# Developing a Methodology for appraising Building Integrated Low or Zero Carbon Technologies

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A thesis submitted in fulfilment of the requirements for the degree
of Master in Philosophy
in
Mechanical Engineering

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING**

2012

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## Acknowledgments

I would like to thank Dr Nick Kelly and Dr Tom Scanlon for their help and advice during the project, they have always been eager to provide guidance and give clarification on any issues faced. I would also like to thank Dr Michael Kummert and Paul Strachan for sparing their valuable time, to help me with issues regarding modelling of Solar Thermal and Solar PV technologies.

I have been grateful to be given industry support during this project and am thankful to my industry supervisors Neil Hall and Malcolm Tait of KJ Tait Engineers Ltd. They provided me with a perspective on the requirements for the design of building integrated Low or Zero Carbon technologies for a modern building services engineer.

Last but not the least; I would like to thank my family for their support and encouragement throughout the duration of the project.

# Abstract

The advent of environmentally driven building regulations, rising energy costs, and heightened client awareness of energy related issues has increased the demand for assessing the potential of Low or Zero Carbon (LZC) energy supply systems. There are many software tools that have been developed to assist the designer in carrying out performance appraisals ranging from simple device models for feasibility assessments through to integrated simulation tools for detailed analyses of building integrated technologies. However, it is seldom the case that any one software tool can undertake a complete appraisal for building integrated LZC technologies. Usually a range of tools is required for different technology options at different design stages. Therefore there is a clear need for an effective assessment methodology for the use of software in LZC technology analysis. The objective of this project was to develop this methodology and apply the software (termed a “toolkit”) to a ‘real design’ problem. The results from the analysis are discussed and clarity for presenting these results to non-technical stakeholders, within the design process, has been emphasised.

# Contents

## Table of Figures

# Tables

# Chapter 1 – Introduction

## Aim

Building designers are now increasingly asked to assess the potential of low carbon energy systems for their projects, due to the recent increase in ‘green’ legislation and hence heightened client awareness of energy related issues. A rigorous assessment is required of the suitability and marketability of LZC technologies for building integrated applications. The aim of this work is to develop such an assessment methodology and its integration within a wider low carbon modelling and design process. The outcome of this assessment was to highlight the better performing technologies for the client to make an informed decision. The LZC technologies appraisal outcome would be based on three performance parameters; to be designed for optimum energy yield, to present significant emissions reduction and to be an economically feasible solution. However, in real terms, this process may well be influenced by client, legislative and planning requirements, this is taken into account when detailing recommendations in the final report.

The use of building integrated Low or Zero Carbon (LZC) technologies historically has been limited in industry due to a lack of expert knowledge and minimal commercial interest. Traditionally developers have been more than comfortable with utilising gas heating and grid electricity; they provide buildings with a secure energy supply that meets demand and is supported by existing infrastructure. However buildings account for 25% of the world’s energy consumption **(1)** and contribute for 46% of the UK’s carbon emissions **(2)**. Hence reducing the $CO_2$ emissions contribution from UK buildings is a vital component for meeting various international treaties (Kyoto protocol, Climate Change Bill). Legislation associated with these commitments, for example local authority sustainability plans, is now compelling designers to take LZC technologies more seriously. The introduction of this “Low Carbon” legislation has been driving the utilisation of energy efficiency measures and the integration of LZC technologies within buildings.

## Legislation

Legislation is the most important driving factor for reducing the carbon footprint of a building. Developers are forced to comply with all mandatory building legislation or risk facing hefty fines and further complications in the build process. More recent legislative measures being introduced for buildings are focusing heavily on reduced carbon emissions **(3,4,5,6)**. This ultimately promotes the installation of building integrated LZC technologies and the implementation of energy efficiency measures.

The building regulations are constantly reviewed to meet the growing demand for better, safer and more accessible buildings. Any changes necessary are brought into operation after consultation with all interested parties. The current Scottish Building Regulations for 2010 are a result of gradual development over the last 50 years, with the more recent emphasis being on the energy performance of buildings **(3)**.

To help meet the UK's climate change commitments, there have been numerous government policies been developed, such as the Energy White Paper, 2007, the Climate Change Act, 2008, and subsequent UK Low Carbon Transition Plan, 2009. Furthermore, the Department of Energy and Climate Change (DECC) was formed in October 2008, responsible for all energy policy and tackling global climate change on behalf of the UK. From the above it is concluded that there is huge interest in improving the energy performance of new and existing buildings for the UK. Specific policy instruments in relation to buildings include:

- UK Building Regulations (Section 6 (Scotland), Part L (England & Wales))
- City/Local Authority Sustainability Plans (e.g. the London Plan)
- Energy Performance of Buildings Directive (EPBD)

The UK Government has established that building energy usage is targeted in order to meet its commitment as outlined in the Kyoto Protocol agreement. The new building regulations are focused on reducing carbon emissions with more stringent requirements upon building energy performance **(3,4).** There are city policies such as the London Plan and Edinburgh Standard for Sustainable buildings **(7,8)**, demanding a mandatory reduction in carbon emissions by way of renewable energy, beyond compliance requirements. Other local authorities are expected to follow the trend, where employing LZC technologies becomes mandatory for complying with planning procedures and also the building regulations. The Scottish government have implemented an amendment to the current building standards, introducing a 30% further reduction in carbon emissions in comparison to the 2007 building regulations **(3)**.

The EU Energy Performance of Buildings Directive (EPBD) was introduced in the UK from January 2006 with a three-year implementation period ending January 2009. Its objective is to improve energy efficiency and reduce carbon emissions as part of the government strategy to achieve a sustainable environment and meet climate change targets agreed under the Kyoto Protocol **(9)**. The advent of the European Energy Performance of Buildings Directive (EPBD) is set to drive changes in the way buildings are designed and maintained. The directive applies to all EU countries and requires them to enhance their building regulations, introduce energy certification of buildings and period inspection of air conditioning and boiler plant **(10).** It introduces Energy Performance Certificates (EPC) for every commercial or residential building constructed, sold or leased; barring a few exceptions. EPC's label the property with an energy efficiency rating and provide recommendations for cost-effective improvements. Buildings with air-conditioning equipment greater than 12kW peak output are obliged by the EPBD to have their system inspected by an energy assessor. These inspections highlight improvements in operation and provide recommendations for reducing electricity consumption, hence operating costs and carbon emissions. Overall the EPBD legislates for implementation of energy efficiency measures through two mechanisms, EPC's and AC inspections to improve the energy performance of buildings. This legislation relates to energy in-use rather than hypothetical energy consumption and this is further emphasised within the CRC Energy Efficiency scheme **(5).**

The CRC Energy Efficiency scheme is the UK's mandatory climate change and energy saving scheme **(11).** This scheme commenced in April 2010, and is mandatory for all large organisations (not intensive energy users) that consumed greater than 6000MWh/annum of half hourly metered electricity through 2008. In brief terms, the organisations involved need to demonstrate a reduction in building energy usage. A league table is formed taking into account energy consumption figures for preceding years, for the organisation. This then identifies a consequential bonus/penalty payment reflecting upon the organisations energy saving efforts in comparison to their fellow competitors. The CRC Energy Efficiency scheme is central to the UK's strategy for improving energy efficiency and reducing carbon dioxide ($CO_2$) emissions, as set out in the Climate Change Act 2008 **(12)**. It has been designed to raise awareness in large organisations, especially at senior level, and encourage change in behaviour and infrastructure.

Further, environmental assessment methods such as the Building Research Establishment Environmental Assessment Method, otherwise known as BREEAM, are not a legislative requirement but have become a desirable within client specifications. BREEAM intends to set the standard for best practice in sustainable design and is a measure of the buildings environmental performance. BREEAM uses a straightforward scoring system that is transparent and backed by evidence based research **(13)**. Credits are awarded in BREEAM for the buildings environmentally friendly features ranging from ecological to transport to energy usage. The environmental rating can range from Pass to Outstanding and is determined by the amount of credits obtained through assessment by a BREEAM assessor. A significant amount of credits can be obtained by installing renewable energy technologies on-site and for reducing carbon emissions below base level (minimum requirement for compliance with building regulations). If property developers achieve a high BREEAM rating for their buildings, it enables them to exploit the increasing demand for a low carbon building. Despite the evident benefits of BREEAM assessments, BREEAM is a virtual scoring system that credits the existence of a technology rather than to assess its capability. It addresses intent and therefore cannot measure the true environmental effectiveness of a building; this requires the analysis of operational data. For the purposes of this study, a more proactive approach is sought to determine the effectiveness of installing LZC technologies for the particular building.

The government along with passing legislation is also incentivising the inclusion of LZC technologies within building integrated applications. Previously this has been done through providing monetary assistance for installations by way of grant schemes. This however is superseded by the introduction of the Feed In Tariffs (FITs) for electricity generating technologies and the Renewable Heat Incentive (RHI) for heat generating technologies. These are introduced through the implementation of the Climate Change Act, 2008 **(12)**. These incentivisation schemes are discussed further in Chapter 2 when looking at incentives for installing small scale renewable energy technologies.

There is a considerable amount of legislation and incentivisation driving the inclusion of LZC technologies within the building design process. This is a recent shift in attention for the building designer. A robust design process and extensive skills base is required for achieving the governments low carbon targets in theory and application.

## Building Design Engineering

The UK's building services engineering sector had an annual turnover of £17bn in 2007, employing 523,000 individuals in over 58,310 businesses **(14).** This diverse sector of the UK economy covers a wide range of skills providing essential design, installation and maintenance services for industrial, commercial and domestic clients. It further plays a major role in the areas of sustainable development and energy efficiency. The emphasis on sustainability is a recent addition to a building consultants remit and does not just extend to new-build projects. As regulation becomes more stringent, building services engineers are increasingly concerned with how existing buildings can incorporate sustainable development appropriately. They are now forced to consider LZC energy supply systems to meet legislative requirements **(3,4).**

Sustainable development of buildings demands the consultant to consider and apply energy efficiency measures and to complement this with LZC technologies. Historically, employing LZC technologies hasn't been emphasised upon by the building regulations and by local authority planning, and hence it has been neglected within the building design process. A lack of support and initiative from the client combined with a shortage of skill level within building services consultancy firms **(15)** may have further slowed progress for sustainable development. LZC technologies have to be a more integral part of the design process for the future, in order to address future energy challenges.

### Design Process

As a precursor to the development of a methodology and toolkit for LZC design, the existing design process for LZC technologies was examined within a building services engineering consultancy. The objective was to describe the current methods and highlight deficiencies within the existing design process.

At commencement of the study, there was no coherent methodology for the design of LZC technologies. There was a lack of integrity and structure within the design process for analysing LZC technologies. However, it was regarded as a new engineering challenge needing to be addressed. There were many constraints to performing an appraisal for the integrated application of LZC energy supply systems. These are summarised below:

- Limited credible data for input at feasibility stage
- Simulation software weak for assessing renewable technologies
- Ad-hoc analysis techniques
- Inconsistencies and poor presentation of results to stakeholders
- Limited awareness of corresponding post-installation issues

These constraints led to inconsistent and mostly inaccurate appraisals of building integrated LZC technology. The existing method for analysing LZC technologies is to first identify technologies based on client specification and preference. Then solve using a user-defined analysis procedure, i.e. a self created spreadsheet, and present results to stakeholders. The user-defined analysis procedure consists of the use of ‘rule of thumb’ data and ‘simple theories’ for a generic location (i.e. Scotland), to determine performance. The results are presented within a technical report, not validated and in occasions not meaningful to a non-technical stakeholder.

As can be seen from the above observations, there are many deficiencies leading to inconsistent analysis models. To address this major problem an analysis methodology was formed (Chapter 4) and solutions were implemented. To improve consistency and accuracy in results for the analytical process, a greater contribution was required from simulation software, in particular renewable energy analysis software. By doing so, the use of ‘rule of thumb’ data would be negated and there would be less reliance on ‘simple theories’ and ‘self created spreadsheets’. A tool was required to ‘regulate’ data and allow for simple representation of the performance review, so that it is interesting for a non-technical stakeholder. These solutions are further discussed when deliberating the assessment methodology.

The aim of this study was to address the issue of inconsistent and mostly inaccurate design appraisals for building integrated LZC technologies. This involved identifying technologies for which an assessment method can be developed. Identify analysis software capable of assessing LZC technologies and meeting the technical data requirements. Develop an assessment methodology based upon the knowledge gained from reviewing LZC technologies and the selection of analysis software. The analysis methodology has been developed for use within a commercial environment for engineers knowledgeable in the low carbon field. And finally demonstrate this developed assessment methodology through a case study and discuss further improvements.

The first task is to perform a study for appropriate LZC technologies that may be utilised within a building integrated application to produce operational carbon savings.

# Chapter 2 - LZC Technologies

This chapter reviews the technologies that are most suitable for integration within buildings, with a view to their inclusion in the LZC evaluation methodology outlined in Chapter 4. The following technologies are reviewed for this study, Biomass heating, Combined Heat and Power (CHP), Ground Source Heat Pumps (GSHP), Solar Photovoltaic, Solar Thermal systems, Micro Wind Turbines and Passive Solar systems. The introduction of renewable technologies provides the desired effect of reducing local greenhouse gas emissions (GHG) and support future energy solutions for buildings.

## Solar Photovoltaics

### Characteristics

Solar Photovoltaic (PV) panels convert solar energy into electricity in an environmentally friendly manner. The fuel for converting to electricity is not polluted and free to use, with plenty of resource. There are four major applications for PV power systems **(16)**:

1) Off grid domestic photovoltaic system
2) Off grid non-domestic photovoltaic system
3) Grid connected distributed photovoltaic system
4) Grid connected centralised photovoltaic system

The first three applications are suitable for building integrated PV applications.

There are three different types of solar PV panel with efficiency in the range of 10% to 20% **(17)**.

1) Monocrystalline
2) Polycrystalline
3) Amorphous Silicon

The optimum configuration of a PV module depends on the general irradiative characteristics of the location, showing a clear dependence on latitude **(18)**.

Therefore, in general, greater electricity output may be witnessed for equatorial locations in comparison with more northern locations. A greater output is further witnessed when the PV panel closely tracks the sun. One study **(19)** concluded through a field test that a 3 position sun tracker PV panel generated 35.8% more electricity than an adjacent fixed PV panel of the same manufacturer, in Taiwan.

The efficiency of a PV module is dependent on module temperature, light intensity, spectral energy distribution and incidence angle **(20)**. Efficient power utilisation depends not only on efficient generation in the cell but also on dynamic load matching in the external circuit **(20)**. In, general, as the module temperature increases the panel voltage reduces and therefore the power output reduces significantly. Therefore, PV panels perform better at lower temperatures **(18)**.

There are certain differences between the performance of PV panels in rural and urban locations; in urban locations lower outputs may be experienced from PV modules due to the attenuation of solar radiation, mainly due to air pollution **(20,21,22)**. Within urban PV installations there are lower panel temperatures witnessed which leads to higher conversion efficiencies and as a result the reduced solar radiation does not pose as great an impact on PV output **(20,21)**.

An optimum energy yield may be sought from the installation of a Solar PV panel; if placed away from obstructions that may cause shading of the cell. Shaded cells can significantly reduce the power output of the panel. A single shaded cell in a string of cells may reduce power output by more than a half **(18)**. Based upon the above evidence, partial shading to the PV panel may have a devastating effect on the actual power output.

In summary, PV panels should be orientated directly facing the sun (i.e. facing South at an angle of incidence 30-45deg, for the UK). The installation engineer should select a suitable site to avoid shading. A gap between the roof and the panel should be kept for maintaining low panel temperatures. This makes up the basis for selecting a suitable site for the installation of an urban solar PV panel.

**Figure 1 - Solar PV panel (23)**

### Market

The market for Solar PV was assessed by looking at the relative cost of the panels, the frequency of new installations and market drivers. It is reported that investment costs of PV have reduced by 70% between 1980 and 2000, however they are still more expensive than grid electricity **(24)**. Photovoltaic panels on average cost £3500 per kWp in 2006, reduced from £4400 per kWp in 2001 **(25)**. The capital cost for PV panels are continuously but gradually dropping to an acceptable level. The cumulative installed PV generation capacity increased by 31% during 2006 reaching a total of 14.2 MWp with the government aiding 70% of installations in 2006 through the PV Major Demonstration Programme, 99% of these installations were grid connected **(25)**. The growth of PV panel installations for the UK were mainly driven by government incentives, making PV a more feasible option. The R&D and field trials budget totalled £15.03 million in 2006 **(25)**, this is an increase from previous years suggesting confidence in the technology. A future aim for developing the technology is to investigate thin film solar cells made from inorganic semi conductors. With the latest introduction of Feed-in-Tariffs **(26)**, it is expected that the number of PV installations shall increase further still. Estimating further clean energy generation and economic boost to the UK PV industry.

### Suitability for Installation

Solar panels are heavy structures and require the roof or façade to have adequate support before commencing installation. It is recommended to have the supply connected to the grid and metered to take advantage of government incentives.

A technoeconomic analysis was done for the installation of solar PV panels for a remote hotel in Greece **(27)**. Despite accounting for a 55% government grant on the capital cost, it was a more expensive option than using grid electricity. The installation of solar PV panels has historically been undermined by the substantial capital cost and unattractive return on investment. However, recent legislation introducing Feed In Tariffs (FITs) in the UK from April 2010 **(26)**, has made Solar PV a more attractive option for building integrated application, presenting a steady income and significantly reducing the payback period to within acceptable limits.

Internationally, there has been many studies into the feasibility of solar power generation **(18,19,24,27,28)** comprising of actual field studies and controlled performance studies. A UK field study **(28)** in PV power generation for domestic buildings assessed 101 photovoltaic panel systems and published results of annual monitoring. The two parameters of interest were final energy yield (kWh/kWp) and system efficiency. There was a range of results for a variety of systems for four different sites. The final yield ranged from 256 to 836 kWh/kWp, with a system efficiency ranging from 3.5% to 11.8% **(28)**. Further analysing this data, the resercher suggests that lower energy yields may have occurred due to faults witnessed during the field study**.** The faults consisted of MPP tracking failure, shading faults and zero efficiency faults (component failure). Had these faults not occured, it is assumed that performance would have matched the manufacturer's efficiency curve. There were also additional losses where the inverter was not sized appropriately. The losses are discussed in great detail within the above study **(28)**. For the purposes of this study, it is assumed that if faults were kept to a minimum and general advice was followed for appropriate installation then a final yield of (700 to 800 kWh/kWp) is achievable, with a system efficiency of around 10%. A good site within the above study, Corncroft had acheived this. However no claims to expected performance of solar PV panels for the UK are made within the monitoring study **(28)**.

In summary, there is potential for extracting clean electricity from solar PV panels but careful consideration is required for certain design parameters that may significantly reduce overall performance. The panels should be installed facing in the direction of the sun and also to avoid shading. The panel performance would be enhanced if MPP tracking was built into the system also the inverter should be sized appropriately for the system. The system faults should be regularly monitored. Due to the high capital costs involved economic performance is only acceptable if the panel is connected to the grid. The user is then able to take advantage of FITs and sell back unused electricity to the grid. Solar PV is likely to perform consistently for the UK if the above is handled appropriately.

## Wind Turbines

### Characteristics

The UK is the windiest country in Europe with 40% available resource; enough to supply the countries electricity needs several times over **(29)**. The energy output for a wind turbine varies with geographical location, meteorological conditions and local positioning of the turbine **(30)**. The maximum power extraction from a wind turbine is derived by Betz **(31)** to be 59% of available energy and therefore overall efficiency cannot exceed this figure. Though is never realistically achieved because of aerodynamic and power conversion losses **(30)**. The two determining factors for power output from a wind turbine are the turbine diameter and the local wind speeds. For a wind turbine, Power $\propto$ Wind speed$^3$ i.e. the power attained is critically dependent on local wind speeds. Hence for optimum energy yield, the ideal location for the placement of a wind turbine would be a smooth flat hilltop with clear exposure to wind. The wind speeds are highly dependent on the local environment – more so than any other renewable source.

**Figure 2 - Micro Wind Turbine** (32)

Large wind turbines are contributing a significant amount of renewable energy **(33)** to provide UK grid electricity. Micro wind systems however are a relatively new technology and do not produce as impressive energy yields in comparison with the larger scale projects. They operate in more turbulent environments; hence more obstructions to flow and lower velocity wind resulting in lower energy yields.

It is widely known that turbulence reduces energy extraction from the micro wind turbine; Betz had also derived that maximum power efficiency is achievable when there is total laminar flow **(31)**. The majority of studies have been unable to explain the power robbing effect due to turbulence for a micro wind turbine. In one study **(30)**, a power robbing effect of 50% was applied for the urban domain and likewise 15% for the rural domain to estimate the effect of turbulence. In another study **(34)**, it was predicted that local turbulence reduced power output by 15-30%. From the above two studies it can be derived that the actual effect of turbulence upon energy extraction is not well understood. The turbulence upon a wind turbine has a highly variable effect and is very dependent upon local surrounding. However, the reduction in obstructions upstream does reduce turbulence for the wind turbine. Therefore the energy produced from small scale turbines may be greatly enhanced if a concerted effort is made to place them in optimum locations; facing unobstructed flow streams at the appropriate height **(35).** This would minimise the power robbing effect from turbulent flow streams for building integrated wind turbines.

### Market

The Department of Trade and Industry (DTI) have estimated that by 2050, 30-40% of the UK's electricity may be produced by microgeneration including 6% from small wind systems **(36).** Micro-wind turbines for domestic energy generation are an emerging technology in the UK marketplace. In 2007, there were in total 650 micro-wind installations with around 1500 further installations allocated under the Low Carbon Buildings programme **(37)**. The micro wind turbine market is growing but its future expansion remains in doubt until there is empirical proof for efficient energy extraction of building mounted turbines, particularly for urban installations. So far the results have not been impressive with one study reporting a financial payback of 30-90 years, for the UK **(35)**. Recent studies such as the EST field study **(38)** and the Warwick wind trials **(39)** have also largely discredited the current impact of micro turbines within the built environment.

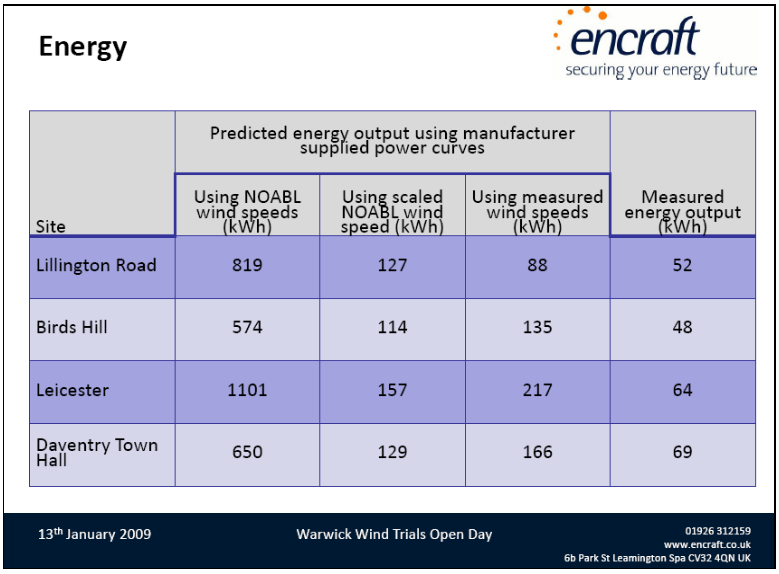
### Suitability for Installation

The suitability of horizontal axis wind turbines (HAWT) for an urban location has largely been questioned due to the complexity of the wind distribution **(35,40)**. There are also aesthetic and safety issues concerning their presence within an urban environment. The turbines are regarded by the general public to be visually obtrusive and their weight adds to the structural design of a building. One study **(41)** concludes that VAWTs are preferable to HAWTs for roof-mounting upon (high) buildings. VAWTs do not suffer as much from reduced energy outputs as a result of frequent wind direction changes, whereas HAWTs must yaw and track the wind to be able to extract energy economically. As of yet there is insufficient evidence to suggest that installing micro-wind turbines within the built environment presents a technically feasible solution. This is also suggested within a technical paper **(42)** where it states that small wind turbines (>100kW) are not technically feasible or economically worthwhile to install for large commercial buildings

### Warwick Wind Trials

From 2006 onwards the Warwick wind trials commenced and 23 rooftop wind turbine installations were monitored. The project monitored turbines for a variety of sites for over 12 months and data collection began late in 2007. Full details may be viewed on the project website **(43)**, 10 of the 23 sites being observed were within Warwick.

The project has demonstrated that appropriate installation of building integrated wind turbines can produce decent energy yield, but this was not in the majority. The in-use capacity factor, this excluded any imported energy for the turbine, for all sites ranged from 0.29% to 16.54% with the overall average being 4.15%. This average dropped to 1.51% when omitting reference and high rise sites. In general, poor capacity factors were witnessed for the majority of the 23 sites that were investigated. The main conclusion therefore was that poor location resulted in poor capacity factors and that a site is to be carefully selected for building mount turbines **(39).** The location is critical, especially for urban installations, as it determines the likely wind resource. This project also discusses possible shortcomings for predicting the performance of building integrated wind turbine installations. It is believed that the comparison between actual energy yield and predicted energy yield was dependent on the inaccuracy of two wind properties for each specific location **(39)**. Namely predicted wind speeds and manufacturer supplied power curves for the site (Table 1). It is essential that the method for both obtaining predicted wind speeds and the corresponding power curves are addressed by the wind industry to better predict actual energy output **(39)**. However, the effect of turbulence was neglected and further analysis may result in proving its contribution to producing lower energy yields. As has been detailed earlier the effect of turbulence is not well understood and therefore not easily quantifiable.



**Energy**

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| Site | Predicted energy output using manufacturer supplied power curves | | | Measured energy output (kWh) |
|---|---|---|---|---|
| | Using NOABL wind speeds (kWh) | Using scaled NOABL wind speed (kWh) | Using measured wind speeds (kWh) | |
| Lillington Road | 819 | 127 | 88 | 52 |
| Birds Hill | 574 | 114 | 135 | 48 |
| Leicester | 1101 | 157 | 217 | 64 |
| Daventry Town Hall | 650 | 129 | 166 | 69 |

13th January 2009
Warwick Wind Trials Open Day
01926 312159
www.encraft.co.uk
6b Park St Leamington Spa CV32 4QN UK

**Table 1 - Predicted energy yield vs. Actual energy yield (39)**

## WINEUR Project

The objectives for the WINEUR project (WINd Energy integration in the Urban Environment) is to identify the conditions for integration of small wind turbines within the urban environment. The following has been suggested for successful small wind installation **(34):**

- Average wind speeds > 5.5m/s
- Mounted on buildings 50% higher than surroundings
- A hub height of at least 30% greater than building height

The above is also confirmed by CFD analysis **(44),** where it is suggested that the hub height should actually be 50% greater than the building height. Based upon the above criteria, few urban buildings would be applicable for small wind turbine installation and those that apply would face significant structural and vibration issues.

## EST Field Study (38)

A study was conducted by the Energy Saving Trust (EST) to assess the impact of micro wind turbines in the UK by monitoring 57 actual installations. The results were not encouraging with no urban or suburban building turbine surpassing 200kWh – this equates to a capacity factor of around 3%. Some turbines were net consumers due to the power requirements of the inverter (10W). The most productive building mounted turbine acheived a capacity factor of 7.4%, a 1.5 kW building mounted turbine in a rural location in Scotland, yielding 975 kWh. The poor results were mainly due to inappropriate installations both in terms of location (wind resource) and poor positioning of the turbine. All of the urban and suburban sites had an average annual wind speed of less than 4m/s. This was deemed a poor wind resource for the installation of building mounted wind turbines. The EST are hopeful for gaining suitable yields from small turbines, especially in Scotland. However, the question remains, how to minimise local turbulence by suitably positioning the turbine?

The key findings for this study were:

- Small turbines performed much better in a rural (free standing) location as opposed to an urban (building mounted) location.
- Turbines performed better in Scotland than other parts of the UK due to higher wind speeds and topography
- Manufacturer power curves were in the majority inaccurate or incorrect, a standard accreditation procedure is required.
- The NOABL database overestimated local wind speeds, an adjustment factor should be applied or anemometry measurements should be undertaken for analysis.
- Wind installations should only be considered where the average annual wind speed exceeds $5ms^{-1}$.

Most wind energy systems in Scotland are predicted to be based in rural areas **(45)** but can a proven technology produce wind energy efficiently in the urban environment which consists of turbulent and irregular flow? In summary of the above discussion and being influenced by the field studies carried out, local positioning of the turbine is critical to performance. If placed in a desirable location horizontal wind turbines may contribute significantly for reducing carbon emissions for a building. The Warwick wind trials **(39)** and the EST location study **(38)** highlight poor location as the main deterrent to efficient utilisation of wind energy. It is key that the positioning of the turbine is such that there is exposure to high average annual wind speeds and reduced effects of turbulence. The process for selecting a suitable location shall be discussed in detail later within Chapter 5.

## Ground Source Heat Pumps

### Characteristics

Ground Source Heat Pumps (GSHP) are proven to be an attractive alternative to conventional heating and cooling systems, as they provide higher energy utilisation efficiencies and are economically preferable for colder climates **(46)**. The heat pump utilises stored solar energy from ground to heat or cool the building. A water/glycol mixture is usually the medium by which this energy is transported. GSHP may provide heating as well as cooling if they are configured to operate in this reverse arrangement. Therefore operate year round as excess heat in the summer can be stored within the ground and utilised in the winter. This energy balance would then allow for more stable ground temperatures local to the ground loop and allow for more efficient energy utilisation from the ground source system **(47).**

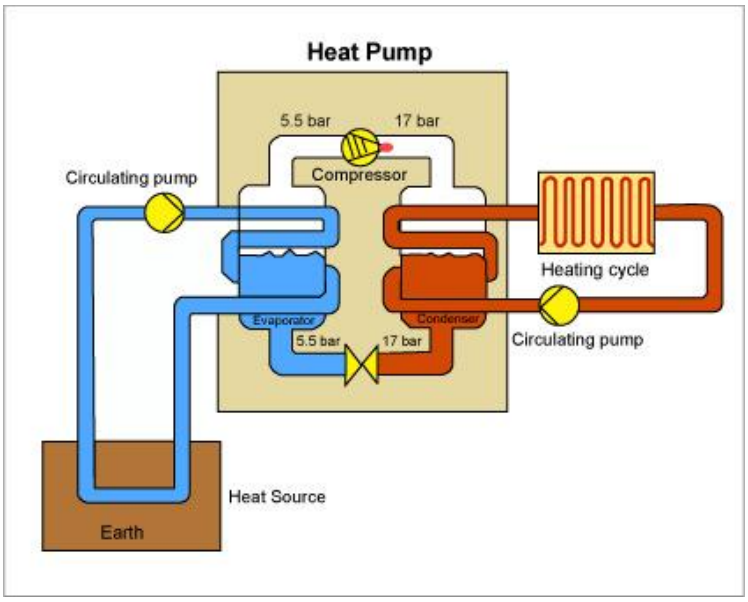


**Figure 3 - Ground Source Heat Pump (48)**

Three important elements to a Ground Source Heat Pump

1) The Ground loop – comprises of lengths of pipe buried in the ground either in a borehole or a horizontal trench. The pipe is filled with a mixture of water and anti freeze (glycol) which is pumped round the pipe absorbing heat from the ground.
2) The Heat Pump – The evaporator takes heat from the water in the ground loop. The compressor moves the refrigerant round the heat pump and compresses the gaseous refrigerant to the temperature required for heat

distribution. The condenser gives up heat, which feeds the distribution system.

3) The Distribution System – Ideally is a low temperature heating system (in most cases underfloor heating), however may also be a conventional wet radiator system and pre-heating for hot water storage.

The effectiveness of a GSHP system is measured by the coefficient of performance (COP). This is the ratio for units of heat gained to units of electricity consumed in driving the compressor and pump for the ground loop heat exchanger. The compatibility of the ground loop with the heat pump and the distribution system makes an efficient system. Therefore to obtain an acceptable system efficiency, the GSHP system has to be designed as one system and not as a collection of components **(49)**. The COP is also dependent on the difference between the ground and the required distribution temperatures. The system is more efficient for underfloor heating because it works at a lower temperature than for radiators. This is because a smaller temperature difference ($\Delta T$) requires less compressor power for the operation of the heat pump**.**

According to previous studies, a GSHP system may be more expensive to run than a mains gas heating system **(50).** However, when displacing electric heating and cooling systems, the potential for utilising GSHP results in reduction of running costs of up to 70% and reduced $CO_2$ emissions of up to 50% **(49,51).** GSHP, therefore is more favourable when substituting for electricity driven heating and cooling. This is due to higher costs associated with grid electricity as well as a greater carbon emissions factor.

It is essential that the system is sized accurately; this provides a better economic return, a better COP, but also prevents any destabilisation of the system **(49).** The system destabilises when soil temperatures become unstable (i.e. significant rise or drop), due to the operating of the ground heat exchanger; hence nullifying its environmental effectiveness **(52).** This can occur if the ground heat exchangers are inadequately designed and the annual heat balance problem is not addressed. This is the most important and difficult problem in relation to effective GSHP design **(47).** There are different techniques available for sizing a GSHP system and the most common, proposed by ASHRAE, is to consider maximum heating and cooling loads along with thermophysical properties of the soil and the minimum COP for the heat pump **(53)**. This usually leads to extended borehole lengths and therefore added capital cost **(53)**. It is better to demonstrate performance through a 20 year analysis, applying hourly loads, characteristic curves for the heat pump and the thermophysical properties of the local soil. The results would provide detail on local soil temperatures, the amount of heat absorption/rejection to and from the ground and configure the borehole dimensions such that annual equilibrium is achieved (i.e. stable conditions). This would result in smaller borehole lengths, therefore less electricity consumption from the heat pumps and a lower overall COP **(53)**.

### Market

GSHP systems in the UK are recently being used more and more, as commercial, private and residential sectors embrace their low carbon, sustainable and cost-effective credentials **(51)**. The industry has been growing at a decent rate with around 4000 installations up till 2007, 1500 were installed that year and a further 2000 installations were expected in 2008 **(54).** This annual figure is expected to rise year on year as demand increases for low carbon building solutions. The GSHP system is more expensive than your conventional system. The indicative capital cost for a domestic vertical borehole system varies from £800 to £1250 per kW, with the bigger systems being less expensive per kW **(49)**. This is a significant investment and merits proper planning and analysis of system effectiveness prior to installation. The horizontal (slinky) system is preferred for smaller applications; for less load requirement and is a cheaper system. However, it may be impractical to install a horizontal trench system in urban locations because land may not be available to lay the required pipework. In summary, due to the significant capital costs involved and specialist contractor works, the design and installation of GSHP systems should be considered early in the design process. The capital costs involved may deter potential users, however with the ever increasing energy awareness within the general public and the potential for low carbon emissions make it an interesting market.

### Suitability for Installation

Ideally GSHP systems should be installed within new buildings where they have been considered since early design stage. This is mainly because installing such a system requires collaboration between different contractors, consultants and extensive works are required for the ground loop. It is difficult to implement this technology in existing buildings because the procedures for retrofitting are expensive and complex. It would be worth considering installation of air sourced heat pumps (ASHPs) instead as they can be easily retrofitted.

The are many design considerations for a GSHP system that need to be evaluated prior to installation. The first consideration is to determine whether the local soil and its geology is appropriate for effective GSHP operation. Thereafter the system is designed for a suitable borehole length, this length is to be kept as low as possible to reduce pump energy and capital costs but also to meet its load requirement. It is important to maintain a good thermal contact between the soil and the ground loop to maximise heat transfer **(49)**. This is achievable through using high thermal conductivity grout for the ground loop heat exchanger. The most efficient GSHPs use a low temperature distribution system; reducing this temperature from 60 degC to 40 degC can potentially increase the COP by 40% **(49)**. The heat pump may only heat water efficiently to 50 degC **(49)** and therefore it may be worth considering GSHP as part of a bivalent system where hot water of greater temperature is required, e.g. domestic hot water. For the bivalent system, the auxiliary heating supply would cater for peak loads and to supply temperatures of greater than 50 degC. If a heat pump was designed to meet 50% load, it may provide 80% to 85% of the annual heating energy requirement. Hence a bivalent system may present a cheaper and more stable system **(49)**. The system would be cheaper because a smaller borehole length would be specified with less ground loop and drilling required. The system would be more stable because less heating and cooling would be extracted from the ground, hence less effect on local soil temperatures.

**EST Field Study (55)**

Field trials were carried out by the Energy Saving Trust, a total of 83 systems were monitored within the UK. This comprised of many different types of systems and inclusive of GSHPs and ASHPs. The study was limited to small scale domestic applications for heating only. The performance varied significantly from system to system, but in general well designed systems operated with COPs of over 3. It was concluded that simple systems performed with better efficiencies and carbon savings were achievable when replacing gas or electric heating with well designed heat pump installations. However customer behaviour did impact system performance and education was necessary to use the new heating systems effectively.

If a comparison was to be made between GSHP and ASHP performance based upon the above field trials **(55).** In general, it could be argued that performance of GSHP was slightly better than ASHPs. The mid range COPs for both system types varied from between 2.3 and 2.5 for GSHPs and 2.2 for ASHPs. However, customer satisfacation was equivalent for both types of systems. Larger scale GSHPs are more complex systems but the potential for improved performance exists. A study **(56)** suggests that GSHPs may offer better techno-economic viability as compared to ASHPs; despite the greater capital cost. Therefore GSHPs may prove more cost effective than ASHPs over a lifetime of operation, if designed properly.

In summary of the above, GSHP technology should be considered for new build developments and should be considered early in the design process. Expert advice should be sought, caring for critical design parameters and designed to avoid energy imbalances for the operating lifetime of the system – 20 years minimum. For retrofit solutions, ASHPs should be considered as they may prove to be a more economically feasible solution. For a well designed system, energy, carbon and economic benefits are achievable.

## Solar Thermal System

### Characteristics

Solar thermal collectors are suitable for heating applications such as providing for domestic hot water, swimming pools, radiators and underfloor heating. There are three types of collector, a flat plate unglazed collector, a flat plate glazed collector and the evacuated tube. There are differences within design for the three different collectors which leads to performance suitable for different applications.

- Unglazed Collector

This is the most inefficient solar collector which is best suited for low grade heat applications, such as for heating swimming pools. The panel consists of a dark absorbing material on top of an insulation layer within a container (Figure 4). The pipe arrangement is sandwiched in between the absorbing layer and insulation layer (Figure 5)

**Figure 4 - Unglazed Collector (57)**

- Glazed Collector

The difference between a glazed and unglazed collector is that a transmitting material (glazing) is present in the former; which enables greater capture of solar energy and hence better performance. This collector is mainly suitable for domestic hot water and space heating applications.

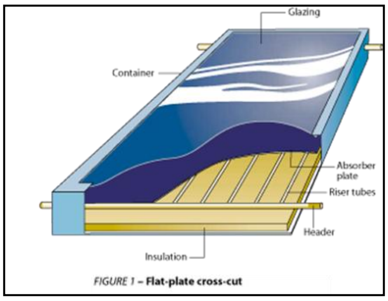


**Figure 5 - Glazed Collector (58)**

- Evacuated Tube

Evacuated tubes are the most efficient solar collector because the vacuum formed within the tubes reduces any convection losses for the panel. It is the most expensive collector and also the most flexible as each tube may be arranged separately for increased flexibility.

**Figure 6 - Evacuated Tube Collector (59)**

The three different collectors have unique performance characteristics and are used for different heating applications. The appropriate collector needs to be selected for the heating application and designed for maximising useful energy yield and also avoid the system from reaching stagnation point. If the system is oversized – low flow rates are experienced. This allows the fluid temperatures to increase beyond design conditions and may approach the stagnation temperature. If the system reaches stagnation point the collector produces no further heat. It is possible that the collector, due to this phenomenon, becomes permanently damaged and therefore needs replacing. Hence when designing a solar hot water system it is better to undersize than to oversize.

Although solar thermal systems are more readily used in hotter countries near the equator due to the obvious greater solar radiation throughout the year. The solar radiation in the UK is approximately 60% of the equator and in Scotland the average annual solar radiation is 900 kWh/m$^2$ **(60)**, this value increases by 10-15% for pitched roofs **(61)**.The efficiency of a solar water heating system is approximately

40% **(60)** but is dependent on the type of collector, material properties, flow rate and the overall system arrangement. For a given collector design and flow rate, the efficiency remains constant, and for hot countries can be higher at 66% **(62)**. For the UK, a well designed system has the potential to provide all hot water demand for the summer and 40% to 50% year round **(60),** this output is heavily dependent on collector area, exposed solar radiation, daily water run-off and system type. The panels require support from conventional systems during the winter months due to the significant reduction of solar radiation.

Solar hot water panels should be installed where minimal shading occurs as shading greatly reduces efficiency of the panel. The greater the shaded area on the panel, the greater reduction in panel output.

### Market

The UK's residential sector accounts for approximately one-third of overall delivered energy use and carbon emissions **(61)**. Solar panels are suitable for collaborating with hot water storage systems within residential buildings. There are approximately 100,000 solar hot water systems installed nationwide **(63)** and potentially a further 21 million homes have a central heating system suited for installing a solar thermal system **(64).** SHW panels within domestic buildings have great potential to contribute to the low carbon economy for the UK. There is also potential for market growth within the commercial sector with buildings that have a large hot water demand, for example hotels and swmming pool centres. With the introduction of the Renewable Heat Incentive (RHI) **(65)**, it can significantly improve the economic performance of solar thermal systems and therefore make it a more feasible low carbon solution.

### Suitability for Installation

The heat medium, for solar thermal panels utilised within a building integrated application, is usually a mixture of water and glycol. The heat energy acquired from solar panels is stored within a hot water cylinder, or equivalent store, and used throughout the day. This maximises utilisation of solar heat because generally hot water is not required when the solar panel is producing in abundance. The best application of solar thermal systems is where there is a large and fairly constant hot water load. Therefore these systems are most suited for residential buildings, hospitals and hotels; because these building types present a significant domestic hot water load. However any building with a base heating or hot water demand may benefit from installation of solar hot water systems, this includes the majority of buildings in the UK.

### Solar Hot Water (SHW) Appraisal

An appraisal **(61)** was done for solar hot water systems, for the UK residential sector, to assess its energetic, environmental and economic performance. The appraisal was carried out for a panel of $2.8m^2$, for a residential storage system. An experimental study was carried out for a daily water run-off of 150l/day with solar energy supplies of between 2330 and 3520 $MJ_{th}$/year. The following observations were made.

Energy

- A net energy benefit was achieved regardless of which system was being replaced – be it a gas boiler, oil boiler or an electric immersion heater.
- If the daily run-off volume is reduced to 110l/day then solar energy utilsation reduces by 9-17%, based on the study conducted by DTI **(66)**.

Environment

- Greatest environmental benefit is acheived when replacing an electricity system with the solar hot water system, whilst also producing least energy benefit.

Economic

- Assessment indicates that the SHW system is currently uncompetitive given the poor Net Present Value (NPV) for various scenarios assessed
- The best scenario, economically, was when replacing an electric system with a SHW system. This provided an NPV of near zero.

In general, the greatest benefit is achieved when replacing an electric immersion heater with a SHW system. It is assumed that the introduction of the RHI scheme improves the economic feasibility of the systems. Therefore SHW systems would be considered to replace all types of heating system – dependent on available space for installing solar panels.

In summary there are three types of solar collectors useful for different applications. Generally the most appropriate use of a SHW system is when the building has a constant and significant hot water load, such as residential, hospitals and hotels. The solar hot water panel would then acquire maximum useful energy and at the best possible efficiency. The greatest environmental benefit is achieved when replacing electric systems. Economically, solar hot water panels are not an attractive investment. Though the introduction of the RHI scheme will make this technology a more attractive economic proposal.

## Biomass Heating

### Characteristics

There is a vast resource of biomass energy with world storage estimated at $1.5\text{x}10^{22}$ J **(17).** It is the oldest and most widely used renewable source. In 2008, the contribution for energy consumption within the UK from renewable sources was 2.3%, and 81% of this energy was provided from a biomass resource **(36)**. Biomass can be considered carbon neutral as the carbon dioxide emitted during combustion is offset by the absorption of carbon dioxide during the photosynthesis process. In photosynthesis, carbon dioxide and water are used to form organic compounds (mainly sugars) with oxygen being the waste product. When these organic compounds are burned, they form carbon dioxide and water and release the energy they contain. In this way biomass functions like a natural battery for storing solar energy.

Biomass fuel is most commonly found in the form of wood chips or pellets. Other resources include co-products and waste generated from agricultural, industrial, and commercial processes. Alternatively, energy crops can be grown specifically as biomass fuels such as short rotation coppice (SRC). Landfill gas and bio-fuels may also be used as an alternative fuel option. Biomass heating systems are usually smaller than their fossil fuel counterparts and this is mainly to minimise irregular loads, hence maintain operational efficiency and also to reduce capital expenditure. Biomass boilers operate best when worked at a constant load and buildings in general have a variable load. Therefore, the most cost effective method for operating these boilers is by utilisng a thermal store and operating the boiler at a lower peak for longer running hours. This strategy will save the user on capital cost and operate the boiler more efficiently.

### Market

About half of the electricity consumed in Scotland is used for heat generation **(67).** Hence there is potential for these electrical heating systems to be replaced by a CHP system utilising biomass fuel; the most encouraging option for reduction in carbon emissions **(68,69).** However, studies suggest that biomass currently has little future growth prospects **(68)**. The Scottish Executive in an effort to boost this market have released a publication “Biomass Action Plan for Scotland” in line with the “EU Biomass Action Plan” **(70)**. Its aims are to promote economic growth, commitment to renewables and diversification of supply through the use of biomass fuel. SRC has the potential to produce 3.3 GW of electricity therefore supplying 31% of Scotland’s 10.5 GW electrical energy requirements. If these are CHP systems then the contribution increases to 5.71 GW, supplying more than half of Scotland’s electricity **(71).** Therefore biomass can be used to produce heat but may also be just as effective in producing electricity. The cost of these systems is high with wood fired boilers costing approximately £450 - £600 per kW installed **(72)**, significantly more than for gas fired boilers**.** However the environmental impact and resource availability for these systems is great and there is less dependence on local conditions.

### Suitability for Installation

Biomass fuel can be used in a variety of ways and unlike other renewable energy systems is not heavily reliant on climatic conditions. Biomass fuel can be used for producing grid electricity as well as replace the “traditional” gas fired boiler. However, there are a few restraints – location of fuel resource and capital cost. The fuel resource should be acquired from close proximity to the site, to maximise environmental benefit and minimise associated running costs. Hence a biomass heating system would be most beneficial for local, rural communities, and even individual farms. They are able to utilise local biomass supply energy systems that are self-sufficient, sustainable, and perfectly adapted to their own needs.

## Cogeneration

### Characteristics

Combined Heat and Power (CHP) is the simultaneous generation of usable heat and power in a single process. Cooling may also be produced through the use of an absorption chiller, known as Combined Cooling Heat and Power (CCHP). CHP systems can be employed over a wide range of sizes, applications, fuels and technologies. It is a highly efficient way to use both fossil fuels and renewable energy therefore can make a significant contribution to the UK’s sustainable energy goals. In its simplest form, it employs a turbine or an engine to drive an alternator and the resulting electricity can be used either on-site or connected to the national grid. The waste heat produced during power generation is recovered, usually in a heat recovery boiler and can be used to raise steam for a number of industrial processes or provide hot water for space heating or cooling.

CHP systems are a major asset where there is a significant demand for waste heat. An average efficiency for UK CHP units for 2008 was 67.2% **(36)**. In contrast the efficiency for conventional coal-fired and gas-fired power stations, which discard the heat, is typically around 38% and 48% respectively at the power station **(36)**. This efficiency is lower still at point of use because of occurring losses through transmission and distribution. CHP is a form of decentralised energy technology supplying customers with heat and power directly at point of use, therefore avoiding transmission & distribution losses. Hence a significant difference in average efficiency yielding environmental benefits which can be further enhanced if a renewable fuel is used. Utilising renewables within a cogeneration system is considered by the European Union as one of the preferred methods for fulfilling the Kyoto Protocol for the reduction of greenhouse gases **(73).** The utilisation of biomass CHP would be one such ‘preferred method’. The capital cost for a biomass CHP system may be higher than using natural gas as the fuel; but one study **(74)** suggests the financial return rate of CHP technology utilising biomass is much shorter**.** This would not be the case for all systems but nevertheless it would be worthwhile to consider a biomass CHP system in greater detail when considering CHP for a building.

### Market

In recognition of the significant carbon saving potential of CHP, following the first Earth Summit negotiations in 1992, the then UK Conservative Government, established in 1993, set the first target for good quality CHP of 4 GW by 2000 **(36).** With the rapid development of schemes, this target was raised the following year to 5 GW as part of the Government’s Climate Change Programme. The Government increased this once again in 2000, establishing the current target of 10 GW by 2010. This remains a key element of the Government’s revised Climate Change Programme, issued in March 2006. The latest Government statistics (up to 31 December 2008) show that 5,469 MW capacity of CHP is operating in the UK **(36)**.

### Suitability for Installation

CHP is a viable technology for building developers to pursue for meeting future legislation but is limited for only certain types of buildings. The performance of a CHP system is heavily reliant upon the building energy demand. The CHP generator is sized to match the buildings significant heating demand. In buildings such as data centres where there is a significant cooling demand, an absorption chiller can be added to form a CCHP system. If the waste heat is being effectively used for heating or cooling of the building then it is possible to achieve a good economic return and greatly reduce carbon emissions.

However the best application for utilising CHP is arguably as a community heating system. This would include providing for residential estates, whole towns, areas of cities, or even whole cities. Here one or more CHP plants supply heating to a grid of insulated hot water pipes that carry heat to a range of buildings including public and private sector flats. Meanwhile the electricity generated may be used to help run the community heating plant and within customer buildings, or is exported to the electricity grid. Community heating systems can be made up from a variety of heating fuels, the most environmentally friendly being biomass.

In summary CHP technology has great potential to be utilised at a large scale, it is highlighted that the technology is more suited for intensive and relatively constant energy use. It is believed that the best application of this technology is through a community heating system utilising biomass as the renewable fuel.

### Passive systems

The most cost-effective technological options for the civil sector to help reduce $CO_2$ emissions between now and 2020 in accordance with the Kyoto Protocol are passive solar systems, thermal insulation for buildings and high-efficiency heating systems **(75).** If designed properly the building can capture heat in the winter and minimise heat gain in the summer. South facing windows, rooflights, awnings and shade trees can all be used for exploiting passive solar energy. Maximising the sun's light and minimising glare is of benefit to the user, it allows for better indoor environment and the effective use of natural ventilation.

Natural ventilation has always been considered to be a fundamental part of 'passive design' **(76)** and is preferred to air conditioning systems in low carbon buildings. Due to an increase in electricity consumption within commercial buildings **(17)** and hence increased cooling loads, there are concerns for overheating with opting for natural ventilation in large commercial buildings. On the contrary, one survey suggests that occupants of naturally ventilated office buildings are more satisfied with their thermal environment than in air-conditioned office buildings **(77).** However there is less control over internal conditions when naturally ventilating a space and passive design measures need to be considered. For low carbon housing mechanical ventilation with heat recovery (MVHR) is preferred. MVHR should be considered where a more controlled environment is being seeked and a less energy intense solution is required. It may therefore be possible to utilise natural ventilation rather than a relatively more energy intensive air-conditioning system, ensuring acceptable comfort levels and working environment for staff, bringing energy and cost savings **(78)**.

The cost of implementing passive systems is relatively inexpensive in comparison to other renewable technologies, since there is little additional equipment that needs integrated within the overall building design. In general passive solar systems and natural ventilation should be encouraged, however summer overheating is a major design concern. For this work precedence was given to LZC technologies analysis in addition a model was developed for passive systems design (mainly concerned with natural ventilation design).

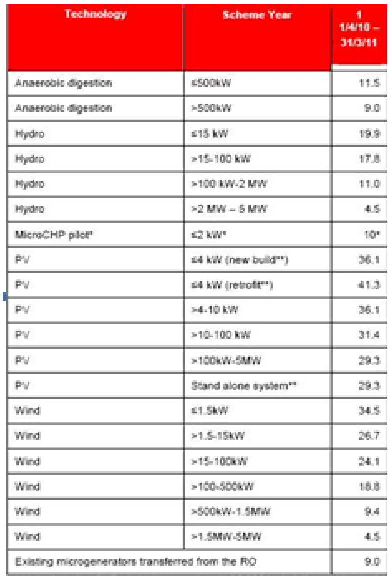
## Renewable Energy Incentives

A number of schemes and incentives have been introduced to promote the installation of the technologies outlined previously, and build towards forming a low carbon economy. An overview of the available incentives and their effect on building integrated installation of LZC technologies follows.

The Department of Energy and Climate Change (DECC) was set up in 2008 to lead the country's effort to avoid dangerous climate change and to lead the transition to a low carbon economy. The Low Carbon Transition Plan **(79)** outlines how the economy shall be decarbonised over the next decade and beyond. This is determined by a five point plan, including providing financial support to individuals, communities and businesses **(79)**. This support ranges from major programmes for installing home insulation and energy efficiency technologies to also promoting micro-installation of low carbon electricity and heat generation technologies.

### Electricity Generation

Since its introduction in 2002, the Renewables Obligation has tripled eligible renewable energy generation **(26)**. There is demand for small scale renewable technologies through generating clean energy at home, in communities or workplaces. The Renewables Obligation was not originally designed for supporting small scale building integrated projects. It can be a difficult support mechanism for those not familiar with the electricity market, and at the very small scales the returns offered were not sufficient to justify investment. To combat this and further promote renewable energy, Feed-in Tariffs (FIT's) **(26)** have been introduced for small scale renewable electricity generation.



| Technology | Scheme Year | 1<br>1/4/10 – 31/3/11 |
|---|---|---|
| Anaerobic digestion | ≤500kW | 11.5 |
| Anaerobic digestion | >500kW | 9.0 |
| Hydro | ≤15 kW | 19.9 |
| Hydro | >15-100 kW | 17.8 |
| Hydro | >100 kW-2 MW | 11.0 |
| Hydro | >2 MW – 5 MW | 4.5 |
| MicroCHP pilot* | ≤2 kW* | 10* |
| PV | ≤4 kW (new build**) | 36.1 |
| PV | ≤4 kW (retrofit**) | 41.3 |
| PV | >4-10 kW | 36.1 |
| PV | >10-100 kW | 31.4 |
| PV | >100kW-5MW | 29.3 |
| PV | Stand alone system** | 29.3 |
| Wind | ≤1.5kW | 34.5 |
| Wind | >1.5-15kW | 26.7 |
| Wind | >15-100kW | 24.1 |
| Wind | >100-500kW | 18.8 |
| Wind | >500kW-1.5MW | 9.4 |
| Wind | >1.5MW-5MW | 4.5 |
| Existing microgenerators transferred from the RO | | 9.0 |

**Figure 7 - Feed In Tariffs (till 31/3/2011) (26)**

The Energy Act 2008 puts in place powers for introducing FIT's. A "clean energy cashback" scheme allowing investment in small scale low carbon electricity, in return for a guaranteed payment for the electricity generated. The aim of this scheme is to incentivise the installation of small scale renewable electricity, bringing the direct benefits of renewable electricity to the wider general public **(26)**.

The scheme starts from April 2010 and the following conditions apply:

- Technologies shall only be considered if commissioned after the 15th July 2009 and its generated electricity is metered.
- The tariff will last for 20 years (25 years for Solar PV) and will remain constant, adjusted for inflation, throughout support period.
- Technologies are limited to 5MW, applicable for household and communities. Greater size technologies shall be considered under the ROC's scheme.
- Support from electricity generation from Biomass will not be provided by FIT's (apart from Anaerobic Digestion)

- Income for ‘householders’ from the FIT’s scheme shall not be taxed if most of the energy is used within the home.

The above bullet points note some of the conditions regarding this scheme and its operation; however the list is not exhaustive. The FIT’s scheme is intended to encourage individuals, householders, organisations, businesses and communities to generate their own electricity. This improves the market potential for renewable electricity from solar PV and micro wind for a building integrated installation. It makes the application of these technologies at a micro or mini scale an economically worthwhile decision.

**Heat Generation**

Heating accounts for 47% of the UK’s carbon dioxide emissions and around 60% of an average domestic energy bill **(65)**. Saving energy continues to be a crucial challenge and this is being done by applying insulation to produce better fabric and minimise heat loss. Furthermore, energy efficiency measures are being applied to reduce this heating demand for new and existing buildings. However, only 1% of the UK’s heating comes from renewable sources hence a requirement for a ‘clean supply’ of heat **(65)**. The Renewable Heat Incentive (RHI) provides the necessary financial support for individuals, communities and public sector organisations, businesses and industry for deploying local renewable heat generation systems. This improves the market potential for solar thermal systems as well as heating from a biomass boiler or CHP unit within a building integrated installation. It makes the application of these technologies at a micro or mini scale more economically worthwhile.

Microgeneration has been disregarded over the years from building owners and property developers. The main reason for this is the low return on investment and hence an unviable payback period. The government has been assisting willing building owners by way of grants, and now the FITs and RHI schemes, to make installing renewable technologies a better economic decision.

There is significant potential within LZC technologies for low carbon applications within the built environment. However, due to time constraints only a few LZC technologies were considered within this study.  It was necessary to evaluate and identify knowledge gaps within these technologies and develop further so that a unique appraisal toolkit was formed.

## Conclusion

The technology categories described within this chapter have very different characteristics in terms of function, operation, energy yield and controllability. The main reason for the installation of any of the technologies is to reduce the carbon emissions associated with the energy usage of the building i.e. heat and power. This premise forms the basis of the assessment methodology discussed later.

In essence all seven technologies mentioned are capable for providing useful low-carbon energy to a building, but have their limitations and constraints. The appraisal methodology, to be elaborated in Chapter 4, considers all possibilities for a low carbon building. However due to time constraints associated with the project, it was decided that priority would be for modelling renewable technologies. This was inclusive of solar photovoltaic, solar thermal and wind turbine technologies and also for the implementation of natural ventilation within buildings. The remainder technologies were considered for feasibility stage development. This decision has been based on the fact that legislation favours the installation of renewable technologies **(3,4)** and also it currently presents the greatest challenge to a building services consultant. Detailed appraisal models may be developed for GSHP, CHP and biomass systems for future work outwith this project.

The focus for this study was to develop analysis models and to prioritise renewable technologies. Therefore software tools were researched that would assist in producing these models as part of the assessment methodology.

# Chapter 3 – Software Tools

Systems such as solar hot water and solar photovoltaic panels and micro wind turbines may well be utilised as a building integrated installation and contribute to reducing the carbon footprint. To measure the impact of these systems within the built environment, it is necessary to simulate their performance in realistic design situations. Modelling and simulation tools provide an appropriate means for doing this and hence assess the renewable capability for a site. Typically, however no one tool is suitable for a complete assessment of building integrated renewable energy systems. Usually multiple tools are utilised at different stages within a design project. This section details the software tools used within the design process and later a methodology is elaborated that sets out how multiple tools can be used effectively and efficiently within a low carbon building analysis.

The basic design stages within which software can be employed include:

Stage A and B – basic building requirements
Stage C – Concept Design
Stage D – Scheme Design
Stage E, F – Detailed Design

Energy systems are first discussed during Stage C of a build project, hence an opportunity to discuss feasibility of renewable technologies for the site. Following up from initial studies; at detailed design stage a comprehensive analysis is required for deciding on the renewable technologies to be integrated as part of the building services strategy.

It was realised that different stages of design appraisals are possible for LZC technologies and it was beneficial to introduce feasibility studies for alternative technologies. Hence instead of targeting only a detailed assessment it was possible to develop as part of this “toolkit” a concept stage study assessing the feasibility of LZC technologies for a specific building site. Software tools were identified in relation to the building design process. The concept and detailed design indeed have separate criterion for analysis, and for this reason a review was conducted for a majority range of simulation tools of differing levels of complexity.

There are currently a broad range of software tools on the market to assist designers in assessing the performance of LZC technology options. These tools fall into four broad (and sometimes overlapping) categories:

- Single issue tools – tools which have been developed to assess the performance of a single technology. Examples include Radiance (daylighting).

- Strategic design tools – tools which enable a designer to make a quick evaluation of the likely performance of a technology early in the design process where relatively little information is available. Examples include Merit (renewable energy) and Energy10 (early-stage building design).

- Building simulation tools – enable the integrated performance of a building to be assessed, though typically with a high data input overhead and sometimes with limited capabilities with regards to the modelling of LZC energy supply options **(80)**. Examples include IES VE, Energy Plus and ESP-r.

- General engineering tools – which are developed to model a broad range of physical process, but which are not intended to model any specific technology, for example computational fluid dynamics (CFD).

Historically, the early development of simulation programs was focussed for evaluating the building as a whole system, mainly through an integrated package **(81)**. At present a number of modules based simulation tools have been developed and are being commercially used. The tools co-exist with their own inherent strengths and weaknesses performing a variant of simulation tasks. Though modellers may be too reliant on a single platform and it may be more productive to choose from a suite of tools to perform the range of simulation tasks **(80)**. It is important to identify the right set of tools for carrying out the required appraisals for design and installation of building integrated renewable energy technologies. For this study, a suite of tools were compared and evaluated and this was done by investigating literature comparing different vendor programs and their simulation capabilities. The US Department of Energy (DOE)'s review of building modelling tools **(80)** provided great insight into the capabilities of these tools and compared them to set criterion. This would assist in identifying software for the LZC modelling methodology. A total of twenty building simulation tools were compared which the author described as a difficult task. This was because a common language was not used within the simulation community to describe the facilities offered by tools and the entities used to define simulation models **(80)**. The findings were as follows:

- General modelling features were present in most simulation packages but ESP-r and Energy Plus provided extra features for importing and exporting data
- Zone loads were most prominent within IES VE
- Building envelope, Daylighting and Solar analysis were comprehensively dealt with by IES VE, ECOTECT, Energy Plus and TRNSYS
- Energy Plus and IES VE gave most analytical data for environmental emissions
- Most renewable energy systems were modelled by TRNSYS, ESP-r had moderate capability, but in general there is very little capability in analysing such systems for building simulation programs.
- TRNSYS and ESP-r have the best validation procedures being research driven software whereas validation for IES VE is regarded as minimal.

The researcher focussed on the building simulation package, IES VE, as this was a readily available tool to develop the LZC methodology. IES VE had performed well in most criterions; for example it had the most comprehensive zone load calculations. However, IES VE has limited capability in assessing renewable energy systems. A holistic solution is desired and few tools are capable for modelling building integrated LZC energy supply systems hence a number of tools form the assessment methodology.

The assessment methodology is the combination of utilising capable simulation software and developed algorithms for ensuring comprehensive coverage of analysis techniques, to perform technical appraisals for building integrated low carbon technology installations. The finer details of this assessment methodology are discussed within Chapter 4, but since the toolkit utilises a suite of tools in a ‘pluggable’ fashion i.e. a variety of tools may be used for a single process; it requires the development of a ‘processing tool’ to regulate all data into a consistent and understandable format. The processing tool is also used for its main operation to summarise the resultant data and present this in an interesting format for non-technical stakeholders. The processing tool is an Excel based program performing the above functions for concept and detailed stage analyses.

For this study, due to brevity and to reduce complexity within the development period, software tools were limited to ‘one’ for each analytical process. Also the software selection process was simplified to make full use of available resources and therefore for concept design, RETScreen and HOMER, freeware from North America were utilised. For detailed design stage, IES VE, building simulation tool and Fluent, CFD tool were available to utilise. Selecting these software tools allowed for better integration within existing design procedures, however the use of tools is not restricted and other combinations may well be used as substitute as long as the resultant data is similar. The selected software tools are now described in greater detail and in particular their role within this newly formed assessment methodology.

### HOMER[1]

HOMER contributes within the assessment methodology as a tool used for early-stage or concept design study, determining feasibility of installation for the proposed site. However, HOMER is limited to analysing electricity generating systems, hence limited to evaluating wind turbine, solar PV panels and CHP for this study.

HOMER is suitable for pre-feasibility analysis; a tool that evaluates the overall effectiveness for a proposed electricity generating system. HOMER is also capable to perform a sensitivity analysis for technology options assessment. Therefore certain properties may be altered as part of a sensitivity analysis to explore alternative solutions. The resource data for renewable energy may be manually inserted and the quality of data may vary from being monthly averaged or hourly averaged. NASA possesses a database[2] from which solar and wind resource data compatible with HOMER may be obtained. The software generates many scenarios and lists them in order of lowest net present value (NPV). Therefore many different combinations of systems may be studied and compared.

### RETScreen[3]

RETScreen like HOMER is a tool used during early design stage, therefore for the concept design study within the proposed assessment methodology. The purpose of

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[1] https://analysis.nrel.gov/homer/

[2] http://eosweb.larc.nasa.gov/sse/

[3] www.retscreen.net

the concept study is to evaluate feasibility of installation for the building site. In this study RETScreen was used for evaluating the performance of solar hot water and GSHP systems. RETScreen is capable for analysing other renewable technologies but HOMER was preferred for the majority of technologies. HOMER provides a greater dataset that may be processed to form the desired results data.

RETScreen may be used to carry out techno-economic analysis of renewable energy projects **(78)**. RETScreen requires technical input by the user and gives a comprehensive environmental overview for the project. This software is used for feasibility stage of the project as an analysis tool deriving various financial implications of an integrated building energy system and estimate environmental and technical performance. It is a tool designed to aid decision making regarding feasibility of a renewable energy project. The tool performs separate analysis for each technology and therefore does not contribute to a sensitivity analysis.

For concept design stage, the majority of data consists of default performance built-in to the tool; hence very little data is acquired for the analysis. However, this is not the case for detailed appraisals; they consist of a detailed modelling exercise and therefore architectural and site specific detail becomes mandatory knowledge. The modelling and data requirements are therefore discussed in more detail for the CFD and building simulation software.

### Fluent[4]

Fluent is a Computational Fluid Dynamics (CFD) tool. Fluent was used within this assessment methodology to assess the micro-climate within which the proposed building is situated. The CFD tool was used to perform a turbulent flow analysis on the exterior of the building **(82)**, then the flow paths within the built environment may be evaluated. The resultant data was applied to appraise the proposed installation of micro-wind turbines and also for the design of naturally ventilated buildings.

The most critical aspect of modelling within CFD is mesh generation. The better the mesh generated within the computational domain the more accurate results are possible. The computational domain and site geometry are constructed allowing for control on cell concentration. A better mesh has a high concentration of cells located near wall surfaces for the building. The model should utilise quadrilateral elements

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[4] www.fluent.com

for improved accuracy, however triangular elements may be used for more complex element shapes. Much deliberation and experimentation is required to produce a quality mesh that is economic in its use of resources but sufficient in providing realistic CFD scenarios. Therefore computational cells are considerably larger further away from the building in uninterested areas, but maintaining acceptable aspect ratios. This is done to minimise use of resources and hence a more efficient calculation. It must be added that due to the use of a velocity inlet profile with steep gradients near the ground, additional computational resources may be required.

There are many numerical models available for modelling turbulent external flow. They can be divided into two main categories

1) Isotropic eddy – viscosity models
2) Second moment stress models

The first of the two is the most widely used models in engineering and also used during this analysis, the second is more accurate and requires more computational effort **(83)**. The numerical model used for this analysis is the two equation kinetic energy – dissipation (k-ε) model. This solves the Reynolds-Averaged Navier-Stokes equations with additional transport parameters, turbulent kinetic energy (k), and turbulence dissipation rate (ε), thus including the convective and diffusive transport of the turbulence itself. The solver uses a first order upwind implicit discretisation scheme.

Initial conditions are required for five parameters, x-velocity, y-velocity, z-velocity, turbulence kinetic energy (k) and dissipation rate (ε). The initial values of k and ε are estimated using the following equations.

$$k_i = 4.5x10^{-3}x(V_{in})^2$$

**Equation 1 - Initial k value (83)**

$$\varepsilon_i = (k_i)^{1.5}x\frac{0.1643}{(0.09H)}$$

**Equation 2 - Initial ε value (83)**

Where $V_{in}$ the Velocity at inlet and H is height of the computational domain, $k_i$ and $e_i$ are the initial turbulence modelling values. There are six equations solved during the iteration process and the convergence criterion is set at 0.001, this is an acceptable amount of residual and provides reasonable results.

The CFD model has been defined to represent realistic local built environment conditions for the building in question. However, there are limitations to the use of CFD within this application. The CFD model may only provide a snapshot for each scenario and therefore only a set number of scenarios are looked at. It would be an inefficient use of resources to look at all possible scenarios for a building integrated wind turbine for one site. Therefore an arbitrary velocity has been used for eight wind directions and flow patterns have been analysed. This data has been further used to determine velocity and pressure coefficients (Chapter 4). The CFD modelling tool also has its limitations. A CFD analysis was done for a cubic structure and similarly experimental data was gathered through wind tunnel testing **(84)**. On comparison of the results, the turbulence kinetic energy was under-predicted near ground level and over estimated around the roof. This discrepancy was also reported in other studies **(85, 86)**. Another study has reported that errors are induced within CFD tools due to the lack of a transitional model (i.e. a model that can detail the transition from laminar to turbulent flow) **(87)**. Is this a genuine concern for modelling a highly turbulent local built environment? In essence, there are uncertainties with using CFD to evaluate the local built environment for the wind turbine that need discussed further.

## IES Virtual Environment[5] (VE)

IES VE is an integrated building simulation software package. The calculation engine is based upon first principles models of heat transfer process and utilises real weather data. IES VE is formed through a number of modules fully integrated through a common user interface. IES VE has the capability to perform a dynamic thermal simulation at sub-hourly timesteps using the module, ApacheSim. The exposed solar radiation may be assessed for building surfaces and a shading analysis may be performed using the module, SunCast. A UK wide energy compliance calculation can be performed using the module, VE-Compliance. Passive design, hybrid ventilation systems and bulk airflow modelling is assessed

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[5] www.iesve.com

through the module, MacroFlo. Finally a range of results processing, export and data analysis is done through the module, ApacheVista.

IES VE has been used as part of this assessment methodology to assess the micro-climate within which the proposed building is situated, as well as to determine the buildings energy statistics. IES VE was used to perform solar shading calculations to determine exposed radiation for photovoltaic panels and solar hot water systems. It was also used to perform a bulk-flow simulation to conduct a detailed appraisal for employing a natural ventilation design strategy for the proposed building.

The process for identifying suitable LZC technologies and appropriate analytical tools is complete. Due to brevity, a limited amount of technologies and corresponding analytical tools were selected for development for detailed design stage. Further studies may look at a greater amount of technologies leading to more analytical tools and inevitably further development of the toolkit. This toolkit was designed with in-built flexibility and to promote further expansion. This is detailed within the next chapter looking at the development and finer details of an assessment methodology for the technical, financial and environmental appraisal of LZC technologies.

# Chapter 4 - Assessment Methodology

The assessment methodology has been developed through gaining an understanding of suitable building integrated LZC technologies and analysis software. The review of LZC technologies and software tools made the lack of method within the current design process clearer. The refinement of existing ad-hoc processes into a functional assessment methodology required the introduction of an 'LZC toolkit'. This resultant toolkit, based upon a robust methodology, enables the design team to make informed choices with regards to which technologies or mix of technologies best meet a specific buildings energy requirement. By applying a methodology the current ad-hoc design process is improved upon, outlined in this chapter.

The methodology forms a logical process from which building integrated technologies are analysed from early design to pre-construction. The primary function of this methodology is to present a structured approach for assessing LZC Technologies within an existing design framework. The deliverables are quantifiable outputs defining technical, environmental and economic feasibility. Essentially the 'toolkit' indicates energy yield and carbon savings potential along with defining the payback period for candidate technologies. The determining factor for technology installation is most likely to be their carbon savings potential, particularly to meet legislative requirements **(3,4).**

The methodology was developed as a two stage process; technologies are assessed at early concept design stage and detailed design stage. The knowledge gained with respect to building integrated LZC technologies and energy analysis tools was taken into consideration through numerous brainstorming sessions for development of the assessment methodology. LZC technology appraisals are performed at concept stage for the whole range of technologies advised in Chapter 2, with the exception of passive systems. For detailed design stage, three analyses for renewable technologies plus natural ventilation design are assessed. For concept stage, feasibility analysis tools are utilised and for detailed stage, dynamic building simulation and CFD tools are utilised. The detailed assessment methodology describes the processes linking each software tool to the data requirements; this is detailed within Figure 8.

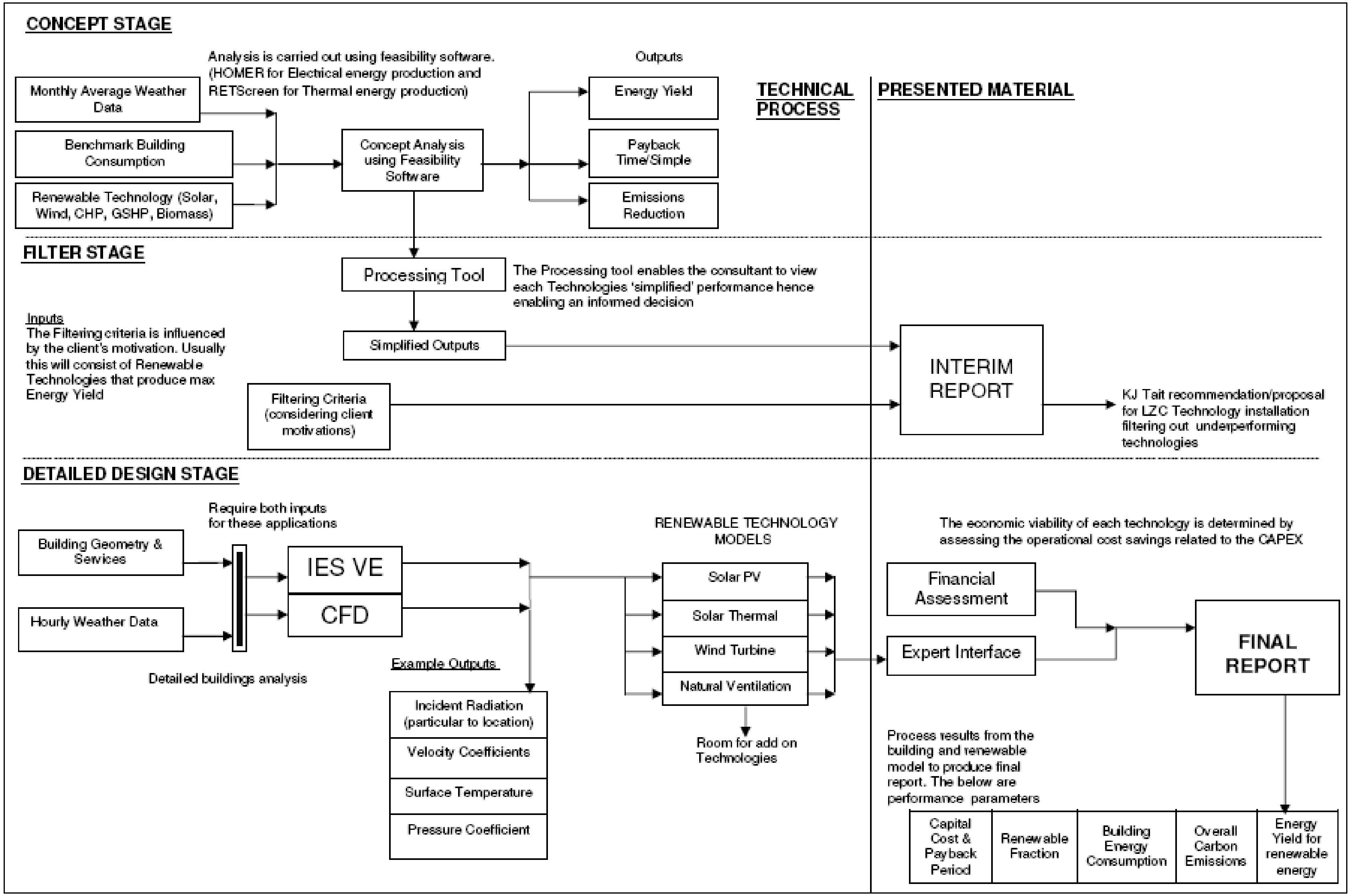

Figure 8 - Assessment Methodology

The above figure details each process involved within the assessment methodology and hence the processes applied within the ‘LZC toolkit’. A relatively simple analysis may be performed for a multiple amount of technologies when evaluating at concept stage. However significant computing effort and time is required to perform analyses for detailed design stage. The ‘filter stage’ identified within the assessment methodology discards poor performing technologies from being assessed at detailed design stage. A decision is made based upon the outcome of the concept study to identify performing technologies for further detailed analysis; hence a more efficient process.

In summary, the development of this toolkit consisted of the selection of feasibility software for concept stage and the building of a compatible ‘processing tool’ to provide three distinct performance parameters. From a knowledge perspective, reliable sources for the selection of input data were sought **(88,89)**, however of low resolution (monthly), to be compatible with the use of HOMER and RETScreen. The development for detailed design analysis however was more involved, consisting of the development of three ‘renewable technology models’, a building specific natural ventilation design analysis model and ‘the expert interface’ (detailed in Chapter 5). A 3D model was built using IES VE, non-existent at concept design stage. An external layout model was constructed using Fluent to assess external fluid flow. The data extracted from these two tools was then used as ‘input data’ for the renewable technology models. The models were built using research based theories for each technology, which then provided data for determining the technologies predicted performance. The feed-in of data for each stage and reporting of results concluded the development phase for the two analyses procedure.

The methodology was compiled with a degree of flexibility. Hence a number of technologies may be assessed using a range of software, possibly alternative to those used within this work, for the assessment of LZC Technologies. There is still scope for developing ‘models’ for other low carbon technologies at detailed design stage. The process flowchart (Figure 8) made clear the development requirements for producing technology appraisals for each design stage.

Having established the assessment methodology; appropriate modelling opportunities were identified. The development of suitable tools was carried out for a two stage design process. A certain structure was followed for developing models to assess BIRE technologies and is defined below:

- A development summary was devised
- The use of modelling tools to supply input data for analysis models
- The development of analysis models
- The development of a processing tool for deriving performance parameters
- A financial assessment performed for all technologies
- A performance comparison of building integrated renewable energy technologies

### Concept Stage Analysis

This appraisal is performed during early design stage and possibly prior to building planning application submission. In summary, the development for appraisals at concept design stage is listed in the table below: identifying the necessary outputs, existing capability and development needs for producing these appraisals.

| DEFINED OUTPUTS | EXISTING CAPABILITY | SOFTWARE DEVELOPMENT | FURTHER DEVELOPMENT |
|---|---|---|---|
| Cost Data<br>Capital Cost, other costs, Financial aids/grants, Simple Payback Period<br>Environmental Data<br>Carbon Dioxide Reductions<br>BREEAM credits<br>Technical Data<br>Energy Yield | Existing ad-hoc process producing single use spreadsheets | RETScreen and HOMER are capable of analysing cost and technical data.<br>HOMER carries out hourly calculations to determine performance data for each technology. | Different defaults are applied to environmental emissions and cost is in dollars. A **processing tool** is necessary to analyse data with local default values. |

**Table 2 - Concept Stage development summary**

At concept level design, an initial assessment is necessary to identify technologies that have good energy potential for a specific site. The goal is to determine the technologies predicted performance with a simple and effective analysis approach. The development summary identifies that a processing tool is required to perform an appraisal at concept stage. North American feasibility design tools, RETScreen and

HOMER was used to perform a technical appraisal for each technology. The technical input data for the processing tool was provided by the modelling tools, described in greater detail below.

## HOMER[6]

HOMER was used to perform a sensitivity analysis for the combination of renewable energy technologies, restricted to electricity generating technologies. The size of installation and basic technical and financial details for each renewable energy system were inputted and an hourly calculation was performed exploring all possible combinations of technologies identified for the analysis. Certain properties were altered as part of the ‘sensitivity’ analysis further exploring different solutions. The software generates many scenarios and lists them in order of lowest net present value (NPV), enabling many different combinations of systems to be studied and compared. The optimum solution is chosen from the sensitivity analysis and exported to the processing tool where this data is transformed into presentable material. The criteria for the optimum solution are determined from understanding the buildings energy requirement. At this stage, the determining factors considered when selecting a solution are renewable energy delivered and cost effectiveness i.e. a low NPV.

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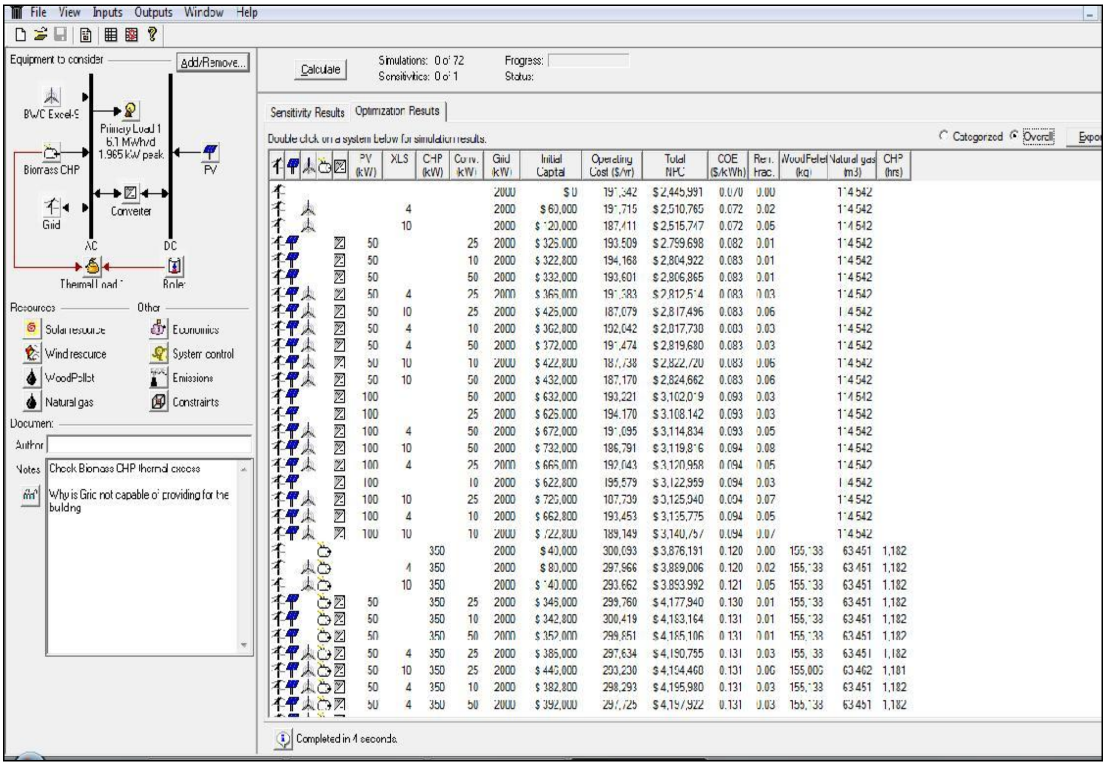
[6] https://analysis.nrel.gov/homer/



Document
Author:
Notes: Check Biomass CHP thermal excess

Why is Grid not capable of providing for the building

Simulations: 0 of 72
Sensitivities: 0 of 1
Progress:
Status:

Double click on a system below for simulation results.

| | | | | | PV (kW) | XLS | CHP (kW) | Conv. (kW) | Grid (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | WoodPellet (kg) | Natural gas (m3) | CHP (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ● | | | | | | | | | 2000 | $ 0 | 191,342 | $ 2,445,991 | 0.070 | 0.00 | | 114,542 | |
| ● | | ● | | | | 4 | | | 2000 | $ 60,000 | 191,715 | $ 2,510,765 | 0.072 | 0.02 | | 114,542 | |
| ● | | ● | | | | 10 | | | 2000 | $ 120,000 | 187,411 | $ 2,515,747 | 0.072 | 0.05 | | 114,542 | |
| ● | ● | | | ● | 50 | | | 25 | 2000 | $ 326,000 | 193,509 | $ 2,799,698 | 0.082 | 0.01 | | 114,542 | |
| ● | ● | | | ● | 50 | | | 10 | 2000 | $ 322,800 | 194,168 | $ 2,804,922 | 0.083 | 0.01 | | 114,542 | |
| ● | ● | | | ● | 50 | | | 50 | 2000 | $ 332,000 | 193,601 | $ 2,806,865 | 0.083 | 0.01 | | 114,542 | |
| ● | ● | ● | | ● | 50 | 4 | | 25 | 2000 | $ 366,000 | 191,383 | $ 2,812,514 | 0.083 | 0.03 | | 114,542 | |
| ● | ● | ● | | ● | 50 | 10 | | 25 | 2000 | $ 425,000 | 187,079 | $ 2,817,496 | 0.083 | 0.06 | | 114,542 | |
| ● | ● | ● | | ● | 50 | 4 | | 10 | 2000 | $ 362,000 | 192,042 | $ 2,817,730 | 0.083 | 0.03 | | 114,542 | |
| ● | ● | ● | | ● | 50 | 4 | | 50 | 2000 | $ 372,000 | 191,474 | $ 2,819,680 | 0.083 | 0.03 | | 114,542 | |
| ● | ● | ● | | ● | 50 | 10 | | 10 | 2000 | $ 422,800 | 187,738 | $ 2,822,720 | 0.083 | 0.06 | | 114,542 | |
| ● | ● | ● | | ● | 50 | 10 | | 50 | 2000 | $ 432,000 | 187,170 | $ 2,824,662 | 0.083 | 0.06 | | 114,542 | |
| ● | ● | | | ● | 100 | | | 50 | 2000 | $ 632,000 | 193,221 | $ 3,102,019 | 0.093 | 0.03 | | 114,542 | |
| ● | ● | | | ● | 100 | | | 25 | 2000 | $ 626,000 | 194,170 | $ 3,108,142 | 0.093 | 0.03 | | 114,542 | |
| ● | ● | ● | | ● | 100 | 4 | | 50 | 2000 | $ 672,000 | 191,095 | $ 3,114,834 | 0.093 | 0.05 | | 114,542 | |
| ● | ● | ● | | ● | 100 | 10 | | 50 | 2000 | $ 732,000 | 186,791 | $ 3,119,816 | 0.094 | 0.08 | | 114,542 | |
| ● | ● | ● | | ● | 100 | 4 | | 25 | 2000 | $ 666,000 | 192,043 | $ 3,120,958 | 0.094 | 0.05 | | 114,542 | |
| ● | ● | | | ● | 100 | | | 10 | 2000 | $ 622,800 | 195,579 | $ 3,122,959 | 0.094 | 0.03 | | 114,542 | |
| ● | ● | ● | | ● | 100 | 10 | | 25 | 2000 | $ 726,000 | 187,739 | $ 3,125,040 | 0.094 | 0.07 | | 114,542 | |
| ● | ● | ● | | ● | 100 | 4 | | 10 | 2000 | $ 662,800 | 193,453 | $ 3,135,775 | 0.094 | 0.05 | | 114,542 | |
| ● | ● | ● | | ● | 100 | 10 | | 10 | 2000 | $ 722,800 | 189,149 | $ 3,140,757 | 0.094 | 0.07 | | 114,542 | |
| ● | | | ● | | | | 350 | | 2000 | $ 40,000 | 300,093 | $ 3,876,191 | 0.120 | 0.00 | 155,133 | 63,451 | 1,182 |
| ● | | ● | ● | | | 4 | 350 | | 2000 | $ 80,000 | 297,966 | $ 3,889,006 | 0.120 | 0.02 | 155,133 | 63,451 | 1,182 |
| ● | | ● | ● | | | 10 | 350 | | 2000 | $ 140,000 | 293,662 | $ 3,893,992 | 0.121 | 0.05 | 155,133 | 63,451 | 1,182 |
| ● | ● | | ● | ● | 50 | | 350 | 25 | 2000 | $ 346,000 | 299,760 | $ 4,177,940 | 0.130 | 0.01 | 155,133 | 63,451 | 1,182 |
| ● | ● | | ● | ● | 50 | | 350 | 10 | 2000 | $ 342,800 | 300,419 | $ 4,183,164 | 0.131 | 0.01 | 155,133 | 63,451 | 1,182 |
| ● | ● | | ● | ● | 50 | | 350 | 50 | 2000 | $ 352,000 | 299,851 | $ 4,185,106 | 0.131 | 0.01 | 155,133 | 63,451 | 1,182 |
| ● | ● | ● | ● | ● | 50 | 4 | 350 | 25 | 2000 | $ 385,000 | 297,634 | $ 4,190,755 | 0.131 | 0.03 | 155,133 | 63,451 | 1,182 |
| ● | ● | ● | ● | ● | 50 | 10 | 350 | 25 | 2000 | $ 446,000 | 293,230 | $ 4,194,460 | 0.131 | 0.06 | 155,003 | 63,402 | 1,181 |
| ● | ● | ● | ● | ● | 50 | 4 | 350 | 10 | 2000 | $ 382,800 | 298,293 | $ 4,195,980 | 0.131 | 0.03 | 155,133 | 63,451 | 1,182 |
| ● | ● | ● | ● | ● | 50 | 4 | 350 | 50 | 2000 | $ 392,000 | 297,725 | $ 4,197,922 | 0.131 | 0.03 | 155,133 | 63,451 | 1,182 |

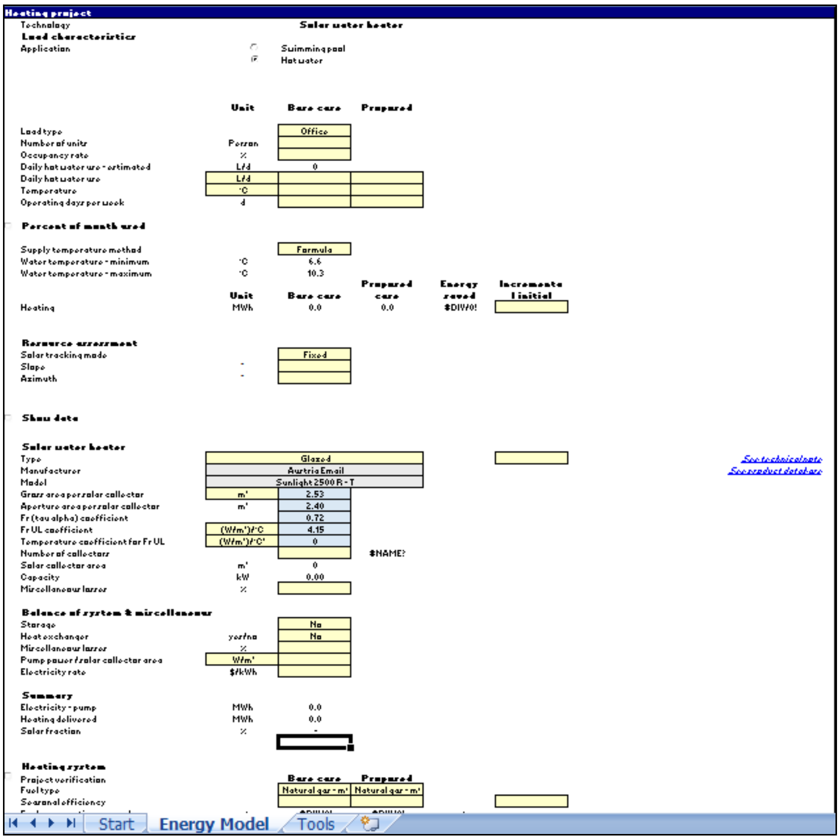
Completed in 4 seconds.

Figure 9 - HOMER screenshot

The above figure identifies the data requirements for conducting a sensitivity analysis for the application of electricity generating low carbon technologies. The technologies modelled using HOMER were Solar PV, Wind turbines and CHP (Biomass or Nat. Gas). The larger window lists the many possible combinations for the technologies assessed, in order of lowest NPV. For this study, the parameters of most concern are the ‘renewable fraction’ and ‘energy yield’ as a separate economic analysis is completed for comparison of all technologies, when technical data has been sought. The system description is graphically presented on the top left hand side and below this are the ‘Resource’ values for the project; they define the boundaries for performance analysis. Input data for this ‘high level’ analysis consists of monthly averaged weather data, benchmark building energy consumption and renewable technology details such as capacity and capital cost. HOMER utilises its randomising algorithms to compile a full year load & weather data from the entered input data **(88,89)**. The best solution is chosen, to consist of all technologies with the highest ‘Renewable Fraction’, and exported to the processing tool.

## RETScreen[7]

RETScreen like HOMER is a tool used during feasibility stage, hence appropriate for the concept design study. RETScreen was used for evaluating the performance of solar thermal and GSHP systems; therefore derive the energy yield for the solar thermal systems and identify the energy contribution for the proposed GSHP system.



**Heating project**

| | | | | | |
|---|---|---|---|---|---|
| Technology | | Solar water heater | | | |
| **Load characteristics** | | | | | |
| Application | ○ | Swimming pool | | | |
| | ● | Hot water | | | |
| | **Unit** | **Base case** | **Proposed** | | |
| Load type | | Office | | | |
| Number of units | Person | | | | |
| Occupancy rate | % | | | | |
| Daily hot water use - estimated | L/d | 0 | | | |
| Daily hot water use | L/d | | | | |
| Temperature | °C | | | | |
| Operating days per week | d | | | | |
| **Percent of month used** | | | | | |
| Supply temperature method | | Formula | | | |
| Water temperature - minimum | °C | 6.6 | | | |
| Water temperature - maximum | °C | 10.3 | | | |
| | **Unit** | **Base case** | **Proposed case** | **Energy saved** | **Incremental initial** |
| Heating | MWh | 0.0 | 0.0 | #DIV/0! | |
| **Resource assessment** | | | | | |
| Solar tracking mode | | Fixed | | | |
| Slope | ° | | | | |
| Azimuth | ° | | | | |
| **Show data** | | | | | |
| **Solar water heater** | | | | | |
| Type | | Glazed | | | |
| Manufacturer | | Austria Email | | | |
| Model | | Sunlight 2500 R - T | | | |
| Gross area per solar collector | m² | 2.53 | | | |
| Aperture area per solar collector | m² | 2.40 | | | |
| Fr (tau alpha) coefficient | | 0.72 | | | |
| Fr UL coefficient | (W/m²)/°C | 4.15 | | | |
| Temperature coefficient for Fr UL | (W/m²)/°C² | 0 | | | |
| Number of collectors | | | #NAME? | | |
| Solar collector area | m² | 0 | | | |
| Capacity | kW | 0.00 | | | |
| Miscellaneous losses | % | | | | |
| **Balance of system & miscellaneous** | | | | | |
| Storage | | No | | | |
| Heat exchanger | yes/no | No | | | |
| Miscellaneous losses | % | | | | |
| Pump power / solar collector area | W/m² | | | | |
| Electricity rate | $/kWh | | | | |
| **Summary** | | | | | |
| Electricity - pump | MWh | 0.0 | | | |
| Heating delivered | MWh | 0.0 | | | |
| Solar fraction | % | - | | | |
| **Heating system** | | | | | |
| Project verification | | **Base case** | **Proposed** | | |
| Fuel type | | Natural gas - m³ | Natural gas - m³ | | |
| Seasonal efficiency | | | | | |

See technical note
See product database

Figure 10 - RETScreen screenshot

The above figure details the technical requirements for the feasibility modelling of the solar thermal system. All 'yellow cells' within the above figure are input cells. The details of the solar panel may be updated via in-built databases hence they are 'blue' cells. The model for solar hot water systems within RETScreen was based upon technical data for the proposed system. This consists of, in brief terms, daily hot water load, storage capacity, solar panel technical details and installation site properties. The energy yield for the installation is produced along with a financial assessment for the installation, once all variables have been entered for the model.

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[7] www.retscreen.net

The financial analysis conducted by HOMER and RETScreen is ignored because a standard economic analysis is produced within the processing tool.

### Processing Tool

The performance parameters derived from this analysis are the energy yield (kWh), simple payback period (yrs) and $CO_2$ emissions reduction ($kgCO_2$). A processing tool was developed and data from HOMER and RETScreen are imported to this tool. From HOMER, hourly results data was exported consisting of PV power, wind power, building energy (electricity and natural gas), CHP energy data and top up boiler load. Annual energy yield for solar thermal and GSHP systems was imported from RETScreen. A range of algorithms are used to configure the input data into presentable performance data. The results are scrutinised by implementing a filtering criterion recommending candidate technologies to be considered at detailed design stage. The filtering criterion states the motivation for the installation of LZC technologies whether its legislative or meeting a certain ‘green’ criteria. Essentially important influencing factors such as meeting environmental targets or taking advantage of funding opportunities are highlighted as client priorities. The processes involved at concept design stage are documented within the proposed methodology for the analysis of building integrated LZC technologies (Figure 8).

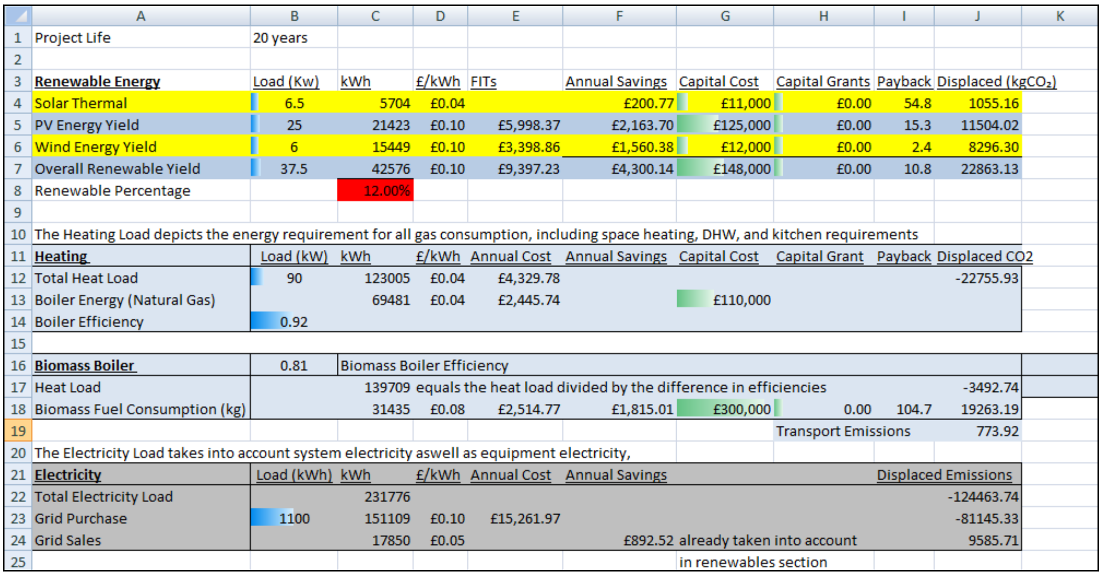
The three performance parameters, energy yield, carbon emissions reduction and simple payback period are defined below. The hourly data was accumulated to obtain the annual “energy yield” for each technology. To obtain the “carbon reduction” the energy yield is multiplied by the relevant carbon emission factor – detailed in Table 3 – for evaluating the environmental impact of a specific technology. The payback period is calculated using Equation 3, where the net capital cost is divided by the operational savings; made through consumption savings and incentives like FITs. Therefore a general viewpoint can be formed for the performance of each technology determining the likely environmental impact of the installation and potential return on investment.

$$Simple\ Payback\ Period = \frac{Capital\ Costs - Capital\ Grants}{Annual\ Energy\ Savings + FITs}$$

**Equation 3 – Simple Payback**

| | |
|---|---|
| Gas $CO_2$ Emission Factor | 0.194 $kgCO_2/kWh$ |
| Electricity $CO_2$ Emission Factor | 0.568 $kgCO_2/kWh$ |

**Table 3 - Carbon Emission Factors (36)**



| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Project Life | 20 years | | | | | | | | | |
| 2 | | | | | | | | | | | |
| 3 | **Renewable Energy** | Load (Kw) | kWh | £/kWh | FITs | Annual Savings | Capital Cost | Capital Grants | Payback | Displaced ($kgCO_2$) | |
| 4 | Solar Thermal | 6.5 | 5704 | £0.04 | | £200.77 | £11,000 | £0.00 | 54.8 | 1055.16 | |
| 5 | PV Energy Yield | 25 | 21423 | £0.10 | £5,998.37 | £2,163.70 | £125,000 | £0.00 | 15.3 | 11504.02 | |
| 6 | Wind Energy Yield | 6 | 15449 | £0.10 | £3,398.86 | £1,560.38 | £12,000 | £0.00 | 2.4 | 8296.30 | |
| 7 | Overall Renewable Yield | 37.5 | 42576 | £0.10 | £9,397.23 | £4,300.14 | £148,000 | £0.00 | 10.8 | 22863.13 | |
| 8 | Renewable Percentage | | 12.00% | | | | | | | | |
| 9 | | | | | | | | | | | |
| 10 | The Heating Load depicts the energy requirement for all gas consumption, including space heating, DHW, and kitchen requirements | | | | | | | | | | |
| 11 | **Heating** | Load (kW) | kWh | £/kWh | Annual Cost | Annual Savings | Capital Cost | Capital Grant | Payback | Displaced CO2 | |
| 12 | Total Heat Load | 90 | 123005 | £0.04 | £4,329.78 | | | | | -22755.93 | |
| 13 | Boiler Energy (Natural Gas) | | 69481 | £0.04 | £2,445.74 | | £110,000 | | | | |
| 14 | Boiler Efficiency | 0.92 | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 16 | **Biomass Boiler** | 0.81 | Biomass Boiler Efficiency | | | | | | | | |
| 17 | Heat Load | | 139709 | equals the heat load divided by the difference in efficiencies | | | | | | -3492.74 | |
| 18 | Biomass Fuel Consumption (kg) | | 31435 | £0.08 | £2,514.77 | £1,815.01 | £300,000 | 0.00 | 104.7 | 19263.19 | |
| 19 | | | | | | | | Transport Emissions | | 773.92 | |
| 20 | The Electricity Load takes into account system electricity aswell as equipment electricity, | | | | | | | | | | |
| 21 | **Electricity** | Load (kWh) | kWh | £/kWh | Annual Cost | Annual Savings | | | Displaced Emissions | | |
| 22 | Total Electricity Load | | 231776 | | | | | | | -124463.74 | |
| 23 | Grid Purchase | 1100 | 151109 | £0.10 | £15,261.97 | | | | | -81145.33 | |
| 24 | Grid Sales | | 17850 | £0.05 | | £892.52 | already taken into account | | | 9585.71 | |
| 25 | | | | | | | in renewables section | | | | |

**Figure 11 - Processing Tool screenshot**

The purpose of the processing tool is to import results data for the selection of candidate technologies to put forward for further assessment at detailed design stage. The screenshot (Figure 11) displays the calculation procedure for obtaining simple results for each technology. The cell data is automatically configured through the presence of general algorithms e.g. linking utilities data to produce annual energy savings. There are data bars for the spreadsheet indicating input data and reference data; the reference data does not affect the calculations. The cells labelled with green data bars are input data whereas blue represents 'reference data'. The capital cost is the only additional data needed to perform calculations within the processing tool, notwithstanding the data procured from feasibility software. Cell data may be altered from a built-in database (Figure 12) to model more appropriately the relevant emissions and cost data (e.g. the cost of fuel £/kWh). This tool calculates the 'simple payback period' and 'carbon reduction' along with 'energy yield' to enable a comparative appraisal for each technology. For low carbon technologies the following calculations have been undertaken to represent the low carbon credentials of these technologies. The energy yield and emissions reduction were calculated using Equations 4 to 9. There is no modelling tool used to calculate the effect of replacing the heating fuel to biomass, it is done within the processing tool using equations 4 to 6.

$$EY_{biomass} = \frac{EY_{ng}}{n_{biomass}} \mathrm{n_{ng}}$$

**Equation 4 - Energy Yield (biomass)**

$$CO_{2\,(reduction)} = CO_{2\,(ng)} - CO_{2(biomass)}$$

**Equation 5 - Carbon reduction (biomass)**

Where

$$CO_{2(biomass)} = EY_{biomass} * CO_2\,(factor) + \ transport\ emissions$$

**Equation 6 - Carbon emissions (biomass)**

The CHP is modelled within HOMER and the energy yield is obtained through the results data acquired from this tool. The total energy yield is defined below (Equation 7). The emissions reduction is defined by equating the replacement of boiler heat and grid electricity with CHP generated electricity and CHP heating.

Energy Yield (CHP) = heating (kWh) + generated electricity (kWh)

**Equation 7 - Energy Yield calculation for CHP generator**

$$CO_{2\,(reduction)} = CO_{2(htg)} + CO_{2\,(elec)} - CO_{2\,(fuel)}$$

**Equation 8 - Carbon emissions reduction (CHP)**

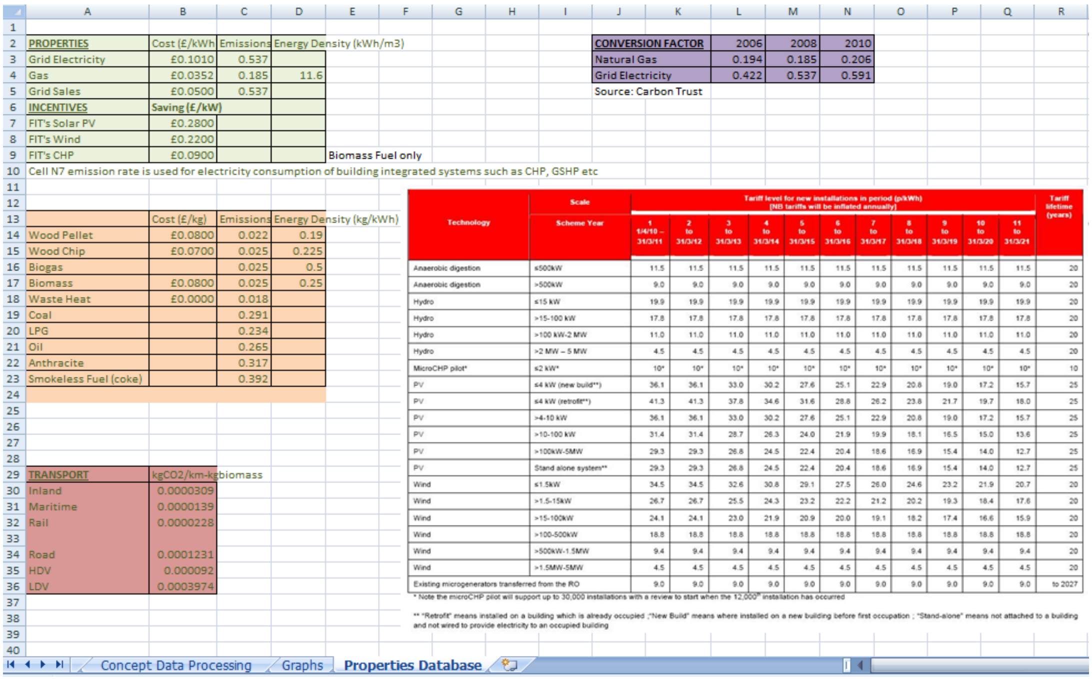
The modelling of GSHP systems was done through RETScreen and the energy yield was imported to the processing tool from RETScreen. The carbon reduction was calculated using the equation below.

$$CO_{2(reduction)} = CO_{2(htg)} + CO_{2\,(clg)} - CO_{2(fuel)}$$

**Equation 9 - Carbon reduction (GSHP)**

The emissions reduction for GSHP is derived by equating the useful heating and cooling provided by the GSHP minus the fuel emissions for running the system. Usually a net positive result is achieved because COPs are regularly in excess of 3.

The economic analysis was consistent for all LZC technologies and was based upon Equation 3. The three performance parameters derived from this analysis are then filtered and the candidate technologies are forwarded for analysis at detailed design stage.



| PROPERTIES | Cost (£/kWh | Emissions | Energy Density (kWh/m3) | |
|---|---|---|---|---|
| Grid Electricity | £0.1010 | 0.537 | | |
| Gas | £0.0352 | 0.185 | 11.6 | |
| Grid Sales | £0.0500 | 0.537 | | |
| INCENTIVES | Saving (£/kW) | | | |
| FIT's Solar PV | £0.2800 | | | |
| FIT's Wind | £0.2200 | | | |
| FIT's CHP | £0.0900 | | | Biomass Fuel only |

Cell N7 emission rate is used for electricity consumption of building integrated systems such as CHP, GSHP etc

| CONVERSION FACTOR | 2006 | 2008 | 2010 |
|---|---|---|---|
| Natural Gas | 0.194 | 0.185 | 0.206 |
| Grid Electricity | 0.422 | 0.537 | 0.591 |

Source: Carbon Trust

| | Cost (£/kg) | Emissions | Energy Density (kg/kWh) |
|---|---|---|---|
| Wood Pellet | £0.0800 | 0.022 | 0.19 |
| Wood Chip | £0.0700 | 0.025 | 0.225 |
| Biogas | | 0.025 | 0.5 |
| Biomass | £0.0800 | 0.025 | 0.25 |
| Waste Heat | £0.0000 | 0.018 | |
| Coal | | 0.291 | |
| LPG | | 0.234 | |
| Oil | | 0.265 | |
| Anthracite | | 0.317 | |
| Smokeless Fuel (coke) | | 0.392 | |

| TRANSPORT | kgCO2/km-kgbiomass |
|---|---|
| Inland | 0.0000309 |
| Maritime | 0.0000139 |
| Rail | 0.0000228 |
| | |
| Road | 0.0001231 |
| HDV | 0.000092 |
| LDV | 0.0003974 |

| Technology | Scale | Tariff level for new installations in period (p/kWh) [NB tariffs will be inflated annually] | | | | | | | | | | | Tariff lifetime (years) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scheme Year | 1 1/4/10 – 31/3/11 | 2 to 31/3/12 | 3 to 31/3/13 | 4 to 31/3/14 | 5 to 31/3/15 | 6 to 31/3/16 | 7 to 31/3/17 | 8 to 31/3/18 | 9 to 31/3/19 | 10 to 31/3/20 | 11 to 31/3/21 | |
| Anaerobic digestion | ≤500kW | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 20 |
| Anaerobic digestion | >500kW | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 20 |
| Hydro | ≤15 kW | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 19.9 | 20 |
| Hydro | >15-100 kW | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 | 20 |
| Hydro | >100 kW-2 MW | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 20 |
| Hydro | >2 MW – 5 MW | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 20 |
| MicroCHP pilot* | ≤2 kW* | 10* | 10* | 10* | 10* | 10* | 10* | 10* | 10* | 10* | 10* | 10* | 10 |
| PV | ≤4 kW (new build**) | 36.1 | 36.1 | 33.0 | 30.2 | 27.6 | 25.1 | 22.9 | 20.8 | 19.0 | 17.2 | 15.7 | 25 |
| PV | ≤4 kW (retrofit**) | 41.3 | 41.3 | 37.8 | 34.6 | 31.6 | 28.8 | 26.2 | 23.8 | 21.7 | 19.7 | 18.0 | 25 |
| PV | >4-10 kW | 36.1 | 36.1 | 33.0 | 30.2 | 27.6 | 25.1 | 22.9 | 20.8 | 19.0 | 17.2 | 15.7 | 25 |
| PV | >10-100 kW | 31.4 | 31.4 | 28.7 | 26.3 | 24.0 | 21.9 | 19.9 | 18.1 | 16.5 | 15.0 | 13.6 | 25 |
| PV | >100kW-5MW | 29.3 | 29.3 | 26.8 | 24.5 | 22.4 | 20.4 | 18.6 | 16.9 | 15.4 | 14.0 | 12.7 | 25 |
| PV | Stand alone system** | 29.3 | 29.3 | 26.8 | 24.5 | 22.4 | 20.4 | 18.6 | 16.9 | 15.4 | 14.0 | 12.7 | 25 |
| Wind | ≤1.5kW | 34.5 | 34.5 | 32.6 | 30.8 | 29.1 | 27.5 | 26.0 | 24.6 | 23.2 | 21.9 | 20.7 | 20 |
| Wind | >1.5-15kW | 26.7 | 26.7 | 25.5 | 24.3 | 23.2 | 22.2 | 21.2 | 20.2 | 19.3 | 18.4 | 17.6 | 20 |
| Wind | >15-100kW | 24.1 | 24.1 | 23.0 | 21.9 | 20.9 | 20.0 | 19.1 | 18.2 | 17.4 | 16.6 | 15.9 | 20 |
| Wind | >100-500kW | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 18.8 | 20 |
| Wind | >500kW-1.5MW | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 | 20 |
| Wind | >1.5MW-5MW | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 20 |
| Existing microgenerators transferred from the RO | | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | to 2027 |

* Note the microCHP pilot will support up to 30,000 installations with a review to start when the 12,000th installation has occurred

** "Retrofit" means installed on a building which is already occupied ;"New Build" means where installed on a new building before first occupation ; "Stand-alone" means not attached to a building and not wired to provide electricity to an occupied building

Figure 12 - Properties database

The properties database has been setup to determine input data for the expected costs and emissions associated with the assessed LZC technologies. This 'sheet' within the processing tool consists of input data for the cost of fuels and associated carbon emissions. The input cells may be altered to link project specific cost and emissions data. This assists for calculating the cost and environmental benefit for each technology in the form of 'payback period' and 'emissions reduction'. It is advised that data provided through the properties database is referenced from a reliable source, for example the conversion factors have been obtained from the Carbon Trust **(106)**.

Within the processing tool, a comparative analysis for the selection of building integrated LZC technologies is done at concept design stage. The results data is formed into a consistent format such that enables a comparative study to take place.

Once the analysis is complete, graphs have been produced to efficiently report findings of the study, to demonstrate easily readable outputs within an interim report for the non-technical stakeholder. The filtering criterion influences upon the recommendations being made for the selection of candidate technologies. Therefore, the combination of data from HOMER and RETScreen is processed into producing results understandable to the non-technical stakeholder.

For concept design stage, the majority of inputs consist of default performance built-in to the tool; hence very little data is acquired for the analysis. However, this is not the case for detailed appraisals; they consist of a detailed modelling exercise and therefore architectural and site specific detail becomes mandatory knowledge. The modelling and data requirements are therefore discussed in more detail for the CFD and building simulation software.

### Detailed Stage Analysis

At detailed design stage a comprehensive renewable technologies assessment is produced. The process applied is more rigorous in its approach than at concept stage. It is a focussed attempt to produce higher resolution performance appraisals for renewable energy technologies and natural ventilation design. The input parameters needed for assessing renewable energy potential are obtained from advanced simulation tools, IES VE and Fluent. Applying this raw data to renewable technology models determines the predicted performance for the proposed installation and hence the carbon reduction for a specific site. In summary, the development for appraisals at detailed design stage is listed in the table below: identifying the necessary outputs, existing capability and development needs for producing these appraisals.

| DEFINED OUTPUTS | EXISTING CAPABILITY | SOFTWARE DEVELOPMENT | FURTHER DEVELOPMENT |
|---|---|---|---|
| Cost Data<br>Payback Period (taking into account savings from plant operation, Capital grants, ECA's, FIT's, other financial benefits plus overheads)<br>Environmental Data<br>$CO_2$ Reductions (%)<br>BREEAM, LEED etc.<br>Does it meet requirement/strategy i.e. 10% $CO_2$ emissions reduction<br>Technical Data<br>Energy Yield<br>Wind: best location for max output after installation (CFD)<br>Solar: Shading analysis for avoiding low output areas. | Solar Shading Analysis can be done using SunCast, IES VE software, identifying locations with shading. Also identifying global solar radiation on external facades.<br>Energy consumption and $CO_2$ emissions can be found using IES VE building simulation program.<br>MacroFlo analyses infiltration and natural ventilation in buildings | Identified external building analyses (CFD) for pressure and wind profiles for evaluating wind energy and Natural Ventilation.<br>Identified use of existing software IES VE for solar analysis and assessing carbon impact of providing Natural Ventilation to buildings | IES VE & CFD have no financial tool (this needs to be developed)<br>Analytical models are required for Solar Thermal, Solar PV, Micro Wind Turbines and Natural Ventilation. Consider theory for each technology and develop Renewable Technology Models.<br>Develop an expert interface for processing data to present outputs defined in first column |

**Table 4 - Detailed stage development summary**

The detailed analysis provides a more in-depth assessment of candidate technologies for building integrated installation. Renewable technology models have been developed to enhance the capabilities of the building simulation tool used (IES VE), which has little renewable energy modelling capability **(80)**. There are in total three renewable technology models developed representing the candidate technologies assessed at detailed design stage, namely solar PV, solar thermal and micro wind turbine technologies.

The following sections explain how existing building simulation and CFD tools are used to generate input data for these models.

### Building Simulation Model

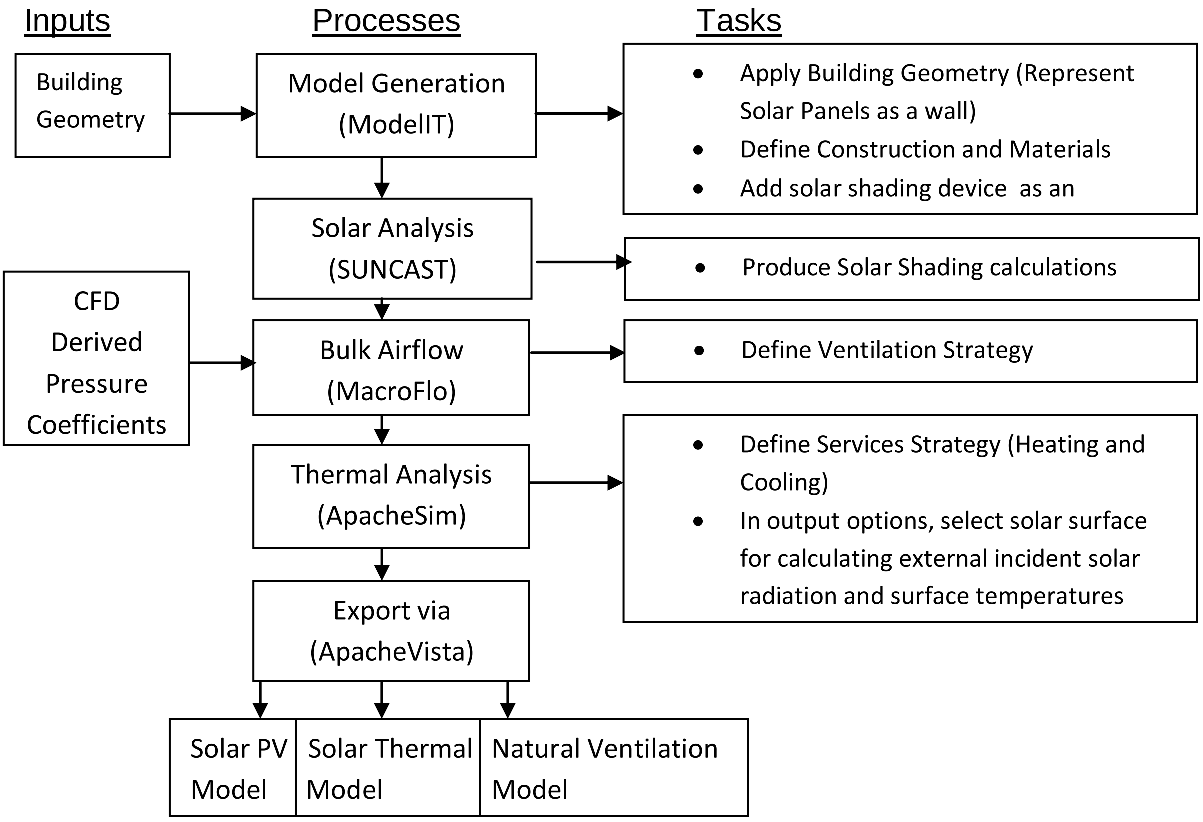


**Figure 13 - Building simulation model flowchart**

The above flowchart details the process for acquiring output data from the building simulation model for determining input data for the relevant ‘renewable technology models’. IES VE was used to perform solar shading calculations to determine exposed radiation for photovoltaic panels and solar thermal systems. It was further used to perform a bulk-flow simulation to conduct a detailed appraisal for employing a natural ventilation design strategy for the proposed building. The CFD derived pressure coefficients were imported into the building simulation tool to provide a more accurate bulk flow analysis for the site.

A dynamic simulation was performed for the building and three IES VE applications were used for obtaining the results data and exporting as input data for the renewable technology models. The impact of solar radiation within the indoor environment and external walls was evaluated using SunCast, a solar analysis application. The impact of ventilation to the building was setup using MacroFlo, a bulk-flow simulation application. Finally ApacheSim was used to perform an overall thermal simulation, determining the buildings energy data. All relevant results data was viewed and exported for processing from the application, ApacheVista.

The model was built-up using the application, ModelIT. Architect drawings for floor plans and elevations for the building were used to build the model, including all internal zones. It was necessary to add detail for the internal zone layout; the more precise the building of the model the greater accuracy achieved for the analysis. All construction details for external walls, windows and doors were entered to best model the ‘real’ building. Hence, it is only viable to do this appraisal once the building geometry was finalised with the client and the design team were progressing with detailed design.

Firstly, a solar analysis was performed for the building using SunCast. The solar shading calculation was done once all internal zones, the external layout for the building and its surroundings were modelled as a good representation of the actual building landscape. Any alterations made to the building layout would require a re-calculation. The SunCast model is used by ApacheSim for evaluating the ‘solar effect’ for the building and this would include solar gains, internal and external solar radiation and the number of daylight hours.

The next step would be to identify a ventilation strategy for the building. A window opening strategy was modelled in MacroFlo using CFD derived pressure coefficients. In this application user specified openable windows are modelled where the user is in control of conditions that determine the opening and closing of windows. This allows the user to develop and apply a natural ventilation design strategy for the building and evaluate its effectiveness. MacroFlo may assist the user with modelling an appropriate window opening strategy and hence provide better user control for the design of naturally ventilated buildings. The MacroFlo model is used by ApacheSim for evaluating ‘comfort’ conditions for the building by way of enhanced user control for natural ventilation design. The use of CFD derived pressure coefficients instead of characteristic pressure coefficients allows for a more specific calculation, taking into consideration the geometry of the building. This is discussed further within the CFD modelling process.

After performing a solar shading calculation using SunCast and applying a window opening strategy through the MacroFlo application; both models are linked to ApacheSim when conducting a thermal analysis for the building. The building was separated into thermal zones, identifying different room types and circulation space. Within this application thermal templates are assigned to each zone, this includes specifying the heating and cooling strategy along with internal gains and infiltration rates. A full building services strategy is formed to determine as accurately as possible the energy statistics for the building. An annual calculation was performed within ApacheSim; and following this the results are viewable in ApacheVista.

Using IES VE, raw input data is provided for solar technologies. Also combined with assistance from the CFD tool, Fluent, a comprehensive analysis of a natural ventilation services strategy may be done. The CFD tool was used to derive velocity and pressure coefficients, specific to the building, for use in the appraisal of micro wind technology and in assessing the viability of natural ventilation design for the building.

**CFD Model**

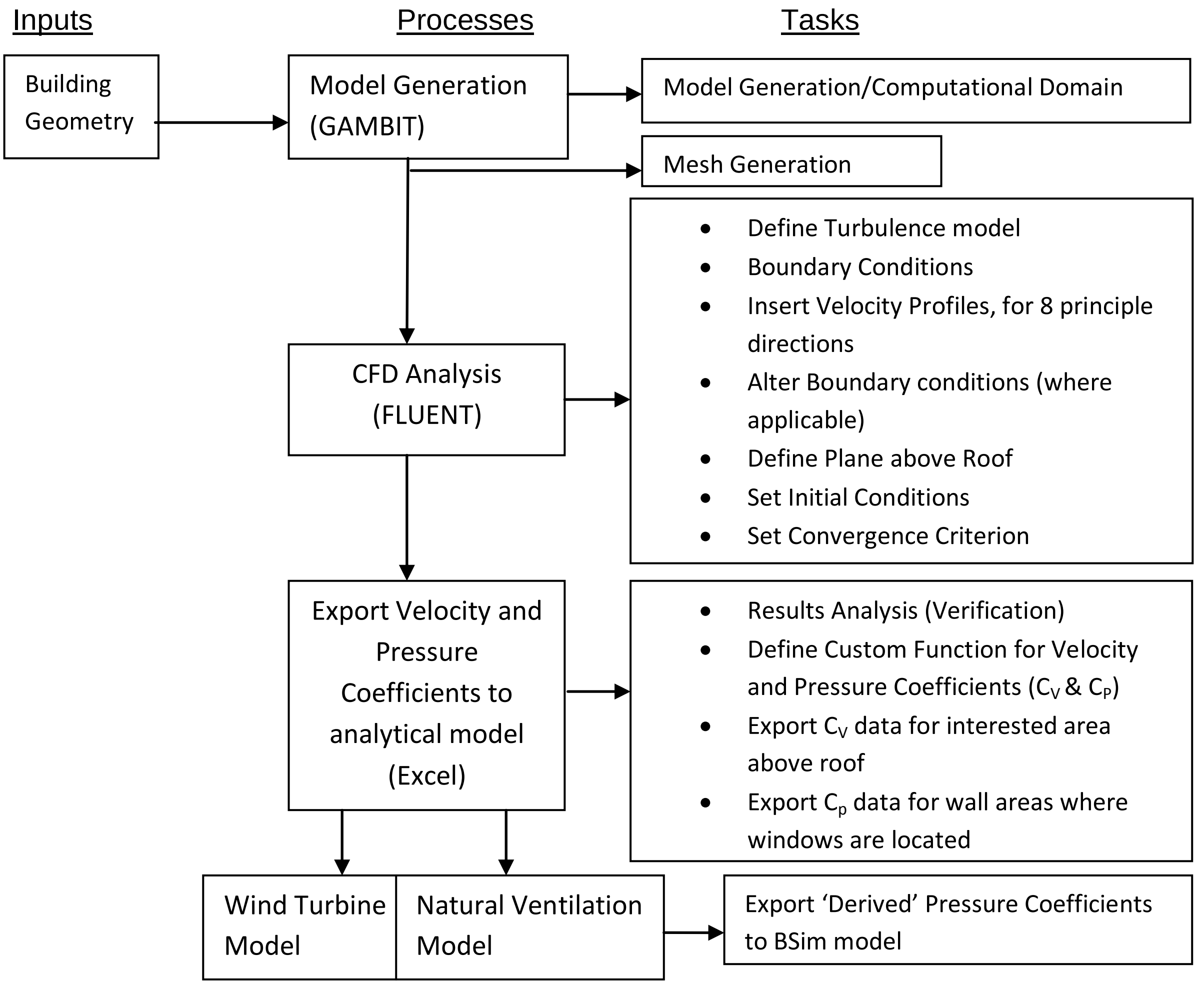
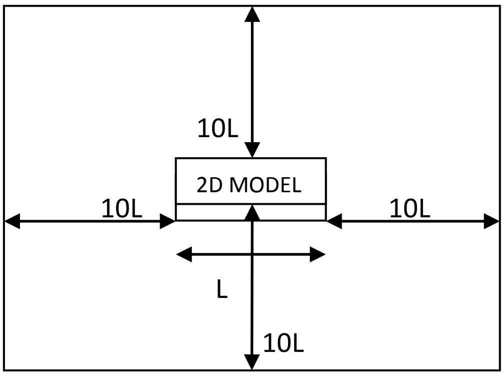


**Figure 14 - CFD model flowchart**

The above flowchart describes the use of a CFD tool to obtain input data for the wind turbine technology and the natural ventilation analysis models. Fluent, a CFD application was used to perform a turbulent flow analysis on the external building geometry. The acquired outputs from this analysis are customised velocity ($C_V$) and pressure coefficients ($C_P$), as defined in the flowchart above. The $C_V$ values assist in defining the optimum placement for the installation of a micro wind turbine. The $C_P$ values assist in defining the expected natural flow of air in and out of the building as part of a bulk flow analysis. The 'derived' $C_P$ coefficients are then exported to the IES VE model. The process for modelling using Fluent, to determine these coefficients, is described in greater detail below.

The process consists of building an external facade model within Fluent to produce a good quality mesh and hence identify flow characteristics such as flow acceleration, stagnation points and areas of maximum flow. Velocity and pressure coefficients were then calculated from the resultant CFD data. The methodology for calculating these coefficients is described below:

The model geometry is defined by site plans, which also determine the correct orientation of the building. The computational domain is sized in proportion with model geometry and is detailed in the diagram below.



'L' is the length of the building as indicated in the opposite diagram.

**Figure 15 - Computational Domain for CFD modelling (not to scale)**

The length and breadth of the domain equals ten times the length of the building as indicated whereas the 3D component of this domain (not shown) equals six times the length of the building. The computational domain and site geometry are defined so that the appropriate level of cell concentration is modelled. A high concentration of cells near wall surfaces allow for more accuracy in flow behaviour around the building. Finally, the use of a velocity inlet profile with steep gradients near the ground may require additional computational resources, hence longer simulation time.

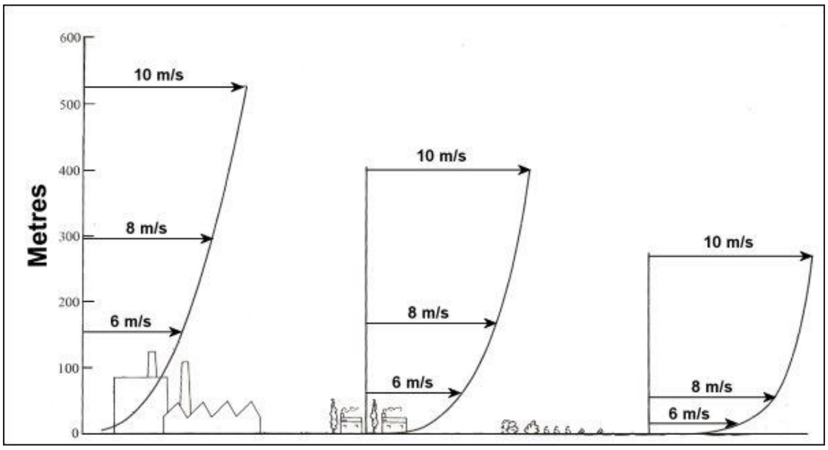


**Figure 16 - Wind profile for different terrain**

When the geometry was formed, the boundary conditions of the turbulence model were setup. The wind speed is represented through the use of customised velocity profiles at the inlet boundary. Figure 16 displays the wind velocity profile altering for the terrain in which it is being modelled.

The mathematical model of the building flow domain was solved for all eight principal flow directions. Boundary conditions were setup to represent likely external conditions for the local built environment. Symmetry boundary conditions are applied for external flow problems at the free stream which is the top surface of the domain. The vertical surfaces identify the prevailing wind direction by input of a velocity profile, which models a realistic atmospheric wind profile varying with height. The opposite surface is defined as a pressure outlet identifying a zero flux condition. The placement of the inlet and outlet faces defines the wind direction. The building walls and the ground have been identified as faces restricting flow and parameters such as surface roughness may be altered to suit the problem.

Initial conditions are required for five parameters, x-velocity, y-velocity, z-velocity, turbulence kinetic energy (k) and dissipation rate (ε). Also before initiating the iteration the convergence criterion for the above six equations was defined. These values are dependent on the type of simulation, for this study all initial conditions are set at 0 with a convergence criterion of 0.001. This was deemed to be an acceptable amount of residual and provides reasonable results for the velocity and pressure coefficients. The coefficients are derived using the below procedures.

### Velocity Coefficients

A plane is created above the building roof covering the exposed wind profile at the proposed height for building integrated wind turbine installation. The velocity coefficients are created using a custom field function in Fluent, dividing the local velocity by the free flowing velocity, defined in Equation 10. The velocity coefficients are identified for the height at which the wind turbine is to be installed and that data is exported to the analysis tool. The coefficients are calculated for each principal wind direction totalling eight different sets of velocity coefficients for each location above the roof.

$$C_v = \frac{V}{V_\infty}$$

**Equation 10 - Velocity Coefficient**

### Pressure Coefficients

The pressure coefficients are used to calculate the air flow through windows for each wall, hence the capacity for providing natural cooling. These coefficients are used within a bulk airflow simulation to determine the effectiveness of servicing a building by way of natural ventilation. The pressure coefficients are identified by creating a custom field function in Fluent, stating the local static pressure ($P_o$) divided by the free stream dynamic pressure ($0.5\rho(V_\infty)^2$), where, $V_\infty$ is the free stream velocity and ρ is the air density, defined in Equation 11. The pressure coefficients for the wall surfaces are exported into an Excel sheet before being used by MacroFlo for defining average values appropriate for the external facade. For example, a single window wall requires average values determined by computational nodes relevant to that area. These 'derived' coefficients are then further interpolated for 16 wind directions as required by MacroFlo.

$$C_P = \frac{P_o}{\frac{1}{2}\rho \mathrm{V}_\infty^2}$$

**Equation 11 - Pressure Coefficient**

Applying the above, allows for determining the velocity and pressure coefficients by use of a CFD tool. The processes for acquiring data from IES VE and Fluent have been described and the results obtained are used as input data for the ‘renewable technology models’. Velocity coefficients are acquired from the CFD analysis for conducting an appraisal for micro wind turbine technology. Similarly, ‘surface temperature’ and ‘external incident radiation’ were acquired for the installation area from IES VE for conducting an appraisal for solar technologies. The pressure coefficients are acquired from the CFD analysis, and the operative temperature is obtained from IES VE for conducting an appraisal of natural ventilation design. The weather provides the source for power capture from building integrated renewable technologies and therefore the relevant weather data was integral to all models. An hourly time step has been used for both analyses as it is compatible with the tools being used, however more qualitative weather data would bring improved results.

Despite the use of simulation software, there are certain addressable knowledge gaps identified for development within this study. The simulation software despite its complexity is weak in analysing renewable energy technologies **(80)**. Therefore the ‘raw’ data obtained shall be processed within a ‘renewable technology model’ to provide results for comparison of performance within the ‘expert interface’. The ‘raw’ data acquired from IES VE and Fluent is far more detailed and complex in comparison with the data acquired from concept stage tools. Hence greater processing procedures are needed for identifying meaningful results. The ‘renewable technology models’ is a set of algorithms incorporating the theory for each technology compatible with the relevant input data obtained from simulation software used at detailed design stage. All analytical data is gathered within the expert interface where a performance review and financial assessment are conducted, discussed in further detail within the following chapter. The following chapter shall also look at the technical description for each renewable technology model and indicate key parameters used for producing the overall technology appraisal.

# Chapter 5 – Toolkit Constituents

## Renewable Technology Models

As part of the development of the design toolkit it was necessary to develop analysis models of renewable devices. These models calculate the energy yield from each technology for the building site of interest. Three models were developed, namely micro wind turbines, solar photovoltaic and solar thermal systems. Additionally, a multi-tool approach for the appraisal of natural ventilation was developed. However, this did not require the development of a specific model. Instead natural ventilation is assessed within the building simulation package. The four models were integrated into the Excel based expert interface from which data for the final report is detailed.

### Solar Photovoltaic

Solar PV panels may provide a predictable source of on-site electricity generation, utilising solar energy. A method is hence developed from which a detailed study into the viability of building integrated solar PV can take place.

Building simulation tools may be used to carry out a solar analysis identifying solar gains for the building, exposed incident radiation and therefore provide data for appraising solar panels. The flow diagram below details the processes involved for quantifying the energy yield for a proposed solar PV panel installation.

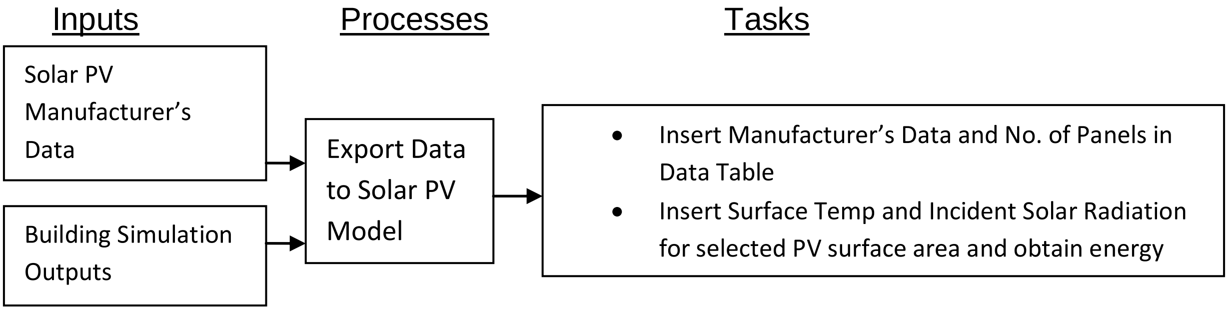


**Figure 17 - Solar PV model flowchart**

### Solar PV model

The modelling of PV cells within a building simulation package; ESP-r has been described within a paper from the ESRU department, University of Strathclyde **(91).** ESP-r is a building simulation package, similar to IES VE and therefore the methodology used within the above paper can be configured for the modelling of solar PV panels for this study. The building simulation output data for this methodology consists of ‘surface temperature’ and ‘incident solar radiation’, this data was available through IES VE when a thermal analysis was done.

The PV panel is represented by a set of series (n) and parallel (m) connected p-n junctions. Each p-n junction has been modelled as an equivalent circuit (Figure 18); this representation allows for the operation of a single cell and hence a panel to be modelled. The following set of equations has been derived for the modelling analogy i.e. the equivalent circuit. The PV panel is operational with maximum power point tracking.

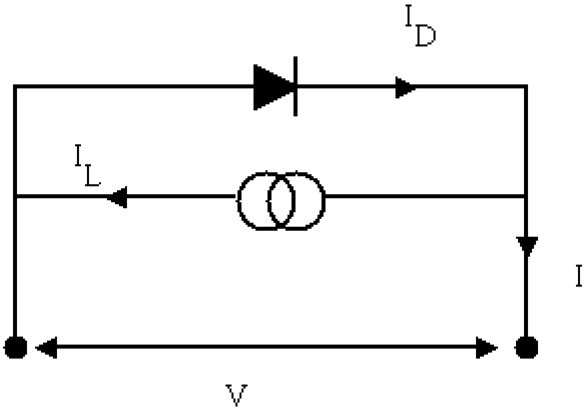


**Figure 18 - Equivalent Circuit (91)**

$$DF = \frac{\left(\frac{e}{knT_{ref}}\right)}{\ln\left(\frac{I_{sc} - I_{mp}}{I_{sc}}\right)} * (V_{mp} - V_{oc})$$

**Equation 12 - Diode Factor**

The diode factor is a design parameter, a measure of the quality of the diode **(92)**. The modelling of a semi-conductor diode allows for the representation of a p-n junction within the equivalent circuit.

$$I_o = 2^{\frac{(T - T_{ref})}{10}} * \frac{\frac{I_{sc}}{m}}{\left(\exp\left(\frac{e\frac{V_{oc}}{n}}{kT_{ref}DF}\right) - 1\right)}$$

**Equation 13 - Diode Current**

The diode current relates to nodal absorption of the incident beam **(91)**. Therefore makes up the resistance current for the equivalent circuit. It is dependent on the 'surface temperature' and arguably it is therefore indirectly dependent on the 'incident solar radiation' **(92)**.

$$I_L = \frac{QI_{sc}}{Q_{ref}m}$$

**Equation 14 - Light Generated Current**

The light generated current is induced by visible light for the semi-conductor diode. Its increase is proportional to the increase in light intensity i.e. solar incident radiation (Q). The greater the light generated current, the greater the power output for the PV panels.

$$1+\frac{I_L}{I_o} = \exp\left(\frac{eV_{mpp}}{kTDF}\right)\left(1+\frac{eV_{mpp}}{kTDF}\right)$$

**Equation 15 - Iterative Calculation for Voltage at Max Power Point**

This equation is used to calculate the Voltage at maximum power point; the control has been built into the set of equations for the equivalent circuit.

$$P = \left(V_{mpp}I_o\left(\exp\left(\frac{eV_{mpp}}{kTDF}-1\right)\right)-V_{mpp}I_L\right)n.m.N_{pnnls}$$

**Equation 16 - Power Equation**

The above set of equations determines the power generated for a solar PV panel, for this model. The hourly power value is gained and accumulated into an annual energy yield value and also the panel efficiency is determined. The above equation does not take into account the inverter efficiency or shading due particle dust or general dirt. For this study, an inverter efficiency of 0.9 has been observed and it is assumed that no shading occurs due to a lack of cleanliness.

The above equations may be solved by acquiring PV panel characteristics from the manufacturer and reference data, these are listed below. The light intensity or otherwise the 'solar incident radiation' as well as the panel temperature or otherwise the 'surface temperature' are obtained from the building simulation tool.

**PV panel properties (obtained from Manufacturer)**

Open Circuit Voltage ($V_{oc}$)

Short Circuit Current ($I_{sc}$)

Voltage at max power ($V_{mp}$)

Current at max power ($I_{mp}$)

Reference Solar Insolation ($Q_{ref}$), this is usually 1000 W/m$^2$

Reference Temperature ($T_{ref}$), this is usually 298K

No. of series connected cells (n)

No. of parallel connected cells (m)

Number of Panels ($N_{pnnls}$)

Solar Panel Area (A)

**Physical properties**

Electron Charge (e) = $-1.602 \times 10^{-19}$ Coulombs

Boltzmann Constant (k) = $1.38 \times 10^{-23}$ m$^2$kg/Ks$^2$

The graphs below show results data for a solar PV panel, located in Aberdeen. Three days data was extracted from the model (08th Aug to 10th Aug), to discuss in further detail the results and relationships between the different parameters. The data has been presented in the form of a line graph comparing the hourly electrical energy produced to the available solar radiation (Figure 19). A graph has plotted the voltage and temperature data for the solar PV panel, and is displayed below:

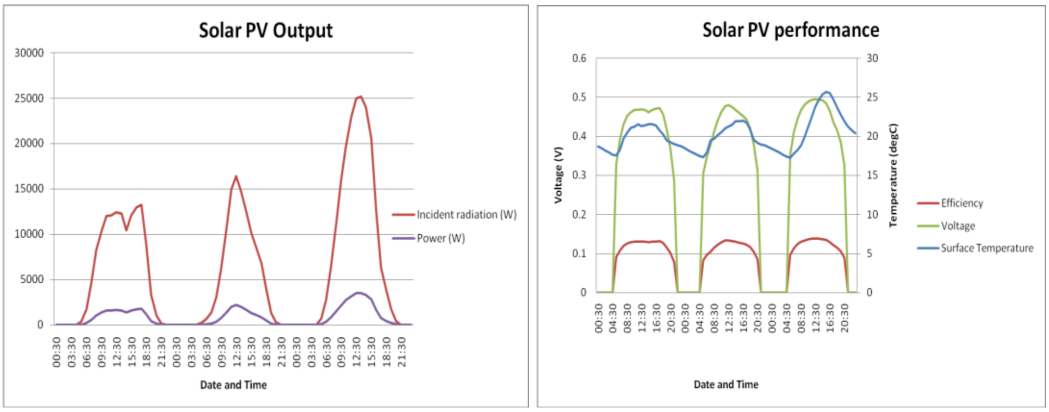


**Figure 19 - Solar PV panel output**

The first graph allows the researcher to appreciate the losses within a PV panel system. The majority of the losses are within the actual capture of light and generation of electricity. However there are further losses from the connecting electrical system and inverter devices. The corresponding voltage, temperature and efficiency data is also shown. From the graphs, the efficiency is fairly consistent for the panel, is determined from the incident radiation and surface temperatures. The relationships between all parameters are more apparent in the tables below:

| Surface Temp, T (Kelvin) | Solar Radiation, Q (W) | Diode Current, $I_O$ (A) | Light Generated Current, $I_L$ (A) | Voltage, Vmpp (V) | Power, P (W) | Efficiency, n |
|---|---|---|---|---|---|---|
| 280 | 0 | 3E-06 | 0 | 0 | **0** | **0** |
| 280 | 200 | 3E-06 | 1.62 | 0.46445 | **23.31738** | **0.116587** |
| 280 | 400 | 3E-06 | 3.24 | 0.49233 | **49.517851** | **0.123795** |
| 280 | 800 | 3E-06 | 6.48 | 0.52032 | **104.82603** | **0.131033** |

**Table 5- Constant Temperature**

| Surface Temp, T (Kelvin) | Solar Radiation, Q (W) | Diode Current, $I_O$ (A) | Light Generated Current, $I_L$ (A) | Voltage, Vmpp (V) | Power, P (W) | Efficiency, n |
|---|---|---|---|---|---|---|
| 280 | 1000 | 3E-06 | 8.1 | 0.52935 | **133.3686** | **0.133369** |
| 290 | 1000 | 7E-06 | 8.1 | 0.51923 | **130.6259** | **0.130626** |
| 300 | 1000 | 1E-05 | 8.1 | 0.50723 | **127.39692** | **0.127397** |
| 310 | 1000 | 3E-05 | 8.1 | 0.49336 | **123.6881** | **0.123688** |

**Table 6 - Constant Incident radiation**

A sensitivity analysis was done to see the effect of altering the external variables, temperature and incident radiation, for the developed model. The general trend witnessed is if incident radiation increases with a constant temperature, then $I_L$ increases and hence the voltage and power increase. The efficiency is improved upon because the constant temperatures mean consistent resistance and therefore more efficient with increased radiation. If however the surface temperatures increase with no increase in solar radiation, then efficiencies reduce and so does power output, because $I_O$ has increased and therefore resistance has increased. These findings are consistent with the research described in Chapter 2 **(18,20,21,22)**. In reality the temperature does not remain constant as incident radiation increases and vice versa, hence the effect is not as magnified as seen in the above tables.

The annual energy yield (kWh) figure is exported to the expert interface where an environmental and financial appraisal is undertaken alongside other renewable energy systems.

### Solar Hot Water Systems

Solar hot water systems may provide a predictable source for heat to a building if a significant heating and hot water demand is present. A method is hence developed from which a detailed study into the viability of building integrated solar hot water systems can take place.

The flow diagram below (Figure 20) shows how input data is used from the building simulation model (Figure 13) to predict the useful energy ($Q_U$) attained from the solar panels. Solar thermal systems may be installed on either the facade or the roof of the building, and this method determines the maximum energy potential for installing a flat plate panel for either arrangement.

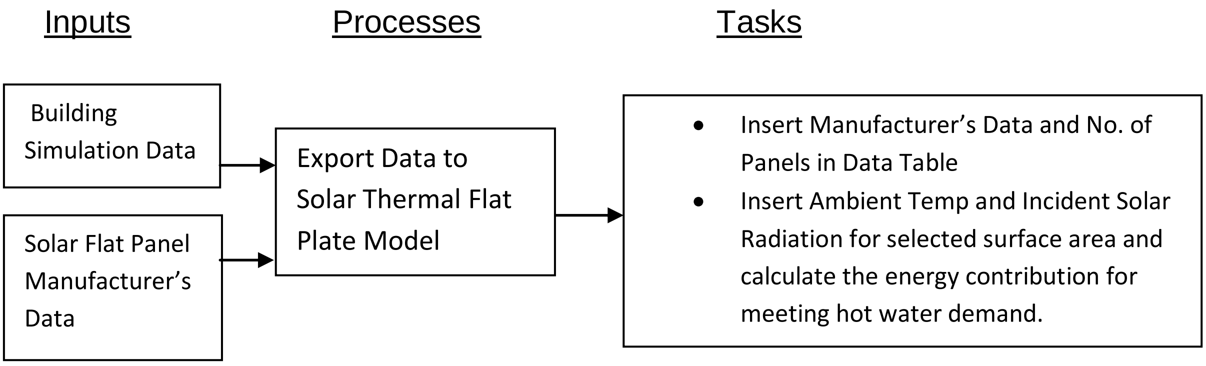


**Figure 20 - Solar Thermal model flowchart**

### Solar Thermal model (Flat Plate Panel)

A solar thermal system consists of a collector that heats the medium (water-glycol mixture). In most common systems the medium is transferred via pipes to a heat store and the heat is transferred to the domestic water via a heat exchanger. For this model, the system has been simplified to determine the maximum energy potential for the solar thermal panel/s.

The model developed for appraising solar thermal installations; the heat store is not modelled and direct transfer to a hot water system has been assumed. This is only viable for a system where water run-off is consistent with solar hot water supply i.e. industrial process warehouse. This system performs at optimum because there is a greater temperature difference across the panel and lower convection losses for the system **(93).** Hence a model has been developed to determine the maximum potential for a solar hot water system.

The following equations represent the modelled system **(94).** A steady state solution is solved for the fundamentals of solar thermal design. It equates for heat transfer from the heat source to the solar panel and direct run off for hot water. This allows for system performance to be determined and to quantify useful heat. Hence a maximum Solar Fraction (the percentage solar contribution towards meeting hot water demand) may be determined. Useful heat may be defined as the potential utilisation of solar energy via a solar panel to provide heat, only considering losses within the panel itself. To model heat storage and demand and supply management would provide a more accurate utilisation of heat from a solar thermal panel and this would be considered for any further development of this model.

The inclination of the panel is defined within IES VE for the surface housing the collector. It is recommended **(95)**, to include for losses of 3% due to shading from other objects and a further 2% because of particle dust ($n_s$) as default.

$$S = (I_{TOTAL} \tau \alpha n_s)$$

**Equation 17 – Useful Solar Radiation**

The total solar radiation exposed to the absorber plate is defined within Equation 17, hence also defines the heat provided to the heat transfer medium. This value is used to determine the available heat produced by the solar thermal panels (Equation 19).

$$T_{w,in} = AVG(T_a)$$

**Equation 18 – Water Inlet Temperature**

The mains water inlet temperature represents the inlet temperature for the panel. An average water inlet temperature has been produced, based upon the ambient temperatures, to better identify this unknown input. Estimating the actual water inlet temperatures allows the user to equate the heat losses for the system (Equation 19).

$$Q_u = A_c F_r (S - \left(U_L \left(T_{w,in} - T_a\right)\right))$$

**Equation 19 – Useful Heat Gain**

This is the fundamental equation applied to the model for acquiring useful heat gain from a solar panel. The equation is simplified by neglecting the ‘mean plate temperature’. This variable is neglected because it is difficult to physically measure. The ‘mean plate temperature’ cannot be calculated through the building simulation program and therefore the above is a modified equation to calculate useful heat ($Q_U$). The heat removal factor ($F_r$) determines the efficiency with which heat is transferred from the absorber plate to the medium. This is determined by using the collector efficiency factor (F’), available from manufacturer’s data.

$$T_o = \frac{Q_u}{mC_p} + T_{w,in}$$

**Equation 20 - Solar Panel Outlet Temperature**

The solar panel outlet temperature cannot exceed the stagnation temperature for the solar panel. This temperature needs to be monitored to maintain acceptable conditions and avoid stagnation of the system, which could result to possible irreparable damage.

**Performance Parameters**

$$\eta_{panel} = \frac{Q_u}{I_{TOTAL}}$$

**Equation 21 - Solar Panel Efficiency**

$$SF = \frac{Q_u}{Q_u + Q_{aux}}$$

**Equation 22 - Solar Fraction**

The panel efficiency and solar fraction along with useful solar heat (Equation 19) determine the overall performance for the system. To calculate the above parameters, using the above theory, the following manufacturer’s data is required:

Absorption factor (α)
Transmission factor (t)
Overall Heat Loss Coefficient ($U_L$)
Collector Efficiency Factor (F’)
Mass flow rate (m, kg/s)
Number of Panels (n)

Solar Panel Area (A)

<u>Physical properties and efficiency factors</u>

Specific Heat Capacity ($C_P$) = 4180 J/kgK

Solar shading & Dust Factor ($n_s$) = 0.95 **(95)**

The terminology for design parameters used within the above theory:

Ambient Temperature ($T_a$)

Total exposed solar radiation ($I_{TOTAL}$)

Useful Solar Radiation (S)

Heat Removal Factor ($F_r$)

Useful Heat Gain ($Q_U$)

Auxiliary Energy ($Q_{aux}$)

Hot Water Demand ($Q_{HW}$)

The useful heat ($Q_u$) is then accumulated to produce, **annual Energy Yield, Solar Fraction** and also **panel efficiency**. A graph can be produced that compares solar heat to domestic hot water (DHW) demand. This graph would indicate the maximum solar heat utilisation for the proposed system.

However for more informed discussion the following data has been acquired:

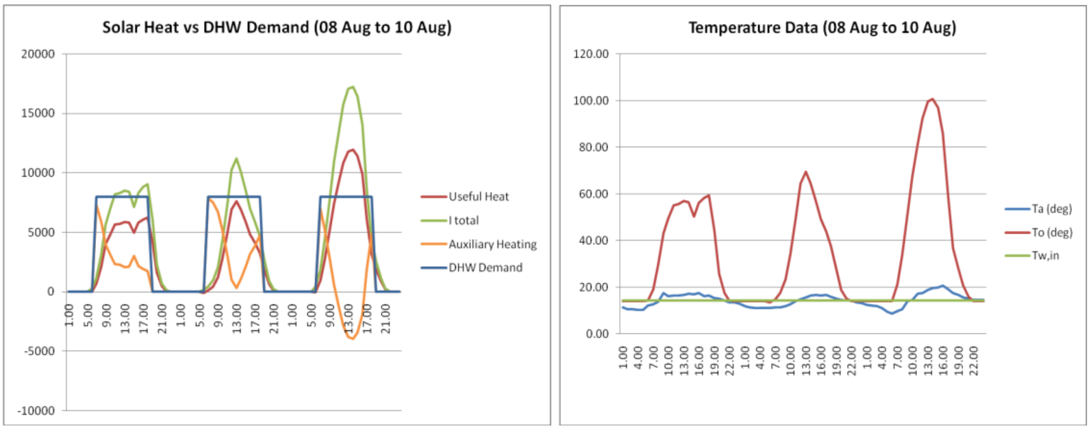


**Figure 21 - Solar hot water panel output**

The above shows three days data (08 Aug to 10 Aug) for a solar hot water system, located in Aberdeen. The useful heat ($Q_u$) is proportional to the incident radiation. A constant DHW demand has been assumed and the auxiliary heating is only used when demand is not met from the solar heat. From the above graphs it is evident that even with such a simple system, adequate controls are required to manage the different components. On the third day the auxiliary heating is recorded to be below zero, this is not a realistic scenario. The constant demand condition limits the use of this model to ideal performance and for an accurate appraisal a more realistic water run-off schedule should be employed. It is also worth noting that the outlet temperature increases as useful heat increases mainly due to the constant hot water demand.

In evidence of the above, the model has achieved its goal to identify the maximum potential for a solar hot water system, but it falls short on producing an accurate appraisal for modelling building integrated solar hot water systems. Assumptions have been made that suggest exaggerated performance of the solar hot water system and future work should address this by introducing storage, demand side management, and a dynamic analysis to equate actual solar heat utilisation.

The annual energy yield (kWh) figure is exported to the expert interface where an environmental and financial appraisal is undertaken alongside other renewable energy systems.

### Micro Wind Turbine

Wind turbines can provide renewable electricity generation for buildings *if* placed in optimum locations. The analysis has two major objectives; these are to optimise the placement of micro wind turbines for a building site and quantify the energy yield. The flow diagram below details the processes involved for achieving the objectives.

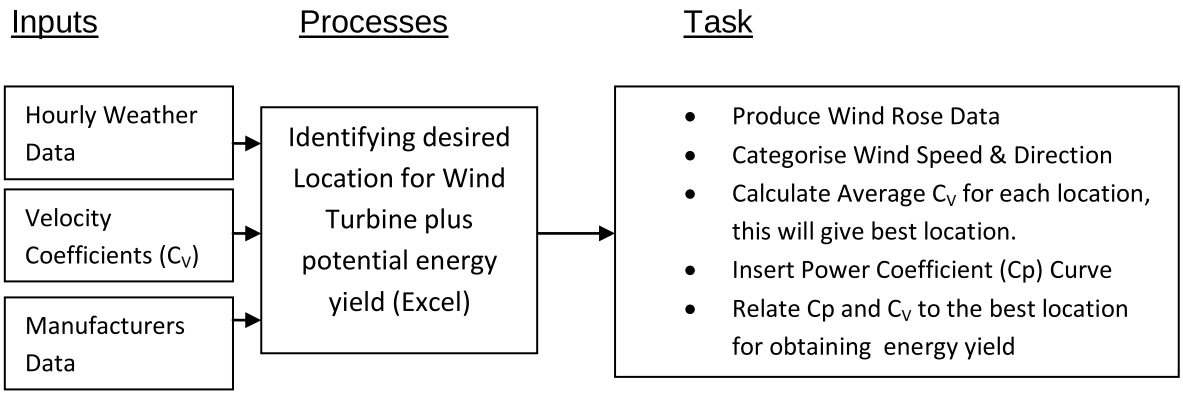


**Figure 22 - Wind Turbine model flowchart**

### Wind Energy Model

The optimisation process is carried out using CFD, analysing flow characteristics for the external facade of the building and nearby obstructions. The CFD tool is used to model wind flow across the building for the eight principal directions, identifying flow acceleration and flow stagnation within potential installation areas. The data is then used to produce velocity coefficients (refer to Chapter 4), which is used to assess viability of installation.

Manufacturer’s data is required for this analysis which consists of:
Power Curve – identify the $C_P$ values for each increment wind speed for the turbine.
Turbine Dimensions – Turbine swept area ($m^2$)

The velocity field around the building is calculated for $45^0$ wind direction increments (a total of eight simulations). Hence there are eight velocity coefficients ($C_V$) for each location above the roof for each wind direction. Hourly wind data is imported and categorised by algorithms that ensure the correct wind speed and hence power coefficients are used for calculating the energy yield, this includes taking into consideration cut-in and cut-out speeds. An average velocity coefficient can be calculated to determine potential micro-turbine sites (Equation 23). This average coefficient is calculated using the incident wind velocity at the height of the micro turbine hub and the individual velocity coefficients from each CFD analysis, weighted according to the wind rose for the site (Figure 23):

$$Cv_{Av} = w_N Cv_N + w_{NE} Cv_{NE} + w_E Cv_E + w_{SE} Cv_{SE} + w_S Cv_S + w_{SW} Cv_{SW} + w_W Cv_W + w_{NW} Cv_{NW}$$

**Equation 23 - Average Velocity Coefficient**

In the above equation, velocity coefficient ($C_V$) and wind rose weighting (w) are multiplied to provide an average velocity coefficient ($Cv_{Av}$) for the location. The location with the highest average velocity coefficient ($Cv_{Av}$) qualifies as the most productive location for the installation of a building integrated wind turbine. An example wind rose for Aberdeen is shown below, based upon IES VE climate files:

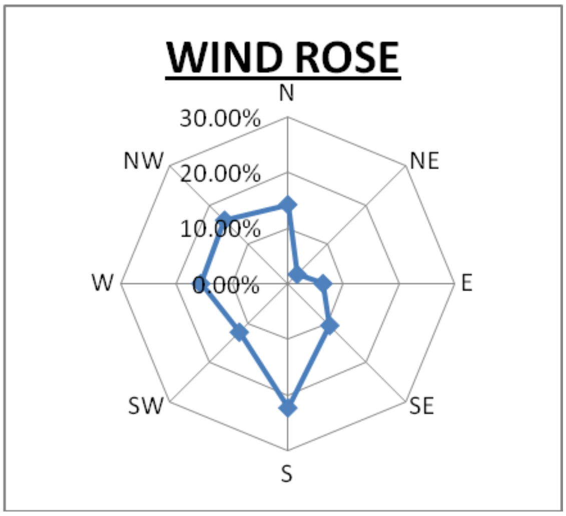


**Figure 23 - Wind Rose, Aberdeen**

The location with the maximum average velocity coefficient produces maximum energy yield. The local velocity coefficients for the best location are applied to the energy yield calculation (Equation 24); these differ for each wind direction. Algorithms have been set up within the model to identify the correct velocity and power coefficients, based upon the hourly climate data, for each time step. By applying the corrected velocity, being the product of the velocity coefficient and the free stream velocity, a better estimation of actual energy yield for the proposed installation is made.

$$P_W = \frac{1}{2}\eta_g \eta_b C_P \rho A (C_V V_\infty)^3$$

**Equation 24 - Wind Power**

In Equation 24, $V_\infty$ is the free stream velocity and $C_V$, is the derived local velocity coefficient for the location and wind direction; providing a corrected velocity for upstream of the turbine. The power coefficient ($C_P$) for the turbine is obtained from the manufacturer and varies with velocity. Finally, $\eta_g \eta_b$ is the overall turbine efficiency, $A$ is the blade swept area ($m^2$) and ρ, represents air density at (1.225 $kg/m^3$). The model has been validated to verify the accuracy for calculating energy yield, detailed in Chapter 6.

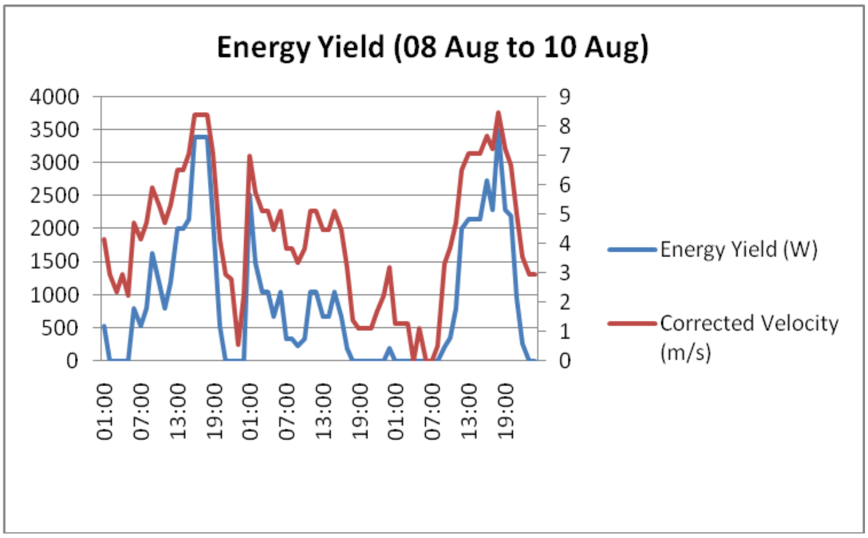


Figure 24 - Wind Turbine energy output

The above graph details the wind energy profile for three days in August. From the graph it is evident that all wind speeds below 2.5 m/s produces zero energy yield. The hourly analysis neglects the true effect of short wind gusts and short periods of turbine shutdown due to low wind speeds. The energy yield may not be as accurate because of negligence of the above. These errors present within the average wind speed value are amplified when calculating the energy yield. The exclusion of short period wind speed alterations, the effects of turbulence and synchronisation of electrical equipment means it is difficult to quantify the inaccuracy. There is also great uncertainty over the use of CFD to determine corrected velocities for the location. The inaccuracies are further discussed within the validation exercise (Chapter 6) for this model. Despite the concerns, a useful tool has been developed that can determine the predicted annual energy yield for the wind turbine within a building integrated application.

The annual energy yield (kWh) figure is exported to the expert interface where an environmental and financial appraisal is undertaken alongside other renewable energy systems.

### Natural Ventilation

Buildings have to be designed such that the occupant’s health and comfort are assured and also there is minimum dissatisfaction as far as practicable. Natural ventilation systems need to be designed to achieve two key aspects of environmental performance **(96)**:

- Ventilation to maintain adequate levels of indoor air quality
- Provides free cooling which tends to prevent buildings from overheating

There are two issues reported within this study related to whether a commercial building may be naturally ventilated.

1) Building Overheating
2) Carbon Emissions

There is concern with naturally ventilated commercial buildings that due to excessive internal heat gains they are more likely to overheat. The driving force for building developers to provide naturally ventilated buildings is the potential reduction in carbon emissions and reduced maintenance costs, hence lower operational costs.

The guidance available for the design of naturally ventilated buildings indicates good design if the following applies **(97)**.

1) If average $CO_2$ concentration during occupied hours is no greater than what is achieved with mechanical design.
2) The building design should only cater for total internal heat loads of 30-40W/m$^2$ (i.e. solar plus internal gains)
3) The operative temperature for maintaining indoor comfort is 25$^{oC}$
4) The operative temperature shall not exceed 28$^{oC}$ equivalent to 1% annual occupied hours.

Operative Temperature: combines air temperature and mean radiant temperature into a single value to express their joint effect.

For the building design, it is claimed that natural ventilation systems can meet total heat loads of 30-40W/m$^2$ **(96)**. Hence, if the building is designed with good solar control and low internal gains then it is possible to apply a natural ventilation system.

### Methodology

A natural ventilation study is carried out to determine whether a comfortable indoor environment is maintained through using a building simulation tool. This would involve ensuring that internal spaces are adequately ventilated with appropriate temperatures for the year. Building simulation tools typically rely on a bulk airflow model for the prediction of pressure and temperature induced room-to-room flows within a building. Key boundary conditions for these models are the wind-generated pressures experienced at the external surfaces with ventilation openings. These are usually calculated using pressure coefficients derived from a table of coefficients for “characteristic” surfaces, which are in turn derived from empirical studies. A more rigorous but computationally intensive approach is to derive building-specific pressure coefficients from a CFD analysis.

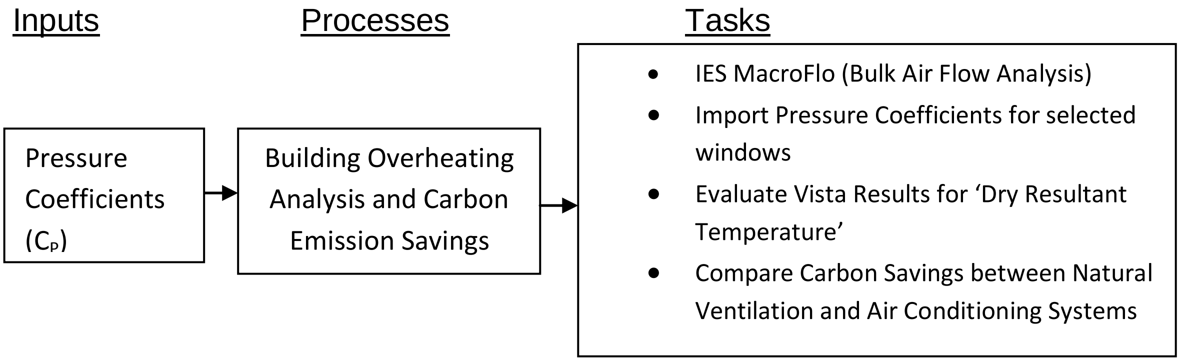


**Figure 25 - Nat. Vent model flowchart**

### Natural Ventilation Model

A natural ventilation study is carried out to determine whether the services strategy for the building does not compromise upon comfort conditions for occupants. The CFD derived pressure coefficients are calculated for each computational node (Equation 11), these are a measure of the pressure exerted on the building walls. The coefficients are averaged for each building face, so they may be applied within MacroFlo i.e. the collective effect of the multiple computational nodes.

| | Y | Z | X | North | North East | East | South East | South | South West | West | North West |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 16.6 | -20.9 | 82.8 | -0.91414 | -0.29083 | -0.64486 | -1.12569 | -0.33218 | -0.32729 | -0.13964 | -0.13964 |
| 2 | 16.0467 | -20.9 | 82.8 | -0.55961 | 0.548394 | -0.29746 | -0.94074 | -0.32854 | -0.34508 | -0.15731 | -0.51377 |
| 3 | 16.0467 | -18.9 | 82.8 | -1.23829 | 0.342381 | 0.528274 | -0.1712 | -0.37486 | -0.41545 | -0.20034 | -0.35353 |
| 4 | 16.6 | -18.9 | 82.8 | -1.27079 | -0.74529 | -0.48707 | -0.89547 | -0.36946 | -0.37079 | -0.15088 | -0.60388 |
| 5 | 15.4933 | -20.9 | 82.8 | -0.53387 | 0.747328 | -0.26917 | -0.927 | -0.33112 | -0.36231 | -0.15641 | -0.62739 |
| 6 | 15.4933 | -18.9 | 82.8 | -1.31581 | 0.525525 | 0.725198 | -0.06543 | -0.37935 | -0.41861 | -0.2023 | -0.32703 |
| 7 | 14.94 | -20.9 | 82.8 | -0.53233 | 0.857343 | -0.2694 | -0.91926 | -0.3338 | -0.37699 | -0.15611 | -0.61086 |
| 8 | 14.94 | -18.9 | 82.8 | -1.3671 | 0.63192 | 0.830803 | -0.01157 | -0.38411 | -0.42068 | -0.2034 | -0.30995 |
| 9 | 14.3867 | -20.9 | 82.8 | -0.53625 | 0.925277 | -0.27807 | -0.91508 | -0.33675 | -0.3889 | -0.15597 | -0.60904 |
| 10 | 14.3867 | -18.9 | 82.8 | -1.3991 | 0.700467 | 0.893697 | 0.01854 | -0.38916 | -0.42031 | -0.20404 | -0.29847 |

**Table 7 - Pressure Coefficients**

The above shows 10 computational nodes; each node has 8 pressure coefficients for each wind direction. If it is assumed that one building wall is made up of the above 10 nodes, then the average of the highlighted column would produce the North coefficient to be inserted into MacroFlo, specified for that building wall. This process is repeated for all walls with ventilation openings i.e. openable windows, that are to be configured using MacroFlo.

| | N | NE | E | SE | S | SW | W | NW |
|---|---|---|---|---|---|---|---|---|
| East Wall | -0.753 | 0.279 | 0.643 | 0.233 | -0.519 | -0.408 | -0.155 | -0.411 |
| North Wall | 0.626 | 0.319 | -0.212 | -0.663 | -0.408 | -0.617 | -0.175 | 0.431 |
| South Wall | -0.416 | -0.658 | -0.178 | 0.429 | 0.616 | 0.298 | -0.224 | -0.674 |
| West Wall | -0.562 | -0.423 | -0.168 | -0.412 | -0.773 | 0.289 | 0.630 | 0.248 |

**Table 8 - Average Pressure Coefficients**

The resultant data of the analysis carried out for eight principal directions is shown in (Table 8). This table has been derived for calculating the average pressure coefficient from the number of computational nodes, for each designated wall. The above values are used for the case study and therefore derived from a far greater dataset than the previously described example (Table 7). However for MacroFlo, 16 different pressure coefficients are needed; these were produced by interpolating the above CFD derived coefficients. The average pressure coefficients were entered into the MacroFlo pressure coefficient (.pco) file in place of the pre-defined characteristic coefficients applied during an ApacheSim simulation. Therefore the flow rates entering and exiting the building are based upon the actual geometry and surroundings. The analytical data was monitored between April and September when there is concern for building overheating. The operative temperature is monitored for every occupied room and this should not exceed 25 degrees equivalent to 5% of occupied hours **(97)**. If some rooms do overheat considerably then a comfort cooling solution may be required or even a more appropriate window opening strategy.

Determining the viability of a naturally ventilated building in place of being comfort controlled through air conditioning systems is first proven through meeting the above overheating criterion as long as the $CO_2$ levels within the room are adequate. Once the criteria for good natural ventilation design are achieved, the carbon savings for the proposed services strategy are determined. Hence a further simulation within ApacheSim was performed for servicing the building by way of a standard air conditioning solution and compared with the proposed natural ventilation scenario. It is most likely that for good natural ventilation design a carbon saving is witnessed when comparing both energy solutions. The energy consumption data for both scenarios is exported to the expert interface and a comparison is made.

### Expert Interface

The results obtained from the renewable energy models are exported to an Excel based "Expert Interface" from where a comparative analysis may be done in relation to building energy consumption. This tool follows a similar method to the previously mentioned 'Processing Tool'. However more analysis outputs are determined (refer to Figure 8) allowing for a more detailed report and recommendations for the installation of building integrated renewable energy systems.

The Expert Interface was used to perform a financial and environmental appraisal for renewable technologies. This was done to present an overall assessment for the viability of building integrated renewable technologies and natural ventilation design at detailed design stage. The following quantities are of interest for each technology:

The ***building energy consumption*** is required for relating technology performance to the building. Hence the user may also determine overall building $CO_2$ emissions.

The ***energy yield*** is calculated by the renewable technology models utilising boundary condition data from the CFD and building simulation tools.

The ***renewable fraction*** is the percentage contribution of renewable energy to the whole building energy consumption (calculated using building simulation software). This is calculated individually for each technology.

The **carbon reduction** factor is the percentage reduction of emissions in relation to the building carbon emissions (calculated from building energy consumption). This is calculated individually for each technology.

The ***payback period*** is calculated taking into consideration the annual savings in energy costs in relation with costs associated for installation and maintenance of each technology. Incentive schemes and inflation of fossil fuel costs are also taken into account, which reduce the payback period.

At this stage, the energy yield and technology specification have already been identified through the analysis carried out using the renewable energy models. It is necessary to perform a financial assessment along with quantifying the predicted building energy consumption and corresponding $CO_2$ emissions so that a comprehensive appraisal is achieved. The above properties are used as the basis for determining an appraisal for each technology and for natural ventilation design.

The results are communicated through a final report consisting of a detailed energy assessment that relates building energy consumption to energy yield for the renewable technologies categorised as ‘feasible’ at concept design stage. Hence by comparison determine the best solution, ideally one or a mix of technologies that reduce overall carbon emissions with a reasonable return on investment. The client is therefore in a position to make an informed decision due to the application of this assessment methodology for the appraisal of building integrated LZC technologies.

### Economic Appraisal

The ‘payback period’ is calculated for each technology using the Excel function, NPER. This function returns the number of periods for an investment based on periodic constant payments and a constant interest rate i.e. the payback period based upon inflation based savings. The analysis takes into account many parameters for determining the payback period for each technology and can be broken down into its terms below: For the above calculation the investments are defined as capital expenditure, the constant payments are defined as savings and benefits and the interest rate represents fuel inflation. The savings from selling electricity to the national grid are not taken into account because a demand and supply matching analysis has not been carried out for this study.

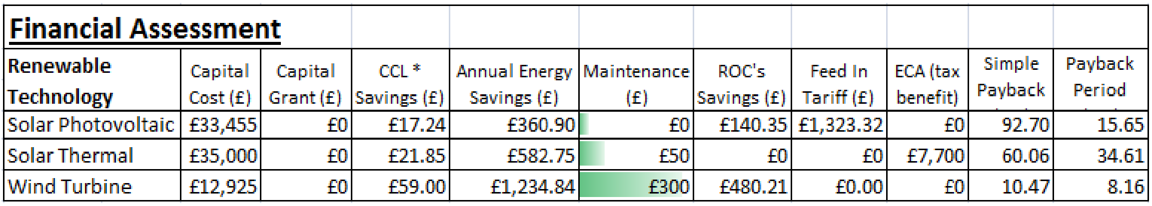
| | |
|---|---|
| Investment | Capital expenditure |
| Savings & Benefits | Resultant savings from fuel & Climate Change Levy (CCL) charges. Renewable Obligation Certificates (ROC’s), Enhanced Capital Allowance (ECA) and Feed in Tariffs (FITs) savings are considered for applicable installations. Energy Inflation is taken into account as most likely fuel costs are going to rise, hence reducing the payback period. |

Interest Rate Fossil fuel cost inflation

The major difference between the economic analyses carried out at both stages is that the detailed design stage caters for better estimation of the actual payback period. The inflation of fuel prices and also the incentives (with exception to FITs & Capital Grants) are not considered at concept stage as these may represent a false gain for the technology, built in within the inaccuracies. The reason for separate criteria for economic analyses at both stages is due to the lack of financial data available at concept stage, and therefore a worst case scenario (i.e. Equation 3) is a more appropriate metric to judge against.

The parameters affecting costs and savings vary on a project by project basis. However, below are fairly standard values for each incentive. It is worth noting that a further incentive scheme, the Renewable Heat Incentive (RHI) has not been taken into account within the economic appraisal. This is because when the analyses were developed there was uncertainty over the 'deeming methodology' to determine an appropriate incentive for consumers **(65)**. The below incentives and corresponding values are considered for the following case study example (Chapter 7).

CCL charges – 0.4p/kWh electricity and 0.15p/kWh gas
Energy savings are derived from the energy yield data imported from the renewable technology models, applying 10p/kWh for electricity and 3.5p/kWh for gas.
FITs and ECA's are variable and dependent on the technology being specified.



**Financial Assessment**

| **Renewable Technology** | Capital Cost (£) | Capital Grant (£) | CCL * Savings (£) | Annual Energy Savings (£) | Maintenance (£) | ROC's Savings (£) | Feed In Tariff (£) | ECA (tax benefit) | Simple Payback | Payback Period |
|---|---|---|---|---|---|---|---|---|---|---|
| Solar Photovoltaic | £33,455 | £0 | £17.24 | £360.90 | £0 | £140.35 | £1,323.32 | £0 | 92.70 | 15.65 |
| Solar Thermal | £35,000 | £0 | £21.85 | £582.75 | £50 | £0 | £0 | £7,700 | 60.06 | 34.61 |
| Wind Turbine | £12,925 | £0 | £59.00 | £1,234.84 | £300 | £480.21 | £0.00 | £0 | 10.47 | 8.16 |

**Figure 26 - Financial assessment (example data)**

Example data is shown for the financial assessment within Figure 26. Within the example data, a benefit has been shown for both ROCs and FITs for Solar PV technology. In reality both benefits are not available and it is shown for comparison only. The benefit of FITs far exceeds the value of ROCs, and ROCs can only be traded for each MWh of produced electricity. Hence ROCs are not appropriate for micro building integrated technologies. The above calculation procedure allows for a financial appraisal for the installation of renewable technologies and is applied in the forthcoming case study.

A financial assessment for the implementation of a natural ventilation services strategy instead of installing an air conditioning system is more complex than what has been described above. For a new building, the immediate capital cost for installing A/C units is diminished and therefore makes a guaranteed saving for the client. For an existing build, an energy saving is witnessed with the reduced usage of electricity. Cost data for the installation of A/C units was not available for the researcher to examine further. However the predicted savings from energy costs may be presented within a technical report as an added value benefit for utilising a natural ventilation services strategy. The payback period has not been calculated for the implementation of natural ventilation design as a more appropriate parametric study may determine its actual benefit to the recipient. Therefore, an economic benefit has not been shown for the natural ventilation study. An economic appraisal should be determined as future work to further develop this toolkit.

### Environmental Appraisal

It is necessary to relate the energy yield for each renewable technology and the reduction of carbon emissions to its contribution towards supplying building energy. This is also important for demonstrating to local planning authorities the environmental contribution from each technology and hence stating the ‘Renewable Fraction’ and ‘Carbon Reduction’ values. The carbon reduction is calculated using Table 3, in a similar manner to the concept design stage.

The assessment data may be used to demonstrate design intent to reduce carbon emissions for the building in an efficient and sustainable manner. In particular the energy yield, payback period and percentage reduction factors may be communicated to a non-technical stakeholder. The results are calculated within the LZC toolkit based upon a structured assessment methodology developed for this study. The application of this toolkit for an example building is determined in Chapter 7. However, the models need to be validated to establish confidence in its use within a design environment. The validation techniques undertaken are described in the following chapter.

# Chapter 6 - Validation

It is important to validate the ‘renewable technology models’, developed for use within the assessment methodology, to establish confidence in the predicted performance. It is assumed that software tools utilised within this project have been through a rigorous validation process. The most commonly accepted definition for validation is as below: **(98)**

> *“Establishing documented evidence which provides a high degree of assurance that a specific process will consistently produce a product meeting its predetermined specifications and quality attributes”*

Ideally, this is done by comparing results obtained from an actual experiment to the results gained from the “technology models”. To produce a fair comparison the input data needs to be consistent for both analyses. Hence an extensive data set is required from the chosen experiments, to relate with the input data required for the ‘technology models’.

Validation procedures were attempted for three technology models, solar photovoltaic, solar hot water and micro wind turbine, ideally using real experimental data. The model produced for appraising a natural ventilation building was a combination of using CFD to derive pressure coefficients and applying them in building simulation software IES VE, hence it was not possible to validate such a model within the constraints of the project. However, IES VE has been approved by the UK building regulations accreditation body to the standard defined in CIBSE TM33, and therefore some validation of results has been done **(99).** The concept analysis was determined, in whole, through the use of HOMER and RETScreen using simple data sets and therefore validating such a process was not considered for this study. However, previously there has been validation tests done for RES software tools **(100-105)**, this is inclusive of HOMER and RETScreen.

## Solar Photovoltaic

The solar photovoltaic modelling theory was built as described within Chapter 5 **(91).** The validation was done using experimental data obtained from a test cell in realistic but controlled conditions at the European Joint Research Centre (JRC) in Ispra, Italy **(106).** The PV module under test was a 120 x 120 cm polycrystalline module composed of 121 cells arranged in three strings of 36 cells. The data chosen for the analysis were three sunny days, 16-18 August 2002, and minute by minute data was recorded, the conditions were applied to the model and results were compared.

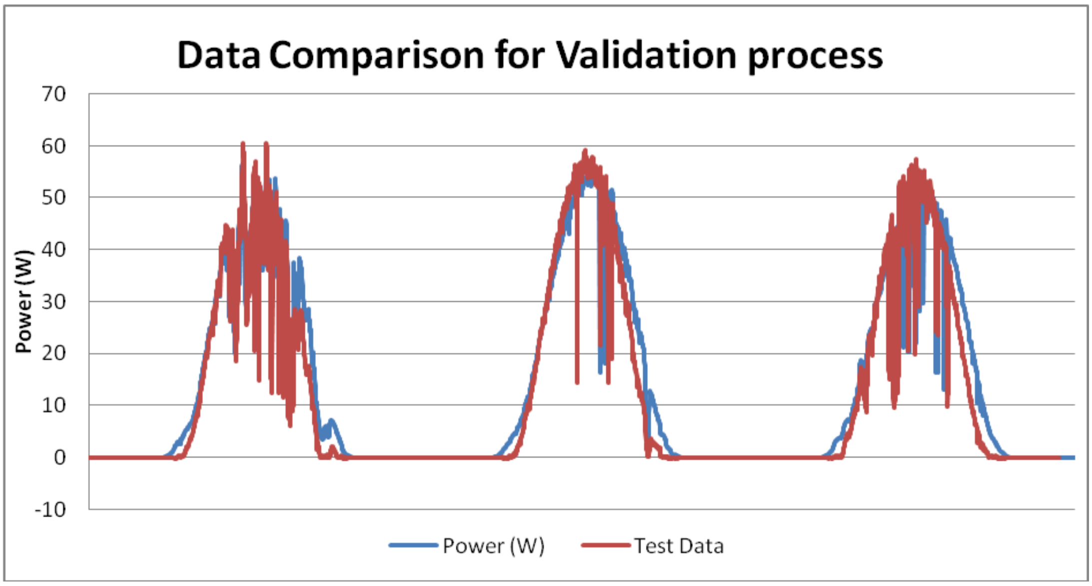


**Figure 27 - Experimental data vs. Model data**

The power obtained through Solar PV Model: 0.99 kWh (blue data series)
Experimental Data: 0.90 kWh (brown data series)

There is a difference of ten percent between the results mainly because at low angles of incidence there is greater power obtained from the model than what is actually obtained, as seen in (Figure 27). This may be a greater concern for the UK where lower angles of incidence are more prominent, in particular during the winter period. In conclusion, a working model has been produced for appraising solar photovoltaic panels. There is cohesion between the results produced by the model and actual outputs from the panels themselves. However the model needs to be adapted to address the exaggerated outputs for lower angle incidences, to obtain better predicted results.

## Micro Wind Turbine

The performance of a micro wind turbine is difficult to predict because of fluctuating local wind speeds as well as determining the turbine's power coefficient ($C_P$). The power coefficient is addressed within manufacturers supplied power curves for the turbine. Within the built environment it is difficult to predict local wind speeds mainly due to its turbulent nature and the effect of local surroundings. However, the model aims to predict local wind speeds for the installation through the use of CFD software. Hence a validation exercise may be carried out for predicting performance when technical data and local surroundings are known for the installation. This exercise is a time consuming affair; to model local surroundings using a CFD tool and obtain suitable wind speeds based on general weather data files and then apply to the model. For this study, the validation exercise consisted of utilising on-site data, hourly averaged wind speeds were applied and the use of a CFD tool was neglected.

The team conducting the Warwick wind trials **(107)** has been monitoring a number of sites where micro-wind turbines are in operation. Measured data has been obtained for Site 21 - Park Farm in Bracknell and was used to validate the wind energy model. The turbine installed at this site is the Ampair 600-230, with a rated output of 600W and a turbine rotor diameter of 1.7m. The turbine is mounted onto a telegraph pole which is tied to the building. The site summary **(Appendix A)** shows a total operation of the turbine from 29/11/07 to 16/10/08 which equates to 7726 hours **(107)**. The average wind speed is 2.83 $ms^{-1}$ and a wind speed distribution graph is shown for the site **(Appendix A)**. A table of wind speed data for the site (Table 9) has been produced to represent the wind speed distribution graph; these derived local wind speeds were entered into the model.

| **Wind Speed ($ms^{-1}$)** | **No. of Hours** |
|---|---|
| 0 | 1623 |
| 1.5 | 1236 |
| 2.5 | 1545 |
| 3.5 | 1236 |
| 4.5 | 927 |
| 5.5 | 618 |
| 6.5 | 309 |
| 7.5 | 155 |
| 8.5 | 77 |

**Table 9 - Wind Speeds for Park Farm**

An analysis was done using the developed wind energy model and performance data was obtained for the turbine at Park Farm in Bracknell. A comparison was made against the actual performance of the turbine, as documented for the Warwick wind trials **(107).**

| **Warwick Wind Trial Site 21. Park Farm** | **Swept Area ($m^{2)}$** | **Rated Power (W)** | **Average Wind Speed ($ms^{-1}$)** | **Energy Yield (kWh)** |
|---|---|---|---|---|
| Actual Energy Output | 2.27 | 600 | 2.83 | 178.62 |
| Predicted Energy Output (Warwick Wind Trials) | 2.27 | 600 | 2.83 | 290.87 |
| Predicted Energy Output (model) | 2.27 | 600 | 2.77 | 286.28 |

**Table 10 - Results comparison for validation procedure**

According to the analysis done by the ‘Warwick wind trials’ team, the major factor in causing an error in predicting energy output is due to the turbine’s actual performance; the power capture not being achieved as detailed within the manufacturers power curve **(107)**. There could be various reasons for this and further extensive research is required to draw a conclusion. For the purposes of validating the model, the turbine performance is assumed to be similar to the manufacturer’s technical data for the turbine and therefore overestimated the actual energy yield i.e. power capture not as efficient as documented. There will always be some discrepancy when using hourly data due to the simplification of wind speed distribution, better results are possible if quality of data improves. This specific turbine is located within the urban environment and it may be possible that lower energy yields are witnessed due to increased turbulence, variable wind direction due to local surroundings and possibly other causes affecting turbine performance. The manufacturer’s power curve is produced in ideal and controlled conditions, unlocking the full potential of the turbine. This may not be ideal for comparison with an installation within the urban environment. In the above discussion, no concrete reasoning has been shown for why lower energy outputs are produced in reality but further field research may allow for a better assessment. It might be prudent to monitor field studies and implement a ‘fudge factor’ to take into account reduced energy yields within the urban environment until a better method is reached.

The validation procedure did not consider the prediction of local wind speed as this was already measured for the site. This is a highly valued piece of information and any future validation tasks for this model should take into consideration the use of the CFD tool for predicting local wind speeds and comparing with measured data. This shall instil full confidence within the analysis methodology for conducting detailed appraisals for micro wind turbines located within the built environment.

## Solar Hot Water System

A basic model was constructed for appraising solar hot water systems not taking into account the hot water distribution system. The most appropriate software used to carry out validation of the solar thermal model is TRNSYS. This software is complex and requires in depth training to conduct a detailed simulation. Therefore a simplistic model was produced to represent the existing Excel model produced as part of this project.

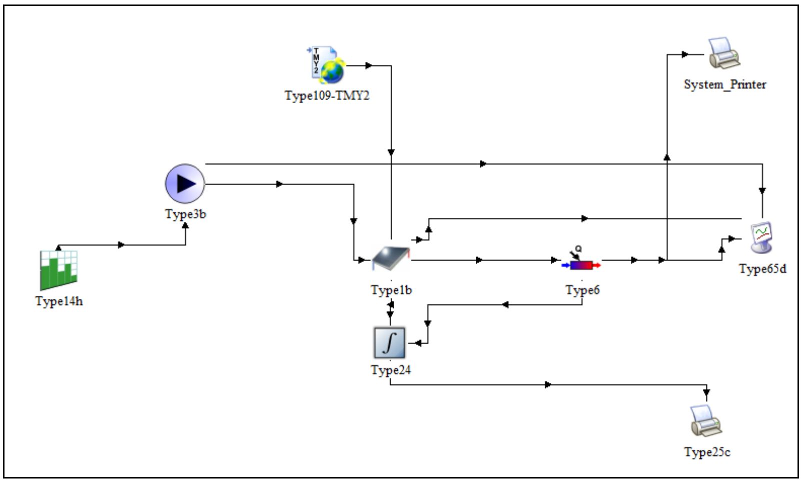


**Figure 28 - Solar Thermal model (TRNSYS)**

The model shown in (Figure 28) does not consider the transient conditions within a solar hot water system. Hence the model represents a system for when instantaneous hot water is required during working hours. These types of simple installations are rare and storage is almost always necessary for a solar hot water system, therefore further development is required. The model has been built to prove the theory that has been applied to the ‘Solar Thermal model’ (Chapter 5).

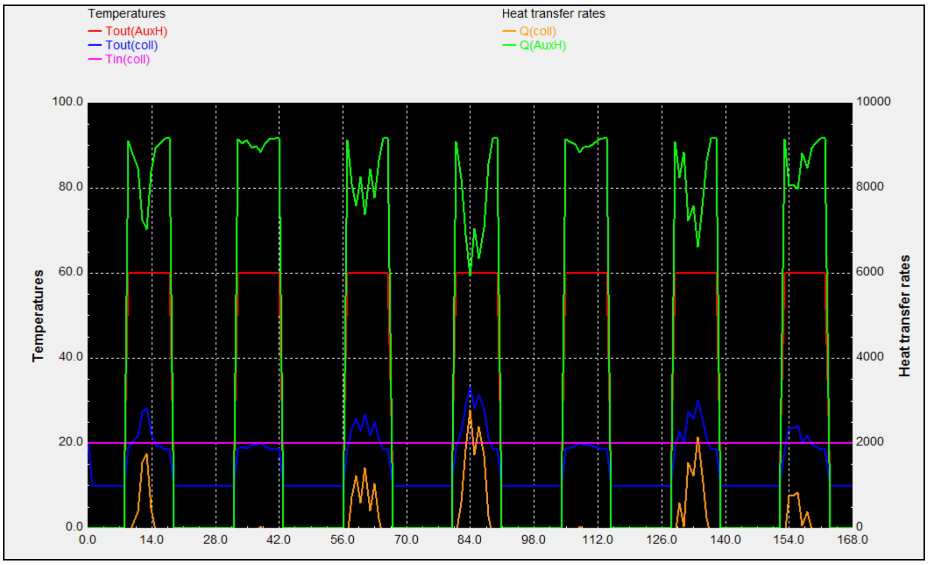


**Figure 29 - TRNSYS results**

The results (Figure 29) show the reduction of auxiliary energy ($Q_{aux}$) when there is solar heat ($Q_{coll}$) available. This proves the theory being applied within the solar thermal model is producing sensible results. There was insufficient knowledge of TRNSYS as well as time constraints within the project to develop more complex models and relate them to results from the developed Excel model. Hence, to develop the model further, an increased range of more complex systems need to be modelled that represent actual installations. It may be useful to utilise simulation software such as TRNSYS and T-SOL to appraise solar hot water systems with buffer systems. The solar thermal model needs to be adapted for meeting storage requirements and variable load requirements before further validation is necessary.

Validation establishes confidence in the models produced and future studies should utilise the conclusions from this section for improving the existing models. The improvements necessary for each technology model have been highlighted within this section; and these should be addressed in any future study. It is also important to determine a validation procedure for the appraisal of natural ventilation within buildings; this has not been addressed in this study. The theory been discussed over the course of this document shall now be demonstrated through a case study building.

# Chapter 7 - Case Study

The appraisal toolkit has been applied to a prospective building design located in Aberdeen.

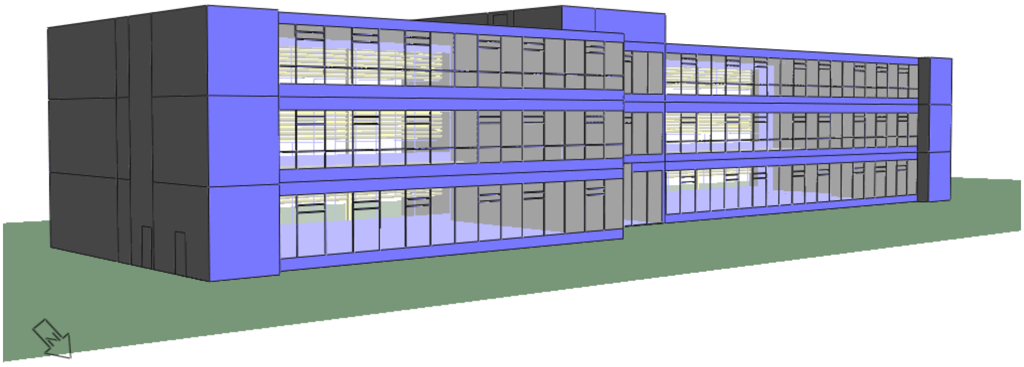


Figure 30 - IES VE generated image of building

The building is a three-storey office block and is part of a suburban office development. Each floor has two open plan offices and a central block, which comprises circulation areas, (including reception) and toilets. The building is orientated North-South with large double glazed areas on the long North and South facades. Solar shading devices have been installed on the south facade reducing internal heat gains from solar radiation. The building is a generally lightweight construction with U-values for all construction elements conform to Scottish building regulations (2007). The office areas are heated and cooled using VRV units and central heating radiators are installed for circulation and toilet areas. The building has been modelled on IES VE using 42 distinct thermal zones. These are augmented with fabric and services data. The model was used to obtain annual energy consumption figures and provide data for the LZC technology analysis (results from which are shown in Table 11 & Table 12).

## Concept Stage Analysis

For concept stage, all considered LZC Technologies were assessed for possible integration into the case study building. These are: Solar Thermal, Solar PV, Micro Wind turbine, CHP, GSHP and Biomass heating. As has been detailed earlier for this analysis, basic input data was used including monthly averaged weather data, device rated power and capital cost, analysed using pre-feasibility software. Building consumption data (heating and electricity consumption); is also required and was obtained by producing a simplified building energy model (SBEM)[8], NCM compliant software.

The technologies being considered have the following specification, specified by the client:

- Solar Thermal - Panels covering 25m² of flat roof area proposed to serve DHW.
- Solar PV **-** a 5 kWp system has been proposed with roof area of 35 m².
- Wind Turbine - a 6 kW device is proposed to be sited on the roof of the building.
- Biomass – sized to provide all heating demand for the building
- CHP – 50 kWe peak load, utilising Biomass fuel.
- GSHP – A 280kW system serving heating and cooling for the building

The technologies were appraised based on its Simple Payback Period (years), $CO_2$ reduction ($kgCO_2$/yr) and Energy Yield (kWh/yr).

| **Technology** | **Simple Payback Period (yrs)** | **$CO_2$ reduction ($kgCO_2$/yr)** | **Energy Yield (kWh/yr)** |
|---|---|---|---|
| Solar Thermal | 70.5 | 1571 | 8100 |
| Solar Photovoltaic | 18.3 | 2731 | 4808 |
| Micro Wind Turbine | 5.1 | 4504 | 7929 |
| Combined Heat and Power (CHP) | 10.3 | 96759 | 306744 |
| Ground Source Heat Pumps (GSHP) | 35.9 | 31888 | 256000 |
| Biomass | 41.5 | 36121 | 277875 |

**Table 11 – Performance data for Concept Design Analysis**

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[8] www.ncm.bre.co.uk

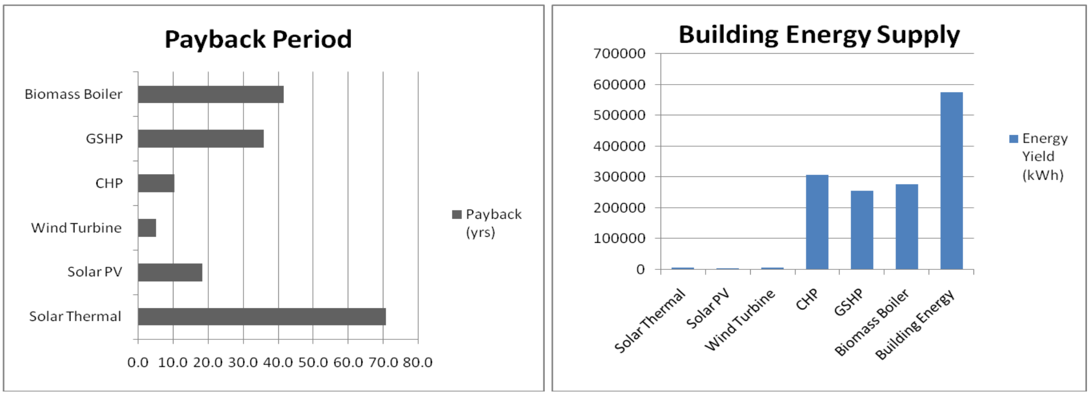

**Figure 31 - Performance Analysis (Concept Stage)**

The above graphs, taken from the processing tool, focus on the economic performance for each technology as well as determining the contribution towards building energy consumption. It is clearly evident from the graph that CHP and micro wind turbine have the best payback periods and apart from solar PV all other technologies are not economically feasible for this particular building. The economic performance has been calculated using Equation 3. These results have been calculated by only taking into account FITs and capital grants as added benefits. The detailed analysis shall determine the payback period based on the criteria set out in Chapter 5, taking into account inflation for fuel costs. It is clear that in potential, CHP, GSHP and biomass heating can provide a great deal more of the buildings energy and hence reduced carbon emissions. The feasibility analysis looks at ideal conditions for these technologies and further detailed analysis is required to consider its installation onsite. This toolkit, however, does not possess detailed analysis tools for the aforementioned technologies.

Overall the best performing technology is the 6 kW micro wind turbine and the 50kWe mini CHP. The solar PV system also performs admirably, when considering FITs assistance, and should be considered above solar thermal technology. The remainder technologies present high payback periods that are unfeasible. There is a low heat demand for this building and hence Biomass at 100% load is not viable, whereas GSHP is an expensive technology hence not viable for this application.

These results provide a relatively quick analysis using basic information. In a real design situation only the more promising technology or technologies (i.e. micro wind turbine) would be carried forward for a detailed design analysis. However, in this case study all technologies that have had models developed during this research are carried through to the detailed design stage for the purposes of comparison. These are namely Solar PV, Solar Thermal and Micro Wind Turbine, along with quantifying the benefits from servicing the building by way of natural ventilation.

## Detailed Stage Analysis

A detailed analysis was done where IES VE was used to generate building specific external surface solar and temperature data, while Fluent is used to generate external airflow data for determining velocity and pressure coefficients. In the analysis for solar PV and solar thermal installations, the incident solar radiation and temperature for the surfaces on which the technologies would be mounted is calculated for each hour of the year. This data along with the manufacturer's technical data is used with the appropriate technical model to calculate the annual energy yield. The wind energy yield is evaluated through the energy model, taking into account CFD outputs for determining local corrected velocities.

The average velocity coefficient was calculated for each node, a map was generated that was used to identify the optimum location for the wind turbine, refer to (Figure 32). For this case, the turbine is best located in the south west corner of the building 2.4 m above roof level. Where wind speeds are witnessed to be around 105% of the free stream velocity.

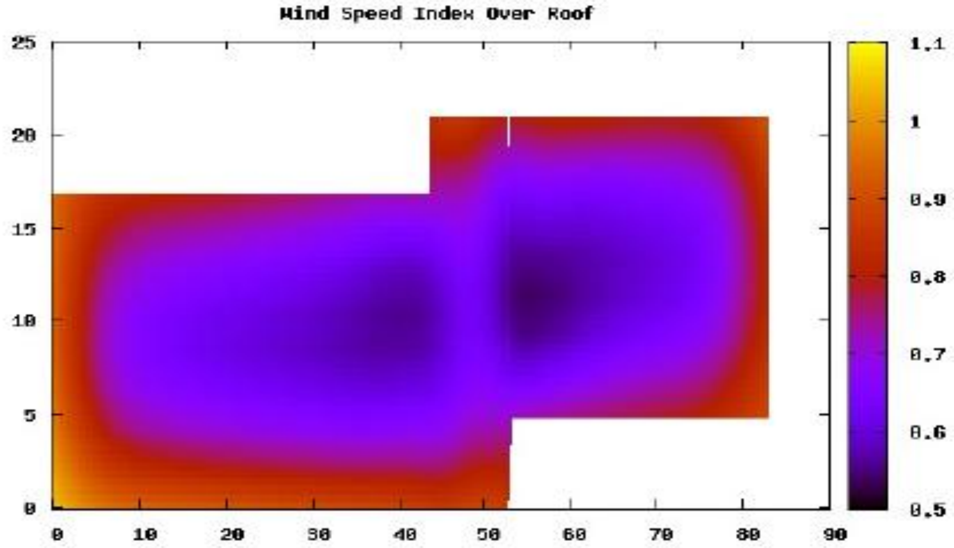

**Figure 32 – Average velocity coefficient map for roof of case study building (at turbine hub height)**

The direction-dependent velocity coefficients derived from the CFD analysis were used in conjunction with climate data and turbine data to calculate the annual energy yield from the turbine:

| Renewable Technologies | Area (m$^{2)}$ | Rated Power (kW) | Energy Yield (kWh) | Renewable Fraction (%) | Carbon Reduction | | Capital Cost (£) | Payback Period (yrs) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | (kgCO$_2$) | (%) | | (Std) | (FITs) |
| Solar Photovoltaic | 36 | 5 | 3609 | 0.99 | 2050 | 1.45 | 33455 | 51.6 | 16.9 |
| Solar Thermal | 25 | 14 | 13740 | 3.77 | 2666 | 1.89 | 20000 | 32.0 | 32.0 |
| Micro Wind Turbine | 23.75 | 6 | 13034 | 3.57 | 7403 | 5.25 | 12925 | 9.9 | 2.8 |

**Table 12 – Performance data for Detailed Design Analysis**

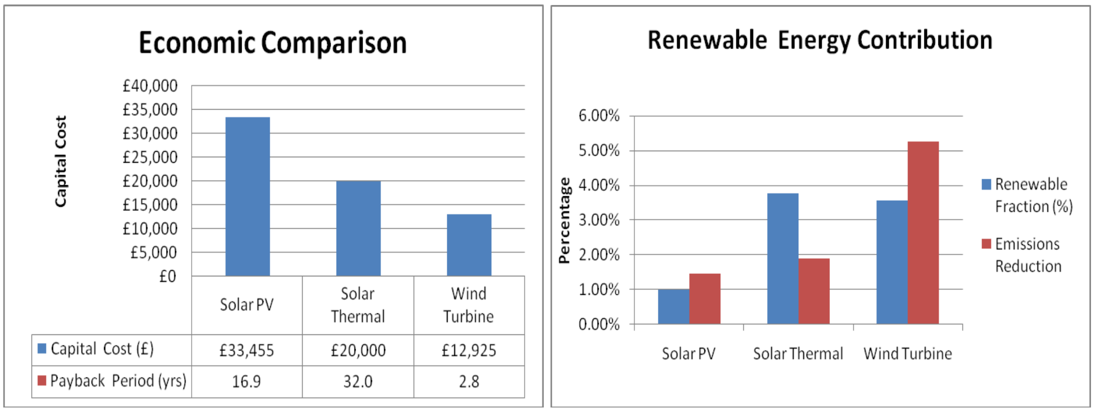

**Figure 33 – Performance Analysis (Detailed Stage)**

The above data shows the overall performance for all three renewable technologies. Based on the above, the technology most prominent and recommended for installation for the case study building is the 6kW micro wind turbine. There are significant differences with the results for the concept and detailed studies, and are explained to an extent through the following discussion. The solar thermal energy yield is greater for the detailed design analysis; this can be explained as the detailed study determines the maximum potential for a solar thermal system. The assumptions made for this model are as described within Chapter 5. The solar PV has a lower energy yield but still an improved payback period, as the inflation of fuel costs is taken into account for the detailed analysis. The power output for the micro wind turbine is almost double that obtained from the concept study, and is greatly more than the monitoring studies. There are two key reasons for why such a figure is possible. First, an hourly analysis has been performed in comparison with a monthly averaged analysis. This approach while still averaging out some wind gusts does give a more accurate estimate of likely power output. Second, the detailed model accounts for appropriate placement of the turbine, maximising energy potential. The model deficiencies are further explained through conducting a critical analysis for the above results for detailed design stage.

### Solar PV

The following extended results are achieved from the technical appraisal of the solar PV panel installation.

| Technology | Rated Power | Energy Yield | Overall Efficiency | Displaced Emissions |
|---|---|---|---|---|
| Solar PV | 4884 W | 3609 kWh | 11.6% | 2050 kg$CO_2$ |

**Table 13 - Solar PV technical data**

From the monitoring study, a good site achieves an energy yield of 700-800 kWh/kWp, at an efficiency of 10% **(28)**. On this basis, the installation for the case study would qualify as a good source of solar PV energy.  A typical winter and summer day have been detailed within **(Appendix B)**. The highlighted columns (i.e. surface temperature and incident radiation) are imported from IES VE. The input data derived from the building simulation tool in this case IES VE is sufficient for producing technical data and hence calculating the predicted annual energy yield for Solar PV (Figure 34).

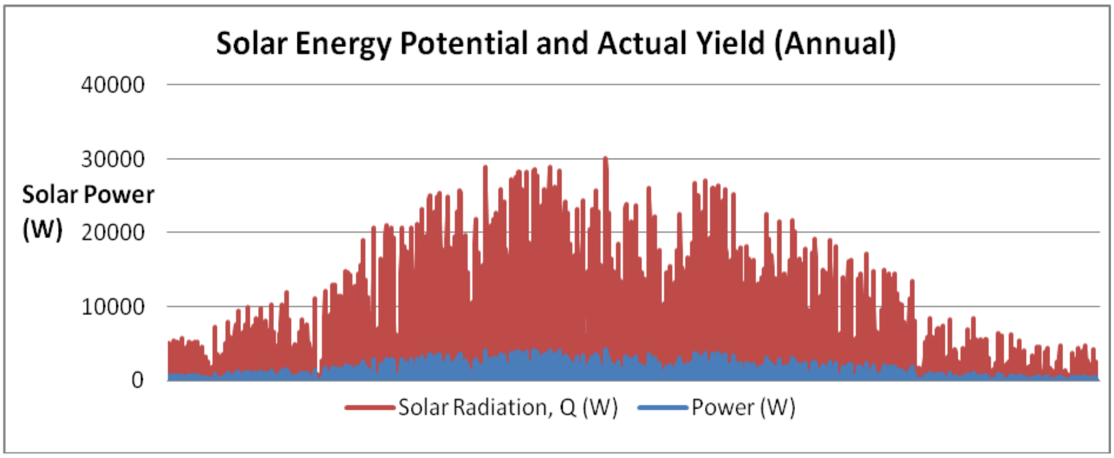

**Figure 34 - Solar PV Energy yield**

From the data analysed for Solar PV, it was noted that the surface temperature was around 10 to 15 degC above the dry-bulb temperature (Figure 35). The surface temperature is less than expected, as a previous study **(108)** has suggested PV panel temperatures can rise from $20^{oC}$ to $50^{oC}$ above ambient temperatures. The monitoring study had also witnessed an increase in surface temperature from $20^{oC}$ to $35^{oC}$ **(28)**.

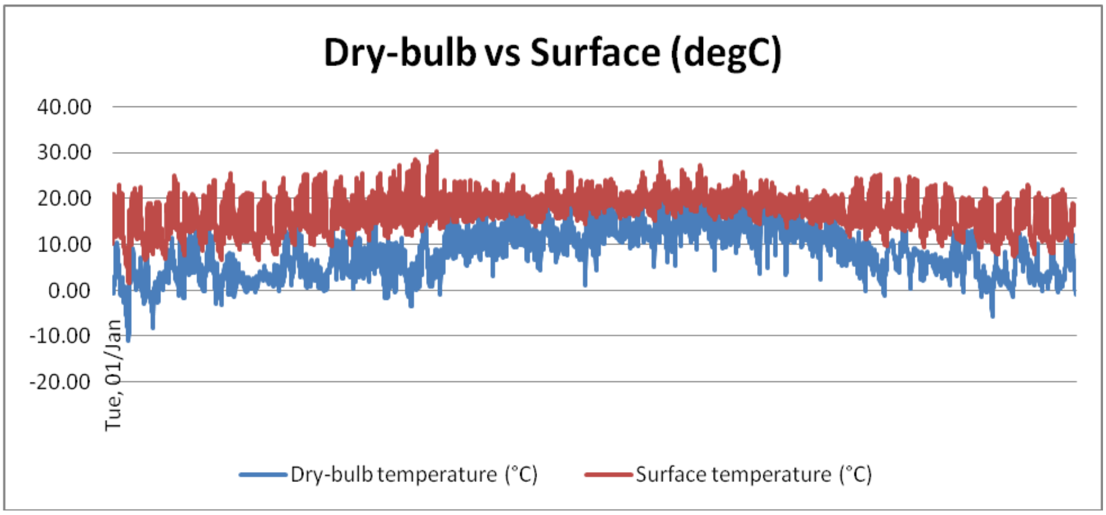

**Figure 35 - Dry bulb vs Surface temperature**

In light of knowledge that the surface temperatures are lower than expected, a review of building simulation modelling for special materials may need to take place as further work. It could be argued that artificially high panel efficiencies have been adopted due to this inaccuracy.

Overall the model was fairly consistent with actual experimental data studied at validation stage (refer to Chapter 6). However the model produced exaggerated results, particularly at lower angle of incidences, greater by 10%. Therefore, it would be prudent to reduce the energy yield for Solar PV by 10%, to quote a more conservative energy yield figure of 3248 kWh, for the case study.

### Solar Thermal

The following extended results are achieved from the technical appraisal of the solar thermal panel installation.

| Technology | Rated Power | Energy Yield | Overall Efficiency | Thermal Efficiency | Solar Fraction | Displaced Emissions |
|---|---|---|---|---|---|---|
| Solar Thermal | 13952 W | 13740.4 kWh | 64.5% | 75.4% | 35.6% | 2666 $kgCO_2$ |

Table 14 - Solar Hot Water technical data

The above technical data allows an analysis to be done for maximum potential heat utilisation for the panel. The system has been designed for a solar fraction of around 40%, this is appropriate for providing all hot water demand for the summer **(60)**. The thermal efficiency is a measure of how efficient the panel is in transporting hot water, this is relatively high at around 75%. The maximum utilisation of solar hot water and therefore the energy yield for this solar panel is described in the figure below.

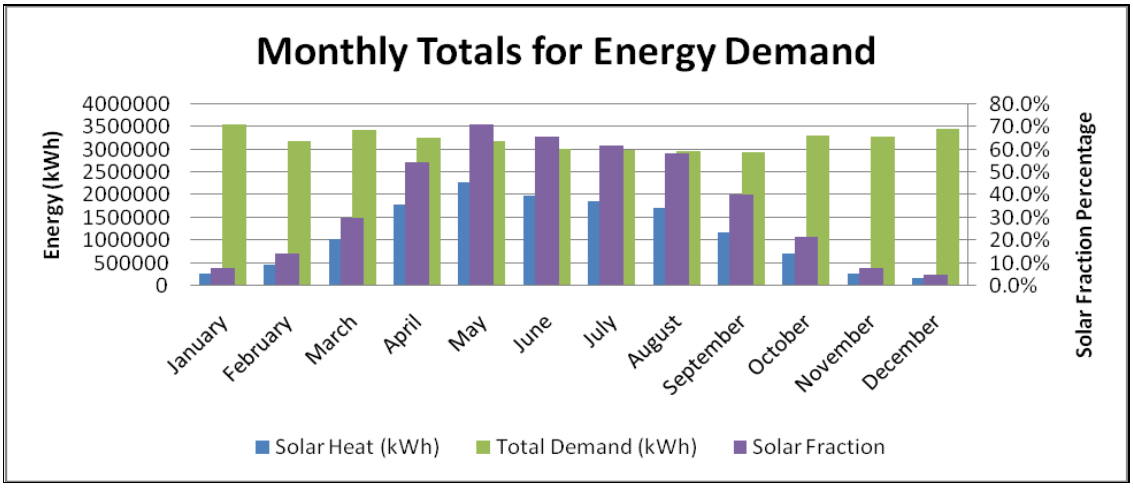

Figure 36 - Solar Heat vs DHW Demand

The graph above highlights the contribution of the solar hot water system for this building in comparison with DHW demand. The ‘total demand’ is fairly constant each month and the solar fraction is greater for the summer months. The above graph may be presented to make more interesting viewing for non-technical stakeholders. A typical winter and summer day have been detailed within a table **(Appendix C).** The highlighted columns (i.e. ambient temperature and incident radiation) are data imported from IES VE.

However, as discussed in the development phase this details maximum utilisation and does not consider demand and supply mismatch or even storage solutions. The overall efficiency is 64.5%; this is exceptionally high in comparison with other studies where overall efficiency is quoted at 40% **(60)**. It would be prudent to further reduce the energy yield for this solar hot water system to an efficiency of 40%, to quote a more conservative energy yield figure of 8521 kWh for the case study.

### Micro Wind Turbine

The following extended results are achieved from the technical appraisal of the micro wind turbine installation.

| Technology | Rated Power | Energy Yield | Average Power | Capacity Factor | Displaced Emissions |
|---|---|---|---|---|---|
| Wind Turbine | 6.3 kW @ 12ms$^{-1}$ | 13034 kWh | 1.5 kW | 23.7% | 7403 kgCO$_2$ |

**Table 15 - Wind Turbine Energy data**

A typical windy day has been detailed within **Appendix D**. The graph below indicates the annual energy yield for the wind turbine, for the case study building. The location is of good wind resource, in the north of Scotland, and by utilising CFD the turbine has been installed in an optimum location.

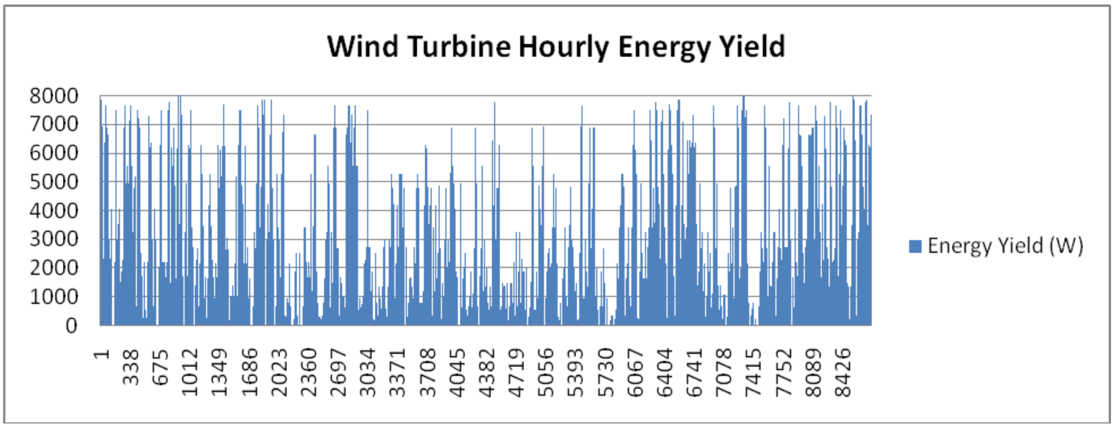

**Figure 37 - Wind Energy yield**

The above graph shows the hourly energy yield for the wind turbine, it is noticed that the value regularly exceeds 6 kW, the peak load. This is not possible in accordance with the power curve provided by the manufacturer. Hence there are errors with the interpolation of Cp values that need to be addressed, implying the energy yield value is exaggerated to an extent.

Based upon previous monitoring studies and general performance of building integrated wind turbines, an installation for an urban or suburban location produces a capacity factor of 3% **(38)**. If a wind turbine is installed within an urban location there is concern with increased turbulence, this would have an estimated power robbing effect of 50% **(30)**. For the validation exercise (Chapter 6), the difference was in actual fact 37.6% between the predicted and actual energy yields. Therefore a more conservative assessment for the proposed installation was to present an energy yield figure of 8133 kWh, taking into account the findings from the validation exercise.

The three renewable technologies can therefore be compared against actual monitoring studies. A conservative assessment was determined to compensate for difficult to quantify deficiencies within the developed analysis procedure.

| Technology | Energy Yield | | |
|---|---|---|---|
| | Analysis Model | Conservative | Monitoring Studies |
| Solar PV | 3609 kWh | 3248 kWh (Validation **(Ch. 6)**) | 3500 – 4000 kWh **(28)** |
| Solar Thermal | 13740 kWh | 8521 kWh (reduced efficiency **(60)**) | 5759 – 8695 kWh (approx based upon **(61)**) |
| Wind Turbine | 13034 kWh | 8133 kWh (Validation **(Ch. 6)**) | 1655 kWh (based upon 3% capacity factor **(38)**) |

**Table 16 - Renewable Technologies assessment**

The most effective analysis model can be determined by studying the above table, and is solar PV. It produces the most accurate results and the model is relatively consistent with monitoring studies for this technology. For solar thermal, it is clear that neglecting system losses to produce a maximum potential tool has its weaknesses. In reality, a solar thermal tool would not be effective without a storage solution and a significant hot water demand. It therefore produces a very optimistic result given the fact that utilisation of solar heat is very rarely 100%. The solar thermal model needs to be advanced to take into consideration the effect of having storage and actual utilisation of solar heat for hot water purposes, possibly through a dynamic model. The micro wind turbine produces the most varied results, the initial intention was to locate the optimum location for the wind turbine and take advantage of flow acceleration areas on the building roof. However, installation is recommended for above roof area beyond any area of flow acceleration **(34)**, to minimise the effects of local turbulence. The monitoring studies have proven far lower energy yields **(38)**. This is also realised in the validation exercise, where there is a vast difference between actual and predicted energy yields.

In conclusion, the models are producing questionable results. A few model deficiencies have been discovered especially for the solar thermal model. Future work on the models should strive to reduce identified deficiencies, improve analysis accuracy and perform model validation through physical testing. This would improve confidence for the developed models.

### Natural Ventilation

An analysis was done for the implementation of a natural ventilation services strategy based upon the methodology devised for this study (Chapter 5). An overheating analysis and a carbon emissions analysis (Table 17) were done to determine the viability of a natural ventilation strategy for the case study building.

Overheating Analysis

The overheating analysis was determined for a window opening strategy, to provide fresh air to the building and to meet the cooling requirement for the office. The overheating criterion was achieved for all occupied areas, i.e. office areas.

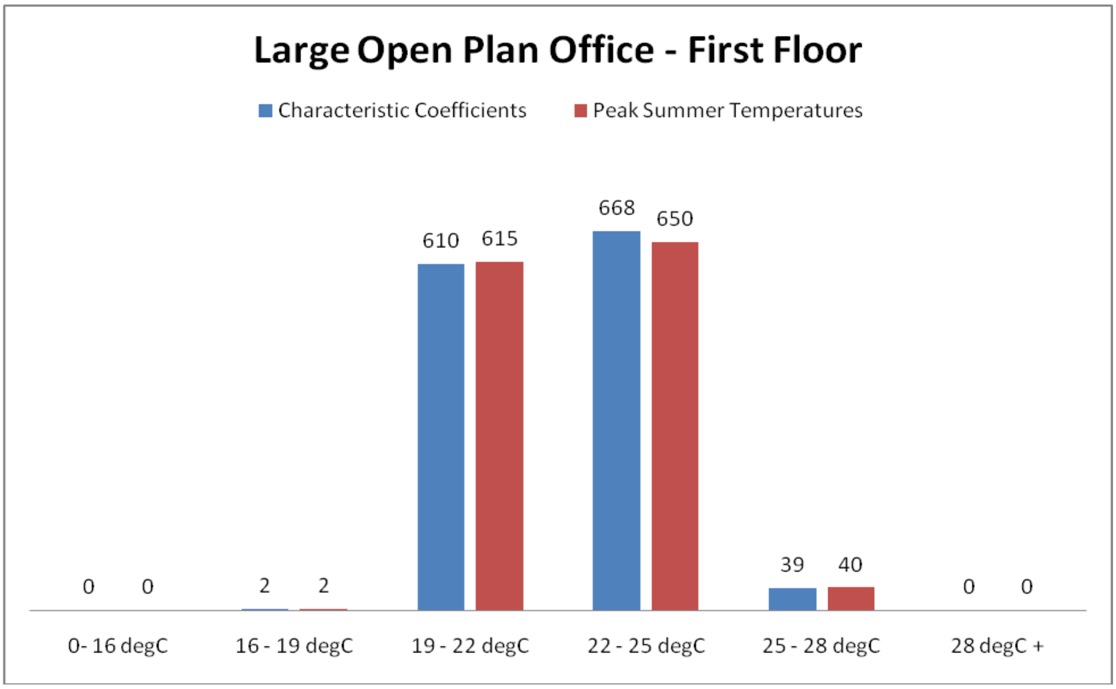

**Figure 38 - Office Overheating hours**

The above graph shows overheating hours for a typical office within the case study building. In this room only 40 hours exceed an operative temperature of 25 degC, this is equivalent to 1.5% of occupied hours. The design guidance states a maximum allowance of 5% above 25 degC **(97)**; this criterion has been comfortably achieved for all rooms. Also shown on this graph are the equivalent results for using characteristic coefficients, the difference is negligible. Therefore for a simple rectangular building such as used for this case study (Figure 30), the use of characteristic coefficients may well provide just as accurate results. However for a more complex shaped building it may be beneficial to use CFD derived pressure coefficients and a further study may prove their worth.

Carbon Emissions analysis

There were two analyses done to compare the carbon emissions for the building. This was for the building to be served by the proposed energy efficient VRF air conditioning system or through natural ventilation. The following results were achieved:

| **Building Services Strategy** | Electricity (kWh) | Natural Gas (kWh) | Carbon emissions ($kgCO_2$) | Carbon Reduction |
|---|---|---|---|---|
| VRF Air conditioning | 308,531 | 56,292 | 141,121 | 0% |
| Natural Ventilation | 250,847 | 125,678 | 130,239 | 7.7% |

**Table 17 - Building Energy analysis**

The expanded data for the above table is detailed within **Appendix E,** and shown in graphical form below.

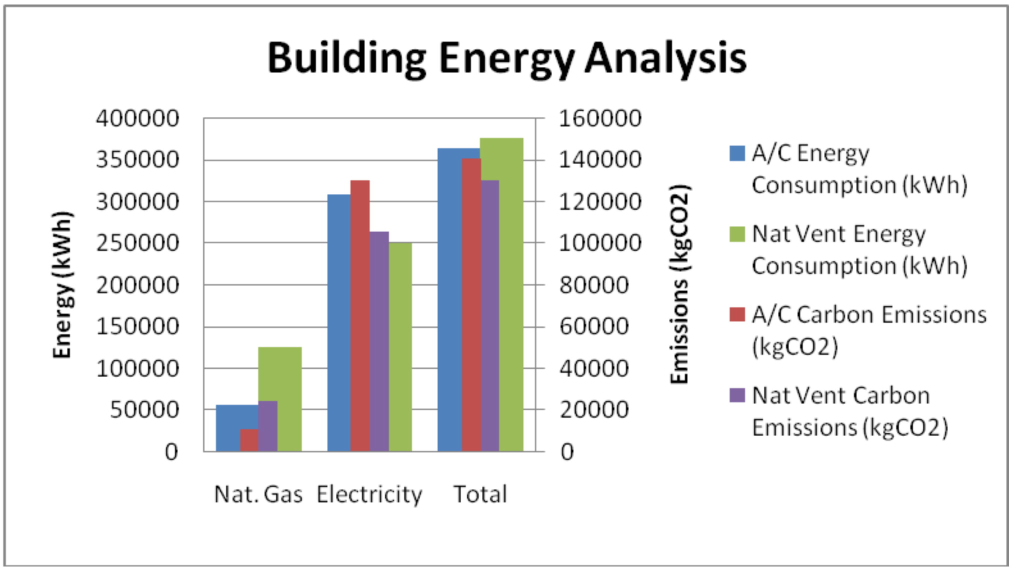

**Figure 39 - Building Energy Analysis**

From the above data and corresponding graph it is clear that a reduced amount of carbon emissions are released when predicting for a natural ventilation services strategy. Interestingly the carbon reduction is greater than for all the renewable technologies assessed. This emphasises the general effect of employing energy efficiency measures to reduce energy demand of the building to be greater than the installation of building integrated renewable technologies. Therefore conducting the above analyses determines a workable natural ventilation services strategy. There is no concern with overheating and also a reduced amount of carbon emissions are predicted.

The technologies were specified to maximise the effect of renewable technologies for the building without being economically unfeasible. The technology sizes specified were considered by the design team as the maximum for each technology, for rooftop installation, and agreed with the client. Based upon the results for the detailed case study (Table 12), it can be argued that micro renewable energy technologies specifically suited for building integrated application yield a minimal percentage of the buildings energy. Therefore it may be a more efficient and cost effective method for reducing carbon emissions, if energy efficiency measures are considered for the building **(75).** For further work on reducing energy consumption of buildings, a strategy should be developed for enhancing the effect of energy efficiency measures within building design. This would be mainly done through the use of a building simulation program and gathering awareness of such technologies. Therefore by prioritising demand reduction in the design process, it shall increase the contribution of renewable energy to the building's energy supply.

Finally it should be noted that several assumptions were made for determining the results for this case study, to reduce complexity. The performance of each technology has been assessed barring minimal disruption from external factors resulting in a better performance for example:

- Neglecting impact of surrounding buildings on approaching wind flow
- Neglecting the effect of turbulence on turbine performance
- No shading affecting solar panels

If the above was considered for a more detailed analysis, then it is assumed that would result in reduced energy yields than what has been found as part of this study.

# Chapter 8 – Discussions

## Further Development

The toolkit caters for LZC technologies design appraisal for two separate design stages; concept and detailed. All the major LZC technologies for building integrated application are assessed at concept stage and only three at detailed design stage with the addition of a natural ventilation design assessment procedure. This assessment methodology can incorporate further technologies as identified in Figure 8 and there is a need to expand design capability for the detailed analysis to the level appreciated at concept design stage – this means an enhancement such that Ground Source Heat Pumps, Combined Heat and Power and Biomass technologies may then be considered for a potential stakeholder at detailed design stage. These technologies comprise of complex systems arrangement determined by many factors. A considerable amount of work is required to understand the fundamentals for design and for developing an appraisal technique for each low carbon technology. With further development a working methodology for detailed design stage analysis comprising of the full set of LZC technologies is possible.

In this study, it has been mentioned that a suite of tools is necessary for carrying out appraisals for LZC technologies and one such suite of tools has been demonstrated via a case study. Though to make the 'LZC toolkit' a more acknowledged methodology within the industry more software tools should be demonstrated. The idea is to develop an assessment methodology which a range of tools can contribute to, as described, in a 'pluggable' fashion. The challenge would be to make the calculation spreadsheets compatible with the range of data and therefore greater processing and data handling capability.

Within the development process for the detailed design analysis, assumptions were made to simplify the process and these were carried forward to the case study. The assumptions were inclusive of, that due to local objects such as trees and local topography there was no shading and no obstructions upstream of the wind turbine. The effect of turbulence was not fully appreciated for this study. The modelling process may be improved taking into account knowledge of a more detailed local surrounding.

It was highlighted when discussing the results for the case study that the energy contribution from renewable technologies was minimal. It is possible that a more cost effective and greater impact may be provided by employing energy efficiency measures. The natural ventilation study may be further developed as part of this toolkit to investigate the above claim. Therefore an added value service may be provided from the toolkit.

Furthermore, in the practical use of this toolkit there will be opportunity to obtain feedback; to determine whether the results make interesting reading for a non-technical stakeholder. However, more importantly it needs to be determined through detailed validation and obtaining feedback that the results derived from each ‘renewable energy model’ reflect on the technologies actual performance. The results from performance monitoring may result in amendments to the ‘Renewable Energy models’ or even the assessment methodology. This will enhance the commercial viability of the toolkit.

However, there are some simple issues that need addressing within the short term future; this would be to perform detailed validation studies for all models. The ‘Expert Interface’ also needs updated with the proposed methodologies for the Renewable Heat Incentive (RHI), when available.

### Advanced Simulation tools

The building simulation tool is used for generating input data for the solar PV and solar hot water models as well as for carrying out a natural ventilation study. It was noted that the ‘surface temperature’ for the PV panel area was lower than expected, as determined by the monitoring study **(28)**. Therefore a review of the modelling process is necessary to accurately calculate this data and apply for future building simulation models.

CFD modelling was used to develop velocity and pressure coefficients for enhancing the wind energy model and the modelling of natural ventilation services strategy. The results obtained for wind energy yield was a lot more optimistic when compared with data for an actual field study. It is believed that turbulence has a profound effect on the operation of the urban wind turbine, yet it is difficult to quantify. It would be useful for future studies to further understand the fundamental principles of CFD modelling for turbulent flow and how to best apply them within the above application

## Renewable Energy Models

The ‘toolkit’ caters for the use of feasibility as well as advanced simulation tools to provide input data for ‘Renewable Energy models’. The model strengths and weaknesses are discussed below.

### Solar PV

The model for appraising solar PV panels caters for the majority of PV technologies. It determines the energy yield for solar PV installation dependent on its performance and location. However, some model deficiencies were noted when conducting the validation exercise and when comparing with the monitoring studies. The validation exercise involved comparison with an actual field study. The energy yield obtained for ‘lower angle incidence’ sun rays was exaggerated; providing an output of 10% greater than actual data. This model deficiency would need to be addressed in the future to improve the results data. Surface temperatures were recorded lower than expected and therefore may have contributed to an exaggerated PV panel output, for the case study.

### Micro Wind Turbine

The analysis method, described in great depth in Chapters 4 & 5, allows the user to determine optimum placement for the wind turbine. The energy yield is calculated taking into account acceleration factors that have been evaluated within the CFD tool, Fluent.

It was noted within hourly energy yields for the case study wind turbine installation (Chapter 7) that the peak wattage was exceeded a number of times. Therefore, there are errors with interpolating power efficiency, Cp, values. A better interpolation method is required to provide more accurate output data.

It is difficult to validate this process due to the many unknown parameters affecting wind turbine installation within the built environment. The model was validated by comparing model data with data from the Warwick wind trials **(107)** consisting of detailed ‘measured’ wind speeds and energy yield for a set period. The difference in results was significant and a solid reasoning had not been established. It was observed that the power efficiency curve for the field trials does not match the manufacturer’s power efficiency curve **(107)**. It is urged that the wind industry investigates the noted difference in performance **(107)**. The effect of turbulence on a wind turbine is not well known but requires further work to understand the low energy yields witnessed within urban environments. The validation process would be more valid if the measured wind speeds were compared with those obtained from the use of a CFD tool. This exercise along with gathering data from monitoring studies would provide an adequate measure of how effective this analysis method is for evaluating potential energy yield for a micro wind turbine installation.

### Solar Thermal

The Solar Thermal model caters for flat plate collectors – looking at the basic design of solar hot water collectors and quantifying 'usable heat'. The model does not take into account storage solutions or intermittency in water run-off, hence a positive result. There are three major refinements possible for this model

1) Identify possible losses in the system, at a given flow rate and daily hot water consumption.
2) Perform a dynamic analysis for determining the solar heat acquired from the panel
3) Cater for more solar thermal panel types e.g. evacuated tube, unglazed collectors
4) Identify true thermal efficiency for panel and actual solar heat gained.

The 'usable heat' details maximum renewable heat at preferable conditions. This needs to be communicated when specifying these results within an energy appraisal document.

It is believed that the modelling of solar thermal systems is better done through a dynamic analysis, taking into consideration stratified zones within the hot water cylinder, variable water run-off periods and the variable temperatures for the external environment, incoming water and the panel itself. This proved extremely difficult to determine by using Excel and therefore any future development should look at better, more efficient means of developing the solar thermal model.

In summary, there is a considerable amount of work required to enhance the existing 'LZC toolkit' and expand it. It is unfortunate that this could not be carried out within the scope of this project or indeed within the agreed timescales. However a suitable methodology has been proven for the appraisal of building integrated LZC technologies, at least for a reasonable approximation of likely performance.

### Economic analysis

An economic analysis has not been undertaken for the natural ventilation study and for other technologies a simplistic approach has been used determining the ‘payback period’. There are other methods for quantifying the economic appraisal such as life cycle costing, return on investment (ROI) and Net Present Value (NPV). It would be useful to investigate a more appropriate means of evaluating the economic viability for each technology.

# Chapter 9 – Conclusions

In Conclusion, this study has introduced an assessment methodology based on the use of multiple software tools for appraising LZC energy supply technologies at different stages of the building design process, for a specific site. This methodology shall assist the building design engineer in making an informed decision for the installation of integrated LZC energy technologies, to reduce the overall carbon footprint of the building. Hence be capable of meeting future stringent legislative requirements and take advantage of 'green' incentives.

A study was undertaken for the selection of LZC technologies best suited for building integration; models were developed for four technologies at detailed design stage. This included the analysis for solar PV, solar hot water, micro wind turbines plus a model for appraising a natural ventilated building. At concept design stage a multitude of technologies are assessed, including the above plus GSHP, CHP and Biomass heating. The development of renewable technology models was prioritised based on the fact that legislation favours their installation.

A selection of software was identified for carrying out detailed appraisals for renewable technologies, however only easily resourced tools were utilised. It was important to identify the right set of tools to carry out the appraisals for the design and installation of building integrated renewable energy technologies. It was recognised that to implement upon a full range of capability, a suite of tools form the assessment methodology. Software was identified in relation to the building design process and it was realised that different stages of design appraisals are possible for LZC technologies, concept and detailed design stages.

For this study, reviewing applicable LZC technologies and assessment software enabled progress for an appraisal methodology for two separate design stages. HOMER and RETScreen were used as software inputs for concept stage analysis. IES VE (Building Simulation) and Fluent (CFD) were used as software inputs for the detailed design stage. By doing so, available resources were utilised for the assessment of LZC technologies.

For concept design, strategic design software tools were used to assess a range of LZC technologies, producing a relatively quick appraisal enabling underperforming technologies to be discounted early. The filtering criterion influences this process and largely this is related to economic performance. The results are presented in a format understandable to the non-technical stakeholder through the ‘Processing tool’ allowing for a comparative analysis.

For detailed design, a comprehensive analysis using advanced simulation software provides an appraisal for suitable renewable technologies. The data is presented through displaying ‘bitesize’ information in graphs, so that there is a visual perspective for stakeholders involved in the design process. This makes the results easily accessible for the non-technical stakeholder.

A real design case study was applied for testing this ‘toolkit’ and it identified micro wind turbine installation as a viable solution for concept and detailed design stages. The solar technologies may present better economic feasibility if demand or advancement in technology reduces capital cost, or they are better placed on the roof at an alternative tilt angle.

Overall building integrated renewable technologies contribute little energy to a building. It is worth considering energy efficiency measures for the building to maximise reduction of carbon emissions. The best course of action for meeting planning legislation at minimal cost may be to introduce energy efficiency measures and introduce an energy aware culture within the building.

A validation procedure was undertaken for the renewable energy models. Further work is necessary for this ‘toolkit’ to conform to an assessment standard for being used within an industry environment. The validation for analysis of solar PV panels identified a shortcoming with the model; lower angle of incidence ‘outputs’ were exaggerated. The model needs further developed to counter this issue and provide improved results. The validation for analysis of micro wind turbines produced exaggerated results without confirming the reason. The effectiveness of using a CFD tool for determining local wind speeds as adequate still needs confirmed. A further validation exercise is needed to determine the effective use of CFD. Hence make a comparison between predicted and actual measured wind speeds for an observed site. The validation for the analysis of solar hot water systems has highlighted that further improvements are required for the model (discussed in

Chapter 8). Ideally, further validation is required to compare an improved model with experimental data.

This ‘toolkit’ has been designed to accommodate further LZC Technologies as models may be added and linked to a central interface. Hence this methodology is expandable and flexible, allowing many different LZC technologies (not just renewable technologies) to be considered at all design stages. Technologies that may be incorporated into an expanded methodology include Ground Source Heat Pumps, Combined Heat and Power and Biomass heating. While these technologies differ widely, the analysis methodology into which each technology type can be integrated (Figure 8) is the same.

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# APPENDIX A

## Site Summary for Location 21.PARK FARM (68)

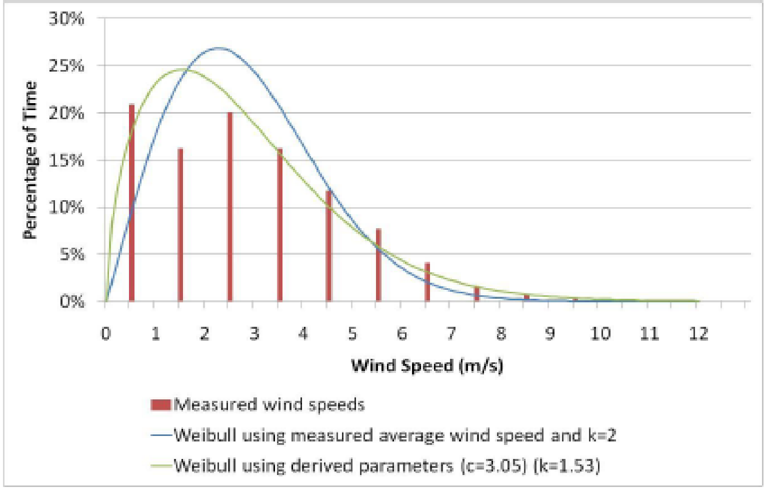
## 21. Park Farm

| | |
|---|---|
| Data collection period | 29/11/07 – 16/10/08 |
| Average wind speed | 2.83ms$^{-1}$ |
| Derived Weibull shape factor | 1.53 |
| Total energy output | 178.62kWh |
| Predicted energy output | 290.87kWh |
| Perfect in use capacity factor | 3.85% |
| Actual in use capacity factor | 3.32% |

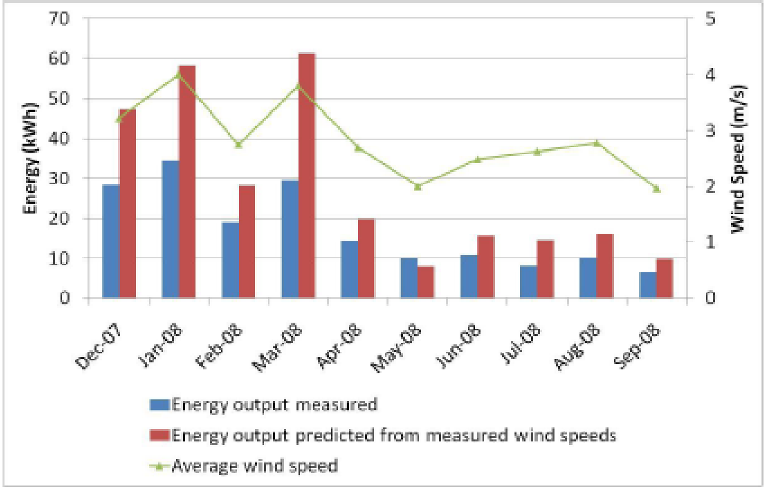
**Notes**

This turbine has been switched on the entire time we have been collecting data for.

Wind speed distribution



Trend in monthly average wind speed and energy output per month



# APPENDIX B

Solar PV Model Data

| Winter 02 Jan (Time) | Surface Temp, T (Kelvin) | Solar Radiation, I (W/m$^2$) | Solar Radiation, Q (W) | Diode Current, $I_O$ (A) | Light Generated Current, $I_L$ (A) | Voltage, Vmpp (V) | Power, P (W) | Efficiency, n |
|---|---|---|---|---|---|---|---|---|
| 08:30 | 18.26 | 0.976 | 35.1 | 7E-06 | 0.01 | 0.23521 | **2** | **0.057** |
| 09:30 | 18.85 | 5.653 | 203.5 | 7E-06 | 0.05 | 0.30373 | **15.3** | **0.075** |
| 10:30 | 19.76 | 17.96 | 646.5 | 8E-06 | 0.15 | 0.34903 | **56** | **0.087** |
| 11:30 | 20.55 | 33.04 | 1189.3 | 8E-06 | 0.27 | 0.37277 | **110.3** | **0.093** |
| 12:30 | 19.92 | 34.57 | 1244.7 | 8E-06 | 0.28 | 0.37563 | **116.4** | **0.094** |
| 13:30 | 18.86 | 25.37 | 913.4 | 7E-06 | 0.21 | 0.36461 | **82.8** | **0.091** |
| 14:30 | 18.98 | 14.85 | 534.6 | 8E-06 | 0.12 | 0.34257 | **45.4** | **0.085** |
| 15:30 | 18.98 | 3.763 | 135.5 | 8E-06 | 0.03 | 0.28719 | **9.6** | **0.071** |

| Summer 03 June (Time) | Surface Temp, T (Kelvin) | Solar Radiation, I (W/m$^2$) | Solar Radiation, Q (W) | Diode Current, $I_O$ (A) | Light Generated Current, $I_L$ (A) | Voltage, Vmpp (V) | Power, P (W) | Efficiency, n |
|---|---|---|---|---|---|---|---|---|
| 04:30 | 16.26 | 16.39 | 590 | 6E-06 | 0.013 | 0.35097 | **51.4** | **0.087** |
| 05:30 | 17.14 | 67.7 | 2437.3 | 7E-06 | 0.55 | 0.40744 | **248** | **0.102** |
| 06:30 | 18.28 | 156.5 | 5633.5 | 7E-06 | 1.27 | 0.44042 | **621** | **0.11** |
| 07:30 | 19.71 | 280.3 | 10091.9 | 8E-06 | 2.27 | 0.46278 | **1170.6** | **0.116** |
| 08:30 | 19.92 | 418.7 | 15072.7 | 8E-06 | 3.39 | 0.47931 | **1812.7** | **0.12** |
| 09:30 | 20.24 | 557.5 | 20069.7 | 8E-06 | 4.52 | 0.49093 | **2473.9** | **0.123** |
| 10:30 | 20.68 | 680.8 | 24509.2 | 8E-06 | 5.51 | 0.49880 | **3070.9** | **0.125** |
| 11:30 | 21.11 | 756.7 | 27240.2 | 9E-06 | 6.13 | 0.50274 | **3440.7** | **0.126** |
| 12:30 | 21.02 | 791.3 | 28486.2 | 9E-06 | 6.41 | 0.50474 | **3612.8** | **0.127** |
| 13:30 | 21.02 | 780.1 | 28082.9 | 9E-06 | 6.32 | 0.50413 | **3557.3** | **0.127** |
| 14:30 | 21.22 | 724.5 | 26083.1 | 9E-06 | 5.87 | 0.50077 | **3281.2** | **0.126** |
| 15:30 | 21.24 | 677.6 | 24394.8 | 9E-06 | 5.49 | 0.49792 | **3050.8** | **0.125** |
| 16:30 | 21.24 | 599.6 | 21586.7 | 9E-06 | 4.86 | 0.49275 | **2670.8** | **0.124** |
| 17:30 | 20.72 | 471.7 | 16982.8 | 8E-06 | 3.82 | 0.48330 | **2059.8** | **0.121** |
| 18:30 | 20.33 | 335.7 | 12083.7 | 8E-06 | 2.72 | 0.46951 | **1422.6** | **0.118** |
| 19:30 | 19.74 | 204.5 | 7360.6 | 8E-06 | 1.66 | 0.44956 | **828.7** | **0.113** |
| 20:30 | 19.52 | 95.4 | 3422.6 | 8E-06 | 0.77 | 0.41815 | **358.7** | **0.104** |
| 21:30 | 19.14 | 25.3 | 909.4 | 8E-06 | 0.2 | 0.36399 | **82.3** | **0.090** |

# APPENDIX C

Solar Thermal Model Data

| Winter 01 Jan (Time) | Ta (deg) | I (W/m2) | S (W/m2) | **Useful Heat** | **I total** | **Efficiency** | **To (deg)** | **Auxiliary Heating** |
|---|---|---|---|---|---|---|---|---|
| 7.00 | -0.80 | 0 | 0 | 0 | 0 | 0 | 2.9 | 9537.6 |
| 8.00 | -0.60 | 0 | 0 | 0 | 0 | 0 | 2.9 | 9537.6 |
| 9.00 | 0.80 | 9.3 | 7.5 | 27.7 | 228.4 | 0.121 | 3.1 | 9509.9 |
| 10.00 | 1.30 | 35.8 | 29.1 | 498 | 882.9 | 0.564 | 6.5 | 9039.6 |
| 11.00 | 1.40 | 91.9 | 74.7 | 1432.6 | 2265.2 | 0.632 | 13.2 | 8104.9 |
| 12.00 | 2.80 | 142.3 | 115.6 | 2351.6 | 3505.8 | 0.671 | 19.9 | 7186 |
| 13.00 | 2.60 | 139.3 | 113.2 | 2289.2 | 3431.2 | 0.667 | 19.5 | 7248.3 |
| 14.00 | 2.30 | 81.5 | 66.3 | 1315.4 | 2008.9 | 0.655 | 12.4 | 8222.2 |
| 15.00 | 2.60 | 34 | 27.7 | 547.8 | 838.8 | 0.653 | 6.8 | 8989.8 |
| 16.00 | 1.90 | 10.6 | 8.6 | 116.8 | 261 | 0.448 | 3.7 | 9420.7 |
| 17.00 | 1.10 | 0 | 0 | 0 | 0 | 0 | 2.9 | 9537.6 |
| 18.00 | 2.20 | 0 | 0 | 0 | 0 | 0 | 2.9 | 9537.6 |

| Summer 03 June (Time) | Ta (deg) | I (W/m2) | S (W/m2) | **Useful Heat** | **I total** | **Efficiency** | **To (deg)** | **Auxiliary Heating** |
|---|---|---|---|---|---|---|---|---|
| 5.00 | 9.30 | 16.4 | 13.3 | 139.9 | 403.8 | 0 | 12.5 | 0 |
| 6.00 | 10.90 | 67.7 | 55 | 1087 | 1668.2 | 0 | 19.3 | 0 |
| 7.00 | 12.10 | 156.5 | 127.2 | 2629.9 | 3855.8 | 0.682 | 30.5 | 5722.4 |
| 8.00 | 13.40 | 280.3 | 227.8 | 4759.2 | 6907.3 | 0.689 | 46 | 3593.1 |
| 9.00 | 14.40 | 418.7 | 340.2 | 7110.4 | 10316.5 | 0.689 | 63 | 1242 |
| 10.00 | 15.00 | 557.5 | 453 | 9444.5 | 13736.6 | 0.688 | 79.9 | -1092.2 |
| 11.00 | 16.10 | 680.8 | 553.2 | 11552.9 | 16775.2 | 0.689 | 95.2 | -3200.6 |
| 12.00 | 16.40 | 756.7 | 614.9 | 12826.9 | 18644.4 | 0.688 | 104.4 | -4474.6 |
| 13.00 | 15.90 | 791.3 | 643 | 13369.2 | 19497.2 | 0.686 | 108.4 | -5016.9 |
| 14.00 | 16.50 | 780.1 | 633.9 | 13220.5 | 19221.2 | 0.688 | 107.3 | -4868.1 |
| 15.00 | 16.30 | 724.5 | 588.8 | 12288.8 | 17852.4 | 0.688 | 100.5 | -3936.4 |
| 16.00 | 16.70 | 677.6 | 550.7 | 11537 | 16696.9 | 0.691 | 95.1 | -3184.6 |
| 17.00 | 17.00 | 599.6 | 487.3 | 10264.2 | 14774.9 | 0.695 | 85.9 | -1911.9 |
| 18.00 | 16.10 | 471.7 | 383.4 | 8092.4 | 11623.8 | 0.696 | 70.1 | 259.9 |
| 19.00 | 16.20 | 335.7 | 272.8 | 5846.1 | 8270.6 | 0 | 53.8 | 0 |
| 20.00 | 15.10 | 204.5 | 166.2 | 3607.3 | 5037.9 | 0 | 37.6 | 0 |
| 21.00 | 13.60 | 95.4 | 77.5 | 1710.1 | 2350.1 | 0 | 23.8 | 0 |
| 22.00 | 12.30 | 25.3 | 20.5 | 470.1 | 622.5 | 0 | 14.9 | 0 |

# APPENDIX D

Wind Energy Model Data (08 Aug)

| Time | Corrected Velocity (m/s) | Power Coefficient ($C_P$) | Velocity Coefficient ($C_V$) | Power (kWh) |
|---|---|---|---|---|
| 01:00 | 4.121565 | 0.53 | 1.17759 | 539.7137 |
| 02:00 | 2.943975 | 0 | 1.17759 | 0 |
| 03:00 | 2.35518 | 0 | 1.17759 | 0 |
| 04:00 | 2.943975 | 0 | 1.17759 | 0 |
| 05:00 | 2.2141 | 0 | 1.10705 | 0 |
| 06:00 | 4.71036 | 0.53 | 1.17759 | 805.6368 |
| 07:00 | 4.121565 | 0.53 | 1.17759 | 539.7137 |
| 08:00 | 4.71036 | 0.53 | 1.17759 | 805.6368 |
| 09:00 | 5.88795 | 0.55 | 1.17759 | 1632.887 |
| 10:00 | 5.299155 | 0.55 | 1.17759 | 1190.375 |
| 11:00 | 4.71036 | 0.53 | 1.17759 | 805.6368 |
| 12:00 | 5.299155 | 0.55 | 1.17759 | 1190.375 |
| 13:00 | 6.476745 | 0.51 | 1.17759 | 2015.309 |
| 14:00 | 6.476745 | 0.51 | 1.17759 | 2015.309 |
| 15:00 | 7.06554 | 0.42 | 1.17759 | 2154.698 |
| 16:00 | 8.360889 | 0.4 | 1.17759 | 3400.31 |
| 17:00 | 8.360889 | 0.4 | 1.17759 | 3400.31 |
| 18:00 | 8.360889 | 0.4 | 1.17759 | 3400.31 |
| 19:00 | 7.06554 | 0.42 | 1.17759 | 2154.698 |
| 20:00 | 4.121565 | 0.53 | 1.17759 | 539.7137 |
| 21:00 | 2.943975 | 0 | 1.17759 | 0 |
| 22:00 | 2.767625 | 0 | 1.10705 | 0 |
| 23:00 | 0.568837 | 0 | 0.568837 | 0 |
| 24:00:00 | 2.275348 | 0 | 0.568837 | 0 |

# APPENDIX E

## Natural Ventilation Carbon emissions analysis

**Energy Consumption**

| VFR Air conditioning | Nat. gas (MWh) | Electricity (MWh) | Total energy (MWh) |
|---|---:|---:|---:|
| Jan 01-31 | 9.459 | 24.2689 | 33.7279 |
| Feb 01-28 | 7.7793 | 20.75 | 28.5293 |
| Mar 01-31 | 6.255 | 22.5093 | 28.7643 |
| Apr 01-30 | 5.2452 | 24.8071 | 30.0523 |
| May 01-31 | 2.8668 | 29.7628 | 32.6296 |
| Jun 01-30 | 1.5673 | 27.3736 | 28.9409 |
| Jul 01-31 | 0.8783 | 32.6359 | 33.5142 |
| Aug 01-31 | 0.5844 | 31.1448 | 31.7292 |
| Sep 01-30 | 1.3045 | 26.5992 | 27.9037 |
| Oct 01-31 | 5.1758 | 24.8111 | 29.9869 |
| Nov 01-30 | 6.8444 | 21.3047 | 28.1492 |
| Dec 01-31 | 8.332 | 22.5634 | 30.8954 |
| Total | 56.2921 | 308.5308 | 364.8229 |

| Natural Ventilation | Nat. gas (MWh) | Electricity (MWh) | Total energy (MWh) |
|---|---:|---:|---:|
| Jan 01-31 | 19.5607 | 22.0677 | 41.6284 |
| Feb 01-28 | 15.0681 | 19.1662 | 34.2344 |
| Mar 01-31 | 11.3284 | 20.0936 | 31.4219 |
| Apr 01-30 | 8.5032 | 21.0598 | 29.563 |
| May 01-31 | 8.1404 | 22.1551 | 30.2955 |
| Jun 01-30 | 8.5027 | 19.3429 | 27.8456 |
| Jul 01-31 | 6.349 | 22.2788 | 28.6278 |
| Aug 01-31 | 4.7684 | 21.293 | 26.0614 |
| Sep 01-30 | 4.7189 | 20.1848 | 24.9038 |
| Oct 01-31 | 9.1704 | 22.0023 | 31.1727 |
| Nov 01-30 | 12.8246 | 20.1077 | 32.9323 |
| Dec 01-30 | 16.7433 | 21.0947 | 37.8379 |
| Total | 125.6781 | 250.8467 | 376.5247 |

## Carbon Emissions

| VRF Air conditioning | Nat. gas CE (kgCO2) | Electricity CE (kgCO2) | Total CE (kgCO2) |
|---|---|---|---|
| Jan 01-31 | 1835 | 10241 | 12077 |
| Feb 01-28 | 1509 | 8756 | 10266 |
| Mar 01-31 | 1213 | 9499 | 10712 |
| Apr 01-30 | 1018 | 10469 | 11486 |
| May 01-31 | 556 | 12560 | 13116 |
| Jun 01-30 | 304 | 11552 | 11856 |
| Jul 01-31 | 170 | 13772 | 13943 |
| Aug 01-31 | 113 | 13143 | 13256 |
| Sep 01-30 | 253 | 11225 | 11478 |
| Oct 01-31 | 1004 | 10470 | 11474 |
| Nov 01-30 | 1328 | 8991 | 10318 |
| Dec 01-31 | 1616 | 9522 | 11138 |
| Total | 10921 | 130200 | 141121 |

| Natural Ventilation | Nat. gas CE (kgCO2) | Electricity CE (kgCO2) | Total CE (kgCO2) |
|---|---|---|---|
| Jan 01-31 | 3795 | 9313 | 13107 |
| Feb 01-28 | 2923 | 8088 | 11011 |
| Mar 01-31 | 2198 | 8479 | 10677 |
| Apr 01-30 | 1650 | 8887 | 10537 |
| May 01-31 | 1579 | 9349 | 10929 |
| Jun 01-30 | 1650 | 8163 | 9812 |
| Jul 01-31 | 1232 | 9402 | 10633 |
| Aug 01-31 | 925 | 8986 | 9911 |
| Sep 01-30 | 915 | 8518 | 9433 |
| Oct 01-31 | 1779 | 9285 | 11064 |
| Nov 01-30 | 2488 | 8485 | 10973 |
| Dec 01-30 | 3248 | 8902 | 12150 |
| Total | 24382 | 105857 | 130239 |