IAgrE Student Awards

NOMINATION SUMMARY

IAgrE CNH Student Project Award

***please delete as appropriate:**

PROPOSER: (usually Course Director/Head of Department)

Name: Dr Sarah J Parsons. Approval for this nomination also given by Dr Ian Moorcroft, Head of Engineering Department, and Greg Rowsell, Deputy Head of Engineering Department, previously Course Manager.

Position:
Senior Lecturer in the Engineering Department

University/College: (name and address)
Harper Adams University, Newport, Shropshire, TF10 8NB

Contact details:	**Tel: 01952 815448**	**Email: sjparsons@harper-adams.ac.uk**

DETAILS OF NOMINATION:

Name of Student/Group of Students: Christian Lovett

Personal contact details (i.e not college) to enable us to contact the student(s) once their course has ended:

Home Tel: N/A **Mob: 07986 655979** **Email: crjl2002@gmail.com**

Name of course studied: MEng Mechanical Engineering

Project Title: USE OF EX-ELECTRIC VEHICLE BATTERIES AS A BATTERY ENERGY STORAGE SYSTEM ON FARMS

Details of material submitted with nomination: Project pdf
This project investigated and modelled the use of ex-electric vehicle batteries to store renewable energy from photovoltaic arrays to supplement peak energy demand for farm dairy milking operatons, using energy data from the University campus. The model illustrated that lifetime savings of £11,529 to £108,389 could be achieved at a rotary dairy milking approximately 350 cows, operating with variable tariffs, with payback times typically 2-6 years.

SIGNED BY PROPOSER: *S J Parsons*	**DATE SUBMITTED:** 31 October 2025

If you wish to provide any additional information to support this nomination please do so in a covering letter. When complete, return this form, together with the supporting documents, to

The Secretariat, IAgrE, The Bullock Building (Bldg 53), University Way, Cranfield, Bedford MK43 0GH
secretary@iagre.org

NB All work submitted is treated with complete Confidentiality, no part of the paper will be published by IAgrE except for the Title and Name of the winner in each category.

Harper Adams University
Newport
Shropshire
TF10 8NB

Friday 31st October 2025

Sarah McLeod
Secretariat
Institution of Agricultural Engineers
The Bullock Building (Bldg 53),
University Way,
Cranfield, Bedford
MK43 0GH

Nomination for IAgrE CNH Student Project Award – Christian Lovett MEng, Harper Adams University graduate

Title: Use of Ex-electric Vehicle Batteries as a Battery Energy Storage System on Farms

Dear Sarah

I am very pleased to nominate Christian Lovett's Masters Engineering Project, titled Use of Ex-electric Vehicle Batteries as a Battery Energy Storage System on Farms, for a 2025 IAgrE CNH Student Project Award.

Chris' project investigated and modelled the use of ex-electric vehicle batteries to store renewable energy from photovoltaic arrays for farm use. His project is described in the Summary on page 8. Chris extracted two years' of energy usage and generation data from the Harper Adams University Building Management System reports, creating a campus energy audit and a large dataset of over two million values, working closely with the Harper Adams University Estates Team. This was an extensive task which Chris persevered with. From this energy audit and dataset, the Harper Adams Dairy was selected as an area of the farm with high energy demands and regular peaks in demand. Ex-electric vehicle batteries were explored and costed, selecting Tesla batteries. A model was produced using MATLAB software for storing the PVA energy generated and then supplying this to the dairy during the evening milking when a variable electricity tariff would charge a peak rate. A range of scenarios of numbers of batteries, milking times per day and milking energy demands were analysed with projected costings produced. These are described in Chapter 5, page 40 onwards.

Chris' models illustrated that lifetime savings of £11,529 to £108,389 could be achieved at a rotary dairy milking approximately 350 cows, operating with variable tariffs, with payback times typically 2-6 years. These cost savings could give considerable commercial benefits to dairy farms, many of whom may already have PVA installations on their farm buildings or land.

The use of renewable solar energy and re-use of electric vehicle batteries are both examples of sustainability and help to reduce use of natural resources and mitigate climate change.

In addition to Chris working closely with the Harper Adams Estates department, and myself, my colleague Dr Sven Peets also provided advice.

The strengths of this project were the engineering and technical details, data analysis and costings. Chris' mark for the criteria 'Plan and utilize appropriate methods to ethically deliver a forward-thinking solution to the engineering problem' element was 72% and 70% for Formulation and Coherence. His application of methods was described as undertaken with care and rigor. His overall project mark was 68%, a high Merit.

This project provided Chris with useful, relevant experience which contributed to him securing a Engineering Project leader graduate role in a related industry.

Thank you for your consideration of this work for an IAgrE CNH Student Project Award.

Yours sincerely,

Sarah

Dr Sarah J Parsons BSc PGCE PhD FHEA CMath FIMA MIAgrE MIET
Senior Lecturer in the Engineering Department
Email: sjparsons@harper-adams.ac.uk *Tel 01952 815448*

USE OF EX-ELECTRIC VEHICLE BATTERIES AS A BATTERY ENERGY STORAGE SYSTEM ON FARMS

by

CHRISTIAN LOVETT

Being a Masters Engineering Project submitted in partial fulfilment of the requirements for the MEng Honours Degree in Mechanical Engineering

2025

Student Declaration Form

Candidate's Name	Christian Lovett
Candidate's Number	20152400
Degree Programme	MEng Mechanical Engineering
Supervisor	Sarah Parsons
Major Project Title	Use of ex-electric vehicle batteries as a battery energy storage system on farms.
Word Count	9986
Confidential?	No

In submitting this Major Project I acknowledge that I understand the definition of, and penalties for, cheating, collusion and plagiarism set out in the assessment regulations. I also confirm that this work has not previously been submitted for assessment for an academic award, unless otherwise indicated.

(Electronic) signature of student C. Lovett

Declaration of the Use of Artificial Intelligence (AI)

Artificial Intelligence (AI) has been used in the development of this project. Specifically, AI tools were employed for the following purposes:

- Spelling and grammar checking
- Word count reduction and text refinement
- Initial generation of MATLAB code

All AI-generated content was reviewed and edited to ensure accuracy, relevance, and alignment with the project requirements.

Table of Contents

List of Tables

List of Figures

List of Equations

Glossary of Terms

BESS – Battery Energy Storage System

BMS – Battery Management System

CHP – Combined Heat and Power

EEM – Energy Efficiency Measures

EMS – Energy Management System

EU – European Union

EUI – Energy Utilisation Index

EV – Electric Vehicle

ESS – Energy Storage System

GHG – Greenhouse Gas

HAD – Harper Adams Dairy

HAE – Harper Adams Estate

HAF – Harper Adams Farm

HAU – Harper Adamas University

MINLP – Mixed-Integer Non-Linear Programming

PCS – Power Conversion System

PERC – Passive Emitter Rear Cell

PV – Photovoltaic

OPEC – Organisation of the Petroleum Exporting Countries

RES – Renewable Energy Source

ROM – Rough Order of Magnitude

TR – Thermal Runaway

WBA – Whole Building Audit

WTO – World Trade Organisation

Summary

This report determines whether ex-electric vehicle batteries could provide farmers with a cost-effective Battery Energy Storage System (BESS). By repurposing these batteries, their life span can be extended and can further offset the effects of production. This allows farmers an affordable energy storage solution, with less use of fossil fuels, helping to mitigate climate change.

To assess the cost-effectiveness of a BESS using second-life EV batteries, an energy audit was conducted to identify a suitable location on the Harper Adams University Campus. Using a large data set from the audit (2.2 million values) and literature, a system was specified and modelled to estimate potential savings, payback period, and lifetime benefits.

The energy audit found that the Harper Adams dairy would see the greatest benefit from the installation of a BESS due to its use of Photovoltaic (PV) arrays and regular energy peaks. The theoretical method employed, showed that the use of ex-electric vehicle batteries in a BESS, for peak shaving, would provide a cost-effective second life for EV batteries. The model illustrated that savings of £11,529 to £108,389 could be achieved at a rotary dairy milking approximately 350 cows, when operating with variable tariffs and using energy generated using the PV arrays.

This report has shown that a BESS using ex-electric vehicle batteries, would provide a dairy farm with a cost-effective method for increasing the use of renewable energy on site allowing a reduction in energy costs and a reduction in use of fossil fuels, helping to mitigate climate change.

Acknowledgements

The author wishes to acknowledge the following people for their contributions to this project

Harper Adams University

Firstly, I wish to thank Sarah Parsons, for supporting me throughout the project as the Project Supervisor. I also wish to thank Sven Peets for his assistance throughout the project.

I would like to thank all members of Harper Adams staff who have assisted with the project particularly the Harper Adams Engineering Department and the Harper Adams Estates Team (in particular Adam Gallagher and Deborah Hudson) and the Harper Adams Farm without whom the project would not have been possible.

I would like to thank my friends and colleagues in the Masters Engineering Office, for making the process of the project an enjoyable one.

And finally, my family for their support thought my time at Harper Adams University, particularly my mother for her constant support, especially in the form of correction of my appalling spelling.

Chapter 1 Introduction

1.1 Aim

This project aims to investigate whether a Battery Energy Storage System (BESS) which uses ex-electric vehicle (EV) batteries could provide a cost-effective solution to dairy farms, whilst providing a second life to ex-EV batteries, further offsetting the environmental impact of their manufacturing.

1.2 Research Questions

Can a Battery Energy Storage System (BESS) using ex-electric Vehicle batteries, provide a cost-effective solution to dairies?

1.3 Objectives

The project will look at how the BESS system works and whether batteries that were previously used in electric vehicles (EVs) can be repurposed for use as a BESS. Following this, an energy audit will be conducted to find the location which would benefit the most from a BESS on the Harper Adams Estate. Data will be gathered and analysed to determine whether the use of an ex-electrical vehicle battery in a BESS will provide a cost-effective method for increasing the use of renewable energy.

1.4 Project Justification

With the Zero Emissions Mandate approaching, the uptake of electric vehicles is growing, an important question arises: what happens to these batteries once they are no longer in use? One solution could be to repurpose them for use in Battery Energy Storage Systems (BESS) (Cusenza et al., 2019) on farms, rather than relying on new batteries.

BESS are systems that store energy in the form of electricity, this energy is harvested in periods of low demand and released in high demand periods, this assists with grid balancing, which is one of the greatest barriers to the uptake of solar energy. If successful, this approach could reduce electricity costs, increase the use of renewable energy in agriculture, and ultimately lower emissions. In doing so, it supports the fight against climate change and helps protect the planet for future generations.

Chapter 2 Information Search and Review

2.1 Information Search and Review Introduction

This section aims to identify a suitable methodology for the energy audit and develop the theoretical framework for assessing whether second-life EV batteries can serve as a cost-effective BESS. It also justifies the project's relevance through a targeted information search and literature review.

2.1 Effects of Fossil Fuels

Greenhouse gases (GHGs) like Carbon dioxide (CO_2) and methane naturally trap heat in the atmosphere, a process known as the greenhouse effect. Human use of fossil fuels has raised GHG levels, becoming the main cause of climate change (Shahveran & Yousefi, 2025). Carbon dioxide accounts for 72% of greenhouse gas emissions. In 2017, natural disasters caused $31 billion in global losses. Indoor air pollution is estimated to cause 4.3 million deaths annually. Climate change vulnerability and food insecurity are increasing the risk of conflict in developing countries (Adams & Acheampong, 2019). Burning fossil fuels releases GHGs such as nitrogen monoxide, nitrogen dioxide, sulphur dioxide, and carbon monoxide, which contribute to smog and harms human health. Sulphur dioxide also causes acid rain, damaging buildings and crops (Shahzad, 2012). Carbon monoxide exposure can cause headaches, nausea, and personality changes at low levels, and may lead to death at higher doses (UK Health Security Agency, 2024).

Fossil fuel extraction harms the environment, coal mining can leave land barren and cause fatalities. Oil spills destroy ecosystems. A notable example is the Ixtoc I spill, which released 500,000 tons of oil into the Gulf of Mexico, contaminating 162 miles of US coastline (Shahzad, 2012). Fossil fuel power plants in Iraq are causing significant pollution. High levels of heavy metals have been detected near these plants, decreasing with distance (Putros & Khadim, 2025).The Organisation of the Petroleum Exporting Countries (OPEC), comprising 12 nations, controls 40% of global oil production. This concentration leads to significant price volatility, often worsened by political instability (Shahzad, 2012). Political instability impacts global oil markets. Since joining the WTO, China has become a major oil consumer, accounting for 16.4% of global demand, while the US accounts for 19.9%. Their political relationship strongly influences oil prices. For example, during the Trump administration, US-China tensions and the trade war reduced Chinese production and oil demand, increasing price volatility. This underscores the significant impact of their relations on the oil market (Mignon & Saadaoui, 2024).

2.2 Need for Change

Fossil fuels are still the main source of global energy as shown by Figure 2-1

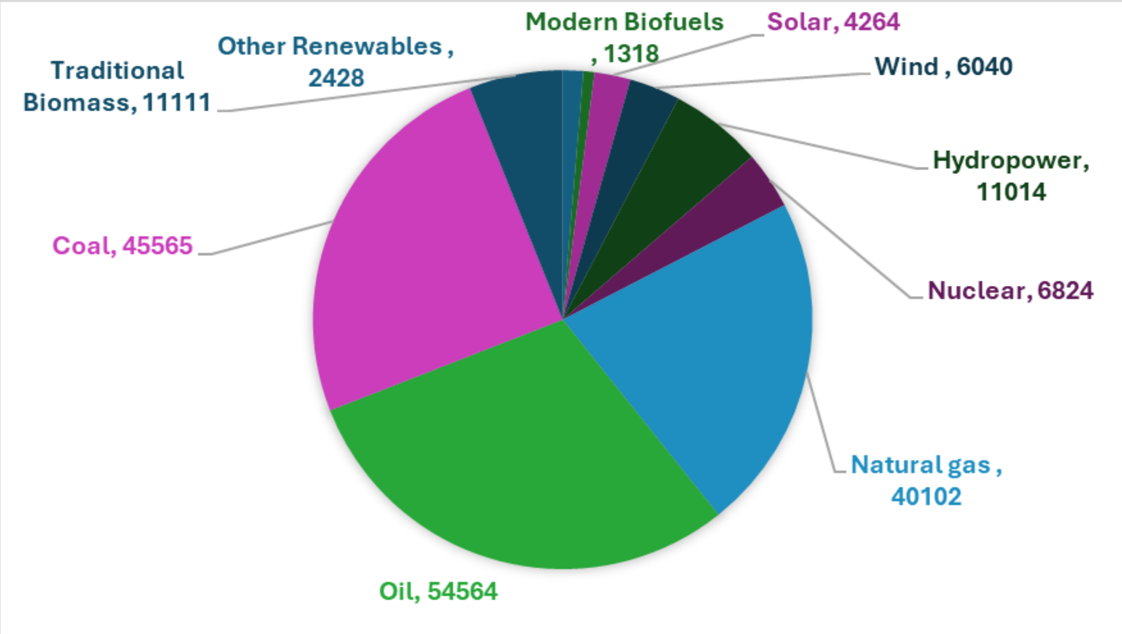

Figure 2-1 Global Primary Energy Consumption in TWh by Source for 2023 (Ritchie et al., 2024)

As shown in Figure 2-1, fossil fuels (coal, oil and natural gas) account for 77% of global primary energy consumption, while renewables make up only 20%. In the EU, transport contributes 25% of greenhouse gas (GHG) emissions, in the UK, transport accounts for 27% (Zhao & Baker, 2022).

To mitigate climate change, many countries are encouraging companies and communities to reduce fossil fuel use and transition to renewable energy sources (Zastempowski, 2023).

Renewable energy is generated from natural sources that replenish faster than they are consumed, such as solar and wind energy, which are continuously available (United Nations, 2024). Renewable energy sources are low risk, clean and inexhaustible (Amponsah et al., 2014).

Greenhouse gas emissions from renewable energy sources are primarily indirect, occurring mostly during upstream operations, front-loading their emissions. In contrast, fossil fuel sources produce direct emissions during energy generation (Amponsah et al., 2014).

2.2.1 Renewable Options

There are many sources of renewable energy such as:

- Hydropower
    - Hydropower, produced by water flowing through turbines, is a reliable and low-cost energy source. However, it involves high initial costs and can significantly affect local ecosystems (Mohtasham, 2015). The Three Gorges Dam exemplifies hydropower's high start-up cost, estimated at $28 billion (Cobalt, 2024), The dam's construction displaced around 2 million people, flooding 13 cities,

140 towns, 1,352 villages, and submerging 100,000 acres of farmland (Mikkelsen, 2015).

- Solar Power (PV panels)
    - Solar energy is the most abundant renewable source on Earth. Unlike fossil fuels, it produces no greenhouse gases during use and, unlike nuclear power, generates no hazardous waste (Mohtasham, 2015). PV panels use phosphorus-doped (N-type) silicon over boron-doped (P-type) silicon. Photons from the sun free electrons, forming electron-hole pairs and inducing a DC current (Fouad et al., 2017). Section 2.7 provides more information on soler panels.

- Wind Power
    - Wind turbines convert wind’s kinetic energy into mechanical energy, which drives a generator to produce electricity. Wind power reduces greenhouse gas emissions and offers low-cost electricity. However, ideal sites are often far from population centres, increasing transmission costs, and environmental constraints can limit suitable locations (Mohtasham, 2015).
- Geothermal Power
    - Geothermal energy harnesses underground heat to generate electricity or heat buildings directly. Its main limitation is geographic, as suitable sites are scarce and difficult to find (Mohtasham, 2015).
- Biomass
    - Biomass, one of the oldest energy sources, can help reduce greenhouse gas emissions. Feedstock from paper mills, lumber mills, or municipal waste can be converted into fuels like crude oil. Its use supports the terrestrial carbon cycle by transferring atmospheric carbon into the soil (Mohtasham, 2015).

2.3 Barriers to Use of Renewables

Whilst hydropower can produce high amounts of energy on demand, its effects on its surrounding ecosystem, high initial cost and reliance on geography make it unattractive to some users (Mohtasham, 2015). Wind and solar energy are weather-dependent, making them inherently intermittent sources (Borkowski et al., 2023). The intermittent nature of renewable energy sources (RES) challenges grid stability, as widespread adoption can reduce balancing capacity risking unmet load demands (Reihani et al., 2016). Power forecasting helps address this issue, but the unpredictable nature of wind limits its effectiveness for renewable energy supply (G. Lacey et al., 2013). Currently, load matching is managed by adjusting large generators, this approach is not feasible with solar and wind due to variable output (Kempton & Tomić, 2005). The growing use of EVs helps reduce GHG emissions but may increase grid load and peak demand, which RES struggle to meet (Albrechtowicz, 2023).

2.3.1 Overcoming Barriers

Energy storage systems (ESS) help mitigate the intermittency of renewable energy. The two main types are Pumped Storage Hydro (PSH), which depends on geography and has limited locations, and Battery Energy Storage Systems (BESS), which are compact, respond quickly, and are less location-dependent (Borkowski et al., 2023). BESS can be used to increase the reliability of supplied electricity from RES (Cusenza et al., 2019).

2.4 Effect of Energy Prices on Agriculture

Agricultural production is sensitive to fluctuations in energy prices, whether through direct energy costs or energy-related inputs such as fertiliser. (Sands et al., 2011). Economic efficiency is essential for maintaining business competitiveness, and the economic sustainability of a dairy is typically measured by its net profit. (Chetroiu et al., 2022)

2.5 Battery Energy Storage Systems (BESS)

2.5.1 BESS Configuration

Battery Energy Storage Systems (BESS) use rechargeable lithium-ion batteries and software to store and manage energy. They include batteries connected in series/parallel, a storage enclosure with thermal management, a Battery Management System (BMS), Power Conversion System (PCS), and Energy Management System (EMS).

The Battery Management System (BMS) monitors output, voltage, and state of charge, controlling charging and discharging. The Power Conversion System (PCS) handles AC/DC conversion, while the Energy Management System (EMS) manages energy flow based on consumer demand using control logic. BESS store excess solar energy when supply exceeds demand and release it during low production, allowing solar use during peak price periods (Ecostor, 2023).

2.5.2 BESS Benefits

BESS are most effective for shifting or shaving peak power consumption, particularly when electricity prices vary by time of day (Barchi et al., 2019). While installing a BESS can reduce peak demand, its peak-shaving capacity is limited by size smaller systems can only reduce smaller peaks (Prasatsap et al., 2017).

The UK’s first transmission-connected solar farm, paired with a 49.5MW/99MWh BESS, will generate enough for 17,300 homes and cut 20,500 tonnes of CO2. Unlike previous solar farms connected to the lower-voltage distribution network, this farm feeds directly into the transmission network, enabling cleaner energy to travel farther and supporting larger projects. The BESS stores excess energy at peak generation and releases it during high demand, maximising efficiency (National Grid, 2023).

Tesla offers a high capacity (3.9 MWh) BESS solution (Megapack) utilising their battery technology, providing energy storage helping to stabilise the grid (Tesla, 2025a). Tesla also offers the “Powerwall” for use in homes, a small system which stores energy from the grid and energy generated on site (Tesla, 2025b).

2.5.3 Limitations of BESS

Although BESS can enhance renewable energy reliability and efficiency, their high-cost limits widespread adoption (G. Lacey et al., 2013). The technology is mature and reliable, but economic concerns remain, requiring lower investment costs and greater market incentives (Borkowski et al., 2023) Lead-acid batteries have been commonly used. However, lithium-based batteries, with higher energy density and storage efficiency, are increasingly favoured, especially in EVs. Their high cost, though, has limited widespread use as BESS (Akinsooto et al., 2024).

2.5.4 BESS Scenarios

Zhang et al. (2024) investigated five scenarios for different electricity market types, these scenarios were.

1. Stand-alone PV Array
2. Peer-to-Grid (P2G) ID User-Owned (UO) BESS.
3. Peer-to-Peer (P2P) IDUO BESS
4. P2P Shared-Design (SD) UO BESS
5. ESS SD Developer-Owned (DO) BESS

Scenario Four was the most efficient, achieving up to 90% savings on electricity bills by using stored energy during peak demand and selling excess to peers. Further details are provided in Appendix I.

2.5.5 Peak Shaving Theoretical Foundation

G. Lacey et al. (2013), proposes a method to determine BESS capacity for peak shaving, where energy is stored during off-peak hours and released during peak demand to reduce grid strain and avoid high rates. Capacity is calculated using the peak power to be shaved and its duration (see Equation 2-1).

Equation 2-1 Calculate Required Capacity of a BESS for Peak Shaving (G. Lacey et al., 2013)

$$B_{cap} = \int B_{pw} d\,t$$

B_{cap}= BESS capacity (Wh)

B_{pw} = Power (W) to be shaved

t= Time (hrs)

BESS should be specified from the peaks which they are required to shave, with the power to be shaved being defined as the difference between the maximum load and the target load. Figure 2-2 shows an example BESS load regulation process. Gan et al. (2025)

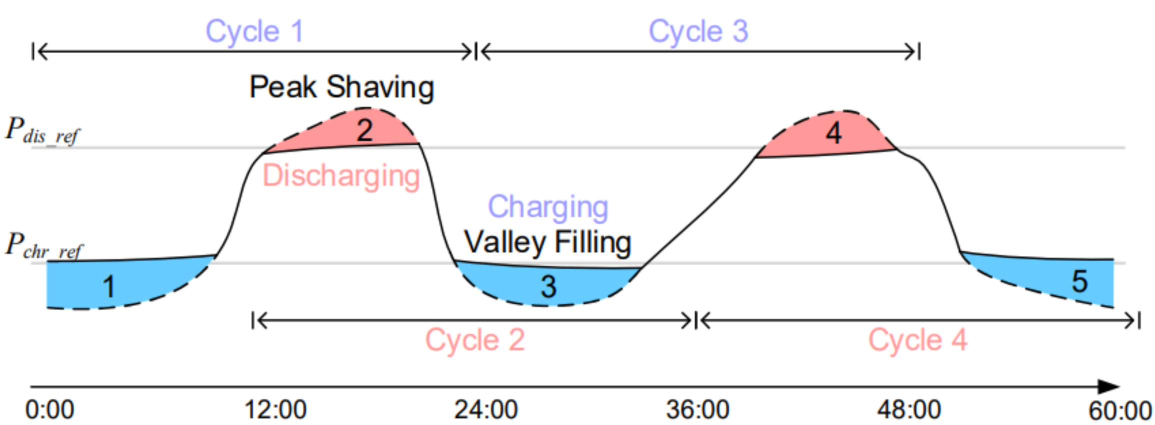

Figure 2-2 BESS Load Regulation Process y axis is power kWh, x axis is time (Gan et al., 2025)

Gan et al. (2025) also state that the energy accumulated by a BESS at time t in its cycle can be expressed as equation 2-2

Equation 2-2 BESS Load Regulation Process (Gan et al., 2025)

$$E_{cyc}(t) = \int_0^t P_{dem}(s)ds$$

$E_{cyc}(t)$ = Energy Accumulated by the BESS at time t

P_{dem} = Power Demand

This equation is similar to that proposed by G. Lacey et al. (2013) and could also be used to determine the required capacity for the BESS.

Danish et al. (2020) also states that smoothing of grid supply and demand is critical and can be achieved using a BESS. The BESS should be specified by determining the area under the power time graph at the point of the peak to be shaved, using equation 2-3, this is the same basic equation used by G. Lacey et al. (2013) and Gan et al. (2025)

Equation 2-3 Calculating BESS Capacity for Peak Shaving (Danish et al., 2020)

$$E_{REQ} = \int_{t2}^{t3} P_L(t)dt$$

E_{REQ} = Required Energy

P_L = Load Active Power

This equation can be used as the basis of a MATLAB script using a trapz function, which implemented a numerical integration using the trapes rule, to determine the energy used during milking peaks.

BESS should be specified to function at end of life, to maximise the BESS lifetime the BESS should not exceed 20% depth of discharge, in a BESS use case a battery is typically considered end of life at 50% of its original capacity, equation 2-4 can be used to calculate the BESS capacity requirements. For use later in the project this equation will be adapted to specify the capacity at the start of the second life of the battery.

Equation 2-4 1st Life Capacity of a Battery Intended for Second Life Use (G. Lacey et al., 2013)

$$B_{capINS} = \frac{\frac{B_{capEOL}}{0.5}}{0.8}$$

B_{capEOL} = BESS capacity at end of life

B_{capINS} = BESS capacity at installation (first life)

2.5.6 BESS Safety Considerations

Between 2017 and 2024, over 30 large-scale BESS experienced fire-related failures globally. Most involved lithium-ion batteries entering thermal runaway (TR), an exothermic reaction often triggered by short circuits. TR converts chemical energy into heat, leading to cell rupture and the release of toxic, flammable gases (Conzen et al., 2023). Considerations must be taken to ensure the BESS are installed safely (for more details see appendix II)

2.6 Use of Ex-Electric Vehicle Batteries as a BESS

2.6.1 Feasibility of Use

Retired EV batteries can be repurposed once their capacity drops to 60–80%, making them unsuitable for continued EV use but still viable for other applications (Ahmadi et al., 2014). EV Li-ion batteries typically reach end-of-life at 70–80% capacity but can be repurposed for less demanding applications like BESS. BESS batteries are considered unsuitable once capacity falls below 60%. With EV batteries lasting around 8 years and BESS having a 20-year lifespan, repurposing offers an additional 12 years of useful life. (Cusenza et al., 2019) suggests that reuse of EV batteries could prevent the need for manufacturing new batteries for stationery use case.

Other studies show that battery capacity can drop from 80% to 50% in about 1,600 cycles. Assuming one cycle per day, an ex-EV battery used in a BESS would last approximately four and a half years (F. Marra et al., 2010), however due to the age of this report this is likely no longer true. (Kotak et al., 2021)

2.6.2 Environmental Benefits of using an Ex-Electric Vehicle Battery as a BESS

As of 2018, there were around 3 million EVs globally, with projections estimating 125–220 million by 2030. Automotive manufacturers are rapidly shifting to electric fleets, Volvo, for example, stopped launching vehicles with standalone internal combustion engines in 2019 (Olsson et al., 2018). While EVs can reduce GHG emissions depending on the electricity source, they have higher human toxicity impacts due to the intensive use of metals, chemicals, and energy in powertrain production (Verma et al., 2022). To produce one tonne of lithium, 250 tonnes of spodumene or 750 tonnes of brine are required. (Meshram et al., 2014)

By 2025, an estimated 250,000 metric tonnes of EV lithium-ion batteries will reach end of life, typically at 70–80% capacity. Repurposing these batteries can help offset the environmental impact of battery production and improve overall sustainability (Olsson et al., 2018).

Making use of a product after its use is the corner stone of circular economy, as through direct use refurbishment or remanufacturing recycling can be eliminated. This prevents the slowing of the resource cycle, whereas recycling closes the resource loop. (Olsson et al., 2018)

2.6.3 Current Recycling Methods for EV Batteries

There are many existing methods used to recycle Li-ion batteries.

Pyrometallurgical Recovery, smelts' battery metal oxides at high temperatures to produce alloys of Co, Cu, Fe, and Ni. It's established for consumer Li-ion batteries and generates metallic alloys, slag (containing Al, Mn, Li), and gases.

The slag is reclaimed via hydrometallurgical methods. High temperatures minimise risk, and exothermic combustion of electrolytes and plastics (40-50% of battery mass) reduces energy use, but these materials aren't recovered. Despite high energy costs, toxic gas emissions, and limited material recovery, this method remains widely used (Harper et al., 2019).

Appendix III shows other methods for Ev Battery recycling

Re-use of electric batteries is considered preferable to recycling, to extract the most value from the battery and minimise the environmental impact (Harper et al., 2019).

2.6.4 Price of Ex-Electric Vehicle Batteries

There are many options for the purchase of ex-EV Batteries, with prices varying depending on the brand and capacity, table 2-1 shows a range of options for ex-EV batteries from Second Life EV batteries (2025).

Table 2-1 Battery Options from Second Life EV batteries (2025)

Brand	No of Units	Capacity kWh	Price Ex vat	Price/ kWh
Tesla	**5**	**26**	**1829**	**70.35**
Jaguar	4	10	949	94.90
VW	4	27	2995	110.93

Green Tec (2025) also offers Ex-Ev batteries, table 2-2 shows their options.

Table 2-2 Battery Options from Green Tec (2025)

Brand	No of Units	Capacity kWh	Price Ex vat	Price/ kWh
Nissan	**210**	**59.10**	**2413.79**	**40.84**
Chrysler	1	2.60	520.37	200.14

For comparison table 2-3 shows prices of new battery systems, however it should be noted that these include BMS and other additional components.

Table 2-3 New BESS Options (Heatable, 2025b) (Cambridge renewables, 2025)

Brand	No of Units	Capacity kWh	Price Ex vat	Price/ kWh
GiveEnergy	1.00	13.50	6942.00	514.22
Tesla Powerwall	1.00	13.50	7995.00	592.22

Whilst the ex-EV batteries will need additional spending, they represent a significantly lower price/kWh than new BESS.

2.6.5 Battery Management Systems Costs

A range of BMS are available, as shown in table 2-4, the price of this solution varies considerably depending on the size of the BESS and the use case of the system (Sunshine Solar, 2025)

Table 2-4 BMS Options (Sunshine Solar, 2025)

BMS	Supplier	Company	Price
Victron Energy Smart BMS CL 12/100	Sunshine Solar	Victron	£134.95
Victron Energy Smart BMS 12/200	Sunshine Solar	Victron	£207.49
Victron Energy VE. Bus BMS	Sunshine Solar	Victron	£104.25
Victron Lynx Smart BMS 500 (M8)	Sunshine Solar	Victron	£807.00
Victron Lynx Smart BMS 1000 (M10)	Sunshine Solar	Victron	£1,111.00
Victron Energy Lynx Shunt VE. Can	Sunshine Solar	Victron	£316.00

2.6.6 BESS Installation and Upkeep Costs

Exencell (2024) suggest that the installation of a BESS will account for 10-20% of the total cost of the project. Exencell (2024) also suggest that installation cost can be estimated, assuming that installation cost will be $50 - $100 per kWh and that the upkeep of the system will cost $50 - $100 per kWh over 10 years.

2.7 Solar Power (PV Array)

2.7.1 PV Array Types

There are many different types of PV array with different lifespans, efficiency and cost as shown in table 2-5. Figure 2-3 shows the basic working of a PV pane.

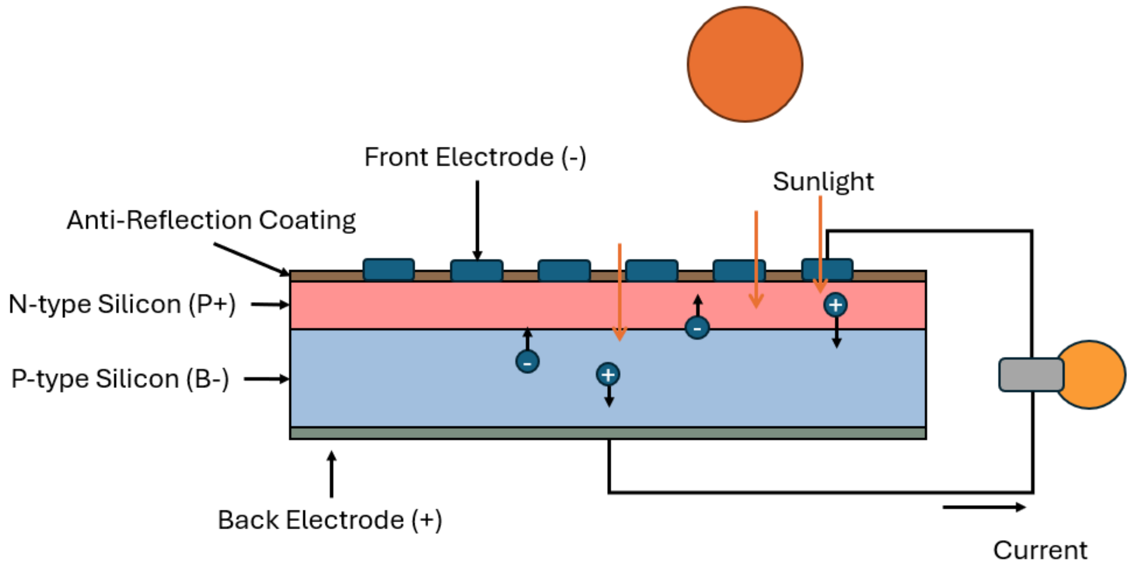

Figure 2-3 PV Panel Workings (Samaulah et al., 2018)

Table 2-5 PV Array Lifespan, Efficiency and Cost (Jackman & Clissitt, 2024)

Type of solar panel	Cost per m^2 (£)	% Efficiency	Lifespan (years)
Monocrystalline	350	18-24	25-40
Polycrystalline	280	13-16	25-30
Thin Film	99	7-13	10-20
Transparent	250	1-10	25-30
PERC	360	17-20	25-35
Solar Tile	294	10-20	25-30
Solar Thermal	670	70	20-25

Different panels utilise different methods to generate electricity, including:

- Monocrystalline
- Polycrystalline
- Thin Film
- Transparent
- PERC
- Solar Tile
- Solar Thermal

Monocrystalline panels using silicon wafers are cut from a single silicon crystal and assembled into rectangular arrays with electrical contacts. Photons release electrons in the silicon, generating electric current (CHINT, 2023). For further workings of solar panels see appendix IV

2.7.2 Factors that Influence PV Panel Performance

The **geographical location** of PV panels affects their performance, either positively or negatively, and must be considered during installation (Humada et al., 2016). External factors influence the energy output of PV arrays, these factors include temperature, geographical location, installation angle and solar radiation (Jiang et al., 2021).

2.8 Energy Audits

2.8.1 Energy Audit Purpose

Energy audits are a powerful tool for discovering potential operational and equipment improvements with the purpose of reducing costs (Baechler, 2011).

Piterà & La (2024) define an energy audit as a systematic procedure aimed at acquiring comprehensive knowledge of the energy consumption profile of a building, group of buildings, industrial or commercial operation, or public or private service. It involves identifying and quantifying opportunities for cost-effective energy savings, assessing the potential for economical use or production of renewable energy, and reporting the findings.

The purpose of an energy audit is to reduce energy use and improve sustainability. Industrial buildings often have large thermal loads and energy losses from ventilation and pollution controls. An energy audit helps analyse how energy-saving methods impact consumption (Dongellini et al., 2014).

The first step in an energy audit is to systematically understand the energy consumption profile, which can be simple or complex depending on the site size (Piterà & La, 2024).

2.8.2 Energy Audit Structure

Cagno et al (2010) suggest that energy audits can be placed into three categories:

- Walk-through
    - This is the simplest type of audit, this consists of a brief review of
    - bills, minimal interviews and a facility walk-through (Cagno et al., 2010).
- Mini-audit
    - An expansion on the walk-through. This involves collecting more detailed information and a more detailed review of energy saving opportunities, also involving a financial analysis of investments (Cagno et al., 2010).
- Maxi-audit
    - Gives a detailed energy project implementation plan, simulates building and equipment operations based on a range of variables. One key aspect of the Maxi-audit is the energy balance, this uses an inventory of energy-using systems, assumptions of operating conditions and energy use calculations, which is then compared to the energy bill (Cagno et al., 2010).

An energy audit is one of the most cost-effective ways to improve energy efficiency by analysing energy flows within a firm and its processes. It represents just one step in a broader energy efficiency initiative, as shown in Figure 2-4 (Kluczek & Olszewski, 2017).

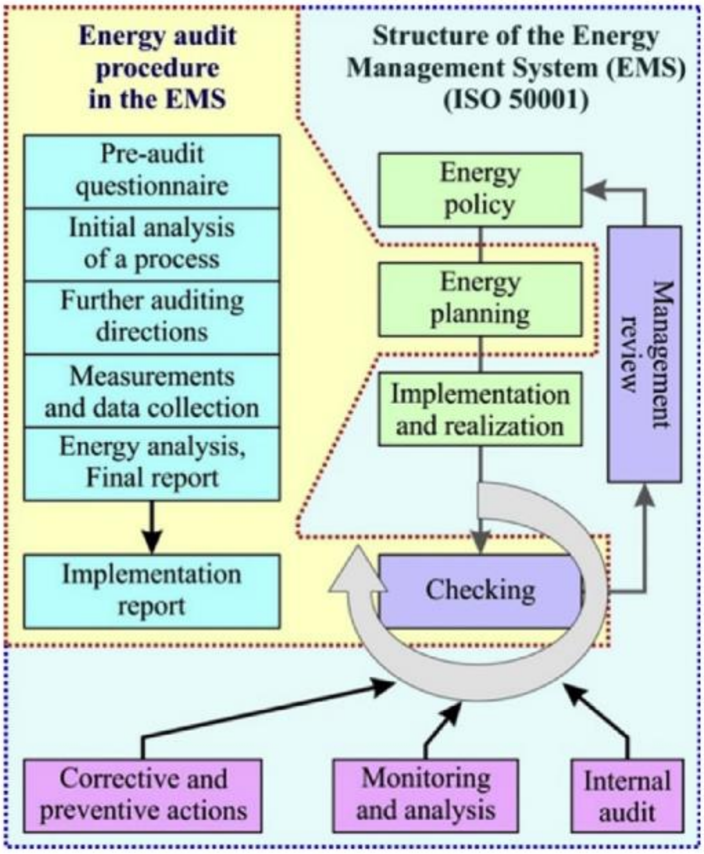

Figure 2-4 Energy Audit Process (Kluczek & Olszewski, 2017).

Kluczek and Olszewski (2017) suggest the following six phases to be used for an energy audit:

- Pre-Audit Questionnaire
    - This one-page questionnaire is intended for non-technical staff and aims to capture basic factory information, including production scale, processes, materials, final products, annual utility costs (from monthly bills), and the most energy-intensive process.
- Initial Analysis of Processes
    - This stage includes a preliminary meeting with the engineering team to review the manufacturing process and energy-saving methods, emphasising a walk-through and identification of known issues.
- Further Auditing Directions
    - This stage defines potential energy-saving strategies and guides activities toward a methodical energy assessment with appropriate measurements selected.
- Measurements and Data Collection
    - All activities from the previous step are carried out, and the audit team meets with facilities staff to review the outcomes.
- Energy Analysis and Final Report

  - Based on earlier data, this often-time-consuming phase requires documenting all assumptions and analyses for reproducibility and verification.
- Implementation Report
  - The final audit stage is a 6-month follow-up to verify observations and recommendations.

Energy audits are most effective when using the Whole Building Audit (WBA) approach, this assesses the building envelope, systems, and operations to identify true energy-saving potential. Focusing only on individual systems like heating or lighting may miss wider opportunities (Baechler, 2011).

Baechler (2011) states that there are three levels of energy audit:

- Level One Site Assessment / Preliminary Audit
  - Used to identify low/no cost improvement opportunities, this typically involves a review of energy bills, and a brief site assessment
- Level Two Energy Survey and Engineering Analysis Audit
  - Identifies low/no cost opportunities as well as providing energy efficiency measures. The level two audit uses an in-depth analysis of energy costs, energy usage and building characteristics, as well as a refined energy use survey.
- Level Three Detailed Analysis of Capital-Intensive Modification Audits / Investment Grade Audit
  - Used to provide financial analysis for major capital investment, in addition to the level one and two audit monitoring, data collection and engineering analysis is used.

For large, previously unaudited facilities, a level 2 or 3 audit is most appropriate (Baechler, 2011). The audit process begins with selecting the audit level; Table 2-6 outlines the subsequent phases.

Table 2-6 Audit Phases (Baechler, 2011)

Phases	Milestones	Activities
Preliminary review of energy use	• Facility benchmarked against similar buildings • Base energy load identified	• Collect and analyse utility data • Calculate EUI and compare to similar facilities • Assess energy efficiency improvement potential
Site assessment	• Site data collected • Immediate energy saving opportunities identified • Exit meeting held to discuss preliminary findings	• Interview building staff • Visually inspect building and key systems • Collect data
Energy and cost analysis	• EEMs prioritised according to project and financial goals • Savings estimates generated	• Evaluate utility and site data • Analyse energy and cost savings • Develop list of recommended measures
Completion of audit report	• Exit meeting held to walk through final report • Action plan developed for next steps	• Summarise findings • Present recommendations

An energy audit typically begins with a preliminary review of energy data, system diagrams, and equipment lists. Ideally, two years of data are analysed to account for seasonal variability (Baechler, 2011). Baechler's energy audit process has similarities to that of Kluczek & Olszewski (2017).

2.9 Variable Energy Tariffs

Variable energy tariffs mean that unit rates can increase or decrease depending on time of day (British Gas, 2025). Octopus Energy also offer variable energy tariffs called Agile Unit Rate. These rates are typically lower than fixed rates in off peak times and higher during peak times (Jackson, 2022). More information is provided in section 3.5.2

2.10 Cost Engineering

Cost engineering is typically defined as the application of engineering principles, techniques, judgment and experience to estimate the cost of a project, as well as the cost through the project's life (Lanen et al., 2014). Lanen et al. (2014) defines Cost estimation as "the approximation of the probable future cost of a product, program, or project, computed on the basis of currently available information."

Cost estimations are made for a variety of reasons:

- Investment decisions, cost estimation is vital to determine the potential return on investment.
- Comparing alternative investments, this requires cost estimation to compare potential investment options.

- Determining selling price, selling price must cover direct, indirect and fixed costs necessary to produce a product or service plus sufficient profit margin.

A cost estimate is based on the forecasting of labour and material or components costs required to complete the project. (Lanen et al., 2014). It is often required to perform Rough Order of Magnitude (ROM) cost estimation, to help choose between different projects and different project options. For example, knowing whether a project will cost around $75 Millon or $200 million will help with decision making (Mislick & Nussbaum, 2015).

Mislick & Nussbaum (2015) define cost estimation as the process of collecting and analysing historical data and applying quantitative models, techniques, tools, and databases to predict the future cost of an item, product, program, or task. It combines the art and science of approximating the probable cost, scope, or nature of something based on information available at the time.

2.11 Information Search and Review Conclusions

The purpose of this section was to inform the project by establishing a suitable methodology for the energy audit and developing a strong theoretical foundation for the model used to assess whether second-life EV batteries could offer a cost-effective BESS for a dairy.

A methodology from Kluczek & Olszewski (2017) was adopted to guide the energy audit. A solid theoretical foundation for the model was established, with multiple studies agreeing on the equations used to determine the required BESS capacity. Literature was also reviewed to estimate the cost of a BESS utilising second-life electric vehicle batteries.

This section has justified the need for the project by highlighting how BESS can support the fight against climate change by increasing the use of renewable energy and providing a viable second life for electric vehicle batteries.

Chapter 3 Harper Adams University Energy Audit

3.1 Energy Audit Introduction

The aim of this energy audit was to understand the energy flows within Harper Adams University (HAU), with a view to finding the area which would benefit most from the installation of a BESS. As well as collecting data on energy consumption for the chosen location of the BESS and information on energy tariffs. The energy audit followed the process set out by Kluczek & Olszewski (2017), with minor adaptations to better fit the requirements of the project.

3.2 Pre-Audit Questionnaire

3.2.1 Background

Meetings with the HAU Estates team were held to gather information on, instrumentation possessed, electricity use, generation, cost and energy intensive activities. Meating where also held with farm and finance personnel. This was considered more suitable than using a questionnaire.

3.2.2 Findings

The four main energy sources at are HAU:

- Combined Heat and Power (CHP)
- Biomass Boiler
- PV arrays
- Grid

The CHP generates electricity and hot water for heating on the HAU estate, supplemented by a biomass boiler for hot water with some independent heating systems. Multiple PV arrays provide electricity, with grid power used when on-site sources fall short.

The Biomass boiler on the HAU estate is a 1MW boiler and provides hot water across the estate figures 3-1 and 3-2 show buildings supplied with hot water by the biomass boiler.

Figure 3-1 Hot Water Supply

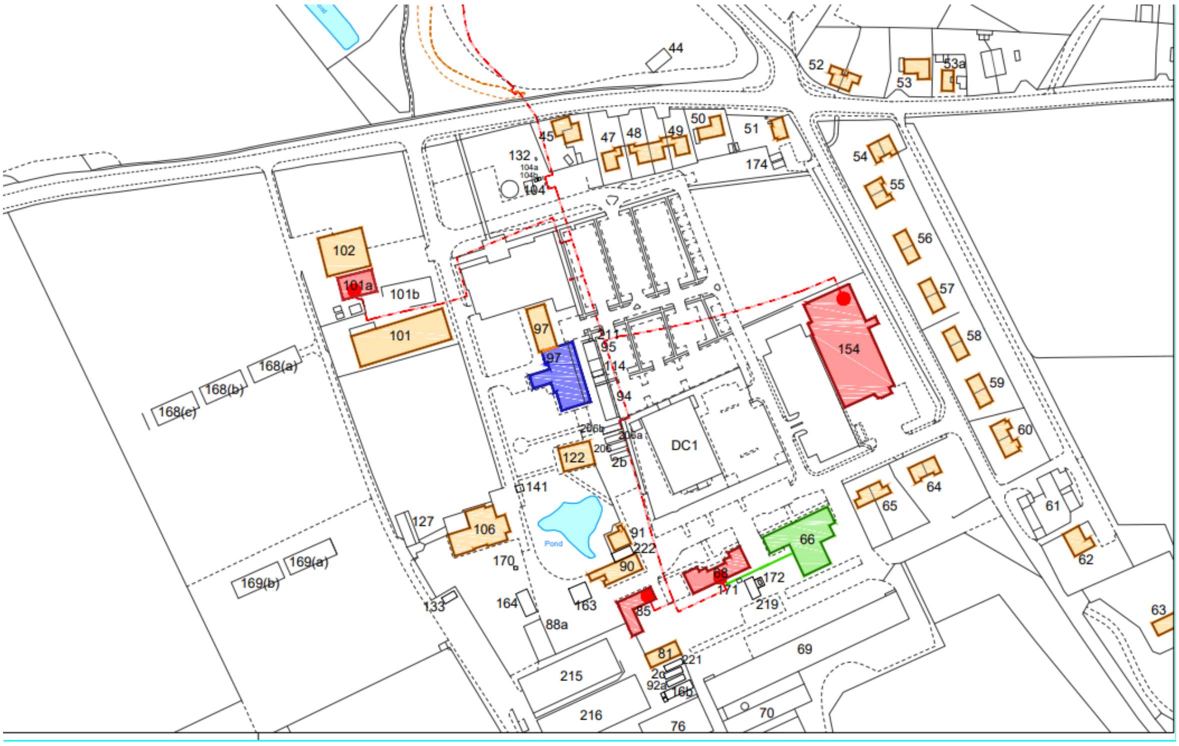

Figure 3-2 Hot Water Supply

Red buildings are directly supplied by the biomass boiler, green buildings receive heat via secondary connections. Main connections are shown in red and secondary in green. Orange buildings have independent heating systems.

Further investigation into the biomass boiler and other heating sources was not pursued due to their low electricity consumption, meaning a BESS installation would have minimal impact.

Figure 3-3 shows the split of electricity used on the HAE in 2023 and 2024. In 2023 HAU PV arrays generated 534568 kWh and 474696 kWh in 2024 making up 15% and 12% of energy consumed respectively.

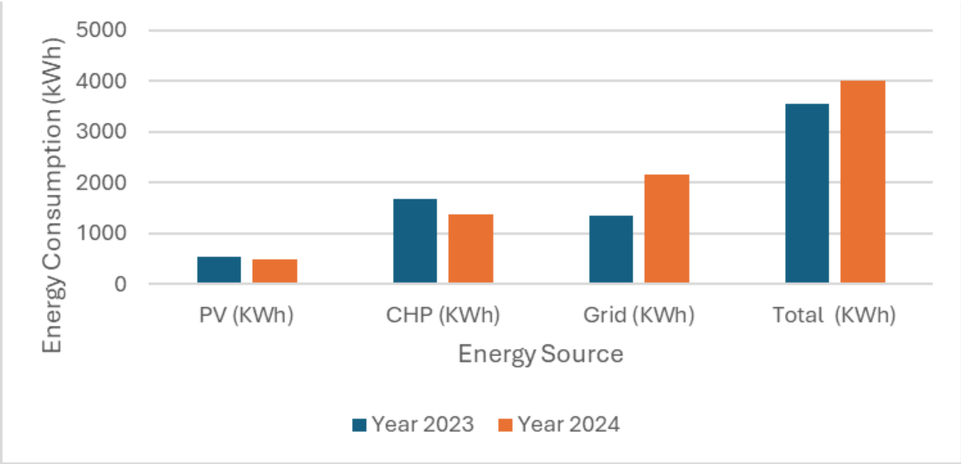

Figure 3-3 Harper Adams University Energy use by Source (Reeves, 2025)

Many buildings across the HAU estate utilise PV arrays on the roof to produce electricity, many of these buildings are either residential or academic, however this use is unlikely to produce peaks that will benefit from the installation of a BESS for peak shaving.

The Harper Adams Dairy (HAD) unit also utilises PV arrays to generate electricity, as well as PV use, the HAD sees significant peaks when milking. This would make the HAD an ideal area for the installation of a BESS. Due to this the HAD was chosen as the focus of the energy audit.

3.3 Initial Analysis of Process

3.3.1 Background

Following the selection of the HAD as the focus of the audit the initial analysis was carried out, for this step Kluczek & Olszewski (2017) place a focus on meeting with the engineering team and understanding the current issues with the process, some changes are required to the process to meet the needs of the project, as the process is tailored to a manufacturing facility.

Meetings were held with HAU estates as well as conducting a walkthrough and observations at the HAD to gain an understanding of the HAD.

3.3.2 Findings

From meetings with HAE, it was found that data had historically been collected on energy consumption for the HAD.

This data was from 1st January 2023 – 14th March 2025, energy readings where recorded half hourly for these data sets.

A visit to the HAD was also carried out to observe and understand energy uses, figure 3-4 shows the layout of the HAD.

Figure 3-4 Harper Adams Dairy

Table 3-1 Building Use

No.	Building
1	Main Herd Shed
2	Heifer Shed
3	Milking Parlour
4	Young Stock Shed
5	Robot Dairy Building (now used for dry stock Shed)

Figure 3-5 Main Herd Shed

The main herd shed shown in figure 3-5 uses fans to improve ventilation, a robot feed pusher, and trial feeders as shown in figure 3-6 and 3-7

Figure 3-6 Robot Feed Pusher

Figure 3-7 Trial Feeders

Figure 3-8 shows building two, which has been fitted with larger fans to improve ventilation. The young stock shed (figure 3-9) does not use fans. The dry stock shed (figure 3-10) had been used for a robot milker but has been repurposed.

Figure 3-8 Building Two

Figure 3-9 Young Stock Shed

Figure 3-10 Dry Stock Shed

Figure 3-11 Milking Parlour

The milking parlour (figure 3-11) uses a 40-point internal rotary design where cows are milked inside a continuously rotating platform. The rotation speed matches milking time, and the milker is automatically removed once milking stops. Table 3-2 compares the current milking times (three sessions) with pre-April 5, 2024 (two sessions).

Table 3-2 Milking Times

Milking	Time	
	Two milkings	Three milkings
1	4:00 – 7:00	4:00 – 7:00
2	14:30 – 17:00	12-15:00
3	na	20:00 – 22:30

Currently HAU energy rates are set each month, meaning a fixed rate is paid for each month.

Table 3-3 shows the current approximate herd size of the HAD. This number varies depending on multiple factors, such as the number of cows in calf. These variations will lead to differences in the time required for milking.

Table 3-3 Approximate Herd size

Cows	Number
Milked	337
Not milked (young, dry etc.)	796
Total	1133

3.4 Further Auditing Directions

3.4.1 Background

This stage was significantly reduced as it focuses on selecting improvements. Since the project is scoped to the use of a BESS. However, decisions on data processing for the next audit stage were made.

3.4.2 Data Extraction

The focus was placed on dairy parlour data due to prominent power peaks. Data was formatted for Excel and MATLAB. This was a time-consuming process, with the reports being provided in 44 different Excel files with each file having around 20,000 rows and six columns of data, each of which required formatting and editing before use, ones edited each file had around 8,500 rows of data, meaning each file had 51,000 data points, meaning in total there was roughly 2.2 million values. Appendix V shows an example of the data in its raw format. Appendix VI shows the data in its process format. To reach this point date and time formats needed to be standardised, and cell placements needed to be edited so data was across a single row. The data was then consolidated into 11 files to represent each individual consumer.

3.4.3 Further Direction

To size the BESS, power peaks where integrated, as proposed by G. Lacey et al. (2013), Danish et al. (2020) and Gan et al. (2025). Daily data is needed by integrating milking peaks for each day and calculating the mean energy requirement. PV array energy production data is also required to assess if it can support peak shaving. Additionally, current and alternative time-of-day energy rates will be collected to optimise potential BESS effectiveness.

3.5 Measurements and Data Collection

3.5.1 Background

In this step all activities defined in the previous step are carried out, typically at this point meetings are held with facilities staff to review outcomes; these were not conducted as no changes were made. Initial data analysis was carried out in this section. Whilst the data shown in this report is historic data, limited work has been done using it due to staffing shortages within the HAU Estates team.

3.5.2 Findings

BESS Specification Data Collection

Energy usage data for the dairy was provided from 01/01/2023 – 14/03/2025. G. Lacey et al. (2013), Danish et al. (2020) and Gan et al. (2025) state that to specify a Battery Energy Storage System (BESS) for peak shaving, it is necessary to integrate the power-time graph at the peak to be shaved. It was decided that this integration should be performed prior to averaging the data, to preserve any peaks. MATLAB was chosen to carry out the integration process. This is covered in more detail in chapter 4 section 4.2.

PV Array Data Collection

Over two years of PV generation data was collected for buildings one and two at HAD, with half-hourly energy readings. PV arrays on buildings five and six only had annual production data available. To assess the PV system's suitability for peak shaving, daily energy generation will be calculated and compared to the peak shaving energy demand. This is detailed further in Chapter 4. Pivot tables in Excel were used to determine the monthly generation of the PV arrays, as shown in figure 3-12. PV generation is centred around May and June, likely due to the longer periods of light. No data was available for April – June 2024. It was also established that HAU consumes all energy generated by the PV arrays on site and does not sell back to the grid.

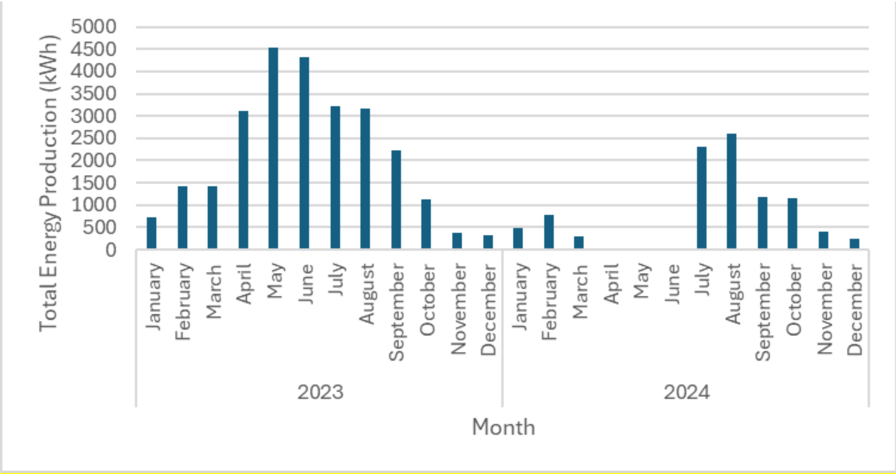

Figure 3-12 PV Generation for PV 1

Dairy Energy Use

Figure 3-13 shows that the energy consumption of the dairy, typically varies by month, with colder months seeing higher energy use. Meaning high energy use does not align with higher energy production.

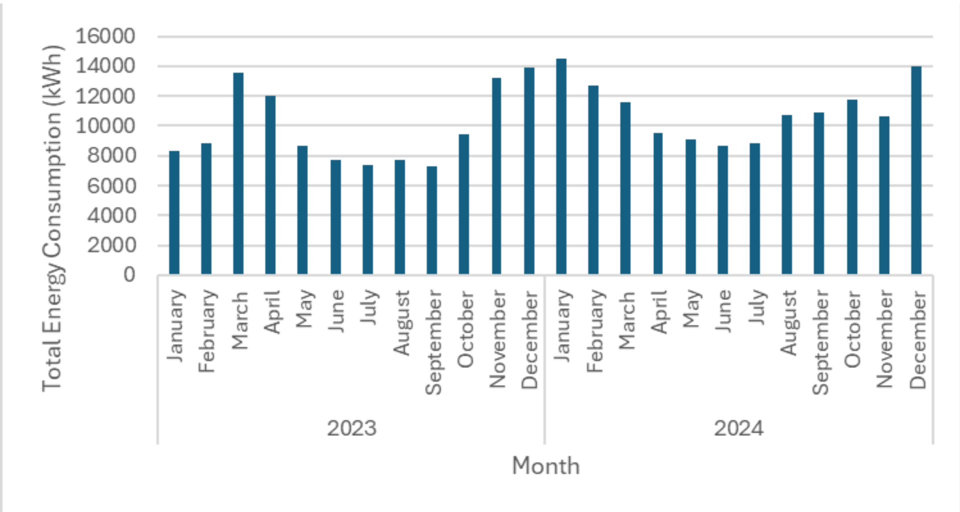

Figure 3-13 Dairy Energy use by Month

Energy Tariffs Data Collection

Figure 3-14 Shows the Energy Tariffs at HAU for 2023 and 2024

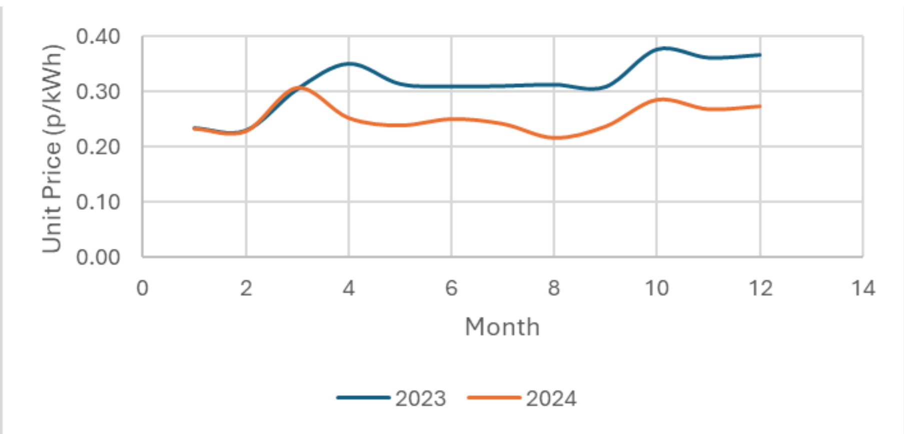

Figure 3-14 HAU Energy Tariffs (Reeves, 2025)

The average unit price for 2023 was 0.32 p/kWh and 0.25p/kWh in 2024, (for monthly tariffs see appendix VII) the use of tariffs that vary monthly will limit the effectiveness of a BESS, as to maximise the cost effectiveness, variable tariffs (changing half hourly) are required.

Research into alternative energy tariffs were carried out and data on Octopus Agile energy tariffs was collected, figure 3-15 shows the variation in energy tariffs from the 10th of May 2025 to 9th of May 2025

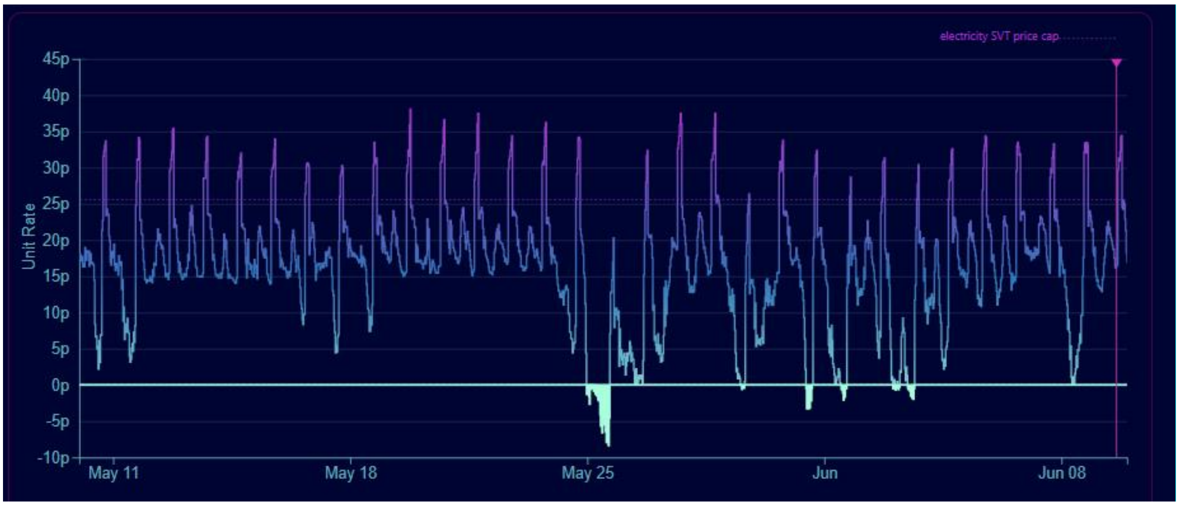

Figure 3-15 Agile Energy Tariffs (Chung, 2025)

Figure 3-15 shows that depending on the time-of-day customers will pay a varied price, in some cases customers are paid to use energy shown as a negative price in figure 3-15 (Chung, 2025).

Figure 3-16 shows an average day for energy tariffs from the 9th of May 2025 to the 9th of June 2025

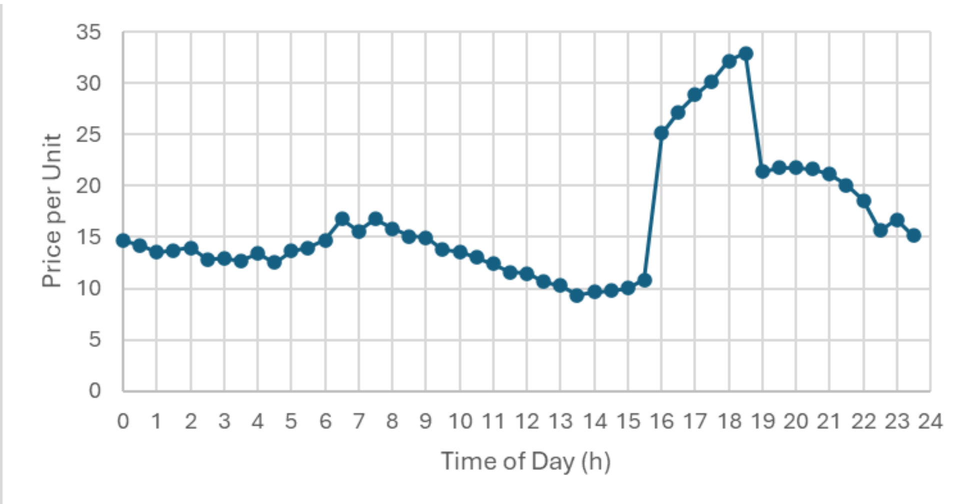

Figure 3-16 Average Day for Variable Energy Tariffs in May 2025 (Chung, 2025)

Figure 3-16 shows that on this scheme customers typically pay a premium for energy between 16:00 and 19:00, however, outside of these times a lower price per unit (PPU) can be achieved.

3.6 Energy Analysis and Final Report

This process was not carried out as it was decided that it does not conform with the needs of the project.

3.7 Implementation Report

This phase was not performed, as physical changes are beyond the scope of this project. Instead, a simulation was conducted as a proof of concept to assess the financial viability of the BESS, detailed in Section 5.0.

3.8 Energy Audit Conclusion

The energy audit aimed to understand the energy flows within HAU. This was achieved by identifying and quantifying the energy sources used on site. The audit also highlighted HAD as the area most suitable for the installation of a BESS. Additionally, data collection and analysis were conducted to support this decision.

The energy audit also found that the dairy uses more energy in the winter months. This limits the effectiveness of the PV arrays installed as high production occurs at low use periods. It was also found that all energy generated by the PV arrays is consumed on site, limiting the effectiveness of a BESS. The audit also suggests that the additional PV arrays should be installed as, currently only 13% of energy use come from PV arrays illustrating there is capacity for increased PV array installation.

Chapter 4 Battery Energy Storage System Specification

4.1 BESS Specification Introduction

The aim of this section is to determine the specification of a BESS required for peak shaving on the HAD. The battery will be specified using the data collected previously and will be specified to perform until end of life using the method proposed by G. Lacey et al. (2013) and (Gan et al., 2025) to calculate capacity, as well as the use of other literature to estimate the cost of installing a BESS.

4.2 BESS Function

Figure 4-1 shows the proposed working of the BESS.

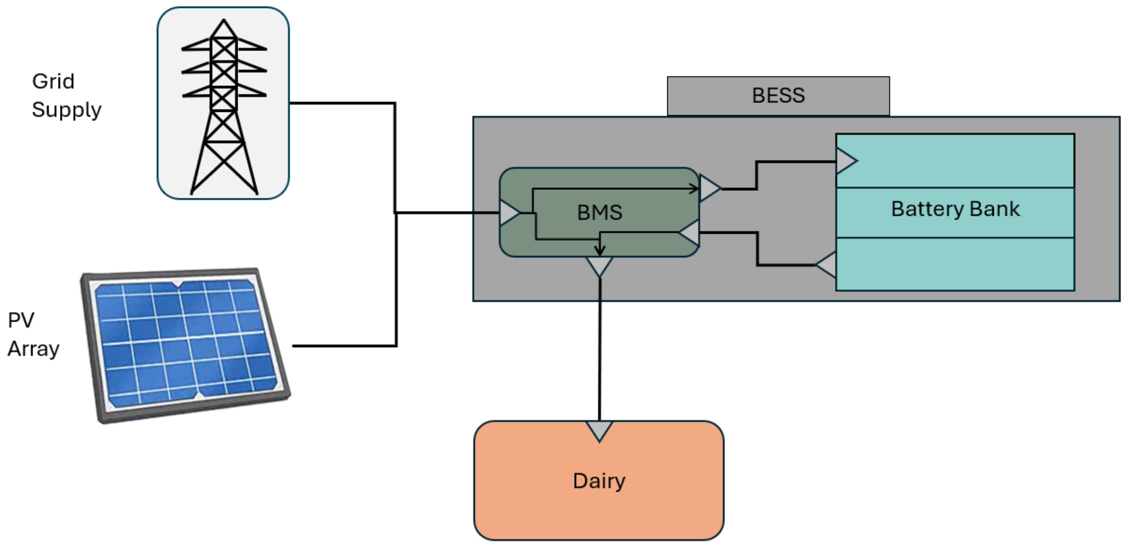

Figure 4-1 BESS Function on the Dairy Authers own

One of the key components required for the Battery Energy Storage System (BESS) to function effectively is the Battery Management System (BMS). The BMS is responsible for controlling the charging and discharging processes, as well as determining the source of charging (either from the PV array or the grid). Additionally, the BMS can divert power directly to the dairy operations, bypassing the batteries when solar production aligns with milking times, to reduce energy losses.

The BMS could also be utilised for an energy trading function, where excess energy is sold back to the grid or energy is purchased at a lower price and sold at a higher price. However, this functionality is outside the scope of the current project.

4.3 BESS Size Requirement Specification

To specify the BESS capacity, (G. Lacey et al., 2013) integration process was used to calculate the capacity required from the BESS, however the use of the BESS must be considered to maximise its cost effectiveness. A decision on the peaks to be shaved must be reached, to achieve this the peaks positions relative to PV generation and grid tariffs must be considered to maximise PV energy use and minimise the cost of energy bought in from the grid.

4.4 Energy Requirements for Milking

To calculate the energy required for milking, a MATLAB script was used to carry out integrations for the period at which milkings were carried out.

The bases of the MATLAB script (see appendix VIII) was the equation 4-1 which was proposed by G. Lacey et al. (2013) and Danish et al. (2020) Gan et al. (2025) use a variation of the same equation (equation 2-2) to determine the energy harvested by a BESS at a given time, this could also be used to calculate the capacity of the BESS by changing the time at which the integration begins. Gan et al. (2025) states that the peak to be shaved should be based on the difference between the peak power and baseload power. For the purpose of this model, the baseload was set at zero as variable tariffs are used as opposed to tariffs which depend on usage, meaning it is desirable to shave the whole peak.

Equation 4-1 Basis of the MATLAB Script G. Lacey et al. (2013) and Danish et al. (2020) Gan et al. (2025)

$$B_{cap} = \int B_{pw} d\, t$$

B_{cap}= BESS capacity (Wh)

B_{pw} = Power (W) to be shaved

t= time (hrs)

The MATLAB script used performed three integrations at set time periods for each day, the script repeated the integration for each day and outputted the results into an Excel file. The MATLAB script utilised the trapeze function to determine the area of the milking peaks and thus the energy used. The times for each integration were based on the daily milking times provided by the Harper Adams Farm, an additional half hour was added to the start and end of the milking times to account for variations in start and end timings. The same script was used for both two and three daily milkings however for two daily milking the second milking (mid-day milking) was removed from the results. Initially the integration process was completed for EMD1 and EMD4, as from previous inspection clear peaks could be seen in these data sets. To provide a more complete view of the data a data set called EMD_{Sum} was produced, EMD_{Sum} was the combination of power draws from all EMD data files, this was done to gain an understanding of power usage across the dairy. EMD_{Sum} was also integrated using the same MATLAB script.

An additional MATLAB script (appendix IX) was used to graph the data, this was done to visualise the data and was used for checking results if unreasonable values where retuned by the original script, appendix X shows examples of these plots.

In some instances, the MATLAB script returned results that where unexpectedly low (0kWh used in a day) these were attributed to sensor dropouts and were removed from the data set. In other instances, unexpectedly high results were returned (over 1000 kWh used in a day) these readings were attributed to sensor errors and were also removed.

After removing incorrect data, the mean energy consumption per milking was calculated for both the 3-milking and 2-milking schedules across EMD1, EMD4, and EMD_{Sum}. The results are presented in Table 4-1, Appendix XI shows an example of the results of EMD4.

Table 4-1 Mean Milking Energy Consumption

	Mean Energy Consumption (kWh)				
	Two Milkings		Three Milkings		
	Milking One 04:00 - 07:00	Milking Two 14:30 - 17:00	Milking One 04:00 - 07:00	Milking Two 12:00 - 15:00	Milking Three 20:00 - 22:30
EMD1	34.9	31.7	27.5	26.8	22.4
EMD4	18.9	8.2	21.2	10.1	13.7
EMD_{Sum}	78.1	60.6	78.4	65.9	59.3

There are several options for specifying the capacity of the BESS. It can be designed for either two or three milkings per day, and for a single milking or multiple milkings. Additionally, a choice must be made between using data from EMD1, EMD4, or EMD_{Sum}. The decision was made to base the BESS specification on EMD_{Sum} data, as it provides the most comprehensive representation of energy use on the dairy. To accommodate dairies that operate with different milking schedules, the report will specify BESSs for both two and three daily milkings. To determine which sessions the BESS should target, a comparison of dairy power consumption, PV power generation, and energy tariffs is necessary.

4.5 Comparison of Dairy Power Consumption, PV Power Generation and Energy Tariffs.

4.5.1 Two Milkings PV Generation and Energy Tariffs.

Figure 4-2 shows a comparison of average power generation from the PV arrays in May 2024 and the average price per unit from Octopus Energy in May 2025, with milking times shown as a shaded area. May was chosen for this as it represents a month with high solar generation, whilst June would likely be higher this was not feasible due to the time frame of completing the project.

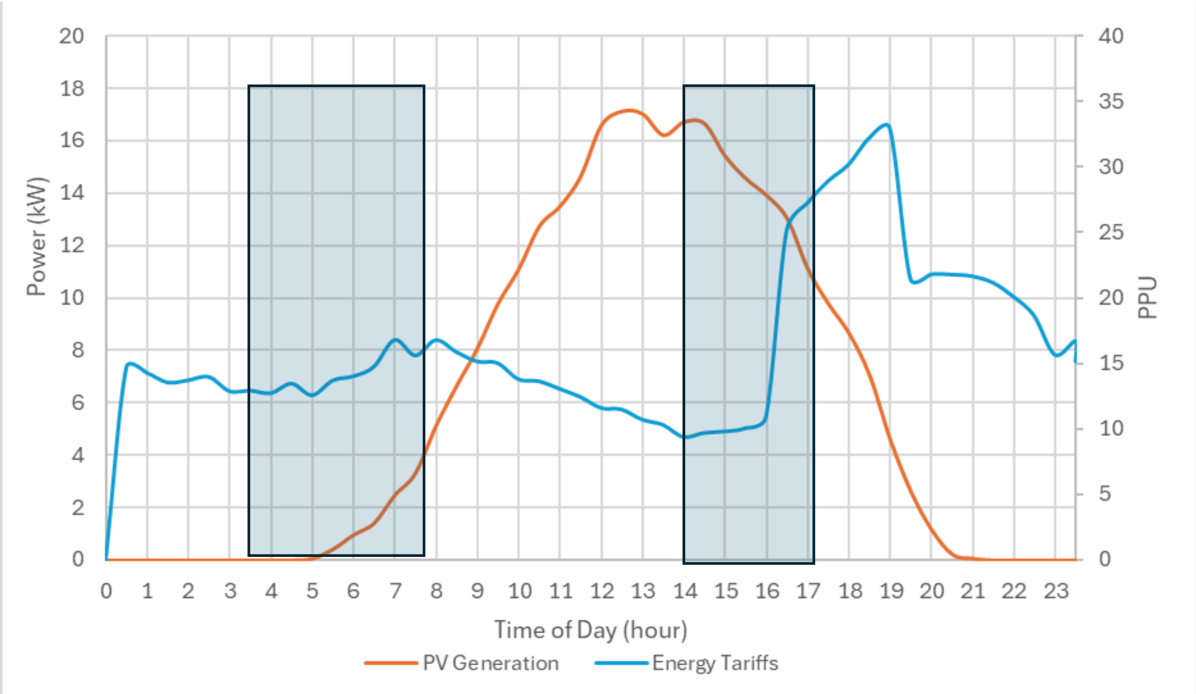

Figure 4-2 Comparison of PV generation in May and Energy Tariffs with Milking Times Shown in Shaded Regions for Two Daily Milkings

Figure 4-2 shows that the first milking takes place during a period of low energy tariffs with minimal solar generation. The second milking begins when tariffs are still low and solar generation is high but later shifts to a period of sharply increasing tariffs and reduced PV output. Since this data is from May, solar generation is near its annual peak.

Figure 4-3 shows the same data with the actual power use of for the 5th of May 2023 from the EMD1 board.

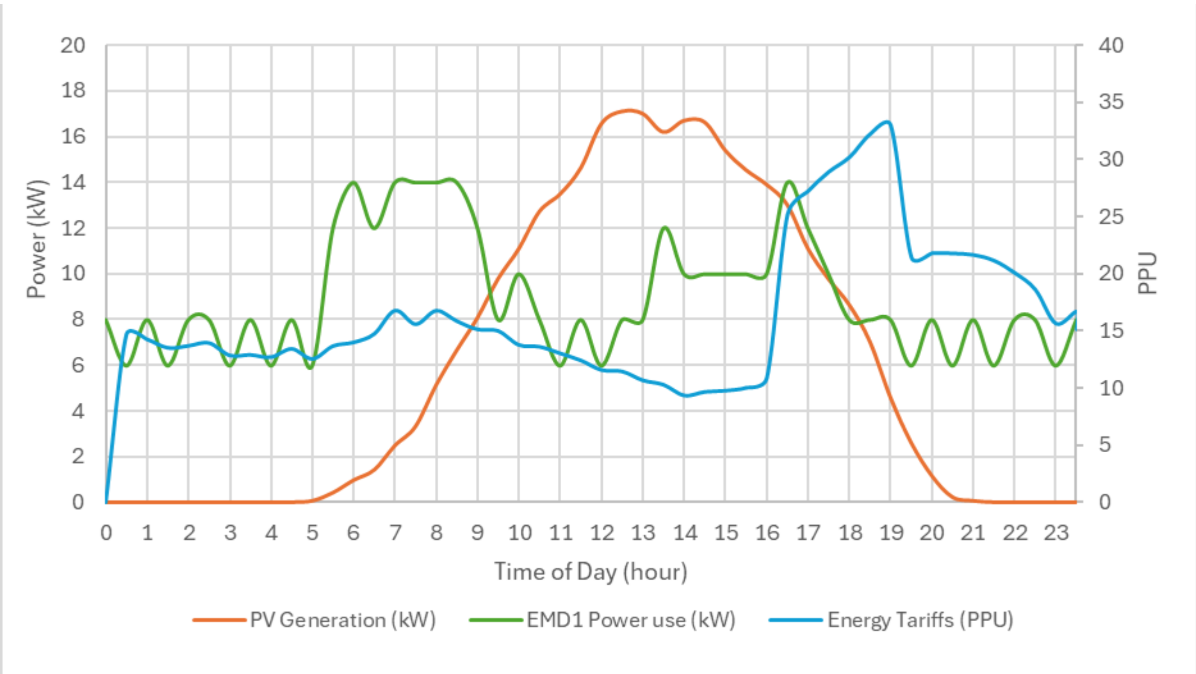

Figure 4-3 Comparison of PV Generation in May and Energy Tariffs with Actual Milking Power for Two Daily Milkings Shown

It should be noted that during shorter daylight periods, solar generation decreases and may fall outside the milking times, as illustrated in Figure 4-4.

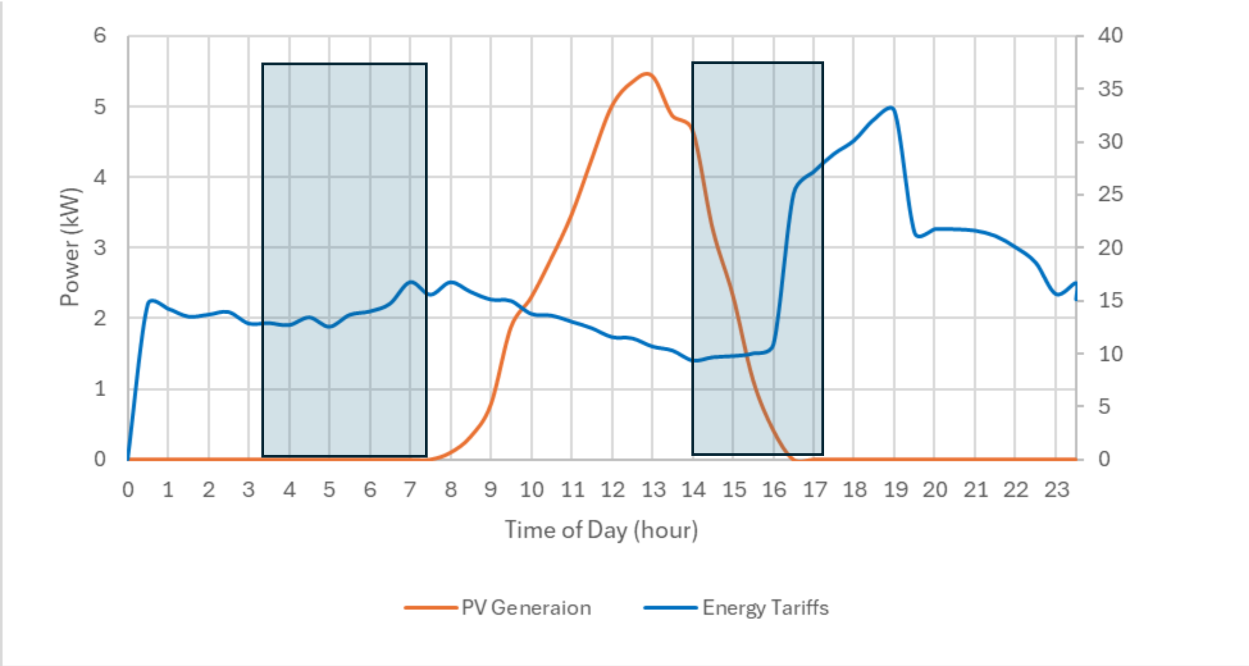

Figure 4-4 Comparison of PV Generation in January and Energy Tariffs with Milking Times for Two Daily Milkings Shown in Shaded Regions

Figure 4-4 shows that minimal PV power is available during milking in the winter months, making a BESS more critical in this period. It should be noted that energy tariffs in January may differ, but data for this is not available.

Based on this information, it was decided that for two milkings per day, the BESS should be sized to shave the peak during the second milking, as this period incurs higher energy tariffs. Additionally, this approach minimises energy losses by reducing the duration for which energy must be stored.

4.5.2 Three Milkings PV Generation and Tariffs

Figure 4-5 shows a comparison of an average day of PV generation in May2024 and an average day of energy tariffs from in May 2025 with three milkings shown.

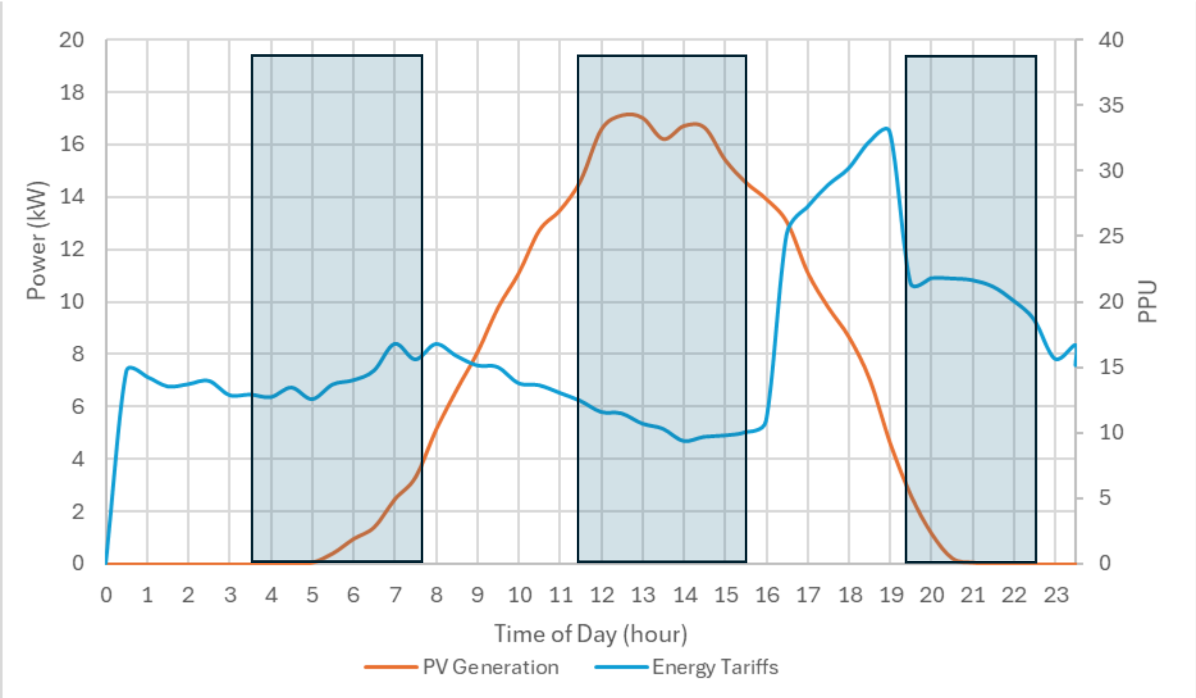

Figure 4-5 Comparison of PV Generation in May and Energy Tariffs with Milking Times for Three Daily Milkings Shown in Shaded Regions

Milking one occurs during a period of lower tariffs, so peak shaving would have minimal effect here. Milking two takes place during the lowest energy tariffs and peak PV generation, while milking three happens during relatively high tariffs and with no PV generation.

Figure 4-6 shows the same data with the actual power use of for the 1st of May 2024 from the EMD1 board.

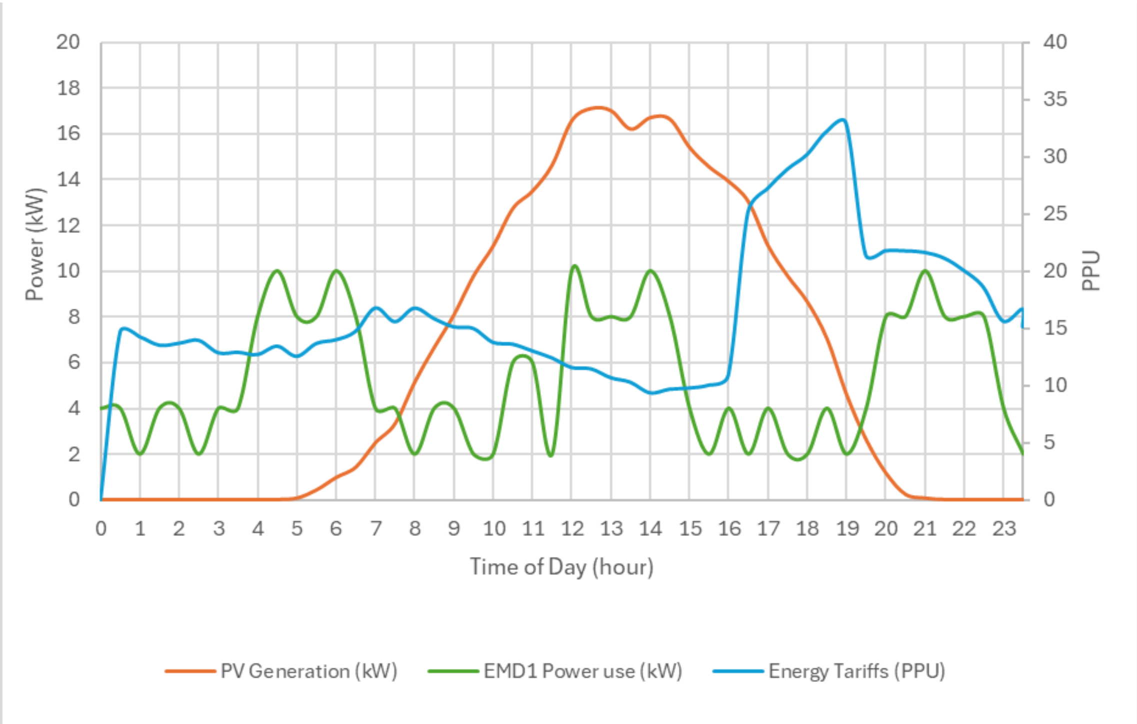

Figure 4-6 Comparison of PV Generation in May and Energy Tariffs Actual Milking Power for Three Daily Milkings Shown

Figure 4-7 compares PV energy production on an average day in January 2024 with average energy tariffs from May 2025. It should be noted that tariffs in January typically differ from those in May, however, data for January tariffs is not available.

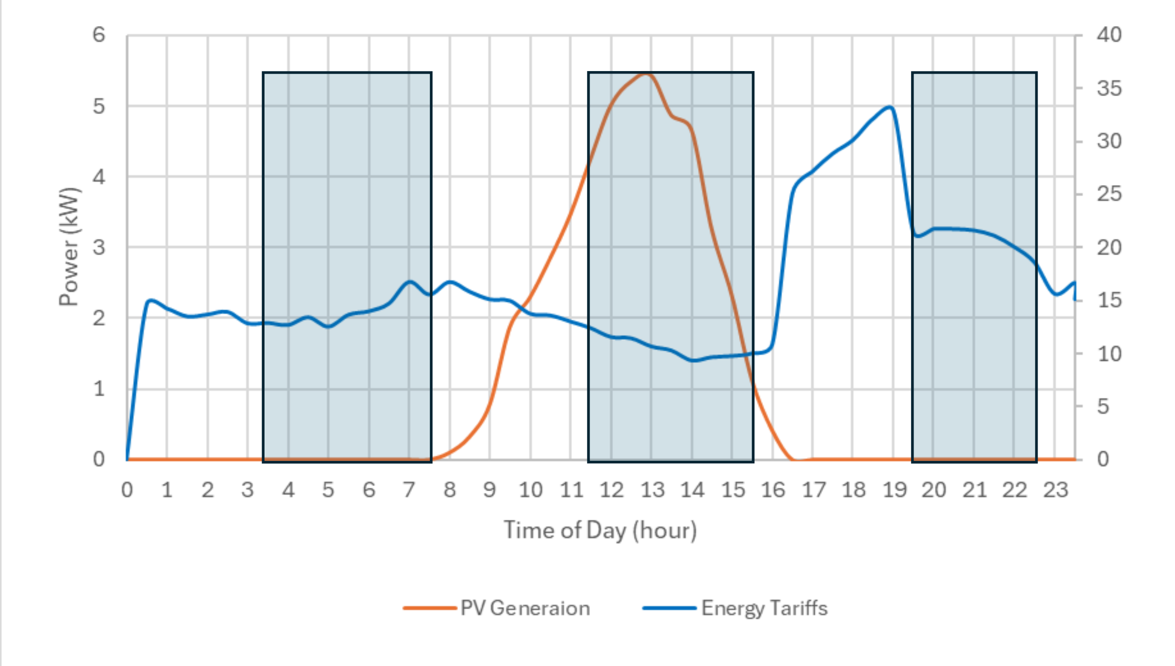

Figure 4-7 Comparison of PV Generation in January and Energy Tariffs with Milking Times for Three Daily Milkings Shown in Shaded Regions

Milking one occurs during a period of low energy tariffs, milking two during low tariffs with high PV production, and milking three when there is no PV production and higher energy tariffs. Based on this, the focus was placed on specifying the BESS for the third milking, since milking one and two both occur during low tariffs and, in the case of milking two, high PV generation. The BESS can charge either from the PV array or from mains electricity, depending on energy prices, while the alternative energy source meets base load demands and powers the second milking.

While the focus will be on specifying a BESS that discharges during the second milking for the two-milking scenario and during the third milking for the three-milking scenario, a BESS will also be specified for all milkings in both cases to allow a comparison of financial payback.

4.6 BESS Capacity

The BESS capacity should be based on the mean peak shaving values shown in Table 4-2. However, to account for instances requiring greater capacity, one, two, or three standard deviations can be added to the mean energy usage. This approach allows for varying levels of coverage depending on the number of standard deviations selected. Table 4-2 shows the percentage of data falling within each standard deviation range, assuming a normal distribution (Rumsey, 2023) .

Table 4-2 Standard Deviation Coverage (Rumsey, 2023)

Standard Deviation	% Coverage
1σ	68
2σ	95
3σ	99.7

It was decided to propose a solution using Mean+1σ and Mean+2σ, as using Mean+3σ would provide minimal benefit to the project whilst significantly increasing the cost of the project. This would provide sufficient energy to meet the demand of 68% and 95% of the daily milkings respectively.

4.6.1 Two Milkings

Table 4-3 presents the proposed BESS capacities for peak shaving during the second milking and for both milkings combined, with one and two standard deviations applied. These capacities represent the requirements at end of life, this capacity is required at end of life to ensure the system can function fully until its end of life.

Table 4-3 Required BESS Capacities for Two Daily Milkings

	Single Capacity (kWh)	All Milking Capacity (kWh)
Mean + 1σ	79.0	174
Mean + 2σ	97	209

4.6.2 Three Milkings

Table 4-4 shows the proposed capacities for BESS for peak shaving for the third milking of the day and all milkings combined, with one and two standard deviations applied.

Table 4-4 Required Capacities for Three Daily Milkings

	Single Capacity (kWh)	All Milking Capacity (kWh)
Mean + 1σ	70	246
Mean + 2σ	82	289

G. Lacey et al. (2013) states that the BESS should be specified for end of life, using the equation presented in Section 2.5 (Equation 2-4). This equation calculates the capacity required at the beginning of the batteries' first life, however, for this project the capacity for the beginning of the second life (80% of first life capacity) needs to be understood, this can be achieved by adapting the original equation and multiplying the equation by 80% to give the capacity at the beginning of the second life. This adaptation gave equation 4-2, which was used to calculate the required capacity for the BESS.

Equation 4-2 Adapted Version of G. Lacey et al. (2013) Equation for Use in the Project

$$B_{capINS} = \frac{\frac{B_{capEOL}}{0.5}}{0.8} \times 0.8 = \frac{B_{capEOL}}{0.5}$$

B_{capEOL} = BESS capacity at end of life

B_{capINS} = BESS capacity at installation (second life)

The results of this are shown in table 4-5.

Table 4-5 Energy Requirement

		Milking Two (kWh)	Total Milking (kWh)
Two Milking	Mean + 1σ	158	347
	Mean + 2σ	195	417
Three Milkings	Mean + 1σ	141	492
	Mean + 2σ	163	577

4.7 BESS Discharge Requirements

To determine the BESS discharge requirements, a similar process to that used for energy was followed. The average power demand and standard deviation for each milking were calculated using a MATLAB script. The results are presented in Table 4-6, (see appendix XII for more detail)

Table 4-6 Proposed Power Requirements for Each Option.

	Two Milkings (kW)		Three Milkings (kW)	
	Single Milking	All Milkings	Single Milking	All Milkings
Mean + 1σ	22.31	45.75	19.67	63.33
Mean + 2σ	27.41	54.93	22.83	74.49

4.8 Electric Vehicle Battery Selection

4.8.1 Battery Selection

As noted in Chapter 2, there are several options for second-life EV batteries, Table 4-7 shows the two cheapest options

Table 4-7 Second Life EV Batteries (2025) Green Tec (2025) Cost-Effective Option

Brand	£/kWh
Tesla	70.35
Nissan	40.84

Although the Nissan batteries are cheaper per kWh, approximately 100 units would be needed to match the capacity of five Tesla units, this would make them impractical for this solution and greatly increase the cost of installation. Therefore, Tesla batteries were chosen for this project, as the smaller number of cells required is expected to reduce installation costs.

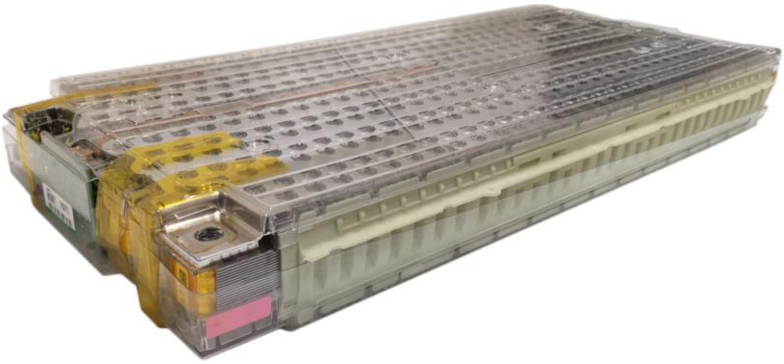

Figure 4-8 Tesla Battery Second Life EV Batteries (2025)

Figure 4-8 shows the Tesla battery to be used in the model.

4.9 Battery Cost Calculation

To calculate the required number of units, the capacity of a single unit was first determined. The total required capacity was then divided by the single unit capacity, and the result was rounded up to the nearest whole number. The required number of units is shown in Table 4-8.

Table 4-8 Number of Tesla's Unites Required for Each Solution

Number of units required rounded			
Two milkings		Three Milkings	
Single Milking	Total Milking	Single Milking	Total Milking
31	67	28	95
38	81	32	112

To Estimate the battery costs, the price of the five-unit system from Second Life EV batteries (2025) was divided by five to determine the cost per unit, assuming that bulk orders would receive the same unit price. This unit cost was then multiplied by the required number of units to calculate the total battery cost, as shown in Table 4-9.

Table 4-9 Battery Cost

Battery cost			
Two Milkings		Three Milkings	
Single Milking	Total Milkings	Single Milking	Total Milkings
£11,339.80	£24,508.60	£10,242.40	£34,751.00
£13,900.40	£29,629.80	£11,705.60	£40,969.60

4.9.1 Additional BESS Costs

The most capable BMS option, as outlined in Chapter 2 was selected at a cost of £1,111(Sunshine Solar, 2025). To estimate the installation and maintenance costs of the BESS, values provided by Exencell (2024) were used. These are detailed in Table 4-10.

Table 4-10 Installation Costs Exencell (2024)

	$/kWh	£/kWh
Installation	50-100	37.22-74.45
Upkeep	50-100	37.22-74.46

It was assumed that the higher end of the estimated cost range would be most appropriate for this project. This value was then used to estimate the installation and maintenance costs of the batteries, as shown in Table 4-11.

Table 4-11 Estimated Installation Costs

	Estimated Cost of Installation			
	Two Milking		Three Milkings	
	Milking Two	Total Milking	Milking Three	Total Milking
Mean + 1σ	£11,756.26	£25,867.81	£10,478.85	£36,645.86
Mean + 2σ	£14,491.10	£31,080.87	£12,135.05	£42,982.28

The same process was used to estimate the ten-year upkeep cost of the BESS, as shown in Table 4-12.

Table 4-12 Estimated Maltenes Costs Over Ten Years

	Estimated Cost of Upkeep Over 10 Years (£)			
	Two Milkings		Three Milkings	
	Milking Two	All Milkings	Milking Three	All Milkings
Mean + 1σ	£11,756.26	£25,867.81	£10,478.85	£36,645.86
Mean + 2σ	£14,491.10	£31,080.87	£12,135.05	£42,982.28

It is also assumed that additional storage would be required to house the BESS, this is often achieved using a shipping container, a suitable shipping container could cost £1,645 (Portable Space, 2025). This cost was added to the installation cost the total installation cost as shown in table 4-13.

Table 4-13 Total Estimated Cost of Installation

	Total Estimated Cost of Installation			
	Two Milkings		Three Milkings	
	Milking Two	All Milkings	Milking Three	All Milkings
Mean + 1σ	£13,401.26	£27,512.81	£12,123.85	£38,290.86
Mean + 2σ	£16,136.10	£32,725.87	£13,780.05	£44,627.28

4.10 BESS Specification Conclusion

The aim of this section was to determine the specification of a BESS for use at the HAD, using the method proposed by G. Lacey et al. (2013), Danish et al. (2020) and Gan et al. (2025). A range of BESS specifications was developed to assess financial viability. The resulting specifications and associated costs are presented in Tables 4-14 – 4-21. These specifications will form the basis for the simulations conducted in Section five.

Table 4-14 Single Milking 1σ Specification and Cost

Single Milking 1σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries (£)	Cost of Installation (£)	Cost of Upkeep for 10 years (£)	BMS Cost (£)	Total Cost (£)
157.91	22.31	31	11,339.80	13,401.26	11,756.26	1,111.00	37,608

Table 4-15 Single Milking 2σ Specification and Cost

Single Milking 2σ specification and cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries (£)	Cost of Installation (£)	Cost of Upkeep for 10 years (£)	BMS Cost (£)	Total Cost (£)
194.64	27.41	38	13,900.40	16,136.10	14,491.10	1,111.00	45,638

Table 4-16 Total Milking 1σ Specification and Cost

Total Milking 1σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries	Cost of Installation	Cost of Upkeep 10 year (£)	BMS Cost (£)	Total Cost (£)
173.73	45.75	67.00	24,508.60	27,512.81	25,867.81	1,111.00	79,000

Table 4-17 Total Milking 2σ Specification and Cost

Total Milking 2σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries	Cost of Installation (£)	Cost of Upkeep 10 year (£)	BMS Cost (£)	Total Cost (£)
417.47	54.93	81.00	29,629.80	32,725.87	31,080.87	1,111.00	94,547

Table 4-18 Single Milking 1σ Specification and Cost

Single Milking 1σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries	Cost of Installation (£)	Cost of Upkeep 10 Year (£)	BMS Cost (£)	Total Cost (£)
70.38	19.67	28	10,242	12,123	10,478	1,111	33,956

Table 4-19 Single Milking 2σ Specification and Cost

Single Milking 2σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries	Cost of Installation (£)	Cost of Upkeep 10 Year (£)	BMS Cost (£)	Total Cost (£)
81.50	22.83	32	11,705	13,780	12,135	1,111	38,731

Table 4-20 Total Milking 1σ Specification and Cost

Total Milking 1σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries (£)	Cost of Installation (£)	Cost of Upkeep 10 Year (£)	BMS Cost (£)	Total Cost (£)
246.11	63	95	34,751	38,290	36,645	1,111	110,798

Table 4-21 Total Milking 2σ Specification and Cost

Total Milking 2σ Specification and Cost							
Capacity (kWh)	Power (kW)	Number of Units	Cost of Batteries (£)	Cost of Installation (£)	Cost of Upkeep 10 Year (£)	BMS Cost (£)	Total Cost (£)
288.67	74.49	112	40,969	44,627	42,982	1,111	129,690

Chapter 5 Cost Estimation

5.1 BESS Simulation/Proof of Concept Introduction

This section is based on the fundamentals proposed by Mislick & Nussbaum (2015) and (Lanen et al., 2014) to evaluate the eight BESS specifications proposed in the previous section and determine which offers the most cost-effective solution for the Harper Adams Dairy. Mislick & Nussbaum (2015) state that cost estimating should be based on the analysis of historical data and the application of quantitative models to estimate project costs, this process produces an approximation of the project's probable value. cost estimation should be based on available information, applying engineering principles, techniques, and judgment to produce a reliable estimate Lanen et al. (2014).

Due to the HAD being a part of the wider HAU campus and not using variable tariffs, the energy production and consumption data was used to model a BESS for a hypothetical dairy which would use PV arrays for energy generation as well as paying for energy on a variable tariff.

Cost Estimation was chosen as the most suitable Method for determining the viability of the BESS as Chetroiu et al. (2022) states that the economic sustainability of a dairy is measured by its net profit; therefore, for a BESS to be considered viable, it must not negatively impact the dairy's profit margin. If the BESS can reduce the dairy's energy costs, it would contribute to both improved economic sustainability and enhanced environmental performance.

5.2 Current State

To determine the payback period for each solution, the current cost of energy was first calculated. This was done using the combined energy consumption data for the dairy, with monthly totals computed and the energy tariffs (Appendix VII) applied. Tariffs from 2024 were used for both the two and three-milking scenarios to allow for a fairer comparison and to account for the unusually high energy prices observed in 2023. The resulting total annual energy cost is shown in Table 5-1.

Table 5-1 Harper Adams Dairy Yerly Energy Cost

	Two Daily Milkings	Three Daily Milkings
Yearly Energy Cost	£25,160.99	£32,570.48

This information will be used to estimate the potential savings for each solution, enabling the calculation of payback time and identification of the most cost-effective option for each milking scenario.

5.3 Modelling

5.3.1 Tariffs

To estimate the savings from each proposed BESS installation, Octopus Agile Energy tariffs were used (Chung, 2025) An average day of tariffs was applied in the model (see appendix XIII for applied average day). While these tariffs change daily, a full year of data was not available; therefore, using an average day was considered the most accurate and practical approach.

5.3.2 PV Array Use

To calculate the savings for each solution, it was assumed that the BESS would be charged entirely by the PV arrays, and that the PV system would generate sufficient energy to fully meet the BESS charging requirements, this would be managed by the BMS.

This assumption is based on the PV energy generation values obtained during the energy audit. In the audit, data was collected for the four dairy PV arrays, average yearly and December generation is shown in Table 5-2

Table 5-2 Average PV Generation

	Smart Dairy PV Array	Young Stock PV Array	PV1	PV2	Total
Average daily generation	337.45	450.39	70.97	65.74	924.55
Average daily generation in December	51.68	68.68	10.36	1.97	132.69

The average daily photovoltaic (PV) generation is sufficient to meet the energy requirements of all proposed solutions. However, during December, when PV generation is at its lowest and consumption at its highest, only the solutions designed to support a single milking session per day are fully met. For scenarios involving multiple daily milkings, the use of grid energy in addition to the BESS would likely be necessary for a small portion of the year. While this assumption may reduce the overall effectiveness of the model for solutions targeting multiple milkings, these cases are included primarily for comparative purposes and are not the central focus of the study. Therefore, this limitation is considered acceptable.

5.3.3 BESS Discharge

To simulate BESS discharge during milkings for each proposed solution, the energy tariff during these periods was set to zero, reflecting the energy offset provided by the BESS. This accounts for the varying coverage levels of each specification, based on the use of one or two standard deviations. Coverage percentages, 68% for one standard deviation and 95% for two were used to estimate the number of days each solution would fully cover. These percentages were multiplied by the number of days in a year, and the result subtracted from 365 to determine the number of uncovered days.

Since values outside the coverage range can fall both above and below the expected demand, and lower-than-average demand days would still be adequately covered, only one tail of the standard deviation distribution was considered. This approach was deemed to provide a more accurate representation of BESS performance. As a result, the number of uncovered days was halved, leading to an estimated 55 uncovered days for the one standard deviation solution and 9 for the two standard deviation solution.

It was assumed that on these uncovered days, energy would be paid for at the full tariff rate from the grid. This represents a conservative, worst-case scenario, as the BESS would still likely supply a significant portion of the required energy. Based on this approach, the estimated annual energy spending for each solution is shown in Table 5-3.

Table 5-3 Yearly Energy Cost with BESS Implemented and Using Variable Tariffs

	Solution	Yearly Energy Cost
Two Daily Milkings	One	£15,678.34
	Two	£15,389.23
	Three	£12,464.63
	Four	£11,407.17
Three Daily Milkings	Five	£17,691.74
	Six	£16,902.37
	Seven	£12,239.61
	Eight	£10,217.82

Using these results, the payback period and savings for each solution can be estimated. To do this, the expected lifetime of the BESS must be defined. Cusenza et al. (2019) suggest that an ex-EV battery repurposed for BESS use could have a lifespan of 12 years, while F. Marra et al. (2010) estimate a lifespan of approximately four and a half years. However, discussions with industry professionals suggest that a typical BESS system lasts around 11 years however this may differ for a BESS using ex electric vehicle batteries due to the different discharge method of their first life (Fox, 2025).

Payback time and savings were calculated based on both estimated lifespans. The cost of upkeep was adjusted accordingly, depending on the assumed lifetime of each solution. Table 5-4 presents the annual savings, payback period, and total lifetime savings for each solution, assuming a BESS lifespan of four and a half years as suggested by (F. Marra et al., 2010).

Table 5-4 Yearly Saving for a Four and a Half year BESS Lifetime

		Yearly Saving	Payback Time (Years)	Lifetime Saving
Two Daily Milkings	**Single Milking + 1σ**	**£9,482.65**	**3.3**	**£11,529.55**
	Single Milking + 2σ	£9,771.76	3.9	£6,304.44
	Both Milking + 1σ	£12,696.36	5.1	-£7,639.31
	Both Milking + 2σ	£13,753.82	5.6	-£15,560.86
Three Daily Milkings	**Single Milking + 1σ**	**£14,878.75**	**1.9**	**£38,761.62**
	Single Milking + 2σ	£15,668.12	2.0	£38,449.10
	Three Milkings + 1σ	£20,330.87	4.5	£845.42
	Three Milkings + 2σ	£22,352.66	4.7	-£5,462.92

For a dairy operating with two daily milkings and assuming a BESS lifespan of four and a half years, the most cost-effective solution is a BESS specified to cover the afternoon milking plus one standard deviation. For a farm with three daily milkings, the most cost-effective option is a BESS sized to cover the evening milking plus one standard deviation. Usings the shorter lifetime some solutions would be installed at a loss due to their high upfront costs.

Table 5-5 presents the annual savings, payback period, and total lifetime savings for each solution, assuming a BESS lifespan of ten years whilst (Fox, 2025) states an 11-year lifespan is typical for a Battery Energy Storage System (BESS) with new batteries. However, a ten-year lifespan has been selected for this model to provide a more conservative estimate due to uncertainty regarding actual lifespan. Additionally, warranties for BESS are typically offered for ten years, making this assumption more appropriate for use in the model.

Table 5-5 Yearly Saving for a Ten-Year BESS Lifetime

		Yearly Saving	Payback Time (Years)	Lifetime Saving
Two Daily Milkings	**Single Milking + 1σ**	**£9,482**	**4.0**	**£57,218**
	Single Milking + 2σ	£9,771	4.7	£52,079
	Both Milking + 1σ	£12,696	6.2	£47,963
	Both Milking + 2σ	£13,753	6.9	£42,990
Three Daily Milkings	Single Milking + 1σ	£14,878	2.3	£114,831
	Single Milking + 2σ	**£15,668**	**2.5**	**£117,94**
	Three Milkings + 1σ	£20,330	5.4	£92,509
	Three Milkings + 2σ	£22,352	5.8	£93,836

For a dairy operating with two daily milkings and assuming a BESS lifespan of ten years, the most cost-effective solution is a system specified to cover the afternoon milking plus one standard deviation. For a farm with three daily milkings, the most cost-effective option is a BESS sized to cover the evening milking plus two standard deviations. Due to the longer lifetime all solutions would now be profitable.

Table 5-6 presents the annual savings, payback period, and total lifetime savings for each solution, assuming a BESS lifespan of 12 years as suggested by Cusenza et al. (2019).

Table 5-6 Yearly Saving for a 12 BESS Lifetime

		Yearly Saving	Payback Time (Years)	Lifetime Saving
Two Daily Milkings	**Single Milking + 1σ**	**£9,482**	**4.2**	**£73,832**
	Single Milking + 2σ	£9,771	5.0	£68,724
	Both Milking + 1σ	£12,696	6.6	£68,182
	Both Milking + 2σ	£13,753	7.3	£64,282
Three Daily Milkings	Single Milking + 1σ	£14,878	2.4	£142,493
	Single Milking + 2σ	**£15,668**	**2.6**	**£146,858**
	Three Milkings + 1σ	£20,330	5.8	£125,842
	Three Milkings + 2σ	£22,352	6.2	£129,94

For a dairy operating with two daily milkings and assuming a BESS lifespan of 12 years, the most cost-effective solution is a system specified to cover the afternoon milkings plus one standard deviation. For a farm with three daily milkings, the most cost-effective option is a BESS sized to cover the evening milking plus two standard deviations.

A longer BESS lifespan allows for a higher initial investment to be justified, leading to a greater return on investment. Additionally, it helps offset the greenhouse gas (GHG) emissions associated with battery production, thereby improving the environmental sustainability of the solution.

5.3.4 Comparison of Ex-Electric Vehicle Batteries with New Batteries

To determine whether the use of ex-Electric vehicle batteries provides a more cost-effective BESS than a new BESS, an off the shelf solution was also simulated to determine the payback time and lifetime saving for this solution. This was done using a 16kWh solution provided by Heatable (2025a), this solution costs £7,795.

For the model it was assumed the price of the system covered all maintenance and installation costs, table 5-7 shows the payback time and lifetime saving for each solution using this off the shelf solution for a ten-year lifetime.

Table 5-7 Yearly Saving for a Ten-Year BESS Lifetime Using an off the Shelf Solution

		Yearly Energy Cost	Yearly Saving	Payback Time (years)	Lifetime Gain
Two Daily Milkings	**Single Milking + 1σ**	**£15,678**	**£9,482**	**6.6**	**£16,876**
	Single Milking + 2σ	£15,389	£9,771	8.0	-£3,617
	Both Milking + 1σ	£12,464	£12,696	10.4	-£44,526
	Both Milking + 2σ	£11,407	£13,753	11.9	-£72,926
Three Daily Milkings	**Single Milking + 1σ**	**£17,691**	**£14,878.75**	**3.7**	**£78,632**
	Single Milking + 2σ	£16,902	£15,668.12	4.0	£70,936
	Three Milkings + 1σ	£12,239	£20,330.87	9.6	-£38,336
	Three Milkings + 2σ	£10,217	£22,352.66	10.1	-£64,888

A ten-year lifetime was chosen, as this is the duration for which a warranty is typically provided. The analysis shows that the off-the-shelf solution is considerably more expensive, reducing the payback period and, in most cases, resulting in the system being installed at a financial loss.

5.4 Simulation/ Proof of Concept Conclusions

The aim of this section was to identify the most cost-effective BESS capacity for installation at Harper Adams Dairy, considering scenarios with both two and three daily milkings. This was achieved through the development of a model that estimates the payback time and total lifetime savings for each solution, based on the assumed BESS lifespan. The model enabled selection of the optimal solution depending on the number of milkings and the projected battery lifespan. Tables 5-8 and 5-9 present the most cost-effective option for each use case and assumed lifespan, as suggested in the literature. The model of the new system also shows that the use of ex-EV batteries provides a cost-effective solution helping to overcome the barriers to the use of BESS.

Table 5-8 Most Cost-Effective Options for Two Daily Milkings Depending on BESS Life

BESS Lifetime	Solution	Yearly Saving	Payback Time (Years)	Lifetime Gain
4.5	Single Milking + 1σ	£9,482.65	3.3	£11,529.55
10	Single Milking + 1σ	£9,482.65	4.0	£57,218.19
12	Single Milking + 1σ	£13,753.82	4.2	£73,832.24

Table 5-9 Most Cost-Effective Options for Three Daily Milkings Depending on BESS Life

BESS Lifetime	Solution	Yearly Saving	Payback Time (Years)	Lifetime Gain
4.5	Single Milking + 1σ	£14,878.75	1.9	£38,761.62
10	Single Milking + 2σ	£15,668.12	2.5	£117,949.46
12	Single Milking + 2σ	£15,668.12	2.6	£146,858.68

Whilst a BESS using ex-EV batteries would provide a cost-effective solution over its lifetime, it has a high startup cost with solution ranging from £37,000 to £129,000. These high startup cost may pose a significant barrier to the uptake of this system as smaller farms may not be able to afford the initial cost.

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Chapter 6 Conclusions

6.1 Project Aims and How They Were Met

The primary aim of this project was to determine whether a Battery Energy Storage System (BESS) which uses ex-electric vehicle (EV) batteries could provide a cost-effective solution to dairy farms, whilst providing a second life to ex-EV batteries further offsetting the environmental impact of their manufacturing. It was found that a BESS using ex-EV batteries could provide a cost-effective solution to a dairy farm, with savings between £11,529 to £73,832 over the system's lifetime being predicted depending on the BESS use and the operation of the dairy. This shows that BESS provide a viable option for the second life of an ex-EV battery.

6.2 Objectives

The objectives of the project were reached by, first conducting an information search and review to determine an appropriate methodology for the energy audit and to build a solid theoretical basis for the model used to assess the financial viability of the proposed BESS. Informing other aspects of the report and justifying the need for the project.

From the information search and review, the methodology proposed by Kluczek & Olszewski (2017) was selected to guide the energy audit. This process also established the theoretical foundation for the model used to assess the financial viability of the proposed solution. The methodology from G. Lacey et al. (2013), Danish et al. (2020) and Gan et al. (2025) was used to determine the appropriate BESS capacity for peak shaving.

Based on the energy audit, the dairy was identified as the most suitable location for a BESS to peak shave during milkings. Data from the audit (2.2 million values), along with literature gathered during the information search and review, was used to specify a BESS utilising second-life electric vehicle batteries.

The specified BESS, energy consumption data from the Harper Adams dairy, and data on variable tariffs were used to build a model to assess its cost-effectiveness.

While this analysis uses data from the Harper Adams dairy, the model represents an independent energy consumer using variable energy tariffs. The results indicate that a dairy could achieve savings ranging from £11,529 to £73,832, depending on the BESS lifespan and the milking schedule. This suggests that second-life electric vehicle batteries used in BESS applications can offer a cost-effective solution for farmers, reducing energy costs and delivering substantial savings over the system's lifetime. Moreover, this approach provides a viable second life for Electric Vehicle batteries, enhancing their environmental value and supporting broader climate change mitigation efforts.

6.3 Research Questions

Can a BESS using ex-electric Vehicle batteries, provide a cost-effective solution to dairy?

The answer to the research question is yes, a BESS using ex-electric vehicle batteries can provide a cost-effective solution to a dairy.

6.4 Future Work

Future research could provide greater understanding of the expected lifetime of the BESS, and as these systems age more data will become available. Methods to overcome the initial cost of the system need consideration to enable the uptake of such solution on farms, but this was outside the scope of this engineering project. Adjustments to milking times to align with optimal energy tariffs could also be considered.

This project has focused on the Harper Adams Dairy energy requirements; To determine whether a BESS is beneficial to Harper Adams University, further investigation could examine the entire campus energy production and consumption.

6.5 Final Statement

This project has shown that utilising ex-electric vehicle batteries in a Battery Energy Storage System can be a cost-effective solution for a dairy farm with photovoltaic energy generation. This solution can provide a viable second life to electric vehicle batteries, helping in the fight against climate change.

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Appendices

Appendix I BESS Scenarios

6. **Stand-alone PV Array:** User consumes generated electricity first; excess is sold to the grid.
7. **Peer-to-Grid (P2G) ID User-Owned (UO) BESS:** User consumes electricity first, then stores excess in BESS before selling to the grid.
8. **Peer-to-Peer (P2P) IDUO BESS:** Electricity is self-consumed, then sold to peers; leftover is stored in BESS and sold to the grid.
9. **P2P Shared-Design (SD) UO BESS:** Stored energy is used during peak demand, then sold to peers.
10. **ESS SD Developer-Owned (DO) BESS:** Installed in microgrid; electricity is self-consumed, sold to peers, with remaining stored in BESS and sold to grid.

(Zhang et al., 2024)

Appendix II BESS Safety Considerations

Advancements in BESS technology have improved energy density, safety, and lifespan. However, lithium-ion batteries still pose a TR risk, with temperatures potentially reaching 800–1000 °C (Close et al., 2024).

In 2019, the McMicken BESS rented by Arizona Public Service experienced a thermal event and explosion. Initially reported as a fire, firefighters investigating the site were injured hours later when an explosion destroyed the facility. The incident was caused by cascading thermal runaway (TR) initiated by an internal cell failure. Although the clean agent fire suppression system activated and functioned as designed, it could not stop TR. Inadequate thermal barriers between cells and modules allowed TR to spread, releasing flammable gases. When firefighters opened the BESS door, the gases ignited upon contact with a heat source (DNV GL - Energy, 2020).

The DNV GL - Energy (2020) report found five main factors which led to the explosion:

- Internal failure in cell resulting in TR
- Fire suppression system was not capable of stopping TR
- Lack of thermal barriers between cells allowed cascading TR
- Lack of ventilation led to a concentration of flammable gasses
- Emergency plan did not have an extinguishing, ventilation and entry plan

Figure I shows the events which led up the explosion, table i shows the barriers which could have prevented an explosion.

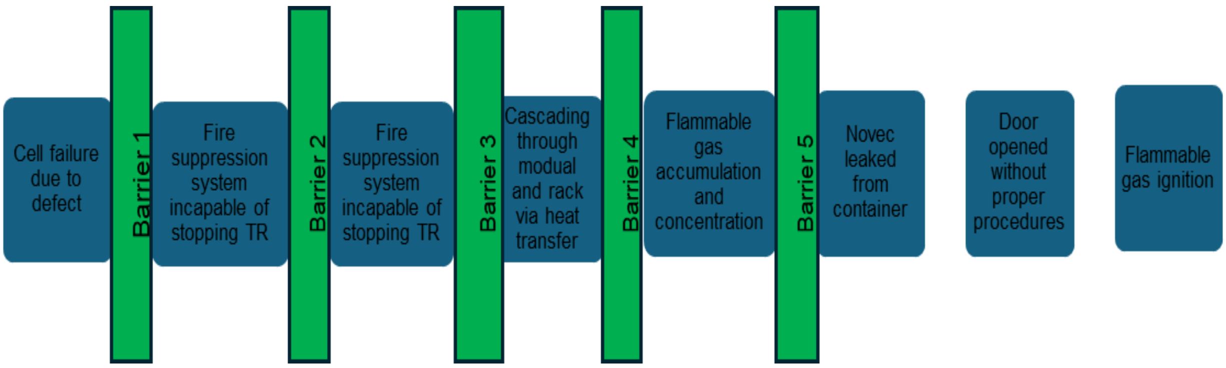


Figure I

Table I

Barrier	Method
1	Limit cell cascading.
2	Limit Module cascading.
3	Limit Module cascading.
4	Monitor and ventilate in a controlled manner.

5	Emergency response procedures and training for entry.

TR poses the most severe risk in BESS systems, and prevention efforts should focus on mitigating it. The Battery Management System (BMS) is the first line of defence, monitoring battery modules and disconnecting them during abnormal conditions. However, the BMS cannot prevent TR caused by internal cell failures or if it becomes damaged. In the event of fire, water is the preferred suppression method—it cannot stop TR once underway but can help contain its spread. To prevent explosions, a mechanical exhaust ventilation system should be used to extract flammable gases and provide dilution air upon detection (Conzen et al., 2023).

If a BESS is operated, the operator has a legal responsibility to comply to health and safety legislation, including:

- Health and Safety at Work Act
- Dangerous Substances and Explosive Atmospheres Regulations
- Electricity at work regulation
- Management of Health and Safety at Work Regulations
- Construction Design and Management Regulations
- Dangerous Substances (Notification and Marking of Sites) Regulations

(Health and Safety Executive, 2025)

Dangerous substances are materials present in the workplace that can cause harm through fire, explosion, or metal corrosion if not properly controlled. Employers must implement measures to eliminate or manage these risks. Areas with a potential for explosive atmospheres should be clearly identified, and all possible ignition sources must be avoided in these zones (Health and Safety Executive, 2002). Operators should take technical measures in accordance with the following basic principles:

- Prevent the formation of explosive atmospheres where possible.
- Avoid ignition sources in areas where explosive atmospheres may occur.
- Mitigate the harmful effects of explosions to protect workers' health and safety.

If necessary, these measures should be combined or supplemented with measures against the propagation of explosions (European Communities, 1999).

Appendix III EV Battery Recycling Alternatives

- **Physical Materials Separation** recycles batteries by using differences in particle size, density, magnetism, and hydrophobicity. Equipment like sieves, filters, magnets, shaker tables, and heavy media separate lithium-rich solutions, plastics, papers, magnetic materials, coated electrodes, and electrode powders(Harper et al., 2019).
- **Hydrometallurgical metals reclamation** uses aqueous solutions to leach metals from cathode materials. Organic solvents can then extract metals from the solution, followed by precipitation reactions to recover the metals (Harper et al., 2019).
- **Direct recycling** involves removing and reconditioning the anode and cathode from Li-ion batteries. Mixed metal-oxide cathodes can be reused, but lithium must be replaced due to degradation or incomplete discharge, leaving the cathode not fully lithiated (Harper et al., 2019).
- **Biological metals reclamation** uses bacteria to recover materials from Li-ion batteries. Microorganisms digest cathode metal oxides, producing metal nanoparticles. This is an emerging recycling technology (Harper et al., 2019).

Appendix IV Solar Panel Types

- Monocrystalline: Silicon wafers are cut from a single silicon crystal and assembled into rectangular arrays with electrical contacts. Photons release electrons in the silicon, generating electric current. Monocrystalline wafers have high efficiency due to their pure, uniform crystal structure, enabling better electron flow (CHINT, 2023).
- Polycrystalline: made by melting silicon fragments together, creating multiple crystals that give a blue hue. These wafers consist of photovoltaic cells with PN junctions that release electrons when struck by photons, generating electric current.(The Economic Times, 2019).
- Thin Film: Thin layers of photovoltaic material are placed on top of each other, the materials typically used for thin films are Amorphous Silicon, Cadmium Telluride, Copper Indium Gallium Selenide and Organic PV cells (Richardson, Janet & Burdett-Gardiner, 2024).
- Transparent: These panels absorb UV and infrared light whilst allowing visible light to pass through. Allowing the panels to be used when transparency is required such as windows (Lozanova, 2024).
- PERC: consists of modified silicon cells which use an additional reflective layer on the back of the panel to utilise unused light by sending the light across the n and p type junctions to increase energy generation (Aurora, 2024).
- Solar Tile: Thin-film solar cells are used to make panels which resemble roofing tiles (VR, 2022).
- Solar Thermal: The sun’s rays are used to heat a mixture of water and glycol, the heated water is then used for heating (Richardson & Burdett-Gardiner, 2024)

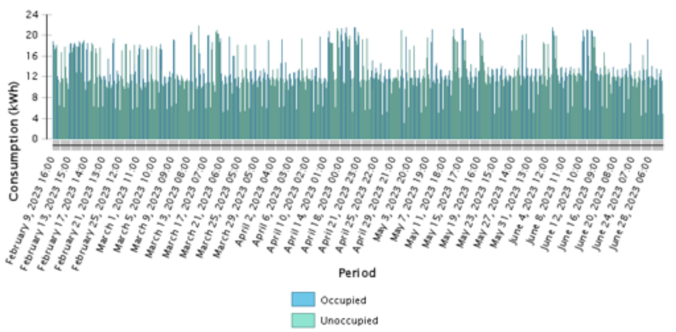
Appendix V   Raw Data Example

Delta CONTROLS
A Delta Group Company

2023_1

Date: March 14, 2025 14:33
Generated by: NMaddock@harper-adams.ac.uk

Consumption by Half Hour
January 1, 2023 to June 30, 2023
Occupied weekdays from 09:00 to 17:00



Meter		Total (kWh)	:cupied (kWh)	:cupied (kWh)	/lax Demand (kW)	Vin Demand (kW)	\vg Demand (kW)
February 9, 2023 11:30							
	B118 Dairy Research (Electric-FARM-NONRES) Dairy Research	13	13	0	30.63	20.00	25.31
February 9, 2023 12:00							
	B118 Dairy Research (Electric-FARM-NONRES) Dairy Research	19	19	0	39.06	36.41	37.74
February 9, 2023 12:30							
	B118 Dairy Research (Electric-FARM-NONRES) Dairy Research	19	19	0	37.50	37.34	37.42
February 9, 2023 13:00							
	B118 Dairy Research (Electric-FARM-NONRES) Dairy Research	18	18	0	36.72	36.25	36.49
February 9, 2023 13:30							
	B118 Dairy Research (Electric-FARM-NONRES) Dairy Research	18	18	0	37.50	35.94	36.72
February 9, 2023 14:00							
	B118 Dairy Research (Electric-FARM-NONRES) Dairy Research	18	18	0	36.56	34.84	35.70

Appendix VI Sample Data for EMD 4 (Split Over Two Tables)

ID	Mounth	Day	Year	Time	Meter
1	January	1	2023	00:00	Dairy 1 and 2 – PV Inverter 1
2	January	1	2023	01:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
3	January	1	2023	01:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
4	January	1	2023	02:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
5	January	1	2023	02:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
6	January	1	2023	03:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
7	January	1	2023	03:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
8	January	1	2023	04:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
9	January	1	2023	04:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
10	January	1	2023	05:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
11	January	1	2023	05:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
12	January	1	2023	06:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
13	January	1	2023	06:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
14	January	1	2023	07:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
15	January	1	2023	07:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
16	January	1	2023	08:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
17	January	1	2023	08:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
18	January	1	2023	09:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
19	January	1	2023	09:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
20	January	1	2023	10:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
21	January	1	2023	10:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
22	January	1	2023	11:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
23	January	1	2023	11:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
24	January	1	2023	12:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
25	January	1	2023	12:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
26	January	1	2023	13:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
27	January	1	2023	13:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
28	January	1	2023	14:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
29	January	1	2023	14:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
30	January	1	2023	15:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
31	January	1	2023	15:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
32	January	1	2023	16:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
33	January	1	2023	16:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
34	January	1	2023	17:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
35	January	1	2023	17:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
36	January	1	2023	18:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
37	January	1	2023	18:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
38	January	1	2023	19:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
39	January	1	2023	19:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
40	January	1	2023	20:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
41	January	1	2023	20:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
42	January	1	2023	21:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
43	January	1	2023	21:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
44	January	1	2023	22:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
45	January	1	2023	22:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3

46	January	1	2023	23:00	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3
47	January	1	2023	23:30	B118 Dairy Research (Electric-FARM-NONRES) :EMD-4 DB3

Total (kWh)	Occupied (kWh)	Unoccupied (kWh)	Max Demand (kW)	Min Demand (kW)	Avg Demand (kW)
0	0	0	0.00	0.00	0.00
0	0	0	0	0	0
1	0	1	4.00	0.00	2.00
0	0	0	0	0	0
0	0	0	0.00	0.00	0.00
1	0	1	4	0	2
2	0	2	8.00	0.00	4.00
2	0	2	4	4	4
3	0	3	8.00	4.00	6.00
2	0	2	4	4	4
3	0	3	8.00	4.00	6.00
2	0	2	4	4	4
3	0	3	8.00	4.00	6.00
2	0	2	4	4	4
3	0	3	8.00	4.00	6.00
2	0	2	4	4	4
3	0	3	8.00	4.00	6.00
2	0	2	4	4	4
0	0	0	0.00	0.00	0.00
1	0	1	4	0	2
0	0	0	0.00	0.00	0.00
1	0	1	4	0	2
1	0	1	4.00	0.00	2.00
0	0	0	0	0	0
1	0	1	4.00	0.00	2.00
0	0	0	0	0	0
1	0	1	4.00	0.00	2.00
0	0	0	0	0	0
1	0	1	4.00	0.00	2.00
2	0	2	8	0	4
2	0	2	4.00	4.00	4.00
3	0	3	8	4	6
2	0	2	4.00	4.00	4.00
3	0	3	8	4	6
2	0	2	4.00	4.00	4.00
3	0	3	8	4	6
2	0	2	4.00	4.00	4.00
3	0	3	8	4	6
2	0	2	4.00	4.00	4.00
3	0	3	8	4	6
1	0	1	4.00	0.00	2.00
0	0	0	0	0	0
1	0	1	4.00	0.00	2.00

0	0	0	0	0	0
1	0	1	4.00	0.00	2.00
0	0	0	0	0	0
1	0	1	4.00	0.00	2.00

Appendix VII Harper Current Energy Tariffs

Month	Tarif (£/kWh)	
	2023	2024
January	0.23	0.23
February	0.23	0.23
March	0.30	0.31
April	0.35	0.25
May	0.31	0.24
June	0.31	0.25
July	0.31	0.24
August	0.31	0.22
September	0.31	0.24
October	0.38	0.29
November	0.36	0.27
December	0.37	0.27

Appendix VIII MATLAB Code for Integration

```
% Script to integrate Power use data from dairy to determine energy
% requirements
% loads Excel file
filename = ['EMD_1.xlsx'];
% 3 milking times for which the script integrates
periods = [
    3.5, 7.5;   % milking one ( add time in hours e.g. 7.5 for 7:30)
    11.5, 15.5;  % Milking two
    19.5, 23   % Milking Three
];
% load data
data = readtable(filename);
% coverts mounth from text to values
monthNames = {'January','February','March','April','May','June',...
              'July','August','September','October','November','December'};
monthMap = containers.Map(monthNames, 1:12);
if iscell(data.Mounth)
    monthStrings = data.Mounth;
elseif isstring(data.Mounth) || iscategorical(data.Mounth)
    monthStrings = cellstr(data.Mounth);
else
    error('Unknown format for Mounth column');
end
data.MonthNum = cellfun(@(x) monthMap(x), monthStrings);

% Build complete timestamp
data.Timestamp = datetime(data.Year, data.MonthNum, data.Day) + hours(data.Time);

% Extract power values from data
powerColName =
data.Properties.VariableNames{contains(data.Properties.VariableNames, 'Power')};
data.Power_kW = data.(powerColName);

% finds indavidual days
uniqueDays = unique(dateshift(data.Timestamp, 'start', 'day'));
```

```
% resulets table
results = table();
results.Date = uniqueDays;
results.Energy_Period1_kWh = NaN(height(results), 1);
results.Energy_Period2_kWh = NaN(height(results), 1);
results.Energy_Period3_kWh = NaN(height(results), 1);

% intergrate for each day
for i = 1:height(results)
    day = results.Date(i);
    dayMask = dateshift(data.Timestamp, 'start', 'day') == day;
    dayData = data(dayMask, :);

    % Get decimal time
    timeHours = hour(dayData.Timestamp) + minute(dayData.Timestamp)/60;

    for p = 1:3
        startHour = periods(p, 1);
        endHour   = periods(p, 2);

        mask = timeHours >= startHour & timeHours <= endHour;
        subData = dayData(mask, :);

        if ~isempty(subData)
            relTime = hours(subData.Timestamp - subData.Timestamp(1));
            energy = trapz(relTime, subData.Power_kW);
        else
            energy = NaN;
        end

        % Store result
        results{i, sprintf("Energy_Period%d_kWh", p)} = energy;
    end
end
```

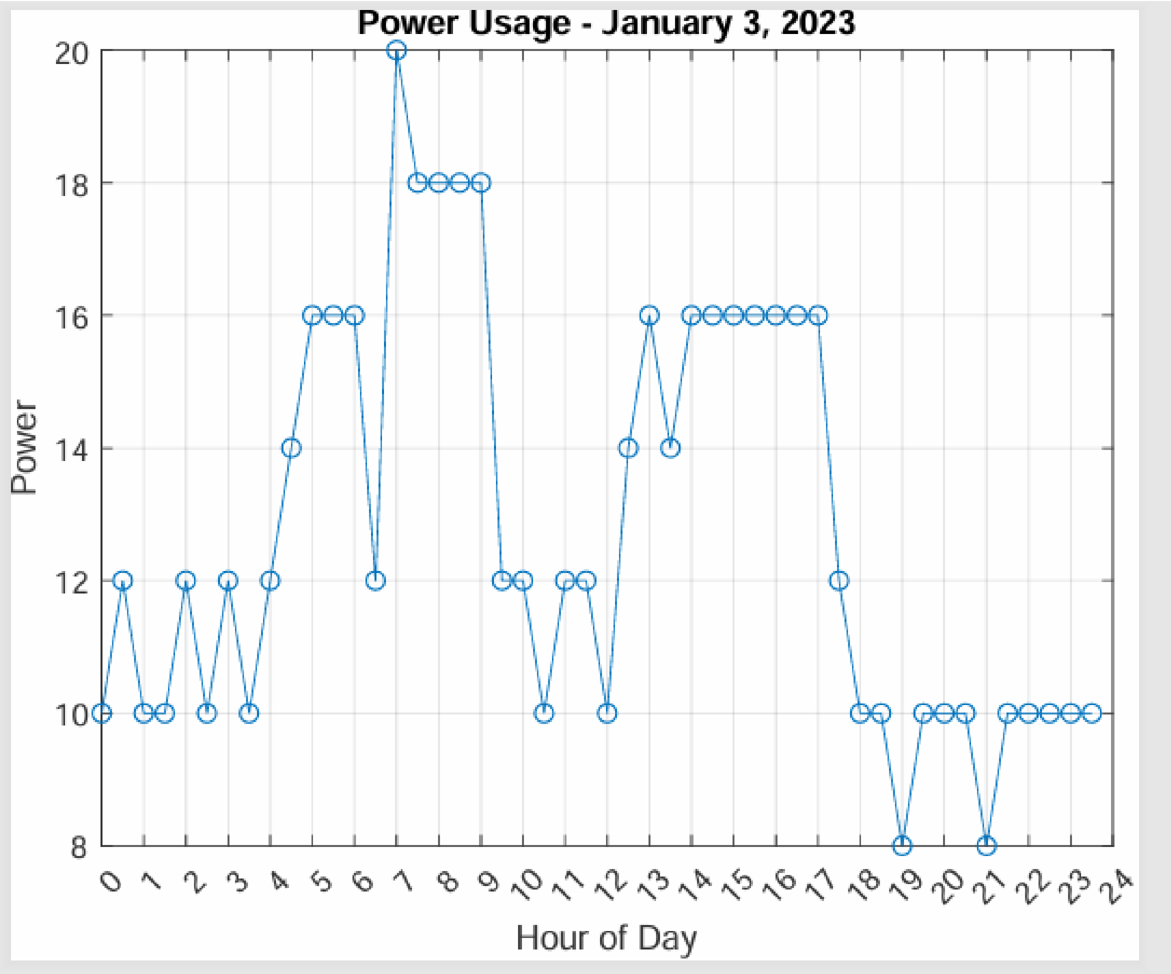
```
% --- DISPLAY ---
disp(" Summary of Daily Energy Use in 3 Periods:");
disp(results);

% --- OPTIONAL: SAVE TO FILE ---
writetable(results, 'EMD1_3milking.xlsx');
fprintf('\n Results saved to: daily_peak_energy_summary.xlsx\n');
```

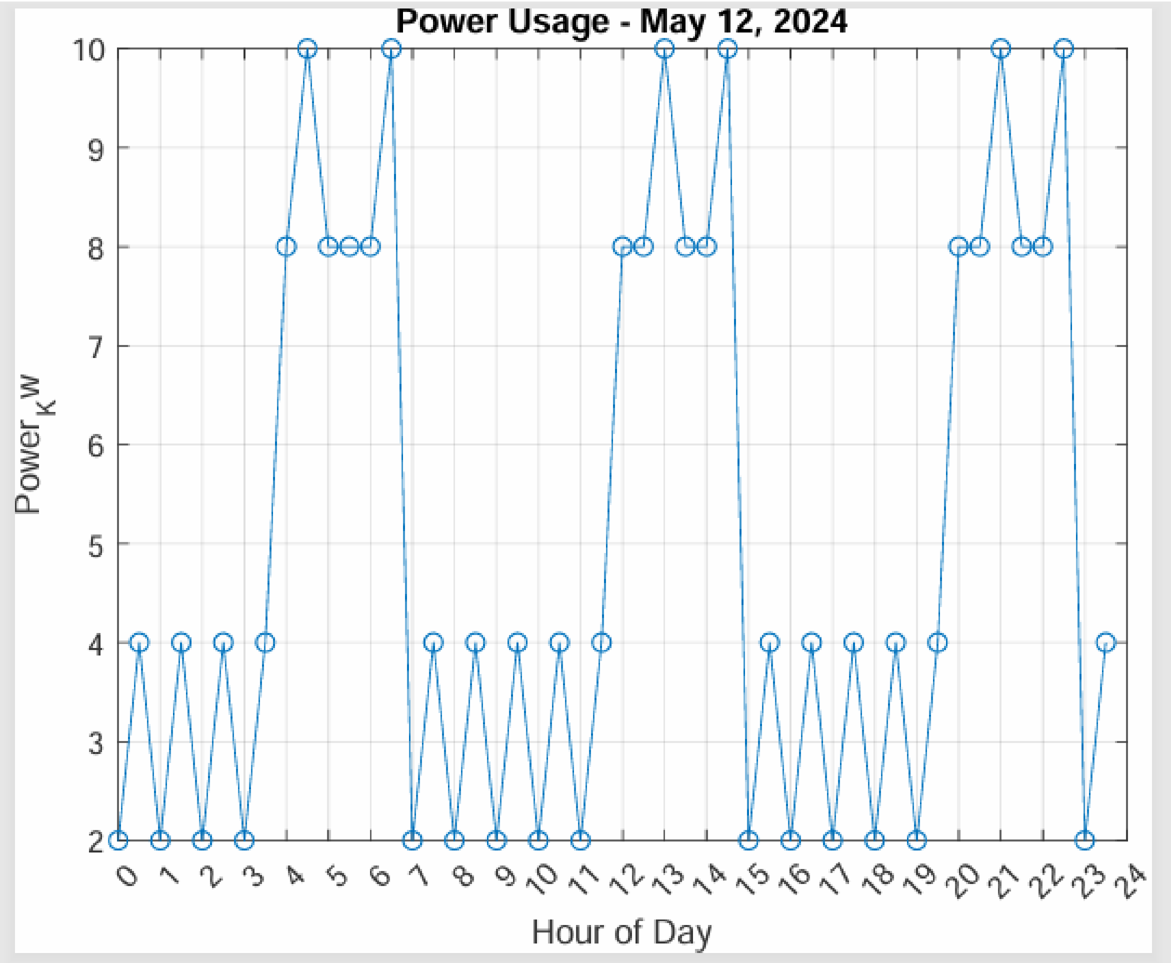
Appendix IX MATLAB Code for Graphing

```
%the scrip plots each day, this scripts produses may take a long time to
%run depending on number of days
% Load the data
data = readtable('EMD_1.xlsx');

% Convert month names to nomber
monthNames =
{'January','February','March','April','May','June','July','August','September','October','November','December'};
data.MonthNum = zeros(height(data),1);
for i = 1:12
   data.MonthNum(strcmp(data.Mounth, monthNames{i})) = i;
end

% Create datetime object
data.DateTime = datetime(data.Year, data.MonthNum, data.Day) + hours(data.Time);

% Get all unique (Year, Month, Day) combinations
[ymdTriplets, ~, groupIdx] = unique([data.Year, data.MonthNum, data.Day], 'rows');

% Set output PDF path
outputPDF = 'EMD_1_labe.pdf';

% Delete existing PDF if exists (optional)
%if exist(outputPDF, 'file')
  % delete(outputPDF);
%end
% Loop through each unique day
for i = 1:size(ymdTriplets, 1)
   year  = ymdTriplets(i, 1);
   month = ymdTriplets(i, 2);
   day   = ymdTriplets(i, 3);
   % Filter data for this day
```

```
    idx = groupIdx == i;
    dayData = data(idx, :);
    % Sort by time
    [~, sortIdx] = sort(dayData.Time);
    sortedData = dayData(sortIdx, :);
    % Plot
    f = figure('Visible', 'off');  % closes figuers generated
    plot(sortedData.Time, sortedData.Power, '-o');
    title(sprintf('Power Usage - %s %d, %d', monthNames{month}, day, year));
    xlabel('Hour of Day');
    ylabel('Power_Kw');
    grid on;
    % Set x-axis from 0 to 24 with tick marks every hour
    xticks(0:1:24);
    xlim([0 24]);
    % Append to PDF
    exportgraphics(f, outputPDF, 'Append', true);

    close(f);  % Close the figure to save memory
end
fprintf(' All plots exported to: %s\n', outputPDF);
```

Appendix X   Example Plot for EMD 1





Power Usage - May 12, 2024
Power$_K$W
Hour of Day

Appendix XI EMD4 Milking Energy Example After Removal of Incorrect Data.

Date	Energy Milking 1 kWh	Energy Milking 2 kWh
01/03/2023 00:00	19.5	15
02/03/2023 00:00	20.5	5.5
03/03/2023 00:00	19.5	7
04/03/2023 00:00	20	10
05/03/2023 00:00	20	7
06/03/2023 00:00	19.5	13
07/03/2023 00:00	21	4.5
08/03/2023 00:00	19.5	11.5
09/03/2023 00:00	20	12
10/03/2023 00:00	21	4
11/03/2023 00:00	19	10
12/03/2023 00:00	17.5	9
13/03/2023 00:00	19.5	8
14/03/2023 00:00	20	10
15/03/2023 00:00	19.5	11.5
16/03/2023 00:00	20	14
17/03/2023 00:00	18	7.5
18/03/2023 00:00	20	7
19/03/2023 00:00	17	4.5
20/03/2023 00:00	19.5	7
21/03/2023 00:00	20	5.5
22/03/2023 00:00	17	4.5
23/03/2023 00:00	17	8.5
24/03/2023 00:00	16.5	3.5
25/03/2023 00:00	19.5	4
26/03/2023 00:00	19.5	8.5
27/03/2023 00:00	19.5	3.5
28/03/2023 00:00	19.5	4
29/03/2023 00:00	19	4
30/03/2023 00:00	19.5	3.5
31/03/2023 00:00	20	18

Appendix XII BESS Power Calculations

	Mean Power Draw (kW)				
	Two Milkings		Three Milkings		
	Milking One 04:00 - 07:00	Milking Two 14:30 - 17:00	Milking One 04:00 - 07:00	Milking Two 12:00 - 15:00	Milking Three 20:00 - 22:30
EMD_{Sum}	19.36	17.22	19.31	16.35	16.51

	σ of Power Draw				
	Two Milkings		Three Milkings		
	Milking One 04:00 - 07:00	Milking Two 14:30 - 17:00	Milking One 04:00 - 07:00	Milking Two 12:00 - 15:00	Milking Three 20:00 - 22:30
EMD_{Sum}	4.08	5.10	3.58	4.42	3.16

These findings were used to specify the Power required from the BESS, using the method stated by Rumsey (2023) to provide a solution that would work for 68% and 95% of the time depending on the Standard deviation applied. the results of this are shown in Table 4-8.

Appendix XIII Variable Energy Tariffs

Hour	p/kWh
0	14.68
0.5	14.25
1	13.51
1.5	13.69
2	13.94
2.5	12.85
3	12.90
3.5	12.70
4	13.43
4.5	12.55
5	13.67
5.5	14.00
6	14.73
6.5	16.78
7	15.58
7.5	16.76
8	15.84
8.5	15.12
9	14.99
9.5	13.77
10	13.61
10.5	13.03
11	12.41
11.5	11.57
12	11.45
12.5	10.68
13	10.29
13.5	9.35
14	9.67
14.5	9.77
15	10.02
15.5	10.87
16	25.14
16.5	27.22
17	28.90
17.5	30.17
18	32.19
18.5	32.95
19	21.42
19.5	21.79
20	21.76
20.5	21.64
21	21.14

21.5	20.06
22	18.60
22.5	15.63
23	16.69
23.5	15.13