# Design Note

| | |
|---|---|
| Project | Net Zero Terrace SIF Alpha |
| Subject | Energy Model |
| Deliverables | M3 D3 Energy Model |
| Date | 27 March 2024 |

| Revision | Description | Issued by | Date | Approved (signature) |
|---|---|---|---|---|
| 1 | Description of NZT energy model | FF/VK | 27.3.2024 | PP/VK |

# Contents

# GLOSSARY

| | |
|---|---|
| BAU | Business As Usual |
| CEMS | Community Energy Management System |
| CoP | Coefficient of Performance |
| DNO | Distribution Network Operator |
| GSHP | Ground Source Heat Pump |
| HEMS | Home Energy Management System |
| NZT | Net Zero Terrace |
| PV | Photo-Voltaic |
| SIF | Strategic Innovation Fund |
| TEM | Techno-Economic Model |

# 1 Introduction

Buro Happold has been appointed by Electricity North West Limited (ENWL) to develop an energy model for Net Zero Terrace (NZT) as part of Strategic Innovation Fund (SIF) Alpha. This report outlines the design of the energy system model, which is one of the core components for evaluating the overall system performance of the NZT solution.

## 1.1 Aims and Objectives

This design note captures the development of the Energy Model used in the SIF Alpha – Net Zero Terrace project. The purpose of the Energy Model was to:

- Model the Net Zero Terrace energy system performance and behaviour under different operation scenarios. This includes modelling domestic property energy base loads, property heating based on ambient loop ground source heating, and community renewable generation. Simulate the operation of Home Energy Management System (HEMS) and Community Energy Management System (CEMS) controllers.
- Inform the Techno-Economic Model (TEM) with end-users' electricity consumption and rooftop generation (optimised against effective use of community renewable energy and off-peak tariffs).
- Inform the deployment planning process on viable options through prediction of additional voltage and thermal demands on the local substation.
- Determine the flexibility available at community level under different pricing and usage scenarios and evaluate that comfort levels that can be maintained under different usage scenarios.

## 1.2 Outputs and interdependencies with other work packages

**Energy Model Outputs**
The energy model is essential to and interdependent with several of the other work packages on this project.
The energy model produces several key outputs, namely:

- A building energy demand assessment
- System energy performance
- Cluster energy performance
- Asset sizing
- Flexibility potential assessment

These allow the model to help shape other flows:

**System Planning Approach –** The energy model helps to identify potential clusters by informing the system planning approach of where the best energy performance lies amongst test clusters. The energy model also informs network integration requirements including renewable energy consumption, grid constraints (voltage and thermal levels) and asset options.

**Techno-Economic Model** – The energy model is able to assess how different preliminary asset sizes perform, so they can be costed in the TEM. The energy model can also provide the sum of imports/exports to/from the system as key outputs. These can then be used to determine energy costs for residents over time.

**System Architecture Development** – The energy model informs how the project is set. It does this by testing the performance of various asset sizes, through its assessment of performance and response (e.g. flexibility)

Similarly, the model can also receive inputs from other flows:

**System Planning Approach –** The system planning approach assesses the substations in the area and their headroom capacity. This then helps select the areas that the energy model should focus its assessment on.

**Techno-Economic Model –** The tariffs calculated by the TEM can be used to ensure the Energy Model simulates the HEMS and CEMS effectively. Additionally, the techno-economic model takes part in an iterative exchange of information with the energy model, in order to find an optimum balance between equipment cost and energy system performance.

**System Architecture Development –** The system architecture development informs the baseline assumptions used to build the energy model. These assumptions are centred primarily around CEMS and HEMS operation parameters.

## 1.3 Scope of work

The process of developing the energy model has taken place over 2 steps:

**Household Energy modelling** – This process is primarily concerned with thoroughly assessing the system performance at the household level. This includes:

- a building energy assessment - which assesses the current size, insulation and energy demands of terraced housing stock in Rossendale,
- equipment assessment - which confirms the parameters of equipment installed in each house under the BAU, counterfactual and NZT schemes,
- environmental dataset assessment - which involves selection of environmental datasets needed for modelling, and
- energy systems modelling - which involves using an industry-leading software, alongside a bespoke in-house workflow, to obtain energy balance outputs for different types of households.

**Cluster Energy modelling** - This process is primarily concerned with achieving a thorough assessment of energy usage across varying cluster sizes. The process includes:

- profile aggregation (adding all energy demands and solar generation for a set cluster size) and
- flexibility modelling (using different flexibility techniques based on the profile aggregation outputs to reduce imports, exports, and electricity usage peaks).

## 1.4 Scale of Study

The model is constructed to be scalable, in line with the ambition that the Net Zero Terrace scheme will be deployed successfully. The energy model has the ability to model clusters of any size and uses a process of aggregation to ensure it is not overly complex in doing this (section 3.5). Analysis of regional building data suggests that there are around 15,000 terraced homes in Rossendale that could be modelled as one cluster using the suite. This has value in determining national balancing support and alignment with larger scale renewable offtake. However, the optimal size of a cluster can be around 200-1000 homes, to ensure the profiling has value in determining sensitivities at a local level.

# 2 Household Energy Model

## 2.1 Household Energy Model Flow

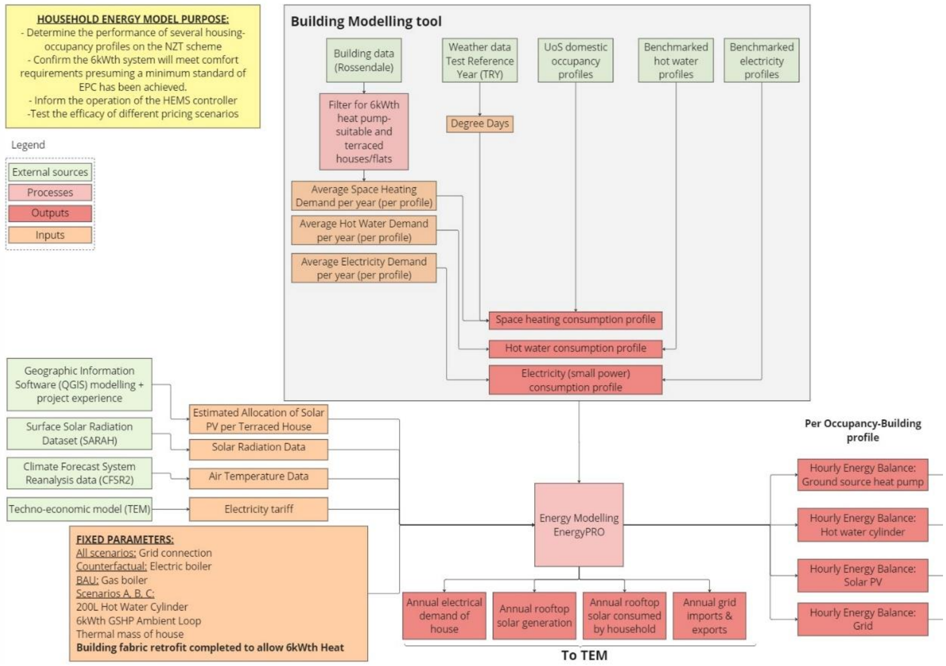

**Figure 2-1 Household Energy Model flow**

A flow diagram of the household energy model can be seen above in Figure 2-1. As stated in the introduction, the household energy model has several components:

**Building Modelling Tool (Building Energy Assessment)** – This tool assesses the energy demand across different archetypes of houses, using housing stock data alongside other calculations, including aggregation of demands in clusters.
**Equipment Assessment** – This component includes an assessment of the different equipment (e.g. solar PV panels, GSHP, hot water cylinder) to be used in the model.
**Environmental Dataset Assessment** – This component includes an assessment of the different environmental datasets to be used in the model.
**Energy Systems Modelling** – This component involves running simulations of the household system in EnergyPRO under different use cases. This incorporates inputs from equipment and environmental data assessments, alongside energy demands from the building modelling tool.

## 2.2 Tool and Dataset Selection

### 2.2.1 Energy systems modelling tool

Various software packages were considered for this workflow's energy systems modelling component.

One of the software packages considered was Simulink and Power Systems Simulation Onramp, a leading power systems simulation tool. This software is advantageous in that the energy flows can be examined extensively, allowing for strong data validation. However, the low-voltage design required for this software is beyond the scope of the project. This is particularly true when implementing solar generation and equipment prioritisation.

Building bespoke Microsoft Excel-based calculations was considered as an option. The software allows the modelling of high-level to detailed design and validation; however, due to the complexity of representing all the different energy system elements, it was considered appropriate for data processing and post-processing purposes only.

The selected energy systems modelling tool was EnergyPRO[1], designed by EMD International. This software tool has a validated, built-in method of calculating generation profiles and equipment prioritisation, that is not only widely used in Buro Happold previously, but other companies and academic institutions across the UK[2]. The outputs from EnergyPRO are also given in an accessible CSV format. This means that Microsoft Excel can be used to analyse these results and to apply the different flexibility methods outlined in Section 4.

### 2.2.2 Solar modelling software

Various software packages can estimate solar PV nominal capacities. PVsyst[3] was selected at this stage as it is one of the most reputable solar PV modelling software tools on the market. The relevant features for the modelling required included the ability to model in 3D and place panels selected (from actual manufacturers) on rooftops.

### 2.2.3 Environmental data

Various environmental datasets were needed to ensure accurate modelling using the EnergyPRO software, as well as for the calculation of building demands. The datasets selected were:

**SARAH2 Solar Radiation** – This dataset includes direct and diffuse solar radiation data local to Rossendale. This is required to calculate the irradiance incident on household solar PV panels.
**CFSR2 Air Temperature** – This dataset includes air temperature data local to Rossendale. This is also required to calculate the irradiance incident on household solar PV panels.
**TRY (Test Reference Year) Weather Data -** This dataset includes dry bulb temperature data in the local degree day area (West Pennines). This is required to calculate the degree days over a year, which can then be used to create space heating demand profiles.

### 2.2.4 Building stock data

The decarbonisation of the building stock, specifically heat, is often the single greatest challenge for an urban area. As such, building stock information is perhaps the most important dataset for NZT after the DNO data. The data quality and appropriateness of the dataset for NZT are more widely discussed in the ***WP3 System Planning Approach*** report, which also highlights their significance for NZT as well as considerations about data permissions and project timelines for future phases i.e. Beta.

From the improved domestic building stock data used for NZT Alpha, the key data fields for the energy model were:

- Standard geographic identifier (e.g. UPRN, TOID) and location
- Property type (e.g. terraced, detached, flat)
- Total floor area
- Energy demand (annual) – ideally split by heat and small power but not required
- Bill breakdown to understand split between space heating and domestic hot water

## 2.3 Building Modelling Tool

The building modelling tool was developed to assess the characteristics and energy usage across the stock of domestic properties in Rossendale. It provides a flexible methodology that takes property characteristics, such as size, energy efficiency and systems, energy rating, and consumption, and assesses the energy usage patterns of different households under archetypes derived in coordination with the planning approach. The methodology allows for input that has been collected from different sources to be automatically processed for the energy assessment of different energy system scenarios and stock clusters. Therefore, the building model is adaptable to the quality and granularity of available data by using them to refine the accuracy of the baseline energy usage of the stock e.g. building stock data sources, Fairer

---

[1] EnergyPro software energyPRO - Modeling & Analysis Software for Energy ProjectsEMD International (emd-international.com)
[2] EnergyPro software: energyPRO License Holders (emd-international.com)
[3] PVsyst software: https://www.pvsyst.com/features/

Warmth App survey refinement, annual energy consumption and granular smart meter data, etc. Domestic demand data at postcode and System Lower Super Output Area (LSOA) was used to validate the available building level domestic stock data as described in the ***WP3 System Planning Approach*** report.

### 2.3.1 Household archetypes

A key aim of the energy model is to assess and establish the system's technical and economic robustness to the impacts of varying energy usage patterns. This includes assessing a variety of scenarios for occupancy patterns and relevance to household size composition.

Household archetypes were developed to represent different types of energy usage scenarios and applied to terraced homes under this scope. The archetypes match a typical occupancy profile to an associated house size to represent when energy usage is distributed during the day throughout a typical year. The household composition scenarios seen in Table 3.1 represent three core groups and variations within these groups:

- Working, no dependents
- Retired, no dependents
- Working family

**Note**: "Large" does not refer to the size of the house, but rather the size of the family existing within the house

**Table 2.1: Household archetype scenarios based on household composition**

| Household composition scenarios | |
|---|---|
| Working, no dependents | Single professional |
| Working family | Family of 4, both parents working |
| Working family | Family of 4, one parent has childcare duties |
| Retired, no dependents | Retired couple |
| Retired, no dependents | Retired single person |
| Working, no dependents | Working couple |
| Working family | Part-time single parent (possibly fuel conservative in this scenario) |
| Working family | Family of 5, one parent working |
| Working family | Large family (4+ children), both parents working |
| Working, no dependents | Large house-share |

Several household occupancy density and use profiles were taken from the DESNZ (formerly BEIS) and the University of Southampton Faculty of Engineering's study "*England's domestic occupancy patterns*"[4] which mapped household typologies based on interviews from the English Housing Survey (2015). These were matched to housing sizes based on the Department for Communities and Local Government's "*Technical housing standards – nationally described space standard*"[5]. The matching process is shown below in Figure 3-1.

---

[4] Developing English domestic occupancy profiles. Building Research & Information, https://doi.org/10.1080/09613218.2017.1399719

[5] "Technical housing standards – nationally described space standard"[5] https://www.gov.uk/government/publications/technical-housing-standards-nationally-described-space-standard/technical-housing-standards-nationally-described-space-standard

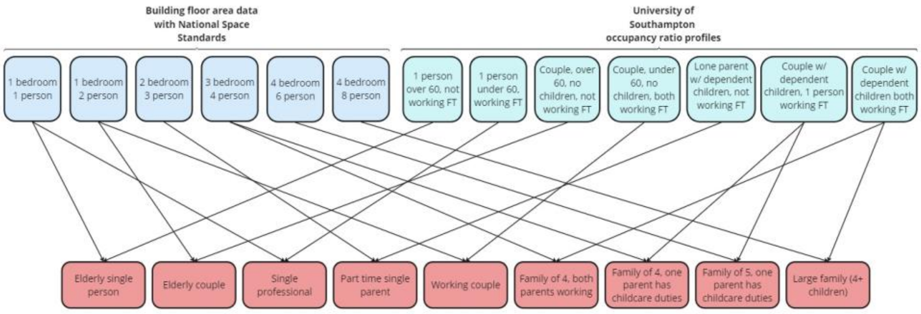

**Figure 2-2: Matching of house sizes and occupancy profiles to archetypes**

Energy demand profiles are then created for each archetype based on the assumption that occupants would use their heating energy systems while being at home. The flexibility methods then build on this assumption by shifting small portions of the demand to when the occupants are not at home, to ensure their needs are met when they are. This is detailed in section 4.

### 2.3.2 Building demands

The above assumptions on household occupancy density and usage profiles have been used to establish how energy is consumed during the year under hourly energy demand profiles for:

- Space heating demand
- Domestic hot water demand
- Electrical demand (from non-heating uses like lighting, appliances, fans and pumps)

The building demands described in the following sections were subsequently used as inputs in the energy systems model to represent the different energy system demands.

**Space heating demand**

Space heating demands were estimated under each cluster scenario (see section 4 for cluster modelling). The total cluster annual space heating demand from the building stock data (i.e. EPC calculations) was used to derive hourly space heating demand profiles. To scale the total annual space heating demand to an hourly profile for a whole typical year, the energy model used the above occupancy profiles as well heating degree days from the Test Reference Year (CIBSE's weather data used for operational energy modelling, in the nearest location to Bacup). An example of this profile is seen in section 4.1.

In future project stages, the energy model can flexibly integrate different sources of energy performance data such as smart meter data, Fairer Warmth surveys, benchmarking to energy bills etc.to be used for the validation of the selected building stock dataset.

**Hot water demand**

Annual hot water demand has been based on building stock data for hot water consumption and the Energy Savings Trust report "*Measurement of Hot Water Consumption in Dwellings*"[6], which provides surveyed hot water usage profiles for typical households. This is frequently used in operational energy modelling.

**Electricity demand**

Annual electricity demand has also been based on building stock data for electricity consumption. The domestic unrestricted Elexon profile was then used to scale this consumption over one year. Elexon half-hourly profiles were used as it provides typical metered electricity profiles across a range of samples properties. The profile used in the modelling provides representative information on occupants' electricity needs, not considering price-based incentives.

---

[6] Energy Savings Trust, 2008 "*Measurement of Hot Water Consumption in Dwellings*". Microsoft Word - Final Report - March 2008.doc (publishing.service.gov.uk)

### 2.3.3 Retrofit analysis

The energy model assumes that the retrofit cut-offs recommended in the NZT System Planning Approach report. This ensures that the energy demands inputted to the energy model are not beyond what a 6kW$_{th}$ heat pump can provide for.

## 2.4 Environmental and Equipment Inputs

### 2.4.1 Heat pump

We have assumed that each household has access to a ground source heat pump with a Coefficient of Performance (CoP) of 4. This value is based on discussions with different heat pump providers, including Kensa. Based on these we have made the following key assumptions:

- The maximum heat output of the heat pump is 6kW$_{th}$. This is based on the specifications of a Kensa Shoebox heat pump[7]
- The heat pump will only provide heat to one type of heating element at any one time. This means that heat cannot be supplied to the space heating system at the same time as the hot water cylinder.

Therefore, careful considerations need to be made around the timing of hot water cycles. As a baseline, we have assumed hot water charging occurs at 12am-1am and 12pm-2pm. This allows for 2 hours of charging during the peak solar generation hours, as well as a shorter night-time cycle to meet morning demands.

### 2.4.2 Thermal mass and thermal inertia

Thermal mass represents the properties' ability to retain, store and release heat within the building construction elements depending on the heat density of the materials used in the construction. This provides inertia against temperature fluctuations. Thermal mass has been considered in the energy model to ensure thermal comfort demands are met by the heat pump system. This is particularly important where the space heating has to be "turned off" to charge hot water.

The Standard Assessment Procedure (SAP) methodology[8] medium thermal mass parameter reference value of 250kJ/m$^2$K has been utilised to represent average thermal mass characteristics across the building stock. This is then multiplied by the total floor area and temperature difference, to find the thermal energy stored in the house over that temperature difference. If we set our maximum comfort temperature as 22°C, and our minimum comfort temperature as 18°C, then we can find the amount of energy needed to preheat the house before disconnecting the space heating system from the heat pump. This also assumes a typical temperature set-point of 20°C.

### 2.4.3 Solar PV

As discussed in NZT System Planning Approach report, a PVsyst simulation model was used to calculate the nominal capacity for two PV options on Street A. For the energy modelling, option 2 has been utilised as the solar PV basis. This option respects the property ownership boundaries between the buildings and consequently has gaps between PV arrays. A reminder of this option is shown in Figure 2-3. The results of this simulation model for Street A suggested an average capacity of 2.24kWp per house. Alongside this average capacity, the modelling has assumed the roofs are south-facing (0° azimuth) with a 27° inclination (measured using DSM data). Adjustments have later been made for streets with deviating values.

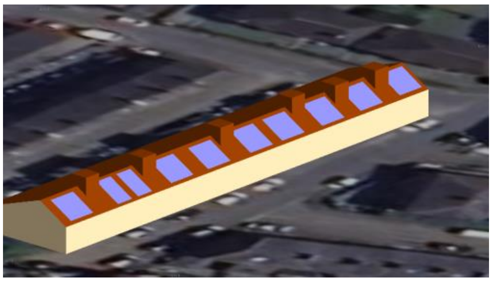

**Figure 2-3 PVSyst model of Street A**

---

[7] Renowned Shoebox Ground Source Heat Pump - Kensa Heat Pumps

[8] Standard Assessment Procedure (SAP 2016) - BRE Group

### 2.4.4 Hot water cylinder

The hot water cylinder selected for modelling purposes was the Mixergy 210L Direct Slimline[9]. This particular model was chosen as 210L is the largest capacity available in the slimline configuration. This will ensure that the store requires minimal charging periods (as it has a large capacity), while ensuring it fits in resident's homes. Mixergy recommends a 210L tank for 5 people[10], and this is comparable with the industry average (typically enough water to provide 2 baths and a shower per day). The 'direct' configuration is used since gas boilers will not be part of the Net Zero Terrace scheme.

Properties of the hot water cylinder most pertinent to use in the energy model include the temperature in the top (65°C), the temperature in the bottom (assumed 40°C), and storage losses (detailed in datasheet). Additionally, we have assumed that the ambient temperature of the house is 20°C, which aligns with the setpoint detailed in section 3.6.1.

**Figure 2-4 Mixergy 210L Direct Slimline, with features**

## 2.5 EnergyPRO Energy Modelling

### 2.5.1 Model overview

EnergyPRO is a modelling software[11] used to calculate energy transfers across thermal and electrical systems. It not only incorporates equipment inputs, but also environmental datasets and financial information. This allows it to model equipment how it would most likely be used by a consumer i.e. using generation on-site rather than exporting.

---

[9] DIRECT SLIMLINE.pdf (hubspotusercontent-eu1.net)

[10] What's the right Mixergy tank for you? • Mixergy

[11] https://www.emd-international.com/energypro/

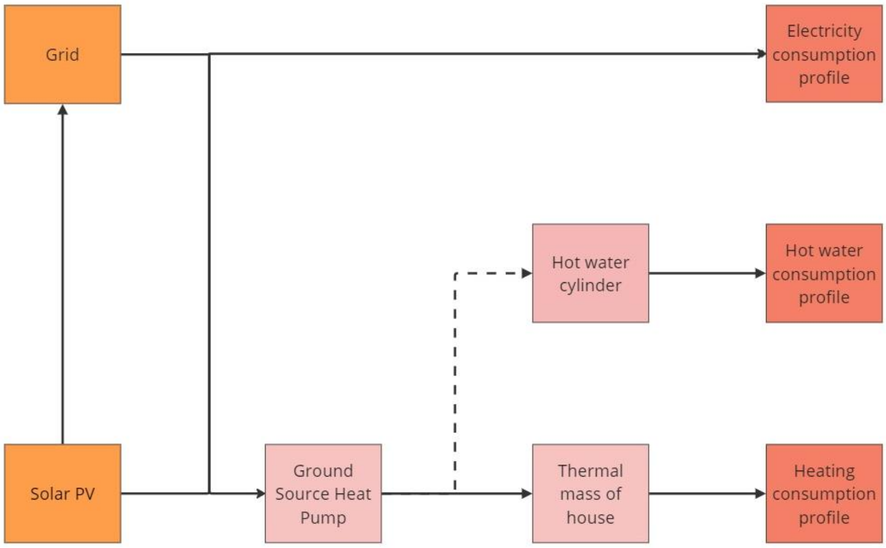

**Figure 2-5 Energy flow modelled in EnergyPRO**

In Figure 2-5**,** the flow of energy between elements can be seen. The dashed line between the ground source heat pump and hot water cylinder indicates that this flow only occurs at certain times, namely the dedicated hot water charging periods.

An EnergyPRO model has been created for each archetype, with all parameters remaining constant between models, except for the consumption profiles. These are the associated demands for the archetype, outputted from the building modelling tool. The EnergyPRO model can then be run to simulate operation of the system over an entire year.

### 2.5.2 Base electricity tariffs and revenues

In order to allow the EnergyPRO model to prioritise consumption of solar PV electrical generation on-site rather than exporting to the grid, energy tariffs needed to be set inside the software. The import tariff was set higher than the export revenue. This ensured solar generation was used wherever possible. It should be noted that the energy model has the ability to use specific import tariffs and export revenue if required, and then optimise to these values.

### 2.5.3 Outputs

After running a simulation over one year (2023) in EnergyPRO for each household archetype model, certain outputs can be obtained. These are in the form of hourly energy balances, which are:

- Grid imports (both kW and kWh)
- Grid exports (both kW and kWh)
- Hot water cylinder usage
- Solar PV generation
- Ground Source Heat Pump heat generation
- Ground Source Heat Pump electrical demand
- Hot water thermal demand
- Space heating thermal demand
- Small power electrical demand

This granular data is stored to be later used in the cluster energy model.

Additionally, certain hourly energy balances can be summed to find their totals over the entire year. This is especially useful as an input to the TEM, where the following annual totals are used to calculate an electricity tariff:

- Annual electrical demand
- Annual rooftop solar generation
- Annual rooftop solar electricity used by household
- Annual grid imports
- Annual grid exports

# 3 Cluster Energy Model

## 3.1 Cluster Energy Model Flow

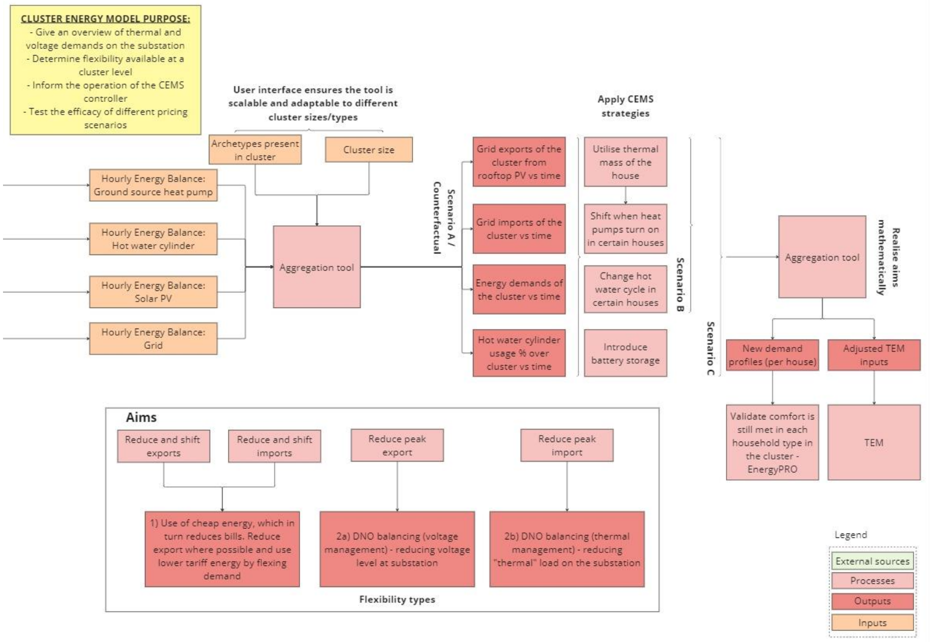

**Figure 3-1 Cluster Energy Model flow**

A flow diagram of the Cluster Energy Model can be seen above in Figure 3-1. As stated in the introduction, the cluster energy model is responsible for profile aggregation and flexibility modelling, to represent the community at scale. The inputs to this flow are the hourly energy balances for each household archetype, obtained as an output from the EnergyPRO software.

The sum of these energy balances is then taken for each cluster. This takes place in the 'Aggregation Tool' (which aggregates the energy balances). The aggregation tool has 2 user inputs:

- Cluster size
- Number of each archetype present in the cluster

The former corresponds to the set cluster sizes outlined in section 3.2. The latter determines the number of that archetype's energy balances which are added to the total sum.

In the second part of the flow, various flexibility techniques are applied, using the aggregated energy balances as an informative tool. This is seen to the right hand side of Figure 3-1. The aims that this process intends on reaching are summarised at the bottom of the flow.

## 3.2 Cluster Sizes

To ensure the study meets the scale outlined in **Section 2.4 – Scale of Study**, the following set discrete cluster sizes have been chosen:

1. 10 homes on Street A (enclosed within the blue border in Figure 3-1)
2. 103 homes centred on Area B (enclosed, but not including every home, within the red border in Figure 3-1)
3. 1000 homes across Bacup (dotted in Figure 3-2)

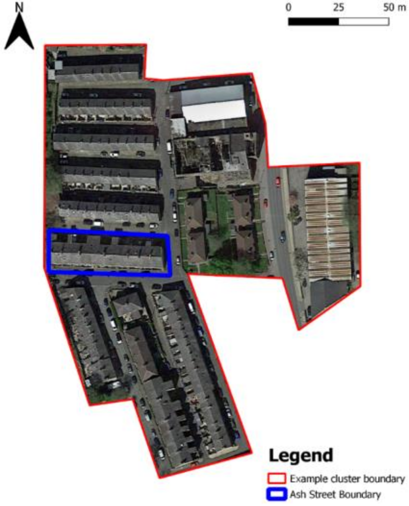

**Figure 3-2 Overview of Street A and Area B**

**Figure 3-3 Overview of the wider Bacup area**

To obtain the size (floor area) of each house within a cluster, building stock data have been used via Rossendale Borough Council. However, other similar data sources can be used to obtain this information.

## 3.3 Cluster Flexibility

While developing this process, the following modes of flexibility have been considered:

- **Mode 1** – Optimisation of demand and generation to reduce bills
- **Mode 2** – Optimisation of demand and generation to reduce peak export (voltage management)
- **Mode 3** – Optimisation of demand and generation to reduce demand on networks (thermal management)
- **Mode 4** – Optimisation of demand and generation for national balancing

Matching these modes against the scale of the model, it has been decided to focus on modes 1-3. Mode 4 has not been explored at this stage due to the size of clusters modelled.

The main ways to apply flexibility across the cluster are: shifting of demand and addition of storage. Storage can be either thermal (i.e. hot water tanks) or electrical/chemical (i.e. batteries). With examination of the resources available for implementation, 3 flexibility levels were then developed:

**Level A** – No cluster flexibility applied
**Level B** – Shifting of demand required for space heating, and daily hot water cycle
**Level C** – Shifting of demand required for space heating, daily hot water cycle, with the addition of electric battery storage in each household

It should be noted that although the daily hot water cycle is changed for levels B and C, this has no effect on the demand pattern for hot water usage. This is because it is assumed each household will have a hot water cylinder (detailed in section 2.4.4), that will be charged from the heat pump at set times during the day, and then discharged when required by occupants.

## 3.4 Summary of Cluster Scenarios

Combining the set cluster sizes with the flexibility levels produces set scenarios that will be examined in this study. These are:

**Scenario 1**

- 1A – Street A, no flexibility
- 1B –Street A, flexibility in space heating demand and daily hot water cycle
- 1C –Street A, flexibility in space heating demand, daily hot water cycle, and battery

**Scenario 2**

- 2A – 100 homes in Bacup (Area B), no flexibility
- 2B – 100 homes in Bacup, flexibility in space heating demand and daily hot water cycle
- 2C – 100 homes in Bacup, flexibility in space heating demand, daily hot water cycle, and battery

**Scenario 3**

- 3A – 1000 homes in Rossendale (find an East West cluster), no flexibility
- 3B – 1000 homes in Rossendale, flexibility in space heating demand and daily hot water cycle
- 3C – 1000 homes in Rossendale, flexibility in space heating demand, daily hot water cycle, and battery

The outputs from each are also fed through to the Techno-Economic Model, where they will be evaluated against the "Counterfactual" and "Business as Usual" scenarios.

## 3.5 Aggregation Tool

As stated in section 2.1, the Aggregation Tool is used to sum the energy balances over the entire cluster. The exact archetype makeup of the clusters is detailed in **section 5**.
An additional purpose of the Aggregation Tool is to find certain weeks over a year where peaks or median values occur. These include the weeks of maximum/average electrical load, grid import, grid export and solar generation.
Finally, the Aggregation Tool to adjust the solar profile for different orientations or amounts. As mentioned in section 2.4.3, we have made a baseline assumption that all houses have solar PV systems that are 2.24kWp, south-facing and have an approximate 25° incline. However, the Aggregation Tool can make adjustments to this profile if needed by substituting different values where required and can also adjust the grid import/export as a result.

## 3.6 Application of Flexibility Methods

### 3.6.1 Usage shifting

As explained in section 3.4.1, the ground source heat pump considered for the Net Zero Terrace scheme will only supply thermal energy to either the space heating equipment (radiators) **or** the hot water cylinder at any given time. Therefore, flexibility methods around both of these demands must be considered separately.

**Space heating demand**

The space heating demand has hourly resolution. Hours where the demand is excessive are identified (detailed further in section 4). **All hours** are then assigned an identifier depending on whether they have excessive demand, and their proximity to the domestic hot water charging cycle.

Next, the cluster is split into two sections. For one section, hours with excessive demand have ¼ of their demand shifted to the hour before. For the other section, hours with excessive demand have ¼ of their demand shifted to the hour after. This maximises the evenness of shift away from the peaks, while still ensuring comfort can realistically be met.

**Hot water cycle**

The hot water cycle can be shifted in two ways. One large cycle can be split into two smaller cycles, or one large cycle can be moved to an entirely different time. The type of shift required depends on the impact hot water charging is having. This is detailed further in section 4.

Because the heat pump used to provide space heating is the same used to charge hot water, the space heating demand must be "moved around" the hot water cycle when it is moved i.e. space heating occurs where the old cycle was, and no longer occurs where the new cycle is. This ensures that comfort levels of space heating are still met for the occupants.

### 3.6.2 Batteries

To select an ideal battery size for each household, the LG Chem RESU range was considered. This is due to their high charging efficiency and compact dimensions [https://www.greenmatch.co.uk/solar-energy/solar-panels/solar-batteries/best]

**Commented [GP1]:** Format of reference - as above comment

To select the best size of battery, a what-if analysis was performed to measure the total annual savings vs battery capacity. This gives an indication of where returns on export savings balance out capital cost.

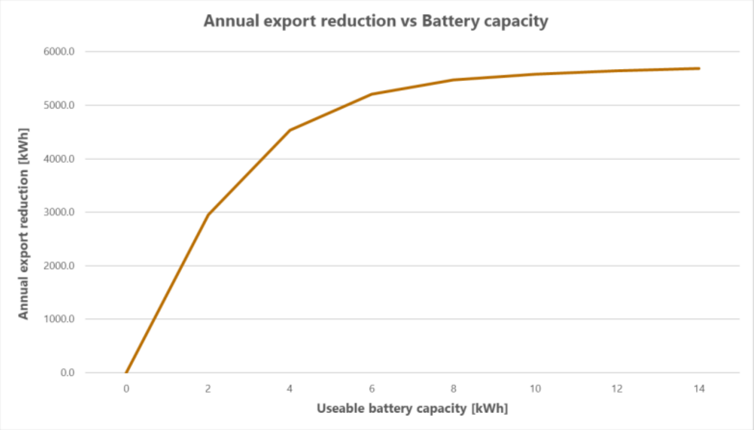

**Figure 3-4 Analysis of household useable battery capacity vs annual export reduction**

As seen on the graph, the slope is greatest between 0 and 4kWh useable battery capacity. Therefore, the LG Chem RESU3.3, with 2.9kWh useable battery capacity, was selected. The next smallest LG Chem RESU battery (RESU6.5) has

5.9kWh useable capacity, so the RESU3.3 was a sensible choice to begin modelling with. Dependent on the results of the model, the battery size can be optimised further at a later stage.

To apply the batteries to the outputs from the aggregation tool, additional battery parameters had to be obtained, specifically the charge and discharge rates. These are crucial for determining how much export can be reduced at any given time. The LG Chem RESU3.3 has both a maximum charge and discharge rate of 3kW, so 2.8kW has been assumed as an average. Additionally, the batteries are modelled as one unit for an entire cluster, so a 75% contingency on capacity and (dis)charge has been applied to account for this.

The battery charging logic is unambiguous. The battery will charge up to its capacity (at the charging rate) when exports would be greater than zero. Similarly, the battery will discharge down to its minimum level (at the discharging rate) when imports would be greater than zero. An exploration of how the battery charging algorithm could be developed further is discussed in sections 4 and 5.

# 4 Results

## 4.1 Preliminary Study at Household Level

A preliminary study was carried out at the household level by examining the outputs of the individual household simulations (explained further in section 2.5). The outputs of the model allowed confirmation that two key main results had been achieved:

- The demands for every house archetype were met by the 6kW$_{th}$ heat pump used in the simulation.
- “Charging” of each archetype’s thermal mass allowed hot water cycles to take place with no interruption to space heating demand.

The space heating and small power demands of an example archetype, “Family of four (both parents working)” over one year, are shown below in Figure 4-1 and Figure 4-2.

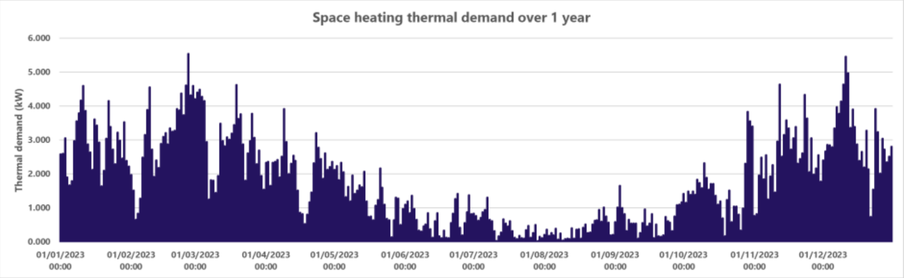

**Figure 4-1 Space heating demand of archetype “Family of four (both parents working)” over one calendar year**

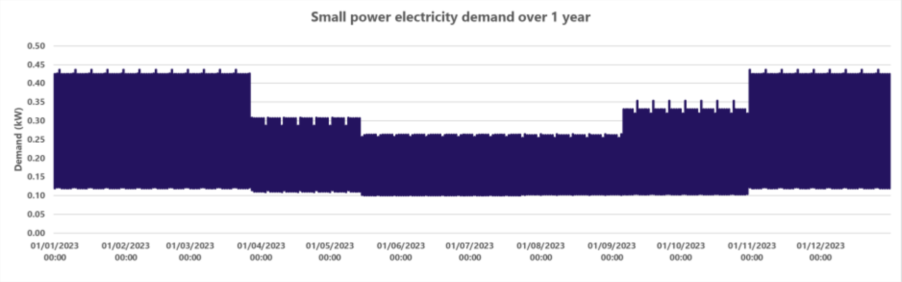

**Figure 4-2 Small power electricity demand of archetype “Family of four (both parents working)” over one calendar year**

Additionally, the graph of daily hot water consumption for the same archetype can be seen below in Figure 4-3.

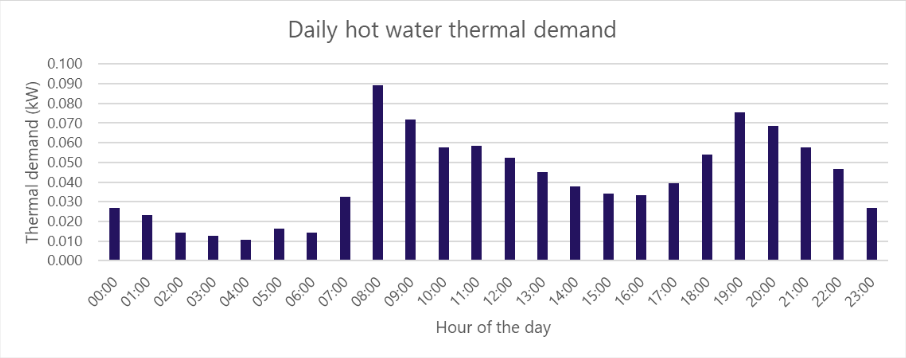

**Figure 4-3 Hot water demand of archetype "Family of four (both parents working)" over one day**

Assuming the archetype has a 2.24kWp solar PV system, with 27° inclination and south-facing orientation, the generation graph over 1 year is shown in Figure 4-4:

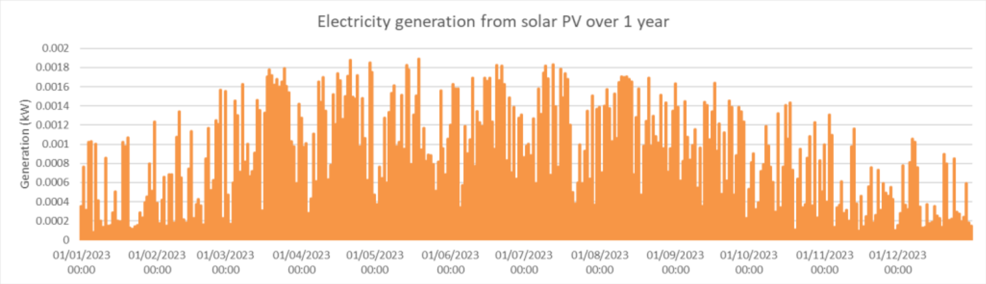

**Figure 4-4 Electricity generation from a household with 2.24kWp solar PV system, with 27° inclination and south-facing orientation**

## Study of 10 homes on Street A

### 4.1.1 Initial archetype selection

Appropriate archetypes had to be selected to conduct our study of the energy model on 10 homes on Street A. First, the floor areas of the houses were obtained from building stock data. These values are shown below in Table 5-1. These estimations can be inaccurate, so for implementation, actual floor areas should be measured and collected to ensure accuracy:

**Table 4.1 Floor areas of properties**

| Address | Total Floor Area (m2) |
|---|---|
| Property 1 | 109 |
| Property 2 | 132 |
| Property 3 | 125 |
| Property 4 | 129 |
| Property 5 | 150 |
| Property 6 | 150 |
| Property 7 | 112 |
| Property 8 | 111 |
| Property 9 | 111 |
| Property 10 | 165 |

Using these floor areas as a basis, we estimated the occupancy profiles.  In our preliminary study, we have assumed a composition of 6 of the households to be of the archetype “Large house-share”, and 4 to be “Family of five, one working” archetype. It must be noted that the occupancy types were based on the surveyed synthetical occupancy profiles described in section 2 and have been matched to the building stock data as presented in our analysis.

### 4.1.2 Scenario 1A (No flexibility)

#### 4.1.2.1 Approach

Although scenario 1A is stated as ”no flexibility”, this refers to the flexibility that has been built upon the HEMS system. Some flexibility inherent in the model exists in these ways:

- The hot water cylinder is only filled to what is needed to ensure it meets the demand in the following use period. This ensures that imports are not unnecessarily made from the grid.
- The household will always use solar PV on-site rather than exporting it, due to the export rate being 5p compared to the import rate of 28p.
- Comfort will be maintained during hot water cycles by preheating the thermal mass of the house

#### 4.1.2.2 Results – winter

The “peak winter” week was first considered. This is the week with the highest import levels. For scenario 1A this is a week in December.

The electrical demands and grid imports over the peak winter week, for scenario 1A are shown below in Figure 4-5.

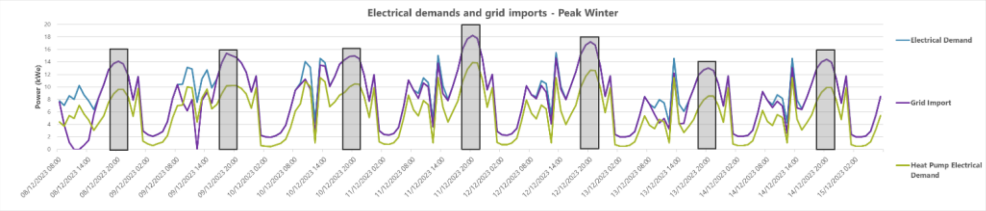

**Figure 4-5 Electrical demands and grid imports for the peak winter week, no flexibility**

It can be noted that the shape of the graph over 1 week, follows a recurring pattern. This is due to two main reasons. Firstly, the hot water cycles occur at the same time each day. Secondly, the occupancy ratios used to shape the space heating demand are similar for most days.

It can be observed that there is a peak in grid imports occurring each day around 19:00-21:00, as outlined in the grey boxes in Figure 4-5. These peaks are due to a high evening space heating demand, coinciding with lack of solar generation.

#### 4.1.2.3 Results - summer

Similarly, the “peak summer” week was considered. This is the week with the highest average solar generation. For scenario 1A this is a week in early August.

The electrical demands and rooftop solar generation over the peak summer week, for scenario 1A are shown below in Figure 4-6.

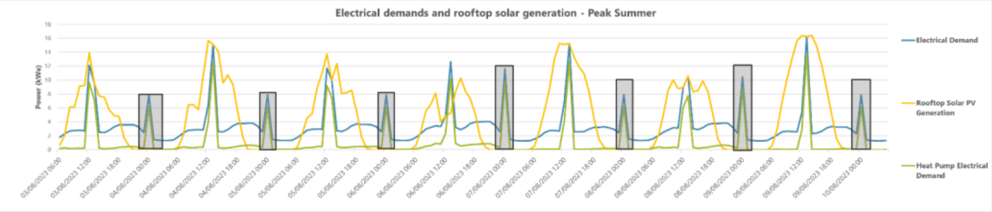

**Figure 4-6 Electrical demands and rooftop solar generation for the peak summer week, no flexibility**

Again, the shape of the graph follows a recurring pattern. However, there are slight variations in the solar generation profile due to the variations in daily radiation and temperature levels.

It can be observed that there are two peaks in demand in summer days. The first is during the day-time hot water cycle. This coincides with the peak of the generation curve – this is ideal for DNO voltage level reduction. However, a lot of the generation is underutilised, and there is a peak in demand outside the generation curve (caused by the night-time hot water cycle)

### 4.1.3 Scenario 1B (Flexibility in usage shifting)

#### 4.1.3.1 Approach - Winter

In winter, the application of flexibility in usage shifting (by changing the timing of heat pump usage and hot water cycle) has one main aim – to reduce the peak import level throughout the day. This has 2 benefits:

1. For the DNO, it has the benefit of reducing the thermal load on the substation.
2. For the residents, it will likely reduce their energy bills. This is because the current peak load (19:00-21:00) coincides with the national balancing peak. Therefore, this price saving can be passed on to the residents as an incentive.

The main strategy is to reduce the space heating demand at the evening peak and increase the demand on either side of the peak. The effect can be maximised by half of the households shifting usage one way, and half of households shifting usage the other. This will have the corresponding effect on the heat pump electrical demand. This can be seen in Figure 4-7.

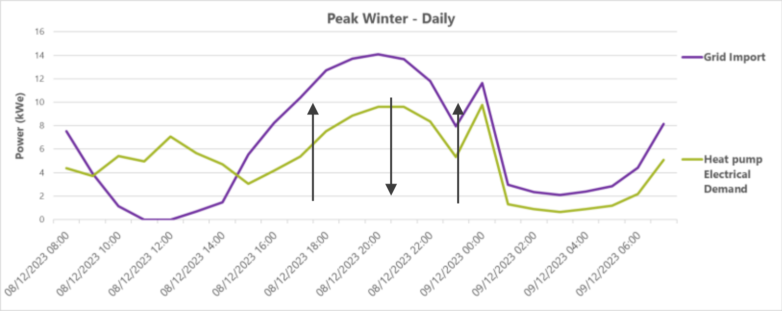

**Figure 4-7 Single day in the peak winter week**

This strategy also has benefits when applied all year round. In days of high solar generation but high space heating demand (i.e. a cold sunny day in spring), this will move more of the load into the generation curve, reducing imports/exports.

#### 4.1.3.2 Approach – Summer

In winter, the application usage flexibility has the aim of moving times of high heat pump demand to coincide with times of high generation. This has the benefit of not only reducing import and export for consumers, but also lowering the voltage level on the local substation (if export peaks can consistently be reduced).
As space heating demand is often low on days with high solar generation, the main demand is from hot water. Therefore, in summer, the main focus should be on changing the timing of the hot water cycle. Figure 4-8, shows that some of the nighttime cycle can be moved into daytime, to maximise usage of generation.

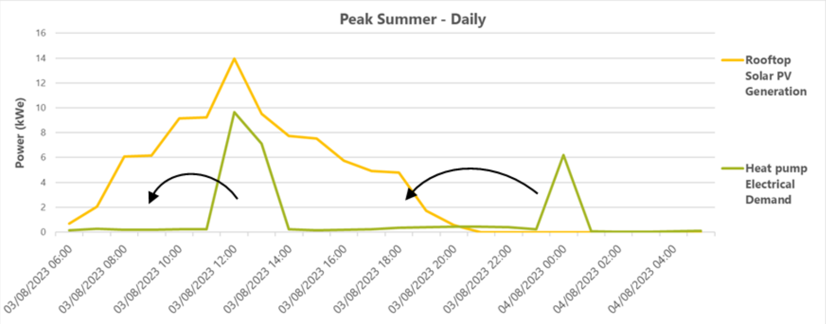

**Figure 4-8 Single day in the peak summer week**

#### 4.1.3.3 Results

The effect of usage shifting in the winter can be seen in Figure 4-9. This graph shows the old grid imports (before usage flexibility was applied) and the new grid imports (after usage flexibility was applied). It can be seen that on many days the overall peak import is reduced. This helps to reduce the thermal load on the substation.
However, it is also observed that the peak reduction is quite small. This is because the demand can only be shifted by a couple of hours either side of the peak. This is due to the fact that there is no guarantee that comfort levels will be maintained if demand is shifted by more.

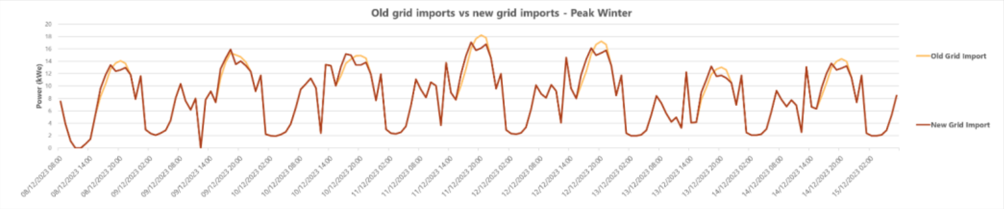

**Figure 4-9 Comparison of grid imports before and after usage flexibility, peak winter week**

The effect of usage shifting in the summer can be seen in Figure 4-10. It can clearly be seen that more of the heat pump electrical demand is occurring during times of high generation. This means that the amount of export and import is reduced, meaning lower costs for residents. However, there is still a lot of generation that is unused. This is exported, meaning the voltage level is not consistently reduced for the DNO. Therefore, batteries are suggested, which is explored in section 4.2.4.

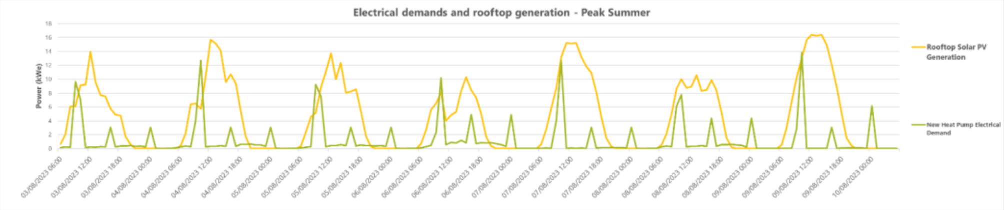

**Figure 4-10 Rooftop solar generation and heat pump electrical demand after flexibility, peak summer week**

The overall annual changes in export, import and usage of solar are summarised in Table 4-2. It can be seen that although there are beneficial changes in all of the values, these are heavily limited by the constraints on comfort we have assumed.

**Table 4.2: Summary statistics of scenario 1B in comparison with scenario 1A**

| | Scenario 1A (no flex) [kWh] | Scenario 1B (flex through use shifting) [kWh] | % change scenario 1B vs scenario 1A |
|---|---|---|---|
| **Rooftop solar used by households** | 14593 | 14675 | **0.56%** |
| **Rooftop solar exported to grid** | 6506 | 6425 | **-1.25%** |
| **Imported electricity from grid** | 35238 | 35151 | **-0.25%** |

### 4.1.4 Scenario 1C (Flexibility through energy usage and battery usage)

#### 4.1.4.1 Approach

For flexibility scenario 1C, we have assumed that an LG Chem RESU3.3 battery (detailed in section 3.6.2) has been installed in each household.

In the winter, the batteries will have little effect. This is due to the fact that there is a negligible generation profile in winter (caused by reduction of air temperature and solar radiation). Therefore, there is little electricity to be stored in the batteries.

In the summer however, batteries can play a key role in reducing export levels consistently. They can charge during periods of high generation, reducing export to the grid and hence reducing voltage load on the substations. This also has benefits for residents in the form of price savings. Batteries also increase independence of homes, in the event of a power shortage or disconnection from the grid.

#### 4.1.4.2 Results

As the batteries have little effect on a week in winter, a study was performed in a week in spring instead. The grid exports from without batteries (black) and with batteries (red) are shown alongside the solar generation profile in Figure 4-11. It can be seen that batteries enable the export level to be consistently reduced throughout the week. This means the DNO can have assurance of a reduced export level on the substation. Additionally, residents can have consistently lower electricity bills.

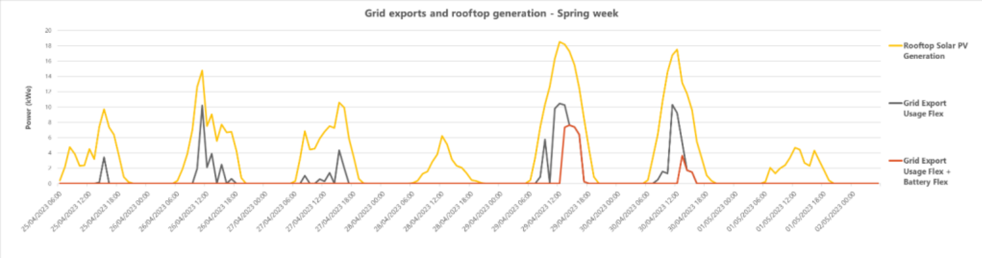

**Figure 4-11 Rooftop generation and grid imports with battery flexibility – spring week**

The same graph is shown for the peak summer week in Figure 4-12. Here, the export level is not consistently reduced, and the peaks are often the same as that without batteries. This is due to 2 reasons:

- The generation level is higher in summer, so the batteries reach maximum capacity more often.
- There is no mechanism in place to ensure the battery is charged at the peak of generation, rather than at the start. This means the battery is fully charged by midday. Therefore, there is a total reduction in export, but the daily peak is still the same.

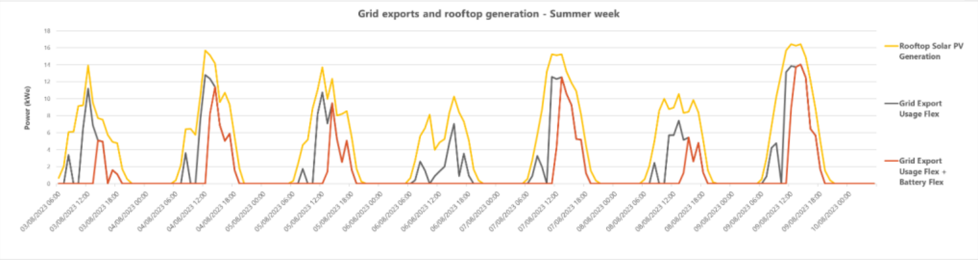

**Figure 4-12 Rooftop generation and grid imports with battery flexibility – summer week**

The summary statistics for scenario 1C vs scenario 1A are shown in Table 4-3. There is a considerable improvement with the addition of batteries, far greater than the improvement shown by scenario 1B (Table 4-2). It can be concluded that batteries are essential to ensure flexibility is successful.

**Table 4.3: Summary statistics of scenario 1C in comparison with scenario 1A**

| | **Scenario 1A (no flex) [kWh]** | **Scenario 1C (flex through battery usage) [kWh]** | **Scenario 1C Oct-March [kWh]** | **Scenario 1C April-Sept [kWh]** | **% change scenario C vs scenario A** |
|---|---|---|---|---|---|
| **Rooftop solar used by households** | 14593 | 18296 | 5914 | 12381 | **25.4%** |
| **Rooftop solar exported to grid** | 6506 | 2803 | 136 | 2667 | **-56.9%** |
| **Imported electricity from grid** | 35238 | 31530 | 24595 | 6936 | **-10.5%** |

## 4.2 Effects of different occupancy makeup on Street A

A study took place to explore the results of the previous study on Street A, but with a different archetype makeup. The new archetype assumption was 7 “Part time single parent” and 3 “Family of 4 both working”. The summary statistics of this new archetype makeup is shown below in Table 4-4. It can be noted that flexibility through usage shifting (1B) is less effective, but flexibility through batteries (1C) is more effective. This suggests a more tailored application of flexibility may be required.

**Table 4.4: Summary statistics of scenario 1C in comparison with scenario 1A, alternative archetype composition**

| | **Scenario 1A (no flex) [kWh]** | **Scenario 1B (flex through use shifting) [kWh]** | **Scenario 1C (flex through battery usage) [kWh]** | **% change scenario 1B vs scenario 1A** | **% change scenario 1C vs scenario 1A** |
|---|---|---|---|---|---|
| **Rooftop solar used by households** | 13531 | 13583 | 17552 | **0.38%** | **29.7%** |
| **Rooftop solar exported to grid** | 7568 | 7517 | 3547 | **-0.68%** | **-53.1%** |
| **Imported electricity from grid** | 28407 | 28345 | 24376 | **-0.22%** | **-14.2%** |

## 4.3 Study of 103 homes in Area B (Scenarios 2A, 2B, 2C)

The study was expanded further to 103 homes in Area B (detailed in section 3.2). A similar process was followed as in section 4.2.1 to determine the archetypes used. This is an **estimation** process based on the house sizes from building stock data. The archetypes used are summarised in Table 4-5.

Table 4.5: Archetypes selected for scenario 2

| Archetype | Number in cluster |
|---|---|
| Working couple | 50 |
| Family of 4 both working | 18 |
| Part time single parent | 16 |
| Family of 4 one working | 9 |
| Large house-share | 8 |
| Family of 5 one working | 2 |

As the housing stock had slightly wider variety than those on Street A, a reassessment of the solar generation profile was needed. A similar process to that detailed in section 2.4.3 was used to determine that the average PV capacity per house was 2.08kWp. This is slightly lower than the average determined for Street A.

The application of flexibility methods (B – shifting of usage, C – shifting of usage with LG Chem RESU3.3 batteries) remained the same.

The results of the study on 103 homes can be seen below in Table 4-6. It can be observed that scenario 2C offers a greater change to 2A than 1C to 1A, suggesting that the application of batteries may be slightly more successful at scale. However, on the whole, the results are not too dissimilar to that of 10 houses. This does show that the model is scalable from 10 houses to over 100 houses.

Table 4.6: Summary statistics from scenario 2

| | Scenario 2A (no flex) [kWh] | Scenario 2B (flex through use shifting) [kWh] | Scenario 2C (flex through battery usage) [kWh] | % change scenario 2B vs scenario 2A | % change scenario 2C vs scenario 2A |
|---|---|---|---|---|---|
| **Rooftop solar used by households** | 124481 | 125021 | 163225 | **0.4%** | **31.1%** |
| **Rooftop solar exported to grid** | 67106 | 66565 | 28361 | **-0.8%** | **-57.7%** |
| **Imported electricity from grid** | 277542 | 276967 | 238763 | **-0.2%** | **-14.0%** |

## 4.4 Study of 1000 homes in Bacup (Scenarios 3A, 3B, 3C)

The study was finally expanded to 1000 homes in the wider area of Bacup. A breakdown of the archetypes modelled is outlined in Table 4-7. Again this is an estimation process. In order to model a larger cluster more accurately, is recommended that data be collected in other ways, in order to better determine the occupancy of households.

| Archetype | Number in cluster |
|---|---|
| Family of 4 both working | 214 |
| Elderly couple | 180 |
| Part time single parent | 169 |
| Working couple | 140 |
| Family of 4 one working | 100 |
| Family of 5 one working | 66 |
| Large family both working | 50 |
| Large house-share | 30 |
| Single professional | 26 |
| Elderly single person | 25 |

**Table 4.7 Archetypes selected for scenario 3**

The solar generation profile was again adjusted slightly, to take into account a couple of the 1000 homes had unfavourable roof sizes. This resulted in an average PV capacity per household of 2.01 kWp, which is slightly lower than for previous cluster sizes.

The application of flexibility methods remained the same, with the results shown in Table 4-8. These are very similar to the results for 103 home. It should be noted that the results may vary from what they could be with a higher average PV capacity per household.

**Table 4.8: Summary statistics from scenario 3**

| | Scenario 3A (no flex) [kWh] | Scenario 3B (flex through use shifting) [kWh] | Scenario 3C (flex through battery usage) [kWh] | % change scenario 3B vs scenario 3A | % change scenario 3C vs scenario 3A |
|---|---|---|---|---|---|
| **Rooftop solar used by households** | 1218695 | 1223759 | 1572265 | **0.4** | **29.0** |
| **Rooftop solar exported to grid** | 578198 | 573134 | 224628 | **-0.9** | **-61.2** |
| **Imported electricity from grid** | 2803210 | 2801907 | 2453401 | **0.0** | **-12.5** |

# 5 Key findings and suggestions for further work

## 5.1 Usage shifting

In this stage of study, usage shifting (or demand shifting) has been implemented in two ways. These are shifting of space heating demand, and hot water demand. Both of these demands are met by thermal generation from the GSHP, under the Net Zero Terrace Scheme. This method of flexibility has been demonstrated to reduce import peaks at points, but its effectiveness in reducing overall import levels is limited by comfort constraints. Across all three cluster sizes studied, the overall annual import level was never reduced by more than 0.25% through usage shifting.

In future stages of the Net Zero Terrace project, work could be focused on two key areas. The first is on comfort levels, where additional studies could look at the exact comfort constraints of a household, either through Living Lab data or detailed building energy modelling. The second is on usage shifting of "small power" electricity demand. Although many household appliances cannot change in their demand (i.e. fridge, lighting), incentives could be used to reduce use of other appliances that are time-independent. This demand shifting could then feed back into the energy model.

## 5.2 Battery implementation

The battery implementation detailed in sections 3.6.2 and 4.2.4 showed strong results in meeting the modes of flexibility outlined in section 3.6. At all three cluster sizes:

- Rooftop solar usage increased by over 25% annually
- Rooftop solar electricity exports reduced by 50% annually
- Electricity imports from the grid reduced by over 10% annually

These changes can lead to considerable reduction in resident's energy bills. They also, with some adjustment, can provide benefits to the DNO as well.
As detailed in section 4.2.4.2, the export peak reduction is more successful and reliable in the spring compared to summer. This is because the solar generation is so high in the summer that the battery is fully charge by midday, meaning that peak reduction cannot occur beyond that point.
There are several ways suggested to mitigate this:

- Implement a remote control algorithm or incentive scheme to allow coordination between battery charging and anticipated peak voltage level. This will ensure or incentivise that the battery is charged in the middle of the day, consistently reducing the peak export. This in turn reduces the peak voltage level at the substation.
- Implement additional community storage systems in the summer. These could be community battery schemes, which allow greater electricity storage in days of high generation; or community thermal stores, which allow storage of heat in summer for winter.
- Reduce the amount of solar generation in the summer through a curtailment process using switch-off at the inverter.

Further investigation into these options could take place at further stages of the project, as well as a more detailed optimisation of household battery size.

Additionally, as generation from solar PV systems is dependent on air temperature and radiation, battery usage is skewed away from winter months. To maximise benefits of a battery system, a hydropower or wind generation profile could provide to the community in winter months. This too requires further investigation.

## 5.3 Data collection

The building stock data, alongside several supplementary studies, provided a good baseline for the energy model. These were validated via workshops with project partners and comparison to data used on other Buro Happold projects.

In order to develop the accuracy of the model further, and to run additional scenarios with confidence, it is suggested that actual performance data and sizing is used. This can be taken from sample properties, likely through some survey process. This could take place at the next stage of the project.

## 5.4 Cluster size

Currently, there is little variation in flexibility scenario performance when adjusting the cluster size up to 1000 homes. This is due to the exact same parameters and methods being applied at each cluster level. This does suggest that the energy model is effective at modelling energy usage at different cluster sizes.

In future stages of the NZT project, work could be done to implement additional flexibility measures as cluster size increases. This could include schemes such as community batteries/thermal stores, or electric car clubs.

Additionally, with these flexibility measures, cluster size could be increased beyond 1000s home. This would allow investigation of sensitivities at scale. It would also allow mode 4 of flexibility (section 3.6) – national balancing, to be investigated.

## 5.5 Archetypes

The archetypes developed in this study allowed a range of occupancy and building sizes to be explored. This also allowed the energy model application of flexibility to be tested with a range of different inputs. The sensitivity of the flexibility to archetype makeup, is small in the samples tested. This is evident from the figures presented in section 4, and suggests the energy model is effective for different communities.

In future stages of the NZT project, a wider range of archetypes could be implemented. These could either be developed from further studies, such as Living Lab data or research papers, or from surveys of residents in the area on their house size and usage. This would allow the model to more accurately reflect the demands of a cluster, and hence provide a more realistic solution to apply flexibility.

## 5.6 General conclusions

The energy model described in this report uses a thorough methodology to determine household energy demands for a range of usage and size archetypes. It then models these demands at household and cluster level to assess a wide range of flexibility scenarios. Early indications are that a level of system control permits some voltage reduction and load management, with voltage reduction being particularly evident through battery storage. To develop these outcomes further, for application at a wider scale with confidence, further work should be conducted into the aforementioned topics, with a focus on battery optimisation and collection of additional occupancy data.