Renewable Energy Technology from Underpinning Physics to Engineering Application

D G Infield
CREST (Centre for Renewable Energy Systems Technology), Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, LE11 3TU, UK.
Email: D.G.Infield@lboro.ac.uk

Abstract. The UK Energy Research Centre (UKERC) in its submission to the DTI’s 2006 Energy Review reminded us that the “UK has abundant wind, wave and tidal resources available; its mild climate lends itself to bio-energy production, and solar radiation levels are sufficient to sustain a viable solar industry”. These technologies are at different stages of development but they all draw on basic and applied Science and Engineering. The paper will briefly review the renewable energy technologies and their potential for contributing to a sustainable energy supply. Three research topics will be highlighted that bridge the gap between the physics underpinning the energy conversion, and the engineering aspects of development and deployment; all three are highly relevant to the Government’s programme on micro-generation. Two are these are taken from field of thin film photovoltaics (PV), one related to novel device development and the other to a measurement technique for assessing the manufacturing quality of PV modules and their performance. The third topic concerns the development of small building integrated wind turbines and examines the complex flow associated with such applications. The paper will conclude by listing key research challenges that are central to the search for efficient and cost-effective renewable energy generation.

1. Introduction
Global warming is now almost universally acknowledged by experts and lay people alike. The Kyoto agreement reflects the international consensus and the serious nature of the challenge and commits its signatories to specific green house gas emission targets with the overall aim of reducing world anthropogenic carbon dioxide production to 5% below 1990 levels. Even major non-signatories such as the USA and China now also accept the need to limit green house gas emissions. This poses a major social and technical challenge for the developed world, and requires a significant change in the patterns of energy supply growth in the developing countries also. Here in the UK, the 2003 Energy White paper outlined the Government’s aim to cut carbon emissions by 60% reduction by 2050, and reiterated the nearer term targets to generate 10% of the UK’s electricity from renewable energy by 2010, and 20% by 2020. However, data since 2004 shows a significant increase in UK carbon emissions despite increases in renewable energy generation and the implementation of other low-carbon technologies such as combined heat and power. This demonstrates the pressing need for more progress in the development and deployment of renewable energy technologies and a continuing need to improve the efficiency of energy utilization, as reaffirmed by the recently published Energy Review [1]. In this publication, renewables were placed at the centre of the Government’s long term energy...
policy. There is no shortage of renewable energy resource, but the outstanding challenge will be to convert these sources to useful energy supplies at acceptable cost, and integrate these so as to provide a coherent and effective energy supply system, including electricity, and fuels for transport, industry and the built environment.

A brief summary of the status of the different renewable energy technologies will be presented drawing on the evidence presented by the UK Energy Research Centre [2]. Three examples of research to improve the performance and lower the cost of renewable energy will then be presented that bridge the gap between the physics underpinning the energy conversion, and the engineering aspects of development and deployment; all three are highly relevant to the Government’s programme on micro-generation. Two are these are taken from field of thin film photovoltaics (PV), one related to novel device development and the other to a measurement technique for assessing the manufacturing quality of PV modules and their performance. The third topic concerns the development of small building integrated wind turbines and examines the complex flow associated with such applications. The paper will conclude by listing key research challenges that are central to the search for efficient and cost-effective renewable energy generation.

2. Status summary for renewable energy technologies
Renewable energy sources are those that make use of naturally occurring energy flows within the environment, they include solar energy, wind power, hydro power, bioenergy, marine energy and geothermal energy. Each of these will be dealt with briefly below.

2.1. Solar energy
Solar energy for space and water heating is well established. More challenging is the generation for electricity from solar radiation. Two approaches exist: solar thermal power stations where high temperatures are used to generate electricity using heat engines; and photovoltaics (PV) in which radiation is directly converted into electricity. Of these two, PV is the technology to have demonstrated most dramatic improvement over the last twenty five years. This film PV cell efficiency in particular is steadily improving, as shown in Figure 1 below. It also has the advantage that it can be used for both small and large scale application.

![Figure 1. History of thin film PV efficiency](image-url)
PV is competitive for grid-remote generation but much less so with large-scale bulk electricity generation. Further development of thin film technologies allied to bulk manufacturing technologies should make systems using these technologies competitive by 2020 and roofs/facades provide ready deployment opportunities of up to 40 GWp total installed capacity in the UK. By 2050, advanced low cost PV technologies that are currently R&D concepts may well become commercial riding on expected developments in the nano-engineering of materials. Germany, Japan and the USA have encouraged both local manufacture and deployment, and a vibrant commercial sector has emerged in these countries. The UK has lagged behind Germany, Japan, the USA and many other countries in terms of market incentives. Currently the total installed UK PV capacity stands at around 4 MWp, and combines a large number of small domestic systems (typically of 2kWp) and larger building integrated systems such as those at Doxford [3] and Delabole [4].

2.2. Wind power
Wind energy technology is relatively mature with proven and replicated designs up to 3MW rated. At the best onshore sites the technology is competitive with all other forms of electricity generation. Offshore, installation costs are higher, and despite a better wind resource, generation is not yet competitive without external support. There are significant economic gains to be made, especially offshore, by scaling up of the technology to 5MW and beyond, but the engineering challenges of doing this reliably and in increasing water depths farther offshore should not be underestimated. Installed capacity will be limited by network and operational constraints on the power system as a whole rather than resource limitations. Up to 30 GW of wind capacity can be absorbed without particular difficulty and minor operational cost penalties [5].

Small scale wind for generation on or near buildings is seeing a rapid growth of interest. Care should be taken as wind speeds in the urban environment are considerable lower than on open sites [6], but on the positive side, the generation is located near to loads thus reducing transmission and distribution losses.

2.3. Hydro power
Traditional hydro-electric generation is well established. Worldwide it accounts for approximately 20% of all electricity production. The UK has a modest hydro resource, mainly located in Scotland, and this currently produces around 3% of UK electricity. Micro-hydro is sometimes regarded as a new renewable, but the potential resource in the UK is very limited.

2.4. Bioenergy
The bioenergy sector in the UK is at an early stage of development. This contrasts with other countries in Europe where biomass for heat and power is commonplace. Some parts of the UK have the potential to commercialise this resource using specialised crops for lignocellulose such as willow, poplar and miscanthus grass. Several large-scale projects are seeking planning permission but more incentive and significant investment is required to support the whole supply chain. In the UK, land resource will constrain advances in bioenergy and a portfolio of different crop types should be maintained where multipurpose uses for plants are developed, including food combined with liquid biofuels. Public sector buildings could benefit from early applications of biofuel CHP.

Currently, the environmental cost of liquid biofuel production is high, since processes are inefficient and this must be addressed through more fundamental bioscience research, enabling effective deployment of liquid biofuels. More carbon-efficient technologies need to be developed, through increased R&D to deliver the long term promise of liquid biofuels from biomass (including waste). The Government’s 2012 target of 5% of transport fuel from bio-sources will be hard to meet from indigenous biofuels. A reasonable target for the UK by 2020 is the cultivation of 1 million hectares for bio-crops, which could deliver a few percent of UK energy demand. Longer term hydrogen from renewables could be used as a chemical feedstock to upgrade biomass to more useful bio-fuels (liquid and gas).
2.5. *Marine energy*

Two forms of marine energy are currently under development: tidal energy; and wave power.

2.5.1. *Tidal Energy.* A number of distinct conversion technologies exist; these are the barrage, lagoons, and tidal current. Of these, tidal current technology is likely to attract most commercial interest. One demonstration device has been operational for almost 3 years and a number of other developers have funding for large scale prototypes. Permission has been given for a 1 MW pre-commercial prototype for Northern Island that will be deployed later this year. This is a fast moving area with considerable support available now for R&D. Market stimulation via multiple ROCs, or similar incentive, will be required soon to catalyse commercial deployment. Such economic stimulation must apply to the whole of the UK, for reasons of market equity. Planning permissions for tidal current projects are being scrutinised by the environmental community. More research is required to identify the impact of tidal current technology on marine life. This research needs to take place within the next 2-3 years in parallel with pre-commercial demonstrators to ensure that full commercial exploitation is not delayed by un-necessary environmental constraint. The issue of electricity network access mentioned in wind is also an issue for both tidal current and wave energy. If marine renewables are to meet 3% of UK electricity demand by 2020 (as predicted by The Carbon Trust) the needs for access to market through reinforced networks must be addressed now.

2.5.2. *Wave Power.* Some variants of this technology are at the prototype demonstration stage, but there remains a plethora of different designs with potential.

The challenges of designing for survival in extreme conditions are well acknowledged but cost implications for simply scaled-up technology need to be reduced based on operational experience. Evidence of long term reliable operation will provide market confidence, but developers require economic assistance to demonstrate this in the short term. Offshore test facilities such as EMEC in Orkney and the proposed WaveHub in the SW will be vital in gaining sustained offshore experience. With additional evidence of a few years of operational experience commercial exploitation will occur and truly competitive technology is expected to emerge between 2010 and 2020.

2.6. *Geothermal energy*

True geothermal energy involves extracting heat whose origin is the earth’s core. Whether this is feasible depends entirely on local geology. In some locations like Iceland, geothermal heat is accessible at the surface as steam, and this can be used for electricity generation purposes. Early research in the UK explored the potential of hot dry rocks, but with no success. Geothermal energy is not regarded as a serious prospect in the UK.

3. *A novel thin film PV cell for low cost and high efficiency*

Exciting recent research undertaken by Professor Tiwari and Dr Upadhyaya of CREST in collaboration with Professor Michael Grätzel’s team at EPFL has shown the potential of combining a thin film CIGS (Cu_In,Ga_Sec) PV cell with a dye sensitized solar cell based on nanocrystalline TiO$_2$ [7]. The resulting multijunction stacked tandem solar cells increase the overall photovoltaic conversion efficiency by significantly improved utilization of the solar spectrum. Nanocrystalline dye-sensitized solar cells can be designed by appropriate choice of the dye to absorb incident photons in specific regions of the solar spectrum while maintaining high transparency across the remaining wavelength ranges. By changing film thickness, pore size and dye loading, optical transmission and short circuit current can easily be adjusted. This makes it an ideal candidate for top cell in a tandem configuration.

The dye cell for this work was produced according to a previously published procedure [15] except that the dye used was Ru(4,4’-dicarboxylic acid-2,2’-bipyridine)$_2$(NCS)$_2$, and that a transparent single layer consisting of 20 nm sized TiO$_2$ particles was employed instead of the light scattering bilayer structure normally used in high-performance dye cells.
The optoelectronic properties of CIGS cells make it highly attractive as a bottom cell in a tandem configuration. CIGS has a band gap that can be tailored in the range 1.04–1.67 eV, with high performance cells having a band gap of around 1.25 eV. The cells can be grown on a variety of substrates including glass and foils. The current record efficiency for such cells, held by NREL in the USA, is 19.5%, which is outstanding for single junction cell on glass.

The motivation for this research lies with the very different spectral responses of the two different cells, shown in Figure 2 below.

![Figure 2](image-url)  
**Figure 2.** Spectral response of CIGS cell (blue dotted) and dye sensitized cell (red)

Whereas the response of the dye cell peaks in the blue region, CIGS performs better through the visible and into the near infra-red regions. It is immediately apparent that a stacked tandem cell would have a significantly improved spectral response and thus higher efficiency.

The research undertaken demonstrated that a tandem cell comprising a nanocrystalline dye-sensitized solar cell as a top cell to intercept the higher energy photons and a copper indium gallium diselenide thin-film bottom cell for lower-energy more penetrating could produce an overall conversion efficiency of greater than 15% under standard test conditions. The resulting device structure is shown in Figure 3.
PV cells are characterized by their I-V curves with the peak efficiency given at the combination of voltage and current which maximizes power output. The I-V curves shown in Figure 4 are for the individual dye cell illuminated from the front (a), and for the CIGS cell (b) with light filtered through the dye cell.
The series connected stacked tandem (two wire) cell is not precisely current matched but nevertheless has an efficiency of near to 15.7%. Figure 5 shows the I-V characteristics of the series connected cell at AM1.5 standard illumination. As might be expected for a series tandem cell, the voltages are much increased, and there has been little loss in current density. This indicates that good interfacing has been achieved with little increase in recombination.

![Figure 5](image)

**Figure 5.** IV curve for series connected tandem cell

The key cell parameters, namely open circuit voltage (Voc), short circuit current (Isc), fill factor (FF) and efficiency, for the tandem solar and individual cells are given in Table 1 below.

| Solar cells          | Voc (V) | Isc (mA/cm²) | FF (%) | η (%) |
|----------------------|---------|--------------|--------|-------|
| top dye cell         | 0.798   | 13.7         | 75.0   | 8.2   |
| CIGS bottom cell     | 0.650   | 14.3         | 77.0   | 7.3   |
| CIGS (without light filtering) | 0.699   | 26.8         | 74.4   | 13.9  |
| tandem cell          | 1.45    | 14.1         | 74     | 15.1  |

It is remarkable that such a high efficiency was obtained even though the photocurrents of the two cells were not perfectly matched, producing the slight hump in the I-V curve of Figure 5, and that there are significant optical losses in the stack. The FTO layer in particular has a higher optical absorption in the near infra red than ITO. There is therefore significant scope for improvement. Furthermore, the high Voc at around 1.45V makes the cell attractive for direct electrolysis of water for hydrogen production.

4. **Assessment of thin film quality**

The spatial variation of key properties of large area silicon thin film PV modules can be investigated using a Laser Beam Induced Current (LBIC) system. The system produces a very detailed current mapping of PV cells, allowing the identification of spatially varying structural defects within photovoltaic modules. It provides an efficient means of defect detection but can also assist in the investigation of localised performance variation. In this brief account of the technique and its
application to full scale modules results are shown for large area single junction amorphous silicon modules from different manufacturers that have been installed outdoors for more than two years. Several defects are identified as probable sources of poor performance and low efficiency for these modules. Some of these defects are likely to have been created during the production process while others develop as the result of operation and outdoor exposure.

CREST has developed a large area LBIC system, which is shown schematically in Figure 6. A detailed description can be found in earlier publications, [8] and [9], so only an outline description is given here. Small areas within separate cells, or alternatively the whole module, can be scanned. The system comprises a two-dimensional scanning laser head, a motorised focusing system, and customised control software. The system allows modules up to 1.5 m x 1.5 m to be investigated, although at the extremes, the angle of laser incidence is above 5°, which is not ideal. Signal recovery is done using a pre-amplifier and a lock-in amplifier, which allows minute changes in current to be identified.

Figure 6. Schematic of CREST LBIC system

Four thin modules (A, B, C and D), previously installed outdoors in the UK for more than two years, have been evaluated with the LBIC system. They are all amorphous Silicon and rated at 13 W. After two years of outdoor operation some degradation is expected and module efficiency measurements undertaken before and after outdoor operation show this. Module A shows the least power degradation of the period with less than 17.5% efficiency drop, while module B shows the highest degradation with less than 50% of the initial efficiency available at the end of the two years.
Although during manufacture each cell in a module is processed at the same time, the scanning results show, Figure 7, that there is a considerable variation of current generation among the separate cells due in the main to lack of uniform thin film deposition across the module surface.

![Figure 7](image)

**Figure 7.** Variation of current signal among individual cells of each module (the red end of the spectrum indicates high current and blue, low current)

Closer examination of the scans of selected regions of modules reveals a range of other defects. Figure 8a for example shows and the incipient failure of the isolation between adjacent cells, but at this stage without marked impact on cell current yield. Figure 8b illustrates small point defects, at this stage not significantly affecting cell output, and lastly Figure 8c shows a the edge region of one of the modules where current generation is seriously degraded.

![Figure 8a](image) ![Figure 8b](image) ![Figure 8c](image)

**Figure 8:** Detailed scans showing a) isolation breakdown; b) point defects; c) edge degradation

5. **Modelling building integrated wind turbines**

Conventionally wind turbines are located away from buildings, and with large commercial turbines there are good reasons for this. There has been a recent growth of interest though in very small wind turbines mounted on or near buildings. One approach is to use ducted turbines as these can be more compatible with the built form than those with free rotors. An added advantage is that the duct can, through contraction, accelerate flow through the rotor, and allow a smaller and potentially cheaper rotor to deliver the same power as a larger conventional free stream rotor.

The design challenge is to identify a combination of duct profile and rotor that delivers good performance. This has been approached in the past through 1D modelling, see for example [10]. In practice however, such ducted turbines will be mounted on buildings, and the influence of the building itself on the flow through the duct will be significant. 1D models cannot capture this complexity, and although a useful guide to outline duct design, more sophisticated flow computation is required.
In the work reported in outline here, the commercial CFD code CFX has been used to calculate the flow through the duct system and the power that in theory could be extracted by a suitable rotor in the duct. 1D modelling does show the importance of the flow downstream of the rotor. An expanding diffuser has the effect of retarding the flow prior to exit from the duct, thus allowing the rotor/duct system to extract more energy from the ambient wind. It is also clear from the simplified modelling that low rotor blockage is required for good performance, since otherwise flow will not enter the duct and energy capture will fall.

A range of ducts of suitable profile have been modelled in CFX in order to identify the most effective contraction ratios and the rotor blockage for optimal duct/rotor system efficiency. Figure 9 shows how the duct with cylindrical rotor is located on the top of a flat office building, the image is one half of the system being cut through the symmetry place on the left side. A section through the duct and the calculated velocity field is shown in Figure 10. The “free” wind speed approaching the building from a distance is 5 m/s and the results show considerable speed up of flow through the duct. The rotor is located in the throat of the duct and has been modelled as an isotropic loss volume (momentum sink) with optimised blockage.

![Figure 9](attachment:image9.png)

**Figure 9.** Positioning of duct on building

![Figure 10](attachment:image10.png)

**Figure 10.** Calculated flow field

The rotor coefficient of performance, \(C_p\), referenced to the duct aperture and upstream wind speed has been calculated from the CFD results and is plotted in Figure 11 against the factor \(K\), which is a dimensionless measure of the rotor blockage. It can be seen that the optimal value of \(K\) depends on the contraction ratio, with lower optimal values at the higher contraction ratios. This is as expected from the 1D modeling and reflects the care that is needed if flow is not to be deflected from entering the duct. The initial design concept assumed a cylindrical rotor, in effect a vertical axis rotor turned on its side and the next stage in this work is to design a rotor with blockage as indicated by the CFD results.
6. Brief overview of key research challenges

Renewable energy is key to sustainable energy supply. Although the technology has improved significantly over the last decades and a real commercial impact is now apparent particularly for wind and photovoltaics, much remains to be done to further reduce the cost of the different technologies. This will be delivered by a combination of basic and applied research and very importantly the scaling up of production, especially in the case of PV.

As the proportion of energy, and in particular electricity, coming from renewable sources rises, integration issues will come to the fore. A much more integrated approach to energy systems will be required in which energy of transport for example, and electricity supply systems, are not seen as disconnected as they are at present.

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