised 239 kW genset + 1.1 MWh BESS (350 kW PCS) ready for 11 kV grid connection (UK)

Cost element	Lean-spec (low)	Typical C&I spec (mid)	Premium / fast-track (high)	Notes & key drivers
239 kW diesel generator (≈ 300 kVA)	**£45 k**	**£52 k**	**£70 k**	Web dealers advertise new Doosan-powered 220 kVA sets at **£15 - 28 k**; canopied Tier IIIa Cummins/Perkins units land at ~£220–£260 /kW.
1.1 MWh Li-ion battery racks (LFP)	**£198 k**	**£242 k**	**£297 k**	Global c (Doosan 220KVA AD220 Diesel Generators, 250 kVA Generators for Sale - Generator Warehouse) $165 /kWh ≈ £132 /kWh**; UK EPC wraps add 20–35 %.
350 kW bidirectional PCS	**£21 k**	**£32 k**	**£46 k**	ENF lists ATESS P (Battery Report 2024: BESS surging in the "Decade of Energy Storage") → £0.035 /W**; UK stock, grid-code firmware & warranty add margin.
EMS, SCADA, protection relays	£10 k	**£13 k**	£20 k	G9 Atess Power Technology
500 kVA 11 kV/0.4 kV transformer	£25 k	**£32 k**	£45 k	Refurbished ONAN units from stock start around £25 k; new Tier-2 Eco-design ester-filled adds 30 %.
11 kV ring-main unit + metering panel	£28 k	**£35 k**	£40 k	DNO budget rates £25–35 k for an indoor SF_6 RMU with import/export metering.
Container fabrication (ISO (Unit cost - esru.strath.ac.uk) suppression, LV board	£60 k	**£85 k**	£110 k	One dual-compartment 20 ft box meets fire separation; optional walk-in switch-room drives cost up.
Factory integration & FAT/SAT	£35 k	**£45 k**	£65 k	Mechanical fit-out, harnesses, 24-h soak, grid-sim tests
Delivery, civils, commissioning & DNO witness	£50 k	**£75 k**	£120 k	Pad, crane, 11 kV tails (<30 m), G99 paperwork, fuel bund

Ball-park project totals (ex-VAT)

Scenario	CAPEX
Lean / minimum spec	≈ £470 k
Typical turnkey	≈ £610 k
Premium / accelerated schedule	≈ £810 k

(Derived by summing the column figures in previous table; ±20 % accuracy for feasibility budgeting.)

Why costs vary so widely

Cost driver	Effect on CAPEX
Hardware spec	Super-silent canopy, Tier 4-Final emissions, black-start alternator add 20-40 % to the genset line.
Battery warranty & chemistry	Stepping from a 10-yr / 4 000-cycle LFP to a 15-yr / 8 000-cycle pack can add £60-80 k even at 1.1 MWh.
Container configuration	A single 20 ft ISO is cheapest; two 20 ft or a bespoke walk-in switch-room adds £25-50 k.
Grid compliance	Additional protection (N-ER, ROCOF, harmonic study) or DNO-specified relays add £10-25 k.
Schedule & origin	EU-built transformer or PCS shortens lead-time but comes at a 10-15 % price premium; rush orders add overtime.
Soft-costs & risk	EPC wrap, bonds and indexation allowances typically run 10-20 % of hardware but climb for small one-off builds.

- The **£610 k "typical" figure** assumes mainstream brands (Perkins genset, CATL LFP racks, ATESS PCS), 14-week lead, 75 dBA @ 1 m acoustic, and a **single 20 ft container** with a fire partition and VESDA detection.
- Grid-application fees, land purchase, ongoing O&M and diesel day-tank/bund are **excluded**, as they are site-specific.
- Pricing is referenced to **Q2 2025** GBP; index by ~3-4 % / year using BEIS plant-cost indices for future estimates.

4.3 Genset Fuel

Fuel consumption for HVO-powered gensets typically ranges from **0.21 to 0.25 litres per kWh** at full load. We'll use a typical value of **0.23 litres per kWh** for HVO, which is in line with manufacturer data. We will further assume that 1 litre of HVO costs £1.50 for illustrative purposes:

BNZ 850kW genset running continuously over a 24-hour period

Daily Energy Output:

850 kW×24 hours=20,400 kWh

Fuel Consumption:

20,400 kWh×0.23 litres/kWh=4,692 litres of HVO

Fuel Cost

4,692 litres×£1.50=£7,0384

Summary:

- **HVO Fuel Consumed:** ~4,692 litres over 24 hours
- **Fuel Cost @ £1.50/litre: £7,038**

AAT 250kW genset running for 23 x half hour periods in a 24-hour period

Daily Energy Output:

250 kW×11.5 hours=2,875 kWh

Fuel Consumption:

2,875 kWh×0.23 litres/kWh=661.25 litres of HVO

Fuel Cost:

661.25 litres×£1.50=£991.88

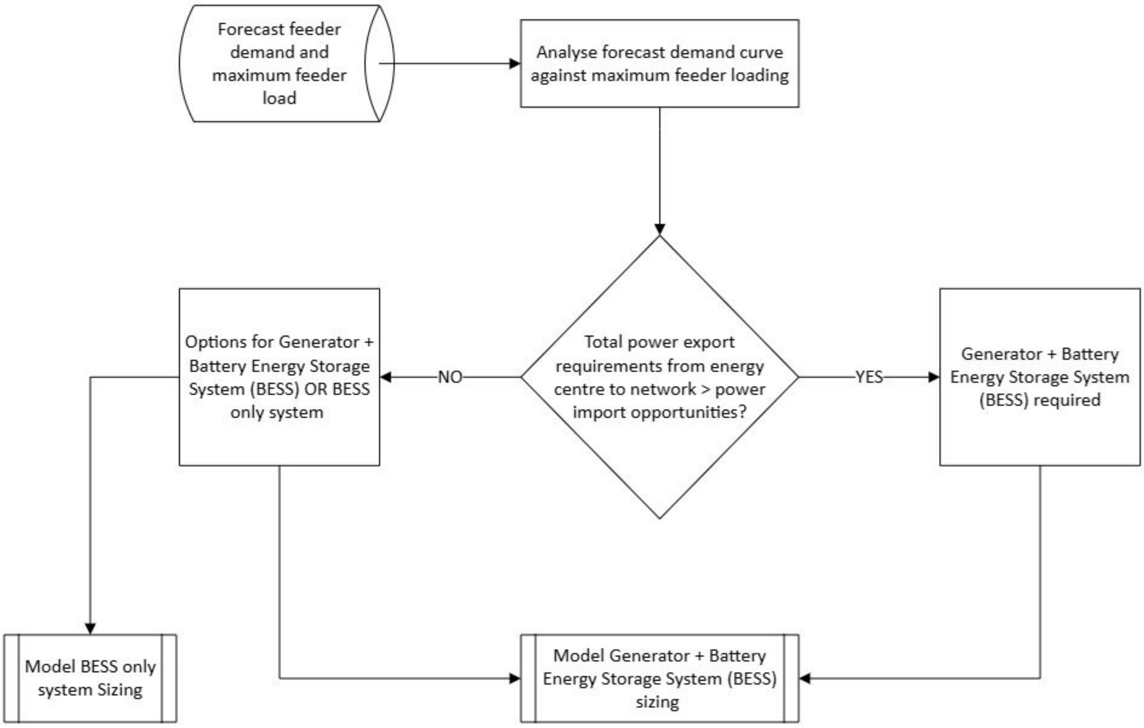
Summary:

- **HVO Fuel Consumed:** ~661 litres over 11.5 hours
- **Fuel Cost @ £1.50/litre: £991.88**

5. Methodology

5.1 Initial data analysis

Upon receipt of the raw data from NGED, the initial analysis involved analysing the forecast demand curve against the maximum feeder loading. The first question to answer was whether the total power export requirements from the energy centre to the network were greater than the import opportunities. This determined whether a generator and Battery Energy Storage System (BESS) was required or whether a BESS only solution was also a viable solution.



5.2 REACH – Battery Energy Storage System Only Sizing Approach

A three-stage approach was used to size the Battery Energy Storage System (BESS) based on the half-hourly forecast data provided where the positive intervals were those where forecast demand exceeded the maximum capacity of the feeder being analysed:

Sum of all positive intervals:	$E_{\text{use}} = \sum_{i:\,E_i>0} E_i =$
Adjust for round-trip efficiency (η = 90 %):	$E_{\text{needed}} = \frac{E_{\text{use}}}{\eta} = \frac{E_{\text{use}}}{0.90} =$
Add 10% safety margin:	$E_{\text{spec}} = E_{\text{needed}} \times 1.10 =$

5.3 REACH – Hybrid (Genset & BESS) Sizing Approach

Generator Sizing

Calculate the average (mean) of all positive values (where demand exceeds the maximum feeder load)	$\bar{E}_{+} = \frac{1}{\text{Number of positives (X)}} \sum_{i=1}^{X} E_i$
We want a constant output genset whose 0.5 h energy exactly equals the mean export:	$P_{\text{gen}} = \frac{\bar{E}_{+}}{0.5\,\text{h}} = 2 \times \bar{E}_{+}$
Add a 10% safety margin	$P_{\text{gen, rated}} = 1.10 \times P_{\text{gen}}$

BESS Sizing

Compute the excess for each half hour where demand is greater than the amount provided by the genset and sum the values	$\sum_{E_i > \bar{E}_{+}} \Delta_i =$
Account for 90% round trip efficiency	$E_{\text{batt,usable}} = \frac{\sum_{E_i > \bar{E}_{+}} \Delta_i}{0.90}$
Add a 10% safety Margin	$E_{\text{batt,rated}} = 1.10 \times E_{\text{batt,usable}}$

6. Discussion

6.1 Two-stage approach

During the Alpha phase of the project, we revised the scope of the REACH Energy Centre in response to insights gathered through repeated workshops and surveys with the communities. The original concept envisaged a single, community-owned hub that would immediately integrate generation, battery storage and ancillary services such as shared EV chargers.

However, it became apparent that differing communities were at different stages in their knowledge and development of building out community owned low carbon technology projects. Accordingly, the team adopted a pragmatic two-stage pathway: **Stage 1** delivers a potentially DNO-financed energy centre focused on stabilising the local network (voltage, thermal headroom) while creating the headroom for individual households to roll out low carbon technologies such as heat pumps and EV charge-points. **Stage 2**, guided by the proposed Options Tool, allows the community to mobilise capital and governance structures to acquire or supersede the initial unit with a wholly community-owned asset once participation, knowledge and funding align. This phased strategy preserves the long-term ownership ambition yet ensures near-term decarbonisation and grid-support benefits are not delayed.

This approach had an impact on the way the sizing of the modular system was approached.

6.2 Edge case communities

The original concept for an energy centre was predicated on the basis that a rapid adoption of low carbon technologies (LCT) could quickly put strain on a network that was not designed to see a potentially four- or five-fold household increase in energy demand. It was always recognised that this would be the exception rather than the rule although rural communities were potentially more likely to experience network reinforcement challenges than urban locations. Whilst DFES 2024 models were used and were even accelerated, it is unclear to the author whether this was a sufficiently aggressive forecast to account for the edge case scenario originally envisioned. A more aggressive forecast may have led to constraints being observed under normal operations as opposed to the abnormal (N-1) scenarios for which the modelling was undertaken.

6.3 Private Wire Consideration

Several of the rural communities expressed an interest in whether the energy centre could provide power in the case of a power outage. Whilst the consensus was generally that the energy centre was not designed for this eventuality consideration was given to whether a private wire connection to a village hall or community centre may be a viable proposition to provide a central location with power in the case of an outage.

6.4 Community Renewable Connection

Several communities expressed an interest in whether the energy centre could provide a fast-track connection option for a community owned renewable generation project such as a solar farm or wind turbine. Whilst this was not envisaged at the outset, this may be worth re-evaluating during subsequent project phases.

7. Conclusions & Recommendations

In the scenarios modelled, a REACH energy centre overcomes the forecast constraints on the networks. Most of the community energy groups engaged by project partner REGEN seem interested in having an energy centre within their community and are interested to engage with the proposed Options tool to learn how a community owned asset may work for them.

Given the change to a proposed two stage approach, it is not clear whether the two selected communities are the optimum sites for the initial centres given that under current forecasts they only become constrained under abnormal operations. A wider review across the NGED network may be required to identify sites that potentially become overloaded under normal operations given the forecasts being used.

VEPOD should engage with Passiv to determine how best to integrate a co-ordinated heat pump control strategy within the energy centre.

8. Glossary of Terms

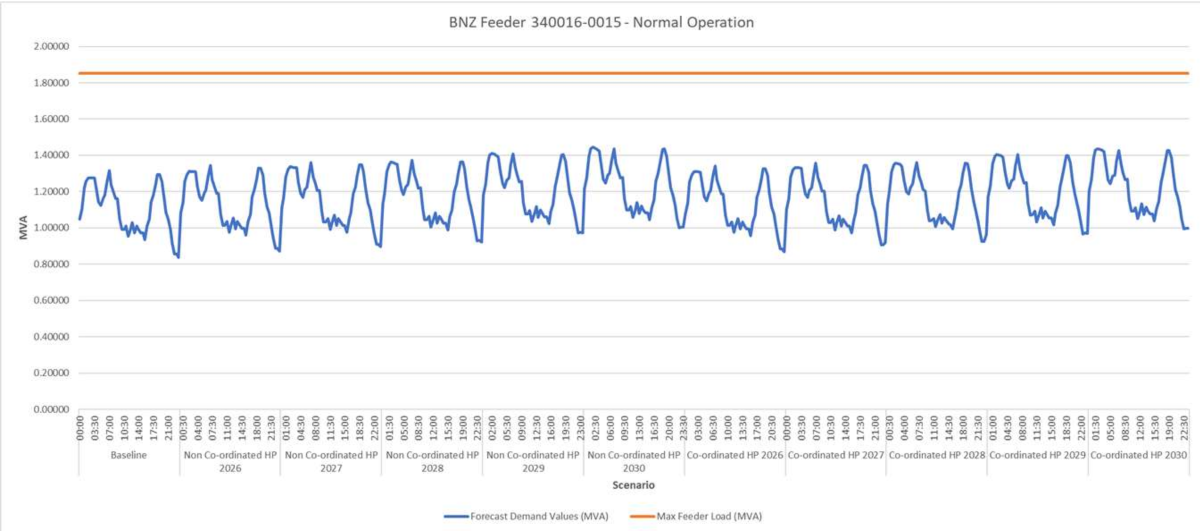
Acronym	Meaning / Definition
AAT	*Amen Awel Tawe* – Welsh pilot community selected for Project REACH
AC	Alternating Current (electricity that reverses direction periodically)
BESS	Battery Energy Storage System
BNZ	*Bigbury Net Zero* – Devon pilot community selected for Project REACH
CAPEX	Capital Expenditure (up-front investment cost)
COP	Coefficient of Performance (heat-pump efficiency ratio)
DC	Direct Current (electricity that flows in one direction)
DER	Distributed Energy Resource (decentralised generation, storage or controllable load)
DNO	Distribution Network Operator (responsible for regional electricity networks)
EMS	Energy Management System (controls generation + storage dispatch)
EPC	Engineering, Procurement & Construction (contracting model for project delivery)
EV	Electric Vehicle
GHG	Greenhouse Gas
HP	Heat Pump
HVAC	Heating, Ventilation & Air-Conditioning
kW / kWh	Kilowatt (power) / Kilowatt-hour (energy)
LCOE	Levelised Cost of Energy (lifetime-average cost per unit of energy)
NGED	National Grid Electricity Distribution (regional DNO for South-West & Midlands)
OPEX	Operational Expenditure (ongoing running cost)
PPA	Power Purchase Agreement (long-term electricity off-take contract)
REACH	*Renewable Energy & Affordable Community Heat* (project title)
SoC	State-of-Charge (percentage of usable capacity in a battery)
TES	Thermal Energy Storage (hot-water tank or phase-change store)
VEPOD	VEPOD Ltd – industrial partner and technology supplier
WPB1	Work Package B1 (Energy Centre Design workstream)
D4	Deliverable 4 (this report within WPB1)

9. Appendices

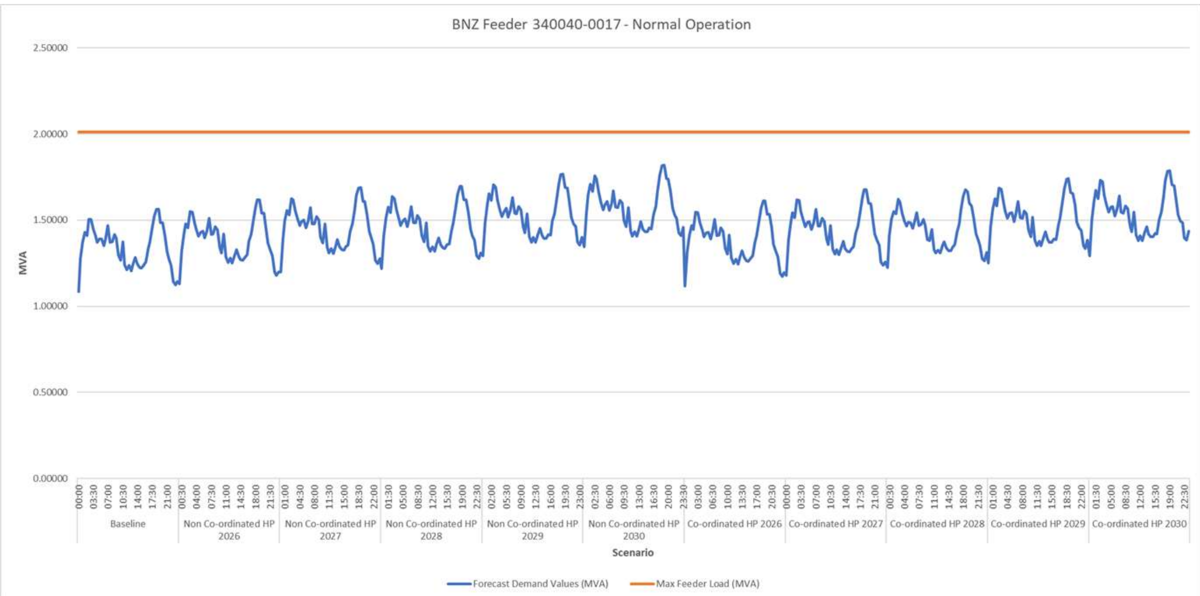
10.1 Raw Data

BNZ Forecast data

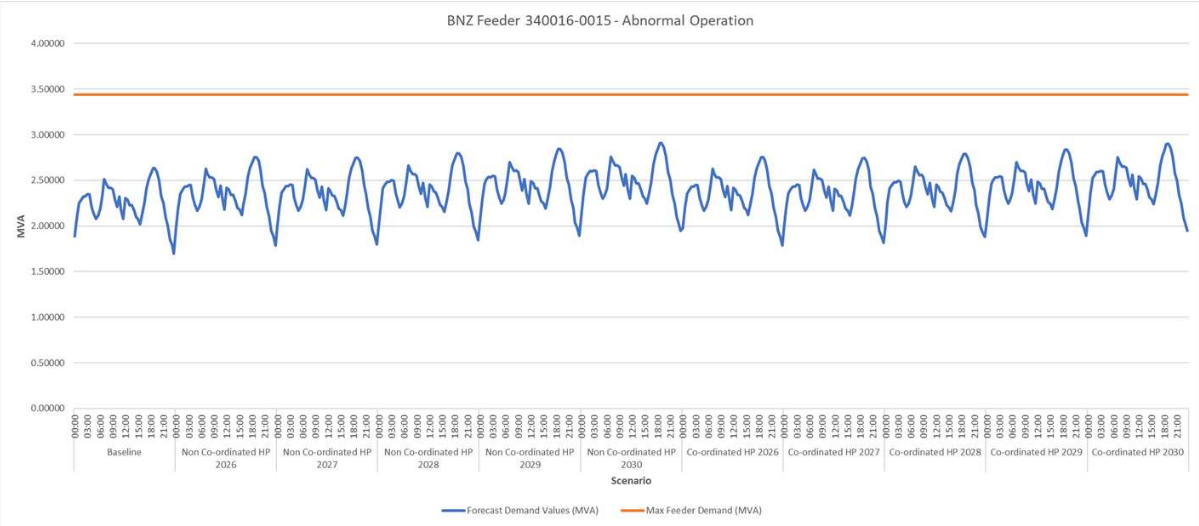
BNZ Feeder 340016-0015 – Normal Operation



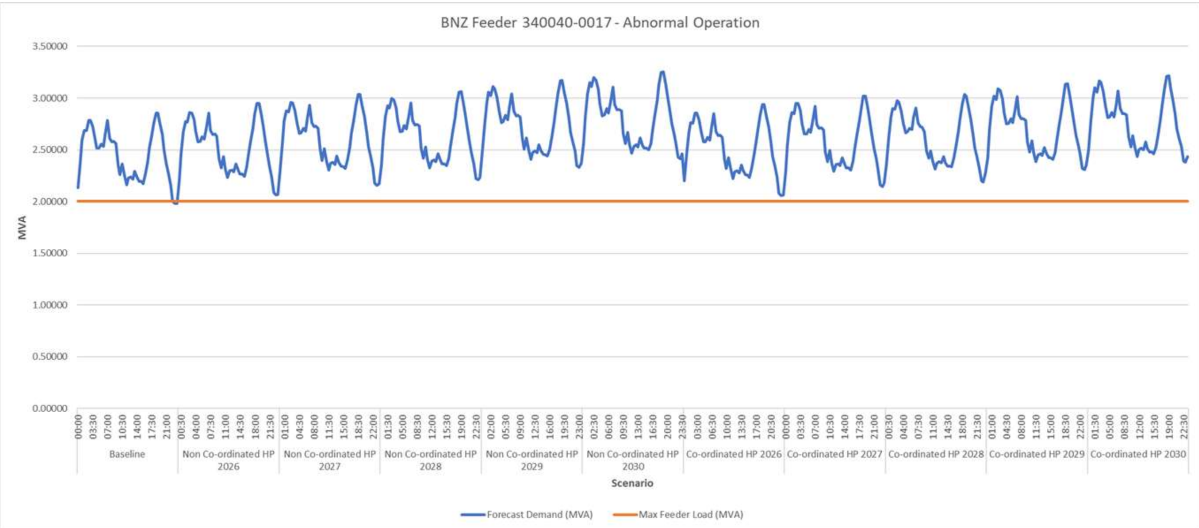
BNZ Feeder 340040-0017 – Normal Operation



BNZ Feeder 340016-0015 – Abnormal Operation

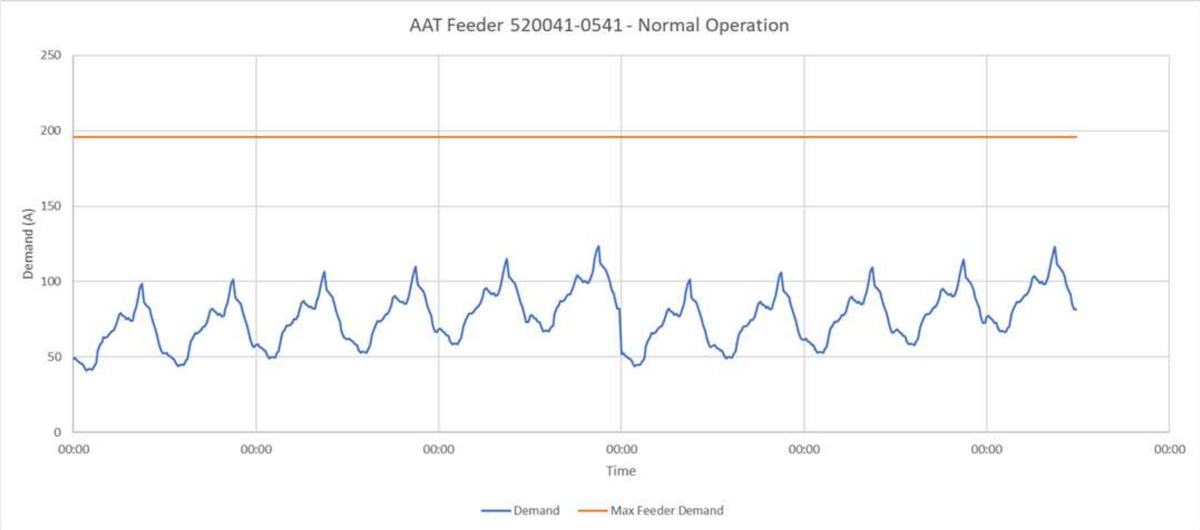


BNZ Feeder 340016-0017 – Abnormal Operation

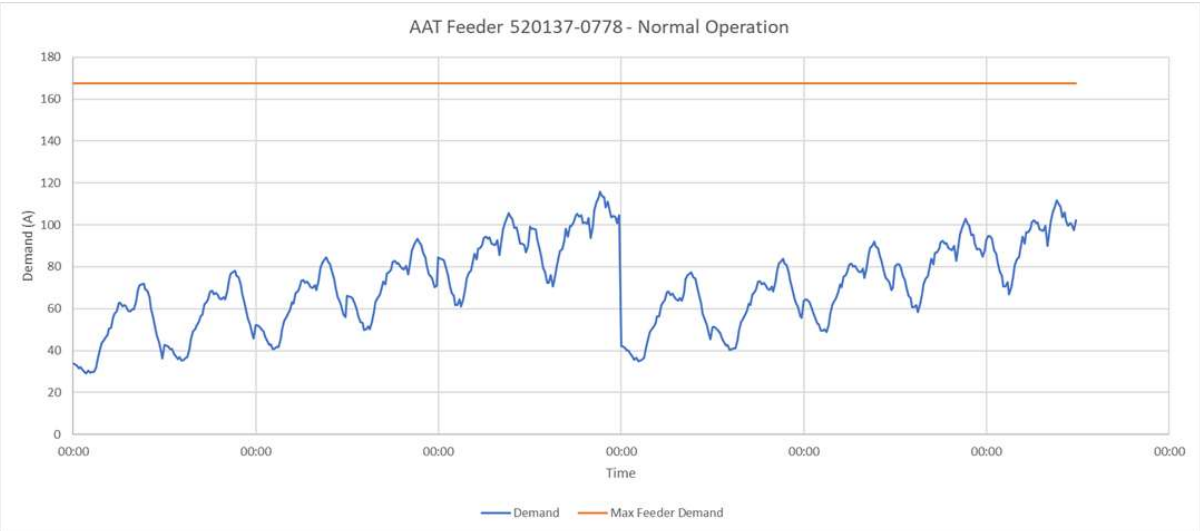


AAT Forecast data

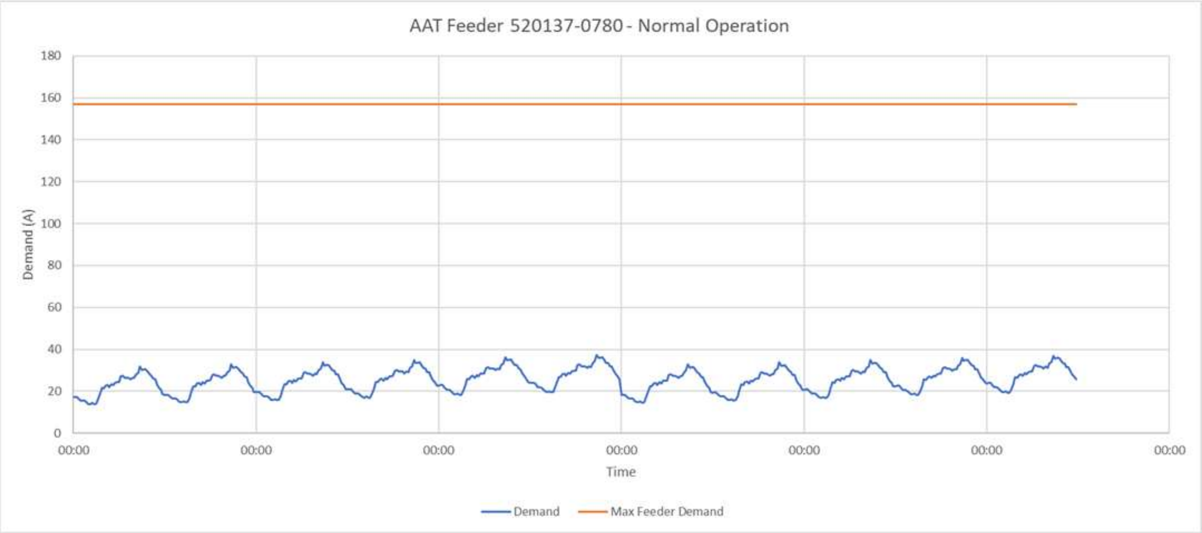
AAT Feeder 520041-0541 – Normal Operation



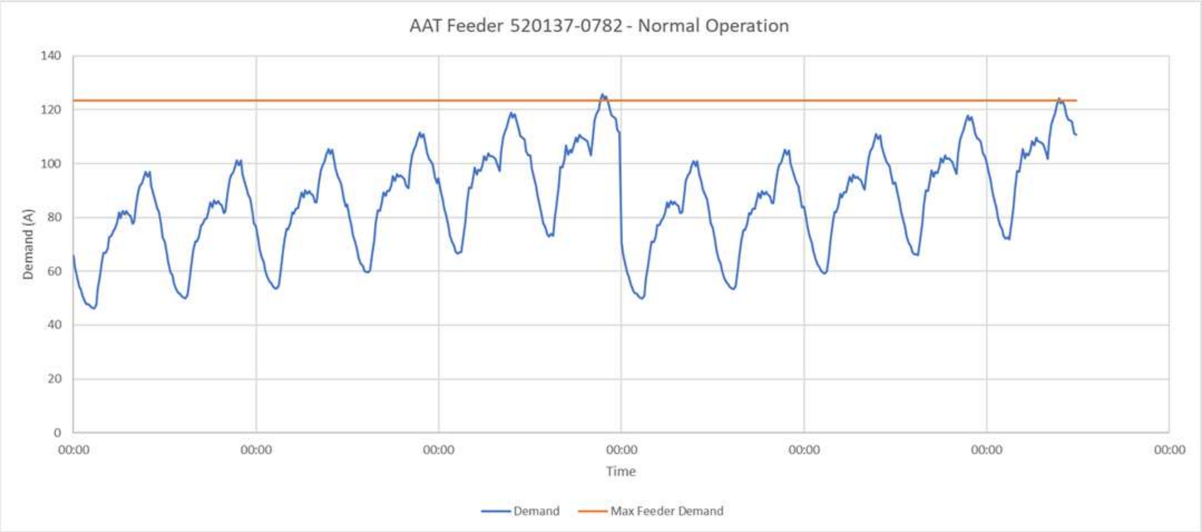
AAT Feeder 520041-0778 – Normal Operation

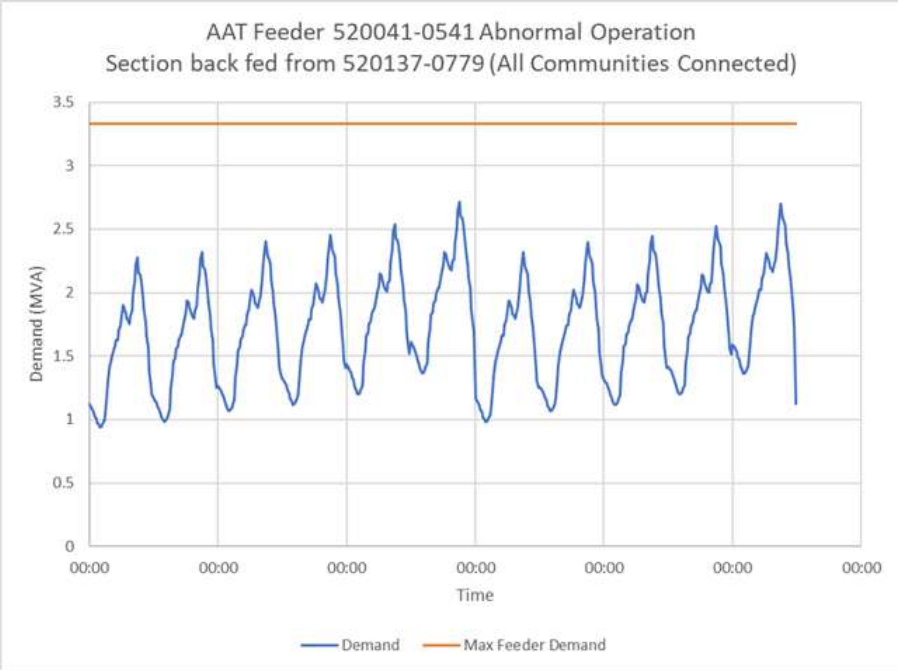


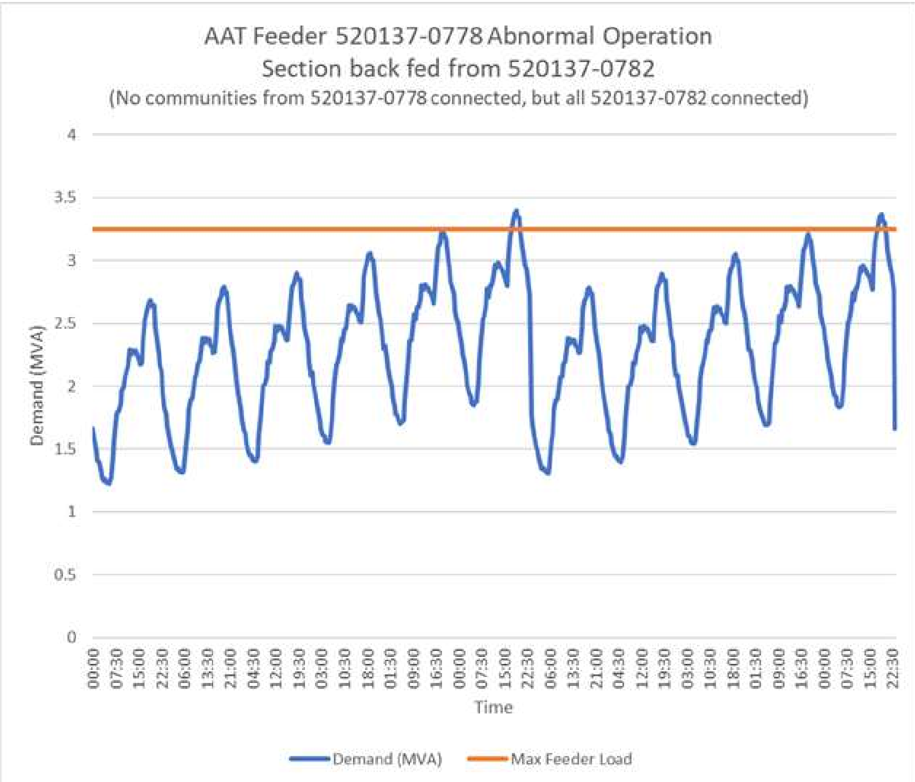
AAT Feeder 520041-0780 – Normal Operation

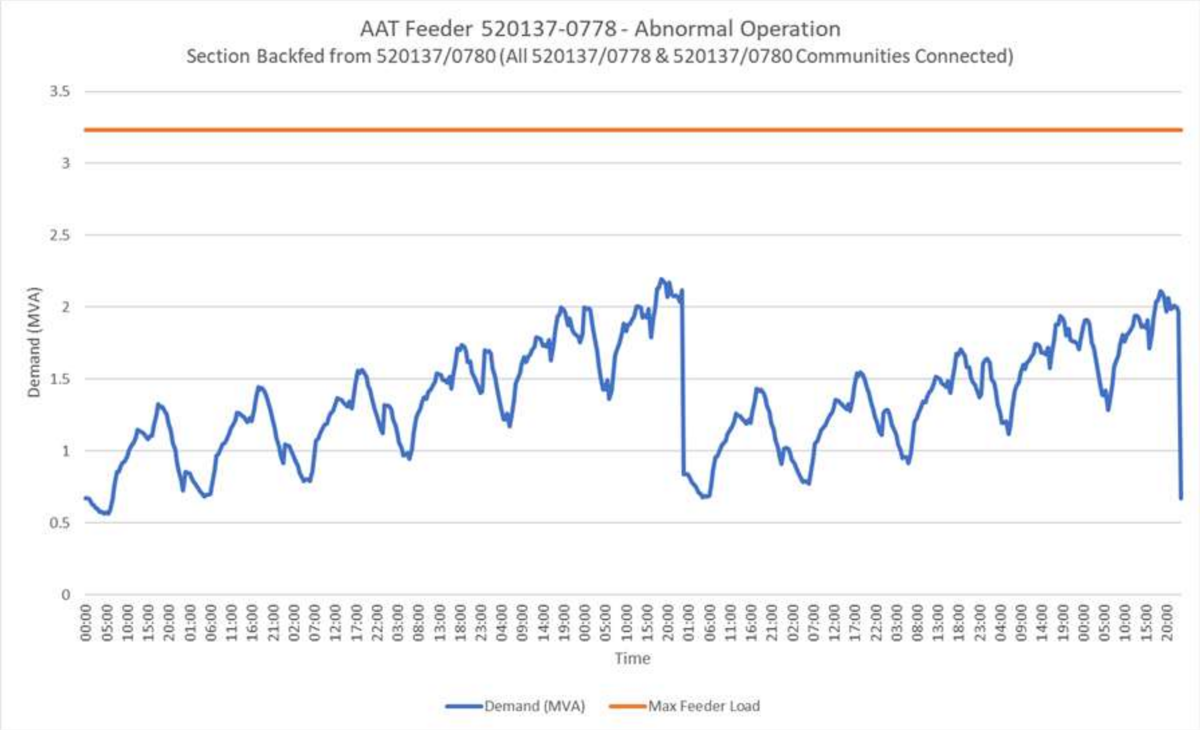


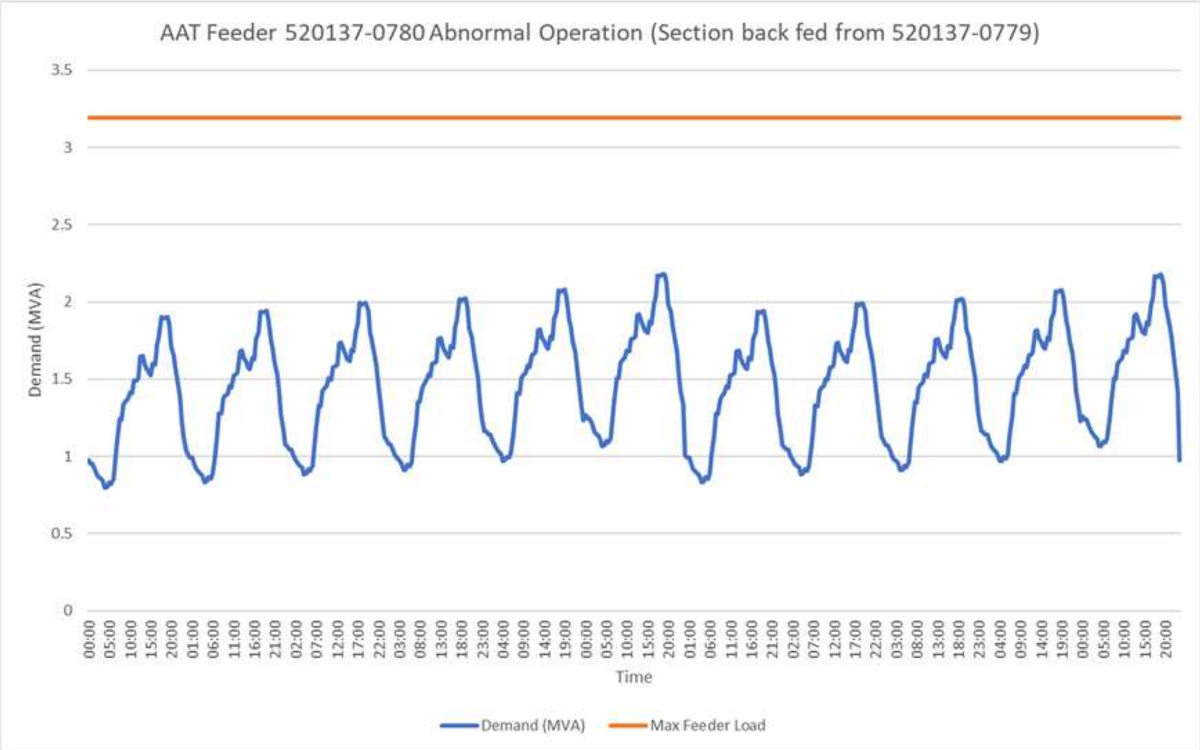
AAT Feeder 520041-0782 – Normal Operation

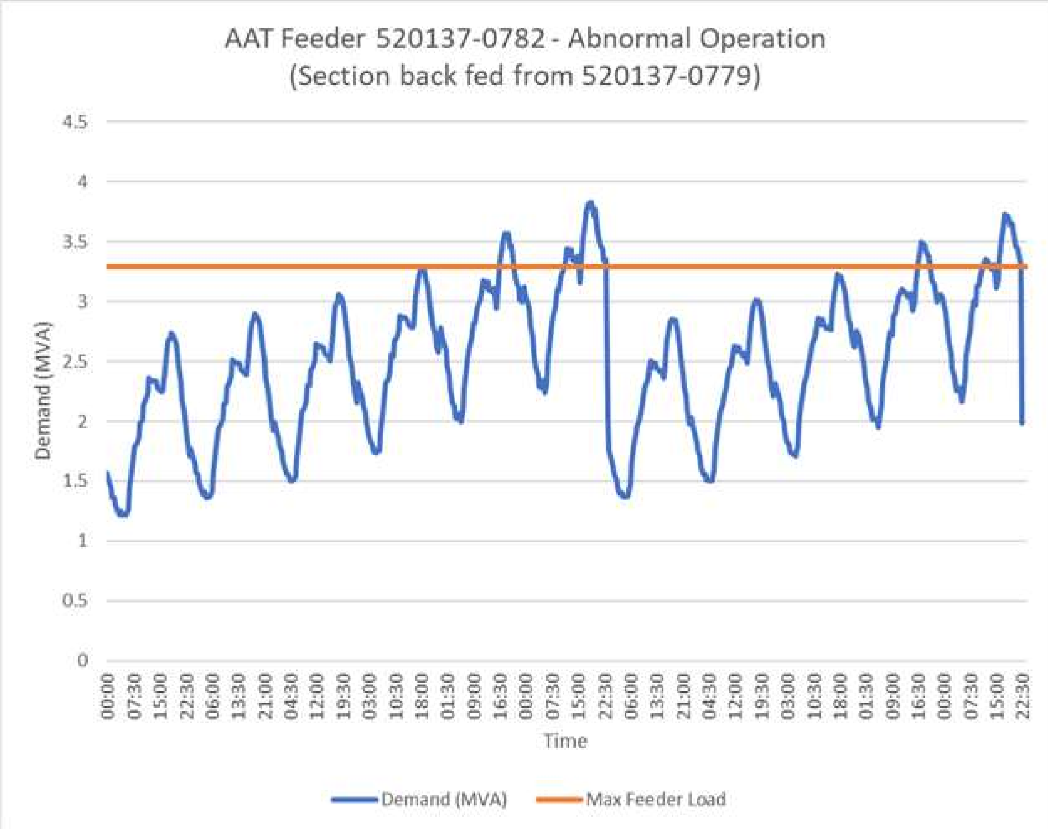


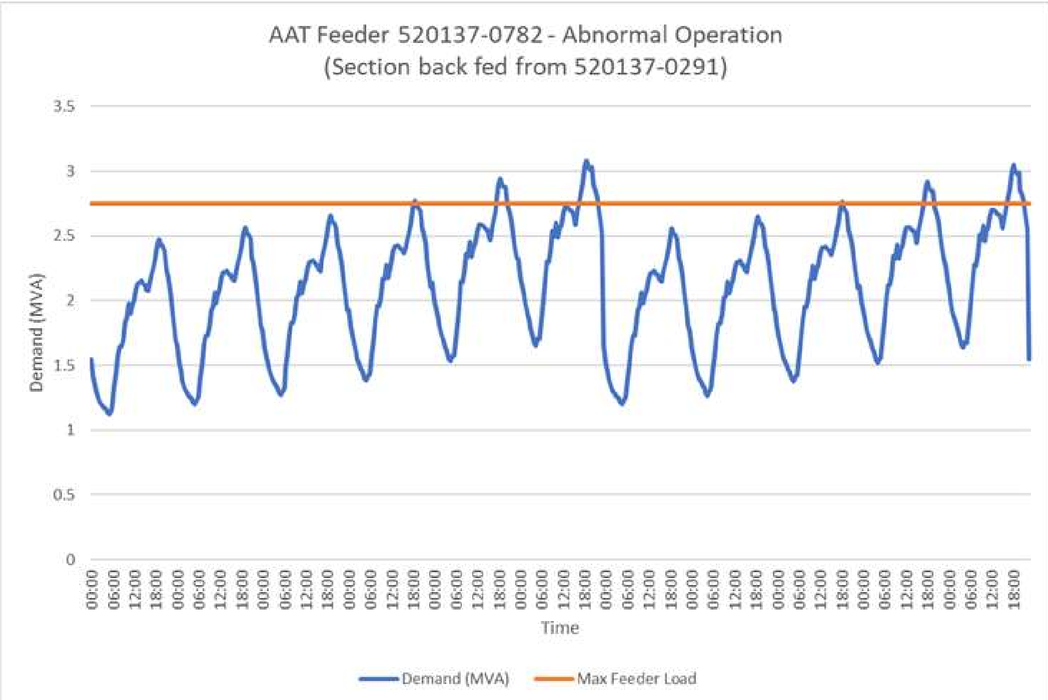

AAT Feeder 520041-0541 Abnormal Operation
Section back fed from 520137-0779 (All Communities Connected)
Demand (MVA)
0
0.5
1
1.5
2
2.5
3
3.5
00:00
00:00
00:00
00:00
00:00
00:00
00:00
Time
Demand
Max Feeder Demand


AAT Feeder 520137-0778 Abnormal Operation
Section back fed from 520137-0782
(No communities from 520137-0778 connected, but all 520137-0782 connected)
Demand (MVA)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time
Demand (MVA)
Max Feeder Load


AAT Feeder 520137-0778 - Abnormal Operation
Section Backfed from 520137/0780 (All 520137/0778 & 520137/0780 Communities Connected)
Demand (MVA)
Time
Demand (MVA)
Max Feeder Load


AAT Feeder 520137-0780 Abnormal Operation (Section back fed from 520137-0779)
Demand (MVA)
Time
Demand (MVA)
Max Feeder Load


AAT Feeder 520137-0782 - Abnormal Operation
(Section back fed from 520137-0779)
Demand (MVA)
Time
Demand (MVA)
Max Feeder Load


AAT Feeder 520137-0782 - Abnormal Operation
(Section back fed from 520137-0291)
Demand (MVA)
Time
Demand (MVA)
Max Feeder Load

10.2 Detailed Calculations for BNZ

Sizing scenario - "Peak-shave only" case (genset always available)

In this scenario, we assume that the generator is always available and running constantly at its maximum rated power. The peaks and troughs of demand (above and below the amount of power supplied by the genset) are handled by a Battery Energy Storage System (BESS).

1. Compute basic stats

- Number of half-hours per period: 48
- Total energy to shave per day

$$E_{\text{tot}} = \sum_{i=1}^{48} E_i \approx 18\,174.16\ \text{kWh}$$

- Mean per half-hour:

$$\bar{E} = \frac{E_{\text{tot}}}{48} \approx 378.63\ \text{kWh}$$

2. Generator sizing

- A half-hourly energy of 378.63 kWh corresponds to a power of

$$P = \frac{\bar{E}}{0.5\ \text{h}} \approx 757.3\ \text{kW}$$

- Add 10 % safety margin:

$$P_{\text{gen}} = 757.3 \times 1.10 \approx \mathbf{833\ kW}$$

When the generator runs continuously at 833 kW it can deliver in each half-hour:

$$E_{\text{gen,hh}} = 833\ \text{kW} \times 0.5\ \text{h} = 416.5\ \text{kWh}.$$

Any half-hour requirement above 416.5 kWh must come from the battery.

1. Compute battery discharge per period

$$d_i = \max\bigl(E_i - 416.5,\ 0\bigr) \quad \Rightarrow \quad \sum_i d_i \approx 1\,642.5\ \text{kWh/day}.$$

2. Account for 90 % round-trip efficiency

$$E_{\text{charge}} = \frac{\sum_i d_i}{0.90} \approx 1\,825.0\ \text{kWh/day}.$$

3. Add 10 % safety margin

$$C_{\text{batt}} = 1\,825.0 \times 1.10 \approx \mathbf{2\,008\ kWh} \quad (\approx 2.01\ \text{MWh}).$$

Battery power (inverter/rectifier) rating

Breakdown of the battery's power-electronics sizing, based on the 833kW continuous generator:

1. Half-hourly baseline energy

$$E_{\text{gen,hh}} = 833\ \text{kW} \times 0.5\ \text{h} = 416.5\ \text{kWh}.$$

2. Discharge (inverter) side
   For each period i,

$$d_i = \max(E_i - 416.5, 0)$$

   the maximum d_i is

$$\max_i d_i \approx 178.35\ kWh \quad \Rightarrow \quad P_{\text{discharge}} = \frac{178.35}{0.5\ h} \approx 356.7\ kW.$$

   +10 % margin ⇒ 392 kW

3. Charge (rectifier) side
   Whenever $E_i < 416.5$, the surplus

$$c_i = \max(416.5 - E_i, 0)$$

   must be absorbed. The peak is

$$\max_i c_i \approx 220.57\ kWh \quad \Rightarrow \quad P_{\text{charge}} = \frac{220.57}{0.5\ h} \approx 441.1\ kW.$$

   +10 % margin ⇒ 485 kW

Conclusion:

- Battery inverter (discharge) rating: ~392 kW
- Battery rectifier (charge) rating: ~485 kW

Or, if a single bidirectional converter is used, size it for the larger figure (≈ 485 kW) or more likely 0.5MW nameplate.

Sizing summary

Scenario	Genset Size	Battery energy	Battery power inverter rating
Model with no co-ordinated heat pump demand	833 kW	2.01 MWh	0.5 MW

10.3 Detailed Calculations for AAT

Sizing scenario 1 – Battery Energy Storage Solution (BESS) only solution

In this scenario, no generator is considered, and the energy centre is sized based on only using a Battery Energy Storage Solution (BESS).

Objective

The design objective is to define the energy and power ratings of a Battery Energy Storage System (BESS) dedicated solely to peak-shaving, incorporating a 90 % round-trip efficiency and a 10 % design margin. The 90% round trip efficiency considers the losses that are incurred in moving energy between the BESS and the electricity network feeder line. The design margin considers a safety margin and the potential degradation of the batteries over time.

Input Data

As indicated above, the positive values indicate discharge (peak-shaving), negatives represent potential recharge that we will *not* be fully capturing.

Interval	Energy (kWh)
…	…
Peak	267.90
…	…

Sum of all positive intervals:

$$E_{\text{use}} = \sum_{i:\,E_i>0} E_i = 2499.49\ \text{kWh}$$

Energy Capacity Calculation

1. **Baseline usable energy**

$$E_{\text{use}} = 2\,499.49\ \text{kWh}$$

2. **Adjust for round-trip efficiency** (η = 90 %):
   To deliver 2 499.49 kWh to the grid, the battery must be charged with more energy:

$$E_{\text{needed}} = \frac{E_{\text{use}}}{\eta} = \frac{2\,499.49}{0.90} = 2\,777.21\ \text{kWh}$$

3. **Apply 10 % safety margin:**

$$E_{\text{spec}} = E_{\text{needed}} \times 1.10 = 2\,777.21 \times 1.10 = 3\,054.93\ \text{kWh} \approx 3.06\ \text{MWh (usable)}$$

Discharge Power Rating

1. **Peak half-hour discharge energy:**

$$E_{\text{peak}} = 267.90\ \text{kWh per 0.5 h}$$

2. **Convert to continuous power:**

$$P_{\text{dis}} = E_{\text{peak}} \times 2 = 267.90 \times 2 = 535.80\ \text{kW}$$

3. **Add 10 % margin:**

$$P_{\text{dis,spec}} = 535.80 \times 1.10 = 589.38\ \text{kW} \approx 0.59\ \text{MW}$$

Recharge (Charge) Power Rating

Assuming the 2,777-kWh recharge is scheduled over an 8 h off-peak window:

1. **Average required charge rate:**

$$P_{\text{ch,avg}} = \frac{E_{\text{needed}}}{8\ \text{h}} = \frac{2\,777.21}{8} = 347.15\ \text{kW}$$

2. **Add 10 % margin:**

$$P_{\text{ch,spec}} = 347.15 \times 1.10 = 381.87\ \text{kW} \approx 0.38\ \text{MW}$$

Summary of BESS Specification

Parameter	Calculation	Specification
Usable Energy Capacity	(2499.49/0.90) × 1.10	3.06 MWh
Discharge Power	2 × 267.90 × 1.102	0.59 MW
Charge Power	(2499.49/0.90)/8×1.10	0.38 MW

Note:

- Round final inverter sizes to industry-standard blocks (e.g. 0.6 MW discharge, 0.4 MW charge).
- The 10% safety margin should account for degradation, temperature effects and inverter efficiency.
- A BESS only approach provides an adequate solution and enables the peak shaving required.

Sizing scenario 2 – Sizing of Generator and Battery Storage for Load Levelling Using Export Demand Data

In this scenario a combination of a generator and a BESS system is considered. The generator sizing is calculated based on the mean export demand value. The peaks and troughs of demand (above and below the amount of power supplied by the genset) are handled by a Battery Energy Storage System (BESS).

There are 23 positive half-hour values; their mean is

$$\bar{E}_{+} = \frac{1}{23}\sum_{i=1}^{23} E_i \approx 108.67\ \mathrm{kWh}.$$

1. Generator (genset) rating

We want a constant output genset whose 0.5 h energy exactly equals the mean export:

$$P_{\mathrm{gen}} = \frac{\bar{E}_{+}}{0.5\ \mathrm{h}} = 2 \times 108.67 \approx 217.35\ \mathrm{kW}.$$

Adding a 10 % safety margin,

$$P_{\mathrm{gen,\ rated}} = 1.10 \times 217.35 \approx 239.1\ \mathrm{kW}.$$

2. Battery energy sizing (for export peaks only)

1. Compute for each half-hour where $E_i > \bar{E}_+$ the "excess"

$$\Delta_i = E_i - \bar{E}_+.$$

2. Sum those "excess" energies:

$$\sum_{E_i > \bar{E}_+} \Delta_i = 901.54 \text{ kWh}.$$

3. Account for 90 % round-trip efficiency (i.e. you must store more than you discharge):

$$E_{\text{batt,usable}} = \frac{901.54}{0.90} \approx 1\,001.7 \text{ kWh}.$$

4. Add a 10 % safety margin:

$$E_{\text{batt,rated}} = 1.10 \times 1\,001.7 \approx 1\,101.9 \text{ kWh} \approx 1.10 \text{ MWh}.$$

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3. Inverter / rectifier power sizing

- Discharge side: highest single half-hour excess was

$$\max(E_i - \bar{E}_+) = 159.23 \text{ kWh}, \text{ i.e.}$$

$$P_{\text{discharge}} = \frac{159.23}{0.5} \approx 318.5 \text{ kW}.$$

- +10 % margin ⇒ 1.10×318.5 ≈ **350.4 kW**

Sizing summary

Scenario	Genset Size	Battery energy	Battery power inverter rating
Model with no co-ordinated heat pump demand	**239 kW**	**1.10 MWh**	**350kW**

NB: All figures include the requested 90 % efficiency derating (for the battery) and 10 % safety margin.