KINGS
MONKTON
SCHOOL

EESW Project Report

2023-24

Kings Monkton School

in association with

STEM Cymru

My Sustainable Community

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Contents

List of Abbreviations

BedZED	Beddington Zero Energy Development
CAD	Computer Aided Design
EESW	Engineering Education Scheme Wales
EV	Electric Vehicle
GSHP	Ground Source Heat Pump
HAWT	Horizontal Axis Wind Turbine
PS	Primary School
SuDS	Sustainable Urban Drainage System
U_g	U-value of glazing
VAWT	Vertical Axis Wind Turbine

Executive Summary

- The project involved designing a **completely new sustainable community** for **500 residents** near Cardiff, in **South Wales**. The community would have **little to no impact** on the local and global environments in its **operation and construction** and would have enough facilities to be **almost self-sufficient**.

- The community would have **221 houses** of a few different types. The majority of homes would be the **standard houses** and a minority would be **either premium homes or more affordable flats.**

- All buildings would have **slightly slanted roofs** to accommodate solar panels and there would be a **thin layer of vegetation to promote biodiversity**. Houses would be heated using **geothermal heat pumps** which provide passive heating to the building and would have **cavity wall, floor and roof insulation and triple glazed windows**.

- **Solar panels and VAWTs** would be installed on **the roofs of all buildings** and in other areas, such as on street lamps. The electricity produced would be **transferred to a central power distribution hub**, and then on to the community. Excess electricity would be transferred to a **lithium-ion battery storage system**. When the electricity demand could not be met, electricity would be drawn from the storage system. Once the storage system has been depleted a **biomass generator fueled with waste** from the community would be turned on to meet demand.

- **Rainwater would be collected on all buildings** and used in applications where untreated water would be acceptable, such as washing cars or supplying radiators. This reduces the demand on water treatment facilities. Rainwater would undergo a **minor filtration process** before being used. A **SuDS would also be used** to reduce the volume of water entering the drainage system, thereby reducing the probability of floods which could contaminate the local environment. This would involve **the construction of swales and filter drains**.

- Residents would be **encouraged to own a form of EV**, such as a plug-in electric or hybrid. EVs would be charged at a **community charging facility** with **8 EV chargers** and **6 standard fuel pumps**. In the future, EV charging stations could be **installed in homes** using **intelligent charging infrastructure**. An **electric bus network** will also be established for easy access to nearby towns.

- The community would **plant a large number of trees of a variety of species**. This would ensure the community was **carbon neutral by offsetting carbon**. The construction of the community would also make use of **sustainable buildings practices** such as **purchasing from local producers**.

Introduction

Kings Monkton School is a co-educational, English medium, independent school. The school is made up of around 300 pupils, aged between 3 and 18, who are in various stages of their academic journey, from nursery to sixth form. It is located in central Cardiff [1, 2]. This project was completed by seven pupils in Year 12 at Kings Monkton, all of whom are studying a variety of A level or equivalent subjects and have a variety of skills and experiences that they can contribute to the team.

STEM Cymru is an independent charity, established in 1989, that runs activities, such as the Year 12 project, to inspire young people to choose careers in science, technology, engineering and mathematics. They are the organisers of the Engineering Education Scheme Wales (EESW), and were responsible for setting the problem, described in the project brief, that the team had to solve. [3]

Student Profiles

Morgan Bleasdale - Studying maths, further maths, physics and computer science. He wants to study engineering at university. In the project, he focused on the more physics and maths oriented parts of the problem as well as overall project management and report writing in his role as the project coordinator.

Amelia Jefferies - Studying design technology, art and physical education. She wants to pursue a career in architecture or sports, but is swaying to the idea of architecture because of the enjoyment of working on a project, solving problems and developing ideas further.

Lucian Tunnicliffe - Studying maths, economics, psychology, music technology. Despite subject choices, he is really interested in science and wanted to do some extracurriculars related to it. He was interested in all parts of the project and wanted to help out in whichever areas needed work.

Arjen Bhal - Studying maths, further maths, physics, chemistry. With an interest in studying some form of engineering at university, he also worked on the physics and maths related parts of the project.

Elian Bryant - Studying design technology, biology, geography, media. He sees himself working outdoors in the future, in a career related to conservation. He worked on the environmental parts of the project.

Aron Hurt - Studying maths, further maths, english literature and religion and philosophy. Interested in social and legal aspects of the project as this lines up with what he wants to do in the future, also interested in the engineering parts of the project as he would like to consider many different careers.

The Project Brief

The project brief given to us was:

> *We need our communities to be **sustainable** for future generations, that means considering the **environment and everything that lives in it.***
>
> *Part 1: Looking at a location or building in your community, such as your school, local hospital, community centre or sports facilities, consider how sustainable these are, and whether any alterations or regeneration work could be undertaken to improve them.*
>
> *Part 2: Imagine an **open piece of land with nothing on it**, a blank canvas, that you need to create your own **community facilities** on. Where will the community buy goods? Where will they work? Where will they go for education or if they feel unwell? And finally, how will they get there? From providing shelter and water, to heating, food sources and your economy, look at what you could design if you had to start from scratch with creating a new community amenity.*

At our first meeting with the organisers of the EESW we spoke about the project brief that was set and specifically what would be required of us. We were instructed to purely focus on either part 1 or part 2 but we were not required to do both. After a discussion with the team, we decided that because of our range of skill sets and interests, we wanted to pursue **part 2 of the brief**. We believed it was a fairly complex and interesting problem that we already started having some ideas for.

Analysis of Problem

Pursuing part 2 of the brief meant that we would be tasked with creating our own sustainable community. The brief was intentionally open ended to allow us to explore the topic area and the various challenges that it involved. Before starting, we wanted to define what we meant by a “sustainable community”. We believed that this was a community that had little to no impact on the local and global environments in its operation and construction and had enough facilities to be self-sufficient, in a sustainable way. Our primary focus would therefore be on making the community sustainable in the way it operates whilst also considering the construction process.

Creating a new community was a fairly complex task drawing from several different disciplines and areas of focus. In order to effectively tackle the task we broke the project brief down into 5 distinct categories listed on the next page.

1. Housing

The design of all buildings within the settlement, including housing and facilities, needed to be sustainable. They should be designed to be efficient as to limit wasted electricity, gas, water, etc; not cause harm to the local environment and preferably work with the local environment; and they should be pleasant to look at. This was one of the bigger focuses for this project as there were a lot of factors to be considered. For example, we considered how the buildings could be insulated to reduce heat losses so less gas would be needed to heat buildings.

2. Power Generation and Distribution

The settlement would need to have its own power grid, supplied by completely renewable sources. The grid would have to be able to supply electricity to the whole settlement at peak usage in any weather conditions (for example, there must be electricity when there was no wind and no sun).

3. Resource and Waste Management

This particularly concerned the design of waste disposal systems, water treatment and rainwater collection. The community would need to make good use of available water supplies that would be renewable and therefore sustainable. The most obvious source of this was rainwater however other potential sources could be considered. The community must also be able to dispose of household waste (for example, food waste) sustainably and without contamination to the local environment. Likewise, drainage from houses would need to be disposed of safely and without contamination - where possible being recycled back into the main supply.

4. Transport and Infrastructure

In order for the community to be socially sustainable, where residents want to live in the village and stay there, the community would need to be well connected to other parts of the country. Therefore, it was important that we looked at the various ways residents could commute to other settlements, in a sustainable way.

5. Environment

We needed to have a good understanding of any special environmental considerations that had to be taken into account in the design of the settlement. We could then attempt to make adjustments to our design in order to accommodate these issues. This also concerned the use of plant life to offset any carbon emissions which could help the settlement to have net-zero carbon emissions.

Procedure

Requirements

Parameters of the Project

The problem we were given was intentionally vague so it was important for us as a team to develop realistic parameters and goals for the project as a whole. Within our first couple of team meetings we were able to get 3 basic parameters which could be used to find more specific parameters:

- The community would have 500 residents.
- It would be located in a semi-rural location in south wales (near the south west of Cardiff).
- It needs to be sustainable.

When discussing and deciding on these basic parameters we went through multiple ideas of what this might mean, for example what “sustainable” should be defined as. We also discussed the opportunities and challenges of designing a larger or smaller village. When coming to a final decision we had to take into consideration a variety of factors. Firstly, designing a larger settlement meant it would be harder to make the community sustainable. For example, it would be easier to make a small village with a few facilities sustainable as opposed to a large city. Secondly, we found that due to the complexity of designing a larger settlement, it would be difficult to go into an exuberant amount of detail in our preferred areas as we would be stretched too thin as a team.

There was a lot of debate over what the exact population of the community would be. We initially considered having between 200 and 2000 people. After analysing the amenities that we would need to design for different sized communities, we came to the conclusion that we would aim to design a 500-person community. This meant there were only a few buildings we would have to design (such as a church, pub or supermarket).

Sampling

With those basic parameters in mind, we began to develop our methodology so we could research and develop the more specific parameters that would be needed to design the community. We wanted to discover the types of buildings that a village of 500 people would have. To conduct this research we acquired a list of Welsh towns through the 2012 census data, which we then organised based on population. We compiled a list of Welsh towns with a population of between 500 and 600, we then chose 5 towns by picking every 3rd town in the list. Our sample then consisted of the 5 Welsh towns: Llandogo (in Monmouth), Coelbren (in Neath), Ffairfach (in Carmarthen), Nantgaredig (in Carmarthen), Henfynyw (in Ceredigion) and Llanarth (in Ceredigion).

Types and Quantities of Buildings and Amenities

Using Google Maps, we created an area of observation for each town. We did this by using the "walk in 30 minutes" function based on the centre of the town that was chosen by Google Maps. This gave a common area that we could reliably use for each town. With this area of observation we counted each type of amenity and building. With this we were able to develop averages for how many of each amenity we would need in our town for it to be consistent with Welsh towns in the 500-600 person size. The results can be seen below in Table 1.

Sample town	Amenities							
	Church	School Education	Shops	GPs / medical services	Pubs	Parks	Post office	Other services
Llandogo	1	1 *(PS)*	1	0	1	1	0	1
Coelbren	1	1 *(PS)* 1 *(education centre)*	3	1	0	1	0	1
Ffairfach	1	2 *(PS)*	3	1	1	1	1	1 *(train station)*
Nantgaredig	0	1 *(PS)* 1 *(cooking school)*	1	1	3	0	0	1 *(health club)*
Henfynyw	3	0	1	0	1	3	1	0
Llanarth	1	1 *(PS)* 1 *(child minding)*	4	0	1	1	1	2 *(hotels)*
Averages	1.17	0.83 *(PS)* 0.5 *(other)*	2.17	0.5	1.17	1.17	0.5	

Table 1: The number of various amenities in sample towns [4]. The term "PS" stands for primary school

Population Density and Area

In order to calculate population density for each sample we needed two numbers: the population and area of each town. It was easy to obtain the population as we used the 2011 census data for each town [5]. However it was more difficult to obtain the area of the town as we had to decide what the town's borders were. We decided that we would assume the border of each town was at the end of the built up areas (indicated by a grey shading on Google Maps). There were numerous issues with this method as it disregarded important areas of certain villages. In an ideal world we would get the settlement data from each of the councils and use the exact borders and populations but we were unable to contact them.

We used 4 out of the 5 sample settlements to calculate the average population density using the population and area. The values at different stages of this method as well as the method itself can be seen in **Appendix A.1**. We calculated an average population density value of 1,550 population/km² which was used for this project.

Housing Parameters

We realised that we needed to have some detailed parameters when it comes to the types of housing. To establish this we needed to find the demographic of the population of villages and the average area of typical houses in villages. We conducted research and after looking through a plethora of data, the most accurate resource we found was the Welsh Government's *Statistical Focus on Rural Wales* [6]. Although our site was located in a semi-rural area, the similarities between our site and the content of the report satisfied us that this was a suitable resource to use. The specific data on rural areas was roughly two decades out of date, the research paper we were using was a meta-analysis of all census data from that year specifically focusing on villages. We thought the specific data on villages in Wales would be the most accurate and generalisable to the settlement we were designing as it too was located in Wales. In particular, data from government sources would be more reliable. Despite there being more up-to-date information in the 2021 census, our team did not have the resources or skills to conduct a robust meta-analysis to inform the project to the standard and reliability of the Welsh Government.

Based on the data, we found that the majority of housing in villages and rural Wales were composed of pensioners, families or other adults. On top of this there was a lower proportion of single people living in rural areas. This indicates that the proportion of housing in the community should have significantly more family and group homes rather than smaller single person dwellings such as flats. However it was incredibly important to consider the massive change caused by Covid-19, since the data was published. People who traditionally would have worked in offices, in larger towns and cities, would have to have lived within commuting distance. Due to remote working, they may no longer need to live close to work and therefore may have settled in more rural areas as they prefer the convenience of remote working. The movement of working people to rural areas as a result of remote working since Covid-19 has changed the demographics of what was traditionally considered a rural population. This needed to be considered for the community we were designing.

The percentage composition of households in Wales and England taken from the *Statistical Focus on Rural Wales* report, is provided in Table 2 and Table 3.

Welsh share by household composition	**In Welsh settlements below 10,000 people**	**Welsh total average**
Single Pensioner	13.7%	15.5%
Other all pensioner	11.3%	10.1%
Other single person	10.5%	13.7%
With dependent children	30.0%	30.2%
Others	34.4%	30.5%

Table 2: Occupied households by percentage household composition in **Wales** [6]

English share by household composition	In **English** settlements below 10,000 people	**English** total average
Single Pensioner	12.7%	14.4%
Other all pensioner	12.5%	9.3%
Other single person	10.2%	15.7%
With dependent children	28.5%	29.4%
Others	36.1%	31.1%

Table 3: Occupied households by percentage household composition in **England** [6]

"Others" refers to households that contain no dependent children, do not consist entirely of persons of pensionable age, and do not consist of an unmarried person.

Measurements of Houses

We considered the exact measurements and types of housing. Data from the UK Government in 2023 on rural housing showed that approximately half of houses were detached and that there was a 1:14 ratio of flats to houses in rural areas compared to 1:4 in urban areas. On top of this we obtained the averages for the floor area of different housing types, see Figure 1.

Figure 1: Types of houses and their average floor area [7]

Final Parameters

We concluded that the settlement should have 1 church, 1 primary school, 2 shops, 1 pub and 1 park as a minimum. We also found that half of the sample towns also had a general practice or some kind of medical service and a post office.

For the sake of simplicity, we decided that this community would not have its own primary school and medical services but would instead use those in the neighbouring village of Sully. However we needed to design the community with room to expand if the strain on Sully became excessive. We decided to merge one of the shops with the post office so both services could be accessible through one building.

The size of the town would be roughly **0.414km²** with a population density of **1,550 persons/km²**.

From the data we collected on housing we concluded that we would need a ratio of approximately 1:14 for flats to houses and approximately half of the houses to be detached. The flats would have a total floor area of 58m², detached houses 149m² and remaining housing 93m².

Legal Parameters

For a residential development to be built, planning permission would need to be acquired from the local council. In the application for planning permission, a variety of conditions would need to be met, such as how many houses must be built, what percentage of them must be affordable and what provisions must be available for the community. The conditions set by the council depend entirely on the location of the community, and since there were no previous developments on our selected site, it was not possible to accurately determine what these conditions would be for our project. Therefore, for the purposes of this project we assumed that **the final parameters we outlined would meet the conditions set by council**. We would fulfil all legal requirements, specifically the following:

- The community needed to have between 10% and 15% of homes as affordable housing. This is a general figure used by councils for most developments in South Wales.

- The community would have access to a range of provisions including public transport, parks/greenspace and education facilities.

These legal parameters had a lot of overlap with the parameters we initially set. We made the assumption that planning permission for this development had already been obtained and there were no other conditions other than those outlined so far in this report.

Site Selection

We decided to locate the community near Cardiff as this was where the team was located and would therefore have a valuable personal insight into the location. On top of this, we wanted to ensure that the community was economically sustainable. This meant residents would be able to easily access jobs, with the size of the community being small these jobs would have to be located in a large town or city, such as Cardiff. Therefore we decided that we would design a commuter town for Cardiff, where most residents would travel into Cardiff for work, entertainment and to access high order goods.

We began by selecting various locations around Cardiff, these locations were large and within them were hundreds of possible sites where we could have designed the community. Once we had selected the general area of the site, we would select a specific location. When selecting the general locations we considered various different factors including, but not limited to, its proximity to Cardiff, existing amenities in nearby settlements, the elevation of the land around it, transport infrastructure and how suitable the site would be for using renewable power.

We considered five different areas but quickly managed to narrow this down to only two. This report details the benefits and drawbacks of these two sites but the list of all the considered sites can be accessed in **Appendix A.2**.

Selected Site - South West of Cardiff

Figure 2: The location of the selected site

The area highlighted by the boundary in Figure 2 was the location we ultimately decided on. It was located near Sully and Cosmeston Lakes with a fairly low elevation and decently high wind speeds from its proximity to the sea. This meant that it was both bright and windy so wind turbines and solar panels could be used together in combination, leading to a high power output from renewable sources.

The site was also very well connected to Cardiff meaning that residents could easily commute for work. The sire has access to a train station located nearby, in Dinas Powys, allowing for quick access to the centre of Cardiff and other cities along that line (including London) via public transport. There was also a direct road through Penarth into Cardiff. The close proximity of the site to Sully meant that residents could use the schools, surgeries and other amenities from Sully. Therefore, we would not have to design them for use within the community.

An issue with this site was that it was a greenfield site that had not previously been built on. This was rather contradictory to the community's sustainable goals that were being incorporated into the design. Building on this site could result in numerous habitats being destroyed and wildlife being displaced. There would however be ways to mitigate this. As often there are not enough available brownfield sites to build new communities on, we believed it was reasonable to build the community in this area.

Alternative Location - North of Cardiff

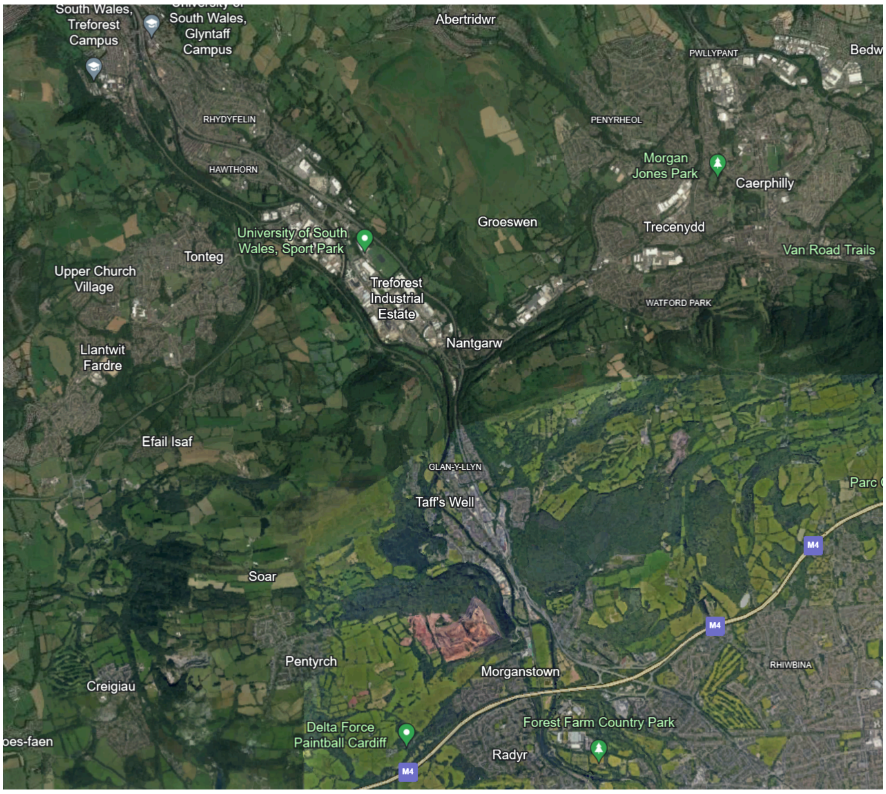


Figure 3: The location of the alternative general area

We also considered an alternative site located north of Cardiff, somewhere in Figure 3. Within this location we would have mainly been looking at the Taffs Well, Nantgarw or Radyr areas. These areas had a particularly high elevation meaning there would be a high quality wind resource available which would help with power generation. Nantgarw had very strong transport connections to Cardiff, with a new transport system under construction, making it an ideal location for a commuter village. There was a possibility of using hydroelectric power from the various rivers and tributaries such as the river Taff. However, the facilities required to harvest hydroelectric power were very expensive and a hydroelectric dam would produce significantly more power than was needed for such a small community.

The main disadvantage of selecting this area was its elevation. While this does mean wind speeds are stronger allowing for increased wind harvesting, other renewable sources were significantly weaker. For instance solar power would be difficult to implement as shadows from hills and elevated areas may block access to sunlight, reducing the potential power yield. Additionally, at a higher elevation geothermal heat would be less accessible making it difficult to use as an alternative source of heating.

Project Management

Distribution of Tasks

After identifying the categories we wanted to focus on we assigned the team members to different categories based on their interests, subject choices and abilities. Most people were assigned to a few categories as they had a broad range of interests. We then broke down each category into the specific subheadings we wanted to talk about and began our research on a separate document for each category. Each person was assigned a variety of tasks (correlating to these subheadings) to explore and conduct research on, this same person would then be responsible for writing about that section in the technical report.

In order to keep track of what was being done, each subheading was given a dropdown where the status of that task could be selected from: Not Started; In Progress; Content Completed; Write-up In Progress; Write-Up Completed; and Completed. The latter was given to a task once it was completed, written on the technical report and read through by everyone and had improvements made to it. This was a good strategy to allow us to monitor progress in certain areas. An example of the planning technique we use can be found in **Appendix B.1**.

Strategy for Ideas

Very few sustainable communities have previously been developed. This made it difficult for us to take inspiration from an existing design. However, one example that we looked at as a case study was Beddington Zero Energy Development (BedZED) [8].This was a similarly sized community in England that had a very similar goal of being sustainable and carbon-neutral. Houses and facilities were built from scratch as an example of how future communities should be designed. Analysing this case study was really useful for us to see what works and does not work in a sustainable community. Some of the features, like the design of houses, was influenced by the success of house design in BedZED. While other features were avoided because they had not proven to be that effective in the case study.

On top of this, there were a variety of specialist sources that explored how society could be made more sustainable, through methods of power generation, insulation, EV charging, etc. For example, the Centre for Alternative Technology, based in Wales, proved to be a really useful source of information [9]. It had a really useful information service that provided great amounts of detail on a variety of sustainable technologies. We used this source to get an idea of what direction we wanted to take with parts of the project.

Time Management

We had about 4 months to complete the project. However, when combined with completing A level qualifications and various other competitions and schemes, not all of this time would be available for use in the project. Therefore, we had to be very efficient with how we approached it. Throughout the scheme, we had meetings almost every week to check team progress and brainstorm ideas. The dates and topics of these meetings are listed in **Appendix B.2**.

Below is a Gantt chart that we followed to ensure we would complete the project on time and at a sufficient quality.

Gantt Chart of Project

Week Starting	6 Nov	13 Nov	20 Nov	27 Nov	4 Dec	11 Dec	18 Dec	25 Dec	1 Jan	8 Jan	15 Jan	22 Jan	29 Jan	5 Feb	12 Feb	19 Feb
Analyse Project Brief																
Considering general ideas																
Researching and collecting information																
Finalisation of content																
Writing of technical report																
Review technical report																

Figure 4: The project Gantt Chart

Design

Layout of Community

There were various factors that impacted the layout of the community. There were some features within the site that we could have easily redesigned to suit the needs of the community such as the location of roads, telecommunications poles or street lamps. Whereas there were other features, such as trees, which could not have been moved. When deciding on the layout of the community, we went through a lot of debate over where certain features would be located.

Our chosen community layout can be seen in Figure 5. We decided to include 221 dwellings of which 113 were standard houses, 33 were affordable housing flats, 52 were repurposed single dwelling flats and 23 were premium homes.

	Standard housing
	Flats (both affordable and repurposed)
	Premium housing
	Shopping and community areas
	Community greenspace
	Bus depot, power distribution hub and composting facility

Figure 5: The layout of the community

The houses were fairly spaced out around the community. This was purposefully done as not to create a divide amongst residents based on which types of housing they had. Also the variety of housing made the community appear less monotonous. Despite this, the more luxurious premium homes and repurposed single dwelling flats were located on the east side of the site, whereas the standard homes and affordable flats were located on the west side. The details regarding the design of specific housing will be covered in the **Housing** section of the report. The community had 33 affordable homes compared to 188 non-affordable homes, this met the 15% requirement for affordable housing established by the council.

There were many community greenspace areas throughout the settlement. From a design perspective, the layout would need to have a lot of woodland which could be used as greenspace. The community could make use of woodland trails and public areas to allow the community to enjoy the area whilst also preserving the wildlife and local ecosystems. Trees are a protected species and so could not be easily removed, there was a large chunk of the site that was forested so this would have to remain as a green area because no other facilities could be built there.

A shopping and community area was designed to include a number of commercial and community provisions, including 2 shops, a general practice, a pub and a multifaith centre. It would be located in the centre of the community on the main road for easy access. The multifaith centre would have a dedicated place of worship and quiet space for use by residents or visitors of the community, this would include the church. All buildings within the community area would be designed to use the same sustainable techniques that are detailed later on in the report, this includes the use of green roofs, insulation and large windows. The design of one of the shops can be seen in Figure 6.

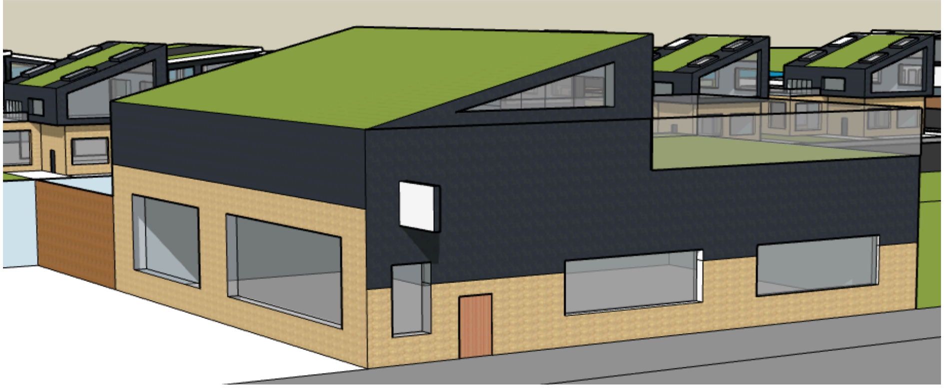


Figure 6: A CAD illustration of one of the community shops

One of our initial ideas was to have a form of town square where all services, like shops, would be easily accessible. Houses would then connect to this central area. Located further away would be a field of solar panels. We dismissed this idea after we had investigated the project parameters and determined there would only be two shops. It would be difficult to create a lively town centre with such a small number of shops and services. Additionally, we determined that solar panels would be located on roofs so there was no need for a separate field full of solar panels.

Housing

Generally, ensuring houses are sustainable relies on various factors such as ensuring that they could be heated from a sustainable source, that they are insulated properly so as not to waste this heat and making sure that the materials houses are made of are sourced from sustainable providers in a way that does not harm the environment. However, achieving sustainability could often lead to compromises in other really important areas of design, not necessarily related to sustainability. We wanted to avoid this by looking at how we could design houses to be aesthetically appealing, practical and cost-effective as to ensure residents would be happy to move to and live in the community. Houses were designed in a standard way so the same design could be constructed in any part of the community and would still be sustainable.

Home Designs

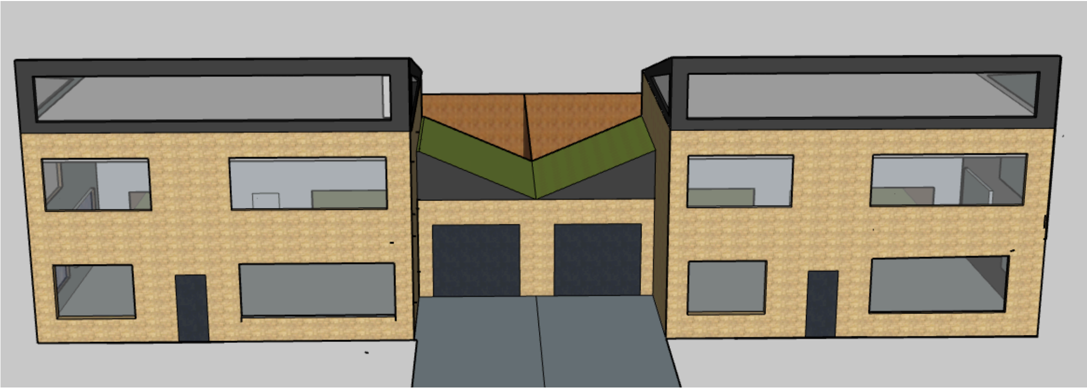
When discussing housing for the community with the team, a few requirements stood out. We decided that the houses should have large windows, allowing the sun to naturally heat the home. This would reduce the amount of artificial heating needed from a gas boiler or geothermal heating system. Additionally, the roofs should be slightly slanted allowing for the easy installation of solar panels without part of the roof blocking sunlight. Having a slanted roof would ensure that water would run off into gutters thereby reducing structural damage caused by the pooling of water in part of the roof. The design of the houses should also comply with building regulations and standards, such as *The Building Regulations 2010* [10].

A variety of materials, such as brick and “green concrete” (concrete where waste material is at least one of the components), would be used for construction. These materials would be sourced from local producers where possible to reduce the carbon footprint of transporting materials. Each house would also be designed to include a solar panel array of up to 10 solar panels which would be installed on the roof of the building. Houses would have several small vertical axis wind turbines installed on the roof and external walls. More about the installation of solar panels and wind turbines can be found in the **Power Generation and Distribution** section of the report.

There would be three types of dwellings within the community: the standard house; flats; and the premium house. Additional images of the CAD modelling process can be found in **Appendix A.3**.

Figure 7: A CAD illustration of the three main house designs

Standard House



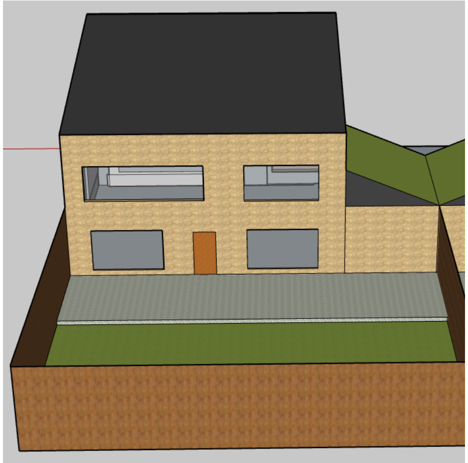


Figure 8: The front and back profiles of the standard 3-4 bedroom house

The standard house was the first of the houses to be designed. It would have 3 to 4 bedrooms, 2 parking spaces, a private garden, a garage and a driveway.

We decided all dwellings would have access to a garden or outside space because of the various environmental, economic and health benefits this brings including promoting sustainability and biodiversity. The standard house, like all houses, would have a thin layer of vegetation on the roof of the building, referred to as a green roof. This would provide habitats to insects and small creatures that may have been displaced by the construction of the community. These green roofs also have benefits in reducing the strain on drainage systems by intercepting rainfall, this is explored in the **Resource Management** section of the report. Green roofs also provide natural insulation which could reduce heat losses in the home, reducing the demand on heating systems which use electricity and/or natural gas.

The garage allows for easy storage of vehicles, with an area reserved for easy installation of electric vehicle charging stations in the future. While cars are often considered unsustainable, it was unrealistic to assume that residents would completely change their habits and forfeit having a vehicle. Therefore, in order for homes to be practical there would still be facilities in place to make car ownership possible. The garage would also hold the control panels for solar panels and wind turbines.

Flat Design

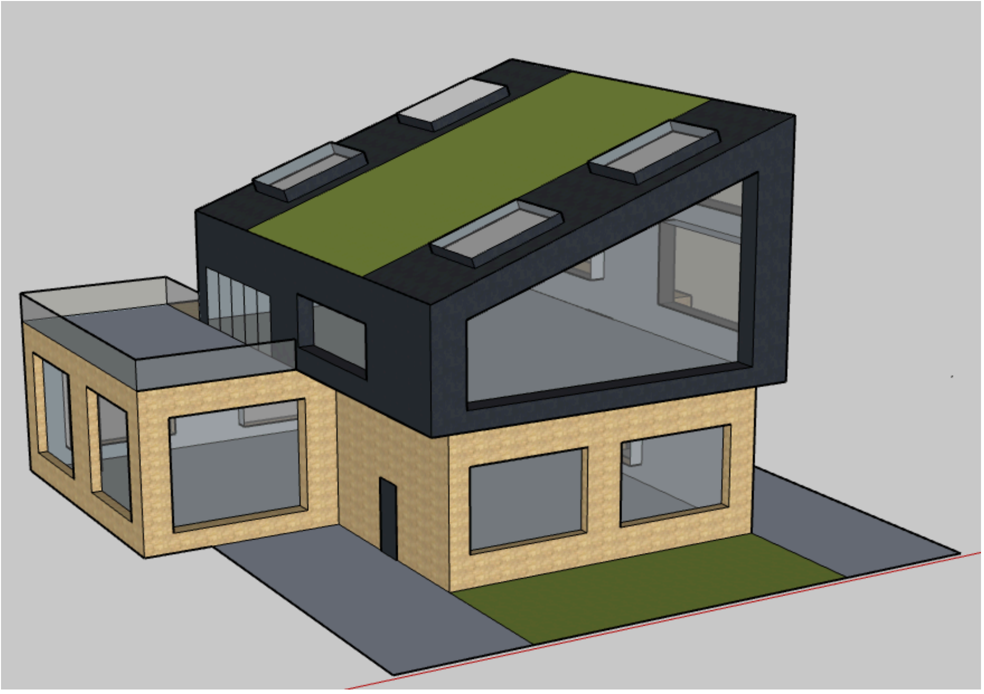


Figure 9: The design of a unit of flats

The flats were designed a few times but the final design was chosen because it had a more modern feel to it and would fit in better with the modern theme of the community (the initial design can be found in **Appendix A.4**). The building would be separated into two flats. The top flat would be a one bedroom flat with essential facilities (such as a bathroom) and a balcony. The bottom flat was designed for a small family with two bedrooms, essential facilities, a bigger living space and a small garden. The bottom flat would likely be more expensive.

Flats were designed to be modular so their design could easily change based on their location in the community and purpose. In some areas there could be a large communal garden between flats and some flats could instead be turned into a single home.

Similar to all housing designs, the building would have a slightly slanted roof with solar panels and wind turbines installed on it. There would also be a green roof to promote biodiversity and improve insulation.

Premium House Design

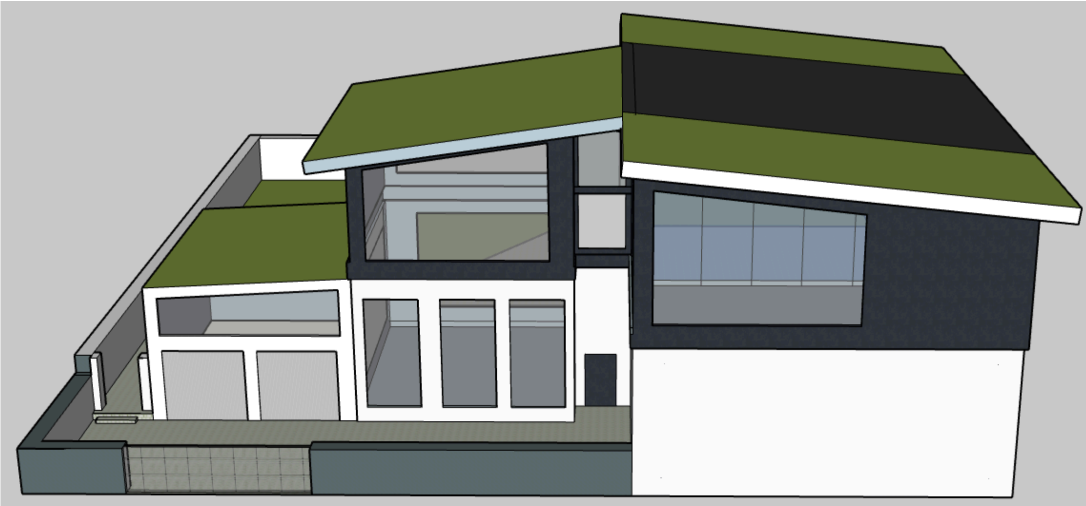


Figure 10: The design of the premium house

The premium house was designed in a similar way to the other dwellings. It would have 5-6 bedrooms, large living spaces, a large private back garden, a gated driveway and a double garage. The roof would have a layer of vegetation, solar panels and wind turbines. The control panel for power sources would be located inside of the double garage. The double garage would also have reserved space for two electric vehicle charging stations to be installed at a later date. The premium houses were designed to be the most luxurious houses in the community and would be significantly more expensive than the other designs. The location of premium houses would be slightly farther away from the busiest parts of the community. The demand for them would be fairly low so only a handful of premium houses would be needed.

Insulation

Where Is Heat Lost In Buildings?

Around 25% of the heat produced by a heating system would escape through the roof of a building; about 35% of the heat would escape through the walls and through gaps, in and around windows and doors; and about 10% of heat would be lost through the floor. [11]

It was essential that our buildings were energy efficient in order to reduce the energy required to keep buildings heated, therefore making the building more sustainable. As well as directly saving consumers money on their bills, lower energy use would also reduce the demand on the energy network. Energy network costs would represent between 5% - 20% of domestic energy consumers' bills. [12]

Cavity Wall Insulation

Cavity wall insulation is a widely used technique that would reduce the quantity of heat lost in a house by escaping through walls. It would involve fitting an insulating material in place of the gap between each of the ‘skins’ of a wall (the cavity). Typically, houses built from the 1920s onward have cavities within their walls. However, their cavities are fairly narrow so only a small amount of insulation is used.

In our community we would have much larger cavities to allow for much more insulating material as this would reduce heat losses. There were various sizes of cavity that we could have used.

- **100 mm insulation** - This would bring about a stable indoor temperature as a result of heat loss being significantly reduced during the winter and it would prevent heat gain during summers. This eliminated the need for unnecessary heating or cooling, hence it would lower energy bills. Thicker insulation could also aid in soundproofing. It would create a quieter and more peaceful environment within a house by minimising noise travelling from outside and between rooms. Additionally, 100 mm insulation would offer increased condensation control. Thicker insulation would regulate the temperature of walls, ceilings and windows efficiently, reducing the risk of condensation formation. [13]

- **50 mm insulation** - While not as thick as 100 mm insulation, 50 mm insulation would still provide adequate thermal resistance. Heat transfer would still be effectively reduced and insulation would help maintain a comfortable indoor environment. As the insulation was thinner, it was a more versatile choice for various areas. It could be fitted into areas where space was limited and its adaptability made it suitable for commercial and residential use. Compared to 100 mm insulation, 50 mm was a cheaper alternative way of insulating an area. If working within a tighter budget, 50mm insulation could be a cost effective solution. [13]

- **25 mm insulation** - Suitable for thin walls and tight spaces. 25 mm insulation would provide thermal resistance whilst not compromising available space. It would be quick and easy to install so could be useful in areas that would require a quick insulation solution. It would be cost effective for minor insulation needs and would allow insulation of targeted areas without the need for extensive insulation methods. [13]

100 mm insulation would be the most suitable for the exterior walls of homes in the community as it ensured that the most heat would be preserved within the home. For other parts of the building, such as the thin walls, 25 mm insulation would be appropriate as there would not be as much of a need for these walls to trap heat or there may be less space available.

Roof Insulation

For this project, the insulation of roofs was a point that required a lot of attention since the design of the homes would use slightly slanted roofs. Flat roofs tend to be less energy efficient than pitched roofs, which means more heat would be lost through the roof and those living in the house would have higher energy bills as a result. This was already an issue because, as previously mentioned, roughly 25% of the heat in a home would be lost through uninsulated roofs.

When insulating flat roofs, there are generally two options; making a cold roof or a warm roof. These roofs could then be covered in waterproofing membranes.

The key difference between a cold flat roof and a warm flat roof is that the location of the insulation material within each differs. For a warm roof, the insulation layer would be on top of the roof structure, meaning that the roof structure would be on the warm side of the insulation. On the other hand, for a cold roof, the insulation layer would be between the rafters and the roof deck, leaving a cold gap under the solid board of the roof.

In a flat roof, where the best thermal performance would be desired, a warm flat roof would be the most suitable option. Additionally, a warm flat roof would be easier to install. Cold flat roof insulation had the main benefit of taking up less space, which would be vital in areas where there were balconies or doors opening onto the flat roofs. Moreover, cold flat roofs would offer greater support for foot traffic, as residents would be standing directly on a faced board, rather than on an insulation board that could be more easily compressed and potentially cause structural damage.

Warm Flat Roofs

The warm flat roof would be built from six sections with insulation. The top layer would be a waterproofing membrane, sitting above an insulation board with a vapour control layer below. This would be secured over the timber roof decking. The roof joists below would be uninsulated, and could be topped with plasterboard. The vapour control layer would help reduce condensation and moisture passing through the flat roof structure. The waterproof membrane would be designed to protect the flat roof from wind and rain. Figure 11 shows a warm flat roof.

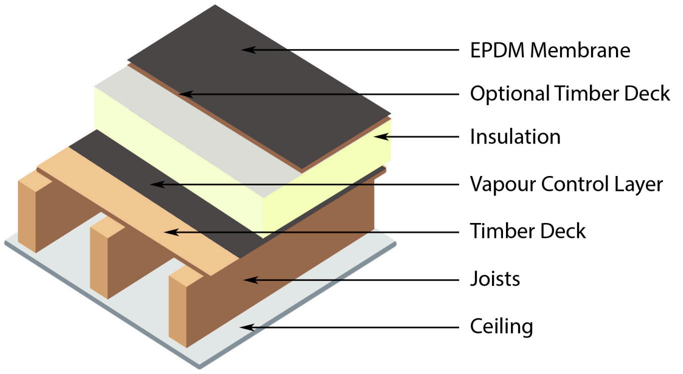


Figure 11: A diagram of a warm flat roof [14]

Cold Flat Roofs

A cold flat roof would be composed of similar components, just insulated from the inside instead. Only the waterproof membrane would sit on top of the timber deck. The insulation boards would be installed within the joists of the roof, possibly with a vapour barrier installed below them, and a plasterboard ceiling below that [15]. A cold flat roof is shown in Figure 12.

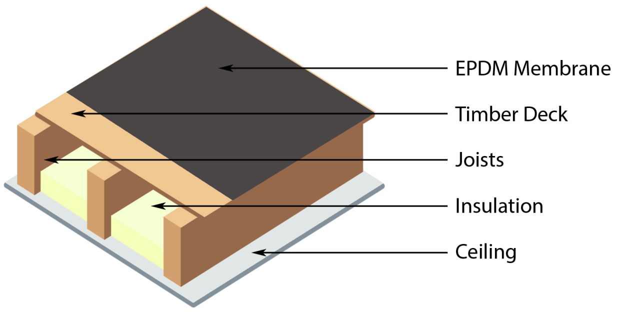


Figure 12: A diagram of a cold flat roof [14]

Insulation Boards

Insulation boards would be made of rigid foam, which would have a very low thermal conductivity. This means it would be great at preventing heat from escaping homes, making homes warmer in the winter and cooler in the summer. Additionally, the insulation boards were very lightweight, so they would be easy to install. Also because they did not absorb water, they would not rot or mould like some other insulation materials could. [16]

Insulation boards would not be the most effective type of insulation compared to other methods such as spray foam. In some cases, insulation boards may be difficult to install, and if not installed properly could result in gaps within the insulation, hence reducing its effectiveness. Additionally, insulation boards would be expensive in comparison to other types of insulation. [16]

Fibreglass Insulation

Fibreglass is currently used often due to its affordability. As it is used frequently, fibreglass would be available in a range of sizes, which would make installation easier.

Fibreglass also had its downsides. It could be compressed, causing it to lose some of its ability to insulate. Additionally, it could absorb water, reducing insulation and possibly giving way to mould. Similarly to mineral wool, fibreglass was a non-combustible material, though it did not provide the same level of fire resistance mineral wool had. As mentioned previously, fibreglass would be less dense than mineral wool, so would not reduce excessive sound as effectively. [17]

Mineral Wool Insulation

Compared to fibreglass, mineral wool had a better insulator performance. It was a greener product too as it was composed of roughly three times more recycled material than fibreglass. On top of its thermal properties, mineral wool would offer superior soundproofing to fibreglass because its density was three times greater than fibreglass. The high density of mineral wool would make its batts (large insulation pieces) stiff, which would make installation easier. Mineral wool was also found to be hydrophobic, so would not absorb water or encourage mould growth and it was found to be very resistant to fires, so could act as a firestop.

However, mineral wool had its drawbacks. In general, it would come at a higher cost than alternatives, with between 25-50% higher cost than fibreglass. Also, it would be a more unusual insulation material so would not be available in a great variety of sizes. Furthermore, due to its high density, it would be heavier, which could cause some difficulties during ceiling installations. Its dense nature would require the use of specific tools such as serrated bread knives or wood saws to cut the batts down to the correct size.

Spray Foam Insulation

Spray foam insulation was one the most effective ways of insulating roofs and had a higher effective rate of insulation than fibreglass or mineral wool. Additionally, it would be a very flexible form of insulation, meaning it would be able to be fitted in areas that other insulation methods could not. Spray foam insulation, if fitted correctly, could last up to 80 years, meaning it would very rarely need to be replaced unlike mineral wool/fibreglass which would be in need of replacement if done incorrectly. Another benefit of spray foam was that it was very effective in keeping water out of homes, preventing the growth of mould.

One of the issues associated with this type of insulation was that it could hinder essential ventilation, so even though the spray foam itself would not retain moisture it may increase the risk of humidity and dampness - and if a timber roof were used, possible decay. Spray foam insulation was also quite expensive, averaging to be two to three times more expensive than fibreglass.

Insulation Methods Use In The Design

For this project, spray foam would be the best form of insulation for roofs, coupled with a warm flat roof. This was because the aim of the insulation was to offer the greatest possible thermal efficiency in order to reduce the need for excessive heating and in turn gas and/or electricity consumption.

Also, spray foam insulation would be used in wall cavities with a thickness of 100 mm.

Insulation of Windows

Windows that are designed to be good insulators often make use of double glazing. However, we have also considered a potential triple glazed window with improved thermal insulation.

The main difference between triple glazing and double glazing would be the fact that triple glazing would contain three panes within a sealed frame, instead of the more common two panes in double glazing. In between the panes we would use krypton gas which would be denser than other industry standard gases, such as argon. As krypton was much denser than air it would offer good insulation when used in windows. Due to the additional pane in triple glazing there would be greater thermal efficiency. [18]

To determine the insulation levels of windows, comparing their U_g *value* was the best method. U-value is a measure of a material's ability to conduct heat. The lower the U_g of the glazing, the better the material would be at keeping heat from escaping. A double glazed window would have a U_g value of around 1.2 and a triple glazed window could be as low as 0.6. From comparing U_g values, clearly triple glazing would be the better choice for insulation therefore it would be the type of window used in houses.

For added temperature control, windows could also be tinted or solar control glass could be used in order to reduce excessive solar heat from entering homes. However, this would most likely not prove to be greatly beneficial as with the location of the site, solar heat is not a large concern. In fact, the design of homes was specifically designed to allow solar heat to enter homes and keep them warm, reducing the need for additional heating.

Insulating floors

For floor insulation, polyurethane spray would be the most suitable insulation type for houses. Polyurethane spray was viewed as the best form of insulation out of all of the different floor insulation types, such as insulation boards, insulating screed, etc. It had a very good seal, and was very effective at insulating. The main advantages associated with polyurethane spray is that it would have very fast installation time and there would be greater variation for different floor insulation thicknesses. Although, a drawback of this installation method was that it would be fairly expensive.

Heating of Buildings

Energy Use Category	Approximate House Size	Average Annual Gas Usage (kWh)
Low	Flat or 1-bedroom house; 1-2 people	7,500
Medium	2-3 bedroom house; 2-3 people	11,500
High	4+ bedroom home; 4-5 people	17,000

Table 4: Estimates of average annual household gas consumption by energy use category [19]

The figures in Table 4 show an average of annual gas use depending on the type of house and its energy use. As expected, the size of a house is proportional to the typical annual gas use. Therefore, it was important to ensure the gas used in homes was not put to waste and trapped effectively within it. Where possible we tried to reduce the amount of natural gas needed to heat homes by using other renewable alternatives. This was particularly important for the larger homes as there was a fairly great difference in gas consumption, of 9,500 kWh per year, between larger houses and smaller ones.

Geothermal Heating

Geothermal energy refers to the heat generated and stored in the ground and it is a source of low-carbon, renewable energy. It is also possible to harvest the heat from the ground and use it to heat homes, as an alternative to using gas or oil boilers [20]. In our community, we decided that heat from the ground should be used to heat buildings as there were a variety of other methods to power the settlement but not many sustainable ways to heat it.

Ground source heat pumps (GSHPs) were considered the most energy-efficient technology for heating the air and water in homes. They were chosen over the similar air-source heat pump because their ability to heat buildings was much greater so they could be relied upon as the main source of heating. Therefore, a backup gas boiler would not be needed. [21]

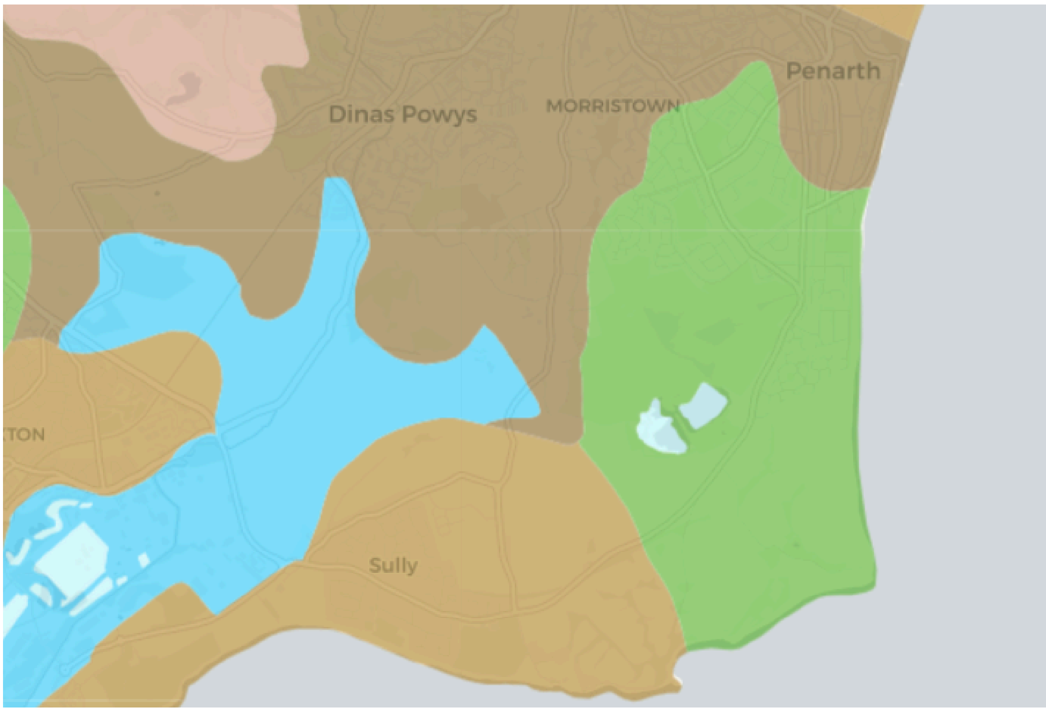
GSHPs harvest heat from the ground. The ground typically would have a constant temperature throughout the year so a GSHP would be a reliable source of heating. The thermal properties near the surface of the ground can be seen in Table 5.

Depth	Thermal Properties
Surface layer (0-1 m)	Temperature is very sensitive to sunlight and weather
Shallow layer (8–20 m)	The thermal mass of ground causes temperature variation to decrease exponentially with depth until it is close to the local annual average air temperature; it also lags behind the surface temperature, so that the peak temperature is about 6 months after the surface peak temperature
Deeper layer (>20 m)	Temperature is effectively constant, rising about 0.025 °C per metre (according to the geothermal gradient)

Table 5: Layers of ground and their thermal properties [22, 23]

The site had a variety of ground types which are shown in Figure 13. All four of the types were some kind of clay. This meant that the ground was either a part of the “dry clay” or “wet clay” category of ground types. We decided to make the assumption that the ground was “wet clay” as this required the most piping so there would not be a risk of installing too little piping [23]. On top of this, based on Figure 13, the site was likely more wet than it was dry so planning for this extreme ensured that the heating system would work no matter how wet or dry the ground really was.

The boundary for wet clay’s deeper layer was 18.0m. Therefore the length of GSHP’s piping would have to be at least 18m.



	Loamy and clayey floodplain soils with naturally high groundwater
	Slightly acid loamy and clayey soils with impeded drainage
	Freely draining slightly acid but base-rich soils
	Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils

Figure 13: The ground types at the selected site

Design of Ground Source Heat Pumps

The design of the GSHP was split into the collector and heat pump.

The heat pump's primary function was to pump heat from underground collectors and circulate it around the building. The heat pump would make use of a heat-carrying fluid which absorbs the heat from the ground via the collector. The fluid would then be pumped up to the surface by the pumping unit and would transfer its heat to water in a boiler via conduction. The water in the boiler then circulates the house (heat would be emitted in radiators), the fluid would then be pumped back underground so it could collect more heat. The process then repeats. A liquid-to-water heat pump would be used as this could be integrated with the design of conventional radiators and underfloor heating systems. The heat of the water in the radiator or underfloor heating unit would heat the air in the building and provide a comfortable temperature for people inside. An illustration of this process is shown in Figure 14.

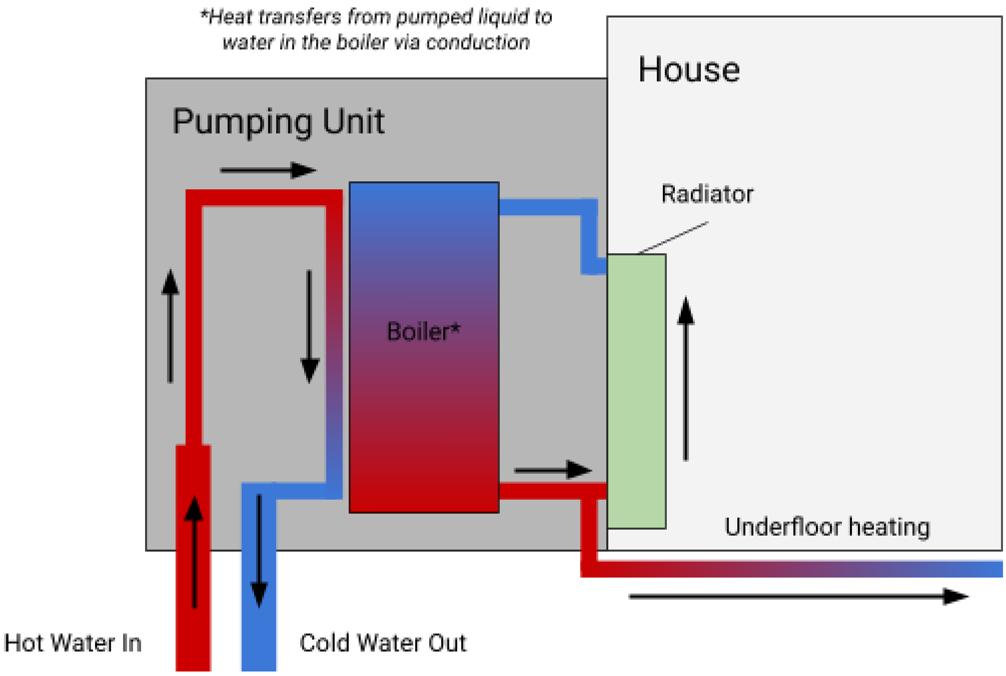


Figure 14: The design of the artificial housing heating system

Generally, GSHPs are not able to produce as high temperatures as conventional gas boilers. Therefore, in the community they would have to provide passive heating to the building - keeping it at a constant, comfortable temperature for long periods of time. As a result, GSHPs would be kept on at all times so they would be able to constantly provide heat. Keeping GSHPs on also would help avoid the large delay in heating while the GSHP was starting up, as GSHPs have a longer start-up time before they could start producing heat.

As for the collector, we decided that a ground collector should be used as not all houses had a nearby source of water. We could have used horizontal or vertical ground collectors, both of which can be seen in Figure 15 alongside other possible types of collectors.

Using a horizontal collector involved a closed loop of pipes being laid out horizontally in a plane within the ground trench. As a result inorder to install them a large trench would need to be dug, with a large enough area to fit the loops. This was fine if they only needed to be fitted at a shallow depth. However, for our application collectors had to be at least 18m below the surface. Digging a horizontal trench at depths below 18m would be an expensive process and so we decided to use vertical collectors as they were significantly easier to install. Vertical collectors would have to be fitted at lengths longer than 18m so the surface area of pipes that were below the 18m threshold could be maximised, and therefore sufficient heat could be harvested at a constant temperature.

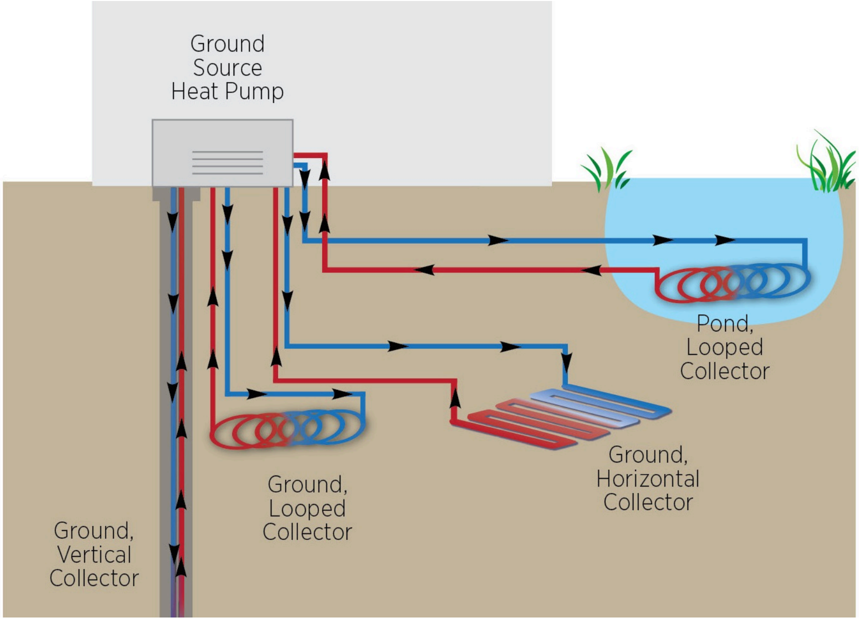


Figure 15: The possible collectors that could be used to harvest heat [24]

One vertical system would have several vertical collectors, each with boreholes drilled up to 122m. Deep fitted, U-shaped pipes would then be inserted into the boreholes. The pipes would carry a heat-carrying fluid that would absorb heat discharged by the ground. Vertical pipes could be integrated with piles that might be used for the structural support of the building. This would be a more efficient use of space [22]. For illustration, a detached house needing 10 kW of heating might need three boreholes 80 to 110 m (260 to 360 ft) deep [25]. With enough boreholes, a geothermal unit could completely heat a home.

Pipes should be very insulating at areas above the 18m threshold, when the ground temperature outside the pipe was not warm enough to transfer any usable heat to the fluid. This would avoid heat losses when pumping the heat-carrying fluid up to the home. However, below this depth, the piping must not be too insulating as heat should be able to be easily transferred to the fluid from the ground.

We also considered having a single centralised heating system that all homes could draw heat from. That way the entire village would be powered by a single heating pump system, with multiple boreholes, and all homes would draw in hot water from a grid. However, this would be inefficient unless incredibly insulating piping was used and it would be less scalable as if new homes were built, the entire heating system would have to be replaced with a higher capacity system.

Large Windows

All homes would have large windows as they provide passive solar heat. Having larger windows would allow more sunlight to enter the building and heat the inside. This would reduce the demand for artificial heating as the building would be naturally warm. Therefore less electricity would be needed to power the heat pumping system (or less natural gas would be consumed if a conventional boiler was used). The orientation of windows was also important as if windows were shadowed there would be no significant gain in heat. However, due to the standardised design of all homes, it would be impossible to orient them to the best angle on a specific building-by-building basis. Therefore, houses have been designed to have windows on all sides of the building.

Solar Cells

Another option we considered was using solar cells. They worked almost the exact same as the geothermal heat pumping system but instead used heat from the sun. The sun would have warmed the heat-carrying fluid inside the cell. The fluid would then be used to heat the home or, more commonly, provide hot water.

This was a perfectly acceptable, and actually very effective way of providing heating. However, solar cells would not be used. If geothermal was at a large enough scale then heating from solar cells would not be needed. Also, there was limited space available on the roofs of buildings, this space was prioritised for the use of solar panels, so electricity could be produced as solar energy would be one of the primary sources of electricity.

Power Generation and Distribution

Expected Power Usage

Estimates of average daily household electricity consumption in the UK were collected from various sources [19, 26, 27, 28], and are listed below in Table 6.

Energy Use Category	Approximate House Size	Average Daily Electricity Usage (kWh)
Low	Flat or 1-bedroom house; 1-2 people	4.93
Medium	2-3 bedroom house; 2-3 people	7.94
High	4+ bedroom home; 4-5 people	11.78

Table 6: Estimates of average daily household electricity consumption by energy use category

The expected electricity usage varied according to the size of the house and the number of people living in it. The community would have a variety of different household sizes, ranging from small 1-bedroom flats to large 5-bedroom houses. Therefore, the power generation system would need to be capable of supplying electricity to even the highest usage homes.

It is also important to note that because GSHPs and EV charging stations would be installed the actual daily electricity usage of houses in the community were greater than the estimates. This meant that the power generation system had to be able to power homes that were using more electricity than these estimated values.

Potential Methods of Power Production

Solar - This would involve installing photovoltaic panels either on the roofs of buildings or in a large nearby solar farm. It would work by absorbing sunlight and converting it into electricity that could be used by the grid. Since the sun was not a finite resource, and since harvesting sunlight would not emit any greenhouse gases, solar power was classified as a renewable, zero-carbon source and was therefore considered sustainable. Solar power was also highly effective, and if coupled with another form of energy, it would be able to generate a sufficient amount of electricity to supply the whole community. The major limitation of using solar energy was that it would only generate electricity when the sun was directly shining on it. This meant that during the night or if there was a lot of cloud cover, the photovoltaic panels would be incapable of producing any power and so a backup system would have to also be designed to meet power demand at all times.

Wind - Turbines would be used to harvest the kinetic energy from the motion of wind, and convert it into electricity through the use of a generator. Similar to solar power, it would harvest a zero-carbon, renewable source of energy so would have no negative impacts on the environment (after their installation). Turbines could either be large Horizontal Axis Wind Turbines (HAWTs) or smaller Vertical Axis Wind Turbines (VAWTs). HAWTs would be located slightly away from the settlement and would be capable of harvesting significantly larger amounts of power, at the expense of their aesthetic, noise pollution and damage to ecosystems [29]. These factors would have negative impacts on the local area and may drive residents away from the community. Therefore, smaller VAWTs fitted on the roofs of buildings or in artificial wind tunnels (created by building placement) would be better if wind were picked. Additionally, if wind speeds were to go below the selected wind turbines ‘cut in’ speed, the turbine would produce no electricity. Again, this meant that wind power would have to be coupled with another form of energy inorder to consistently meet demand.

Geothermal - This would involve harvesting the natural heat radiated by the ground inorder to produce electricity. In the selected site, geothermal hotspots were not of sufficient quality to produce power at scale [30]. Therefore they were not suitable as a renewable source of electricity. However, geothermal energy could be utilised by a heat pumping system to provide heating to buildings (as mentioned in **Housing**) as this would not require such a high quality geothermal resource. As a result, underground space was reserved for the geothermal piping needed for the heating system and so was not designed to be used for electricity generation.

Hydroelectric - Could have been used in various forms but most commonly involved water flowing through a turbine which could spin a generator to produce electricity. The site of the community was not near enough to a consistent supply of above-ground water capable of being used in this type of system. Therefore, it was not a suitable form of power.

Biomass - This refers to when organic matter, such as human waste; plant material; food waste; etc, is burnt to heat up a water reservoir, causing steam to spin a turbine. Most of the fuel provided to it would be renewable as it would often come from sources that could be regrown. Biomass generators were capable of producing large volumes of electricity. If a large enough generator was installed, then it could supply the entire settlement at peak demand. Therefore, it was a very good backup power system that could be used in the event the other selected sources could not produce enough electricity to meet the demand. Especially given how it would be fueled by matter found within the community (eg: human or food waste). The main associated risk was that certain substances, when burnt, release toxic gases that might pose a threat to nearby humans or to the local ecosystem. [31]

Design of Power Generation System

The power generation system would make use of 2 primary systems (solar and wind) and 1 redundancy/backup system (a biomass generator), all connected to a central power distribution hub. The distribution hub would also contain a power storage system. This is illustrated in Figure 16.

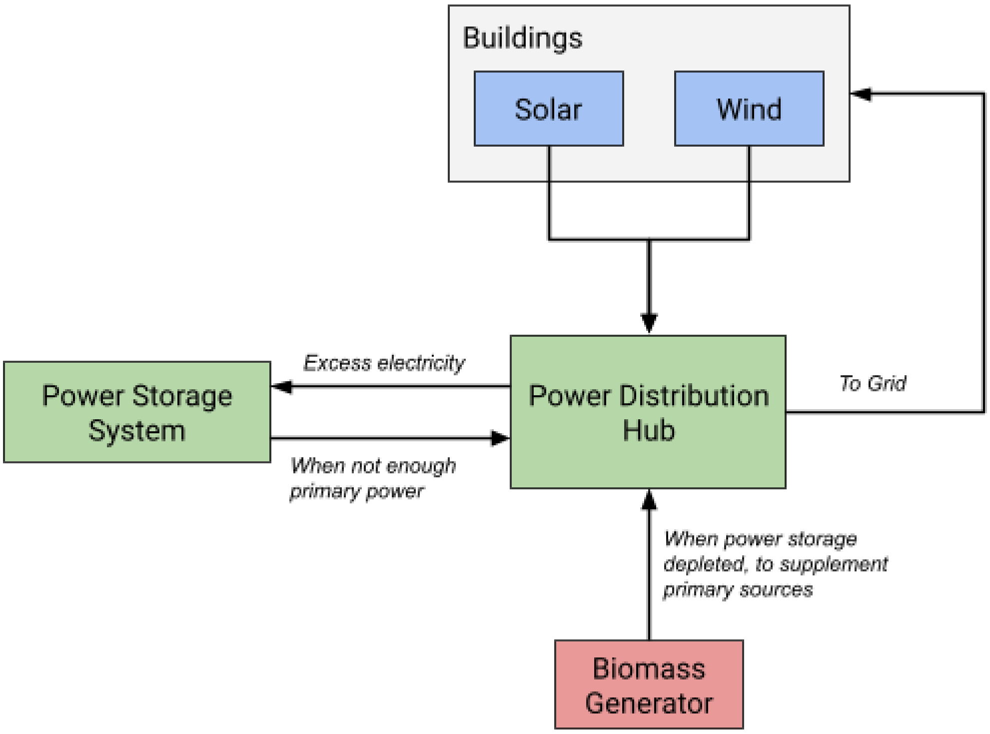


Figure 16: The power generation and distribution system

Solar and wind would be used together to make up the primary sources of electricity. They would be installed near or attached to buildings. The electricity produced by these systems would then be transferred to a central power distribution hub. The hub would be responsible for redistributing the electricity to areas based on their current consumption. If excess electricity was being produced by primary systems (the current supply of electricity was greater than the current consumption) then the excess would be stored in the power storage system. In the event that the current supply of electricity was less than the current demand, the power distribution hub would first draw out all excess energy stored in the power storage system and distribute it to the community's power grid in order to meet demand. Once the power storage had been depleted, a biomass generator would be turned on to meet the remaining demand. The biomass generator would only burn waste and therefore produce electricity at the rate required to meet the demand. An emergency connection to the national grid would also exist, in the event the biomass generator fails.

Solar Panels

We estimated that most solar panels produce about 350 to 450 watts of power [32]. It was reasonable to assume that for a community built with the main purpose of being sustainable, it would be financially justified to spend more money to use higher power solar panels. *EnergySage* listed various high wattage models, we picked the *SunPower SPR-M440-H* solar panel due to its high wattage per square metre. It had a wattage of 440W and its dimensions were 1872 mm by 1032 mm [33]. These panels would be installed on the roofs of buildings, which were specially designed for solar panels as to maximise the amount of sunlight that fell upon them thereby maximising power output.

Solar power, as mentioned earlier, was highly dependent on the amount of sunlight available. The following table estimates the average daily sunshine hours, per month for an average year in Cardiff (which was representative of the selected site).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Daily Sunlight Hours	1:44	2:41	3:58	5:38	6:21	6:54	6:09	6:01	4:40	3:21	1:56	1:30

Table 7: Average daily sunlight hours by month in Cardiff [34]

Solar panels would be really effective during the day, during summer months, as the average daylight hours was greater and there was significantly less cloud cover. However, during the winter sunlight hours were low and during the night power could not be produced. This could be overcome with an effective storage system or by using the power produced by solar panels to supplement other power sources. The solar panels would not be able to consistently meet the power demand of the settlement on their own.

The daily **energy** produced by a single solar panel, *E,* (measured in kWh), was calculated as the product of the panel's output **power**, *P*, (in kW) and the **time** it was able to collect power, *t* (equal to the sunlight hours), using the formula:

$$E = P \cdot t$$

[35] (1)

Given that the output power of the chosen solar panel was 440 W (0.44 kW), the energy that could be produced by the solar panel in the month with the most and least sunlight hours, June and December respectively, was calculated. This result is shown in Table 8.

Month	Energy Produced (kWh)
June (Highest)	3.04
December (Lowest)	0.66

Table 8: Energy produced by solar panels at the months with the highest and lowest average daily sunshine hours

Buildings would have 10 solar panels installed on the roof, which means the power output of each 10-panel system would be between 6.6 kWh and 30.4 kWh. Therefore on a day with a high number of sunshine hours (mainly during the summer months), just solar panels alone would be able to power a whole house with a significant amount of excess electricity for distribution to other facilities and/or storage. However, during the winter, when electricity consumption would likely increase (as residents would likely turn on heating), there would be less electricity available from the solar panels so they would need to be supplemented with the other primary system, wind turbines.

Wind Turbines

Solar panels are often unable to meet power demand (for instance, at night or during thick cloud cover). Conveniently, the months with the least sunshine hours are also, on average, the months with highest wind speeds. Therefore, for this community, when little electricity would be produced by solar panels, there would likely be greater electricity produced by wind turbines. This means that pairing wind turbines and solar panels together would have an increased likelihood of consistently meeting the electricity demand using the primary systems alone.

Wind speeds in Cardiff are fairly consistent at around 4.23 ms^{-1} to 5.91 ms^{-1} (8.22 knots to 11.49 knots) across the year [36]. This meant that the majority of the time wind turbines would be able to produce electricity. However, specific predictions of the energy output from wind turbines was harder to obtain. There would also be the possibility that there would be no wind available for a long period of time, in which case wind turbines would not be able to provide any electricity so the community would have to be powered using the other methods.

There were several types of wind turbine that could have been used, each with their own advantages and disadvantages. However, we decided to install a large number of smaller Vertical Axis Wind Turbines (VAWTs). Which, as opposed to conventional wind turbines, spin around a vertical axis. This would avoid some of the potential problems of installing a larger structure so close to the residents, most notably how noisy they would be for people living nearby. Using VAWTs would be significantly quieter, and therefore would be more likely to encourage residents to the community. However due to their size, on an individual basis each wind turbine would produce significantly less power and would be less efficient than their alternatives. This could be overcome by installing a large number of VAWTs to meet the same power output.

Turbines would be installed in various locations, these include but are not limited to, the roofs of houses; the tops of street lamps and utility poles; and in narrow gaps between buildings where the wind would be focused and its speed would be slightly greater, often referred to as “wind tunnels” or “urban canyons” (while a greater wind speed may be guaranteed on such a small scale, research has found this phenomenon occurs in larger cities [37]). A diagram of wind turbine locations can be seen in Figure 17.

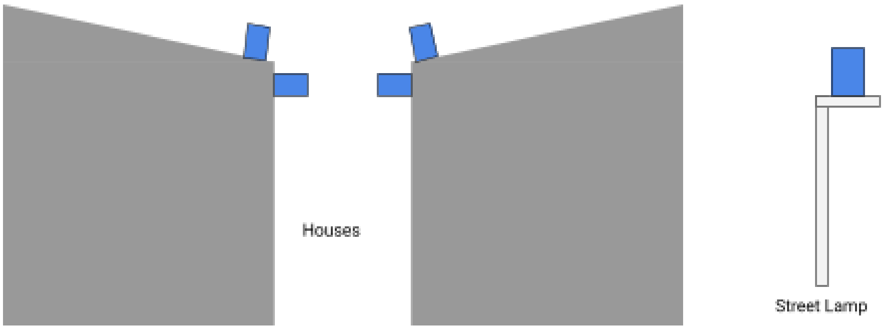


Figure 17: The location of VAWT wind turbines

The installed wind turbines would be the *EN-600W-HX* VAWT model by *ENGELEC*. They are designed to be very compact VAWTs and can start producing electricity at very low wind speeds (with a cut-in speed of 2.5 ms^{-1}), which is a major issue with other wind turbine designs where a high wind speed is required to overcome the blades inertia and cause the turbine to “cut-in”. Therefore, it would be possible to produce electricity almost all the time, even though the actual power output would vary with wind speed. Additionally, the use of a VAWT meant that electricity could be generated regardless of which direction the wind was flowing, which again was a problem with conventional designs. The chosen model was also designed to be integrated with solar panel units allowing them to be placed on utility poles and street lamps together, see Figure 18. [38]

Figure 18: shows the *EN-600W-HX* VAWT mounted on a pole with solar panels

Using Equation (1) and assuming that wind would blow for 24 hours a day, very approximate estimates for power output from a singular wind turbine unit were obtained at the highest and lowest average wind speeds, 4.23 m/s and 5.91 m/s respectively. These are shown in Table 9.

Wind Speed (ms^{-1})	**Power** (kW)	**Energy Produced** (kWh)
4.23	0.06580	1.58
5.91	0.15984	3.84

Table 9: Energy produced by wind turbines at highest and lowest average wind speeds, power data extracted from power curve on [38] and WebPlotDigitizer [39]

Evidently, the energy output from wind turbines per day was comparable to the energy output of the solar panels, and is on average higher. Therefore, they would be an effective source of power to be used within the community.

Biomass Generator

Wind and solar power are both fairly inconsistent sources of energy, with large spells of little to no wind and/or sunlight available. Therefore, a third source of energy would be needed in the event that the combined power output from solar panels and wind turbines (and batteries are depleted) was insufficient. This could be done by a variety of electricity sources that could produce a specific output of electricity at a fairly quick start-up time. However, very few of these methods were considered to be sustainable.

A general purpose biomass generator would be installed near the location of the central power distribution hub and power storage area. It would be fuelled by organic waste produced within the community, for example, food waste and human waste. This would be a far more sustainable fuel source in comparison to using fossil fuels like coal, oil or natural gas. The generator would consist of several furnaces which have a combined maximum power output above that of the expected power usage of the entire settlement. Therefore, if no power was available from other sources, the generator would be able to supply the entire community. Additionally, in order to be more sustainable and less wasteful the generator system would have a method of only loading a specific quantity of fuel into the furnace to produce the specific amount of energy that would be needed to supply the settlement. The power output would likely be much greater than would be consumed on a day-to-day basis but it was important that the whole community could run off of biomass in the event other methods fail.

There was a risk that burning some substances (such as plastic - which may not have been separated from food waste properly) could release toxic gases into the air when burnt. This could cause harm to residents that live near the generator or to the local environment. To reduce this risk, waste would be carefully sorted before being loaded into the furnace.

Despite this it would still be difficult to fully overcome this issue, therefore the generator would be located away from the most densely populated and most biodiverse areas.

Design of Power Storage System

When deciding how the energy created by the generation systems would be stored we had two general ideas.

- **A battery based system** - which would convert electrical energy into chemical energy for storage. The best way of doing this would be to use lithium-ion batteries as lithium has a high electrochemical potential and can accumulate large amounts of energy. [40]

- **A non-chemical based approach** - this would make use of another form of energy, such as gravitational potential energy, to store the produced electrical energy. In real life, this approach is often carried out using two reservoirs and a hydroelectric dam. Electrical energy would be used to pump water to an upper reservoir, transferring the energy to gravitational potential energy held in the water, where it could then be stored. When the energy is needed, the water would be released converting the energy into kinetic energy which would be harvested by a hydroelectric dam. [41]

We decided to use a battery based system instead of the hydroelectric one. This was because the site where the settlement would be constructed was fairly flat and most of the land was at the same elevation. Therefore, it would be very difficult to have an upper and lower reservoir with significant enough height difference without artificially raising or lowering one of them - which could be very expensive. Therefore the battery system would be a much easier and cost effective method to use.

One of the issues with batteries was that they can be very expensive. In the UK some can cost as much as £7,000 for only a small amount of storage space. Additionally, they only have a 10 year lifespan so would need frequent replacement which again would be very expensive but would also lead to sustainability issues with their disposal and manufacture. Disposing of the chemicals could be difficult and manufacturing batteries would release a lot of carbon dioxide into the atmosphere. This was not as sustainable as we would have liked it to be but at the moment it was one of the best options available and so would be used. However, in the future manufacturing techniques may become more sustainable making batteries a more attractive solution. [42]

Resource Management

Generally the majority of resources consumed by a community (for example, food and water) are not fully depleted and often large volumes are wasted. In the UK, 9.52 million tonnes of food is thrown away per year - equivalent to 25 million tonnes of CO_2. [43]

Water efficiency is also an important concern. It is estimated that 25% of the UK's daily water consumption is wasted [44]. This wastes the energy and resources that would be used to process and deliver the water, often with an environmental impact. Therefore, this was a major focus for improving the sustainability of the community.

Rainwater Collection

To reduce the amount of water the community would need to consume from potentially environmentally taxing water treatment facilities, the community would need to collect water from natural sources, like rain. South Wales experiences a lot of rainfall which means that there would be a sufficient volume of water available to supply the community [45].

This solution would involve the community having a rainwater collection system set up on almost all buildings and in other areas where a large amount of water would collect, such as streets. There would be various ways to go from this point. Rainwater would be untreated and so in order to be consumed or used in most household applications (such as cleaning, cooking, etc) there would have to be some form of water treatment for it [46]. This would involve connecting the rainwater to the water treatment network, leading to a greater demand on water treatment facilities. However, there was also an option to only use collected rainwater in applications where there was no risk when using untreated water. For example: watering plants, washing a car or to supply water to radiators.

We explored using rainwater in only certain applications and not feeding it into the treatment system. A lot of the treated water being drawn from the main water grid would be used for purposes where untreated water could be used. Therefore, the community would encourage residents to use rainwater collected from their own home and stored outside, on their property. This would have a lower environmental impact as treatment would only take place on water that needed to go through the process.

We specifically designed the roofs of houses to be slightly slanted so that rainwater would not collect on the roof and cause structural damage. This design choice would also help direct the flow of rainwater into gutters that then feed the rainwater store. There would be a minor filtering process using a mesh filter to ensure that particles (such as small rocks, leaves, or dirt) would not feed into the store. Water from the store would then be used as a medium to carry heat around the house in radiators or underfloor heating and as a supply for residents to use water outside. Figure 19 shows an illustration of a rainwater collection system, similar to the one that would be used.

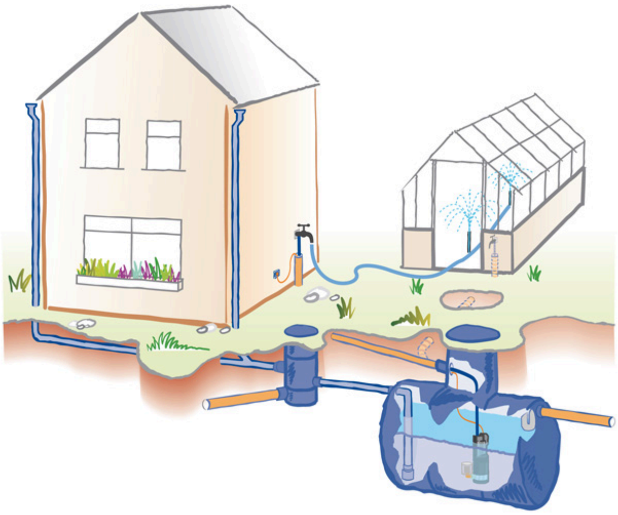


Figure 19: A rainwater collection and storage system [47]

Water Treatment

The site was located very near an existing water treatment plant facility operated by Welsh Water, called Cog Moors. This facility was responsible for treating water from Dinas Powys, Sully, Penarth, Barry, and the West of Cardiff. Welsh Water has heavily invested in making the facility carbon-neutral and ensuring it operated sustainably. One such example was the introduction of an Advanced Anaerobic Digestion facility which produces biogas from the biological digestion of sewage sludge. This biogas could then be used to generate electricity which powers the rest of the plant. [48, 49]

We originally considered implementing a bespoke water treatment facility in the settlement that would be designed to operate more sustainably than existing local facilities. However, due to the close proximity of the site to an existing water treatment facility it would make more sense to just use this facility for the community's water treatment. Moreover, Cog Moors was one of Welsh Water's more sustainable facilities so there was not much scope for improvement to make it more sustainable.

We also considered using greywater to reduce the volume of water being passed through the treatment system. It was decided that greywater had too many logistical issues, such as storage and processing requirements, that made using it not worth its potential costs. Greywater achieved the same goal as rainwater harvesting so was not necessarily needed.

Sustainable Urban Drainage System

A Sustainable Urban Drainage System (SuDS) would provide an alternative to directly channelling surface water through pipes and sewers. Generally in urban environments, much of the surface is made up of non-permeable surfaces such as concrete or stone, resulting in natural infiltration being limited, in other words the rain cannot soak into the ground. In a conventional drainage system this rainwater, or drainage, would be diverted through a network of pipes. If these drains reach capacity, they would not be able to discharge water quickly enough which could lead to flooding. Flooding causes a whole host of negative environmental impacts such as causing harm to local ecology, damaging habitats and soil erosion. [50]

In order to combat these negative impacts, we decided that the community would make use of two key components of sustainable drainage systems: source control and site control.

Source Control

This involved dealing with run-off water at, or close to, the surface where rainfall lands, such as the roofs of buildings. The community would make extensive use of source control measures, most notably the use of a rainwater collection system which is outlined earlier in this report. This would reduce the volume of water that must flow through the drainage system as the rainwater would instead be collected and stored at the home where the rain lands. This would in turn reduce the risk of flooding and help mitigate other negative impacts of drainage systems becoming overflown.

Additionally, the roofs of all buildings would be layered with vegetation. Originally designed to increase biodiversity by providing habitats, these “green roofs” would double up as a means of reducing water entering the drainage system. The vegetation of the roof would intercept rainwater which would either evaporate or be absorbed by the plants, thereby preventing the water from reaching the drains. [51]

Site Control

This involved dealing with water over a larger area, for example the entire community. Rainwater that lands in an urban area typically cannot infiltrate into the soil and become groundwater. This rainwater therefore has to enter the conventional drainage system which leads to the aforementioned issues. We needed to find a way of transporting this rainwater from a built-up area to a part of the community where infiltration of water into the soil was possible. This could be done through the use of swales. Swales are fairly shallow, broad, vegetated channels that store or transport the runoff water to an area where groundwater infiltration would be possible. During this process the vegetation would also remove pollutants from the water making it less ecologically harmful later on. One of the major benefits of using swales was that they would be easy to incorporate into landscaping so

Figure 20: An example of a swale in an urban area [52]

would not look out of place within the community. An example of a swale can be seen in Figure 20. [52]

Another option would be to construct paving, or sections of paving, out of a permeable material. An example of this would be a filter drain, which is a trench lined with gravel allowing water to seep through and infiltrate groundwater stores below the paved surface. Similar to a swale, this would reduce the volume of runoff water that enters the drainage system preventing the risk of flooding.

Overall sustainable urban drainage systems reduce the volume of runoff water that would enter the pipes and drains. This would reduce the risk of flooding which in turn would prevent the negative environmental impacts such as harm to the local environment and soil erosion, thereby helping the community to operate more sustainably.

Composting

The average household in the UK produces 1.96 kg of food waste per day [43]. This means that the average weekly household food waste would be 13.72 kg. For the community the food waste produced by the 221 households would be approximately 3,032 kg per week. Food waste would be collected weekly and transported to a food waste processing facility, located next to the power distribution hub. At this facility, the majority of food waste would be stored for use in the biomass generator. However, there would almost always be an excess of food waste needing disposal because of the limited space available for storage.

Processing of excess food waste would take place at a community-level composting facility. Composting would be used to convert food waste into organic matter that could act as plant fertiliser and could therefore improve the biological and chemical properties of the soil. Compost would be used to aid the growth of plants within the community, such as those in public parks, on the roadside, or in gardens. This would enhance local soils and conserve natural ecology.

Transport and Infrastructure

Electric Vehicles

The community would be at the forefront of promoting sustainable and renewable technologies. It would be highly encouraged for residents to use electric vehicles - which would be charged at a charging station, powered by the power generation system mentioned earlier.

Electric Versus Petrol/Diesel Cars

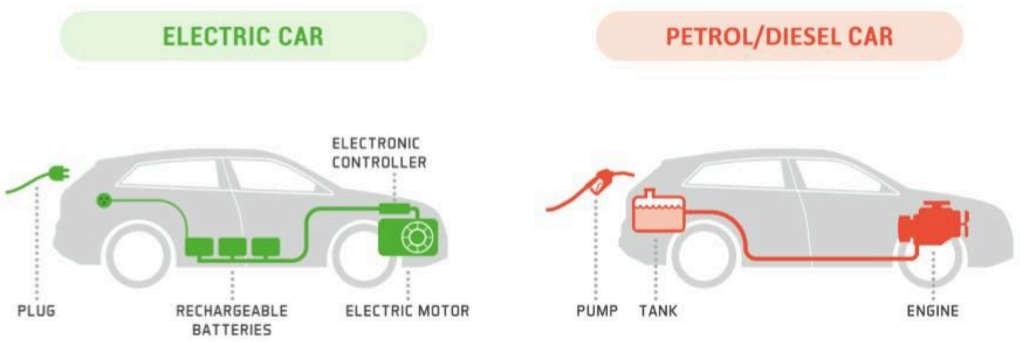


Figure 21: An electric car and a petrol/diesel car [53]

Despite looking the same as a conventional internal-combustion-engine vehicle - electric vehicles (EVs) operate differently. EVs make use of a traction battery pack to store electricity - electricity is then used by an electric traction motor to drive the vehicle's wheels. There are various EV models, some only use electricity (plug-in electric) whereas others use a combination of both electricity and conventional fuels (plug-in hybrid and hybrid-electric).

Types of Electric Vehicles

- **Plug-in electric** - This car purely relies on electricity. It does not require petrol or diesel to run - meaning it has no combustion engine nor a fuel generator. Instead it makes use of an electric traction motor. This means it does not release greenhouse gases like traditional cars. Plug-in electrics can be charged by being plugged into a source of electricity. [54]

- **Plug-in hybrid** - This car mainly runs using electricity but also has a traditional fuel engine, so can substitute out electricity for conventional fuels if required. This means that they have both an internal combustion engine and an electric traction motor. They produce some greenhouse gas emissions - but only when they run out of electricity. They can be charged by a source of electricity but also need to be refuelled. [55]

- **Hybrid-electric** - This car runs mainly on fuel but also contains an **electric generator** - which charges itself when the vehicle brakes. This energy is stored in a **traction battery pack** which is used to power the **electric traction motor.** This car also has an **internal combustion engine** which runs on traditional fuels. This allows residents to switch between a fuel and 'EV' mode at the touch of a button. It is a more cost-effective and clean alternative to the traditional car. Unlike the two plug-in models - this car cannot be recharged by an energy source. [56]

Plug-in electric vehicles release the least emissions, closely followed by the plug-in hybrid and then the hybrid-electric vehicle. A graphic of the annual emissions per vehicle can be seen in Figure 22.

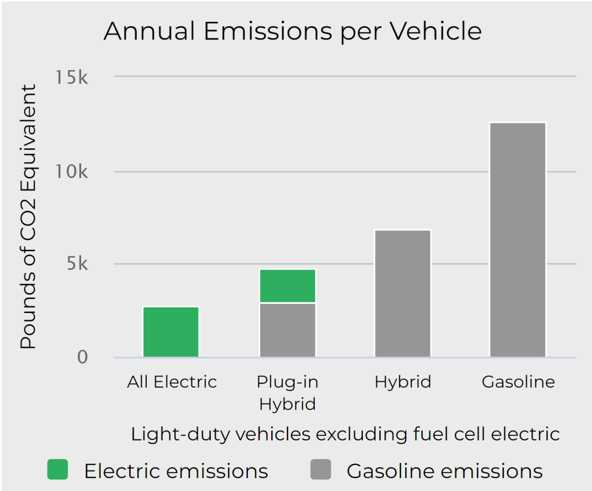


Figure 22: Graph of national average emissions per vehicle [57]

The implementation of charging stations at the community would be a 2 phase process.

- **Phase 1** - Having a community charging facility
- **Phase 2** - Installing charging stations in homes

Phase 1 - Community Charging Facility

Although the UK is fairly accommodating of electric vehicles (there are currently 53,029 charging stations in the UK [58]), it would be an unrealistic expectation for all members of the community to have purely electric cars. We anticipate that the most common car within the community would most likely be the plug-in hybrid. Our charging facility would therefore have to have conventional fuel pumps in addition to EV charging stations, so residents could use a variety of vehicle types. Generally a community of this size would have at least 1 fuel station - so it makes sense to include access to conventional fuels.

When determining the number of charging stations, we needed to account for the charging stations' longer charge times and the shorter range of electric vehicles, leading to more frequent charging sessions. Petrol cars have an average range of 700 km compared to the average range of EV's which is between 340 - 509 km [53, 59, 60]. If all residents had an electric car - we would need between 11 and 16 charging stations (the method for these calculations are accessible in **Appendix A.5**) Due to financial constraints however, we have decided to only have around 8. This would be scalable however, and as more people choose to purchase electrical cars, the number of EV charging stations could increase.

In regards to the number of fuel pumps, the average fuel station has 8 pumps on the higher end [61]. We would have 6 fuel pumps in the charging stations - which would be slightly less than the industry standard. This would be acceptable as we anticipate that the majority of residents would have some form of electric vehicle. We also wanted to discourage the use of internal-combustion-engine vehicles as these are large environmental polluters.

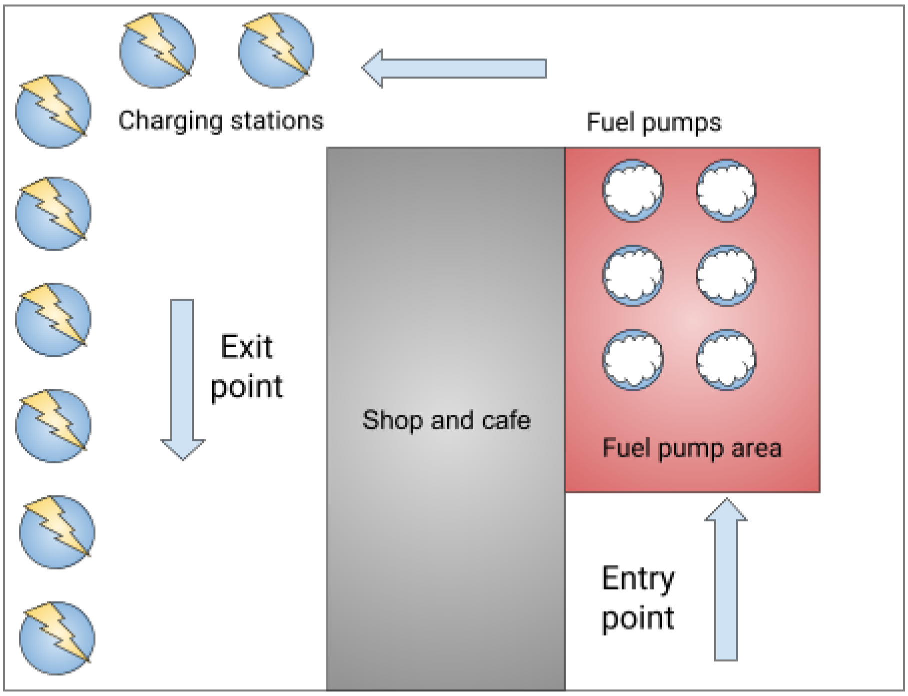


Figure 23: An example of the drive through fuel and charging facility. It is loosely based on [62]

Design of Phase 1 Charging Stations

Figure 24: Different types of charging stations - it is worth noting that the charge times are only based on the time it takes to charge an EV and not a hybrid [63]

We considered 3 types of charging stations, these are shown in Figure 24.

- **Level 1** - Level 1 chargers work at 120 volts. They can charge a plug-in electric vehicle, from 0 to 80%, in 40-50+ hours. However, it only takes them around 5-6 hours to do this for a plug-in hybrid vehicle. Additionally, these chargers only cost around £450. [64, 65]

- **Level 2** - Level 2 chargers work at 240 volts. They can charge a plug-in electric vehicle, from 0 to 80%, in 4-10 hours. However, it only takes them around 1-2 hours to do this to a plug-in hybrid vehicle. The chargers cost around £5,700. [65, 66]

- **Level 3** - Level 3 chargers work at 480 - 1000 volts. They can charge a plug-in electric vehicle, from 0 to 80%, in 20 mins to 1 hour. However, the majority of plug-in hybrids don't work with level 3 chargers. [66, 67]

For the charging station, it is likely that level 2 chargers would be used. Eighty percent of publicly available EV chargers are level 2 in the US and it makes sense to implement industry standard chargers. Due to the majority of the residents using plug-in hybrids, we would be unable to use level 3 chargers. Additionally, the lower charge time that level 3 chargers provide would not be worth the additional £33,890 per charger.

Overall, the cost of 8 chargers in the community would be around £40k.

Phase 2 - Implementing Charging Stations in Homes

We would recommend the implementation of charging stations in homes several years after the construction and initial operation of the community. This would occur when the price of charging units had decreased and their efficiency had increased.

We needed to take into account the type of EV that each person would be using, as this would affect the type of charger which would be required:

- **Plug-hybrids:** For anyone using a plug-hybrid, it would be optimal to use a level 1 charger. These chargers would be cost-effective (currently they are only £475 to install) and only take around 5-6 hours to charge a plug hybrid from 0% to 80%. This means that plug-in hybrids could easily be charged overnight, and potentially even faster in the future.

- **Plug-in electric:** Level 1 chargers are a less feasible option if someone had a plug-in electric car, but level 2 chargers should be used. This is due to the fact that for Level 1 chargers, it can take 40-50+ hours to charge from 0 to 80% making them extremely inefficient. They cannot even fully charge the EV over two consecutive full days. Level 2 chargers are able to charge plug-in electric vehicles in only 4-10 hours (from 0 to 80% - depending on the vehicle). This is a much more reasonable timeframe. However, level 2 chargers can be expensive, but may become cheaper in the future.

How charging stations would be powered

These charging stations would be implemented into the house's garage so that the vehicles could be left to charge while not in use. The stations would draw power from the house's ring main - which would be powered via the distribution hub and the house's power generation system, see **Power Generation and Distribution.**

Intelligent Charging Infrastructure

The biggest concern with having EV's was the dilemma of a vehicle having only a half-charged battery in the morning - especially if someone had to drive a fairly long distance.

Although the technology is not currently available, we would hope to add intelligent charging infrastructure to the community in the future. Intelligent charging infrastructure would allow optimisation of energy usage so that little energy would be wasted. It is a system that would analyse various factors such as: demand on the ring main/generator system, the user's driving patterns and electricity rates. This would ensure that users would have an EV that would most likely be sufficiently charged. Additionally, an intelligent charging system would allow energy flow between the EV and the ring main. This would enable any surplus energy from EV to be fed back into the ring main if it was required. This would allow energy to be fed back into the grid itself. [67]

Electric Bus Network

Public transport was a very important consideration when designing the community, if residents could not easily access the community or nearby towns and cities, residents would not be inclined to live in the community. For many residents public transport would be their only form of transportation. This could be because they did not own a vehicle, could not drive (due to their age or medical status) or for other reasons could not use their car. Public transportation would be particularly important for accessing workplaces and education. For instance, the closest secondary school to the edge of the settlement was approximately 3.8 km away which translates to a 55 minute walk.

Approximately 23% of the population do not own a vehicle, of which approximately 44% say they struggle to access medical services [68]. This would correspond to a large portion of the community's residents, consisting mainly of elderly, young and disabled individuals as well as those who could not afford a vehicle. It was crucial that a form of public transport infrastructure existed so these individuals could have access to services and amenities available in other communities.

Another more utilitarian factor for public transport was the ability to reduce congestion. Due to the majority of the roads in the area of our settlement being single-lane country roads, the level of congestion would be extremely high. Approximately 298 people within the community would be working, of which 205 would be commuting to nearby towns and cities on a daily basis [6, 69]. In a typical residential area, 189 of these individuals would take their own vehicle to work. This would lead to a significantly large volume of traffic on the roads into and out of the community. Additionally, by implementing public transport there would be less greenhouse gas emissions from vehicles as a single electric bus would be used in place of multiple cars.

Design of Buses

The design of buses had to be practical for the road conditions near the community. Buses had to be able to go on country lanes and run without pause during peak hours. For the project, we assumed that peak hours are 7:30 - 9 am and 4:30 - 6:30 pm and off peak hours were all the remaining time. However, in real life these figures are incredibly dependent on the location. Buses would need to be fully charged for at least two periods of the day, each 90 minutes long. We aimed for buses to be able to transport at least 200 people during peak hours.

We decided to use a single-deck electric bus with a maximum capacity of 73 passengers (45 seated and 28 standing). Single-deck buses would be used because they were considered safer for use on narrow country lanes. Buses would have 230 kWh batteries located on the roof, this is illustrated in Figure 25 along with the other design elements of the electric bus. [70, 71]

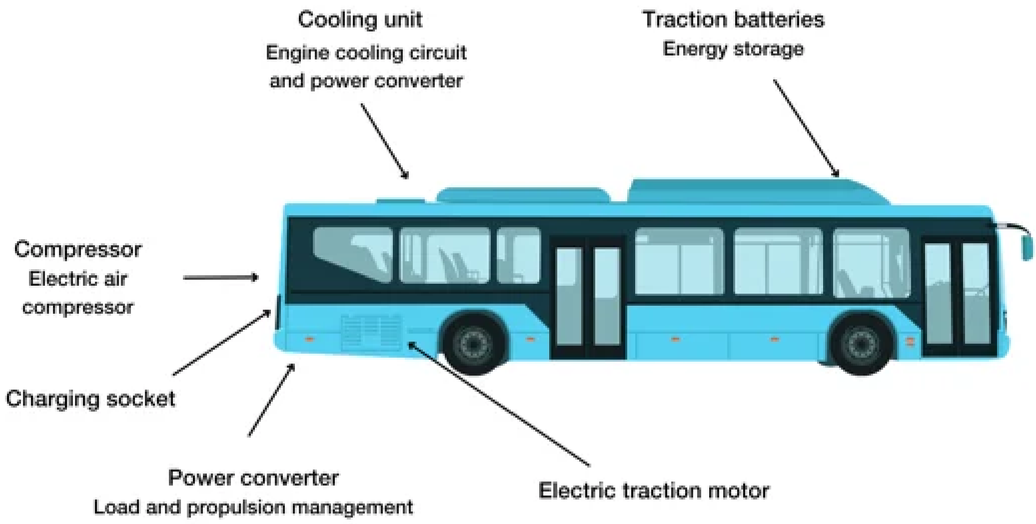


Figure 25: A diagram of design of the electric bus [72]

One of the initial public transport routes is shown in Figure 26. It would be 14.9 km long with 9 stops: 3 in neighbouring towns, 2 near schools, 2 within the community itself, 1 near Cadoxton train station (in Barry) and 1 being the charging station/depot.

Figure 26: One of the electric bus routes, an interactive version can be found in [73]

Buses would have an average speed of 25 mph (based on the variety of 20 mph and 30 mph speed limits). Without stops it would take buses 21.5 minutes to complete the route. Allowing 1.5 minutes per stop, the total length of each route would be 35 mins.

There would be two buses active during peak hours. With 205 expected passengers and 45 seats on each bus, 4.5 bus trips would be needed to give each passenger a seat. A total of 5 routes would be completed within the 90 minute period. The first bus would leave at the start of the on peak period and the second one would leave 17.5 minutes later, the buses would then repeat their routes for the remainder of the on peak period. During off peak hours, only one bus would be in use. There would be no bus services past 11:30 pm.

Depot Storage, Charging and Timetabling

Buses would be charged using a *Heliox Flex* 180 kW charger [74]. It would charge two on peak buses and two off peak at separate times and be powered by the community power grid, see **Power Generation and Distribution**.

A total of 4 buses would be stored in a bus depot overnight. On peak buses would be stored between 6:30 pm and 7 am. One off peak bus would be stored between 6:30 pm and 9 am, the other would be stored between 11:30 pm - 2 pm.

Table 10 shows a timetable for when buses would be in use, in storage or being charged. On peak buses are numbered 1 and 2, off peak buses are numbered 3 and 4.

Time	On road	Off road (not charging)	Charging (60kW)	Charging (120kW)	Charging (180kW)
7:30 - 9:00	1, 2	3	4		
9:00 - 14:00	3		1, 2, 4		
14:00 - 16:30	4	1, 2			3
16:30 - 18:30	1, 2	3			4
18:30 - 23:30	3	4*	1, 2, 4**		
23:30 - 7:30		4	1, 2, 3		

Table 10: The electric bus timetable. On peak hours are highlighted in blue.
**if fully charged ** if not fully charged*

Charge Times

Buses will use 230 kWh batteries. They could be charged at various degrees of power.

Power (kWh)	**Charge Time** (hours)
60	3.83
120	1.92
180	1.27

Table 11: Charge times of electric buses at various degrees of power

With a fully charged battery buses’ would have a range of 155 km meaning 10 routes, taking approximately 5.8 hours could be completed with one full charge.

Evaluation

The design of the bus network does not take into consideration the strain on other transport networks. For example, we did not conduct research into the capacity of Cadoxton train station. With approximately 102 residents potentially commuting from the community to large cities like Cardiff, there would be major overcrowding within the station and on carriages. Additionally, having buses on roads would cause additional congestion. If we had more time, we could have considered this additional strain. However, such things are incredibly difficult to predict without significant time and resources.

Environment

Carbon Offsetting

When designing the community we made our best attempts to ensure that both the construction process and day-to-day operations were as low carbon as possible. However, one of the only ways to ensure that the community operations would be completely carbon-neutral was to offset any potential carbon dioxide emissions. One of the most effective ways of doing this would be to plant vegetation, in particular trees, which would act as carbon sinks, absorbing carbon dioxide for biological processes. The community would have a range of different trees, described below, all with unique advantages and disadvantages. The variation in tree species would also help promote biodiversity as a range of habitats would be available to wildlife.

Types of Trees

- **Fast-Growing Trees** - advantageous for carbon offset projects due to their rapid carbon sequestration. They offer a quick return on investment and would be suitable for short-term projects. However, they come with a downside – a short lifespan, requiring frequent replanting. Additionally, their wood density would be limited, making them less effective for long-term carbon sequestration, and there would be a risk of competition with food crops for land.

- **Hardwood Trees** - known for their high wood density, making them effective for long-term carbon sequestration. They provide durable and versatile wood products and boast a long lifespan. However, the trade-off would be their slower growth compared to fast-growing species. They may require more time to sequester a significant amount of carbon, and the initial investment and time to maturity would be higher.

- **Evergreen Trees** - contribute to carbon sequestration year-round, providing a continuous environmental benefit. They also offer habitat for wildlife and could act as windbreaks and erosion control. On the downside, they tend to have slower to moderate growth and may be less effective in colder climates. Their wood density would also be limited compared to hardwoods.

- **Nitrogen-Fixing Trees** - bring benefits beyond carbon sequestration by improving soil fertility, enhancing biodiversity, and facilitating the growth of other plants. However, they may require specific soil conditions, and some species may be invasive. The effectiveness of carbon sequestration would also vary among different species.

- **Local Indigenous Species** - well-adapted to the local climate, supporting local ecosystems and promoting biodiversity. However, they may have slower growth compared to exotic species, and their availability may be limited in certain regions. There would also be a potential for disease or pest susceptibility.

Environmental Concerns

A number of environmental concerns were identified, these are listed below.

Environmental Impacts of the Community

- The construction phase of the community which would include the use of heavy machinery, activity of construction team personnel and the import of materials. These would have impacts on soil and water pollution, local wildlife, local trees and the wider global environment through the emission of greenhouse gases.

- The impact of construction and operation of infrastructure and services including transport links, internet services, sewage systems and connection to the electrical and gas grid.

- The global impact of the operation of the community once the community had been constructed such as the emission of greenhouse gases.

Mitigating the Environmental Impact

- Ensuring sustainable building practices were used to minimise impact of the construction phase of the community. This would include the use of local providers for materials to avoid transporting resources from other parts of the planet - a process that releases a lot of greenhouse gases.

- The design of the community would be as advanced and eco-friendly as possible. For example: systems would be highly efficient; buildings would have high quality insulation; the community would make use of renewable energy; it would blend into landscape; and would not cause local environmental issues.

- Carbon-footprint offsetting via environmental improvement plans would be used as part of the building project, such as tree-planting, to reduce the carbon footprint of the community.

Great Crested Newts

In almost all sites in the UK, great crested newts are present. They are a protected species and so they should be carefully relocated prior to the start of construction. There are few ways to avoid great crested newts so during our design we made the assumption that all great crested newts could be sustainably relocated.

Conclusion

The project proved a sustainable community of 500 residents in 221 homes could be built at the selected site in South Wales. Many of the sustainable methods we used proved to be effective at ensuring the whole design operated sustainably and did not cause harm to the local environment.

The design of the community took into account five of the most important areas of sustainable design: housing, power generation and distribution, resource and waste management, transport and infrastructure and environment. It showed that a design could be created in a way that satisfies the requirements of each of these areas. The design takes into account both the importance of sustainability and the requirements of residents such as their personal needs, their occupations and wider economic factors. This ensures the community is also practical and livable for residents so that it is successful in the long-term.

The team believes that future sustainable communities designed in Wales or the UK could take inspiration from the design of this community. While it was specifically designed for this location and size, the same design principles could be replicated and applied to any other part of the country or scaled up to any amount of residents. Aspects of the project could easily be implemented into the design of new housing estates which are attempting to be more sustainable, some could even be installed in existing housing estates. Other aspects, such as the design of houses, would be significantly more complex to introduce and would require the new community to be built around them.

The overall cost of building a sustainable community would be significantly more than the cost of building a standard housing estate. Many of the technologies and techniques used in the community are novel so are significantly more expensive at the moment compared to what they would be in the future when they have become more commonplace. Additionally, some technologies have not been fully developed yet and so would not be ready to be used in actual developments. As these technologies advance, building sustainable communities will become easier and more cost-effective.

Evaluation

It was difficult to evaluate the successes of the project against the original project brief because the project brief was intentionally vague to allow us to explore the topic areas that suited our team's skills and interests. Whatsmore, this project was only hypothetical and it would be nearly impossible to accurately prototype. This meant it was difficult to test whether the suggestions we made would, in practice, be as effective as we believed they were. Despite this, there were a few areas that we believed could have been explored in more detail or if we had taken a different approach would have yielded a different outcome.

Our approach to collecting data for the parameters of the project could have been significantly improved upon. We compiled a list of only five towns, which was nowhere near what would be considered a reliable sample. In retrospect, we should have sampled about fifteen towns in a variety of locations around Wales. The sample towns also should have been the same level of rurality as the selected site of the community. For example, the five sample towns were located rather far away from other settlements and in rural areas of Wales. However, our community was located very close to Cardiff making it comparably more urban than the sample towns. This meant that the data we collected about population density, required amenities, household composition and total floor area was related to rural areas. Therefore it may not be completely representative of a community located at our selected site. Additionally, some of the data collected was nearly two decades out of date. This was for a fair reason, as our team did not have the skills or resources to conduct a meta-analysis on rural areas to the same quality as the Welsh Government. However, this still may have impacted the results of our analysis and therefore impacted the parameters that we used when designing the community.

When developing the project we wanted to focus more on the qualitative areas of sustainable community design. This involved researching and designing what the methods and different features of the community would be and how they would work. This meant that the report was not as quantitative as it could have been. For example, we designed how the power generation system would work in great detail, including deciding where units would be located, how they would work and how they would connect together to form a power grid. We calculated the expected power output of power generation units (eg: a solar panel array or a VAWT) and we related this back to the estimated values of power generation. However, we could have also looked at the expected power consumption of the entire community over an entire day and calculated exactly how many power generation units would be needed to power it and when they would be most effective. We could have gone into more quantitative detail in a number of areas but we decided not to so we could cover a wider scope of the project brief as this satisfied the different interests of the team. Each one of the five categories we identified (such as power generation) could easily have been their own projects. However, our approach involved a design which considered various design areas, which meant that we did not have the time to go into this more quantitative detail.

Early on in the project we had the idea to develop a physical scale model of the whole community to illustrate how it would be laid out and help people visualise it at the presentation day. We ultimately dismissed this idea because we did not have the adequate time or resources to plan, gather resources for and construct the physical model. We instead opted for a digital model which we were really proud of and would also serve the purpose of showing the community layout. However, if we had the time to construct a physical model alongside the CAD model, it would have been a better visualisation of the community.

In designing this community we did not consider the difficulty of implementing our suggestions nor how expensive they would be. The project was intended to be an example of the most effective design for a sustainable community, when cost and time restraints are not the main focus. However, in some cases we did consider the cost of a design as it would be wholly unreasonable to expect it to be implemented. In reality, the construction of this sustainable community would be a very expensive and long procedure. However, this is to be expected with any large construction project and most modern housing estates take several years to complete. The process to take this conceptual idea and develop it in real life would involve a detailed blueprint of every aspect of the community (including exact measurements for houses, exact quantities of materials, etc). Surveying of the site would take place to determine environmental conditions. Planning permission would then need to be obtained. This could take several years and would face objections from local residents. After this the construction of the community would take place. This entire process is time consuming and expensive. If this project were to be constructed in real life it would cost tens of millions of pounds, although it is reasonable to assume that residents would be willing to pay more for property that is sustainable. Regardless, the profit margin for a company developing a sustainable community is likely to be less than a standard housing estate.

However, we believe the project was a success overall. The project covered all five categories we originally identified: housing, power generation and distribution, resource and waste management, transport and infrastructure and environment. Each of these areas were explored in great detail, with extensive research being conducted on each one. This research then informed us as we were designing the solutions to the problems and requirements of each category. For example, our houses were designed using CAD modelling software which helped readers to visualise the designs of buildings. The design of houses took into account the requirements of other categories, such as the need for flat surfaces when mounting solar panels and VAWTs on roofs; the need for a large enclosed space to store an EV charger; the fact large windows should be used to reduce demand on the GSHP; the design of a vegetative layer as a part of the SuDS. This was just one example of how the design of the community was well thought out and considered from a range of different angles. This also highlights how the team was able to work together and communicate effectively our different ideas so that the overall design was cohesive and consistent.

The community achieved its most fundamental goal, being sustainable. It made use of a variety of sustainable techniques. If only a few of the designs were implemented into new housing estates, they would be significantly more sustainable and environmentally friendly.

Recommendations

The list of recommendations, beyond this report, to the company responsible for developing and/or managing this sustainable community are listed below.

- Identify a method of generating income to be used to fund community facilities such as the central power distribution hub, power generation system, composting service, drainage system and EV charging facility. The council could provide partial or full funding, through taxation, for the majority of these services as they would reduce the demand on other council services. However, the council may not fund facilities that cost more to run than their conventional alternatives. The company should aim to make a profit on services like electricity, compost and EV charging to fund other community services.

- Consider establishing level 2, 240 volt EV charging stations in the homes of residents. The chargers should be located in the reserved space in the garage of the house. Residents would be expected to pay for their own EV charging station and should not be forced to have one. However, the company could aim to install the same EV charger, from the same provider in all houses at the same time as this would reduce the individual cost of installation.

- The company should phase out fuel pumps in the EV charging facility and replace them with additional EV charging stations until EV charging stations are installed in homes.

- Regularly update the power generation and distribution infrastructure and GSHP systems with more-efficient models to ensure less energy is being wasted. This should not be done excessively as to waste resources in the manufacture of these items.

- Explore environmental charity initiatives in the United Kingdom and the rest of the planet. The company could explore awareness campaigns for residents to ensure that they are living sustainably within the community, which would aid the sustainable designs that have been proposed.

Acknowledgements

As a team we would like to express our appreciation for Jeremy Morgan, the South East Wales Coordinator for the Engineering Education Scheme Wales. He was responsible for setting the original project brief. Throughout the project he would make time to have meetings with the team about our progress, he would answer any questions we had and give feedback and suggestions which we ultimately incorporated into the final report. His enthusiasm, guidance and expertise has been invaluable in the completion of this project and he has helped us develop new skills that will be useful in our future careers. We are extremely grateful for his support.

We would also like to express our gratitude for Sian Cornwell-Shaw, who through her role as a surveyor, gave us guidance, expertise and feedback. She spoke to us about how in her industry a project like this would be designed and constructed. Her high quality feedback allowed us to ensure the design of the project was more robust and similar to what would be developed in real life. She gave us an insight into the process of surveying, gaining planning permission and construction - all of which were included in the writing of this report.

We would like to acknowledge Kings Monkton School and our Head of Sixth Form, Mrs Alexander for their time, passion and enthusiasm in allowing us to take part in EESW and supplying us with the time and resources needed to complete it to a satisfactory standard.

Finally, we would like to thank STEM Cymru and the Engineering Education Scheme Wales for the invaluable and exciting opportunity.

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Appendix A: Design Methodology

A.1. Calculating Population Density

When calculating population density we used the following formula:

$$\frac{population}{area}$$

The results we obtained can be found below:

Town	Nomis area name[1]	Population (people)	Area (km²)	Population Density (population/km²)
Llandogo	W37000241	547	0.476	1,149
Ffairfach	W37000344	534	0.213	2,507
Nantgaredig	W37000151	524	0.685	765
Llanarth	W37000068	503	0.283	1,777

Average population density: **1,549.5 pop/km²**, nearest whole value: **1,550 pop/km²**

Determining the Area of a Town

An illustration of how the area of a town was determined using the Google Maps measure tool is shown below. In this example the town was Ffairfach.

[1] Refers to the area name used by Nomis (a branch of ONS) to access local area reports. Local area reports can be found here: https://www.nomisweb.co.uk/reports/localarea

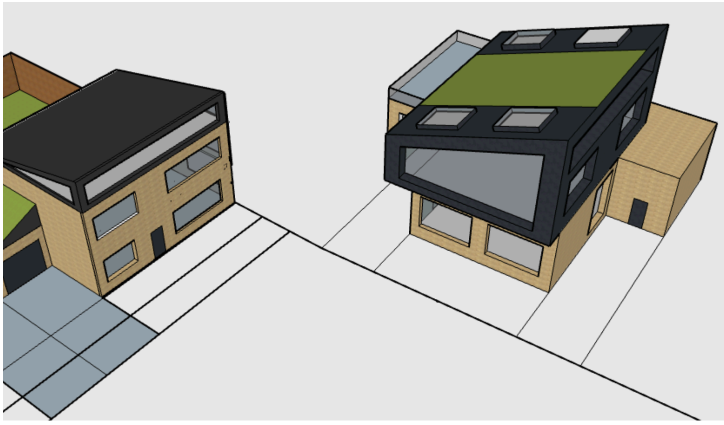
A.2. Potential Settlement Locations

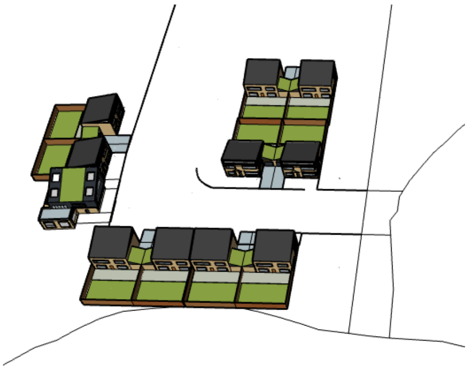
All five potential locations considered are listed below:

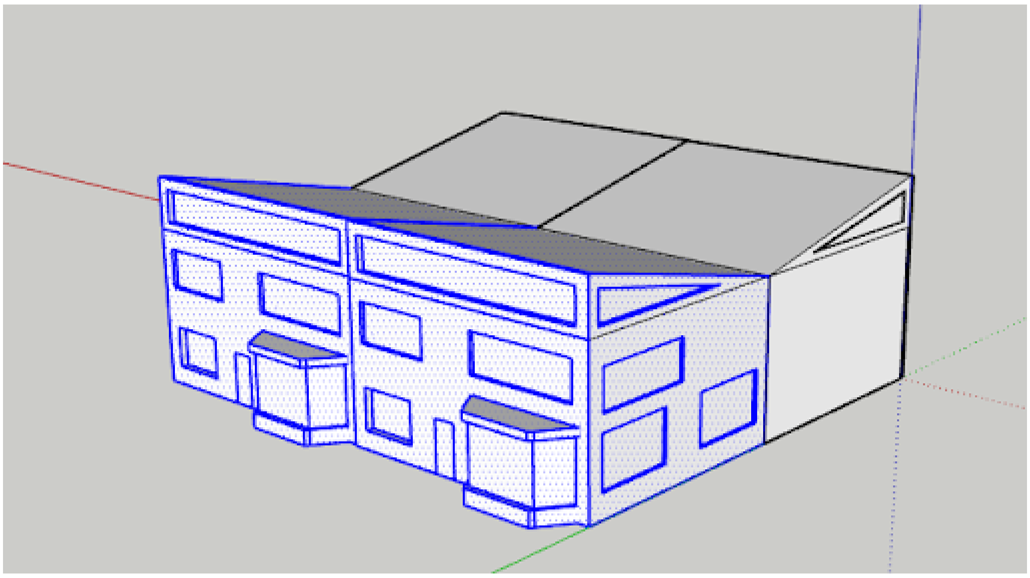
- The south west of Cardiff near Dinas Powys, Sully, Penarth and Barry. This was referred to as location one and was the selected site.
- The north west of Cardiff near Taffs Well, Radyr and Nantgarw. This was referred to as location two and was a close contender for being selected.
- The north east of Cardiff between Cardiff and Newport. This was dismissed early on.
- The west of Cardiff near Llantrisant. This was dismissed early on.
- The English side of the Severn Bridge in the area between Chittening, Pilning and Bristol. This was dismissed early on.

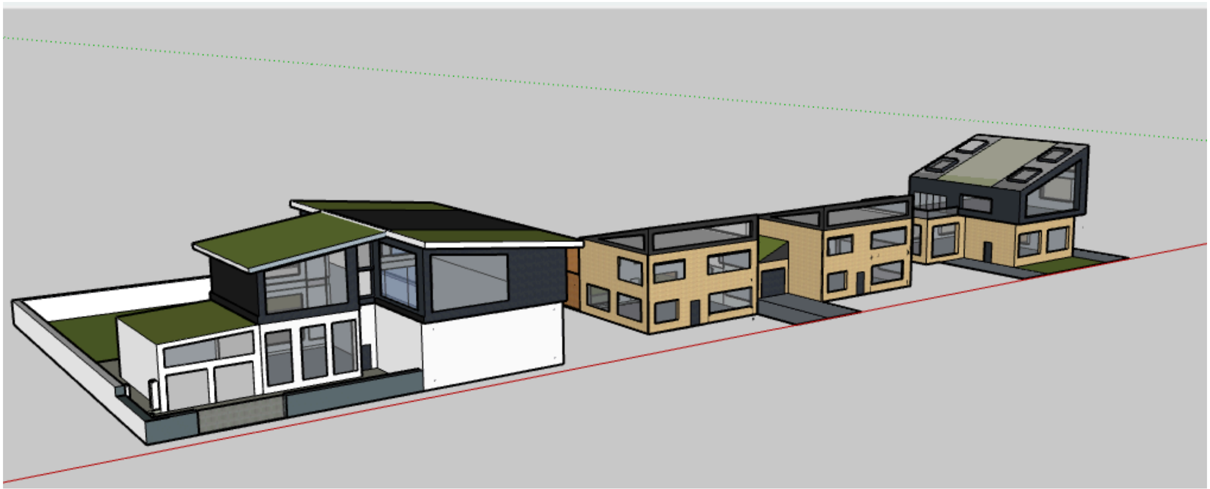
A.3. Additional Images of the CAD Modelling Process of The Community

The following images were developed during the project as a part of the modelling of houses and designing the layout of the community. Selected images were included in the main report, some additional ones are included in this appendix.



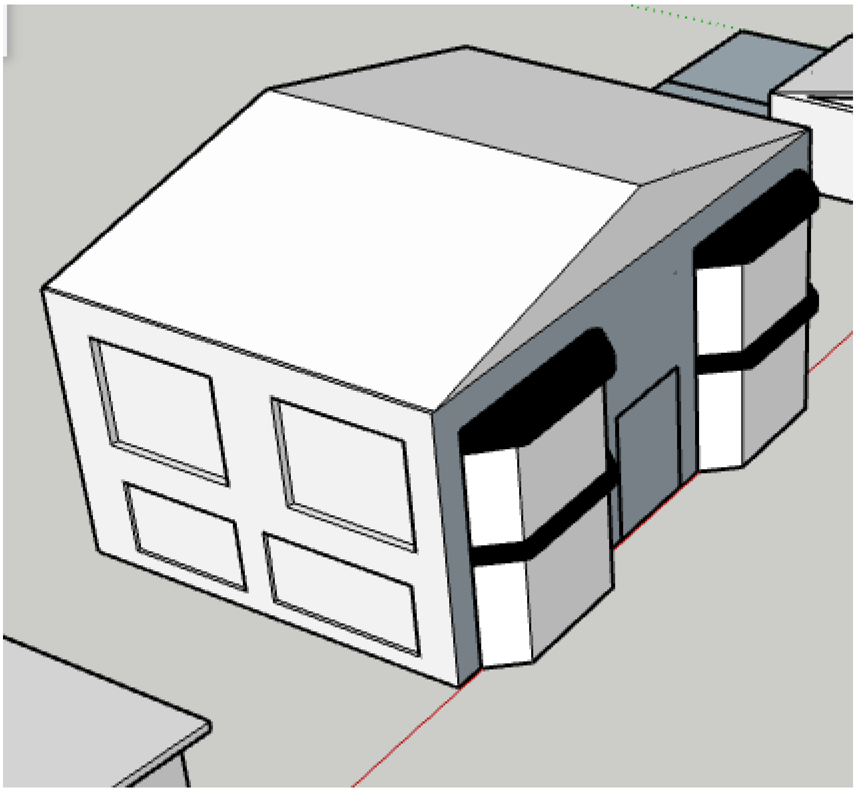






A.4. Initial Flat Design

The image below shows the initial design of the flats. Each unit was made up of 4 flats. It was redesigned during the project as the team was not too happy with the design as they felt it was a bit “clunky”. The bay windows were removed as they ended up making the house look too “old fashioned” and because we wanted to go with a more modern style.



A.5. Calculation of the Number of Charging Stations Needed

$$Number\ of\ pumps\ needed\ for\ petrol\ vehicles\ =\ 8\ pumps$$

Upper Bound of Pumps Needed

$$Lower\ bound\ of\ EV\ range\ =\ 340\ km$$
$$EV\ range\ relative\ to\ petrol\ range\ = \frac{340}{700} = 0.4857$$
$$Number\ of\ pumps\ needed\ =\ \frac{8}{0.4857} \approx 16\ pumps$$

Lower Bound of Pumps Needed

$$Upper\ bound\ of\ EV\ range\ =\ 509\ km$$
$$EV\ range\ relative\ to\ petrol\ range\ = \frac{509}{700} = 0.7271$$
$$Number\ of\ pumps\ needed\ =\ \frac{8}{0.7271} \approx 11\ pumps$$

Appendix B: Project Management

B.1. Example of the Planning Technique

Below is an example of how headings were broken down into smaller subheadings and assigned a status dropdown that was used to track progress of the project This was the method we used in our project.

Design

- Case study - BedZED ???? **Non-priority**
- Housing
  - Number of houses needed + why **In Progress**
  - Housing requirements (big windows, etc - link to point below) **In Progress**
  - Explain the need for a standardised design **Not Started**
  - Settlement layout **Content Completed**
  - Design of exterior + rationale **Content Completed**
  - Greenery on roofs, but consider solar panels (go into detail) **In Progress**
  - Insulation (cavity, etc) + materials **Not Started**
  - Harvesting natural heat to prevent excess use of heating **Write Up Completed**
  - Savings of water (?) **Non-priority**
  - Designs of other building types like church, shop, etc using standard **Not Started**
- Power Distribution
  - Expected power usages **Write Up Completed**
  - Evaluation of various methods of production **Write Up Completed**
  - Design of primary/secondary system **Write Up Completed**
  - Solar power (explained) + fitting to houses **Write Up Completed**
  - Wind power (explained) + locations (wind tunnels, etc) / fitting to houses

B.2. Dates and Topics of Meetings

Note: All team members were present at almost every meeting. All meetings also involved going around the group checking progress and brainstorming ideas.

Meetings with external people are highlighted in blue.

Date of Meeting	Meeting Topic
8 November 2023	Initial meeting with EESW organisers
10 November 2023	First team meeting to discuss project brief
17 November 2023	Site selection, review project parameters, initial design of power system
24 November 2023	Community layout, requirements of house design, power storage system
1 December 2023	Progress and feedback meeting, with EESW
6 December 2023	Team progress check in
12 December 2023	Planning and structure of technical report
12 January 2024	Team progress check in and report writing
23 January 2024	Team progress check in
25 January 2024	Progress and feedback meeting, with EESW
2 February 2024	Progress and feedback meeting, with EESW and chartered surveyor
7 February 2024	Team progress check in
20 February 2024	Final team meeting ahead of submission