

University of Dundee

REF 2013

Burford, Neil

Output 3 (Design)

**Prototype Energy Autonomous
Studio**

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Prototype Energy Autonomous Studio – Botanical Gardens, Dundee, 2013.

General Description:

Research Output 3 ‘Prototype Energy Autonomous Studio’ is a zero-energy, self-sufficient demonstrator prototype— the first entirely renewable-powered ‘off-grid’ building to be constructed in the UK. This interdisciplinary practice-based research project was initiated by Burford in the Department of Architecture in July 2011. Located in the City’s Botanical Gardens the prototype was developed and constructed as a self-build project with the Department of Architecture’s Macro Micro, MArch research unit and MSc student research projects in Civil Engineering, Physics and Applied Computing. A consortia of over 50 manufacturers and suppliers was brought together to provide specialist know-how, donation of in-kind materials and components and expertise in the installation and implementation of technical systems. Dundee City Council Building Control Department advised on regulatory requirements, Buro Happold Engineers, Edinburgh on structural design and certification, Sir Robert McAlpine and Hardies on construction management, CDMC and HSE compliance and Edinburgh Napier’s Forest Products Research Institute on the use of Scottish sustainable timber construction products. Construction commenced in December 2012 and the prototype was completed to a wind and water tight stage in October 2013. The building was subsequently instrumented to capture data on physical performance of the construction, the performance of the energy generation and storage technologies and user behaviour. The prototype provides a ‘live’ test-bed to monitor its technical performance over a period of initially four years. It will also generate understanding of how user behavior affects the performance of the technical systems and how limited energy and water resources alter user behaviour to lower an individual’s carbon footprint. The data will give a measure of the efficacy of producing ultra-low and ‘off-grid’ buildings powered and heated by renewable energy alone in the context of the UK’s strategy for a low-carbon and renewable energy generation future and the EU’s strategy for a 100% zero-carbon based power sector by 2050.

The aim of this research is to generate new knowledge and technical solutions for a new generation of regional high performance buildings that are affordable, self-build and net-zero energy. The project has been designed to initiate the up-skilling and up-scaling of the regional building industry to meet the significant energy efficiency challenges required of housing of the future. This addresses the significant challenges the Scottish construction sector faces in fulfilling the requirements of Scottish Government’s Sullivan Report, 2009 and the UK’s Code for Sustainable Homes Legislation which will be mandatory for all new-build housing in 2016. It goes beyond this providing transferable and exportable new know-how and solutions for ultra-low energy construction practices coupled with the integration and control of renewable energy generation and storage technologies. When completed the prototype will be open to the public and will showcase these new strategies and their wider applicability to the building and housing sectors and the general public. It will provide a seminar space for outreach activities to industry, the professions, colleges and schools and office space for Solar Cities Scotland¹. Collaboration

¹ *Solar Cities Scotland develop and promote the use of renewable energy and offer practical advice on low carbon living for urban communities across Scotland sharing knowledge and best practice on tackling climate change and peak oil. Solar Cities Scotland is part of a worldwide movement that was established in 2003.*

from across the profession, industry and policy makers has generated in-kind industry funding in excess of £150,000. Grant funding to support parallel R+D projects was obtained from Scottish Funding Council Innovation Voucher and Forestry Commission Scotland along with a number of charitable trust grants. The project has been internationally published in research journals, popular press and in design and architecture forums on the web and through exhibitions.

Research Questions:

- a) How to design a 50m² ultra-low energy, off-grid, self-build, Passivhaus compliant building using renewable, low-carbon energy generation and storage systems and low-embodied energy materials in a Scottish climate and regional construction sector context.
- b) How to mainstream best and new practices in ultra-low energy building design integrating regional technologies and construction practices, up-skilling and up-scaling local manufacture, trades and expertise.
- c) How to develop a new and appropriate architectural expression for an ultra-low energy, off-grid building responding to the landscape context of the University Botanical Gardens.

Aims/Objectives:

- To design and build a full-scale, fully-working demonstrator prototype live/work unit to showcase high quality architectural spaces and ultra-low energy technologies and construction practices suitable for use in low energy housing considering in particular the regional Scottish research and building industry context.
- To carry out research into existing and emerging energy and construction technologies and solutions and evaluate these in terms of their ability to deliver appropriate solutions to up-skill and up-scale Scottish industry in its ability to deliver ultra-low energy housing.
- To work collaboratively with key industry stakeholders, research organisations and specialist consultants in the field of low energy building to develop new market-applicable solutions to the problem.
- To define the existing barriers to developing very low energy housing in a Scottish context and address these by creatively developing integrated design and technologies that could form the basis for further research and development work.

Research Context:

The design and construction of ultra-low energy buildings has become a critical issue in Europe in the struggle to fulfil the requirements of the Kyoto Protocol for the reduction of CO₂ emissions. The current drive to reduce carbon emissions is a response to the European Commission's European Energy Performance of Buildings Directive (EPBD) common legislation for European Member States to reach the EU climate and energy targets by 2050. Buildings currently account for approximately 47% of CO₂ emissions and total energy requirements in the UK. Consequently the construction sector in the UK and Europe faces serious challenges to make the step change needed in design and construction practices to deliver a future generation of very high performance buildings and construction professionals with the skills and expertise to generate these.

The UK has set some of the most stringent criteria in Europe for zero carbon development, through new legislation embodied within Code for Sustainable Homes and the Sullivan Report (2007). The new targets are designed to minimise the impact of housing energy consumption through offsetting carbon emissions using renewable energy generation. In Europe, equivalent low energy approaches such as Passivhaus (PH) (Germany) and standards such as Minergie (Switzerland) focus on energy conservation through minimizing heat losses from buildings. PH in particular is recognized as a worldwide benchmark for the design of ultra-low energy buildings and attains considerably higher energy performance values than those aimed for in the UK's CSH Level 6 standard. It has been recognised that in order to make serious inroads into cutting CO₂ from UK housing, reducing the heating energy requirement is imperative as this accounts for 66% of overall household energy use. PH has shown that in addition to improved technical performance appropriate orientation and optimization in the design of internal spaces and building form are needed to produce ultra-low energy buildings. The Passivhaus methodology differs from the UK codes in that the simulation software used assumes lower internal gains, considers linear thermal bridging and regional climatic data. This approach has been successful in Europe, because climate data, building design, orientation and fabric specification are all taken into account in the design methodology allowing specific design solutions to be tested and quantified. There are now over 30,000 built Passivhaus examples in Europe which has led to the establishment of a robust Passivhaus supply chain and skills base in contrast to the UK.

To date there has been a lack of strategic research that recognizes the influence of regional climatic variations on the design and performance of low energy rural housing in the UK. BRE has carried out the majority of research and development into zero-carbon housing through the innovation park at Garston, Watford, but this work does not adequately address the regional contexts of the UK. While PH has seen increasing use in the UK with around twenty certified examples, only five of these are in Scotland and there is only a limited body of more generic PH knowledge available. Coupled to this, the Scottish Government has yet to define the highest Platinum standard of the Scottish building codes resulting in uncertainty for the future direction of the industry. The need for regional approaches to Scottish housing becomes evident when it is considered that 18% of the population live in accessible rural and remote rural areas which account for 94% of the landmass reflecting the dispersed nature of the rural population (Scottish Government 2012a). Current mass-market approaches to rural housing, whilst making incremental improvements to the technical performance of the building fabric give little recognition to orientation, density, lifestyle, contextual response or the development of an appropriate identity for housing. Scottish Government Policy Statement - Designing Places and Sustainable Places, recognises the barriers to creating successful and sustainable places and calls for a shift in attitudes, expectations and practices. It highlights the need for a marked improvement in design quality, place specific design responses, new housing and community models, as well as improvements in the technical efficiency and sustainability of construction. A parallel research study by the author has shown the extent that Scottish regional climatic differences influence low energy housing design and technology². Due to these more onerous regional climatic variations than the rest of the UK and the shifting demographics of population in rural areas, there is now a critical need to develop new sustainable, economic, low-energy Scottish rural housing models and up-skill the regional construction industry to respond to this (Scottish Government 2012a).

² Burford, N. & Pearson, A., Defining the Balance between Energy Efficiency, Human Needs and Contextually Responsive Design for Ultra-Low Energy Regional Scottish Rural Dwellings, Intelligent Buildings International, Volume**, August 2013, Routledge, London.

Over the past four years, Burford has been building a body of knowledge in the design and construction of ultra-low energy housing. This research acknowledges reference to the developing international profile for distinctive Scottish rural architecture demonstrated through the work of Dualchas, Rural Design, NORD and Graeme Massie Architects. It furthers these agendas, first developed in Frampton's Critical Regionalist critique concerning the particular and peculiar relationships between design and place, by integrating regional and local approaches to design with low-carbon generation, use and storage of renewable energy. It is influenced by the integrated approaches to sustainable and passive low-energy design exemplified in the work of Caminada, BERE and Riches, Hawley, Mikhail Architects and specifically the approaches pioneered by Bearch and Deplazes in the design of the Monte Rosa Hütte, Zermatt, Switzerland.

Research Rationale and Method:

Research Background:

This research furthers understanding of the implications of the new UK regulations on the design and technologies of low energy housing and the design and provision of new sustainable low-carbon communities.

Its aims are to address:

- a) The use of sustainable low-carbon, regional Scottish construction products in the construction of a Passivhaus compliant building.
- b) The development of a renewable energy generated power, LED lighting, heating system and controls using an intelligent building management system.
- c) The monitoring and evaluation of the buildings performance including weather data capture, fabric energy performance, internal environmental performance, power generation, energy storage and user behaviour.
- d) The understanding at a regional and national scale of the coupled relationship between the provision and location of affordable housing and the pay-back periods for renewable energy revenue generation.

There are a number of specific objectives:

- 'Researching the enabling technologies that could catalyse buildings in becoming the power stations of the future' - A prototype intelligent building management system will be developed to control energy flows considering direct use, storage and micro-grid export, including interactions with Electric Vehicles (EV's).
- 'Developing smart bottom-up systems thinking that is driven by needs for warmth, cooling, power and convenience' - Sensor technologies will be used to provide understanding of the spatial aspects of user behaviour and capture data on the relationship between occupants, the building fabric (e.g. opening windows) and technical systems (hot water use, ventilation etc). These data will be used to develop intelligent user controls for the building that provide feedback on system performance, allowing users to alter their energy consumption behaviour and/or control the building behaviour.

- 'Integrating DC power systems to supply consumer electronics from DC sources, for example, photovoltaics, fuel cells, without the need for conversion to AC' - The project will investigate the options, efficacy, efficiencies and appropriate standards for combined AC/DC power supplies to optimise energy efficiency, and develop control technologies to provide solutions for the practical implementation of PV and wind based energy production.
- 'Use of energy harvesting and storage systems' - Incorporating modular Li-ion battery technology into the building will provide the opportunity for flexible management of storage, import and export of energy.
- 'Information and communication technology (ICT) as an enabler, for example, to enable heating, cooling and power sharing' - The project will generate data on the interrelationships between on the one hand, the technical systems required to operate a building that relies entirely on renewable energy for its operation and how energy consumption is affected by occupant behaviour, and vice-versa. This will also take into account building fabric performance and internal environmental quality to optimise real-time performance of the building environment. It will integrate day to day onsite weather data and predicted national statistics weather data.
- 'Development of protocols to enable the trading and sharing of heating, cooling and power' - Protocols will be developed which enable electricity to be traded between the prototype building and the Botanic Gardens site.
- 'Developing techniques which enable these more complex systems to be understood and managed, allowing both vulnerabilities and opportunities to be identified' - A prototype 'live-in laboratory' provides an integrated technical platform and a unique opportunity to develop and study the efficacy of the interfaces between the building, the decentralised local-grid, and the user.

The project was initiated by Burford (Architecture) and Rodley (Physics) through discussions with several Scottish construction companies who were interested in the development of 'energy autonomous' buildings using ultra-low energy technologies and the sustainable use of material resources. They were keen to see how their products could work together and the impact this could have on energy use. As well as providing new markets for "packaged solutions" to the building sector, the companies were keen to see what alternative solutions were available to address future environmental legislation impacting on future housing design and construction. They were interested in sponsoring through in-kind contributions a project that would demonstrate and lead to further innovation of existing products and provide a vehicle for showcasing the integration of innovative design and technology. A design brief for a 50m² live-work unit was developed through engagement with the key industry stakeholders that would be autonomous in all its operational functions including space heating, power generation, potable water, waste and rainwater disposal. Designed to deliver an alternative spatial and technical concept for ultra-low energy, rural housing it was envisaged this could meet industry needs by providing new markets for existing products and market competitiveness through the development of new products, techniques and their integration. The manufacturers recognized that while there was significant data available on the performance of their individual

technologies there was a lack of know-how on how these technologies would work together such as wind, solar pv and battery storage and the controls. Additionally, in any building user behaviour has a significant impact on the building's performance. The prototype would provide a vehicle for monitoring the specific influence of the environment on the actual performance of the technologies and changes in human behavior and how this would influence future performance and the perception of 'user-comfort'. In order to demonstrate that the technologies were practical and affordable the project was conceived as a self-build using semi-skilled labour assisted by skilled apprenticeships provided by Dundee College.

This research builds on previous work by Burford, Smith and Gengnagel in the Lightweight Structures Unit where several highly innovative industry centered prototype R+D projects were developed between 1994 and 2006 in response to existing industry problems including:

- Self -Deploying Grandstand Canopy System for Arena System and PERI GmbH.³
- Lightweight Rapidly Deployable Military Shelter System for UK MOD and JT Inglis and Sons Ltd.⁴

Research Team:

The design and research was conducted through the Department of Architecture and Planning's Macro Micro MArch research Unit over the course of two years. A parallel MSc study under the direction of Rodley and Reynolds in physics developed the design of the energy system and economic feasibility which informed the development of the business plan for the project. Additional contributors to the University team were identified that included Jones, Mackie and Smith (Engineering), the University's Estates and Buildings Department and Peter Wilson from the Forest Products Research Institute at Edinburgh Napier University. Buro Happold's Mike Barrett and Paul Roberts agreed to provide structural design advice and the Structural Engineering Report required for building warrant approval.

Project Phasing:

In the first phase between July 2011 and July 2012, the design was developed from concept to building warrant submission. This initial stage was based on a design brief for a working studio environment for an Architectural Masters unit of 12 students occupying the space. The initial construction was based on a new CLT panel that was being prototype manufactured by NorBuild in Forres in conjunction with FPRI. The energy strategies and the quantification of energy use defined the PV area, roof angle, battery store and wind turbine size based on predicted data. An important aspect of this work was an economic feasibility study which influenced the development of a business plan to underpin the future funding of the construction. In the second phase from July 2012 to July 2013 the brief was adapted to include wet services, a toilet and kitchen making the building suitable for letting commercially. These changes were prompted by the funding strategy which was based on Solar City's Scotland renting the space as their headquarters. The occupant capacity was reduced to four people – considered a more

³ Aries Canopy System was developed for international events seating provider Arena Seating Ltd. between 2004 and 2006. Details of the research are discussed in Burford, N., & Gengnagel, C., *A Very Rapid Deployable Canopy System, Transportable Environments 3: Theory, Context, Design and Technology* Taylor and Francis, London, 2006.

⁴ Military Shelter System was developed for JT Inglis and Sons Ltd. between 1994 and 1998. Details of the research are discussed in Burford, N.K. & Smith, F.W., *Developing a New Military Shelter System: A Case Study in Innovation*, *Building Research and Innovation*, Volume. 27, Number 1, January / February 1999, E&FN Spon, London.

realistic occupancy for the size of the space. The construction was changed to a lightweight frame due to the limitations and availability of the CLT panel technology which required a reworking of the construction and buildups. A new warrant application was submitted in early January. The move to a lightweight frame construction facilitated the frame to be prototype manufactured in the Fulton Structures Laboratory in Civil Engineering. This provided a safe indoor environment for resolving the complex geometry issues of the frame, machining and assembly of the parts. The shell was manufactured and pre-assembled in the laboratory which allowed any faults or problems to be rectified before it was disassembled and moved to the Botanic Gardens.

Research Funding:

The construction of the prototype was funded primarily through industry in-kind donations of materials, components, manufacture and expertise. Direct funding was obtained through philanthropic donations. Grant funding from a number of sources funded parallel aspects of the work such as measurement, monitoring equipment and software. Although there was considerable interest from industry in contributing through in-kind donations it also provided significant problems due to the lack of 'capital' buying-power associated with the project. There were aspects of the build that could not be sourced through in-kind contributions; some products could only be acquired at a discounted price and some donated products were simply incompatible with the technical and design ambitions of the project. Consequently a strategy was devised to pump-prime the build through a capital investment from the University of £30,000 on the basis this would be recovered from revenue generation from renting the office space and from FIT's income from the renewable energy generation.

Dissemination:

1. Research and Professional Publications

- Defining the Balance between Energy Efficiency, Human Needs and Contextually Responsive Design for Ultra-Low Energy Regional Scottish Rural Dwellings, Intelligent Buildings International, (August 2013)
- Edwards, B., Rough Guide to Sustainability, Chapter 9 - Super Low Energy Houses, p220-240, 4th Edition, RIBA Publications, London, 2013.
- Reynolds, Rodley and Burford, PROTOTYPE ENERGY AUTONOMOUS STUDIO IN DUNDEE, SCOTLAND, Proceedings of SEEP2013, 20-23 August 2013, Maribor, Slovenia

2. Exhibition

- CECHR Conversations Exhibition, Lamb Gallery, Tower Building University of Dundee, 24th February to 6th April 2012.
- Dundee House, Dundee City Council Exhibition Foyer, 07th July to 14th September 2012
- RSA Open Architecture Exhibition, Edinburgh, 2013.
- Dundee Doors Open Day, Botanic Gardens, September 2013.
- Dundee Guildry Exhibition, Wellgate Library, Dundee, November. 2013

3. Popular Press

- Various articles/reports in local and Scottish national news papers including Courier, Scotsman and Guardian.
- Royal Incorporation of Architects in Scotland, EBulletin, December 2012.

4. Online Publication & Debate

- <http://www.bdonline.co.uk/news/dundee-masters-unit-propose-self-build-project/5046875.article>
- <http://www.kickstarter.com/projects/842476245/macro-micro-studio>
- http://homemadedessert.org/whats-up.php#.UOrZyKze_j6
- <http://inhabitat.com/macro-micro-studio-students-to-build-uks-first-net-zero-livework-studio-at-dundee-botanic-gardens/>
- <http://plusmood.com/2012/12/timber-studio-macro-micro-studio/>
- <http://www.macromicro.co.uk>
- <http://macromicrodundee.wordpress.com/>
- <https://www.facebook.com/MacroMicroStudio?ref=nf&filter=1>
- <https://twitter.com/MMStudio>
- <http://vimeo.com/53426702>
- http://www.jji-joists.co.uk/index.php/news/detail/james_jones_timber_systems_supports_first_net_zero_carbon_timber_structure
- <http://www.itw-industry.com/news.php?newsid=138>

Esteem Indicators:

- University of Dundee Honorary Graduates Award for Innovative Teaching 2012
- College of Arts and Social Sciences Innovative Teaching Award, University of Dundee, February 2012

Impact:

The impact of this research has been fourfold:

1. To inform directions for professionals, policy and decision makers on new architectural approaches and solutions relating to the designing of ultra-low energy and zero-carbon buildings;
2. To inform wider society of the critical debate and issues surrounding appropriate low-energy architectural designs and the application of low-carbon and renewable energy technologies for developing a future sustainable built environment;
3. To establish benchmark reference approaches guiding design judgements and technical responses for ultra-low energy and zero-carbon buildings;
4. To transcribe integrated low energy design principles and ideas to a wider context and bring these to the forefront of general public consciousness.

Research Outcomes:

Formal Design and Innovation

The formal and aesthetic language has been developed to respond to the different views and spaces within the garden and the technical requirements of energy conservation and renewable energy generation (Figures 1 to 4).



Figure 1: View from South West



Figure 2: View from West

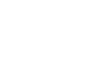


Figure 3: View from South East



Figure 4: View from North East

The building form is a compromise between aesthetic considerations, Form Factor and energy generation. The Form Factor governs a three dimensional form's efficiency in relation to energy conservation and is the ratio of surface area to volume of an object (Figure 5). It is generally accepted that ultra-low energy buildings should have a Form Factor of $\leq 0.7\text{m}^2/\text{m}^3$ which is difficult to achieve with floor plans less than 75m^2 . Initial studies started with a cubic volume with the floor area arranged over two storeys with an approximate distribution of 2/3rd to 1/3rd ground floor to upper floor. Subsequent studies investigating changing orientation of the plan from due south to 45 degrees in relation to different roof forms to optimize passive solar and active solar energy generation. This resulted in the requirement for a 30m^2 south facing 40 degree roof pitch optimized for solar photovoltaic power generation. The cranked north elevation releases space on the lower floor while allowing the remaining roof pitches (cranked walls) to complete the overall form. The resulting crystalline geometry is closer to a sphere and results in a Form Factor of 0.85. An analysis carried out in the Passivhaus Planning Package (PhPP) showed that the Specific Space Heat Demand (SSHD) was within the benchmark value of $15\text{kWh/m}^2\text{a}$. The abstract nature of the resulting building geometry has the presence of an 'erratic boulder' within the landscape.

7m X 7m X 7m Cube				6m X 6m X 6m Cube			
							
50	24	58	42	25	25	25	25
21	49	24	15	24	21	21	21
245	257	300	210	180	180	180	180
245	270	240	210	185	185	185	185
45	18(16.2)	28	33	20	20	20	20
6.75	2.43	4.2	4.95	3	3	3	3
23.5	8.1	14	16.5	10	10	10	10
							
50	56	38	41	26	30	30	30
56	42	42	48	74	40	40	40
245	212	205	210	162	157	157	157
245	217	199	209	198	168	168	168
45	25(24)	21(20)	38	19(18)	21(20)	23(21)	23(21)
6.75	3.6	3	5.7	2.7	3	3.15	3.15
22.5	12	10	19	9	10	10.5	10.5
							
50	55	32	42	32	29	30	30
21	21	35	15	35	33	22	22
245	220	250	210	155	164	156	156
245	217	251	210	184	190	173	173
45	19(18)	22(21)	38	16(15)	16(15)	27	27
6.75	2.7	3.15	5.7	2.25	2.25	4.05	4.05
22.5	9	10.5	19	7.5	7.5	13.5	13.5

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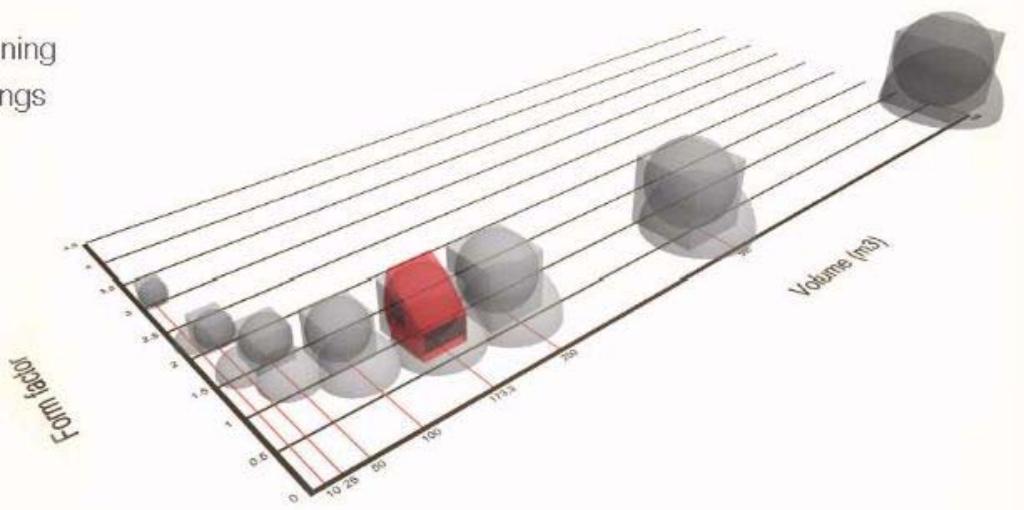


Figure 5: Form factor analysis of different volumes and shapes

The new building creates a formal landscaped courtyard rationalizing the relationships with the existing buildings at the entrance to the site (Figure 6 and 7). This sits in juxtaposition with the informal landscape of the gardens. The form and internal spaces create a dialectical relationship

with the open landscape spaces that are left between the existing planting beds and the internal volumes.



Figure 6: Existing landscape showing introduction of VAWT

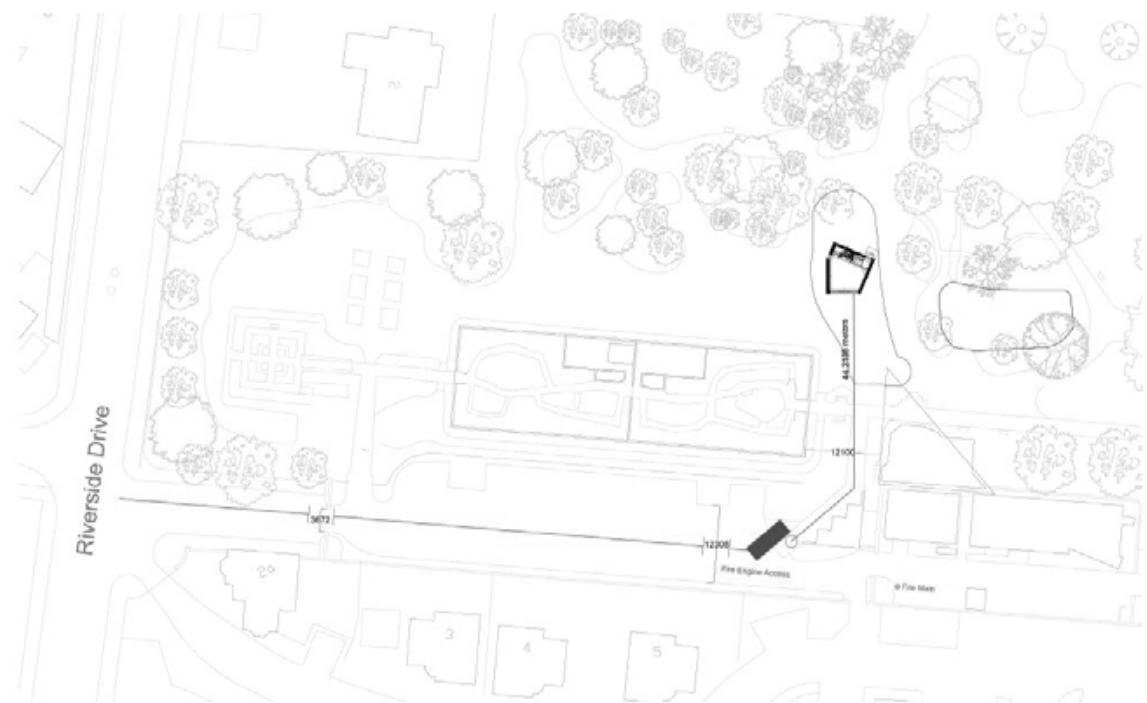


Figure 7: Site plan

Externally the form presents as a composition of aggregated internal and external spaces articulated and unified by a continuous faceted surface (Figure 8). This is further emphasized by its material expression - the seamless, matt Anthra Black zinc finish and the reductive detailing serve to minimize the depth and sub-division of this surface at the interfaces with other components such as openings or changes in surface angle allowing the building to be read as a single unified whole. Externally, the form appears as a number of uniquely expressed views when read from the different spaces within the garden. The horizontal interlocking cladding panels and detailing of the panels at the main geometry lines and around doors and windows was specifically developed to emphasize the horizontal banding giving the appearance of 'contour lines' (Figures 9).

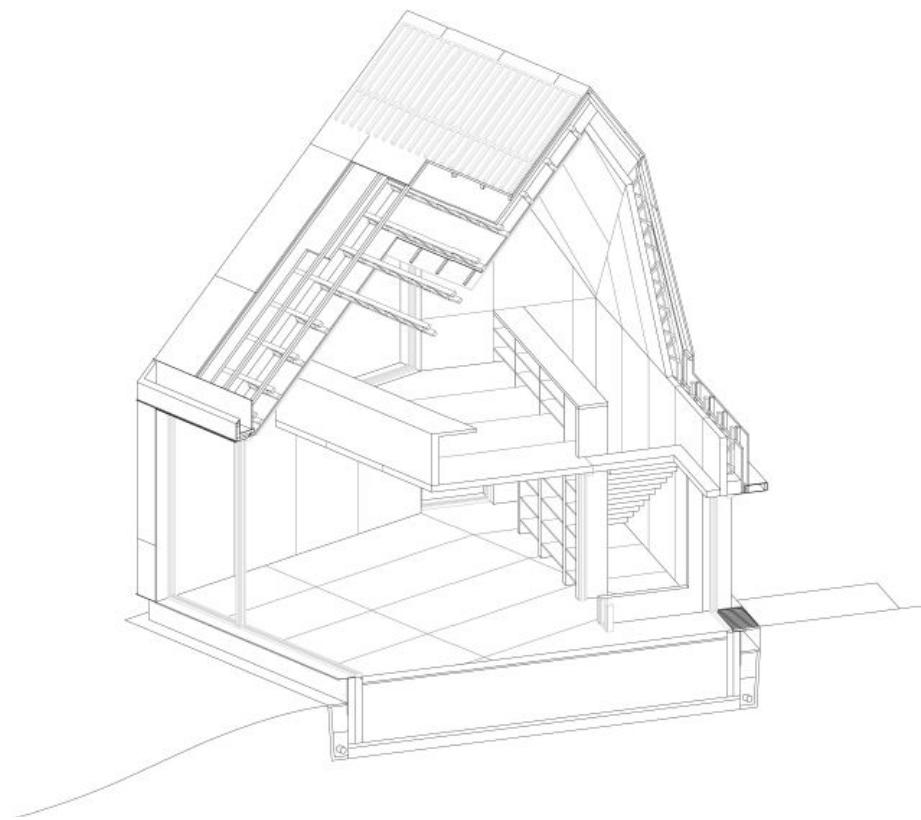


Figure 8: Axonometric demonstrating spatial configuration



Figure 9: Detailing of the zinc facade

Built over one-and-a-half storey's, the space internally is carefully segregated into three volumes with different programmatic functions (Figure 10). A service zone to the north of the plan contains entrance lobby, toilet, mechanical services and kitchenette. The main ground floor area is a flexible multi-function space for studio, meetings and exhibition. The mezzanine level is a private space contained within the steeply sloping roof pitches for working and storage.

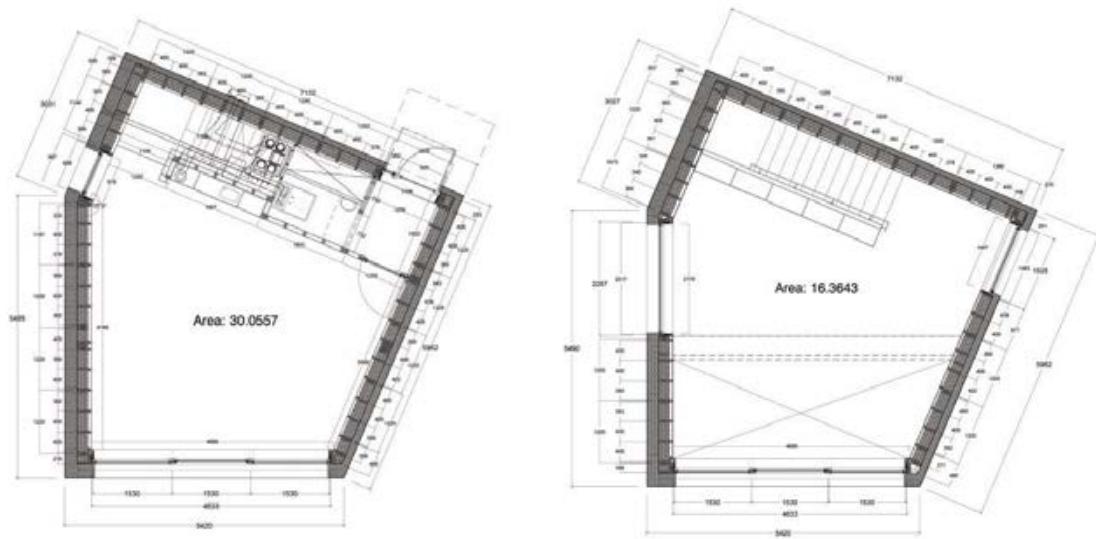


Figure 10: Floor plans

The positioning of windows is precisely controlled between consideration of passive solar gain, views and the external form (Figures 11 and 12). Floor to ceiling glazing engages the landscape directly with the internal spaces and the circulation sequence. The windows are anchored into the strong geometrical seam lines between the different plates that make up the external form and the organization of the different internal spaces. This creates a logical and recognizable relationship between the formation of the internal volume and external spaces and views. Internally, the single, varied volume has the feel of a much larger space, heightened by the connections to the external landscape and the large asymmetric roof volume of the upper floor. The ground floor has a main glazed elevation to the south looking into the public entrance

courtyard and reflecting the more public function of the ground floor space. The upper floor has a main window in the west wall which addresses the formal lawn adjacent to the greenhouse.



Figure 11: Internal perspective of ground floor



Figure 12: Internal perspective of upper floor

Construction Innovation

The choice of construction systems and details has been in response to developing a low cost, self-build Passivhaus standard building envelope that makes best use of local and regional products and expertise (Figures 13 and 14). It has also been developed to allow the building to be simply and safely constructed by low-skilled labour. The geometry of the building's form provided significant challenges that required substantial innovation in the development of the timber frame.

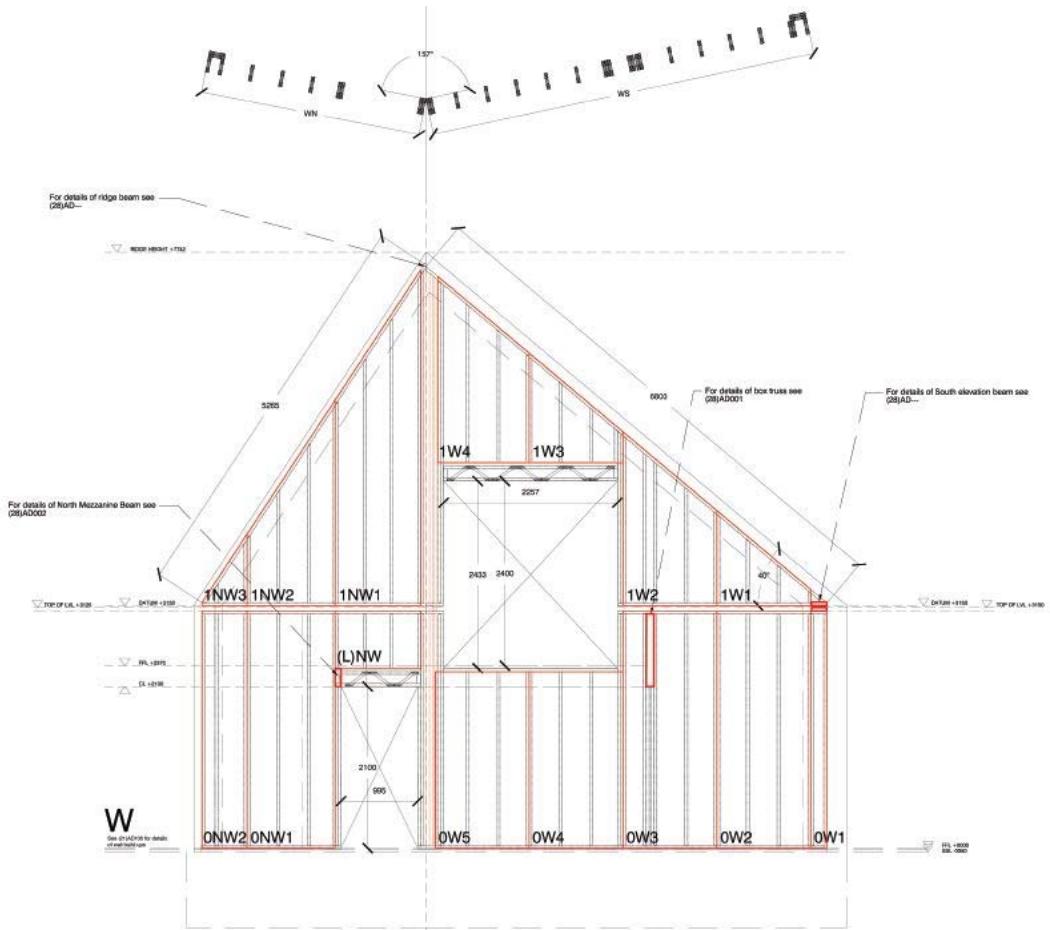


Figure 13: Elevation of west wall framing layout

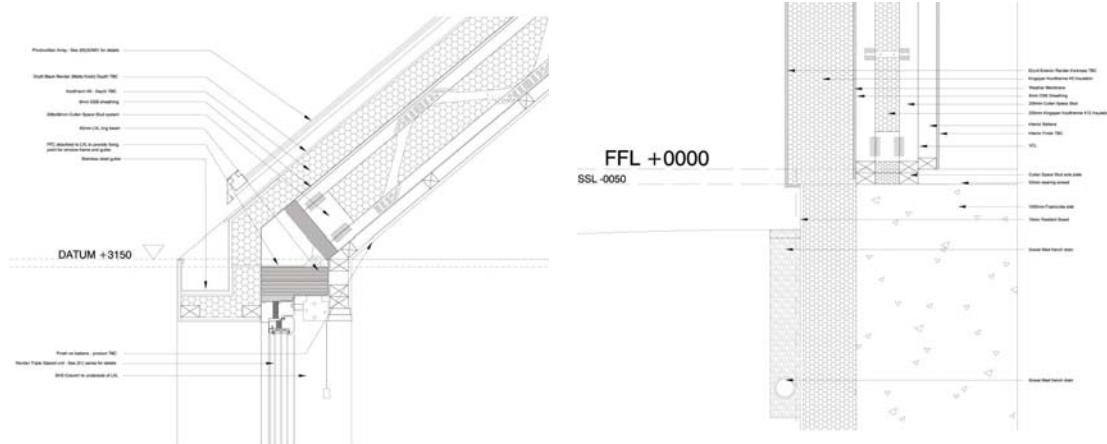


Figure 14: Details of the construction build-ups

Cross Laminated Timber Construction:

Timber is the most sustainable low-carbon renewable form of construction available today. The Scottish housing industry is dominated by mass produced timber-kit construction exemplified by Stewart Milne and Scotframe. This form of construction currently accounts for around 80% of the market in new build housing in Scotland in contrast to the rest of the UK where the market share is only around 30% (Sustainable Homes 2010). However, although Scotland has significant timber resources, the majority of timber is imported from Scandinavia and Canada which limits the capacity for developing a regional cradle to grave Scottish timber industry. Edinburgh Napier University's Forest Product Research Institute (FPRI) is the foremost UK Centre developing innovation within the forest industry; a specific focus being to develop high value timber applications that optimize the intrinsic properties of Scottish timber. Early discussions with FPRI identified a prototype Cross Laminated Timber product that was in the process of being developed by Napier and NorBuild in Forres using small element timber sections. However, later in the research it became evident that this product was too early in development, the production panel sizes being limited to 1.2m x 3m by the size of the press used to manufacture it. In the long spanning elements in the floor and roof, the CLT would have required an additional framing structure to support it obviating the intrinsic benefits of the CLT as a single material 'plate-structure' and finish.

Lightweight Frame Construction:

The focus subsequently changed to the Alpine SpaceStud and SpaceJoist framing systems, new products that had recently been developed with Cullen Building Products in Fife and which had not previously been demonstrated in a practical application (Figures 15 and Figure 16). The SpaceStud had previously been identified in the early research as a possible low-thermal bridge purlin system to support the cladding. The lightweight SpaceStud was specifically developed to meet the thermal requirements of the Building Regulations and the Code for Sustainable Homes and is one of the most cost effective wall stud systems on the market. The 'space stud' uses two vertical 38mm x 44mm timber sections that are connected by pressed steel brackets. This accommodates thicker insulation, reducing U-values and thermal bridging in the walls. It is also 20% more resistant to racking than conventional 38 x 140mm timber frame panels which can reduce the requirement for sheathed internal walls and double sheathing of external walls. Significantly, this product makes use of readily available stock sizes of Scottish timber which made it suitable for use in the wall construction.



Figure 15: SpaceStud used in the wall construction



Figure 16: SpaceJoist used in the roof and floor construction

The lightweight open web design of the SpaceJoist system was recently developed by ITW Industries (Cullen's parent company) for low-thermal bridging floor and roof joists for timber frame applications. It provides on-site savings in labour with no need for drilling or notching for installation of services. SpaceJoists are suitable for long span applications eliminating the need for intermediate load bearing walls and can be bespoke designed to reduce site wastage. This system was used for the spanning elements in the mezzanine floor and the long spanning elements that make up the roof plates. The components for both the SpaceStud and SpaceJoist were donated by Cullen BP, and with the purchase of a 4 ton press allowed the studs and joists to be manufactured in the Fulton Structures Laboratory of the University. The SpaceStud system was developed for assembly into a cassette panel type construction to allow the wall elements to be pre-manufactured in larger sections to increase accuracy and site-safety and reduce construction time and complexity on-site (Figure 17) .



Figure 17: Manufacture of the wall cassettes in Fulton Structures Laboratory

Foamed-Concrete Slab Construction:

Foundation design in Passivhaus compliant buildings is particularly onerous in having to eliminate thermal bridging whilst needing the capacity to transmit the superstructure loads to the ground. Inevitably this results in complex and expensive detailing and the risks of having to rectify construction defects. In the studio, the foundation design is a particularly innovative aspect of the construction having developed a completely new technique using foam concrete in a foundation slab to provide insulation and structure in a single material. Lightweight foamed-concrete materials had been in development with the Concrete Technology Unit at the University of Dundee and Propump Engineering Ltd since 1991. Usually used in civil engineering large void-fill applications or in the construction of lightweight bridge decks and road

foundations, discussions with Professor Rod Jones in Civil Engineering led to the idea of a 'thermo-concrete' foundation slab (Figure 18 and Figure 19). The relationship of the building to the slope on the site was important in reinforcing the abstract form, which relied on creating a plinth which resolved the 1m fall across the site. Additionally, the subsoil over-layed a bedrock layer 1m below the surface at the rear of the building which resulted in concerns of achieving the accuracy needed in the base using more traditional methods of foundation construction. Calculations showed a U Value of 0.1W/mK could be achieved at 1m depth using a 600kg/m^3 mix, which could be poured in a single volume into a formwork. Although the superstructure loads were comparatively low, the engineers raised concerns over using a new and relatively unproven material which necessitated carrying out load strength tests on sample blocks. Pull-out tests on fixings were required to establish a method for anchoring the timber frame to the slab necessitated due to the low tensile/compressive strength of the material and the frame being very close to the edge of the slab (Figure 20 and 21). Initial ideas to cast in thermal -water storage tanks into the slab were abandoned due to complexity and cost. However, similar ideas were carried over into the battery service void which was cast into the rear of the slab due to the limited space requirements in the plant room.

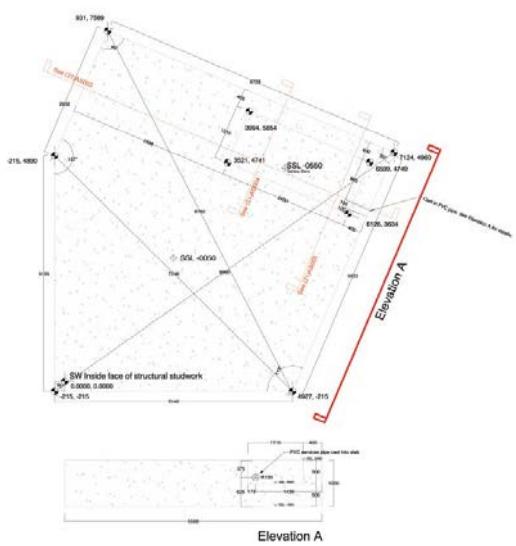


Figure 18: Foundation slab plan



Figure 19: Construction of formwork for slab



Figure 20: Load testing of fixings for sole-plate into a foam concrete block

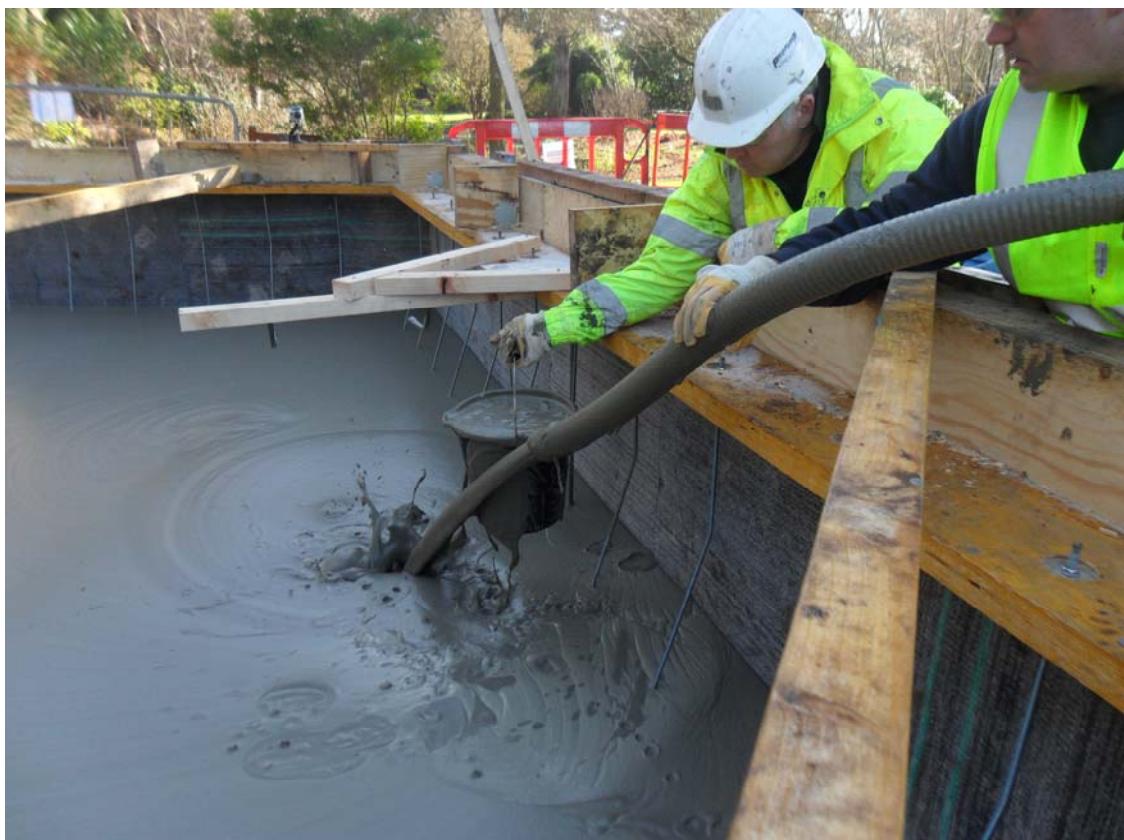


Figure 21: Pouring the aerated concrete slab.

Form, Geometry and Detailing:

The building's form is a result of aesthetic considerations and PV electricity generation. There is a distinct relationship between the geometry of the plan and the geometry of the roof that defines the three-dimensional form. This was modeled parametrically in Grasshopper in order to allow the form to be manipulated to accommodate different design changes to the internal space such as plan dimensions and volumes. However, there were still a number of significant problems in translating the theoretical geometry into a buildable construction. The building's form was a shell comprising a continuous internal surface and a continuous external surface. It was important that the individual surfaces that made up the three-dimensional geometry intersected at single points in space in order to maintain the aesthetic ambitions of the design. However, because the object was non-spherical, in order to maintain a coherent external and internal surface meant that each of the plates that defined these had to be different thicknesses. This was generated in Autocad by setting a scale point within the volume thus defining the points of intersection on the outside and inside surfaces respectively. A strategy was devised to maintain a constant depth of structure but take up the difference in plate thickness in the insulation layer on the outside and in the lining layer on the inside. This resulted in every wall/roof-plate having a different overall depth. Whilst this would resolve the overall surface geometry there were still issues to resolve in joining the different elements of the construction due to the compound angles between the various plates. A solution was found in treating each plate as an independent element of structure comprising a number of rafter components contained within a Laminated Veneer Lumber (LVL) ring beam. This would allow the SpaceJoist rafters to be cut at a single angle in one plane allowing a simple connection to the triangular ring beam (Figures 22 to 24). Following this, each plate would be connected to the adjacent plate using CNC machined LVL spacers that would take up the change in angle between them. To assist in fabrication and assembly on site, a specially designed hinge bracket was developed and fabricated by Cullen. This was used to accurately locate each of the plates with the hinged bracket facilitating in the lifting of the roof plates to their final angle whereby they would be secured mechanically by the LVL spacing brackets and proprietary timber fixing plates.



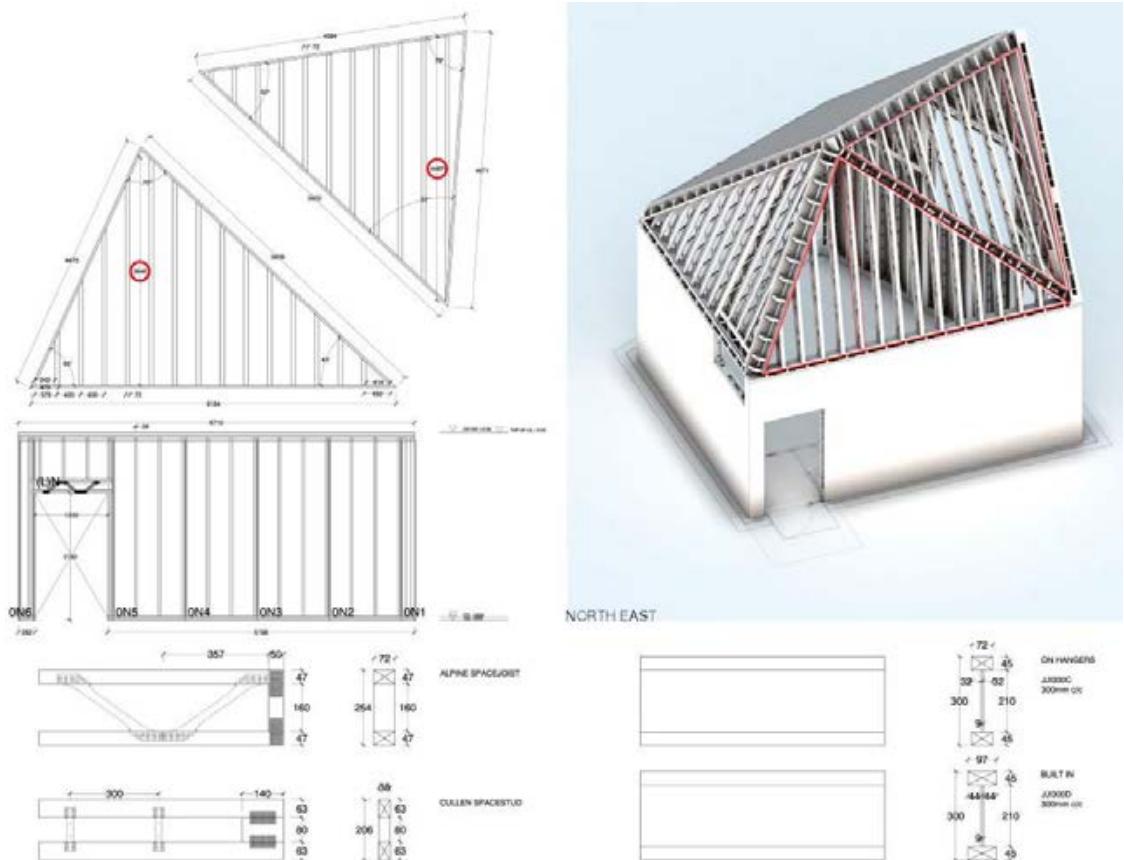


Figure 22: Axonometric showing plate connections.



Figure 23: Roof plate Connections Installed



Figure 24: Construction of the roof onsite

Energy and Environmental System Design and Innovation

As regulations move further towards a low-carbon energy generation sector, with renewables having an increasingly important role in this scenario, questions of energy security and balancing supply and demand are key concerns. The Botanic Garden project was set up as a standalone building to demonstrate the feasibility of an off-grid ultra-low consumption building combining innovative technology with innovative architecture (Figure 25). In the prototype, the energy and environmental system is a central aspect of the research both in terms of how it led to the formation of the formal design concept and how the technical systems operate and perform in day to day use (Figure 26). This aspect of the work is new in that there is very little data available for how different renewable energy technologies operate together and this was of particular interest to the manufacturers of the wind turbine, PV and battery systems. This aspect of the research has been conducted with Renewable Resources Ltd, who are supplying and installing the PV system, Axeon batteries in Dundee who are world leaders in the development of electric vehicles and Rodney Grant electricians who have expertise in the installation and control of renewable energy technologies. There is currently little existing know-how on the requirements and design of the control systems needed to monitor external and internal environmental conditions, energy generation, demand and storage and the user interfaces needed to optimize energy use. Consequently, the energy autonomy of the prototype is crucial in being able to provide answers to these problems and as such goes beyond current research which is focusing on compliance with 2016 regulatory requirements.

The prototype was conceived as a development test-bed that would have enough flexibility to allow future adaptation of the technologies as these developed, but would also permit different technologies to be tested simultaneously. While predictions were made in terms of external environmental factors (solar insolation, wind speeds) and the energy needs of the building occupants it was not possible to accurately predict the relationship between these in terms of the efficiency of the system. A best 'fit' was developed and this was used to make the final design decisions on the energy system. In the Phase 1 brief this was estimated as 9.8kWh per working day in the 'worst-case' scenario. This value complied with the upper limit for Passivhaus. The battery store was then designed to provide electricity for three days and the solar array yield was estimated via professional software according to the available south-facing roof pitch. To deal with the shortage of energy in winter months various wind turbines were assessed and their individual productions estimated using Weibull distributions combined with their power curves. This showed that a 2kW turbine would generate an excess of energy that could be used for the space heating.

This system optimisation and economic assessment was undertaken in a parallel Physics MSc project⁵. A number of assumptions based on current knowledge and best practice were made in the calculations as follows:

- a) System component lifetime (PV + Wind Turbine + Batteries) was assumed to be 25 years giving the economic lifetime period as 25 years.
- b) Current energy price considered as £0.13/kW with a constant increase of 7.5% per annum
- c) System efficiency will decrease by 1% each year until stabilizing at 80%

⁵ Tissot, J., Autonomous Studio, Technical and Economic Assessment of an Off-Grid Passivhaus Hybrid Renewable Energy System, MSc Thesis, September 2012.

- d) From 1st August 2012, the feed-in tariffs, FIT's, solar PV array with a nominal capacity of 4.9kW peak is £0.145/kWh and £0.28/kWh for a wind turbine between 1.5kW and 15kW.
- e) FIT's undergo a constant inflation of 3% per annum
- f) In order to recover all the potential FIT's income 100% of the available solar and wind energy will be converted into electricity and 100% of it will be used either by the building or through feed-in into the Botanic Garden local grid and diverted to other buildings.

The revenue calculations showed potential future energy generation revenue and energy cost savings. An important insight from this study showed a correlation between the FIT's revenue income and the capital cost of the construction giving an insight into potential future funding mechanisms for affordable low energy housing.

The monitoring and measurement of the building's environmental and energy control system was funded by an SFC innovation voucher. Although the prototype was conceived as being autonomous, it is connected to the Botanic Garden local grid as this was required in order to realize the FIT's income needed to fund the project. The Studio's electrical system was assessed to be economically and technically viable. Optimization of the control part of the system, coordinating the invertors and sensors to optimize energy balance are to be developed in a future research project.

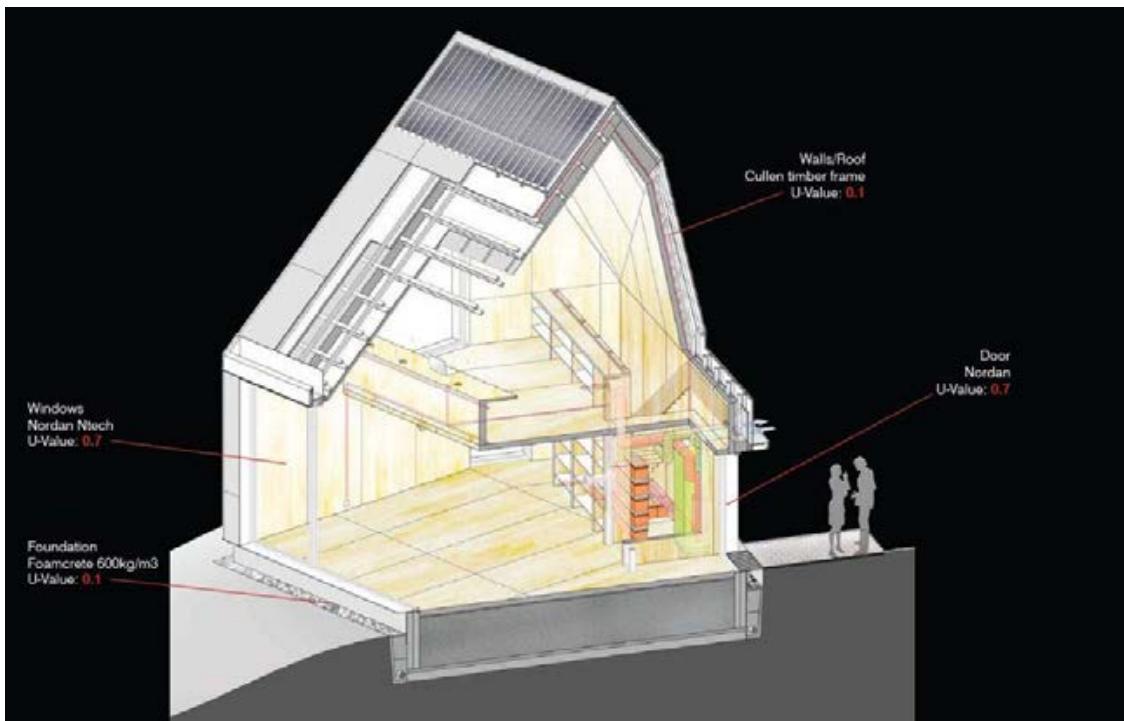
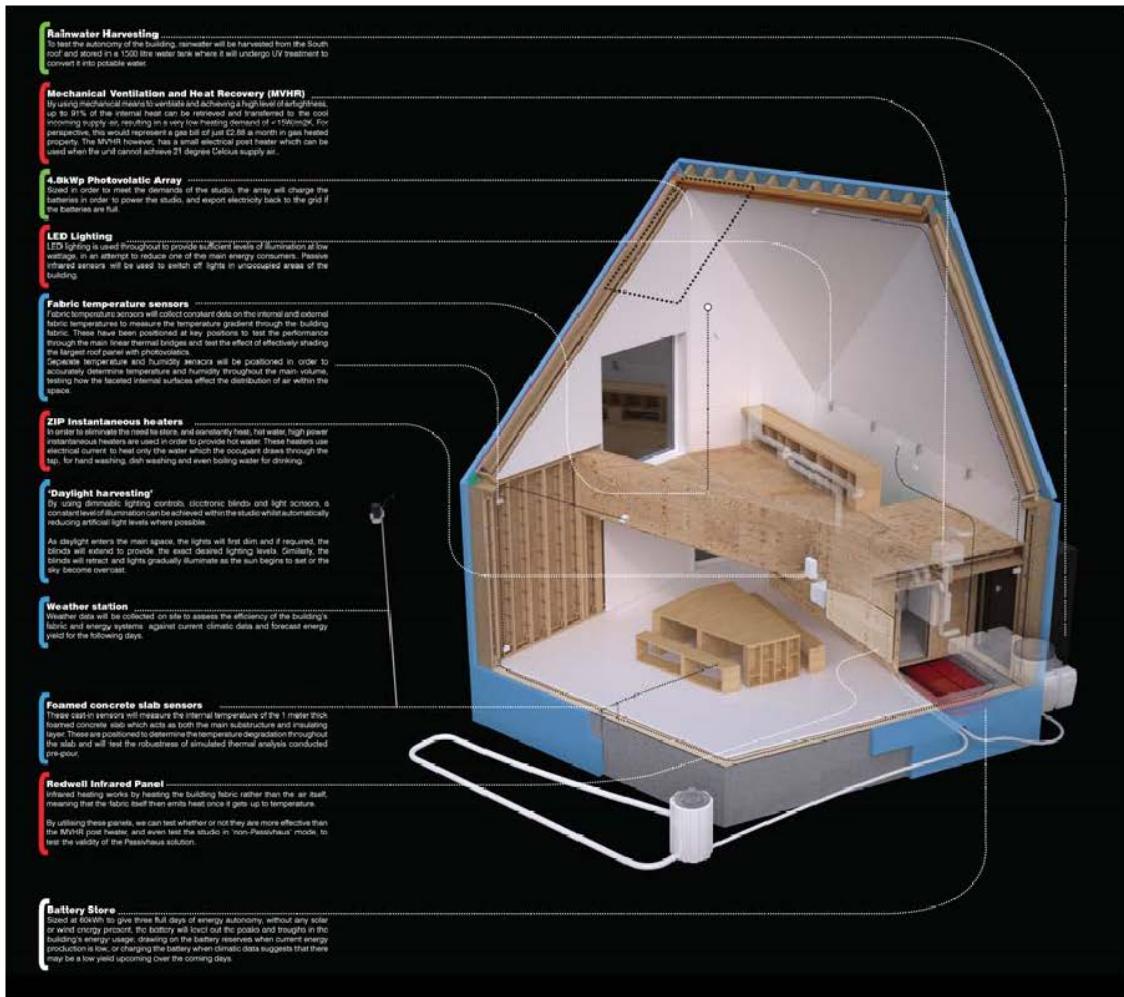


Figure 25: Passivhaus construction U Values.



Data Providers Consumers

Building management and control system
The DMGS will be integral to evaluating the performance of the building, both from an energy perspective and from a user behaviour perspective. By being able to monitor and control the flow and distribution of energy between the renewables, batteries, consumption and export to grid, we will be able to extrapolate a huge amount of data to determine the performance of the building and the influence of user behaviour.

The consumption of each socket will be measured to see which appliances are contributing the most towards energy consumption and allow the identification of possible areas that further energy savings can be made.

Much of this data will be relayed back to the occupants via a touch-screen, making the occupants aware of their consumption and their energy reserves, whilst detailed raw data will be uploaded online for further analysis and public display.

In the future a joint collaboration will be formed with UoD Computing Department in order to further extrapolate information on the user behaviour of the occupants, testing how a building with short term finite energy stores influences behaviour.

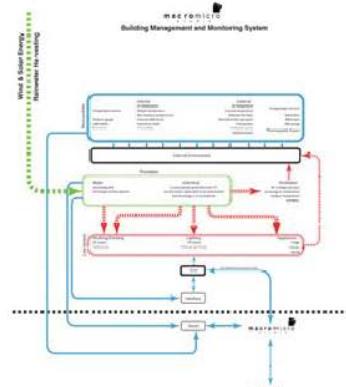
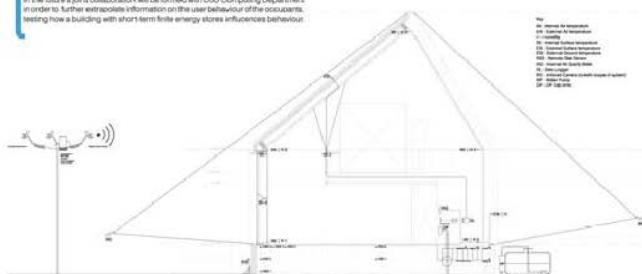


Figure 26: Integrated technical systems, building monitoring and intelligent building controls.

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Andy Leitch, Timber Development Policy Advisor, Forestry Commission Scotland
Jake Findlay and Jim Robison, Building Control, Dundee City Council
Trudy Cunningham, Sustainability Officer, Estates and Buildings University of Dundee

Manufacturers and Suppliers Contributing to Research:

NorDan Windows, Cullen Building Products (ITW Industries), Paul Heat Recovery Ventilation, Marley Plumbing and Drainage Solutions, CETCO, Glidevale, ProPump Engineering Ltd., Burton Roofing Merchants, iGuzzuni Lighting Consultancy, Pavatex, R.B.Grant, Electrical Contractors, Sir Robert McAlpine Balmoral Rainwater Harvesting, Zip Systems, Renewable Resources Ltd., Speedy Tool Hire Services, Axeon Batteries, Alutec Guttering, Adamson Doors, Soluis Scotland, Proven Wind Turbines.

Appendix 1
Design and Technical Drawings
(Refer to attached file)