LCRI 2015 Overview of LCRI Research 2008 to 2015

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LCRI 2015

Overview of LCRI Research
2008 to 2015

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Professor Alan Guwy South Wales University	Hydrogen
Dr Ian Masters Swansea University	Marine
Professor Phil Bowen Cardiff University	Large Scale Power Generation

Industry Partners

LCRI has worked with a number of industry and government partners, including:

1st Attraction, Alexander Bullock, AP Electrical, Arup, Atkins, BASF, BIPV Co, Bluefield Caernafon Ltd/ Twenty20Homes Ltd, BP, Building Research Establishment, Butler and Young, Cable and Wireless, Cardiff County Council, Cenin Ltd, Central Roofing SW, CGL Services, Charter Housing, Clive Edwards Ltd, CH2M HIL, Coed Cymru, Conwy C.C, Core Citis, D.B. Francis DEFRA, Ecolek, Edward Perkins, Environment Agency Wales, Envirovent, EON, ETI, European Aviation Safety Agency, GB-Sol GE (USA), GEM, Glyn Sebburn, Gwynedd Council, Hafren Power, Halcrow, IBM, ITM Power, J.J. Williams, Joyner PA Cymru Ltd, Links Electrical, Manchester City Council, Marine Current Turbines (Siemens), MSK Controls, Neath Port Talbot Council, Neath Port Talbot Homes, NSG Pilkingtons, NT Leyshon, Orielton Mill, Panasonic, Pontrilas Timber, Rhondda Housing Association, RICS, Rockwool, Rolls Royce, Roman Projects, RSPB, Scottish and Southern Energy, Sharp, SIPS Wales, SMA, Sony UK Tec, SPECIFIC, SQE Ltd, SSE, Tata, Tidal Energy Limited, Toshiba, Total Home Environment, Towy Projects, United Welsh Housing, Vellacine, Vintage Joinery G Adams, Wales and the West Housing, Wall Lag, Warm Wales Ltd, Welsh Government, Western Power Distribution, X-Fab, ZETEXREFGAS.

PREFACE

The Low Carbon Research Institute (LCRI) was set up in 2008 to unite and promote energy research in Wales to help deliver a low carbon future. Working with industry and government, the LCRI's research agenda included low to zero carbon energy supply systems, reduced energy demand, knowledge and skills transfer, and dissemination and industry partnerships. Since 2008 many successful projects highlighted in this report, have been realised. The scale of which is impressive and can serve as an excellent example of outcomes of value made possible through research funding.

The original support and funding by HEFCW and subsequently by ERDF has resulted in a body of work and an advancement towards new technologies and new thinking needed to meet and exceed national and international goals. The creation of jobs, laboratory facilities and investment in Welsh industry are additional outcomes of value to the Welsh economy.

The next stage in the LCRI journey promises to be as exciting as the previous seven years; with plans to expand the network and continue a substantial contribution to a low carbon future. Collaborative projects and the knowledge and experience gained to date will contribute to each of the Welsh Government's seven Well-being Goals.

The LCRI has an important role to play in a country focussed on sustainable development with ambitious climate change targets. As Chair of the Climate Change Commission for Wales and in my role as Commissioner for Sustainable Futures I am pleased to see the great work delivered by LCRI to date. I look forward to the next stage of LCRI and know it will play a key role in delivering outcomes defined in the Well-being of Future Generations Act and the Environmental Bill in order to make Wales a better place for our future generations.

Peter Davies
Commissioner for Sustainable Futures and Chair of the Climate Change Commission for Wales

EXECUTIVE SUMMARY

The LCRI has built research capacity in Wales, linking academic research with industry and government relating to the low carbon agenda. Many projects have been near market, working with industry partners on emerging low carbon technologies. Each have a key role to play in supporting recent legislation in Wales and contributing to a more sustainable future.

The Low Carbon Built Environment (LCBE) programme based at the Welsh School of Architecture, Cardiff University, has carried out research at a range of scales, from components, to buildings, to urban, and finally to the Wales region. New products developed at component level have been integrated into the design of new buildings as well as the retrofit of existing buildings. The Sustainable Building Envelope Centre (SBEC) at Tata Shotton and the SOLCER energy positive house are two buildings that were designed within the LCBE programme. They demonstrate new technologies for generating energy from fully integrated renewable energy systems that also form a construction component of the building envelope. Energy retrofits have been investigated for housing, factories, retail and schools. Buildings in-use have been monitored and design guidance produced. Computer simulation models developed at building scale have been extended to urban scale, for new build and retrofit applications. The implementation of new technologies and processes has been examined at regional scale, in relation to industry innovation and government policy and regulations. Research on transitions to a low carbon future has included projects in the UK, Europe and China. International collaboration activities have taken place, including, the European Smart Energy Regions COST network, and research links with China. The built environment is key to achieving a low carbon future. The challenges now are to further develop and demonstrate new low carbon technologies and processes that can be integrated into building design in an affordable and replicable way, to measure their performance in use, to develop simulation tools to assist research and design activities at building and city-region scale, and to work with industry and government to understand the barriers and opportunities in relation to the wide-scale implementation in practice of sustainability and low carbon policy.

The Solar Photovoltaic Academic Research Consortium (SPARC) has formed a strategic link between the solar energy research in the partner universities of Glyndwr, Bangor and Swansea. This has established Wales as an innovation centre for new PV solar energy products and, together with LCBE activities at SBEC, has contributed to the establishment of the SPECIFIC centre in Swansea where manufacturing processes are being developed based on the materials research carried out on SPARC. Wales has a strong tradition of PV supply chain companies from power electronics through to module manufacture and the SPARC team have been effective in working with these industries to help to develop new products that will fuel the rapidly growing solar PV industry. SPARC has built the world's first in-line atmospheric pressure deposition system for thin film PV manufacture based at its dedicated centre for solar energy research (CSER) in the OpTIC Centre at St Asaph. It has new rapid processing techniques for dye sensitised solar cells (DSC) compatible with high volume manufacturing. It has researched new power electronics designs for efficient extraction of the electrical power from PV solar energy modules, leading to a new ultra-light-weight thin film PV technology for space in collaboration with Welsh industry

The LCRI Hydrogen theme investigates the development and deployment of hydrogen and fuel cell technologies as a low or zero carbon solution for both energy and transport systems. Led by the University of South Wales, much of the research and development activity is world-leading and covers many aspects of hydrogen and fuel cell technology. Research includes hydrogen production techniques, novel hydrogen storage material development, infrastructure and distribution development, and a range of application technologies including fuel cell materials research and development of both fuel cell and combustion technologies for energy conversion. The hydrogen theme also incorporates techno-economic and environmental assessment of hydrogen and fuel cell technologies. As the relevance of hydrogen and fuel cells is being understood, worldwide interest in hydrogen and fuel cell technology has dramatically increased in recent years. Industrial deployment of hydrogen and fuel cell technology for energy and transport is now a reality and future challenges centre around technological and economic improvement. There remain a number of critical R&D issues to be addressed, including, the development of hydrogen solutions for grid-scale energy storage to allow for increased penetration of renewable electricity, utilisation of existing grid assets to enable hydrogen based energy storage (power-to-gas), investigation of novel hydrogen storage and fuel cell materials and techniques including the engineering to incorporate these at commercial scale, development of improved hydrogen fuel cell electric vehicle and hydrogen combustion based propulsion systems, optimisation of the deployment of hydrogen refuelling infrastructure, continued improvement of fermentative and bioelectrochemical hydrogen and methane production processes, development of industrial hydrogen separation and recovery techniques including upgrading via reforming and other methods. With active academic and industrial partners and the engagement of government, Wales is ideally placed to be a leading European region deploying hydrogen and fuel cell technologies and deriving economic and environmental benefit in the process.

Cardiff University's Gas Turbine Research Centre (GTRC) at Margam is carrying out research on a wide variety of projects including fuel variability, operational flexibility and risk and hazard assessment. LCRI capital funding has been used to set up a world leading experimental simulation facility through the addition of a flexible 5-component gas mixing station to its high-pressure/ temperature facilities'. This new mixing station can accurately mix different gas fuel compositions, including varying concentrations of hydrogen, and is investigating hydrogen-rich syngas from high-efficiency gasification processes with or without carbon capture. In the short term, increasing amounts of imported natural gas and LNG from around the world are having a significant affect on the natural gas composition being utilised by power generators. As a result modern gas turbines can experience operational instability issues which adversely affect reliability and emissions. Further research is required to understand this phenomena to assist UK and EU natural gas regulators in standardising gas composition and quality. The research is also important to the gas turbine Original Equipment Manufacturers and end users to optimise the reliability of current and future gas turbines. In the medium term, consideration must be given to increasing levels of Hydrogen created from renewable sources being injected into the natural gas grid and being utilised by power generators. Hydrogen has been shown to increase burning rate and flame temperatures which could adversely affect gas turbine operation. Due to the reliance on natural gas for power generation in the UK, the integration of carbon capture and storage alongside gas turbine power stations is required. The GTRCs input in this area will be with oxygen enriched combustion and exhaust gas recirculation which are both techniques for enriching the CO_2 stream in the exhaust to enhance capture efficiency. With the research infrastructure now in place at the GTRC it is well positioned to be a significant contributor in these research fields.

LCRI Marine led by Swansea University provides independent and world-class research to enable, support and help build a sustainable marine energy sector in Wales. It develops engineering tools, which optimise the design and performance of technology that recovers energy from waves, tidal streams and tidal ranges around the Welsh coast. In addition, it considers the likely effects that these devices have on the environment, such as their effect on seabed communities, sediment transport and marine wildlife. The future of the Marine Renewable Energy sector in Wales is very positive. Technology development continues, devices are ready to deploy, and commercial projects planned. Two 100MW demonstration zones have been created (one wave, one tidal) which are managed by community companies; Strategic investment planned by WEFO into the infrastructure of these sites will make Wales a world class destination for the sector. The universities are fully engaged with the companies deploying on the demonstration sites, providing a pipeline of the highest quality research and development to continue the growth of the sector into a mature industry. The key issues for future R&D are: uncertainty of energy resource, particularly where waves and currents interact; extreme storm loadings; fatigue and life prediction; optimum positioning of arrays and devices within them; cost reduction intelligent design; standardisation and supply chain diversification. An integrated partnership of universities, developers and supply chain is working to make this a reality.

LCRI now aims to build on its success and continue to provide Wales with a research network that can work with industry and government to help deliver and implement low carbon policy in Wales, and help promote low carbon research on the international stage.

SECTION 1: Introduction to the Low Carbon Research Institute (LCRI)

Professor Phil Jones – LCRI CHAIR

The LCRI unites the diverse range of low carbon energy research across Welsh universities at Cardiff, Glyndwr, Bangor, South Wales and Swansea, covering research topics relating to the built environment, solar PV, hydrogen, large-scale power generation and marine. Although individual universities took the lead for these topics, many projects involved collaboration across the partners.

Working with industry and government, the LCRI's research agenda included, low to zero carbon energy supply systems, reduced energy demand, knowledge and skills transfer, and dissemination and industry partnerships. LCRI has links to other related research initiatives in Wales, including SPECIFIC, IBERS and the Anglesey Energy Island. It has also collaborated on specific projects with research partners across the UK, including UKERC, Imperial College, Cambridge University and Manchester University.

The LCRI was set up in 2008 with an initial investment of £5.2 million by HEFCW under its reconfiguration programme to stimulate universities in Wales to work together and pool their strengths. In December 2009 LCRI secured European ERDF structural funding of £19.2 million to provide a research base for the Welsh energy and low carbon industry sector. The combination of HEFCW and ERDF funding has successfully established a low carbon research capacity in Wales, helping to secure a total programme of £80.2 million, including £20.4 million from UK research councils, another £20.2 million from EU framework and other sources, with a further £15.1 million support from industry and the partner universities (figure 1.1). Over 180 researchers based in Wales have been associated with the LCRI on a range of research programmes in high priority research areas identified by the Welsh Government, including, renewable and clean energy supply, energy efficiency and smart living. Wherever possible this research has been used to promote Welsh industry and attract industry to Wales, many projects involving near market collaboration with industry partners.

A major source of funding to the LCRI partners was the ERDF programme, funded through the Wales European Funding Office (WEFO). It initially focused research towards specialist topics of built environment, solar PV, hydrogen, large-scale power generation and marine. A second phase of research aimed to bring together these topics through a 'systems' approach, combining reduced energy demand, renewable energy supply and energy storage. This second phase programme, named SOLCER (Sustainable Operation of Low Carbon Energy Regions), led to a series of demonstration projects, from building to regional scale. Also included in the WEFO programme was the ESF work package, Wales Energy Sector Training (WEST), which set up a series of master's level training modules.

The LCRI has provided funding to support a range of laboratory facilities throughout Wales (figure 1.2), including:

- SBEC – The Sustainable Building Envelop Centre in Shotton was opening by the 1st Minister in March 2011, with funding of £0.5million from WG and £1.5 million from Tata. It has been developing new energy generating technologies integrated into steel based building envelopes.
- GTRC – The Gas Turbine Research Centre at Margam carries out research on the fuel variability for gas turbines. Additional funding through LCRI has enabled them to attract major projects from industry and EPSRC, including leading the combustion programme of the £6 million EPSRC Centre for Conventional Power Generation.
- SPARC – The Centre for Solar Energy Research (CSER) at OpTIC, St Asaphs carries out work on solar

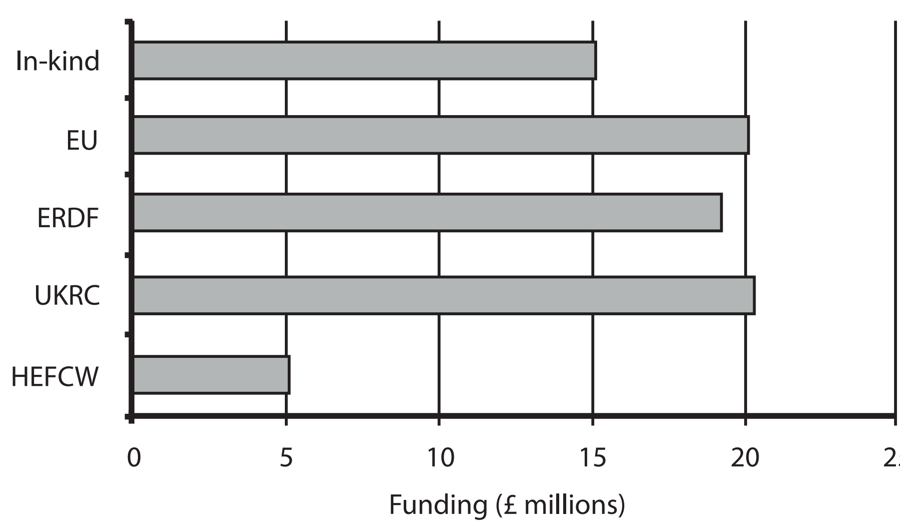


Figure 1.1 Summary of LCRI funding (2008 – 2015).

Figure 1.2 Location of LCRI research facilities.

PV technologies. The LCRI in-line facility at OpTIC has led to EPSRC and industry funded projects.

- Hydrogen Centre – The Hydrogen Research Centre at Baglan provides a platform for electrolytic hydrogen and fuel cell R&D. Funding through the LCRI has been used to enhance the facilities which has led to the designation of South Wales as the "Low Carbon Economic Area for Hydrogen" by BIS and the Welsh Government.

These world-class facilities have enabled the LCRI partners to attract funding from industry, UKRC and Europe to help provide a sustainable future for LCRI partners.

The LCRI is an example of how government funding can be used to build research capacity and create jobs in Wales. LCRI Director Professor Peter Pearson reported that, *'its current level of research funding is almost 15 times its initial HEFCW 4th year target of £5.5M and 12 times the 5th year target of £7M, with high levels of funding from UK Research Councils, European framework and industry.* LCRI is competing effectively with, and partnering with, the best UK research universities, and developing a strong international profile. LCRI Chair Professor Phil Jones states that, *'LCRI's unique role in uniting low carbon energy research interests across academia, industry and government, is providing a solid research base for existing Welsh industries, including anchor companies like Tata, and SME's, and provides a attraction for industries coming into Wales'.* On a visit to Wales in 2010, the European Commission President, J M Barroso, said the LCRI was one of *'the best examples in Europe of Research, Innovation and Sustainable Development'.*

This report contains and an overview of the breadth of research and the main outcomes delivered by the LCRI programme between 2008 and 2015. It demonstrates the benefits of academic research groups working closely with industry and government to establish Wales as an important player in the emerging low carbon economy.

SECTION 2:
Low Carbon Built Environment (LCBE)

Introduction

The construction and operation of the built environment uses huge amounts of energy and is responsible for around 40 to 50% of global carbon dioxide emissions. There are many projects throughout the world, from individual building scale to mega constructions, which do not embrace the concept of low carbon design. The UK government has set an ambitious target of 80% reduction of carbon emissions by the year 2050. As part of this target, it is predicted that the emissions related to buildings in 2050 will need to be close to zero. While the design of new zero carbon buildings has been researched, the potential for zero emission retrofit is less understood. It is estimated that 80% of buildings that will exist in 2050 have already been built, and the interactions of carbon emission reduction methods, such as fabric improvements, occupant behaviour and renewable technologies in the urban retrofit design process need to be researched further. Energy efficiency is a major feature of the low carbon economy, especially the efficient use of energy in the built environment. Reducing energy demand in buildings requires an integrated and holistic approach to all aspects affecting energy performance, whilst ensuring comfortable healthy conditions for occupants, and within the context of the local climate. Achieving a low or zero carbon building requires a combination of reducing energy demand and providing energy supply from renewable sources. Building and community integrated renewable energy systems can localize energy supply, taking pressure off central supply grids. Energy storage can be used to bridge the gap between available renewable energy supply and when demand occurs. A future built environment could therefore involve a high percentage of distributive energy, with an appropriate mix of local and central energy supply.

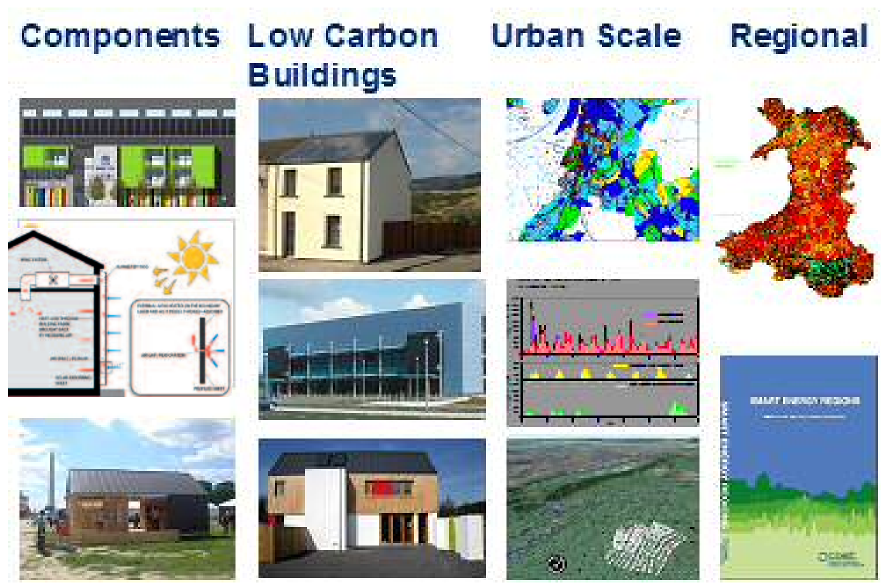


Figure 2.1 Summary of LCBE range of research activities at different scales.

Overview

The Welsh School of Architecture at Cardiff leads LCRI's work on low carbon buildings. The LCBE research programme operates at a range of scales, from components, to buildings, to urban, and finally to the Wales region. Figure 2.1 illustrates the range of activities carried out within the LCBE programme at different scales. New products developed at component level have been integrated into the design of new buildings and the retrofit of existing buildings, including work packages on steel technologies (with Tata), timber based products (with BRE) and low energy lighting (with Swansea University). The Sustainable Building Envelope Centre (SBEC) at Tata Shotton was designed within the LCBE programme (see figure 2.22). Its design demonstrates new technologies for generating energy from fully integrated renewable energy systems that also form a construction component of the building façade. Work carried out on the design and construction of new buildings and retrofitting existing buildings include monitoring buildings in use. Computer simulation models developed at building scale have been extended to urban scale, for new build and retrofit applications. The implementation of new technologies and processes has been examined at regional scale, in relation to industry innovation and government policy and regulations. There has also been research on transitions to a low carbon future. International collaboration activities have taken place, for example, through the European Smart Energy Regions COST network, and research links with China.

Projects

Innovative Building Components

Studies on solar air collectors and solar PV have been carried out in collaboration with Tata Steel, with contributions from NSG Pilkingtons. The work included PV panel development for power generation, and air collectors for generating thermal energy. Both developments have focused on building integrated applications. Examples of the work are summarized below.

PV SOLBOND

This product uses traditional crystalline silicon PV panels that are bonded to metal cladding systems (figure 2.2), therefore reducing the overall weight of the system compared to a standard PV panel system. The bonded system carries Tata warranty and has been taken from concept stage to a marketed product within the LCRI programme.

Figure 2.2 The SOLBOND system PV panels bonded to a standing seam metal cladding roof system.

BIPV encapsulated thin film system

Initial studies within the SBEC programme indicated that dye-sensitised solar panels developed at Tata would not be market ready for some years, so attention was transferred to thin film BIPV (Building Integrated Photo-Voltaic) using Generation 2 CIGS Technology (refer to Section 3 for background on solar PV). Thin film PV cells are encapsulated and bonded to a metal cladding system (figure 2.3). This can either be incorporated into new build, or bonded to an existing metal cladding as a retrofit measure. SBEC and SPECIFIC have spun out a new company named BIPV that is attracting around £3 million private sector investment. This aims to produce 130 jobs within a 4-year period.

Figure 2.3 Thin film PV cells are encapsulated and bonded to a metal cladding system.

Transpired Solar Collector (TSC)

A Transpired Solar Collector (TSC) pre-heats the ambient outdoor air, which is then used in a building for space heating. A TSC wall or roof system consists of a perforated solar absorbing outer metal cladding sheet, ducting and a fan (figure 2.4). The cladding sheet has a high solar absorption external coating, often, but not necessarily of a dark colour, which encloses an air gap. A fan is connected to the TSC air gap at high level, and ductwork connects to the buildings heating and ventilation system. The TSC works by drawing outside air across the relatively warm external surface boundary layer of air, through perforations in the external metal sheet, into the air gap where it can be additionally heated by the internal surface of the perforated sheet. It can be integrated into the building envelope through wall or roof mounting. TSC's can collect up to 65% of the energy falling on their surface, which equates to approximately 650 W/m^2 (capacity) of the collector's surface area. On an annual basis, the yield of the collector is typically 250kWh/m^2. The orientation of a TSC is ideally south facing although orientation between east and west is possible but with lower solar gain. Up to half of the space heating demand of a building could potentially be met with a suitably sized TSC system. This technology therefore has the potential to make a significant impact on renewable energy generation. It is potentially a low cost technology with a typical payback of around two years for large installations.

Sustainable Building Envelope Demonstration (SBED) Building

The Sustainable Building Envelope Demonstration (SBED) project involved monitoring transpired solar collectors (TSC) in six 'buildings in use' in Convergence Areas of Wales. SBED monitored the construction, implementation and real-life performance of the demonstration systems, disseminating best practice to the wider industry. Information gathered during the project enables the economic viability and cost

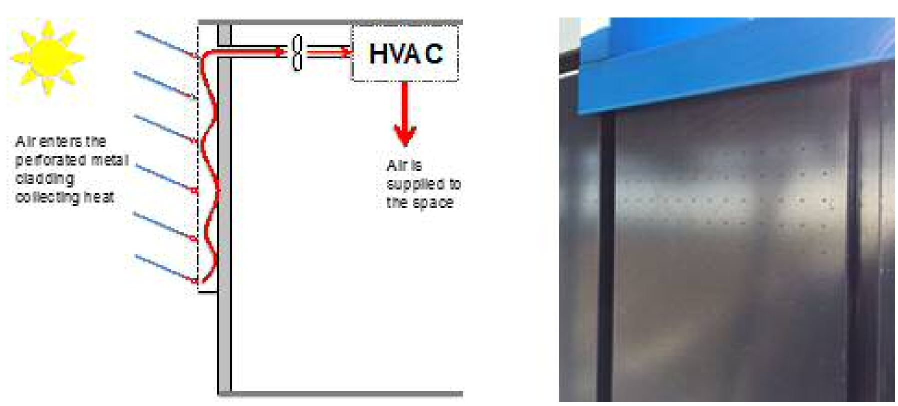


Figure 2.4 (left) Schematic of TSC wall; (right) Close-up of TSC perforations..

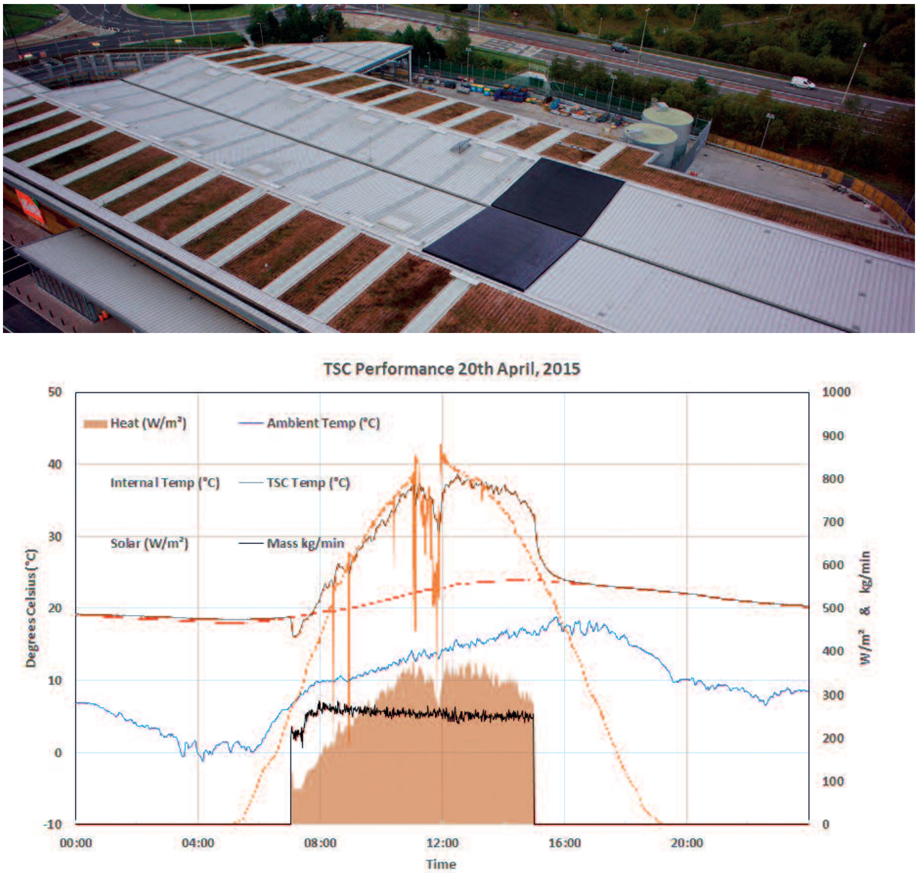


Figure 2.5 Installation of TSC on the B&Q store in Merthyr Tydfil with example result indicating the contribution of the TSC to space heating for a typical day.

Figure 2.6 Initial Glazed-in collector test rigs at Pilkingtons laboratory.

effectiveness of the technologies to be assessed for the different building types. The range of building types, includes residential, commercial, industrial and institutional. An example is presented in figure 2.5 for the B&Q retail store in Merthyr Tydfil, together with example results. Initial monitoring results from February to April 2015 indicated a contribution of 15 MWh space heating, saving, 3 tonnes CO_2, with a peak system efficiency of 55%.

Solar Air Storage and Heating (SASH) Project

Following on from the TSC work introduced above, the SASH project investigated the performance of two more solar thermal air collector systems. The work involved collaboration with Tata and NSG Pilkingtons. Tests were carried out on a range of configurations of glazed-in collectors, initially at small scale (figure 2.6), and then at larger

Figure 2.7 Three selected collector units tested at SBEC.

scale (figure 2.7). Results indicated that relatively high air temperature rises (50 to 60°C) and operating efficiencies (60 to 75%) could be achieved. The best performance was achieved for a glazed-in TSC collector, due to the high transmission properties of the glass and the internal heat exchange between the TSC surfaces and the supply air. An option would be to use the system linked to a heat pump and thermal storage, which could provide diurnal to seasonal storage options. An investigation was also carried out on a standard TSC collector coupled to thermal storage. This included developing a TSC software sub-model that could link to the commercial building energy model, IES. Initial evaluations of TSC technology combined with diurnal thermal storage have indicated payback periods of less than 10 years. Further developments with SPECIFIC are investigating inter-seasonal energy storage using chemical storage technology. It is expected that a house designed to Passivehaus standards (similar to the SOLCER House described later in this section) would typically require inter-seasonal thermal storage of only 750kWh, which would equate to an inter-seasonal storage system with a volume of around $2m^2$.

Figure 2.9 Input and output panels from the BAPS tool.

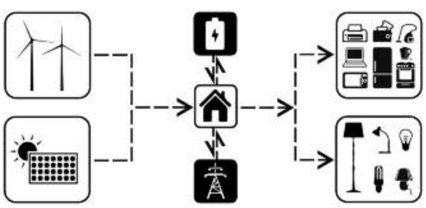


Figure 2.8 Input and output panels from the BAPS tool.

Buildings as Power Stations

The concept of 'Buildings as Power Stations' (BAPS) represents a major shift in the way that energy is generated, stored and released in a building. As indicated in the previous sections, buildings can become an energy generator. Some buildings are already being designed to function like small-scale power stations, with photovoltaic systems integrated in their roofs and excess generation capacity feeding in to the electricity grid.

A collaborative research project with SPECIFIC developed a BAPS tool for simulating any domestic-scale energy system, combining energy generation, storage and use (figure 2.8). Data on the house design, renewable energy system and energy storage can be input to the BAPS tool and performance output provided immediately (figure 2.9). The extent to which such systems act to reduce of grid peak demand or provide near autonomous energy supply with grid back-up, will be determined by the size of renewable energy system and the storage capacity, in the context of the building's reduced energy demand.

Low Energy Lighting

The "Electronics enabling the Low Carbon Economy" Innovation Network that was launched at Swansea University in September 2009, has hosted events such as "Illuminating the Power Electronics Roadmap – A vision for Low Carbon Lighting in 2020" in June 2011. This vision examined how new efficient lighting systems and their associated power electronics could be a key enabler in reducing future carbon dioxide emissions. Further work on LED lighting and efficient appliances, led by Professor Ken Board, has resulted in a network of spin-out SME's developing low energy appliances and lighting technologies, aimed to reduce electricity demand in buildings.

Figure 2.10 Margam Discovery Centre demonstrating innovative, sustainable construction.

The Use of Welsh Timber in Construction

Research on the use of Welsh timber has been carried out in collaboration with the Building Research Establishment (BRE), the Welsh School of Architecture's Design Research Unit, and Coed Cymru, to investigate the potential for greater use of Welsh timber in building construction. Timber is viewed as a carbon neutral material, but concern over the quality of Welsh timber is such that it has not been used extensively in the construction industry. Research has included a critical evaluation of the strength, durability, energy and environmental performance, and life-cycle costs for timber grown in Wales. This research has focused on increasing the use of Welsh timber by developing design strategies for components and buildings that exploit the properties of Welsh timber, and minimise its shortcomings. It has incorporated the use of home grown softwoods in innovative panels and other structural systems. The research has pioneered the successful introduction of Welsh home grown softwoods into mainstream timber frame housing in the UK, and has shown that home grown softwoods can be used in sophisticated, contemporary structures; as well as in everyday, mainstream open panel manufacture. The timber constructed Margam Discovery Centre (figure 2.10), designed by DRUw, received an RIBA design award in 2012.

The forest sector in Wales contributes some £429 million to the Welsh economy per year. Across all businesses within the Welsh timber sector, the industry currently generates a revenue stream of over £1.7 billion per year, rising to more than £4 billion with the inclusion of the construction industry. With government commitment to new regulatory standards requiring all new homes to be zero carbon by 2019 there is a potential to expand the market for low-cost and low-energy timber framing system, and the Welsh timber sector is

Figure 2.11 Prototype Brettstapel wall panel.

Figure 2.12 Finger jointed timber for long-length cladding.

Figure 2.13 Glulam beams in the Sumika Pavilion.

Figure 2.14 Lightweight I-Joists installed in place of traditional solid timber joists.

Figure 2.15 Ladder Trusses used in the Larch House Ebbw Vale.

Figure 2.16 CLT construction of the MK40 tower.

well placed to take advantage of that emerging market, adding considerable value to the industry, as shown through the following LCBE programme of work.

Welsh Brettstapel Panel System

Collaboration with Welsh SMEs, using home grown timber in mainstream open panel manufacture, has led to the development of a Welsh Brettstapel Panel System, resulting in the delivery of Britain's first Brettstapel building using home grown softwoods (figure 2.11). Brettstapel is a solid timber construction system fabricated from low-quality small-dimension softwood timber posts that may not otherwise be suitable for construction. Connected with hardwood timber dowels, Brettstapel uses neither glue nor nails, producing a better-quality internal environment from an air quality point of view.

Primary Processing: Finger Jointing / Cladding Systems

At its most basic, value added production occurs at the primary processing stage, where round-wood becomes sawn timber. With a little extra investment in timber grading and finger jointing machinery it is possible to produce higher value products, such as stable, long-length cladding systems (figure 2.12).

Structural Systems: Laminated Timber Beams / Glulam / Endless Beams

The primary benefits of glue-laminated timber beams are their strength, dimensional stability, and large section sizes and long lengths (figure 2.13). Comprised of layers of small section dimensioned timber, bonded together with adhesive under heat and pressure, glue-laminated (glulam) beams are relatively straightforward to produce. Manufactured with either horizontal or vertical laminates, the individual timbers are typically finger joined at each end to give continuity to the laminations, enabling the production of 'endless beams', with few limitations on size. The automation of the manufacturing process has the potential to significantly increase efficiency and production speed, resulting in a price competitive product.

Structural Systems: I-Joists

Compared to solid timber sections, I-Joists (figure 2.14) use significantly less quantities of material, and have a high strength to weight ratios for equivalently dimensioned sections. Typically comprised of solid timber flanges with oriented strand board (OSB) webs, they are both lightweight and materially efficient. Given the extensive production of oriented strand board in the UK, the potential for the development and expansion of domestic I-Joist manufacturing is significant.

Structural Systems: Ladder Truss

Ladder trusses are a type of parallel chord truss utilising stress-graded timber chords, pleated together, either with timber, or with a metal web (figure 2.15). As with I-Joists, ladder trusses provide a lightweight, dimensionally stable alternative to solid timber, particularly where the dimensions required would either be unavailable, or cost-prohibitive in solid timber form. The open nature of the ladder truss also provides a benefit over the I-Joist of being able to run services directly through the structure. The utilisation of low-grade timber in a high-strength product, along with a relatively simple manufacture process, has the potential for the significant development and manufacture of ladder trusses within the Welsh timber industry.

Solid Core Systems: CLT Panels

Cross-Laminated Timber (CLT) is a solid-core construction system that enables rapid construction times due to large panel sizes and limited numbers of joints. The panels consist of single layer boards, each board made up of individual planks finger jointed for strength, with layers of boards cross-laminated with adhesives for bonding (figure 2.16). The cross-lamination and gluing ensures minimal shrinkage and settlement over time, with the higher thermal mass of solid core construction produces greater thermal stability when compared to standard timber-framing systems.

PassivHaus Products

Produced entirely from wood-fibre, and bonded from the natural adhesiveness of the lingin resin within the wood itself, wood-fibre insulation is an entirely natural material, and can be produced from the waste material of other timber processing (figure 2.17). The potential for the development of wood-fibre insulation manufacturing as part of a zero-wood-wastage strategy is significant, but inevitably dependent on quantities of production, and quality of supply of waste-wood as a raw material.

High-value products such as window frames (figure 2.18) that make use of small-section timbers could prove

Figure 2.17 Woodfibre insulation.

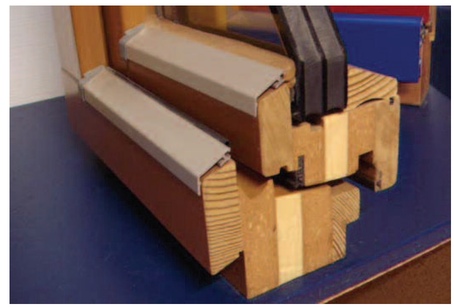


Figure 2.18 PassivHaus certified windows.

Figure 2.19 Ty Unnos Prototype at Wales in Washington.

Figure 2.20 Ty Unnos Ebbw Vale Classroom.

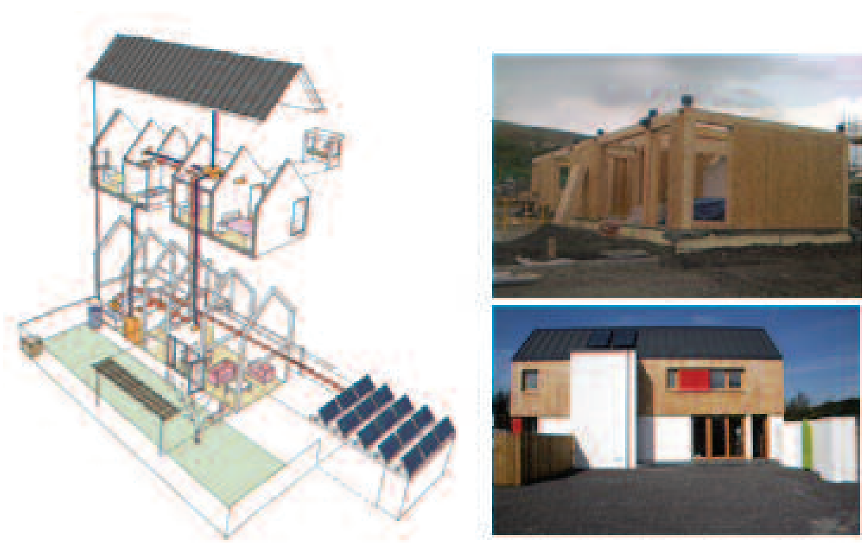


Figure 2.21 Low Energy House Ebbw Vale. Designed by DRUw.

particularly valuable to the Welsh timber and manufacturing industries. The development of the UK's first PassivHaus certified windows by the Vale Passive Window Partnership proved the potential for the manufacture of high-quality, high-tolerance timber products.

Ty Unnos System

Ty Unnos is a new concept for timber construction, allowing for affordable, sustainable construction from local resources. It is an innovative timber post and beam system developed by the Welsh School of Architecture, Wood knowledge Wales, Coed Cymru and partners, using Welsh grown Sitka spruce to create a high quality, sustainable build system. The structural system makes use of low-grade Sitka spruce, along with simple manufacturing processes such as those used for pallet fabrication. The box beam was originally envisaged as part of a complete package that could provide both the structural frame and a system of infill panels. Examples of its use include, the Ty Unnos prototype (figure 2.19), the education centre at The Works, Ebbw Vale (figure 2.20) and the Ebbw Vale house (figure 2.21).

The low energy Ebbw Vale house designed by DRUw featured Welsh sycamore flooring, super-insulated walls, roof and floors and triple glazed Welsh timber windows developed by Vintage Windows. These projects have been already proven successful, and generated serious interest in the building trade. The Ty Unnos concept is not only limited to housing, its flexible design makes it suitable for a range of applications.

Low Carbon Buildings

The LCBE research programme has included the design and construction of new buildings and the retrofit of existing buildings, using many of the component technologies developed above, leading to a systems approach, to achieve low carbon and even positive energy performance, at an affordable cost and replicability.

Figure 2.22 SBEC building with its TSC thermal air collectors forming the façade..

Figure 2.23 SOLCER house with PV roof and battery storage, constructed from SIPS panels.

Sustainable Building Envelop Centre (SBEC)

Figure 2.22 presents the Sustainable Building Energy Centre (SBEC), which is part of the LCRI research facilities. The building has been inserted into the existing shell of the existing industrial building at the Tata Shotton site. The building is the base for research into energy generating building envelopes, integrating solar air collectors and solar PV into the walls and roof of the building. The TSC façade elements generate thermal energy for the building.

SOLCER House

The 'SOLCER' house (figure 2.23), designed and constructed by the WSA, is located at the Cenin site in Stormydown. It has a PassiveHaus level of energy demand and has been designed to meet social housing standards. It uses a SIPS timber panel construction, manufactured off-site, and has an integrated heating and ventilation system.

The systems approach integrates reduced energy demand, renewable energy supply and energy storage (figure 2.24). In winter space heating is provided by passing external air through the 1st floor TSC air collector, then through a mechanical ventilation heat recovery (MVHR) unit, which is then delivered to the space. Exhaust air is passed through the MVHR and then through an exhaust air heat pump, which heats the thermal water store. The thermal store heats domestic hot water (DHW).

An integrated solar PV roof provides electricity to the battery store, which powers the heat pump, LED lighting and other internal electricity loads. There is grid electricity back-up.

The house was constructed in 16 weeks and will be monitored to measure its performance. The predicted performance is 70% autonomous in energy use with a 1.75 grid 'export to input' energy ratio. Its estimated cost for replication is around £1,200 per m^2.

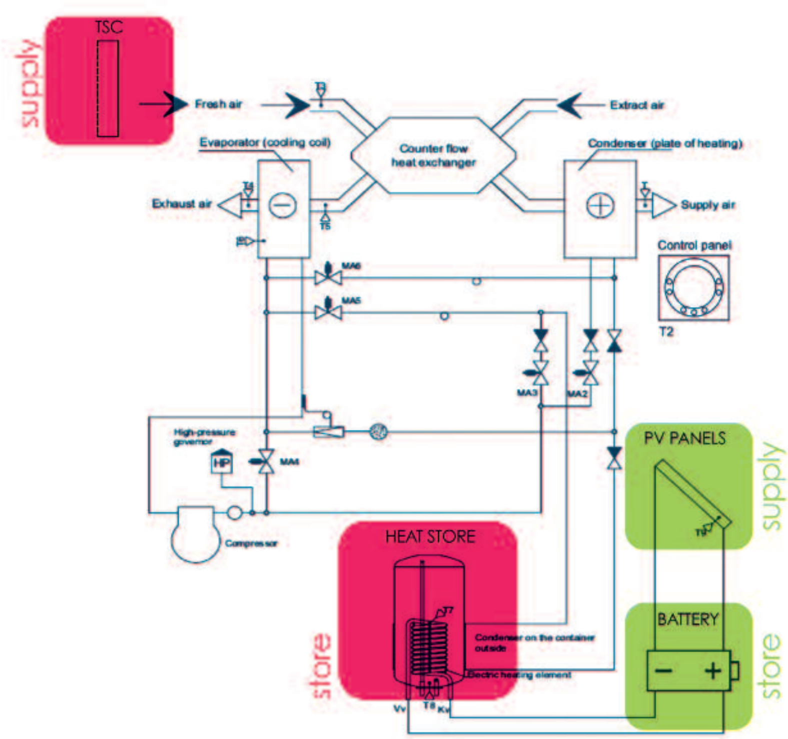


Figure 2.24 The SOLCER house integrates the architecture and the energy systems.

Housing Retrofit

Housing energy retrofit is a main target for reducing CO_2 emissions. Most retrofit programmes are of an elemental nature, installing one or a few measures, such as external wall insulation, new heating systems, and solar PV. These tend to be large scale, such as through the Welsh Governments ARBED programme. To meet government targets, a 'whole house' approach needs to integrate a specific package of measures appropriate for the house type. However the cost of whole house retrofits have up to now, been prohibitively costly. Figure 2.25 illustrates the range of costs versus CO_2 reductions taken from an LCBE study. Large scale elemental and whole house retrofits having been investigated in the LCBE programme. They are presented below.

Large Scale Retrofit Programmes

An evaluation was carried out of the Warm Wales Retrofit Programme, funded

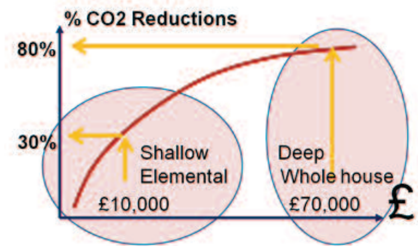


Figure 2.25 Range of retrofit costs versus CO_2 emission reductions.

under the Welsh Government's ARBED 1 Scheme (figure 2.26). The scheme aimed to increase the energy performance of existing homes in Wales, particularly those most energy inefficient, reduce the impact of fuel poverty, generate employment opportunities for Welsh residents and economic opportunities for Welsh businesses, and promote the growth of local supply chains in the energy efficiency and renewable generation sectors.

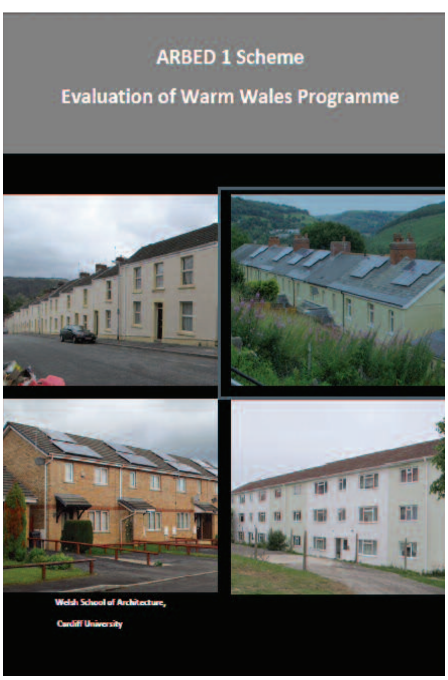


Figure 2.26 ARBED Scheme evaluation.

Warm Wales', a partner of the LCBE programme, were involved in project design and contract management of ARBED 1, working alongside Local Authorities (LAs) and Registered Social Landlords (RSLs) to steer and support the project. Warm Wales selected private and public sector households to receive energy efficiency retrofit measures, creating employment opportunities and educating residents on energy efficiency.

LCBE worked with Warm Wales to obtain a comprehensive set of information on the implementation of the Warm Wales programme to provide an environmental, economic and social assessment. This included interviews with all local RSLs and LAs involved with the project. It also included the design, administration and assessment of questionnaires to obtain information from householders, as well as modelling work to provide emission and savings data.

The total number of properties included within the Warm Wales programme was 1,147. 40% of properties were built before 1919, therefore having solid wall construction, 25% of the properties were built between 1945 and 1964, 18% from 1965 to 1980, and 18% after 1980. A total of almost £7.5 million was invested in the Warm Wales programme. The measures implemented included, external wall insulation (EWI), solar PV, solar thermal and fuel switching. 905 properties received one measure, 240 received two measures and 2 properties received three measures. Although the ARBED Scheme initially aimed to take a whole house approach, the projects within the Warm Wales programme took more of an elemental approach, improving many properties with fewer measures, with the dominant measure being external wall insulation (EWI). 502 properties received fuel switching, mainly from electric to gas. This provided about 55% energy savings for an average cost of just over £3,000. For the 645 houses that did not involve fuel switching, their total cost of measures was £4,927,361, giving an average cost of measures per property of £7,639. The average CO_2 saving, calculated by the WSA's EEP model, of about 25%. Figure 2.27 summarises the cost per measure alongside average CO_2 emission reductions. Fuel switching (based on Economy 7 being the original fuel source) provides the most cost effective savings, achieving about 50 to 60% emission reductions per year. One of the key training opportunities provided through the Scheme was the recruitment of 15 Community Energy Wardens who worked with Warm Wales and the main contractor to support community engagement, installation of measures and a basic after-care service to residents.

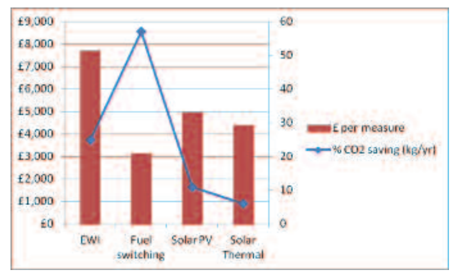


Figure 2.27 Summary of cost per measure and average carbon dioxide emission reductions.

Turnstiles Retrofit House, Newport

The TSB government 'Retrofit for the Future' programme funded 86 'whole house' schemes across the UK aimed to achieve 80% reductions in CO_2 emissions. The Turnstiles low carbon retrofit project (figure 2.28), received an extensive package of retrofit measures, including dry lining insulation on internal walls, triple glazed non-pvc windows, improved air tightness, a mechanical ventilation heat recovery system, time and temperature zone controls, solar thermal DHW, PV panels, and a ground source heat pump.

The cost of the measures, including the cost of a small extension to the living space, was around £70,000. The predicted reduction in CO_2 emissions was 83%, from the pre-retrofit 103kg/m^2/annum to a post-retrofit 17kg/m^2/annum. The initial monitoring of

Figure 2.28 Before and after photographs of the Turnstiles retrofit project.

energy performance over the 2011 to 2012 heating season showed measured CO_2 emission reductions of 74%. This demonstration project, provided much needed information, not only on the performance of low carbon technologies, but also on issues associated with carrying out refurbishment, and costs.

SOLCER Retrofit

The LCBE SOLCER Project designed and implemented energy retrofits of five typical houses located across South Wales (figure 2.29). Each is of a different style, construction and age and is to be monitored over a two-year period. The retrofit has applied a systems approach, combining reduced energy demand with renewable energy supply and storage. Market available technologies have been used, employing local industries to provide low cost high impact solutions to housing retrofit. The purpose of this project is to develop further understanding of how to increase UK market demand for affordable, whole house retrofits.

Figure 2.30 The five SOLCER retrofits and their predicted energy and CO_2 performance.

Properties	Property 1	Property 2	Property 3	Property 4	Property 5
Type	Pre-1919 solid wall, end terrace.	1960s, semi-detached house	2000s, semi-detached house	Pre-1919 solid wall, mid terrace	1950s, semi-detached house
Floor area	60-70 m²	70-80 m²	80-90 m²	70-80 m²	70-80 m²
Retrofit strategies	EWI Low-E double glazing Loft insulation & flat roof insulation (rear extension) MVHR LED lighting PV roof (2.5 kW_p) +lead acid battery storage	Cavity wall insulation EWI (first floor front wall) Loft insulation MVHR – LED lighting throughout PV roof (2.7 kW_p) +lead acid battery storage (8.5kWh)	Loft insulation LED lighting throughout 4.5 kWp Roof Integrated PV 18kWh + lead acid battery storage New Boiler with Hot Water Tank + Immersun using excess power from PV	Rear ETI Front IWI Loft insulation Utility room floor + roof insulation LED lighting PV roof (2.5kW_p) + lithium battery storage (2.0kWh) + inverter for lighting circuit.	EWI Loft insulation LED lighting 4.0 kW_p Roof integrated PV array Lithium battery storage (10kWh, supplying LED lighting or the whole house electric devices.)
Retrofit cost[s]	£30,452	£27,438	£30,446	£23,852	£30,510
CO_2 reductions	75.7%	78.7%	89.9%	81.3%	109.5%

Table 2.1 Summary of SOLCER retrofit data.

The first house retrofit, completed in September 2014 (left in figure 2.30), used a whole house 'deep' retrofit systems approach including, integrated solar PV (the whole of the south facing roof is replaced with a PV roof system), MVHR, external wall insulation, battery storage, and increased airtightness. The total package of measures cost around £30,452, with an estimated CO_2 emission reduction of 70%. An additional £25,000 was spent by the housing association to bring the house up to current Welsh Housing Standards. Prior to retrofit, the house was unable to be let due to its poor condition and location, thus losing the RSL around £450/month in basic rent. Post-retrofit, a tenant was easily found, and the house rented at an increased rate of around £540/month, therefore achieving considerable additional cost benefits for the housing association. All five SOLCER retrofits are presented in figure 2.30 and table 2.1 along with costs and estimated CO_2 savings.

Figure 2.29 Five SOLCER retrofit houses located across South Wales.

The project has used both lead acid and lithium batteries (figure 2.31) for electrical energy storage.

The retrofits are being monitored and initial results are presented in figure 2.32, for low grid feed-in and high grid feed-in. The project demonstrates that the cost of deep retrofits for housing can be reduced significantly whilst still achieving considerable CO_2 reductions.

Low Carbon Buildings Design Guidance

LCBE investigated low carbon design solutions through developing concept designs for a range of building types. The aim was to achieve holistic low carbon design by combining energy demand reduction, innovative service solutions and renewable energy supplies. The 'Design of Low/Zero Carbon Buildings' project included definitions, standards and challenges of delivering low carbon buildings in Wales. It focused on providing design teams involved in the delivery of low/zero carbon buildings with clear, but non-prescriptive design guidance based on current best practice, covering each stage of the design, construction and operation phases. Detailed case studies from around Wales were collected, with selected examples from the wider UK and Europe, to demonstrate exemplary standards of low carbon design and construction in the housing and educational sectors. Whole building design has been considered, from inception to construction, and in operation. Socio-economic backgrounds, in terms of how buildings are developed and delivered, have also been considered in as much depth as other technical aspects, to reach affordable solutions. Generic, robust, repeatable design solutions that can be adopted across the breadth of the construction industry have been developed. Project outputs include best-practice case study reports 'Dwelling' and 'Learning', provide a series of exemplar construction details and on-going development of an exemplar housing design scheme figure 2.33.

Figure 2.31 Lead acid and Lithium Ion batteries used in the SOLCER retrofits.

Simulation Tools

The LCBE programme has included the development of simulation tools for predicting energy performance and CO_2 emissions at building, urban and regional scales. They have been evaluated through a range of projects and workshops with industry.

SAP tool

The SAP sensitivity tool is a web menu-driven calculator for simulating energy performance for housing, based on the SAP2009 method. It is designed to help architects and planners to estimate building performances, providing an a quick SAP rating. The simple tool allows the user to: estimate the proposed design performance, test different design and system options, and to optimise the design to achieve required SAP results.

Figure 2.33 Design Guides for Schools and Dwellings.

The user interacts with the APP by employing three elements: sliders, push buttons and radio buttons. Results displayed during the sensitivity analysis are dynamically shown. The outputs are: class of performance of the building (from A to G), target emission rate (TER), dwelling emission rate (DER), SAP rating, "DER < TER" check and electricity balance. The tool is also able to assess the overheating risk and the percentage of CO_2 reduction over a baseline building.

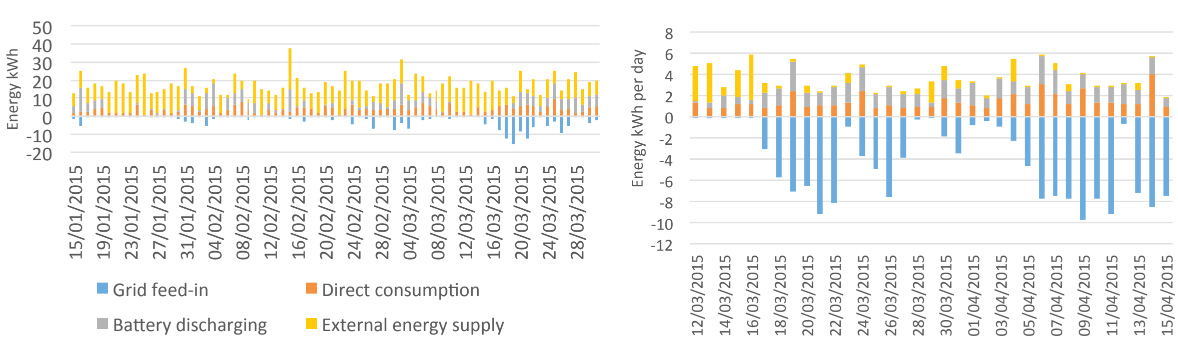


Figure 2.32 Monitoring results for 2 occupied houses, indicatingenergy use , battery performance and grid feed-in.

Figure 2.34 The SAP Sensitivity tool.

It can be used for new and existing buildings. It is available on the internet and has been developed as an APP (figure 2.34)

Mapping Domestic Energy

An Environmental Assessment method has been developed to advise Welsh Local Authorities on the best approach to retrofitting. The example presented in figure 2.35 is the Castleland Renewal Area, Barry. The analysis is based on establishing the current status of the buildings in an area, based on the information available from Energy Performance Certificates (EPCs), SAP

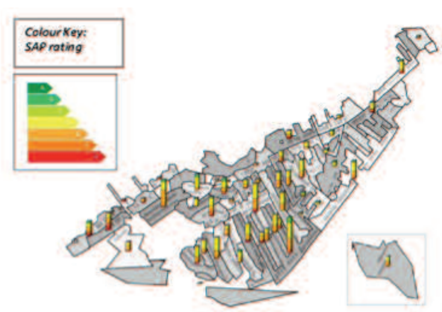


Figure 2.35 Castleland Renewal Area, showing distribution of SAP ratings per post code.

ratings and further sources. This analysis contributed to their ARBED scheme project, providing consistent baseline data to enable them to decide on the most appropriate package of energy saving measures for specific house types.

Bulk EPC model

The 'Bulk EPC' model developed by the WSA within the SOLCER project

Figure 2.36 Representation of current housing stock for a local authority.

aims to provide Local Authorities with the foundation needed to develop strategies to tackle the inefficiency of existing dwellings. A model can be created to represent the current state of the housing stock which can be understood by decision makers (figure 2.36). A database of all available EPCs for an area are used to describe the state of all dwellings within the Local Authority, broken down to smaller geographical areas. Pathways for improvements can be created in line with current energy efficiency targets and costs can be explored. Results have shown that the consumption reduction / cost ratio of measures is greatly reduced if refurbishment measures have already been carried out to reduce consumption. For deep retrofits a mixture of improvement types (systems, fabric or renewables) is required. If subsets of property types are targeted rather than whole areas, concentrating on the least efficient properties would most definitely have the greatest impact

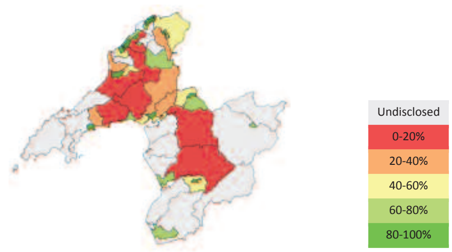


Figure 2.37 Mains Gas Grid Connection per LSOA.

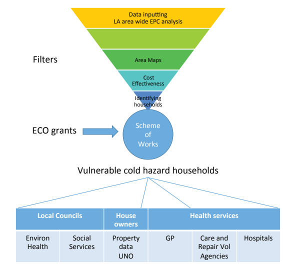


Figure 2.38 Structure of the FRESH project linking energy performance data to local authority and health professionals.

on overall consumption reduction. Combining this model's results with work already undertaken by the Local Authorities would mean that decisions can be made combining both economic and social arguments for targeting resources (figure 2.37).

FRESH

The WSA has worked with Warm Wales to develop an energy prediction mapping tool based on bulk EPCs purchased from DCLG to be part of the Foundation data for creating Robust Energy Strategies for Housing (FRESH) system (figure 2.38).

Data forming the basis of the FRESH approach is presented in table 2.2. FRESH uses a SAP-based modelling system and compliments existing

Table 2.2 Data forming the basis of the FRESH approach", combining EPC data with deprivation indices to identify fuel poor properties.

	EPC Method	Welsh Index of Multiple Deprivation
Main Data	Current and potential energy consumption of improvement options	WIMD ranking (LSOA within 10% most deprived etc.)
Other Data	Cost of Improvements options Breakdown of property types % FG rated properties % Solid walled properties % Off gas properties Current and potential SAP rating distribution Current and Potential CO_2 Emissions	Deprivation indexes ranking: Income Employment Health Education Geographical access to services Housing Physical Environment Community safety

property-based systems within Local Authorities. It offers the advantage of enabling an all-tenure private/public stock overview, quickly identifying the areas with concentrations of energy inefficient housing. It also incorporates a unique costing tool enabling easy and accurate mass modelling of properties to allow project submissions that are most likely to attract higher rates of mass carbon ECO grant and/or other grants or rewards. The results of the SAP based modelling system can be combined with existing data sets to provide guidance at a LSOA level where to target energy efficiency measures based on the deprivation data provided through the Welsh Indices of Multiple Deprivation .

Urban Scale Energy Modelling

Large ‘urban-scale’ energy simulation is a field that has not been approached as widely as energy simulation for individual building design. However access to high levels of computer power can now facilitate the modelling of large numbers of buildings at the same time, using advanced simulation models, such as WSA’s building energy model, HTB2. The approach developed in LCBE uses Trimble SketchUp to construct the building development and to provide information on the shading of buildings by each other. The data is then supplied to the energy model, and the simulation is run from within SketchUp and the results displayed. The approach aims to provide results for operational energy use, embodied energy and the potential for solar energy for building integrated renewable energy systems. Individual building performance can be identified alongside whole site performance. A range of ‘plug-ins’ have been developed in order to extract information from a simple SketchUp model, generating information on each building and making each building ‘aware’ of its surroundings (figure 2.39).

An example project, where modelling the overshadowing impact on solar insolation, is the joint project carried out with the collaboration of Toronto-based Internat Energy Solutions Canada (IESC) (figure 2.40). This demonstrates the impact of urban obstructions on façade solar insolation. The results indicate that the tilted sections of the façades see an average reduction of solar insolation of 14% and the vertical façades receive up to 35% less solar radiation, due to overshadowing from surrounding buildings.

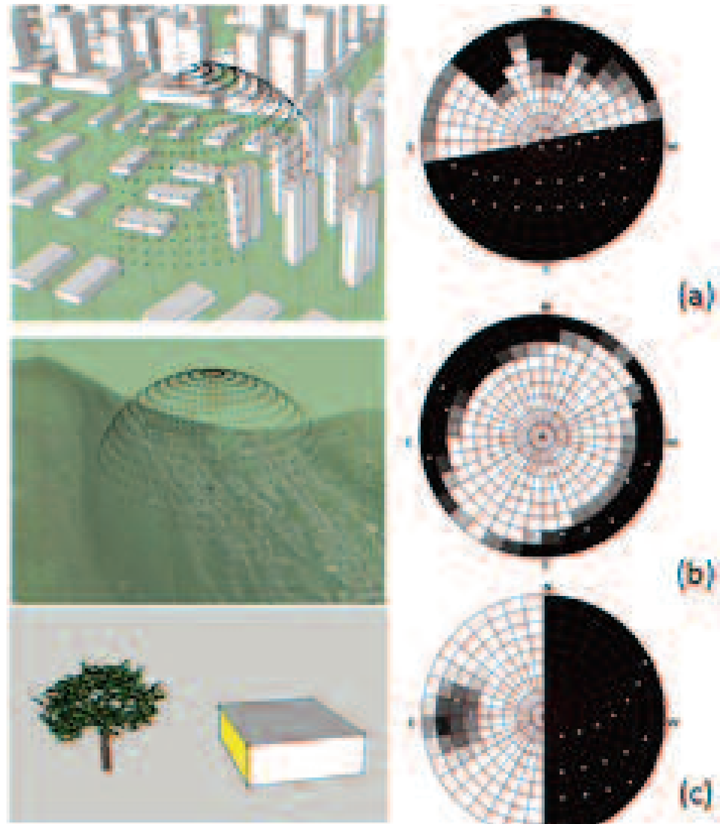


Figure 2.39 Shading masks are produced to account for be overshadowing by other buildings or landscape features.

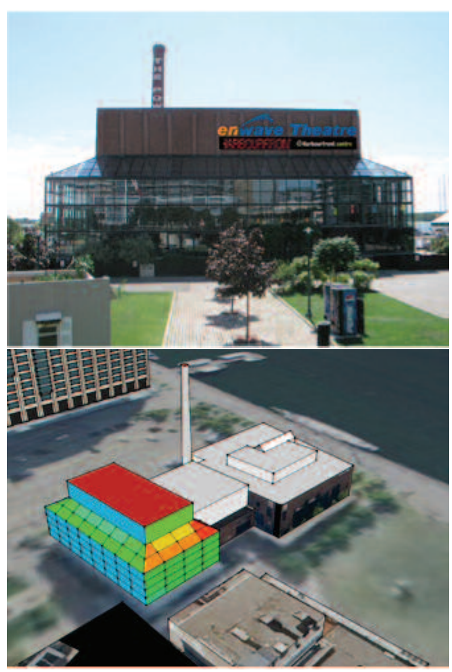


Figure 2.40 Example of modelling the impact of overshadowing on solar PV potential.

An example from a low carbon master-plan study of about 300 buildings, including residential, commercial and industrial, in Chongqing, China, illustrates the energy analysis features of the model (figure 2.41). The energy performance of the whole development or individual buildings can be simulated. Results are accessed through the SketchUp environment, divided into elements of performance, including, heating load, cooling load and solar gain. Outputs include the overall operating energy, the embodied energy and the potential for collecting renewable solar energy on building façades.

The model has also been applied to a new development in Tianjin. Figure 2.42 presents the overall energy performance results.

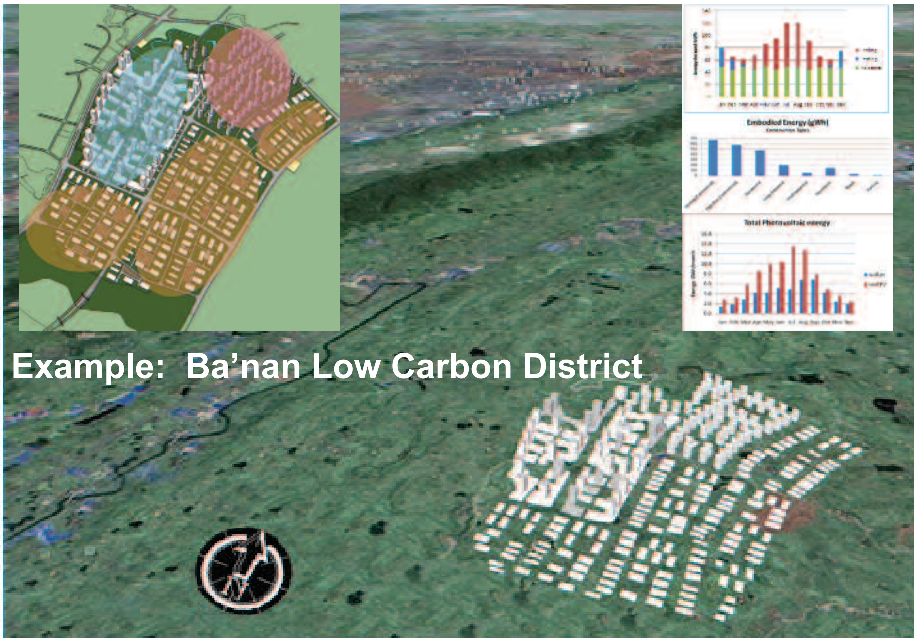


Figure 2.41 Example of urban scale application – Banham, Chongqing.

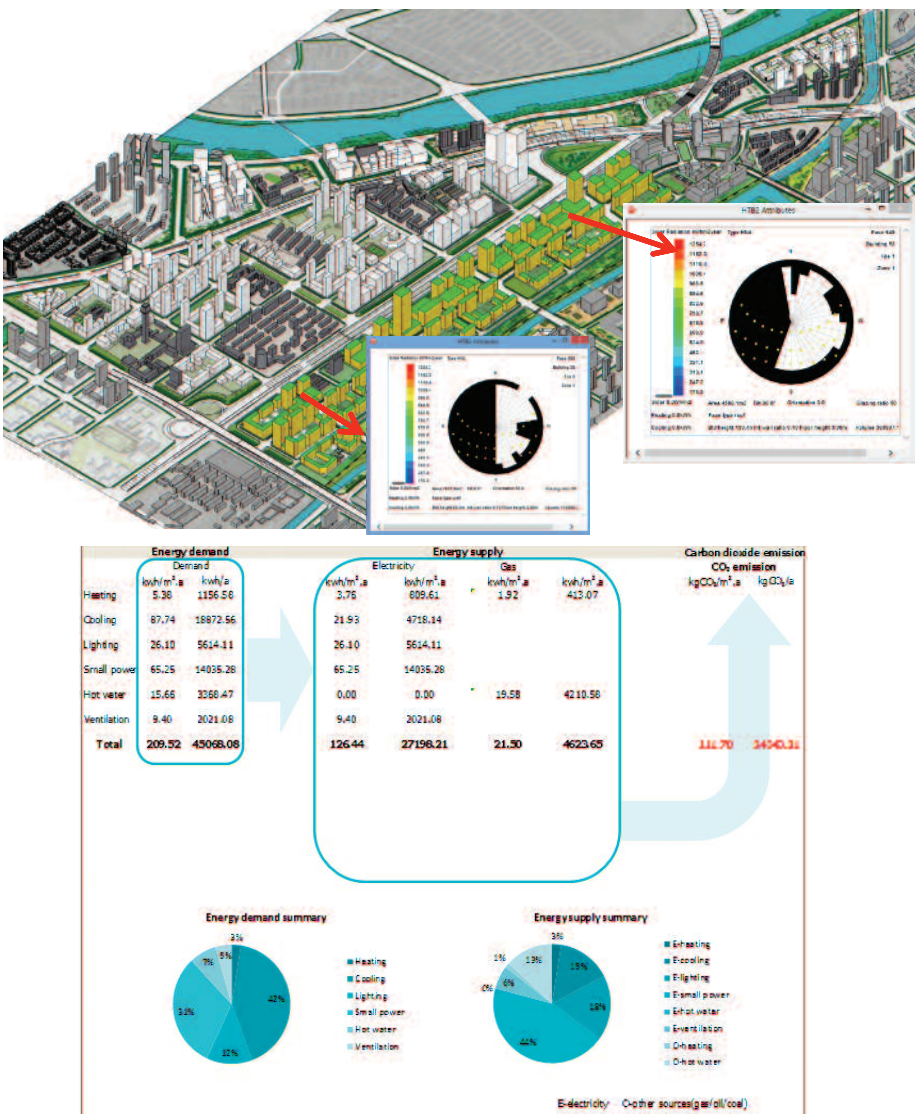


Figure 2.42 Example of urban scale application and summary of results for energy demand, energy supply and CO_2 emissions – Tianjin.

Monitoring Performance in Use

Design reviews, fabric and systems performance tests and post-occupancy evaluations have been carried out in a number of low carbon domestic and non-domestic buildings in different phases of their life cycle. The practical usability of monitoring methods were analysed, resulting in the development of a series of guidelines and processes for industry to embed building performance monitoring in practice. The main outcomes of this research is that what happens in 'so-called' low energy buildings is often significantly different to predictions. There are major departures from design intentions during the final stages of building design, at construction stage and, most markedly, during operation. It is recognised that evaluating building performance of low energy buildings is never straightforward and requires bespoke solutions for each building because even small differences between buildings can result in much larger variation in performance.

The LCBE has explored and applied methods for monitoring and assessing the performance of low carbon buildings through their conception, design, construction and operation. Some applications have been described in the above SOLCER retrofit projects. Other examples are introduced below.

60 Apartment Development in Bristol

A basic review of the energy consumed by the apartments was carried out using utility company metered data. The evaluation aimed to determine whether the Swedish NIBE heating/ventilation exhaust air heat pump systems were delivering comfort conditions at acceptable energy consumption levels and that the occupants understood how to operate the system to their best advantage. The heat recovered from the extract ventilation is used via an 'air to water' heat pump system to provide

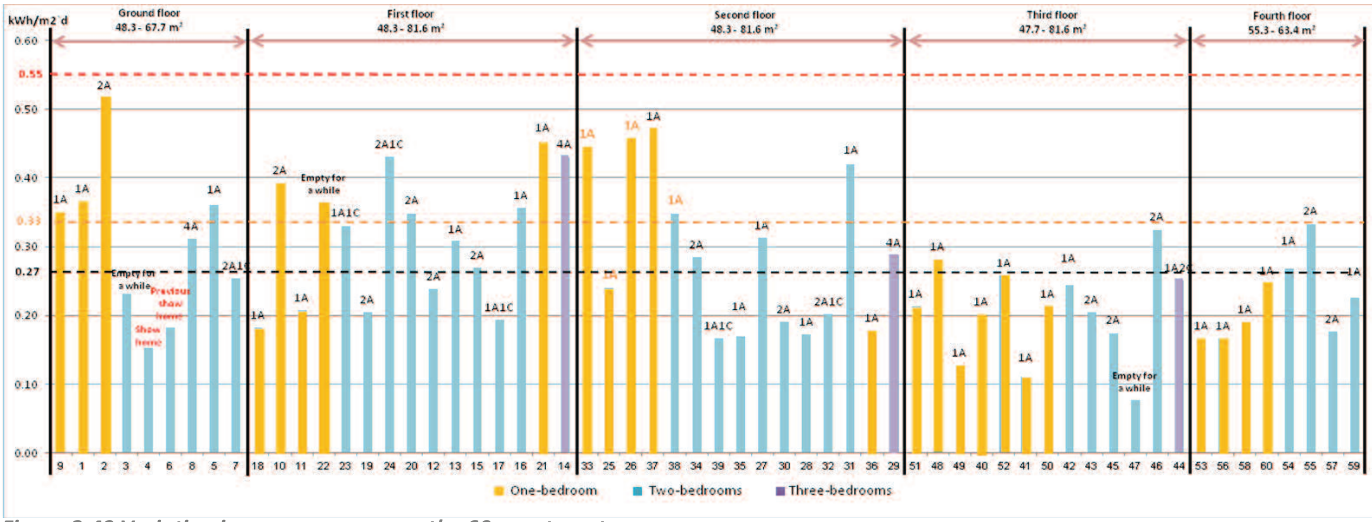


Figure 2.43 Variation in energy use across the 60 apartments.

hot water for both the under floor room heating and domestic hot water use, although for the bathroom showers, hot water is provided by electric point of use units. The heating systems were required to operate continuously for 24hrs a day to derive optimum performance. There are 60 flats in development constructed to a high thermal performance standard with external wall u-values of 0.19 W/m²K and roof values of 0.10 w/m²K, and high quality double glazing throughout.

The energy consumption figures varied greatly by a factor of 5 between the best and worst case (figure 2.43) between apartments even when occupancy patterns and floor areas were taken into account. However, based on this limited data, most of the apartments appeared to show consumption levels that were close to, or below the predicted energy demand indicted SAP calculations. A post occupancy evaluation questionnaire indicated that most tenants found it possible to maintain comfort conditions within their apartment throughout the year although some found the apartments too warm in the Summer. A third of the respondents felt their utility bills were too high. Many of the tenants interviewed stated that they had not received sufficient instruction in the optimum use of the NIBE system and felt that this may be the cause of the higher electricity bills.

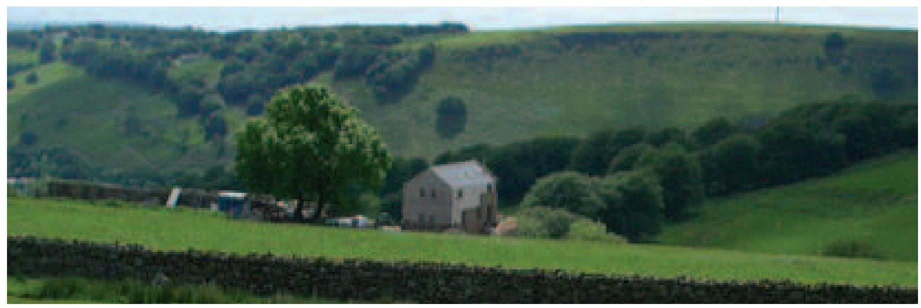


Figure 2.44 Maes yr Onn Farm.

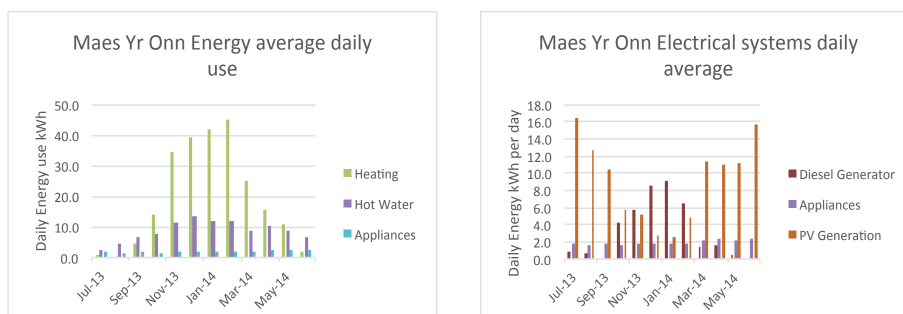


Figure 2.45 Monthly energy use breakdown.

Maes yr Onn Farm, Caerphilly

Maes yr Onn is a new built off-grid farmhouse which was completed in June 2013 (figure 2.44). The monthly profile of the energy use (figure 2.45) shows that the heating is the dominant demand, and that it was being used for 10 months of the year, reflecting the exposed nature of the site.

The monitoring results showed that PV is dominant energy source for over half the year, heating demand for the year is 6,908 kWh, 65 kWh/m², the appliance use in the house on average is 2.0 kWh per day, compared to a BRE quoted value of 6.7 kWh per day, and water use of two thirds of the water predicted at 63 litres/day/person. There are positive views about off-grid living and the feasibility of a sustainable lifestyle in an off-grid house. The occupants do not think that they have made significant changes to their lifestyles nor that they are compromising activities or comfort. While some changes have been adopted in terms of washing/ironing during sunny days, these are considered reasonable and do not pose any disruption to their routines.

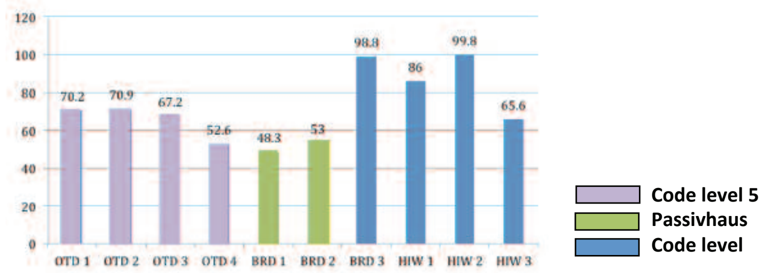


Figure 2.46 A cross site comparison of total annual energy consumption delivered energy (kWh/m2/annum).

Place	Building type	Level	Floor area (m^2) Monitored	Annual delivered energy consumption (kWh/yr) regulated	unregulated	EPC rating (kWh/yr) (regulated)
OTD 1	Flat	Code level 5	61	1529	2753	915
OTD 2	Flat	Code level 5	61	2786	1540	854
OTD 3	Flat	Code level 5	50	827	2533	950
OTD 4	Flat	Code level 5	50	1570	1059	850
BRD 1	Semi-detached house	Passivhaus standard	100	3211	1624	8019
BRD 2	Semi-detached house	Passivhaus standard	100	2830	2468	8019
BRD 3	Mid link house	Code level 4	98	5888	3794	10506
HIW 1	Semi-detached house	Code level 4	77	3909	2715	4709
HIW 2	Semi-detached house	Code level 4	77	4807	2879	4709
HIW 3	Semi-detached house	Code level 4	77	2309	2745	4708

Table 2.3 Energy consumpton vs EPC rating.

Welsh Government, Sustainable Homes Pilot projects

Ten sample houses and flats from amongst the Welsh Government, Sustainable Homes Pilot projects were monitored under the Assembly Government funded 'Academia for Business (A4B)' initiative. The total delivered energy was monitored together with an approximation of regulated and unregulated energy. Hot water use was monitored separately where possible. A cross site comparison of total annual energy consumption delivered energy is presented in figure 2.46. The predicted Annual energy consumption vs EPC rating all dwellings are presented in table 2.3.

TRANSITIONS

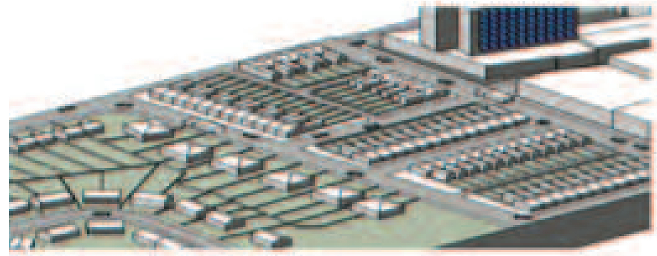
Realising Transition Pathways to a Low Carbon Economy

LCRI Director, Prof Peter Pearson, led the 9-university EPSRC-funded £3.17m research consortium Realising Transition Pathways to a Low Carbon Economy (2012-16). The interdisciplinary RTP project is a key part of the RCUK Energy Programme's Whole Systems strand. The consortium explored three pathways to a low carbon electricity system, and shown that they could feasibly contribute to the UK achieving its greenhouse gas (GHG) emissions reduction target of 80%by 2050. The analysis of these pathways contributed to a deeper understanding of the future interplay of the energy policy 'trilemma': achieving deep GHG emission reduction targets, whilst maintaining a secure and affordable energy system, and addressing the way in which resulting tensions might be resolved. The project has influenced the activities of UK bodies such as the Committee on Climate Change (CCC), Department for Energy and Climate Change (DECC), the public-private Energy Technologies Institute (ETI), and the market regulator Ofgem. They have placed the UK energy community and the LCRI in a leading position in relation to research on energy transition pathways.

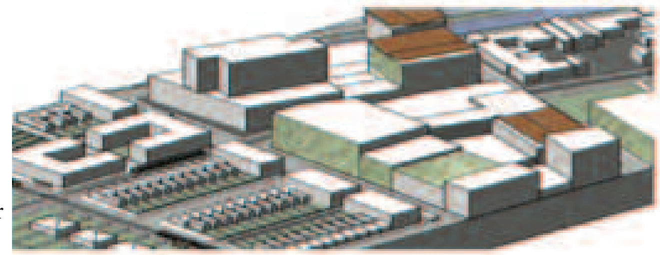
Professor Pearson, was a partner in The UK Energy Research Centre (UKERC) NERC-funded £410k consortium Carbon Capture and Storage: Realising the Potential? (2010-12). The project had partners at Edinburgh, Imperial College and Sussex University. It produced an inter-disciplinary assessment of the viability of CCS technologies from now to 2030. Its core report was launched at a high-profile meeting at the Royal Society in April 2012. The report concludes that previous technologies have faced similar challenges to those affecting CCS technologies today. The findings offer some optimism that, given the right actions by government and industry, the considerable uncertainties surrounding CCS could also be addressed.

Professor Pearson, was a partner in The UK Energy System: Public Values, Attitudes and Acceptability (2011-13), led by Prof. Nick Pidgeon (Cardiff). The interdisciplinary £586k UKERC/NERC-funded project included a nationally representative survey that explored British public values and attitudes towards climate change and energy choices and acceptability of whole energy system change. It developed valuable, widely cited, theoretical and empirical insights into public perceptions and the public acceptability of de-carbonisation pathways, including what choices might gain broad public support or where resistance/ conflict might be expected. Its core report was launched at the Royal Society in July 2013.

Connected Cardiff
An efficient, innovative city-region with global influence
A vibrant economy focused on green technological solutions. Investment in the 2010s and 2020s drove stronger collaboration between the knowledge sector and commerce to create business clusters that are internationally competitive. Efficiency is a key policy goal, with all utilities overseen by a single body to consider resource management issues in the face of scarcity. Economic growth has underpinned investment in high quality housing, environments and social care services.



Compact Cardiff-Wilderness Valleys
High density urban areas in harmony with green hinterlands
Urban centres predominantly comprise medium rise buildings based around boulevards and parks. Distinctive 'villages' within the city ensure a culturally rich region, connected by electrified rail and shared electric cars. The rural hinterland is returned to wilderness or used for food and biomass crops. Extensive investment in the 2020s - 2040s enabled rebuilding of urban centres with mixed use development and energy, water and waste networks fit for a compact city.



Orchard Cardiff City-Region
A flagship city-region championing self-reliance and community governance
Sustainability is at the heart of every policy. With far greater dialogue with communities, planning decisions are much more connected to the needs of communities. Academic research is focused on useful, practical knowledge. Half of all food eaten is produced with the city-region, with urban agriculture making a significant contribution to local employment. Priority is given to local energy production delivered by community-owned schemes.

Figure 2.47 Three city region visions using Cardiff as a case study.

RETROFIT 2050: Re-engineering the City: Urban Foresight and Transitions Management

The Retrofit 2050 project, led by LCRI Professor Malcolm Eames, delivered a step change in current knowledge and capacity for urban sustainability by illuminating challenging but realistic social and technical pathways for the systemic retrofitting of UK city-regions. The project worked with key stakeholders to explore options for systemically retrofitting two core UK city-regions: Greater Manchester and the Cardiff City-region. With the objective of overcoming the separation between 'what' needs to be done and 'how' it can be implemented, it explored ways of promoting a managed transition to sustainability in the built environment between 2020 and 2050. It brought together a consortium of six leading UK universities (Cardiff, Durham, Cambridge, Reading, Salford, and Oxford-Brookes) and some 14 non-academic partners: RICS, BRE, TATA, ARUP, Core Cities, DEFRA, Welsh Government, Manchester City Council, Cardiff Council, Carillion, Environment Agency Wales and Neath Port Talbot Council. As well as working closely with Welsh Government and local authorities in Wales, the project has provided high-level briefing to a quarterly meeting of the UK Government's Chief Scientific Adviser's Committee (CSAC).

The project sought to develop the knowledge and capability to support city-regional scale retrofitting in order to promote a managed socio-technical transition in the built environment and urban infrastructure of our existing cities. It brought together an understanding of future technological options and possibilities with the behavioural, political and wider institutional and governance challenges involved to support city-regional scale retrofitting in order to promote a managed socio- technical transition in the built environment and urban infrastructure. Four important questions for cities were brought together developing understanding of future technological options and possibilities with the behavioural, political and wider institutional and governance challenges, which have all too often been treated in a disconnected way: (i) "what" is to be done to the city? (ii) 'who' is involved in this process? (iii) 'why' will change take place? and "how" will it be implemented? A specific objective was to articulate and appraise city-regional visions and prospective pathways for urban-scale retrofitting of the built environment. The project has made a significant contribution to this emerging field of research at both national and international levels.

Key project outcomes have included: detailed case studies of the governance and implementation of UK national and retrofit programmes, focusing particularly on Cardiff/SE Wales and

Greater Manchester; an analysis of emerging retrofit practices in the UK commercial property sector; an extensive programme of horizon scanning and foresight activities; regional scale modelling of the energy, cost and carbon savings from low carbon retrofit of the domestic sector; a Retrofit City Futures participatory back-casting tool; and the development of long-term city regional scenarios with key stakeholders in Cardiff, Manchester and Reading. An example of the outcomes is the Connected Cardiff analysis (figure 2.47).

Smart Energy Regions: COST Action TU1104 (Smart-ER)

This Action was led by Professor Phil Jones and the grant holder as Dr Jo Patterson. The aim of the action was to investigate drivers and barriers that may impact on the large scale implementation of low carbon technologies in the built environment. It had 28 European partner countries and held regular meetings, workshops and engagement activities with early career researchers, and government and industry partners in the member countries. Europe has set targets for sustainable development, including CO_2 reductions, which are implemented through national governments. Regional level governance has been shown to be fundamental for the delivery of sustainability. Therefore the focus of the action is set at a regional scale. Smart-ER showcases the benefits of low carbon innovation in the sectors of policy, planning, design and technology, addressing technological issues as well as societal and economic needs. Guidance is being provided for the larger scale transition to a low carbon built environment. Drivers and barriers are being identified through a series of case studies. A framework of solutions are being developed as the main outcome of the Action when the programme ends in Spring 2016. This will be disseminated to the following target audience, including, national and regional governments and governmental organisations, homeowners, social landlords and private businesses, professionals of the building sector such as planners, designers and developers, and academics. The activity of the Action is structured in 4 Working Groups:

Working Group 1—Policy, industry innovation and case studies

This group is reviewing how different policies are implemented in European Countries at a regional scale through a series of case studies to illustrate low carbon initiatives taking place across Europe. (A handbook, figure 2.48, containing this material has been published in June 2014 and is available via the following link http://www.smart-er.eu/content/publications.)

Working Group 2—Skills, knowledge, training and supply chains

This group focusses on the availability of different skills that are needed for appropriate design and installation of low carbon technologies, and is reviewing existing training programmes and schemes. The development of local supply chains for low carbon materials and components is also covered by this group.

Working Group 3—Cost and value

This group investigates additional costs that arise when low carbon buildings are delivered. It is necessary to understand how these can be reduced through economies of scale and counterbalanced by the added value brought by low carbon technologies.

Working Group 4—End user engagement and dissemination

This group will bring together the outcomes of the other Working Groups looking at appropriate ways to engage with the end users of the built environment. This group will deliver a series of dissertation initiatives and events to communicate the outcomes of the Action to its target groups.

The Action is currently working on two further books, one on Skills and Training and another on Cost and Value to disseminate the outcomes from Working Groups 2 and 3. It will hold an international conference in Cardiff planned for February 2016.

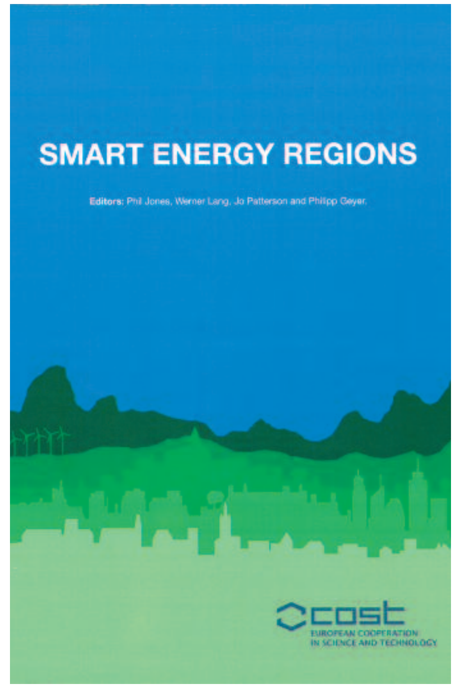


Figure 2.48 Smart Energy Regions publication.

LCBE Researchers

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SECTION 3: Solar PV (SPARC)

Introduction

Recent years have seen the rapid growth of photovoltaic (PV) solar panels to generate electricity. This has been supported by increased application through government incentives such as Feed In Tariff (FIT), driven by European targets for increasing the proportion of renewable energy. The main application areas have been in small scale domestic and more recently with large scale solar farms. Building integrated PV systems offer a large opportunity in the UK but technical and commercial challenges have meant that the early uptake in this sector has been slower.

There are three areas of development of PV technology, often referred to as generation 1, 2 and 3:

Generation 1: Crystalline silicon are the traditional solar PV panels which have been in production since the 1990s. They have relatively high module efficiencies of around 15-20%, and they form around 90% of all PV applications. As they have been produced for a number of years, their costs have come down over time as manufacturing scale has increased and the technology has improved. They are normally encapsulated in glass panels, although the SBEC Sol-Bond product described in the Built Environment section, is bonded directly on metal roof cladding panels, hence reducing the PV panel weight. ***Amorphous silicon*** are thin film panels made from silicon and are relatively low cost. Early versions n single junction form had efficiencies of around 5-6%, but more recent multiple junction forms have efficiencies of around 8-11%. Their main advantage over crystalline silicon is their relatively low cost. They also exhibit relatively higher efficiencies for diffuse radiation.

Generation 2: Thin film PV CIGS and cadmium telluride are lower cost to manufacture than crystalline silicon and have a higher efficiency than amorphous silicon. Gen. 2 PV can be more flexible than Generation 1 and are therefore applicable to curved surfaces. This PV technology has been applied in the SBEC SPECIFIC BIPV product described in the Built Environment section, where the thin film PV is encapsulated and bonded to a metal cladding panel. Typical efficiencies are around 14%. It replaces the lower efficiency Generation 1 thin film systems.

Figure 3.1 The OPTIC centre where SPARC is located.

Generation 3: Printed PV panels use a printing technique to produce panels. Generation 3 PV technology may be defined as earth abundant materials, non-toxic, and low cost. It includes dye-sensitised coatings, OPV (Organic PV) coatings and Perovskite coatings. Dye-sensitised solar cells were a potential subject of investigation for SBEC, but as with the other two coating methods, they are sensitive to external weathering. Perovskite is especially sensitive to water. Although they have potential for a low cost system, they are still about 5 to 10 years away from the market. However they have other advantages of higher efficiencies for diffuse solar conditions (around 25% higher), and when they do become available will enable new market applications in BIPV and consumer off-grid products.

The original Generation terminology originally represented a route of improvement for solar PV, however as Generation 3 technologies drift further into the future in relation to improvements, developments within the earlier generations, and in particular Generation 2 are of more direct interest in relation to market uptake.

The embodied energy needed to manufacture PV panels is of major concern, as well as panel efficiency and cost. This has been continually improved over time, with energy payback time (EPBT) reduced to around 2.5 years for Generation 1 crystalline silicon to approximately 1.5 year for thin film systems in the market.

Overview

PV research within LCRI has been led by the Solar Photovoltaic Academic Research Consortium (SPARC) based at OpTIC in St Asaph (figure 3.1). This is one of the LCRI Research Centres. The work has been led by Professor Stuart Irvine of Glyndwr University with partners Professor David Worsley and Dr Petar Igic at Swansea University and Dr Peter Holliman at Bangor University. SPARC is developing new types of PV panels that will radically reduce the energy used in production and reduce harmful materials used in manufacturing. The SPARC project director Prof. Stuart Irvine says, "*The amount of energy used in the production of PV panels largely comes down to the processing temperature. The lower the process temperature the less energy that will be needed.*" While crystalline silicon require temperatures well over 1000°C, SPARC's thin film processes needs less than 400°C.

SPARC's pioneering in-line thin film coating process will dramatically reduce the temperatures needed in conventional thin film processes, reducing energy inputs and their costs. This is an atmospheric pressure process compared to the vacuum deposition process used on other Generation 1 and 2 thin film products. It therefore has potential for a low cost relative high efficiency product. The in-line process provides a generic manufacturing plant which is able to deposit a series of layers on glass or other materials to produce thin film PV panels. It can be deposited on steel and can be eventually used with generation 3 technologies, such as Perovskite panels which are being developed at SPECIFIC.

The in-line production involves sequential deposition of each of the active layers in the thin film PV structure onto a suitable substrate such as glass. It is a high yield process with over 50% material utilization, compared to 5% for the research process. The combination of an atmospheric pressure production system with high material utilization provides a low carbon product. In future materials used in PV production will also have the potential to be recycled.

The panels produced by the in-line process are particularly applicable to building integrated PV applications, and also space applications, where reducing weight is of major importance. It is able to layer onto ultra-thin glass, which provides a more durable flexible system than transparent plastic. Micro-modules have also been produced where each cell is defined by laser scribing and monolithically integrated. So testing can be carried out at a more realistic scale than laboratory produced solar cells, taking account of large-scale effects of electrical connection, a major area of cell performance efficiency.

SPARC has team partners at Bangor and Swansea Universities, who are taking a different approach to PV development, including Generation 3 dye sensitised solar cells. A new low temperature process for forming the nano-porous titanium, which holds the dye, could be as low as 150 °C. These developments hold the prospect for low cost solar PV panels being manufactured in the future with energy payback time of much less than a year and with a focus on containment of gaseous materials in production, will also reduce waste. Further developments from these teams on rapid annealing of the titania with infrared lamps and a new patented rapid dying process could drastically reduce manufacturing time to increase throughput and reduce cost. The SPARC team also includes the power electronics team at Swansea University who have been investigating novel converter technologies to increase the extraction of power from PV modules.

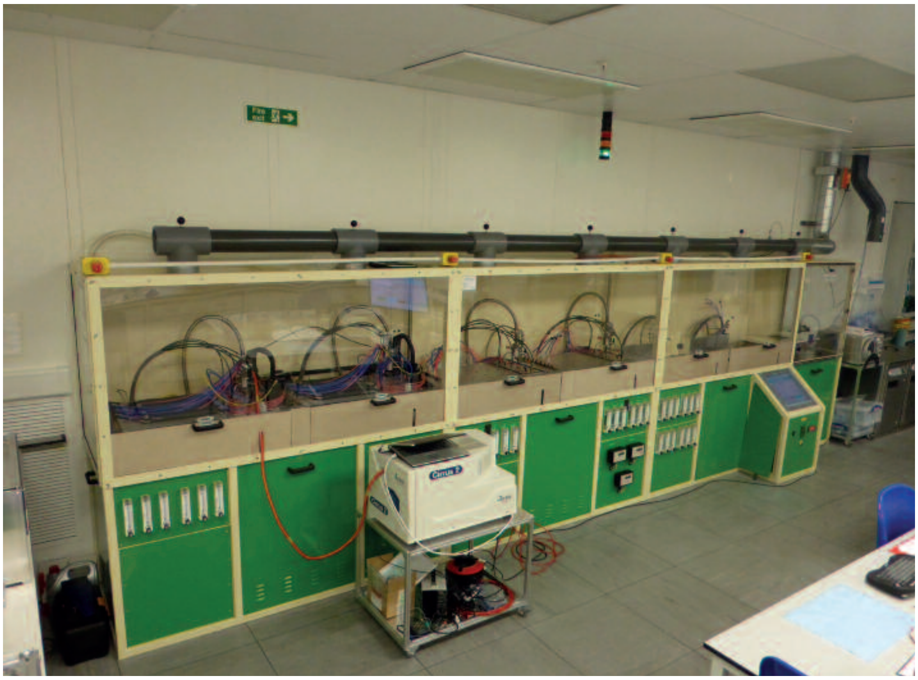


Figure 3.2 SPARC's chamberless in-line PV manufacturing plant.

Swansea's LCRI Power Electronics group combines power devices and mixed-signal circuits in the same silicon chip. This represents the leading technology for the development of energy efficient electronic circuits, for example LED driver circuits, novel PV inverter technologies, smart appliances, electric and hybrid cases, 'more electric' aircrafts, etc. Dr Petar Igic's leading work on the functionality of the novel Power Switching Devices and isolation structures has led to work with ZETEX, one of the world's largest semiconductor manufacturers. Its engineers tested Swansea's designed silicon chips and verified the findings. The cooperation also included X-Fab Semiconductor Foundries. Prof Birchby of ZETEX described the Swansea group as having, *'an international reputation for their work in power electronics, power semiconductor devices and the design and modelling of power integrated circuit process technologies'*, and *'a good example of knowledge and technology transfer from academia to industry'*.

Work at OpTIC has led to partnerships with industry, such as working with Pilkingtons NSG on thin film substrates on glass, with Sharp on lamination technology and with the SME Egnitec on measuring the performance of PV panels in use. The work is closely linked with other LCRI research, including building integrated solar energy systems at Cardiff and Tata and with power electronics at Swansea on inverter technology.

Technology	Efficiency (%)	Cell weight (kg/m2)	Cell weight with CMG (kg/m2)	Specific Power (kW/kg)
TJ	30	0.86*	1.06	0.28
Silicon	16.9	0.32*	0.52	0.32
CdTe	14**	0.03***	0.24	0.59

Table 3.1 Compares performance to related technologies.

Projects

Al-doped ZnO by Inline MOCVD

Transparent conducting oxides (TCOs) are widely used in the photovoltaic (PV) and flat panel display industries. They provide a highly conductive layer on the outer side of the semi-conductor layer, which is transparent to solar radiation, allowing the solar radiation to reach the active semiconductor layer. As manufacturers continue to pursue cost savings, recent research into relatively earth abundant and non-toxic materials has gained momentum. A viable alternative to the commercially available TCO ITO is Al doped ZnO (AZO).

The in-line production of such materials over batch-type manufacture is preferable for a number of reasons, in particular with regards to scalability potential and reduced fabrication time. This research has successfully achieved deposition of AZO layers onto float glass using a novel inline chamberless metal organic chemical vapour deposition (MOCVD) system operating at atmospheric pressure,. It has demonstrated good performance characteristics compared to a commercially available TCO, achieving Rs < 10 Ω/□ for a 600 nm film, comparable with commercially available but more expensive TCOs. Further improvements are underway to improve the TCO structure, using multi-layer depositions and lower sheet resistance AZO.

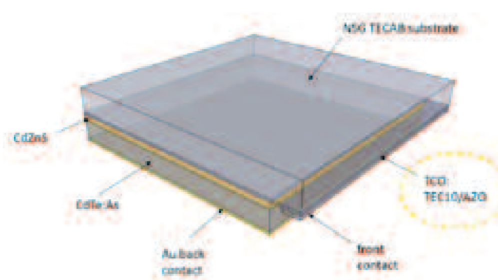
Thin Film CdTe Photovoltaics on Ultra-thin Space Qualified Cover Glass

Ultra-thin film glass provides a flexible lightweight thin film PV system. An EPSRC funded grant has followed on from SPARC to investigate the development of a light-weight, high specific power and low-cost thin film cadmium telluride (CdTe) solar cell for space application. A CdTe solar cell is deposited directly onto a cerium-doped micro-sheet glass, which is a radiation stable product currently laminated to all photovoltaics deployed in space. The projects best result to date for a CdTe on cover glass under space irradiation conditions is a mean efficiency of 13.9 % for an 8 x 0.25 cm^2 device. Table x compares performance prediction for specific power (power to weight ratio) compared to related technologies. Excellent adhesion of the device structure to the cover glass has been demonstrated. The device structure and performance remains intact after severe thermal shock cycling of +80 °C to – 196 °C showing no signs of delamination. New demands on extraterrestrial PV technology include; space-based solar power (SBSP) arrays transmitting their power to earth based receivers, Lunar and Martian bases, and solar electric propulsion (SEP) through the use of ion thrusters.

Further research has demonstrated the feasibility of thin film CdTe photovoltaic structure deposited directly onto the industry standard space cover glass. A thin film CdTe on cover glass technology can compete with current more efficient triple junction Space solar cells in terms of a predicted higher specific power and lower production cost. As well as photovoltaic performance the durability of this type of structure has been considered. The full device structure demonstrated particularly good adhesion strength of above 306 N over 5 different measurement points. No delamination was observed under the Scotch Tape Test before or after extreme thermal shock of 10 cycles of 80 to – 196 °C. Further testing is required to establish under space qualified conditions and monolithic integration is to be demonstrated.

Luminescent Down-Shifting (LSD) on CdTe Micro-Modules with Fluorescent Quantum Dots

Not all the solar radiation is captured by solar `PV cells. This includes wavelengths



CdTe device PV parameter	TEC10	AZO
η	14.1	10.4
J_{sc} mA cm^{-2}	24.7	21.3
V_{oc} mV	767.7	747.5
FF %	74.2	65.5
R_s Ω cm^{-2}	3.4	7.1
R_{sh} Ω cm^{-2}	2777	1053

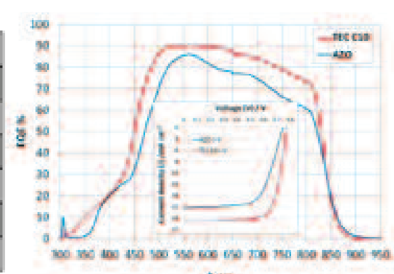


Figure 3.3 Demonstration of cadmium telluride deposition onto ultra-thin glass using the SPARC chamberless in-line systemPV device.

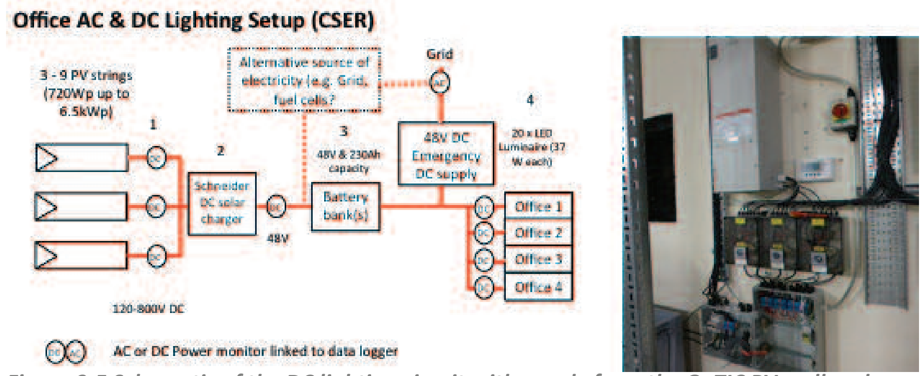


Figure 3.5 Schematic of the DC lighting circuit with supply from the OpTIC PV wall and battery storage with picture of the DC battery charger taking the power from the OpTIC PV wall.

in the blue and uv part of the solar spectrum. Solar cells can be designed to capture more of the solar radiation and therefore produce a higher output. Nano-particulates in polymer films effectively capture the blue and uv wavelengths. This creates a fluorescence that re-emits radiation in the red range which is then captured by the solar cell. This can result in an efficiency gain of between 5-10%, which can potentially increase the cell output from typically 15 to 16.5%, that is a 1.5% improvement. Dyes can be used to the same effect but nano-particules have a longer life than dyes.

The fluorescence effect by LDS can also be used to improve the aesthetics of the PV, providing access to a wide range of colours depending on the properties of the luminescent material.

SPARC Fluorescent QDs incorporated within a PMMA film have increased the photo current production of a CdTe cell by > 4%. This has been confirmed through EQE and I-V measurements. More efficient QDs would yield further improvements. Research has investigated the mix of CdSxSe1-x/ZnS QDs with poly (methylmethacrylate) (PMMA) to create an LDS film. The QDs emit at ~525nm and have a quantum yield of ~50%. The QD film is highly transparent and exhibits high levels of haze, which can act to increase the optical path length of light through the micro-module.

QD/PMMA films have the potential to increase the uptake of cadmium telluride PV Technology for BIPV applications through both improved performance and enhanced aesthetics.

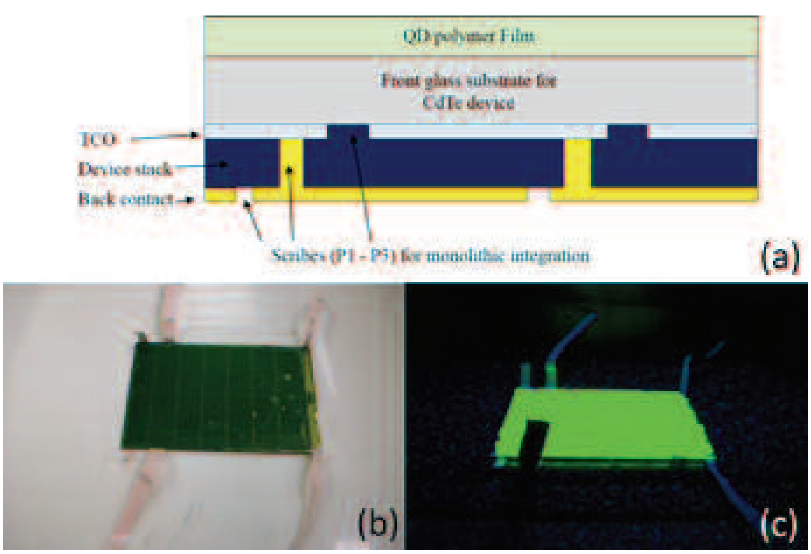


Figure 3.4 Diagram of the monolithically integrated CdTe micro-module with the LDS layer a)the actual micro-module with the LDS layer b) and as in 1b under UV illumination.

Performance of EVA Encapsulated CdTe Devices and Micro-Modules Grown by MOCVD under Heat/Humidity tests

SPARC has established a process for accelerated lifetime testing. This has particular applications for new materials but has been used for a range of devices to investigate failure mechanisms. Un-encapsulated devices were tested to see what part of the cell was most vulnerable to failure. Analysis of the results showed that the contacts were the first to fail and is directing research in module technology to establish more robust contacts.

SOLCER office DC lighting demonstrator

The development of this required not only to look at the supply, but also transmission, storage and demand. It evolved, in collaboration with Swansea University (WP2) & Links Electrical.

The initial phase of this project was to replace standard fluorescent luminaires with LED luminaires and to monitor both the light output and the energy demand. Under operational conditions it was found that a 50% energy saving was achieved. Further savings of 10% alone was possible by switching the LED luminaires from AC to DC supply. The DC platform system at OpTIC enables various types of batteries to be tested, however, the current work has focused on 4 lead acid batteries with 230Ah capacity at 48V (preliminary test were carried out with NiFe type of batteries, however, voltage could not be sustained during discharge). In terms of supply, a number of strings on the PV Wall at OpTIC were used with a PV capacity which could be altered from 2.2 to 6.6 kWp. The energy flow has been reported and will be the subject of a peer-reviewed paper in the coming months. During the summer, it can be said that a considerable amount of spare solar energy is available as the batteries are often fully charged (i.e. solar charger operating away from MPPT). This provides potential for a secondary charging facility, such as hydrogen, to shave of the demand dependent on seasons, as well as the development of a smarter control system. One of the advantages of using such system is that using storage provides a buffer to remove spikes in the grid related to Renewable Energy supplies. Switching to the DC LED luminaires has seen the peak energy consumed reduced by more than half, compared with the AC fluorescent luminaires. Also, a better match in energy is observed, using DC supply and demand, with surplus peak energy for storage even in winter. The database, providing useful information for WP4, can be securely access anywhere via a web browser, by all members of the SOLCER consortium.

SPARC Researchers

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Dr Petar Igic
Dr Richard Lewis

SECTION 4: Hydrogen

Introduction

Hydrogen is an attractive, sustainable clean energy vector or carrier, with the potential to play a major role in future, low-carbon diversified energy systems. As a carbon free energy carrier, hydrogen can be used as a clean fuel for transport and the built environment and can be part of an energy storage system to enable greater penetration of renewables onto the electricity network. It can be used as a source of fuel for combustion, with no direct CO_2 emissions and the major output being water. Hydrogen can also provide a sustainable energy carrier for fuel cell electric vehicles (FCEVs), allowing greater vehicle range, short refuelling times, high efficiency energy conversion and the potential to improve air quality by eliminating emissions of sulfur dioxide, oxides of nitrogen, and particulates. Hydrogen can also be used to feed stationary fuel cell systems for buildings, backup power, or distributed generation. It can be used to store energy, particularly as a store for excess electricity for demand balancing of the electricity grid. As a result of the intermittent nature of most methods of producing renewable electricity, there will be future periods of under production and excess. Hydrogen can be generated during excess renewable production periods, stored and then converted back to electricity when demand arises. Hydrogen can be stored in various forms, but at utility scale an attractive storage solution is proposed by injecting this hydrogen into the gas grid, accepting that regulations would need to be updated to allow this to happen.

Figure 4.1 SERC's laboratory at Glyntaff.

Figure 4.2 USW's Hydrogen Research Centre at Baglan.

Hydrogen is already an established global industry. The estimated current global market for hydrogen is between 50-55 million metric tonnes p.a., growing at approximately 5% per year, servicing industries such as chemicals and petrochemicals, metals, food and electronics. Global hydrogen sales are equivalent to an estimated value of between $85-150 billion per year. As a result, there is significant global expertise in methods of producing and handling hydrogen. However, nearly all the hydrogen currently produced comes from fossil fuels. In order to progress the use of hydrogen as a clean source of fuel and energy storage, there are a range of issues to address and effective solutions required. These challenges relate to the efficient, sustainable, low carbon production of hydrogen and the with renewable energy supply systems, novel purification and storage solutions, and development of efficient end use application technologies based around electrochemical and combustion based conversion to power and heat. In addition to these technological developments, improvements are also required in cost and affordability, public awareness and acceptability, safety, regulation, codes and standards. Furthermore, the transition to market of hydrogen requires strategic planning at all levels and implementation to make hydrogen solutions available to end-users. The LCRI Hydrogen programme, via the CymruH_2Wales project has addressed all of these issues.

Overview

The Sustainable Environment Research Centre at the University of South Wales is one of the leading hydrogen and fuel cell research groups within the UK. With over 35 active research staff, SERC has multidisciplinary and internationally leading expertise in renewable hydrogen production, novel biogas and bioprocess systems, hydrogen storage, novel fuel cell developments and hydrogen energy systems. Led by Professor Alan Guwy, who also heads the University's Energy and Environment Research Institute, SERC's research activity is located at two main centres. The majority of the biogas and bioprocess research, together with the novel hydrogen and fuel cell material research is based at SERC's main laboratories in Glyntaff (figure 4.1). The Hydrogen Research Centre located at Baglan Energy Park (figure 4.2) is the location for SERC's electrolytic hydrogen, reforming and fuel cell systems research and provides the focus for much of SERC's industrial collaborative R&D.

The nature of the research that SERC undertakes in the hydrogen and fuel cell field means that the activity is largely collaborative, with industry and academic partners. This has been the case with the R&D conducted in the LCRI CymruH2Wales project, where collaboration with industry and LCRI partner institutions has focused on the following broad areas:

- Hydrogen and Renewable Electricity
- New Materials for Hydrogen Storage
- Hydrogen Vehicles and the Strategic Build up of Hydrogen Refuelling Infrastructure
- Biohydrogen and Biomethane Production
- Bioelectrochemical Systems (Microbial Fuel cells, Microbial Electrolysis and Microbially Catalyzed Electrochemistry)

In addition, SERC have contributed to the LCRI Smart Operation for a Low Carbon Energy Region (SOLCER) project in the area of Energy Storage.

Projects

Hydrogen and Renewable Electricity

At low levels of renewable electricity capacity, the electricity grid effectively absorbs the inherent variability of the electricity produced. However, as we increase the renewable portion of electricity supply towards the penetrations targeted by UK and Welsh Government over the next decade and beyond, the increased renewable contribution will increase variability in supply and the potential disparity between supply and demand. Hydrogen can act as a long duration energy store and can be used to overcome these imbalances caused by the intermittency of renewables. There is growing international evidence that this can be realised in an economically viable way in the near term, rather than being a remote future prospect. Furthermore, addition of hydrogen energy storage has the potential to avoid additional expenditure on grid strengthening, particularly for remote renewable grid connection in weak grid areas.

The University of South Wales (USW) has a substantial track record in the R&D of the link between hydrogen and renewable electricity (figure 4.3). Through the LCRI CymruH2Wales project USW has built on its investment in the Hydrogen Research Centre on the Baglan Energy Park. Specifically, R&D has focused on investigating the technical and economic viability of the production of electrolytic hydrogen from renewable electricity, with particular emphasis on the role of hydrogen in overcoming the variability of renewables. The CymruH2Wales project has also enabled the USW team to extend the level of industrial engagement in hydrogen energy storage collaborative R&D in Wales and provides a basis for further industrial development of electrolytic hydrogen technologies.

The past decade has seen a step-change in the acceptance of the need for effective electricity storage mechanisms to be developed to allow the integration of increasing levels of renewable electricity generation. This need is being recognised by the industry, but also increasingly by policy makers

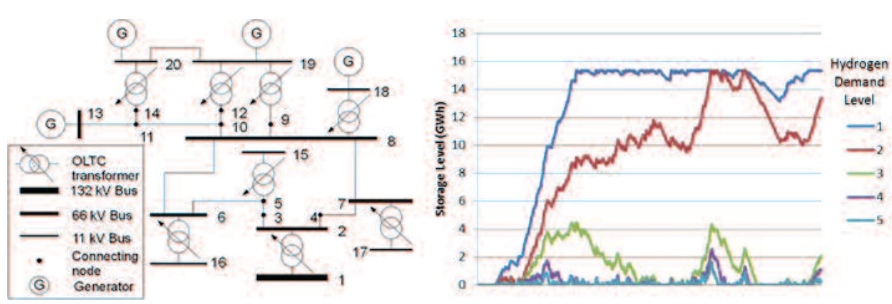

Figure 4.3 Left – Model of the electricity network in South Wales used to model hydrogen energy storage. Right – Modelled hydrogen energy storage scenarios to optimise wind power onto electricity distribution networks.

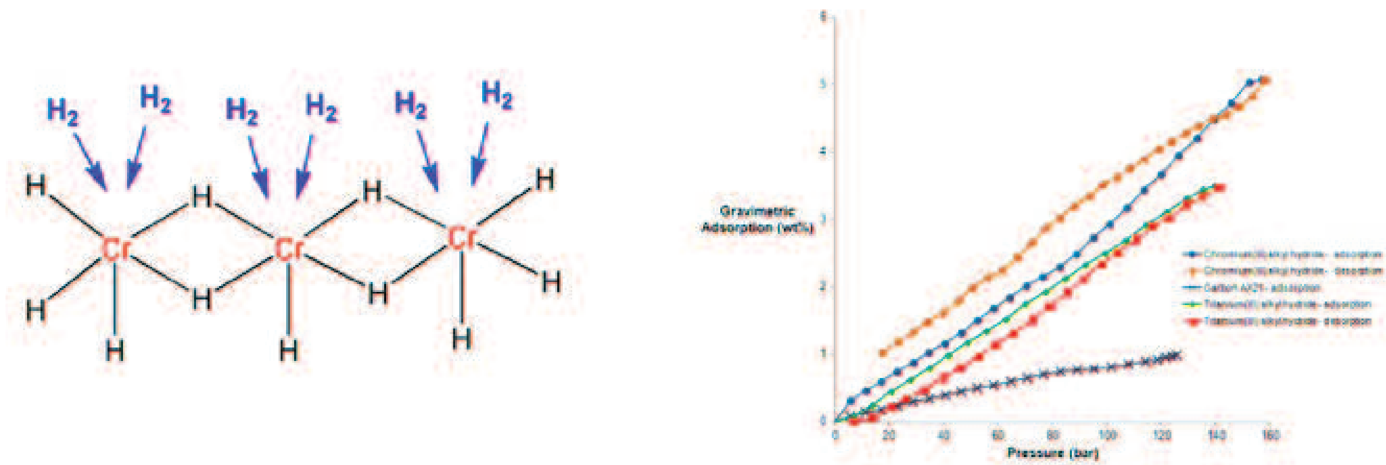

Figure 4.4 Left - Proposed structure of chromium(III) hydride with additional Kubas bound dihydrogen shown in blue. Right - H_2 adsorption–desorption isotherms of chromium and titanium hydride materials recorded at 25 °C.

in order to achieve CO_2 emissions goals, whilst keeping overall system costs in check. This need is not just to meet 2050 goals, but is apparent within the next decade. Alongside battery technology, pumped storage and other technologies, hydrogen provides a promising option to achieve large-scale electricity storage. The USW team has provided advice to the Welsh Government on this area and, as the need for large-scale electricity storage becomes more apparent, it is anticipated that there will be an increase in this activity.

Through the collaborative EPSRC SUPERGEN UK Sustainable Hydrogen Energy Consortium, the University of South Wales investigated the integration of hydrogen generation with embedded renewable energy systems. The research demonstrated that energy stored in the form of hydrogen could increase the amount of energy accepted onto the electricity networks. This research was extended via the LCRI CymruH2Wales project, particularly concentrating on the modelling, validation and optimisation of renewable hydrogen systems and investigation of novel system control methodologies, for on and off-grid renewable-hydrogen systems. An example of the academic output from this work has included techno-economic analysis and the development of an optimal power flow (OPF) methodology to investigate the provision of hydrogen as a means to maximise wind power generation in relation to a constrained electricity network. In addition, research has focused on the Life Cycle Assessment of electrolytic production and utilization of low carbon hydrogen vehicle fuel. As interest in hydrogen for energy storage increases, activity at the Hydrogen Centre will continue to include experimentation and academic analysis of the application of electrolytic hydrogen as an energy storage enabler.

The Hydrogen Research Centre has provided the base for a number of collaborative experimental development activities. In particular, electrolytic hydrogen equipment testing and development has been part of the collaborative activities with ITM Power, with a focus of investigating hydrogen for energy storage at scales from 1kW to multi-MW. Collaborative R&D in this area remains of significance, not just to the hydrogen industry, but also to grid operators, electricity generators and suppliers and to energy intensive industries. The potential cross-over to produce hydrogen as a fuel from grid electricity also provides an ongoing area of R&D interest.

These projects allowed extensive development of knowledge and experience in installing hydrogen storage equipment, including regulations, safety, protection and integration. Testing and monitoring of the operation of prototype units has led to design improvements of the equipment in future iterations. The centre is now equipped with two types of electrolyser, PEM and alkaline, at different capacities which enables researchers to further investigate the feasibility of hydrogen application at different scales, such as building, community and grid as well as at different topologies, such as on – and off grid. With the development of a wind power emulator and a solar test bed, the centre will be capable of testing the system's characteristics of hydrogen production under different renewable power inputs and further investigate the approaches to improve its performance.

New Materials for Hydrogen Storage

Hydrogen storage remains one of the most challenging areas in materials science. The goal is to pack as much hydrogen as possible into a given volume with minimum excess weight. The US Department of Energy (DOE) is the most commonly used international standard in this area and has set ultimate system goals of 7.5 wt% and 70 kg/m^3 at or near room temperature, but to date no material has come close to meeting these specifications. The two main classes of hydrogen storage materials are hydrides, which generally possess high hydrogen binding enthalpies that require exotic engineering solutions to deal with the excess heat absorbed and released when hydrogen is enters and leaves the storage materials, and physisorption materials, which use high surface area porous solids to bind hydrogen at very low enthalpies necessitating extreme levels of cooling at elevated pressures in order to function. Such cooling systems increase weight and reduce overall energy efficiency of the hydrogen storage system for this reason new classes of materials must be developed.

Research carried out in SERC as part of the LCRI projects involves the design and synthesis of specifically tailored transition metal polymers and gels for applications in a new type of hydrogen storage, in which Kubas-type binding (a type of weak chemisorption of hydrogen with enthalpies in the 20-30 kJ/mol range predicted to be ideal for room temperature application) is the principal storage mechanism, making them distinct from traditional hydrides and physisorption materials (figures 4.4 and 4.5).

The materials were first discovered in 2009 at the USW by Professor David Antonelli and graduate student Leah Morris and show remarkable storage properties with volumetric storage capacities that already are comparable to many of the 2015 DOE system targets without the drawbacks of physisorption materials or hydrides. These materials are thermodynamically neutral and have no kinetic or thermodynamic barriers to storage at 298 K (room temperature), and operate using pressures as the toggle for instantaneous uptake and release of hydrogen. Computational studies carried out by University College London suggest performances as high as 9.9 wt% in some cases, such that the potential of these materials in commercial applications appears exceptional at this early stage. One of the key objectives of recent work funded through the LCRI CymruH2Wales project has been to scale up the production of these novel materials. To help achieve such goals partnerships with Chrysler and Hydro Quebec have attracted significant inward investment to the Antonelli group resulting further grant funding to improve synthesis of the material via funding from Academics for Business (A4B).

Figure 4.5 SERC's activity includes the design and synthesis of transition metal polymers and gels for hydrogen storage using Kubas-type binding.

Hydrogen Vehicles and the Strategic Build up of Hydrogen Refuelling Infrastructure

Increasing evidence points to the benefits of introducing hydrogen vehicles for ultra low carbon transport. There are also opportunities for hydrogen vehicles to minimise local air pollution and for

Figure 4.6 Hydrogen Fuel Cell vehicles at Cardiff Millenium Centre. Manufacturers are preparing for commercial sales of hydrogen vehicles, but refuelling infrastructure needs to be put in place.

associated R&D and manufacturing to generate economic growth. However, this will all need to be supported by the development of a hydrogen refuelling infrastructure. Wales is well placed to be part of the early development of this infrastructure, partly due to the University of South Wales' activity on the LCRI CymruH2Wales project (figure 4.6).

The transport sector has traditionally been a major source of CO_2 emissions and whilst improvements have been made, it is clear that longer-term greenhouse gas emissions reductions targets can only be met through a shift towards ultra-low emissions vehicles. Hydrogen fuelled vehicles have been widely recognised as offering the best solution for reducing CO_2 (figure 4.7). However, hydrogen vehicles will need to refuel and to move from discreet demonstration projects, refuelling stations will need to be strategically located to enable the journeys that hydrogen vehicle drivers wish to take.

Wales has a number of advantages in the early adoption of hydrogen energy and hydrogen vehicles, including existing industrial hydrogen production capacity along the M4 corridor, a strong automotive sector, a large renewable energy resource and fleet vehicle

Figure 4.7 Hydrogen Fuelled Vehicles offer a Zero-Carbon Transport Solution.

activities. To realise the benefits to Wales arising from these advantages, the University of South Wales continues to play a leading role in the establishment of a hydrogen refuelling infrastructure in Wales and more broadly in the UK. Through the CymruH2Wales project, the University has taken a number of major steps forward, by establishing the first hydrogen refuelling stations in Wales and raising awareness and activity among industrial and government partners to the steps required to establish a hydrogen refuelling infrastructure.

The CymruH2Wales project has included an analysis of the strategic deployment of hydrogen refuelling stations in Wales as part of a broader UK and European network. The impact of this research has been to further inform the industry and government decision makers and assist in the strategic planning for the development of hydrogen refuelling infrastructure including optimal transition paths. This has specifically supported the dialogue with industry and government stakeholders to provide the basis for further infrastructure investment in Wales. To underpin this advisory role, the University's research in this area has included spatial, logistics traffic flow and technology-uptake modelling and mathematical optimisation. In addition, the research activity has covered the economic development of hydrogen production, storage and distribution technologies and has addressed the socio-economic aspects through collaborative effort with LCRI partners and other academic partners via the EPSRC SUPERGEN Hydrogen and Fuel Cell Research Hub.

One major advantage of hydrogen vehicles, whether fuel cell or combustion propelled, over battery electric vehicles is the range between refuelling and speed with which of refuelling that is consistently available. As such, it makes sense to take advantage of the range afforded by hydrogen in arranging refuelling stations. In a relatively small country such as the UK, it makes sense to deploy the initial stations along our main trunk routes. The initial output of UK H2Mobility had indicated the highest density of early stage hydrogen refuelling stations in the South East of England, although this has now been revised to take account of the range benefits afforded by hydrogen and the existing hydrogen activity hot-spots, like South Wales.

One way of deriving economic benefit from the development of the hydrogen refuelling infrastructure is to establish manufacturing capability in the sector. As a direct consequence of collaboration with the University of South Wales, ITM Power has established a wholly owned subsidiary ITM Motive in Wales to assist with the establishment of a hydrogen refuelling infrastructure. The ultimate intention is to establish a facility for assembly and after sales support. This aligns with the University's collaborative R&D in this area with ITM Power, in particular via the Innovate UK project "Island Hydrogen". Led by ITM Power the project includes partners such as Cheetah Marine, SSE, IBM, Vodafone, Arcola, University of Nottingham, NPL and Toshiba. Arising from the University's activity in this area on LCRI CymruH2Wales, the project sees the deployment of two hydrogen refuelling stations incorporating on-site electrolysis systems. The University has contributed through analysis and evaluation of electrolyser performance at the University's Hydrogen Research Centre in Baglan and advice on improvement of system design.

The University of South Wales established the first hydrogen refuelling station in Wales in 2008, at the Baglan Hydrogen Centre. As part of the CymruH2Wales project, the University has enhanced this refuelling station to include a renewable hydrogen export facility. The facilities at the Hydrogen research Centre also include the UK's only H2/CNG refuelling station, which enables R&D into emissions reduction from gaseous-fuelled engines. To broaden the R&D capability in Wales, the CymruH2Wales has also enabled the installation of Wales' second hydrogen refuelling station, 38 miles away at the University's Glyntaff campus. These novel fuelling stations provide the basis for hydrogen vehicle R&D and demonstration, for vehicles developed by the University and with industrial partners.

These developments are valuable in enabling initial vehicle research, development and demonstration, but the establishment of a full-scale refuelling infrastructure requires a major effort from government, finance sector and industry. It is also clear that this cannot happen in Wales in isolation from activity in the rest of the UK. To support the roll out of hydrogen infrastructure networks in the UK and with the specific aim of encouraging the introduction of Hydrogen Fuel Cell Electric Vehicles (FCEVs), the Office for Low Emission Vehicles (OLEV) launched the HRS Infrastructure Grants Scheme in February 2015. The scheme will provide up to £5.5 million in capital grant funding over 2 years (2015-17) for infrastructure projects seeding the development of an initial hydrogen refuelling network in the UK. The University of South Wales has managed to secure over £400k funding from this scheme to upgrade the existing hydrogen refuelling station at the Baglan Hydrogen Centre (figure 4.8). The upgrade will enable hydrogen vehicles to be filled at pressures of 350bar and 700bar. The station will meet all the latest international standards and will have a full capacity of 80kg/day. It is anticipated that the upgraded refuelling station will be commissioned during the early part of 2016.

Biohydrogen and Biomethane Production

SERC has been working on improving the performance of hydrogen and methane production from biomasses resources using naturally occurring micro-organisms. Research has been targeted at utilising low grade biomass resources which are not directly used as primary food resources. These substrates have included high sugar grasses, wheat straw, food waste, whole crop maize,

Figure 4.8 SERC have just won an OLEV grant of £400k to upgrade the hydrogen refueling station at Baglan.

wheat feed and sewage biosolids. SERC's expertise in the work of both biohydrogen and biomethane research is recognised internationally. Improved performance monitoring techniques to improve reactor performance have been investigated including magnetic induction spectroscopy (MIS), mass spectrometry and artificial intelligence approaches using FT-Near Infra Red (NIR) sensor data. Other optimisation techniques include the development of molecular biology techniques such as Q-PCR and pyro-sequencing to identify productive microbial cultures or systems.

The integration of a biohydrogen production reactor with a conventional methanogenic reactor treating wheat feed (a co-product of wheat feed) showed a 37% increase in methane yield and when fodder grass was used an 18% improvement in methane yield was also achieved (figures 4.9 and 4.10). As a result of their work the SERC team has developed an improved integrated anaerobic bioprocess with significantly improved productivity over conventional biogas systems. This work also identified that the quality of biogas could be enhanced with the addition of a hydrogen rich biogas and the added advantage of better process stability and improved waste stabilisation. SERC are working on an even more advanced process that couples the biohydrogen fermenter with microbial electrolysis instead of the biomethane process to produce a 100% H2 biofuel. The biohydrogen process could also be used to produce liquid high in volatile fatty acids as a platform for the production of sustainable chemicals.

SERC have published 19 international refereed journal papers in the area of biohydrogen and biomethane production and microbial electrolysis (ME) production of hydrogen as well as one patent application arising from the LCRI CymruH2Wales project. Funding has been sought from the UK research councils and European Framework funds to further support this work. In particular, this area of research was the only hydrogen production research supported in the EPRSC SUPERGEN Sustainable Hydrogen Energy Consortium renewal operating from 2007 until 2012.

Funding has been recently granted as part of the EPSRC to investigate the integration of electrodialysis and ME to further enhance the production of hydrogen from low grade biomass. The H2&FC SUPERGEN Hub champions the complete hydrogen and fuel cell landscape in and outside the UK. SERC has two members on this consortium's scientific board, thus representing this key area of research within the consortium and globally. The University's expertise in the work of both biohydrogen and biomethane research is recognised internationally by the selection for the UK representation on the International Water Association Anaerobic Digestion Committee and the IEA-HIA Task group for Biohydrogen.

Fig 4.10 Advances made by SERC have resulted in up to 37% increase in biomethane yield through the integration and optimization of a biohydrogen rector.

Bioelectrochemical

Bioelectrochemical Systems (BES) describe Microbial Fuel Cells (MFC), Microbial Electrolysis (ME) and several other processes use living microorganisms as catalysts to directly generate electrical power from the considerable chemical energy available in biomass, wastes and effluents and this power may be used externally as a power source as MFC and as hydrogen in ME. The developments at USW will contribute to increasing global energy resources by making the chemical energy in low value biodegradable waste streams, available for the production of energy carries (electricity, hydrogen, methane, fuels or chemical reducing power) and by driving resource recovery and material production Hence waste treatment is an important collateral feature of BES.

As MFCs are a subset of BES and as such can inform a plethora of BES applications in respect of some of the key questions associated with the deployment of the technologies. Scale-up is an important and complex issue, as are the increase of power at scale and the suitable integration of BES with other processes, for optimal benefits. The important issue of stability and control of modular

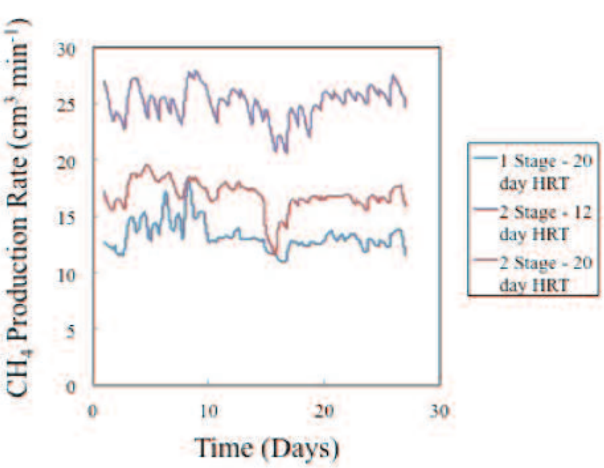

Figure 4.9 SERC's biohydrogen R&D has developed enhanced yield and increased measurement accuracy from 2-stage bioH2/bioCH4 fermenters. Repeatable methane yield increases of up to 37% have been reported from the 2-stage process.

stacked devices has also been studied by the team through a programme of research, which has contributed significantly to the understanding and resolution of these hurdles.

SERC has focused on improving power performance through novel scalable designs of MFC and ME systems. The systems are able to convert waste streams, crops and/or other co-products, directly into electricity, hydrogen, or other materials and functions; and can simultaneously treat waste streams. Hence, their industrial applicability lies primarily in making use of such low grade energy such as in waste-waters and consequently, large volumetric throughput is an important target.

SERC's BES research is continuing within a NERC project Resource Recovery from Waste which is led by Newcastle University and includes University of Surrey and University of Manchester along with several leading international affiliate company interests. Further funding has been secured from the new EPSRC SUPERGEN H2FC Hub to investigate enhanced generation of hydrogen by integration other biological hydrogen processes with microbial electrochemical processes. This follows work, which was funded primarily through the RCUK SUPERGEN Biological Fuel Cells Consortium project, led by Oxford University (financial hub) and University of Surrey (as the management hub), together with the Universities of South Wales, Glasgow, Newcastle, UWE, UCL and UEA. Follow-on funding was secured as part RCUK SUPERGEN Biological Fuel Cell Consortium Project, from April 2010, in which USW continued as lead for the Microbial Fuel cell Theme.

In respect of scale-up, the team has increased the system capacity without the associated loss of performance which is typical and which derives from internal over potential losses (figure 4.11). The tubular reactor system was able to increase the electrical power in direct relation to the capacity of the system; hence showing a mechanism for scale-up which simultaneously considered manufacturability of the system. SERC has developed novel scalable MFC and ME system and since 2009 the team has published 26 refereed journal papers in the area of MFC/BES in high impact journals e.g. Journal of Energy, Environment and Science.

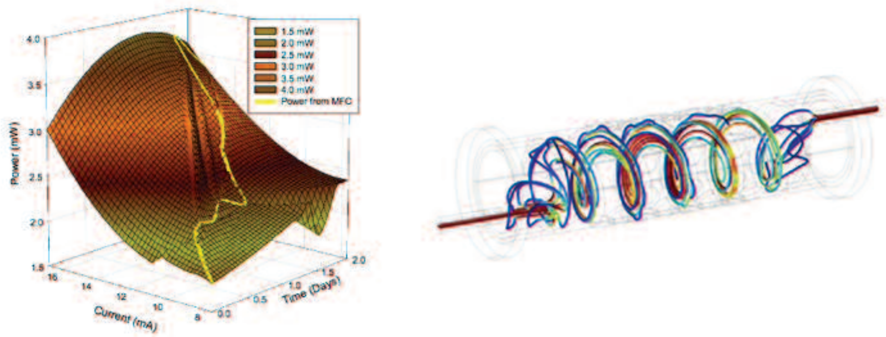

Figure 4.11 Left- Maximising power extraction from an MFC during system acclimation Right- Modelling the flow path through helical MFC anodes.

The power density of the tubular system has also been increased from approximately 6W/m^3 to 30W/m^3, with the volume referring to the anode chamber capacity in an air cathode MFC. A power density to a peak 63 W/m^3, a 10 fold increase has been recorded. Operating conditions are of considerable importance in MFC/BES where the metabolic processes live organisms and the associated electrochemistry, define performance. SERC has shown that operation in temperate climates without the need for heating, is plausible, which is untypical of other microbial bioprocess. Operation at 15^{o}C would save significantly on operational energy costs. USW have filed two patents to protect SERC novel developments in this rapidly growing area of low carbon research (figure 4.12).

An industrial feasibility study has been conducted, during which 15 companies from a number of different sectors were engaged. A study was also conducted to ascertain the efficacy of our first generation tubular MFC system to remove pollution in energy efficient way, reducing costs of discharge of waste-waters to sewer (figure 4.13). Several funding applications with support from various companies across Europe have been made as a result. For example, investigation with support from e.g. Mast Carbon and Fuji Film in which the companies provide specialist materials for use in an MFC, are continuing.


Figure 4.12 Patented Tubular Microbial Fuel Cell.

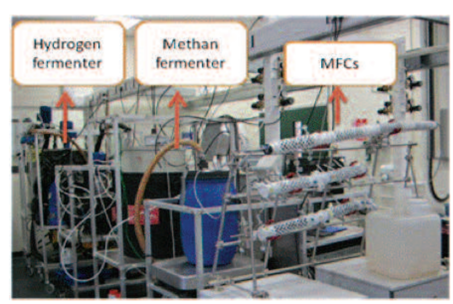

Figure 4.13 SERC are investigating the integration of Bioelectrochemical and Fermentative hydrogen and methane production.

Biopolymers

One of the research areas which SERC has been developing and demonstrating is the conversion of organic wastes and low value biomass to a low carbon polyhydroxyalkanoates (PHAs) biopolymers and other precursors i.e. carboxylic acids and nutrients, which can also be used in numerous industrial and agricultural sectors. This biopolymer synthesis research was initiated under the CymruH2Wales project, initially investigating the potential to produce biopolymers from the organic residue of the 2-stage biohydrogen/ biomethane process.

PHAs are biobased, bioproduced and biodegradable plastics with applications in a variety of sectors e.g. medical and packaging. Considerable investigations have already been carried out towards developing the process of PHA production using bacteria. The R&D work has involved the integration of energy processes such as biohydrogen and anaerobic digestion with the PHA production process using pure bacterial cultures. Investigations have included the development of novel operational strategies as well the establishment of innovative monitoring, modelling and control systems in order to improve the biopolymer production through process conversion efficiencies, sustainability as well as costs.

The immediate impact of this area of research has been the increase in the interaction between industrial partners and academic partners with an interest in developing the biopolymer supply chain, both in Wales as well as in the UK and in the EU. Interaction between industrial and academic partners has improved the relevance of research and development activities undertaken, and is expected to accelerate the uptake of processes and products developed. Two product improvements have been achieved and 3 new processes have been trademarked.

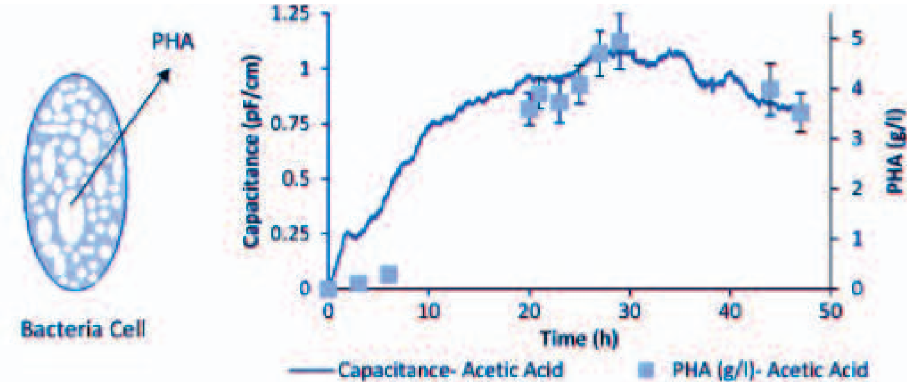

Figure 4.15 Optimising the polyhydroxyalkanoates (PHA) harvesting time from bacterial cells by measuring capacitance in real-time.

A feeding strategy for carboxylic acids generated from a variety of organic wastes was developed to avoid inhibition and allow process intensification and a reduction of process footprint. An enhanced 30% biopolymer accumulation was achieved using a non-reactive, non-toxic, and low-cost NaCl addition of 9 g/l.

The novel use of low cost digestates based media was demonstrated. Results showed that due to possibly the nutrients/trace elements in digestates (from food wastes and wheat feed) the PHA accumulation was enhanced by 3-fold (to 12.29 g/l) as compared to conventional nutrient media; with a resulting highest-ever-reported PHA accumulation of 90% from pure culture bacterial sources.

A novel application of a capacitance probe was demonstrated to be able to monitor maximum PHA accumulation in-situ and in real-time, so as to prevent product and substrate loss, and to increase PHA process understanding and fermentation kinetics (Figure 4.15).

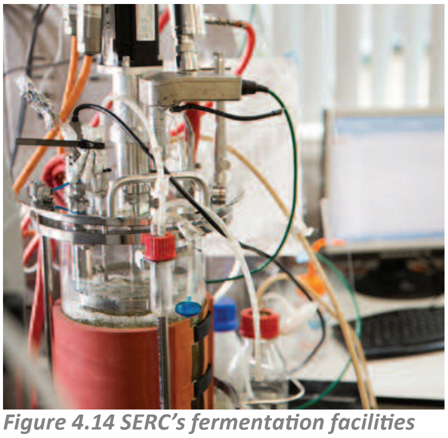

Figure 4.14 SERC's fermentation facilities for pure bacterial cultures where short chain polyhydroxyalkanoates (PHAs) are produced from a range of organic wastes.

Biopolymer research transcends a number of sectors including biotechnology, manufacturing and process engineering, retail, as well as wastewater treatment and waste management. Such interactions have already aided in securing future funding streams for further process development and optimisation, commercial deployment and high quality impact publications.

The work initiated during the CymruH2Wales project has continued through the Systems and Product Engineering Research for Polyhydroalkanoates (SuPERPHA) project, which was a Collaborative Industrial Research Project (CIRP) supported by the ERDF and Welsh Government through the Academic Expertise for Business (A4B) funding programme. These projects have included collaboration with Swansea and Bangor Universities and the companies Aber Instruments, Loowatt, Welsh Water, Thames Water, FRE-Energy, Axium Process, Kautex-Textron, Excelsior, Waitrose, NCH, Nextek, SciTech and Veolia/Anoxkaldnes. Two product improvements have been achieved and 3 new processes have been trademarked.

Figure 4.16 SERC developed a building scale hydrogen energy storage test rig, with ITM Power.

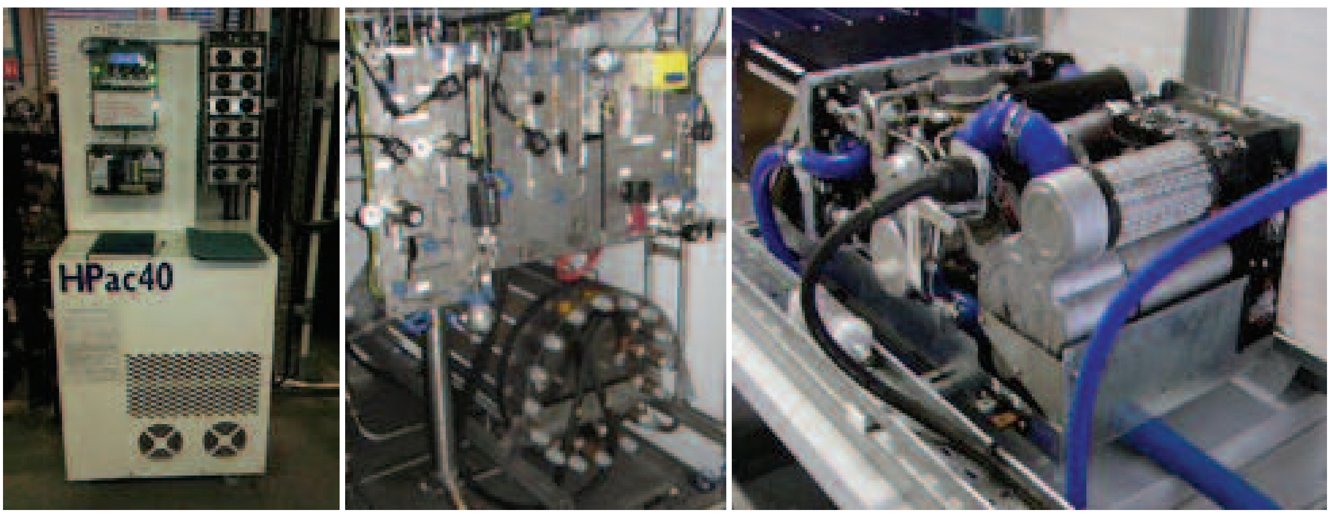

Figure 4.17 Two larger scale (12kW and 48kW) hydrogen based energy storage systems rigs.

SOLCER Energy Storage Research

The issue of energy storage is emerging as an important aspect of energy technology and policy. However, the topic is complex and not well understood in technical, commercial or policy terms. As a direct result of this project, further dialogue with the Welsh Government and industry stakeholders has initially identified the importance of energy storage, particularly at grid/urban scale to Wales' energy future.

SERC's role in the SOLCER project was to lead the activity on energy storage within the context of a full energy system at building, community and urban/grid scale. Energy storage is an increasingly important element of the whole energy system, particularly in the context of carbon reduction, where storage has a role in balancing between the variable supply of renewable electricity and end user demand. Heat storage is also an important feature of the future energy system, particularly in optimising energy efficiency.

Much of the technical output has developed understanding, both technical and commercial, of energy storage. In particular, there is a much deeper understanding of the benefits and constraints of different energy storage systems at different scales, especially hydrogen energy storage and power-to-gas energy storage (figures .4.16 and 4.17). The project has supported the need for energy storage, particularly electricity storage, as part of a future low carbon electricity system. This is particularly the case at grid scale, where the intermittency of increased large scale renewable electricity supplies have potential to cause imbalance between supply and demand, necessitating either storage or expensive curtailment of renewable electricity supplies. The project has also demonstrated that hydrogen based energy storage systems can be both flexible in accommodating wide variation in input power and enable long term, but fast response provision from storage to demand (figure 4.18).

Investigation from the project has identified the opportunity to use the natural gas grid as the storage mechanism for hydrogen used to balance occasional over-production of renewable electricity and imbalance between supply and demand. There are technical and administrative/legislative constraints to this and further R&D and demonstration activity is necessary. However, there is compelling evidence that this Power-to-gas approach is a cost – and technically effective method of grid scale electricity storage to meet the needs of the overall energy system based on high penetration of renewable electricity supplies. As well as providing effective supply and demand management, there is also a case that this approach will avoid some of the considerable expenditure on electricity grid strengthening anticipated by the proliferation of large-scale renewable electricity supply.

Investigation suggests that battery storage technology has improved significantly over the last decade, but technical and cost constraints, scale issues together with long-term durability constraints mean that battery storage is less likely to be attractive to grid scale electricity storage. However, battery storage becomes more viable for certain community scale and off-grid buildings, as well as the current application of providing power back up for critical applications. There is also a clear acceptance, supported by the findings of the project that electricity storage should be complemented by demand management approaches (from domestic to industrial to grid scale). The technical and market complexity of the electricity system means that a co-ordinated approach is required to ensure that counter-productive measures are not adopted as the system develops.

The investigation by the USW team on the project has provided less compelling evidence for the need for electricity storage at the domestic/ individual building scale, where the building is connected to the electricity grid. The cost and overall economics, complexity, space and load requirements, safety aspects and technical need for building scale electricity storage is not well supported by the evidence. Off-grid buildings present a different challenge and in this case the integration of storage into building's overall electricity system.

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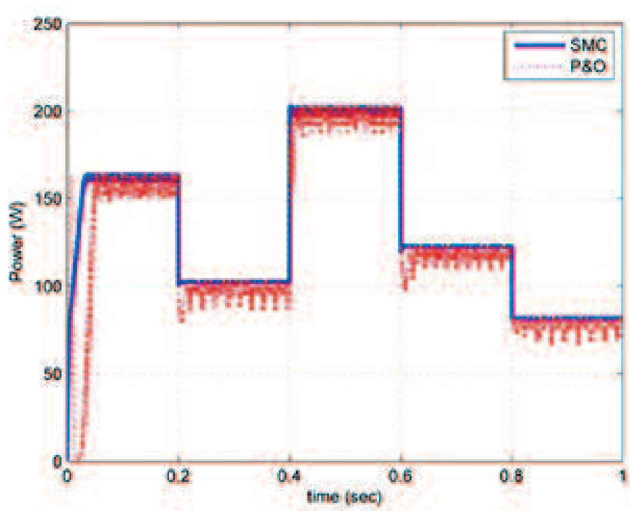
Dr Stephen Carr
Dr Tim Patterson



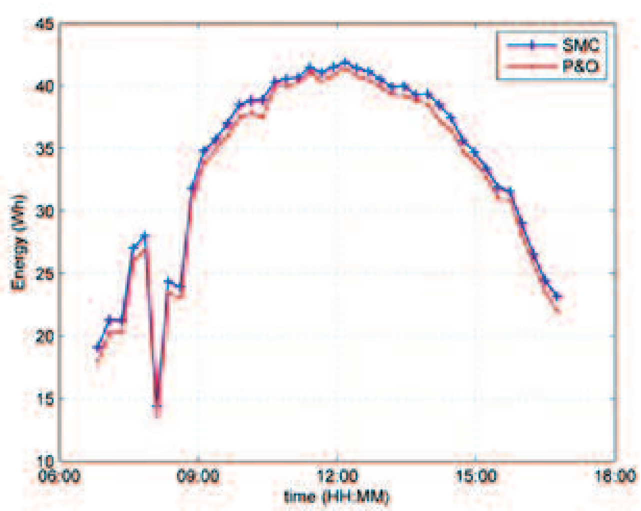


Figure 4.18 Research on the SOLCER project has enabled the development of a novel photovoltaic MPPT method based on a sliding mode control strategy, which has benefits for energy yield.

SECTION 5:
Large Scale Power Generation (LSPG)

Introduction

Gas is a significant source of energy in the UK and will continue to be so into the future, whilst gas turbines are increasingly used to generate electricity. At the same time the increase in renewable power sources introduces intermittency on the grid supply, and in future a variety fuels could be stored in the gas grid causing variations in fuel mix. The ability of gas turbines to accommodate these changes is therefore of concern to the power generators.

Research interests in relation to gas turbines and the low carbon agenda include:

- Fuel flexibility: this relates to the functionality of gas turbines to be able to accommodate changes in fuel mix, for example increased hydrocarbons or hydrogen in the natural gas supply. There is the potential for enriching the gas supply to gas turbines with hydrogen generated from excess renewable power. Alternatively, gasification of solid fuels (for example biomass) results in so-called syngases (including hydrogen and CO) which may be integrated with carbon capture technology before entering the combustor. These processes again pose challenges to the gas turbine in accommodating such a wide range of potential fuel mixtures. Burners are sensitive to the gas mix, but in future will require greater flexibility and control.
- Operational flexibility: relates to gas turbines being able to modulate with changes in load, driven by, for example intermittency of renewable energy supply. Part load efficiency is a concern, whilst ramping gas turbine up too quickly can introduce instabilities and resonances in the combustion chamber. The latter leads to performance degradation of the gas turbine and may even result in the gas turbine being taken offline if the amplitude of the instabilities gets too high. This abnormal running of the gas turbine will also create higher emission profiles.

Figure 5.1 The Gas Turbine Research Centre at Margam.

Burner emission performance, including pollutants NOx, CO and particulates, is an integral part of the optimisation process. Also, associated risks and hazards need to be understood and quantified, for example, in relation to explosion hazards after accidental fuel releases. These considerations provide further research opportunities.

Overview

Cardiff School of Engineering's Gas Turbine Research Centre (GTRC) at Margam (figure 5.1) is carrying out research on a wide variety of projects including fuel variability, operational flexibility and risk and hazard assessment. The research is led by Professor Phil Bowen of Cardiff University. He states that, 'initial LCRI capital funding has been used to set up a world leading experimental simulation facility through the addition of a flexible 5-component gas mixing station to its high-pressure/temperature facilities' (figure 5.2). This new mixing station can accurately mix different fuel compositions, including varying concentrations of hydrogen. This facility was utilized on a leading £560k EU FP7 project, led by the EU Turbine Network (ETN), to investigate hydrogen-rich syngas from high-efficiency gasification processes with or without carbon capture. Further industrial collaboration with EON and Tata has resulted also, as well collaborative research with SMEs on other issues including fuel variability through fuel conversion processes.

This new facility has also enabled the GTRC to become recognised in the EU as a prestigious research 'Infrastructure

Facility'. It is part of Europe's bio-energy facility network – the EU-FP7 project 'BRISK' – which funds operation of the facility to allow pan-EU industrial and academic access.

Figure 5.2 The 5-Gas Mixing facility with gas storage hard standing.

In relation to the potential for huge CO_2 savings in the process industries, work with Tata has investigated the impact of fuel variability from gas captured from its Port Talbot steel making processes. These gases can then in principle be utilized onsite for heat or power, to reduce energy costs and the environmental footprint of steel making, significant steps towards low carbon steel production.

Cardiff's School of Engineering also has a well-established 20-year international reputation for risk, hazards and safety in the energy sector and is currently contributing to the development of international standards in this field. For example, an HSL-led joint-industry project is developing a new methodology to assess explosive area classification for high-flashpoint liquid fuels, which will inform the development of international standards – a critical step in getting low carbon transport fuels approved for future application.

Within the LCRI suite of projects, the LSPG project has worked with the LCRI Hydrogen Centre in the development of a potential hydrogen economy, including jointly hosting a conference on 'low carbon power generation'. There has also been productive collaboration with Aberystwyth's Institute of Biological, Environmental and Rural Sciences (IBERS) on biomass gasification research, for example with SME Spencer ECA, a biomass fuel supplier.

Burner testing facility

Swirl burner combustor designs have emerged to achieve emission requirements while maintaining the high combustion efficiency and good flame stability characteristics of conventional combustors.

The key experimental test rig comprises of a High Pressure Optical Chamber (HPOC) allowing for the observation and optical analysis of gas and liquid flames operating in diffusion and premix modes. In non-premixed combustion, fuel and oxidizer enter the reaction zone in distinct streams. This is in contrast to premixed systems, in which reactants are mixed at the molecular level before burning. Examples of non-premixed combustion include pulverized coal furnaces, diesel internal-combustion engines and pool fires.

The CAD drawing of the HPOC can be seen in figure 5.3a. The combustion air is supplied by a 2.2MW Joy compressor capable of delivering up to 5kg/s of air at 16bara. This air is pre-heated by a non-vitiating heater capable of raising the air temperature to 900K. The setup time before the Joy compressor and heater can be started is one hour, after which time the hot air is used to heat the pipe-work and rig until a steady state is reached, which takes a further hour after which time combustion experiments can begin.

Combustion air enters the high pressure casing via twelve flexible metallic hoses and then through a perforated drum before entering the air plenum. The perforated drum ensures a more uniform air flow characteristic in the plenum.

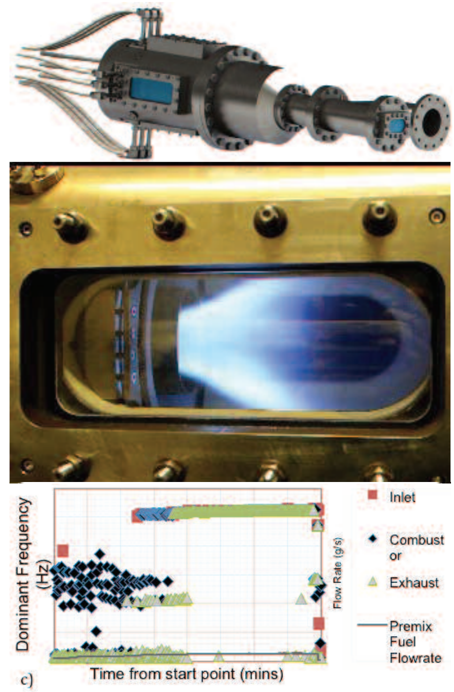


Figure 5.3 a) CAD model of the High Pressure Optical Chamber (HPOC) b) HD still image of gas turbine combustor in HPOC and c) acoustic results from dynamic pressure transducers during HPOC combustion experiments.

Combustion can then happen in the chamber following on from the injector as observed in figure 5.3b. Fuel is supplied by a series of Coriolis mass flow controllers, capable of providing up to 5 gas components, which allows for the simulation of a variety of natural gas or syngas components. Liquid fuel is delivered via a pressurised accumulator which can supply different liquids including heating oil, kerosene and bio-derived oils. Oxygen enhancement is supplied either unmixed or pre-mixed with the air upstream of the inlet, where the fuel is then introduced to the oxidant mixture via a specific mass flow controller. Downstream of the combustor in the exhaust there are thermocouples to give representative turbine entry temperatures. High Speed imaging was also used, as captured in figure 5.4.

A back pressure valve is used to pressurise the combustor and upstream of this the gas analysis sample is taken. At this point the gas sample is quenched and maintained at 150°C ±5°C for analysis. Combustor acoustics are measured using

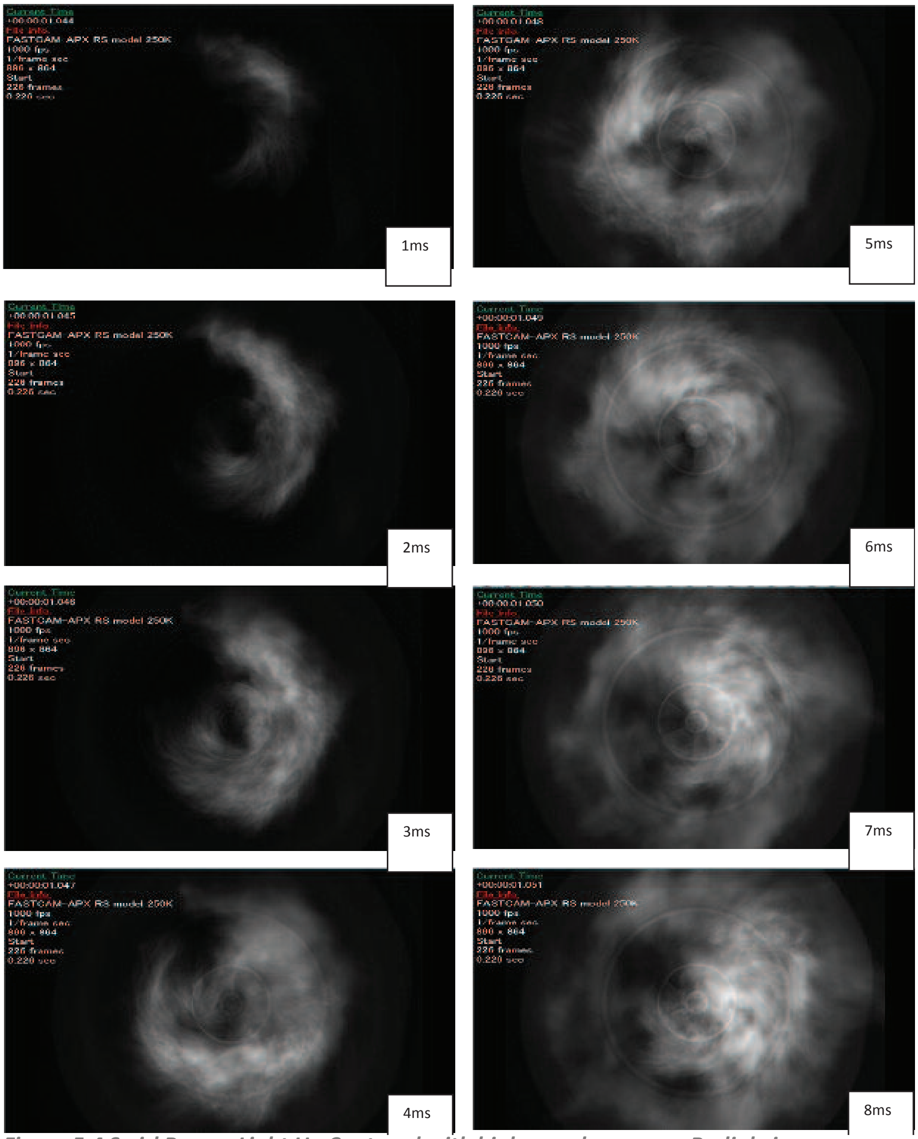


Figure 5.4 Swirl Burner Light Up Captured with high speed camera – Radial view.

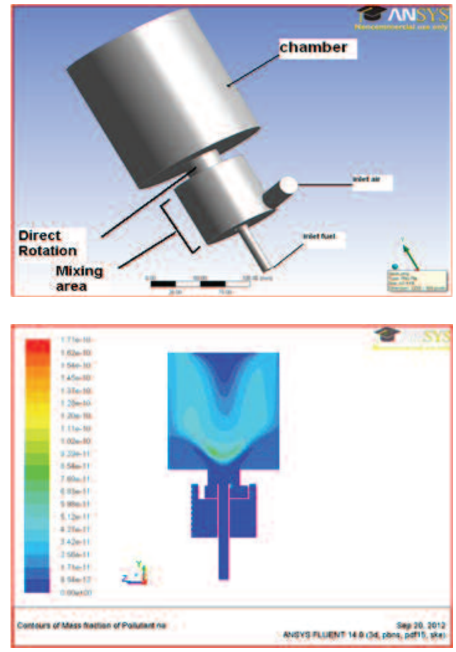


Figure 5.5 Modelling of syngas combustion in the High Pressure Generic Swirl Burner.

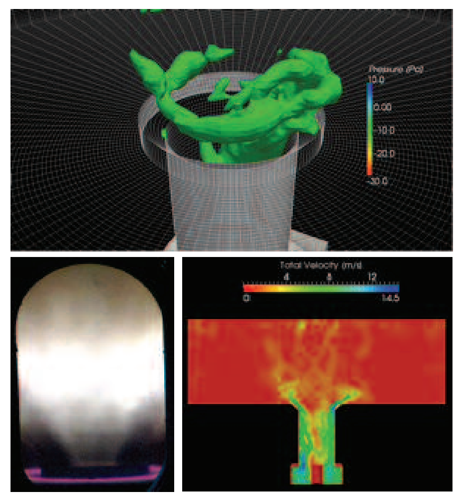


Figure 5.6 Modelling and validation of a swirl burner demonstrating Flashback.

multiple dynamic transducers across the rig. All data is logged continuously at 1Hz, and the dominant acoustic results plotted against fuel flowrate are shown in figure 5.3c.

Numerical models were used for solution of turbulent swirling flows using the standard k-ϵ model for non-premixed combustion. Combustion simulations were performed on the High Pressure Generic Swirl Burner (HP-GSB) with the use of the commercial CFD software FLUENT. The simulations were with the turbulence selection of a non-premixed combustion system as shown below in the figure 5.5.

Further simulations were performed studying the instability limits and effects of flashback and blow-off on the generic swirl burner, as shown in figure 5.6.

Projects

The LSPG project has added a research capability that has been utilised to deliver projects and enable the group to acquire further funding from UK and European research bodies – and to be recognized as a facility contributing to internationally-leading research in the field.

EU-FP7 Project 'H2-IGCC'

This €17.8M EU-FP7 research project, led by ETN, has investigated the design of gas turbine burners to accommodate variations in fuel mix. Burners may need to operate across a range of fuels, Hydrogen enriched, CO_2 enriched as part of post combustion stripping and standard methane burners may need to change from gas mix one to another due to failure in the system. The main goal of the project was to demonstrate and de-risk components of an Integrated Gasification Combined Cycle (IGCC) process with the potential for pre-combustion carbon capture.

This information was provided to manufacturers Ansaldo, Siemens as well as researchers at the full-scale ENEL test site at Sesta in Southern Italy to inform the design and delivery of their full-scale test programme. The output and impact of this research programme has informed burner design for the development of IGCC-CCS systems. This data provided by GTRC in this programme provides an excellent benchmark for future low carbon developments by manufacturers.

Cardiff's role within the project was to support the Italian gas turbine manufacturer (Ansaldo) in assessing the performance of their combustor designs under various fuel combinations and operating conditions. New burners were manufactured and an optical chamber was re-designed to enable safe and representative combustion-scaled research and diagnostics up to 2MW output. Phenomena such as combustion flashback, blow-off and zones of oscillatory combustion were recorded utilising a variety of diagnostics techniques.

European Aviation Safety Agency (EASA): 'SAMPLE' series of projects. Developing Methodologies for characterisation of Aviation particulate emissions

This research has investigated the levels and characteristics of particulate pollution exhausted from civil aircraft engines. GTRC was first invited to contribute to the EASA funded consortium project in 2009 in support of industrial partner, QinetiQ. Other partners include leading institutions in this field such as Onera (France), DLR (Germany) and University of Manchester.

The original role of GTRC was to provide a gas turbine simulator to enable various diagnostic techniques for the measurement of airborne particulates from aero-engines to be appraised and compared. This first SAMPLE project was led by DLR (Germany), and has led

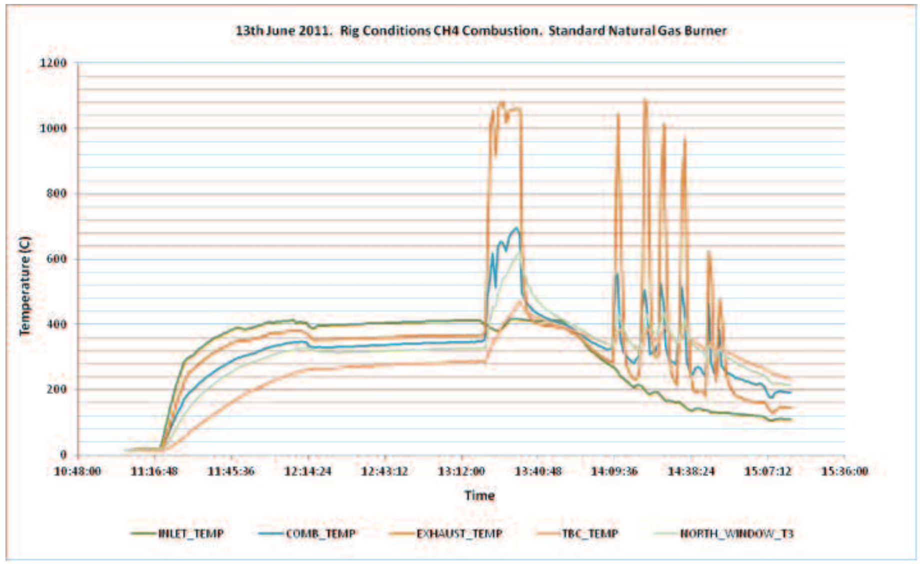


Figure 5.7 Thermal performance and rig conditions of a CH4 gas turbine burner.

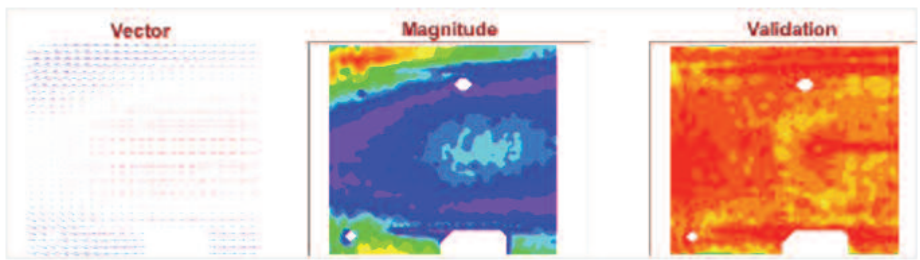


Figure 5.8 Axial Characterisation of swirl in a gas turbine burner.

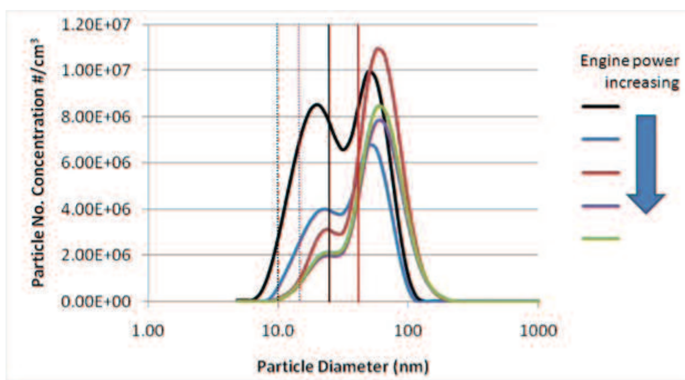


Figure 5.9 DMS500 Size Spectral density chart showing the rich burn aero-engine conditions.

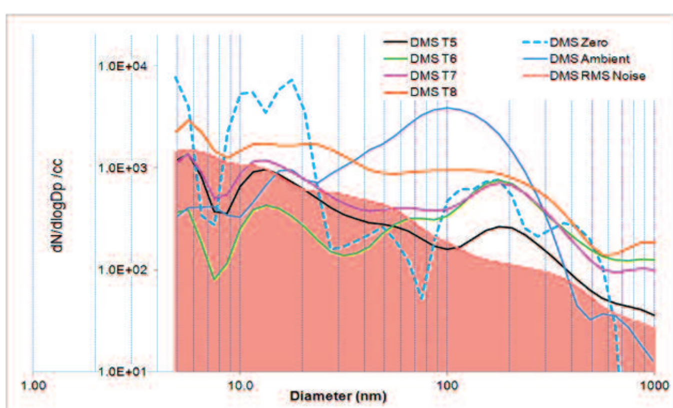


Figure 5.10 DMS500 Size Spectral density chart showing the zero, ambient and RMS limits of detection against the low carbon lean burn aero-engine conditions T5-T8.

to a continuing series of funded projects from EASA since, amounting to over £1M research funding to Cardiff University.

LCRI research fellows were actively engaged in the SAMPLE series of programmes, which is providing the EU contribution to development of a unified international standard for measurement of airborne particulate emissions from aero-engines. Former LCRI Research Fellow Andrew Crayford is now an elected member of the international SAE E-31 Aircraft Exhaust Emissions Measurement committee advising the International Civil Aviation Organisation (ICAO).

EU-FP7 Project 'BRISK': Research Infrastructure Network in Biofuels

EU Research Infrastructure Networks are prestigious networks of rare/unique research facilities and infrastructures across Europe, which have been collectively funded to enable EU researchers access to world-class facilities in areas of strategic importance. CERN is probably the most well-known example, though this unusually is a single-site RI facility. GTRC is a founding member and member of the Executive Committee of the BRISK network consortium, Europe's research infrastructure network of facilities for biofuels research.

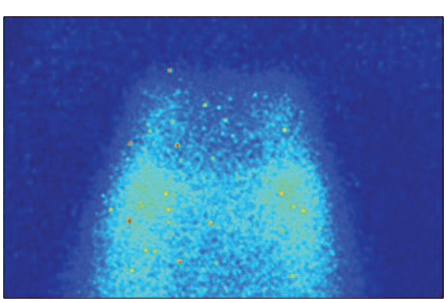


Figure 5.11 Averaged PLIF Image of Butane burner during commissioning –Axial view.

There are only two members of the BRISK consortium from the UK, Cardiff and Aston. GTRC will deliver access up to five research programmes. The output and impact of this research project will enable the development of new bio-related fuels and processes throughout the EU e.g. an Italian manufacturer is developing technology for utilising waste bio-fuels, appraised at GTRC as part of the BRISK project.

Industrial Consortium: Development of International Standards for pressurised storage and transportation of liquid fuels

This research investigates and develops legislation and guidelines in relation to transporting and pressurising gaseous fuel, through the application of knowledge of two-phase fuel characterisation and flame propagation. GTRC is the main research subcontractor on this multi-industry research project, which aims to develop a new international standard for explosive area classification for pressurised releases of high flashpoint liquid fuels (figure 5.12). A recent review demonstrated how these types of hydro-carbon explosions are more common than previously anticipated. Various advanced optical techniques are being used to characterise accidental releases of pressurised high-flashpoint liquid fuels, and this data is then being utilised to validate simulation methodologies or to derive simpler engineering guidelines which can be utilised in international standards, this has far –reaching applications including the acceptance of low carbon biofuels.

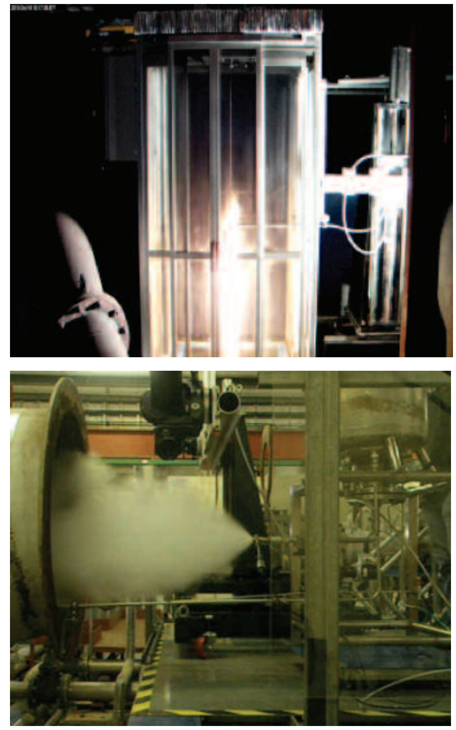


Figure 5.12 Ignition and releases of various different liquid fuels.

EPSRC Project: 'FLEXEPLANT'

This research investigates the flexibility of gas turbine combustion in relation to fuel variations, for example, hydrogen, methane and LNG. This £5M EPSRC project comprises six university partners led by Loughborough and includes Cardiff, Cranfield, Nottingham, Imperial, Warwick, and a broad range of industrial partners comprising most UK operating utilities and manufacturers, such as Siemens, EON, Alstom, RWE. The project is over 50% funded by industry, with Cardiff's total project value over £400k. This project is subdivided into four work programmes, with Cardiff leading the Combustion Fuels and Operability work package.

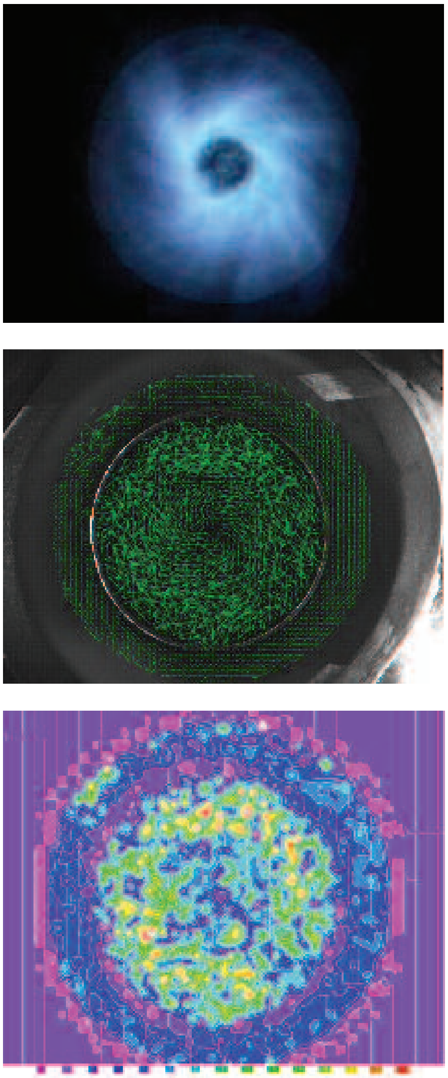


Figure 5.13 Radial Characterisation of swirl in a gas turbine burner.

The output and impact will provide guidelines to operators and manufacturers concerning ranges of stable operation of gas turbines as well as appraisal of new diagnostic techniques in order to improve the synergy of gas turbines as standby power for intermittent renewables.

EPSRC Project: 'SELECT' Selective exhaust gas recirculation for carbon capture with gas turbines

This £1.1m consortium project, led by former LCRI Research Fellow Richard Marsh and Cardiff/GTRC, includes Sheffield and Edinburgh Universities, and is investigating the influence of exhaust gas recirculation on an integrated gas turbine power generation/CCS system. The research will provide advice to manufacturers and operators on the influence of passing increased selected exhaust products through the GT burner.

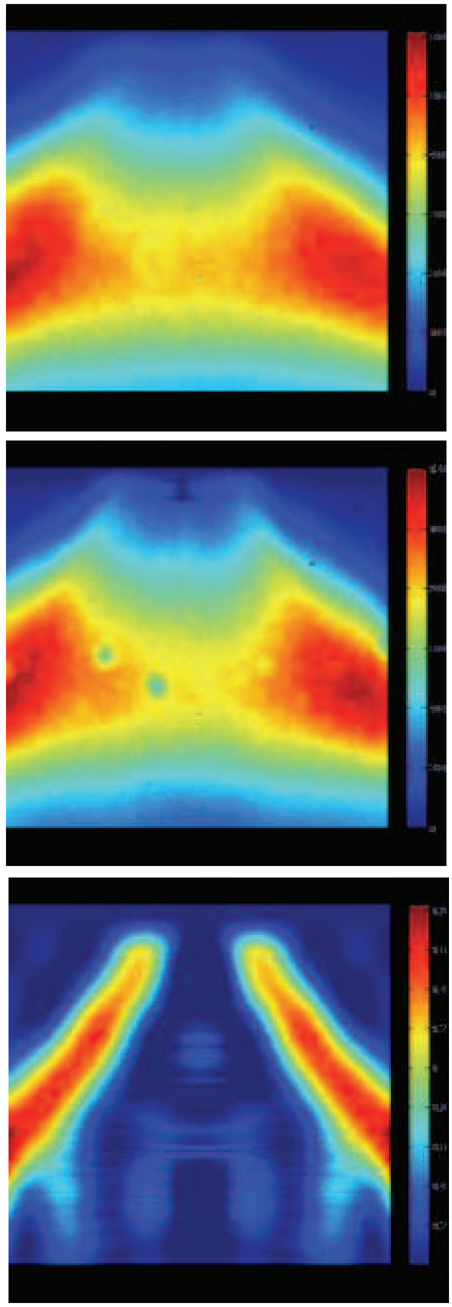


Figure 5.14 a) OH chemiluminescence image of BOS gas flame, b) CH* chemiluminescence image of BOS gas flame and c) OH* chemiluminescence image of CH4 flame.*

Though only preliminary research, the impact of this line of research could be considerable if Gas Turbine integrated CCS plant is developed and installed in the next 10-15 years as a low-carbon option.

LSPG Researchers

Prof Phil Bowen
Prof Nick Syred
Dr Richard Marsh
Dr Andrew Crayford
Dr Agustin Valera Medina
Dr Yura Sevcenco
Dr Dan Pugh
Dr Tony Giles
Steven Morris
Gina Goddard Bell
Rhodri Daniels
Sally Hewlett
Liz Locke

SECTION 6: Marine

Introduction

The success of the LCRI Marine project has followed the growing confidence of the Marine Energy sector over the last 6 years. Over the course of the project there has been real consolidation of technology, experience and environmental understanding. Marine Energy in Wales is small but growing, and LCRI Marine has engagement with every significant company and project. Companies have a common problem in the transition from technology development to commercial revenue which is the removal of technical and environmental uncertainties in order to convince government to provide appropriate market incentives and persuade utility investors to build the first commercial projects. The strategy of LCRI Marine has been simple, to collaborate with our industrial partners to identify the issues for the next 10 years and then undertake high quality applied R&D to provide the technology base that addresses these issues and supports the whole industry. The work covers wave devices, tidal stream turbines and tidal range barrage/lagoon technology. There are currently environmental questions over impacts on fish, marine mammals, wading birds and sediment flows. There are also engineering concerns over design loadings, grid connection, reliability and maintenance costs, and on coastal management issues such as navigation and fishing. LCRI Marine is researching across these issues.

A recent report for the DECC Marine Energy Programme Board (Capitalising on Capability, 2015) summarizes the world leading position of the UK industry. £450m has been spent on technology development and 1,700 people work in the sector in the UK. With the potential of a £76bn world market and 20% of UK electricity supply this could grow to over 20,000 skilled jobs over the next decade.

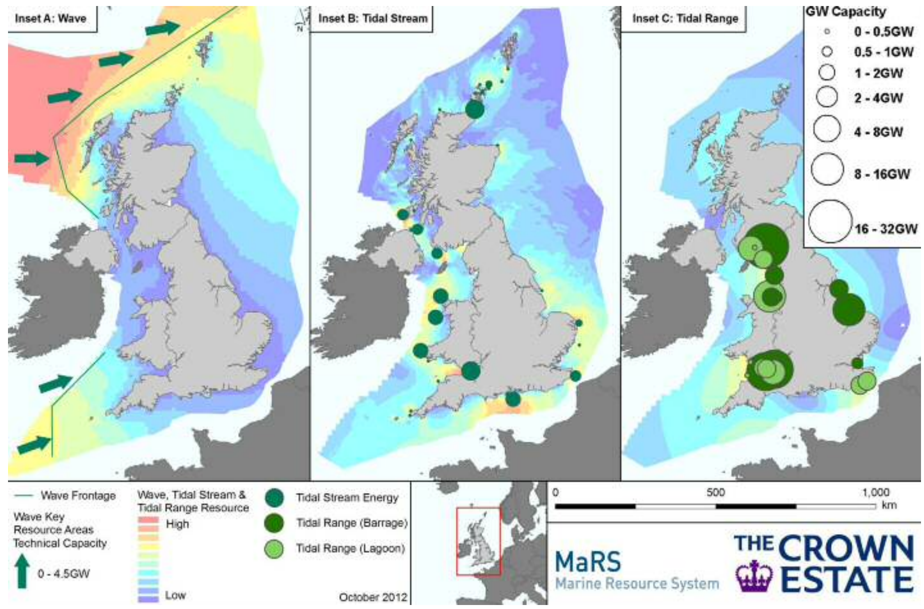


Figure 6.1 Wave, tidal stream and tidal range resource around the UK.

A number of studies have identified the key resource areas around our coastline and Wales has excellent immediate opportunities for all forms of Marine Energy, partly due to the excellent grid connections on North and South coastlines (figure 6.1). Pembrokeshire faces the Atlantic wave resource, there are good tidal currents around Anglesey and Pembrokeshire and the tidal range of North Wales and the Severn Estuary can be exploited for tidal range.

Overview

Marine energy is a rapidly growing industry. LCRI is working to develop supply chains to maximise the economic benefits to Wales of generating electricity from the sea. Dr Ian Masters leads Swansea's LCRI's work on marine technologies, in close collaboration with Cardiff and Bangor. The teams are researching both the engineering and environmental aspects of deployment sites on every coast of Wales. LCRI works in Pembrokeshire with Tidal Energy Limited on the first grid connected tidal stream turbine in Wales, and in Anglesey with Marine Current Turbines on one of the world's first tidal turbine arrays. Dr Ian Masters of Swansea stated '*the attraction of Wales as an international base for marine energy has led to companies such as the Swedish based Seabased, developing a wave energy array in Pembrokeshire'.* Swansea and Cardiff are members of the Engineering and Physical Sciences Research Council (EPSRC) Supergen Marine Centre (UKCMER) and Prof Tim O'Doherty of Cardiff has secured a £1.7M UKCMER project with LCRI partners at Swansea and Bangor, focused on enhancing the reliability of tidal turbines. Prof Roger Falconer of Cardiff is leading research on the Severn Barrage and has successfully demonstrated that two-way tidal flow generation, as opposed to just ebb flow, can generate the same amount of electricity with less harm to marine life and with negligible far field environmental effects. His work links up with the interests of NGOs, such as the RSPB, and his centre is working with industry partners, such as Severn Tidal Power, CH2M HILL, Halcrow and Arup. Prof Falconer stated, '*the development of a marine industry in Wales will generate a host of supply chain companies with the barrage expected to generate at* *least 20,000 jobs in South Wales and the South West of England, and during the 9 year construction period will indirectly create another 30,000 jobs'.*

Marine research includes tidal turbine design and performance prediction across a range of scales from mm to km and from a section of a turbine blade to a whole coastal region. Developments have also been made to the engineering of prototypes and components with industrial partners, with particular advances in the area of prediction of structural forces, loadings and optimisation. Research has also focused on tidal range technology and the Severn barrage in particular. In contrast to Barrage Schemes, some work by the team considers tidal stream arrays in the Bristol Channel and compares the power predictions against the tidal range schemes. Measurements at sea of areas of interest have provided essential information to the design process and the team has published work on the improvements of measurements, particularly in the estimation of turbulence from acoustic doppler current profilers and improvements to the measurement of underwater noise in high tidal flow areas. LCRI Marine has developed a range of analytical and survey capabilities to enable Wales to become a major player in future Marine research (figure 6.2).

Figure 6.3 Delta Stream; 400kW Demonstrator ready for deployment at Ramsey Sound and subsequent monitoring.

Delta stream demonstration

*L*CRI Marine has collaborated closely with Cardiff based Tidal Energy Limited on the Delta Stream demonstration programme (figure 6.3). LCRI partners have been working with the project for over 10 years and have supported many aspects of the engineering and environmental challenges faced by the company. The tidal stream turbine prototype has been constructed in Milford Haven and will be deployed in Ramsey Sound. Many of the leading edge research topics within LCRI have used the Ramsey site as a test case, supporting the specifics of Delta Stream while at the same time providing solutions for the whole industry. Collaborative projects based on Ramsey Sound include: visual observations of marine mammals, background noise measurements, resource measurement, turbulence measurement and analysis, performance prediction, flow modelling, array studies, public perception, fatigue life prediction. Some of these topics are discussed in more detail elsewhere in this chapter.

Projects

Project within the LCRI Marine programme have focussed on:

- The effect of the **environment** on marine energy **devices**
- The effect of marine energy **devices** on the **environment**

Site Resource survey, modelling and constraint mapping

The Marine consortium has studied extensively the resource capacity around the Wales coast for both wave and tidal devices. Wales's offshore renewable energy resources have significant development potential and are considered as being among the best in the world, with the practicable tidal energy resource estimated up to 9.5 GW with annual energy output of 28 TW/year and wave energy resource estimated up to 8.7 GW (combined England and Wales) with annual energy output 23 TW/year (The Crown Estate 2012). Therefore Wales has the potential to become a world-leading developer and manufacturer of the technologies that will enable the harnessing of ocean energy resources. To achieve this, continuous investment in research projects into marine energy resource capacity is necessary to enable building the innovation infrastructure that will enable the industry to move forward.

Swansea has identified and verified high energy sites as suitable device array locations such as St David's

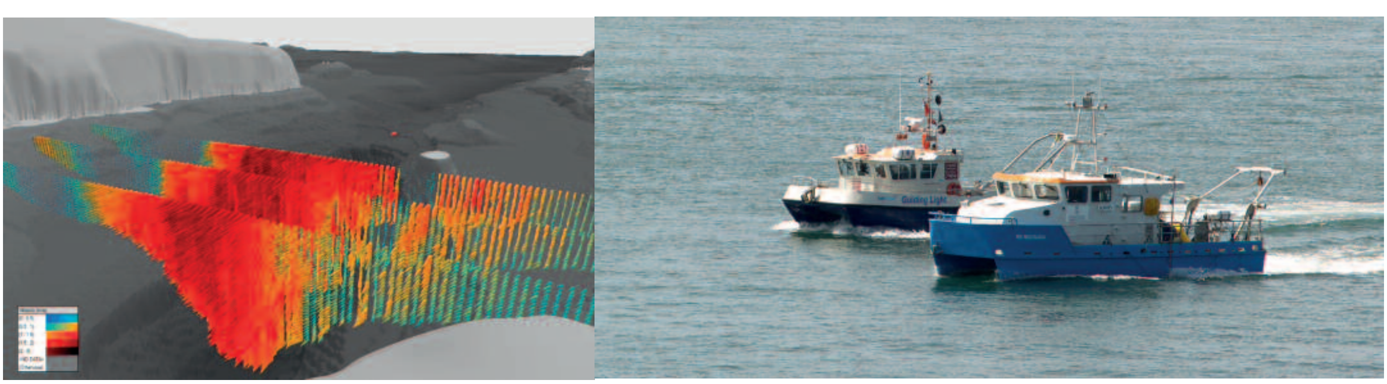


Figure 6.2 Measurement of tidal stream resource in Ramsey Sound, Pembrokeshire, using Research Vessels Noctiluca (front) and Guiding Light.

Pembrokeshire, by considering GIS analysis of constraints and resource modelling. In addition, characterisation of high energy sites was carried out by Cardiff and Swansea, measuring the current velocities using shipboard ADCPs and computing the tidal energy flux through the channels formed by small offshore islands including Ramsey Sound. Previous resource assessments have suggested that this area is one of the most promising for tidal stream deployments in the UK and this contribution confirms the commercial viability of the area for tidal energy extraction. This analysis has been extended to consider the spatial variability of raw resource and the impact of bathymetric features on constraining suitable areas. A similar approach was taken for wave energy resource assessment where an economic analysis of spatially varying costs in a GIS was combined with resource data to identify prime deployment areas in Pembrokeshire. Consideration of measured data obtained from wave buoys within and close to the Pembrokeshire resource areas has confirmed the commercial viability of the area which was previously modelled and documented in a number of reports. Bangor have supported this work with multi-decadal studies of the annual variability of the wave resource and the consequences for the tidal resource.

Cardiff CMERG has carried out resource assessment studies at a site in the Severn estuary, due south of Llantwit Major. The velocity at the Severn estuary is unlikely to provide a suitable level of power to be a viable tidal stream site as shown by bathymetry and ADCP data. Other work by the consortium concluded that the environmental impact of deployment at the site was low, and that there was significant shipping in the area and by a small relocation of the site, navigational risk was reduced and could be managed. Additional work has also been undertaken for a site in the Anglesey Skerries, where the findings confirmed that the sitting of tidal devices could produce high levels of energy.

Much of the contribution of the Bangor group has been characterising the tidal and wave energy resource at a variety of spatial and temporal scales. They have collaborated with modelling and in situ studies led by researchers at Swansea and Cardiff Universities on quantifying the marine resource in the Pembrokeshire region. This has led to enhanced understanding of how the resource varies spatially, and highlights the challenges faced in using tidal energy to generate electricity in such a turbulent high flow environment. The group have also undertaken several field surveys and model simulations of the tidal energy resource off northwest Anglesey, where energy companies are looking at sites such as Holyhead Deep and the Skerries Channel. Modelling studies at larger scale have quantified intraseasonal and interannual variability in the wave energy resource of the entire northwest European shelf seas. This high impact work is important for developers trying to quantify the risks related with reliance on the wave resource of a particular region at decadal scale, and how this resource is likely to vary in the future as a result of climate change. Expanding on this, work has focused on the range of uncertainty within the wave resource. High frequency wind variability has been applied to wave model simulations to assess the impact of the wind forcing time step upon the predicted wave power resource. This can be applied to future research into wave-tide interaction where it is important to include temporal as well as spatial variability. Moreover the group has also applied a diverse range of unstructured grid 3D tidal and wave models. The advantage of using these models (compared with traditional finite difference based models) is the smooth transition from large scale to small scale (e.g. shelf sea scale to regional scale) without nesting, and also resolving irregular geometries conveniently. These models are also more stable in the case of shock waves and highly irregular bathymetries – issues in many of the extreme environments suitable for marine renewable energy schemes. Ongoing work in resource assessment is simulating wave/tide interactions; particularly how consideration of tidal processes modulates our shelf-scale estimates of the wave energy resource and, at regional scale, how the inclusion of waves in numerical models affects our understanding of the tidal stream energy resource.

Barrage power output studies

Extensive work has been carried out in assessing the resource potential of the proposed Severn Barrage site of the Severn Estuary (figure 5.4). In recent studies, Cardiff HRC described two different methods to estimate the total annual energy output from the proposed barrage including a theoretical estimation based on the principle associated with tidal hydrodynamics, and a numerical estimation based on the solutions obtained from a 2D hydrodynamic model (figure 6.5). The predicted results obtained indicate that the magnitude of the annual energy output would range from 13 to 16 TWh, which is similar to the value of 15.6 TWh reported by the Department of Energy and Climate Change, in the UK. Further investigations showed that the total annual energy output could exceed the value of 16 TWh if future technological advances in both sluice gate construction and turbine performance are included. More recent studies of the Severn Barrage have shown that the new design, as outlined and published through research funded via the LCRI

Figure 6.4 Extensive work has been carried out in assessing the resource potential of the proposed Severn Barrage site of the Severn Estuary.

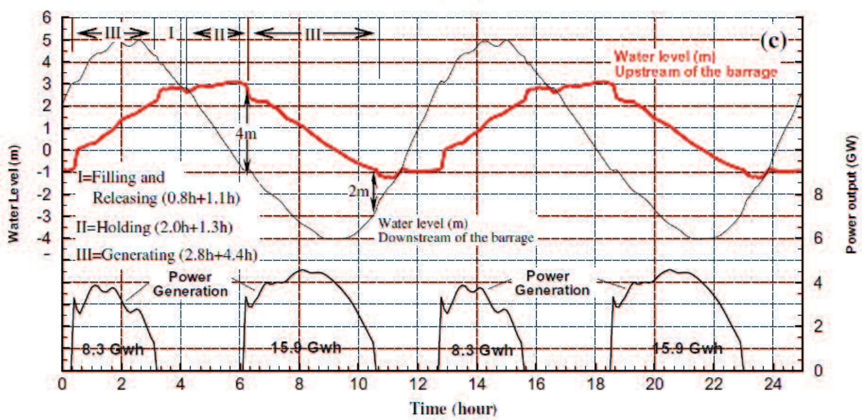


Figure 6.5 Impact of different operating modes for a Severn Barrage on the tidal power and flood inundation in the Severn Estuary, UK.

programme, has shown that a barrage with two-way generation and low head turbines would have no far-field effects on the water levels outside of the Bristol Channel and Severn Estuary. This work has far reaching implications for power generation from the estuary and was presented to the House of Commons Energy and Climate Change Select Committee in their evidence gathered for the Severn Barrage project. Other technology options for tidal range electricity generation have also been studied in the project. The main alternative to a Barrage is the concept of a lagoon, a breakwater that is attached to land at both ends and stores water within it. As the tide rises and falls, flow through the turbines generates electricity. The most advanced project of this kind is proposed for Swansea Bay (figure 6.6).

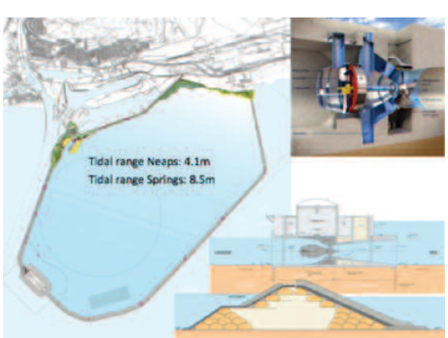


Figure 6.6 Lagoon tidal power project.

LCRI Marine Waverider

The Waverider installation project (figure 6.7) has been used to collect information on wave conditions and is helping to promote the waters off Pembrokeshire for electricity generation from wave power. This region has recently been highlighted as an area of excellence for wave power, via the creation of The Crown Estate Wave Demonstration Zone. In July they announced the creation of six demonstration zones for wave and tidal energy around the UK coast, with two located in Wales; wave energy in Pembrokeshire and tidal energy off Anglesey.

Pembrokeshire is particularly attractive for the development of commercial wave energy extraction projects due to the proximity to port facilities in Milford Haven and strong electrical grid connections. Detailed knowledge of the wave conditions however is lacking, which hinders accurate estimates of wave energy extraction levels. While there has been a wave measurement buoy off the coast of Pembrokeshire for many years, it does not provide adequate information for the renewables industry to have high levels of confidence.

LCRI Marine recently purchased and installed a state of the art directional waverider buoy which provides a much more detailed description of the sea state, enabling both industrial developers and potential

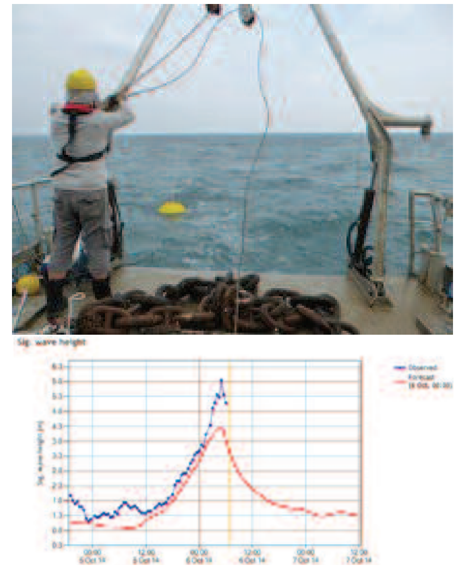


Figure 6.7 Wave rider project.

investors to have greater confidence in the suitability of the area. The new buoy not only provides wave height information but, crucially, information about the wave spectra. Wave spectra describe the energy within different frequencies of a given wave condition and is vital for wave energy developers to predict how well their devices will work in a given area. Additionally, the LCRI marine project has developed computer simulations of the region so that spatial variability in resource about the region can be quantified and the areas that are most suitable for project development identified.

It is believed that this study will demonstrate the commercial viability of wave energy extraction in the area and hence encourage investment in Welsh based projects and lead to growth of the renewables industry in the region. Real time data from the buoy is uploaded via satellite to the CEFAS website and this is already providing an important service to the Welsh surfing community!

Tidal turbine performance, extreme and lifetime loading modelling investigations

T O'Doherty's group at Cardiff University has been actively involved in examining the critical aspects required for the deployment of tidal arrays. This has included novel techniques for: maximising the power generation through contra-rotating rotors, calculating the effects of the structure on the turbine characteristics (figure 6.8), characterisation of the swirl component in the wake to its length, and the interaction between turbines in an array. In addition to these aspects of the design requirements for a tidal array are the difficulties with regard to the scaling laws for the devices themselves. The research has shown the conditions under which a laboratory scale turbine can be scaled up to any deployed scale. This is a critical element to substantially reduce prototype costs when developers are designing a new turbine.

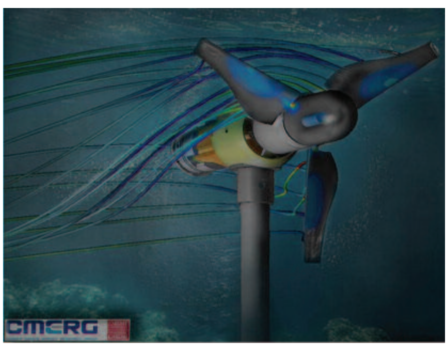


Figure 6.8 Fluid Structure Interaction CFD Modelling of tidal turbines.

LCRI Marine has also been working on the development of a computationally inexpensive turbine design tool capable of quickly obtaining results for a wide range of operating conditions. Blade element momentum theory (BEMT) was chosen as a basis for the model due to its low computational demand and reasonable accuracy. It is in common use for marine and aviation propellers and wind turbines. The group has shown that the approach can be used for tidal turbines. The correct solution for the BEMT equations is typically found by treating it as an optimization or iterative problem; converging to a suitable solution can be quite challenging, and Masters et al presented a robust implementation of the method. Further work has shown that the BEMT can predict turbine performance and loading away from optimal conditions, including the "high induction" condition found at overspeed.

Tidal Turbine Wake Effects and Array Design

Although much of the theory behind tidal stream turbines is common with wind energy extraction technologies, the contrast between atmospheric and aquatic environments is vast. There is a growing interest in the hydrodynamics around a tidal stream turbine both in terms of how the performance of the device may be affected by variations in free-stream flow conditions, and the sheltering effects due to upstream obstructions, particularly neighbouring devices within the context of a turbine farm.

The LCRI Marine consortium has conducted investigations to improve our understanding of this emerging technology, particularly in the light of the deployment of the first array of devices in offshore environments as a precedent to more permanent and multiple installations.

Research on a combined Blade Element Momentum-Computational Fluid Dynamics model has examined the flow structure around a 10-metre diameter turbine. This work contributed to gaining a better understanding of how downstream wake interference between neighbouring tidal turbines can be related to the longitudinal and lateral spacing between the devices (figure 6.9). The results of this study will be beneficial for the planning of turbine array configurations.

Moreover, different tidal turbine array layouts were assessed in the Severn Estuary and Bristol Channel using a 2D hydro-environmental numerical model developed by Cardiff University. Modelling and comparison of different layouts of the arrays was carried out investigating their significance on the power output and the hydro-environmental impacts. The study has shown that when tidal stream turbines are deployed in one location with the same number of turbines, the layout of the turbine array can have a significant impact on the power output and, to a lesser extent, the hydro-environmental impacts.

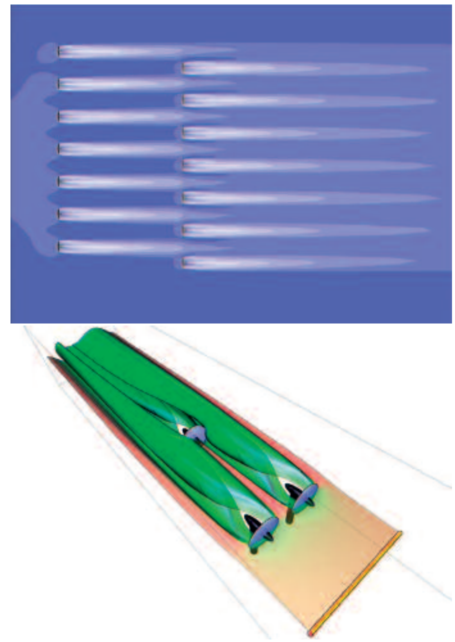


Figure 6.9 Simulating downstream wake interference between neighbouring tidal turbines.

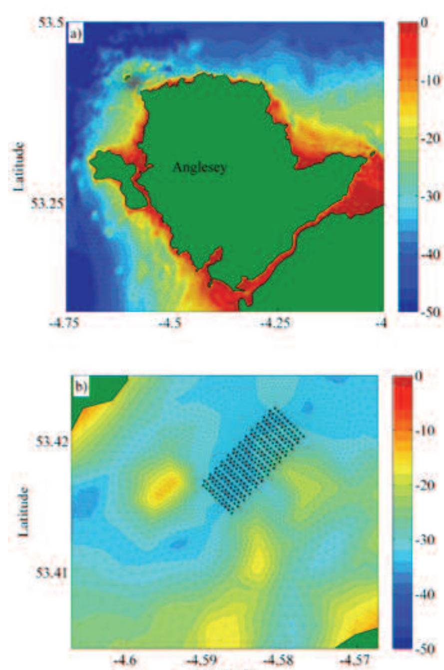


Figure 6.10 Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes.

Figure 6.11 Background noise measurement.

Impact of tidal streams on sedimentary processes

Simulations have been carried out on the Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes (figure 6.10).

Device Components design, prototyping and test

Cavitation: Studies have includes the onset of cavitation using a BEMT performance prediction tool. The shock waves associated with cavitation can significantly damage the blade surface and reduce performance; therefore, this model is a useful addition to BEMT and can be used in turbine design to minimise cavitation occurrence. The results are validated using the cavitation experiment observations. Other investigations have focused on the conditions under which cavitation may affect the operation of horizontal axis tidal turbines. The approach utilised computational fluid dynamics (CFD) to measure the individual and combined influence that operational parameters, including flow velocity, rotor angular velocity, and depth of submersion exert on the operation of a 3 bladed turbine.

Condition Monitoring and Reliability: With the deployment of devices in the harsh marine environment developers will need to have confidence in their monitoring and control of the devices. The Marine consortium have been developing the initial strategies for the condition monitoring requirements and ultimately the remote control of individual, and arrays of, devices. The deployment of more intelligent monitoring systems will enable data capture and analysis to proceed autonomously. The requirement for expert input will be reduced to allow engineers to concentrate on actual problems. Part of this approach will be to collect and analyse performance variations associated with transient data that may have normally not been detected.

Condition monitoring and process management tools deployed within the marine consortium projects will support the development of device monitoring and management tools. Information includes total energy generated, continuous performance assessment and performance degradation over time. Installing such monitoring systems will enable the acquisition of performance data that can be used to produce quantitative assessments of device operation and thus accurate analysis of the effect of design changes. This in turn can lead to guidelines for more effective device design, installation and operation. These elements can all be tested using CFD modelling techniques which is a core area of expertise within our group.

Supply Chain

In order to realise the potential of tidal power, it is critical that the UK energy sector ramps up the development and production of tidal energy technologies. The key challenges for the supply chain are development of specific technical expertise throughout all the stages, the capacity available and the speed of response. It is likely that during the introduction of these sustainable energy technologies, some difficulties will be experienced in obtaining materials, components and sub-assemblies from domestic suppliers. In most instances, the market for renewable energy technologies is not yet mature enough to support established supply chains of any size. This may be related to uncertainties regarding the specifics of which materials and components are required, as much of the technology itself is developmental. A number of areas have been identified in this area by T O'Doherty's group, in conjunction with colleagues from the University of South Wales, including R&D, Manufacturing, Maintenance and decommissioning, to name a few.

Increasing characterization of the oceans through improved sensors (Smart Monitoring Sensor Technology Development)

Underwater Noise: Our marine consortium has experience in researching anthropogenic underwater noise and its interaction with marine life including determining any behavioural changes or physical injuries such as temporary or permanent threshold shift (TTS PTS). Assessments have been carried out to establish the background underwater noise at high energy sites including Ramsey Sound, in order to obtain a baseline from which to measure potential disturbance impacts associated with marine energy devices. Willis has researched into the mechanisms of the background noise in Ramsey Sound, a tidal stream hot spot (figure 6.11).

Published work has paid particular attention on the variation of background noise throughout and at different tide (spring, neap) and highlighted the importance of how the background noise is presented, particularly when the ambient noise is to be compared with anthropogenic noise.

Underwater Noise Sensor Technology and Protocol Development: The consortium academic partners have extensive experience in acoustic underwater noise monitoring. Following data collection at the pre-installation stage of device deployment, models of interactions with a turbine, both physical and acoustic, have been developed. Knowledge exchange partnerships have been established with the two major developers MCT and TEL to undertake acoustic monitoring studies at their tidal energy sites in order to develop a cost effective and user friendly underwater noise monitoring and post processing protocol. There is considerable uncertainty about the environmental impact of the underwater noise throughout all the phases of wave and tidal energy extraction projects (installation, operation, maintenance and decommissioning). It is anticipated that during growth of the marine renewable energy industry a large number of environmental consent applications will be submitted for both small scale pre-commercial demonstration devices and the next generation of small arrays of devices.

Turbulence: Development of world-leading novel turbulence measurement techniques by our Consortium has provided critical information on how turbulent flows interact with tidal turbines. The ongoing research in this area will remove uncertainty and determine the effective siting of marine renewable energy arrays. Moreover, Acoustic Doppler Current Profiler (ADCP) data will allow us to analyse the most important parameters of turbulence from the point of view of device fatigue and peak loading and will inform the wave and tidal stream device developers on site specific device design optimisation.

TEL has recently conducted a tidal stream resource survey in order to inform the detailed positioning of the DeltaStream tidal energy unit in the vicinity of Ramsey Sound, Pembrokeshire. Our consortium is collaborating with TEL to conduct a similar study in the area further north from Ramsey Sound, at St David's Head the area under development for a 10 MW device array. The purpose of this study is to assess the resource in detail at the site with regards to a characterisation of turbulence. Monitoring of current speed and direction throughout the water column throughout the tidal cycle will be achieved with a bottom-mounted ADCP.

Coastal Management and Coastal Impacts

Michael Phillips' group (University of Wales Trinity St David) studied the coastal morphology of the Pembrokeshire coast focusing in the vicinity of Tenby, West Wales to gain a comprehensive understanding of coastal processes. Using long term historical data and direct field measurements he examined the morphological behaviour of adjacent beach systems. Accretive, erosive and rotational patterns were analysed as part of a continuous research study to develop a multi-variate model for predicting beach morphological response to environmental change and various risk based scenarios. It has highlighted the importance of effective monitoring and management of dune resources and developed a methodology to readily assess changes over time and to compare dune sites on a regional scale. A projected rise in the sea levels which may affect the Bristol Channel informs future coastal management strategies, especially at the vicinity of Severn Estuary where there are plans for the construction of the Severn Barrage.

The Severn Barrage has the potential for far field impacts and impacts to water quality in the region. Roger Falconer's group (Cardiff University) carried out a comprehensive review on the potential water quality impacts of different tidal renewable energy systems including the Severn Barrage. In addition, collaboration with Aberystwyth University has examined the potential impacts of two different modes of operation of the Severn barrage (i.e. one-way and two-way operating modes) on the eutrophic status and eutrophication potential of the Severn Estuary using the UK's Comprehensive Studies Task Team (CSTT) approach. This work was supported by Prof. David Kay at Aberystwyth University who provided evidence to this work through boat based water quality surveys in the vicinity of the proposed Cardiff-Weston barrage line. In these studies, the Severn Estuary was found to be potentially eutrophic with no net change in the status of the estuary following the operation of barrage under the one-way and two-way operating modes. However, the studies predict an increase in primary production under both the one-way and two-way operating modes, with the potential productivity significantly lower under the two-way operating mode compared to the one-way operating mode. These findings have wider implications for the estuary which could be perceived as both positive and negative. Further studies using the Environmental Fluid Dynamics Code (EFDC) model has also shown that there would be a reduction in salt intrusion upstream of the Severn Estuary following the construction of the proposed barrage, with implications for nutrient concentrations and water quality in the estuary. Other recent EIA studies has also been carried out on the impacts of the Severn Barrage on the far-field hydrodynamics in the Bristol Channel and Irish Sea, as outlined and published through research funded via the LCRI programme. This study has predicted a noticeable difference in the maximum water levels in Cardigan Bay, with a maximum difference of up to 9 cm in the northern part of Cardigan Bay following the construction of the Severn Barrage.

SOLCER Marine

Within SOLCER, the Marine team was looking at community scale renewables from relatively small tidal range schemes. In particular the project worked closely with the historic tidal mill at Carew in Pembrokeshire (figure 6.12). Carew is located at the top of the Milford Haven estuary and has an existing medieval tide mill with mill races and sluice gates in place. If a tidal range electricity scheme was developed at the site, it could contribute to a diversified and localized energy mix, providing intermittent but predictable power generation and the potential for a small amount of energy storage. The results from this study showed that the peak power output from the site might be a few hundred kW. However, the pool empties completely for a relatively long time at low tide and therefore the percentage utilisation of the equipment will be relatively low, reducing the total power that can be captured. The environmental and heritage impact of changes to the site will also need to be considered before any scheme is installed.

In addition, there are a significant number of other structures within the ports and harbours of the Severn Estuary and Bristol Channel that could be retrofitted in the same way with small tidal range turbine technology. These could provide power and pumped storage opportunities within the integrated supply, demand and storage system proposed by SOLCER.

Figure 6.12 Carew Tidal Mill and LIDAR data showing the pool depths.

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SECTION 7:
Welsh Energy Sector Training (WEST)

The main objective of Welsh Energy Sector Training is to develop skills to aid the utilisation and uptake of new technologies developed through the LCRI industrial research programme. This will ensure that industrial research is disseminated through both traditional educational streams as well as directly to industry through Continuing Professional Development (CPD).

WEST reviewed the current delivery of low carbon education within both the Further and Higher Education Sectors in Wales, to develop and implement a Skills Needs Analysis. WEST also aimed to produce a low carbon educational programme for Wales and develop a continuation strategy, to ensure legacy and main streaming of the courses developed. WEST aimed to deliver programmes at training levels 4 and above, covering each of the key research themes within the LCRI. Twelve courses have been developed, accredited with Agored and delivered, namely:

- Essentials of Hydrogen and Fuel Cells
- An Introduction to Combustion Science
- The Nature of Fuels
- Welsh Timber in Building Construction: Myths and Facts
- Low Carbon Building Principles
- Energy Simulation: Building & Urban Scale
- Long Term Wave Analysis
- Wave Energy Conversion
- Tidal Energy Conversion (figure 7.1 and 7.2)
- PV System Design Considerations
- Buildings as Power Stations
- End of Life Considerations

Figure 7.1 WEST training session.

Figure 7.2 Flyer for WEST training session.

In addition, two other courses were developed and delivered before the Agored Learning Centre was established:

- Low Carbon Combustion
- Gas Turbine Technology

111 people representing a variety of companies and organisations from across the Welsh Convergence region participated in the courses. Fifty participants undertook more than one course, with the maximum number of courses undertaken by one participant being six. 36 participants qualified for 53 certificates.

Feedback from the participants was very good. Comments include:

> "Thank you for providing me with an excellent opportunity to broaden my knowledge regarding the nature of fuels. I have attended many courses (seminars) over the years and can tell you that this course is one of the few that has allowed me to bridge a gap between what I knew and what I should know"

> "Fuel variability – Excellent for me in terms of new knowledge which is useful in my role in power generation. Lab work! Brill."

> "Furthered my understanding of area. In particular the viability/limitations of alternative fuels vs. conventional"

> "The information given was well explained and we did assessments to track understanding"

> "Very well explained and demonstrations aided understanding"

> "it was very good"

> "The course would be difficult to improve upon"

> "I have learnt how to quickly and easily create models which will help in solar shading calculations and building energy use. The HTB2 software looks very powerful and this plug-in makes it accessible within the more user-friendly sketchup environment. I will definitely begin to incorporate this into my day to day work"

> "I was at an introductory level but the software was well explained so I did not have difficulty understanding"

> "the course was very well delivered"

> "workshop was good along with content"

> "I can speak with more confidence about renewable technology in a way that matches rhetoric to reality"

> "A concise overview of marine technology. An engineering perspective to contrast to ecologist's perspective"

> [I developed an] "understanding of tidal and wave energy. The UK resource and Welsh potential"

> "The course was very informative"

> "Thank you for an excellent course yesterday which I thoroughly enjoyed"

> "Thanks for delivering the WEST course on Tuesday, I found it very informative and a good bridge between university and industry"

The work of WEST was disseminated in the following publications and presentations, which raised the profile of WEST nationally and internationally:

- Overview: Welsh Energy Sector Training: A Case Study of Research Informing Education: Educational Alternatives, Vol 12, 2014
- Development of a Hydrogen Training Programme for the Welsh Energy Sector: Needs Analysis and Course Content – 2nd International Symposium on Energy Challenges and Mechanics, 19-21st August 2014, Aberdeen, UK.
- Low Carbon Built Environment: Linking Higher Education Training and Industry in the Welsh Low Carbon Sector: Educational Alternatives, Vol 12, 2014
- Training needs to realise low carbon buildings: the Welsh built environment sector – 5th International Conference on Harmonisation between Architecture and Nature 24-26 September 2014, Siena Italy
- The Need for Industrial Influence in Higher Education Training: The Welsh Low Carbon Building Sector – Zero Carbon Buildings Today and in the Future 2014, 12 September 2014, Birmingham UK.*
- A blended Learning approach to addressing the low carbon educational needs of the Welsh built environment sector (Presentation) iBEE, 15-16th May 2014, Nottingham, UK*
- A Welsh case study: the WEST project and its context (Presentation), SB14, 28-30th October 2014, Barcelona, Spain
- Large Scale Power Generation: Up-skilling Welsh Industry: Energy and Environment Research, Vol 4, No 1
- Large Scale Power Generation – Pilot Welsh Energy Sector Training: Higher Education, Skills and Work-Based Learning Journal
- WEST – Large Scale Power Generation – The Nature of Fuels, Cardiff University, 5th August 2014*
- Welsh Energy Sector Training, International Conference on Social Sciences and Education, 20-21st November 2012, Milan Italy.*
- Marine Energy: Growing the Marine Energy Supply Chain in Wales: Educational Alternatives, Vol 12, 2014
- Solar PV: A Skills and Training Needs Analysis for Solar Photovoltaics a Welsh and UK Perspective: Educational Alternatives, Vol 12, 2014

- Developing Resilience through diversity in the Welsh Photovoltaic Industry (Presentation), Regional Science Association International – British & Irish Section, 43rd Annual Conference and Doctoral Colloquium, 19-21st August 2014, Aberystwyth, UK*
- In addition, the WEST Project Manager was invited to South China University of Technology to deliver training materials from WEST.

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