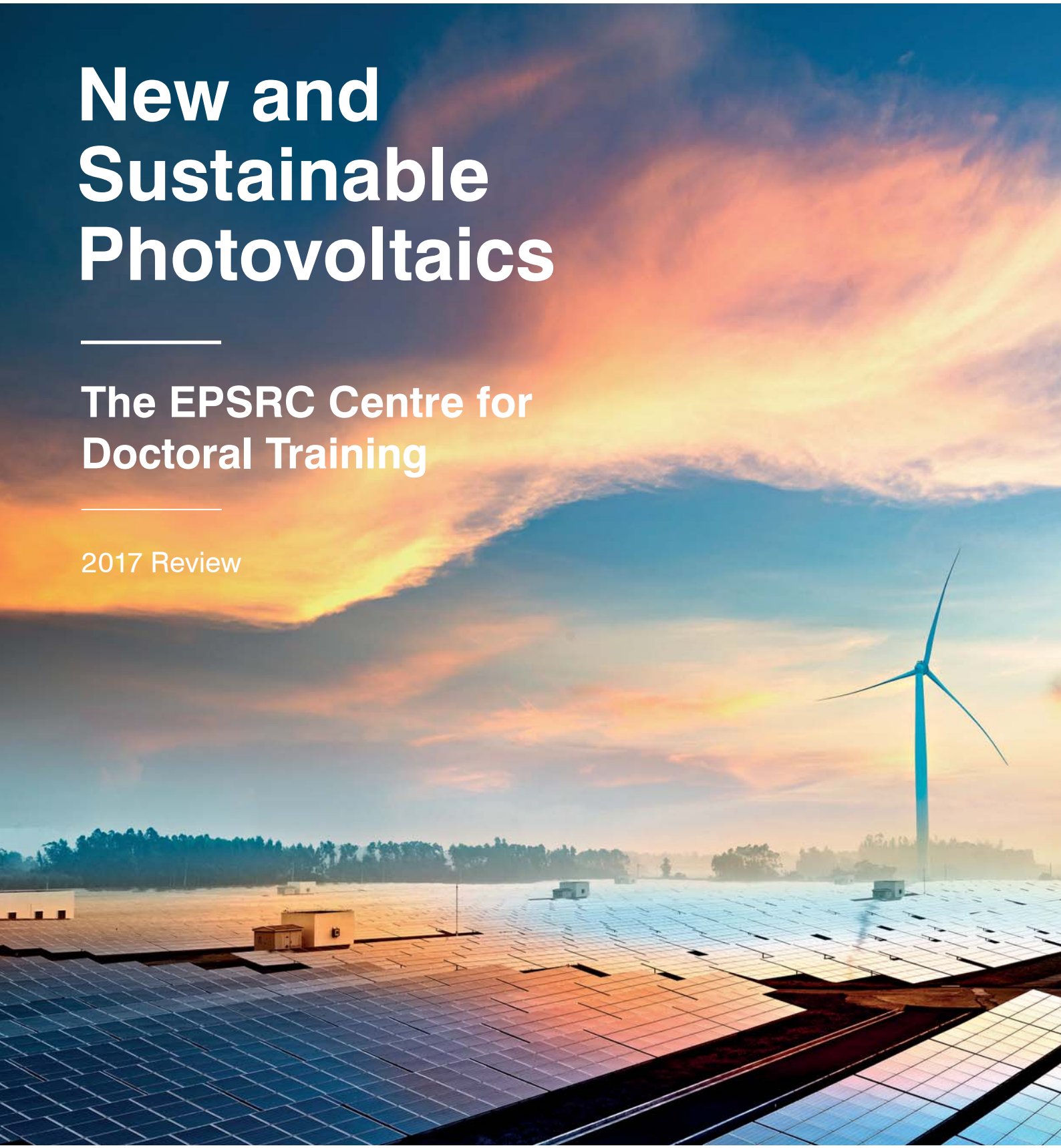
EPSRC CENTRE FOR DOCTORAL TRAINING
NEW AND SUSTAINABLE PHOTOVOLTAICS

EPSRC
Pioneering research and skills

New and Sustainable Photovoltaics

The EPSRC Centre for Doctoral Training

2017 Review



UNIVERSITY OF LIVERPOOL
UNIVERSITY OF BATH
UNIVERSITY OF CAMBRIDGE
Loughborough University
UNIVERSITY OF OXFORD
The University Of Sheffield.
UNIVERSITY OF Southampton

LIFE CHANGING
World Shaping

The EPSRC Centre for Doctoral Training in New and Sustainable Photovoltaics

All future energy forecasters agree on one thing: solar photovoltaics is now at the brink of mass adoption. But questions remain. Where can the technology go from here? What's in store for the future of solar energy? The principal ambition of the EPSRC Centre for Doctoral Training in New and Sustainable Photovoltaics, (known as CDT-PV), is to provide the future leaders who can answer these questions.

Led by the Universities of Liverpool and Bath, the Centre comprises seven leading academic institutions, the partners being Cambridge, Loughborough, Oxford, Sheffield and Southampton. The Centre is also supported by Eight19, LSA, NSG, Ossila, Oxford PV, M-Solv, Semimetrics and Silicon CPV.

We are training 60 of the best graduate students to guide PV in industry and in universities. Students are registered for PhDs at each of the partner universities. In contrast to many CDTs, the research that will form their PhD thesis is started at the beginning of the studentship. The principal skills developed by our students are established by undertaking these projects. In addition, each of our students undertakes a formal PV training course during their first year, visiting each of the seven programme nodes for two weeks each. In this way they develop not only the specific knowledge for PV research but experience the research environments of some of the UK's leading labs. More importantly, they develop a network of academic and industrial contacts and connections that will serve them throughout their careers.

We invite you to read more about the Centre and its activities in the pages that follow. Should you require information, would like to study with us and/or support our objectives, then we invite you to contact our leadership team.

August 2017

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Contents

CDT-PV Partners

Academic Partners

The following summary highlights the main expertise of each academic partner laboratory. For an exhaustive list, including all the project supervisors please see ww.cdt-pv.org/directory/

University of Liverpool
The Centre for Doctoral Training in New and Sustainable Photovoltaics is led by the University of Liverpool and has a physical base within the Stephenson Institute for Renewable Energy. Students engaged in research projects here benefit from a huge range of expertise delivered by Prof. Ken Durose and Dr. Jon Major on CdTe based solar cells, novel earth abundant solar absorbers and advanced electrical characterisation of semiconductor materials. A significant research outlook on transparent conductors is also provided by Dr. Tim Veal and very close links and collaborations with NSG, one of the world leading float glass manufacturers, who are a key Industry Partner for the CDT.

University of Bath
Prof. Alison Walker's research group located at University of Bath (Department of Physics) is a world leader in the modelling of electron transport in hybrid perovskite and organic PV solar cells. With key links to a number of EU funded projects on organic PV and electronics, the CDT benefits from access to a wide range of potential collaborators through this partner. Additional contributions from academic supervisors based in Chemistry complement computational research capabilities by providing expertise on advanced spectroscopy (Dr Enrico Da Como), electrochemistry (Dr Petra Cameron) and film deposition techniques for solar energy (Prof Mike Hill).

University of Oxford
Prof. Henry Snaith's group at the University of Oxford is at the forefront of research on metal halide perovskite materials for solar and is making a huge international impact in the field of novel low cost solar concepts. Their experience of and facilities for device fabrication and optoelectronic characterisation are world leading and they are making strides in improving the stability of perovskite solar cells. The group has strong links with the spin-out company Oxford PV who are aiming to commercialise the technology that is being developed.

University of Cambridge
The participation of Prof. Neil Greenham and Prof. Judith Driscoll's research groups at the University of Cambridge bring a strong outlook on the fabrication and optoelectronic characterisation of inorganic semiconductor nanocrystals, organic polymers and functional oxide materials for PV. The groups also bring their strong links with flexible organic PV solar manufacturer Eight19 who contribute to the CDT-PV training programme (see page 18). There is also a focus on novel strategies in increasing the upper limit of photovoltaic conversion efficiencies.

Loughborough University
Groups led by Dr. Jake Bowers and Prof. Mike Walls at Loughborough University specialise in CdTe device fabrication and optimisation, solution deposited CIGS and CZTS solar cells, and transparent conducting oxides. Their teams are engaged in research that is highly complementary to that performed at the University of Liverpool, and they provide key links for the Centre to experts in this field based at the National Renewable Energy Laboratory (NREL) in Colorado, USA. In addition, Dr. Ralph Gottschalg's research group brings a focus on large scale module monitoring and characterisation. The SuperSolar Hub (see inset) is coordinated by Loughborough University.

University of Sheffield
Prof. David Lidzey's group at Sheffield bring a specialism in enhanced polymer blend materials for organic PV and novel solution based processing methods for pervoskite solar cells. They provide access to advanced characterisation tools for both solar materials. Their strong links to the tech startup Ossila is of high value to the CDT. The company contribute to student training and research projects and have a highly collaborative relationship with the CDT.

University of Southampton
Dr. Giles Richardson's group (Mathematics) brings a focus on the advanced mathematical modelling of the electronic transport in solar materials to the CDT. Research projects within this group are contributing to a fundamental understanding of the limitations of solar PV, as well as informing the experimental development of existing and novel PV technologies. This is complemented by Dr. Stuart Boden's expertise in silicon clean room device processing and Southampton's suite of high precision nano-fabrication equipment which the CDT has access to in order to provide additional training for its students.

The SUPERGEN SuperSolar Hub

The EPSRC funded SUPERGEN SuperSolar Hub is an inclusive solar community that links research carried out by universities and industry. Led by the Loughborough University's Centre for Renewable Energy Systems Technology (CREST) the project partners are co-located with CDT-PV. The Hub has over 70 Associate and more than 500 Network members internationally.

Key activities of the Hub include:

- Maintaining a UK network for PV R&D composed of partners in the relevant University, Industry and Finance sectors.
- Training for new University and Industrial PV researchers.
- Provision of an accredited UK national cell efficiency measurement facility.
- Organisation of events and conferences of interest to all sectors of the PV community.
- Funding for international and industrial research secondments, conference attendance and research projects.
- Business and Industry Engagement.

The relationship with the SuperSolar Hub means that CDT-PV students have access to an existing research effort of international importance, providing a culture, environment and context focused on all aspects of PV. Research projects (page 16) undertaken by CDT-PV students are linked to research funded by the Hub and complemented by linked projects from outside the Hub, for example EU projects. CDT-PV students are also eligible for the SuperSolar Hub's International and Industrial Engagement Fund – an initiative having the aim of growing PV research partnerships between UK and international collaborators. The Case Study on page 10 gives two examples of how this fund has benefited CDT-PV students.

You will find further information about the Hub, the work being carried out and the project partners at www.supersolar-hub.org

Industry Partners

Eight19 Ltd
A company focused on the commercialisation of unique organic photovoltaics (OPV) concepts, including next generation flexible and lightweight products.

Silicon CPV Ltd
An international company who manufacture conventional PV and hybrid PV technology solutions. Silicon CPV focus on both the large scale and niche application of commercial grade concentrated PV systems.

Oxford PV Ltd
A spin-out from the University of Oxford to commercialise new perovskite thin-film solar technologies.

LSA Ltd
Loughborough Surface Analysis is an independent analytical laboratory, providing support to industrial researchers, academia and process engineers.

NSG Ltd
A global leader in innovative high performance glass and glazing solutions, contributing to energy conservation and generation, working safely and ethically.

M-Solv Ltd
A company focused on research, design, engineering and manufacture of micromachining and micro deposition equipment, specialising in bespoke, hybrid solutions.

Semimetrics Ltd
A provider of bespoke, high precision electrical characterisation equipment for semiconductor research.

Ossila Ltd
A specialist in the development of new components, equipment and materials to enable faster and smarter research and discovery in the fields of thin-film and organic polymer device applications.

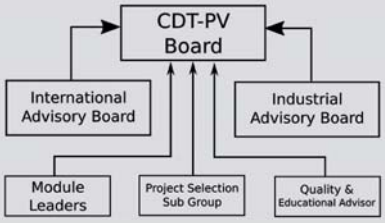
Advisors

International Advisory Board:
David Mitzi, Duke University
Gary Rumbles, NREL
Phil Dale, University of Luxembourg

Industrial Advisory Board:
Paul Warren, NSG (Chairman)
Including representatives from each industrial collaborator

Quality and Educational Advisor
Adam Mannis, University of Liverpool

Operational Structure



How the Centre operates

The key aspiration of the CDT-PV is to train future leaders in the field of photovoltaics (PV). We are currently on target to recruit a total of 60 high quality postgraduate students, across our seven academic partners, from Physics, Chemistry, Maths and Engineering backgrounds. Each year we recruit a cohort (see page 7) of about 12 students. Our existing 37 students are engaged in cutting edge research projects within world leading research groups across the UK.

All our students undergo a seven month formal training curriculum at the very start of their studentships that contains the expected depth and breadth of material to support them both in their research projects and their future careers. This curriculum is coordinated, delivered and assessed collectively by all the academic CDT-PV partners and several industrial collaborators in a series of two-week intensive modules (see page 17 on Training). Beyond their first year of study, continued training actions from the CDT are designed to give the students space to develop their main research projects while empowering them to join collective training initiatives or participate in special workshops and conferences of their choice. The annual CDT-PV Showcase, held at the University of Liverpool every November, promotes significant student interaction and opportunities for further training and collaboration. Whole group training actions are ramped up in the final year to support students prepare their theses and get ready for their future careers.

Students are invested in the operation of the Centre at all stages of their studies and are encouraged to feedback regularly on the training they receive in order for it to be improved iteratively. The students are also encouraged to instigate additional training according to their own and collective developmental needs. Recent examples of this include the coordination of a programme of talks for the CDT's Showcase and the organisation of a bespoke international Summer School on Solar Energy in Uppsala, Sweden. Each cohort of students is represented at the CDT-PV Board by a nominated representative.

A heavy focus is placed on promoting engagement between students and the CDT's industry partners (see page 5). This engagement has taken many forms, with partner involvement in research projects, provision of in-kind support, and contribution to the delivery of modules and special training actions. As a result, the students benefit from a substantial amount of collaboration and interaction with potential future employers. Furthermore students benefit highly from co-location with the SUPERGEN Supersolar Hub and the potential for additional collaboration, international links, exchange of ideas and international secondments (see Case Study on page 10).

Cohort 3 students engaged in core-level training at the University of Bath: Arduino Workshop.

Students from the CDT-PV's first cohort interacting with technologist Dr. Max Reinhardt from Ossila.

The Cohort approach

A unique feature of the Centres for Doctoral Training (CDT) initiative is the establishment of highly dynamic, self-supporting groups of students known as cohorts. The cohort model facilitates strong interactivity between peers and ensures that each student always has access to a group of like-minded individuals with whom they can discuss ongoing research and problems. A vital objective of the CDT-PV is that a high level of communication is maintained amongst each of its cohorts. Each student is able to share their experiences for the benefit of others, and in return receive support from their peers as and when needed. High onus is placed on all students within a cohort to maintain the wellbeing of their fellow students.

The Role of the Cohort

The cohort approach to postgraduate training has led to significant advantages for CDT-PV students compared to those engaged in more conventional PhDs. Such advantages include:

Collaborative troubleshooting: Common technical problems encountered by our students in their research are likely to have been experienced, and perhaps even already solved, by other members of the cohort. This is especially true for day to day 'nitty gritty' lab problems – as the cohort model significantly increases the productivity and efficiency with which our students pursue their research projects. Each cohort acts as an open technical forum and is a valued resource for problem solving. Within the CDT-PV this process is greatly facilitated by the use of specialised online communication tools (see the Case Study on page 15).

Comparing experiences with colleagues: Our students are given lots of opportunities to present their research work to the cohort and engage in detailed technical discussions during more informal seminar events. Peers within the cohort provide honest and constructive feedback on such work and expect the same in return. This type of group feedback often picks up on aspects of a student's activities that have been overlooked or sometimes misinterpreted by a supervisor, and so can be extremely useful.

Research collaboration: Each of the academic partners associated with the Centre have a distinct set of capabilities, e.g. specific characterisation or deposition equipment, computing resources, etc. Students within the CDT are encouraged to visit cohort members at other institutions in order to engage in collaboration on an informal basis. This allows students the opportunity to greatly strengthen their own research and encourages knowledge transfer between CDT-PV research groups.

Student induction and parenting: New CDT-PV students are immediately given the opportunity to interact with existing students from previous cohorts. This often happens prior to a new student's project start date. It enables each new student to obtain a good idea of what they can expect as a member of CDT and to hit the ground running when they start their PhD. Furthermore, all new students are assigned an 'academic parent' from an earlier cohort. It is the responsibility of these parents to ensure that new recruits are up to speed.

Jonathan Warby (Oxford) and Thomas Shalvey (Liverpool) enjoying some down time during a residential core-level training module.

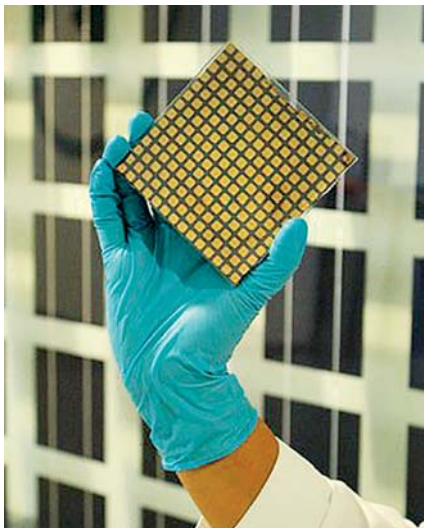
Winners of CDT-PV Showcase 2016 prizes. From left to right: Giulio Mazzotta (Oxford), Heather Goodwin (Cambridge), Robert Treharne (Liverpool), Juliane Borchert (Oxford), Lewis Wright (Loughborough), Lucy Whalley (Bath).

Cohort 2 on top of the roof of Bath Abbey during their core-level training.

Research vision and key themes

Presently the world market in solar photovoltaics is dominated by crystalline silicon which is manufactured in high volume in the Far East. The product is excellent, with commercial efficiencies falling in the 15 to 20% bracket. The economies of scale mean that the halving of the cost every ten years – 'Moore's law for solar' – is set to continue. There is a concurrent fall in the price per watt of peak power (Wp). Nevertheless, in most countries solar PV still requires government incentive schemes to promote consumer uptake – especially to sweeten the capital cost of investment in PV systems.

This leaves the industry at the mercy of political control, and it expands and contracts as subsidies come and go. For example, the UK PV industry swelled from 2,500 jobs to an estimated 25,000 with support from the Feed in Tariff by 2011, but has now declined to an estimated 5,000. It is our contention that if the cost of PV modules were genuinely lower, then the market will have a chance to become self-sustaining. Although costs of silicon modules are falling due to mass production, the fundamental need to purify and crystallise the silicon will always be a limit. It is therefore a principal research aim of this CDT to develop alternatives to silicon that have low cost and high sustainability.



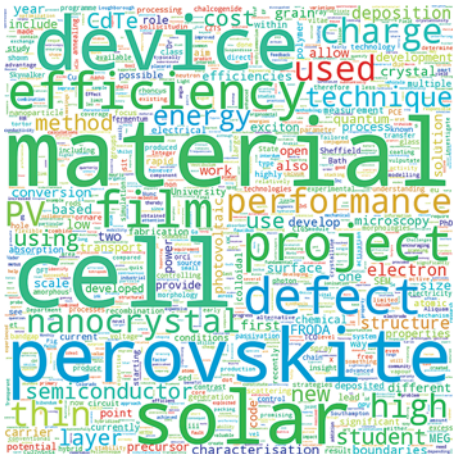
The fabrication of high efficiency solar cell devices is a key priority for CDT-PV's research outlook.

High efficiency devices

Some alternatives to crystalline silicon are already in the market place. Foremost among these are the thin film compound semiconductors cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). The efficiencies are in the range 12 to 16%, and since the production costs are intrinsically lower than for silicon they are considered to be cost-effective. CdTe is produced at 2.5 GWp per annum, with CIGS at about half that rate and amorphous silicon half that again. The thin film technologies are in a continual price reduction race to stay ahead of silicon. As a consequence there are ongoing research challenges for thin films, not least to bring in new design features, and to understand and control the underlying factors that limit the efficiency of these polycrystalline devices. The CDT therefore supports ongoing research efforts on these thin film materials.

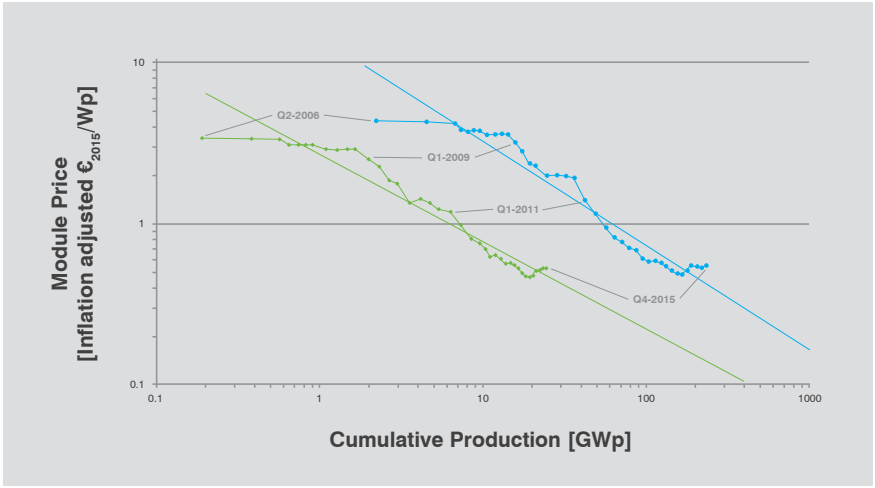
Sustainable materials

Another driver for our research comes from the predictions for the future role of PV in the world energy provision landscape. While the scenarios differ in points of detail, all of them agree that in the medium to long term future, the world will come to rely more and more on solar power. Over the next 20 to 30 years we can expect a growth in the solar PV market of more than 100 times its present level. A consequence of this is that the materials used for present day low cost solar PV, notably indium and tellurium, will be in short supply. Current annual production volumes of the raw materials will struggle to satisfy the demand. The CDT has therefore taken up an important strand of research to begin to address this problem. We are actively researching new semiconductor material choices that comprise elements that are Earth-abundant. Of these perhaps the most well-known is copper zinc tin sulphide (CZTS): each of its elements is cheap and abundant, and it has a band gap suitable for PV applications. The research challenge is to improve the voltage of CZTS solar cells – for which there seems to be some fundamental limit. Other materials of interest include copper antimony sulphide, copper bismuth sulphide and copper oxide.



Word cloud created from CDT-PV project summaries.

Student, Silvia Mariotti (Liverpool) discussing her work on novel perovskite materials for solar cells.



Price learning curve for PV for cumulative production up to 2015. Reproduced with permission from Fraunhofer ISF.

www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Estimated cumulative production up to Q4, 2015:

- c-Si 235 GWp
- Thin Film 24 GWp

Crystalline Technology (from Q2-2006 to Q4-2015)

Thin Film Technology (from Q2-2006 to Q4-2015)

Transparent conductors

One common feature of all advanced solar cell designs is for transparent electrodes, and most often these are transparent conducting oxides or TCOs. The function of the TCO is to not only allow light in and conduct the photo-generated power away, but often to have a direct contribution to the band structure of the solar cell itself. Industrially TCOs are produced directly onto hot glass as it emerges from the float line using chemical vapour deposition (CVD) methods. It is universally acknowledged that the performance of TCOs is a limit to modern PV devices – and the underlying problem is the mobility of the charge carriers. Our CDT projects include CVD and fundamental investigations into the limits of carrier motion in TCOs as well as device making programmes.

Hybrid perovskites

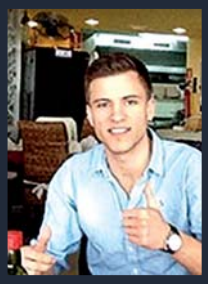
Undoubtedly the highest profile news in solar photovoltaic materials in the last decade has been the new class of 'hybrid perovskite materials'. They have hit the headlines since they achieved high efficiencies – up to nearly 20% in just three or four years. This is unprecedented in the 50 year history of PV. The first material in this class to be noticed was methyl ammonium lead iodide (MAPI) which may be crystallised from solution into films having the perovskite lattice. While it may be used to make high performance solar cells in its own right, its band gap makes it an ideal partner for silicon to form a tandem solar cell. Since the start of the Centre coincided with the onset of the excitement with perovskites, our first cohort of students comprises more than 40% who are working on these materials and devices. One of the main challenges are that the material degrades under the action of UV light and oxygen, and that it displays electrical hysteresis. Hence there is much interest in exploring chemical analogues of the hybrid perovskites and in determining the fundamental mechanisms of their electrical behaviour.

SUPERGEN SuperSolar Hub Secondments

The relationship between CDT-PV and the SUPERGEN SuperSolar Hub (page 5) is of high value to many of our students who interact with the Hub on a continual basis; participating directly in technical meetings and presenting work on behalf of their extended research groups. Furthermore, CDT-PV students are eligible for the SuperSolar Hub's International and Industrial Engagement Fund – an initiative with the aim of growing PV research network partnerships with UK and International Industry/Research collaborators.

To date, two of our CDT-PV students have made successful applications to the fund and have participated in international secondments. This case study highlights their experiences.

James Cave



Thomas Fiducia

James Cave, Cohort 1, University of Bath

Supervisor: Prof. A. B. Walker, University of Bath

James Cave was awarded the sum of £1,752 from the SuperSolar Hub for a five week secondment with the University of Newcastle, New South Wales, Australia and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The funding covered travel costs. Additional living and sustenance costs were covered by CSIRO.

James worked under the supervision of Dr. Krishna Feron on the kinetic Monte Carlo modelling of excitonic transport in organic solar cells. The research was highly aligned with James' CDT-PV project and has greatly accelerated his learning of the computational techniques that he will use throughout his studentship. James worked as part of a team comprised of both computational and experimental chemists, and his computational work was used to directly inform the design of a series of key experiments, the results of which led to a joint publication between Universities of Bath, UK and Newcastle, New South Wales and CSIRO..

The success of the secondment has led to further collaborations between the two groups, and James has successfully secured second awards from the SuperSolar Hub and CSIRO to return to CSIRO in February 2017 for an eleven week secondment to engage with Dr. Feron again, this time on a perovskite PV based project that has increased alignment with James' existing CDT-PV project and also that of many other CDT-PV students.

"Even though my project is computationally based and I could have performed the programming work remotely, working on location with Dr. Feron's group and interacting directly with experimental researchers was necessary for the project to progress in a timely manner and also accelerated my own personal rate of learning."

Thomas Fiducia, Cohort 2, Loughborough University

Supervisor: Prof. M. Walls, Loughborough University

Thomas Fiducia was awarded the sum of £9,500 from the SuperSolar Hub for a three month secondment with Colorado State University (CSU), USA. The funding covered all costs for Thomas' travel and living for the duration of the secondment. Under the joint supervision of Profs. W. Sampath (Mechanical Engineering) and J. Sites (Physics), Thomas engaged in a project involving the fabrication and characterisation of CdTe based solar PV devices. The Sampath and Sites groups at CSU are internationally recognised for their world leading work in this area, and Thomas has benefitted greatly from access to their know-how, facilities and the codes of best practice for lab management and experimental design. The secondment included specialised training in electron microscopy and a visit to the National Renewable Energy Laboratory (NREL) in Colorado.

The timing of the secondment was immediately after Thomas' CDT-PV core-level training, i.e. before beginning to focus on his project. The experience has helped Thomas to map out a path for his PhD investigations and future characterisation, and analysis will undoubtedly be informed by the knowledge gained during his secondment at CSU.

Existing collaborations between CSU and Loughborough University have been strengthened and extended thanks to Thomas' SuperSolar Hub funded secondment. Collaborative work from the secondment was presented by Thomas at the IEEE Photovoltaics Specialist Conference (PVSC), Portland, USA which he attended while on the secondment with the CSU group.

"Doing a secondment before starting my CDT-PV project has heavily informed the direction of my work and helped me prioritise the key aspects of my research."

Commonwealth Scientific and Industrial Research Organisation (CSIRO), Newcastle, New South Wales, Australia.

National Renewable Energy Laboratory (NREL), Colorado, USA.

Case Study

Research Cluster on Perovskites

Approximately 50% of CDT-PV research projects to-date have focussed on hybrid perovskites, a class of materials that attracted worldwide attention for their dramatic rise in power conversion efficiencies of solar cells since 2012/2013. These projects went through a selection committee, with funding shared across the seven partner Higher Education Institutions (HEIs) to establish this novel/timely research – for which there is no other similar mechanism within the UK Research Councils. Therefore, the CDT-PV is making a distinctive national contribution to perovskite developments. It draws on the origins of perovskites research kick-started by the Snaith Group at Oxford, and also builds on additional Research Groups at most other CDT-PV partner institutions, thus indicating that this is a truly consortium-wide activity at national level.

Cohort 3 visiting Prof. Henry Snaith's clean rooms at University of Oxford and learning how to make perovskite solar cells.

Students have been instrumental in sharing ongoing research, and associated EPSRC capital equipment, from their universities, to make explicit the critical mass theme devoted to perovskites by the CDT-PV:

> *"Perovskites were headlined in the 2016 CDT-PV Annual Showcase that I and a group of fellow CDT students organised... Many across different cohorts are involved in perovskites research, and there was a real buzz… We organised a Researcher Forum to discuss research and equipment. Lots of information was shared on perovskites, demonstrating the collective strengths of that CDT-PV funded work."*
> **Heather Goodwin, Cohort 2 student**

The science of perovskites is cutting-edge - with the main benefits being reduced costs and enhanced performance efficiencies - whilst major challenges focus on stability and degradation over their operational lifetime. This has therefore been brought fully into the programme of core-level training as an exciting and contemporary area of the PV industry. Perovskites will drive a paradigm shift in solar energy generation, along with manufacturing processes that can consistently produce high-efficiency PV panels. In fact, since they can be incorporated into thin-film architecture, perovskite-based solar cells are potentially compatible with lightweight and flexible substrates, leading to new opportunities for their deployment.

CDT-PV students discussing their work on Perovskite Solar Cells at the PVSAT conference 2016, University of Liverpool.

It is important to note that the Oxford two-week component of core-level training has been heavily focused on perovskites, so that other students in the CDT who are not directly involved in such specific research then get to learn of that aspect of PV. Cohorts become skilled in making a perovskites device and characterise it; these also application techniques relevant to any other PV material. In addition, all CDT-PV students gain insights into how perovskites technology is being commercialised by Oxford PV, a university spin-out company that also highlights highly relevant career opportunities for CDT-PV graduates.

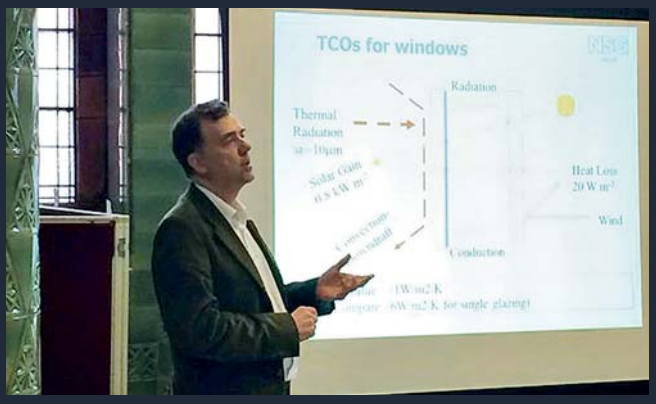
In a short space of time since the establishment of the CDT, the perovskites community in the UK along with global research in this area of PV has expanded quite dramatically. The CDT reflects this trend, in its drive to ensure that perovskites are embedded into the programme of training on offer for all CDT students; and that there is also a critical mass of associated research projects of significance at national level in the UK, to represent the dedicated research focus into perovskites occurring within the PV/solar sector worldwide.

Already, journal papers (see page 23) have been produced by CDT students as scientific outputs, with many others currently in preparation. The large sub-group of CDT-PV research into perovskites has been disseminated by students at annual international events: e.g. PSCO (Perovskite Solar Cells & Optoelectronics) conference, and the well-established HOPV (Hybrid & Organic Photovoltaics) international conference.

Collaboration with a Large Industrial Partner, NSG

This case study highlights the involvement of NSG (with head-office at its European Technical Centre in Lathom, Lancashire, UK) as one of the end-user partners of CDT-PV. The company had already forged a professional relationship with the University of Liverpool (UoL) prior to the award of the CDT. This initially stemmed from two relatively small Knowledge Exchange voucher schemes, one in 2012 and the other in 2014. From such mutual interaction, NSG and two academics of the UoL's Stephenson Institute for Renewable Energy, Dr Tim Veal and Dr Vin Dhanak, put together a joint EPSRC grant proposal in 2015 – titled 'Donor Design for Maximum Mobility for Transparent Conducting Oxides' – and at the same time a joint UoL-NSG successful application for a CDT studentship.

Jack Swallow (Liverpool) giving an overview of his work on transparent conductors with NSG to visitors from XJTLU University, Shanghai.



Paul Warren, Principal Technologist, NSG, presenting a company and technology outlook to CDT-PV cohorts at the CDT-PV Showcase, Nov 2016.

The EPSRC grant proposal was successfully awarded and got under way in 2016, as a three-and-a-half year project to the value of £1.4million, with the CDT student from Cohort 2, Jack Swallow, having commenced in October 2015. This Research Council grant is also in partnership with University College London (UCL), and has three main areas of focus: (i) Computational Chemistry, directed by UCL, for the screening of novel dopants to enhance TCO performance; (ii) CVD (Chemical Vapour Deposition), led by NSG, in producing doped thin films; and (iii) TCO Physics, managed by UoL, to characterise the doped films. The grant funding provides a post-doc scientist working on each of these three areas. Similarly to UoL, UCL wrote two studentships into the grant, one of these from their CDT in Molecular Modelling and Materials Science (M3S CDT). In terms of further synergies, the CDT-PV at the UoL is ensuring that engagement with NSG is strengthened through an additional joint academic-company student, Tom Featherstone, from Cohort 3, who is overlapping with the scientific work of that from Jack.

All of this active partnership of NSG with academia, through the CDT-PV and reinforced by an associated EPSRC grant, is aimed at developing TCO thin films (which are the mainstay of the company's technology for large-scale architectural glass and solar cell applications) in future that are indium-free with greater charge mobility, and hence having higher performance for lower cost:

> *"We are benefitting through partnership with the CDT-PV from an academic understanding of fundamental sciences involved in TCO-related challenges. This will result in the research being transferred from the lab to industrially-viable processes on our float glass line."*
> **Paul Warren, Principal Technologist, NSG**

For example, the CDT-PV student in Cohort 2 has been attending meetings on a one-to-one basis with industrial research scientists at the company, initially focused on XPS (X-ray Photoelectron Spectroscopy) analysis. Not only has this interaction benefitted the student scientifically, their personal confidence and professional insights have been enhanced:

> *"From regularly visiting NSG, I have been able to see R&D from a real-world perspective, where industrialists work on multiple projects in parallel, these highly structured and undertaken under different timescales and priorities to those at university… I have learned about aspects of IP and commercialisation, as well as resource flows in production… I now also have a fuller appreciation of the sheer scope of PV work beyond that of a university lab-scale research environment."*
> **Jack Swallow, Cohort 2 student**

It must be noted that NSG has embraced the CDT-PV by becoming industrial supervisor for the work of their two students, in Cohorts 2 and 3. Moreover, to ensure all CDT students gain insights to their business and its technologies, the company has contributed annually to core-level training: a TCO workshop, along with a float-glass-line tour of their St Helens facilities. This is critical for CDT student development, given that TCO is common to all PV device platforms. NSG is also committed to providing both of their CDT-PV students with periods of off-campus placement at head-office operations in Lathom, which will enable the learners to reinforce insights obtained from their initial periods of set research meetings. Planning for these real-world experiences is currently under way. Further company input is provided by Paul Warren, Principal Technologist at NSG, bringing his experience as Chair of the CDT-PV Industry Board.

Collaboration with a Small Business, Ossila

The case study details the ongoing relationship and interaction between CDT-PV and one of its key industry partners, Ossila – a Sheffield based university spin-out SME, linked to Prof. David Lidzey's PV-related research group. The company provides a bespoke range of highly-engineered materials and small-scale lab equipment specifically for the PV, organic and thin-film research communities. Furthermore, Ossila freely and openly distribute a large volume of technical resources to researchers, and they place a heavy emphasis on two-way knowledge transfer to further develop their product 'ecosystem' (i.e. range).

CDT-PV students Mike Stringer, Benjamin Freestone and Claire Greenland, based at University of Sheffield, are engaged in research projects highly aligned to ongoing development activities at Ossila. The students interact regularly (often on a weekly basis) with the company, and feedback experimental data and analyses from their CDT-PV research that focus on perovskite solar cells and related materials for device fabrication. This knowledge exchange is of major significance since the company has limited in-house research capacity. In return, students are receiving highly-valued experiences from collaborating with an SME: they assimilate business/project management skills, observe direct impacts their results have on product development for a commercial market, and are exposed to future employment opportunities beyond their CDT-PV studentship.

In particular, Mike Stringer has focused his work on developing perovskite precursor inks for air processing and novel contact materials in standard perovskite architectures – Mike's research results giving an increase of standard architecture cell efficiencies from 13% to 17%, with this then enabling Ossila to translate know-how from academic literature into new products on the Ossila website for commercial sale. Furthermore, Benjamin Freestone, in collaboration with Dr. Max Reinhardt from Ossila, has focused on developing alternative deposition techniques for optimised perovskite cell fabrication to help Ossila customers use their products. The resultant collaboration has generated further publishable work.

> *"I interact between the university and Ossila on-campus, and now understand how a small PV company operates through exposure to their working practices. This will be useful for future employment… There is also a sense of pride in being able to use your emerging research in new product development; my work on FTO (Fluorine-doped Tin Oxide) substrates assisting Ossila in business."*
> **Mike Stringer, Cohort 1 student**

In addition to collaboration with individual student research activities, Ossila contribute to the CDT-PV's core-level training curriculum, in providing a series of hands-on workshops, masterclasses and lectures to all CDT-PV cohorts. For instance, there is specific training on lessons learned by Ossila in the protocols of experimental methods, and in skilling of company products that have been developed to assist researchers achieve long-term statistical data (e.g. the Xtralien X100 source-measurement unit). The company is also very active as a member of the CDT-PV Industry Board, and in providing additional training

Max Reinhardt, Ossila, working with Mike Stringer (Sheffield) on precursor inks for pervoskite solar cells at Ossila's labs in Sheffield.

with particular emphasis on the teaching of business skills and how to set-up a high-tech SME. This is very relevant for all CDT cohorts, since the PV industry is dominated by many university/research start-ups – as is the case of Ossila, and also Oxford PV – alongside a fewer number of much larger companies with small operating margins (such as NSG) comprising that sector:

> *"Having CDT-PV links has generated more of an uptake of Ossila products across the user community… Specific research supported by the CDT has led to an extension of our product offering and lab techniques… We also contribute to wider cohort training, an innovation with Rob [CDT-PV Academic Manager] the co-development of Python coding based on one of our products."*
> **Professor David Lidzey, Chairman, Ossila**

Cohort 3 participating in a "Python Coding for Scientists" workshop at the University of Sheffield, delivered by Ossila.

In summary, the CDT-PV's ongoing symbiotic relationship with Ossila enables students from multiple cohorts to directly collaborate with a SME, allowing them to see that their research outputs can have an immediate commercial impact. In return, the company has ready access to a valuable resource for high-level research that directly informs their product design and enables increased success in the scientific PV/materials sector.

The CDT Student Community

"During the seven months of [core-level] training, I travelled with my cohort between partner universities… Living with the cohort for two week blocks over seven months was so much fun, and a great way of making friends from all over the country. We still keep in touch… The thing that really made the experience was the CDT-PV cohort, and I look forward to seeing everyone again each November along with a new intake of students."

Elizabeth Parrott, Cohort 1 student

The CDT-PV's distributed, split-site operation might have been a barrier to student training. But this barrier has not materialised. On the contrary, it is a key strength, since the CDT has used the programme of two-week institutional visits each month (to all seven partner HEIs), from November to May for new starters, to forge cohort interactions of much meaning and substance. The starting students also interact with other CDTs and their peers in universities visited 'on tour'. These relationships, personal and professional, then continue within the CDT-PV.

Loughborough students Rachael Greenhalgh (Cohort 1), Lewis Wright (Cohort 2) and Christos Potamialis (Cohort 1) visiting the TESLA stand at the Clean Energy Live expo, Birmingham NEC, Oct 2016.

Members of Cohort 1 on a trip to the Isle of Wight during their core-level training at the University of Southampton.

So, what makes this all work? A detailed handbook and kick-off Induction at the lead site (the University of Liverpool) sets the tone. This induction is combined with the annual CDT-PV Showcase event organised by previous cohorts, who are glad to share their experiences. These existing cohorts play a vital role in passing on their advice and guidance to the new arrivals. The earlier cohorts, along with the CDT management team, demonstrate to the new arrivals that the core-level training programme has a set of well-thought-out principles, explaining the rationale and setting expectations. The incoming students are also informed that they can provide feedback on any element of their CDT experience, and that their opinions are valued for the development of a coherent programme relevant to the national PV community.

The CDT-PV website facilitates student communication, both intra- and inter-cohort. It links together all the CDT's training content provided across the seven partner institutions. This is unique and its substantial archive of training content has been viewed thousands of times internationally making it a public asset. In addition, every CDT student has their own personal 'Portfolio' that

Cohorts 1, 2 and 3 preparing for the third CDT-PV Showcase at University of Liverpool, Nov 2016.

they can use to update all of their specific project outputs (papers, posters, presentations), and can share these with others. An embedded electronic feedback system within the website also makes students feel part of the PV community.

Consistency of training across the modules offered by the seven partner institutions is an important principle that ensures cohort building takes place early at the CDT, as students experience the different modules. This consistency is achieved in that for each module: (i) lecture content is high quality and linked to robust assessments; (ii) hands-on activities are included encouraging joint working; (iii) time is devoted to an external industry-related group tour/visit; (iv) lab exercises promote the skilling of students again in teams; (v) opportunities are available to give presentations to technical and non-technical audiences; and (vi) space is set aside during each block of training for informal social gatherings.

After the initial period of core-level training, 'Slack' software is used by all cohorts beyond CDT events around the country. 'Slack' is a real-time discussion tool for teams, able to collate verbal feedback that is anonymous. It is used to follow-up on elements of feedback that have been received through the website, checking the extent of issues raised and canvassing opinion of ongoing matters. Collaboration and dialogue on multiple topics such as researcher experiences, conferences, publications, etc are also facilitated. To-date, there have been over six thousand student interactions on topics by CDT-PV cohorts across the partner institutions. In addition, all students meet up at research events, either those sponsored by the CDT or others related to PV. This further ensures associations and networks are strong across cohorts:

"From using my personal dedicated training budget, I have been able to present my research at events such as PVSAT and Clean Energy Live. The CDT was well represented by students from mine and other cohorts. We made sure to promote the CDT-PV brand while projecting a strong group identity of UK-funded research. This was also another means for us to meet as a PV cohort again."

Lewis Wright, Cohort 2 student

Student Driven Training

"How do I know the CDT-PV is working well? As elected Student Rep for my cohort, I was able to see the importance given to investments in the website and electronic feedback system, and that at Board meetings the CDT Management Team took the views of each cohort seriously. Discussions on training were a regular item, and action was taken based on the collective opinions of students."

Peter Yates, Cohort 1 student

Feedback mechanisms have been established by the CDT-PV through a strategic investment in the development of an in-house high-quality component of the CDT website, which is dynamic database-driven, providing coherence to the CDT-PV activities of the seven partner institutions. Key features of the website include: a tagged directory of all CDT projects and people; a centralised assessment submission and marking system that keeps track of researcher training outputs; and an anonymous system that automatically collects and collates all student feedback on the training and other aspects of the CDT. The time invested in creating the feedback component has been rewarded through it being regarded as professional and intuitive, so students take it seriously.

Jack Swallow (Liverpool) and Olivia Ashton (Oxford) preparing feedback on their CDT-PV core-level training.

Student feedback was recognised at the outset as being critical to enhancing CDT-PV training and cohort approaches, as well as allowing change to happen through gathering ongoing evidence from participants. In terms of its implementation, there has been much success from strong levels of engagement. High response rates are also provided to requests from the CDT management team for feedback from cohorts (>85%).

Importantly, the CDT ensures that the feedback loop is closed through promptly and regularly communicating with students about remedial/change actions taken. The CDT creates routine dialogue amongst and between cohorts. Also, the feedback has been used as a resource for training in the role of student representatives on CDT-PV governance structures. The representatives use this evidence to learn how to be sensitive and give constructive feedback, and they could see that their opinions were valued.

Since its inception, the CDT-PV has built up an annual set of comments and feedback from each cohort. Using a web-based

Ned Booker (Cambridge) and James Cave (Bath) presenting at the CDT-PV Summer School, Uppsala Sweden. The event was entirely student driven.

form, feedback has been obtained from each individual student on each taught element of their student experience. This has meant that developments can be benchmarked, improvements can be monitored, and a baseline of trends relating to training/development has been established between cohorts. All of this information is made available as one source for reporting purposes, and in the curriculum review processes that comprise elements of CDT-PV governance structures.

As a result, the CDT-PV management team has been able to identify aspects of the curriculum (i) where there may have been some unnecessary duplication, and/or (ii) that required further development. This information was acted on, making the training more relevant and useful for follow-on cohorts. Examples are provided below of where feedback has been instrumental in shaping CDT ongoing developments:

Entrepreneurship training for Cohort 1 was felt by students as too generic and overly commercial. Feedback was acted upon for the next year, with a change of course provider, and student satisfaction greatly increased. The event is now much more personal, with smaller group exercises, and it is focused on the discipline area in terms of applications/case studies used in that taught element of core-level training.

A lot of projects in Cohort 2 involved a combination of both experimental and computational research. So, the CDT developed a workshop on Python coding in-house that received very positive feedback, and set the students up well for much more advanced PV training later. There were two elements of feedback here: (i) in identifying a training gap from Cohort 1 comments; and (ii) Cohort 2 taking that training and giving feedback on its use. Both Cohorts 1 and 2 became co-developers in constructing the training content and practical coding exercises, to ensure relevance and appropriate delivery. This workshop is now a staple in the CDT programme, and is being cascaded to other CDTs and to partner institutions. 'HiPy' (see Highlights on page 22) training is being developed as an outreach activity, from that initial Python set-up that was instigated through the CDT-PV.

Project Directory

COHORT 1

New heterostructures for perovskite solar cells and investigation of the stability of methylammonium lead iodide layers
University of Liverpool
Silvia Mariotti | Prof. Ken Durose

Evaluating new polymeric materials for photovoltaic devices
University of Sheffield
Ben Freestone | Prof. David Lidzey

Perovskite photovoltaic devices
University of Sheffield
Mike Stringer | Prof. David Lidzey

Investigation of non-standard materials and materials deposition method for hybrid perovskite solar cells
University of Bath
Peter Kubiak | Dr. Petra Cameron

Mesoscale model for hybrid solar cells employing sulfides and perovskite structure materials
University of Bath
James Cave | Prof. Alison Walker

Recombination in solution-processed photovoltaics studied by magnetic field effects
University of Cambridge
Edward Booker | Prof. Neil Greenham

Doped binary oxides for enhanced performance solar cells
University of Cambridge
Lana Lee | Prof. Judith Driscoll

Microstructure and functionality in thin film solar cells from sustainable materials
University of Liverpool
Peter Yates | Prof. Ken Durose

Characterisation of radiative and non-radiative charge carrier lifetime of solar cells using optical methods
Loughborough University
Vincent Tsai | Prof. Ralph Gottschalg

New back contacts for thin film CdTe solar cells
Loughborough University
Christos Potamialis | Dr. Jake Bowers

Photophysics of organometal halide perovskite materials for next-generation solar cells
University of Oxford
Elizabeth Parrott | Prof. Laura Herz

Carbon based electrode technologies for novel solar cells
University of Oxford
Giulio Mazzotta | Dr. Moritz Riede

Modelling charge transport in perovskite solar cells
University of Southampton
Nicola Courtier | Dr. Giles Richardson

Ultrathin hybrid photovoltaics
University of Southampton
Giacomo Piana | Dr. Pavlos Lagoudakis

COHORT 2

Mesoscale simulations of polymer based organic photovoltaics
University of Bath
Alexander Smith | Prof. Alison Walker

Multi-scale simulations of point and extended defects in thin-film solar cells
University of Bath
Lucy Whalley | Prof. Aron Walsh

Multiple exciton generation in nanoparticle solar cells
University of Cambridge
Heather Goodwin | Prof. Neil Greenham

Pyrolysis of solution-processed CZTS for upscale
Loughborough University
Lewis Wright | Dr. Jake Bowers

Micro-structural defects in thin film photovoltaic devices
Loughborough University
Thomas Fiducia | Prof. Mike Walls

New design features in lightweight and low-cost inverted CdTe solar cells
University of Liverpool
Tom Baines | Dr. Jon Major

Transparent conducting oxide glass coatings for photovoltaics
University of Liverpool
Jack Swallow | Dr. Tim Veal

Vapour deposition of perovskite solar cells
University of Oxford
Juliane Borchert | Prof. Michael Johnston

Characterizing the nanoscale morphology of organic metal halide photovoltaic materials
University of Sheffield
Konstantinos Tsevas | Dr. Alan Dunbar

Understanding degradation mechanisms in perovskite based PV devices
University of Sheffield
Claire Greenland | Prof. David Lidzey

Hybrid semiconductor nanocrystals/perovskite solar cells
University of Southampton
Christopher Bailey | Dr. Pavlos Lagoudakis

Perovskite solar cells
University of Oxford
Olivia Ashton | Prof. Henry Snaith

COHORT 3

Hot-carrier harvesting in hybrid metal halide perovskites for solar cells
University of Oxford
Alexander Knight | Prof. Laura Herz

New p-type transparent conducting oxides
University of Bath
Christopher Morris-Knox | Prof. Michael Hill

Modelling ion motion and hysteresis in perovskites
University of Southampton
Evan Turnill | Dr. Giles Richardson

Charge transfer processes at perovskite/organic interfaces, the role of doping
University of Bath
Joshua Macdonald | Dr. Enrico Da Como

Investigating alternative transparent electrodes for photovoltaic devices
University of Sheffield
Francesco Bastianini | Dr. Alan Dunbar

Improved efficiency of thin film photovoltaic devices
Loughborough University
Rachael Greenhalgh | Prof. Mike Walls

Hotwire chemical vapour deposition of boron doped epitaxial silicon for interdigitated back contact solar cells
University of Southampton
Edris Khorani | Dr. Stuart Boden

Encapsulation technologies for thin-film photovoltaic devices
University of Sheffield
Joel Smith | Prof. David Lidzey

Band gap tuning of metal halide perovskites for multi-junction all perovskite solar cells
University of Oxford
Jonathan Warby | Prof. Henry Snaith

Combinatorial TCO physics and optimization for photovoltaics
University of Liverpool
Thomas Featherstone | Dr. Tim Veal

Breaking the voltage barrier for CdTe solar cells
University of Liverpool
Thomas Shalvey | Dr. Jon Major

Training

For further information about our training modules, including access to resources, please see our website www.cdt-pv.org

Training Overview

CDT-PV first year training curriculum:
- 14 weeks
- 7 x 2 week modules at each HEI partner
- Provides specific training that is relevant to projects
- Equips students with additional knowledge and skills that might not be gained through independent research and study
- Curriculum is specifically designed to address the field of Photovoltaics
- Wide range of subjects including: semiconductor and device physics, UK energy policy, entrepreneurship, nanotechnology and advanced materials.
- This training, placed within the context of an individual's research activities, provides a very broad research outlook that most PhD candidates do not get.
- Modules designed to promote student interaction within the cohort, on both professional and social levels.

"Core level training modules have not only provided a great cross-disciplinary learning opportunity, but were also fun and we really grew together as a cohort"
Juliane Borchert, Cohort 2 student

Years 2-4:
- Embedded at HEI
- Specific research problem chosen by CDT-PV selection committee
- Aligned with national/international PV research landscape
- Heavy focus on presenting work at conferences (national/international)
- Summer Schools
- Showcase Events
- Formalisation of work for academic publications
- Public Engagement and Outreach.

Fundamentals of Photovoltaics

Summary
This course is an introduction to the relevant fundamental physics required to understand the operation and characterisation of photovoltaic devices. It is divided into several components; a lecture course (8 lectures), practical lab-work, a group project and a materials workshop. The course also includes a series of problem classes and an examination. In addition, there is a site visit to the NSG float line in St. Helens when it is practical to arrange that to fit with the plant schedule.

Training Elements:
- Lecture Course: Fundamentals of Photovoltaics
- Communicating Science: Podcasting
- Lab Practicals
- Workshop: Transparent Conducting Oxides
- Team Challenge
- Tour of NSG float line, St. Helens

Assessments:
- Podcast
- Exam on lecture course
- Team Challenge presentation

University of Liverpool

Module Co-ordinator: Prof Ken Durose (ken.durose@liverpool.ac.uk)

CDT-PV Director Prof. Ken Durose welcoming our first cohort of students at University of Liverpool, Nov 2014.

Cohort 3 students Tom Shalvey and Christopher Morris-Knox recording a podcast on renewable energy as part of their core-level training at the University of Liverpool.

Module 1

Renewable Energy and Entrepreneurship

Summary

In the first half of this module students are introduced to the technological aspects of a wide range of renewable energy technologies including wind, tidal, energy storage, as well as solar. They receive a balanced overview of climate change science, and also review global and UK energy usage/supply.

In the second half of the module students receive an introduction to technological commercialisation and entrepreneurship. This includes an overview of entrepreneurship theory and practice, the basics of intellectual property (IP) protection and the role of IP in business/university policies, as well as an introduction to finance and responsible business practices in the context of sustainable technology. There is also a tour of Eight19 Ltd (printed plastic solar technology).

The module assessment includes an "open-book" examination that occurs the first Monday after the training.

Joel Smith (Sheffield) learning about Stirling engines during the Cambridge module, Dec 2016.

Training Elements:

- Lecture Course: Renewable Energy
- Visit to Eight19
- Research Seminars
- Entrepreneurship Workshop

Assessments:

- Exam on lecture course

University of Cambridge

Module Co-ordinator: Prof. Neil Greenham (ncg11@cam.ac.uk)

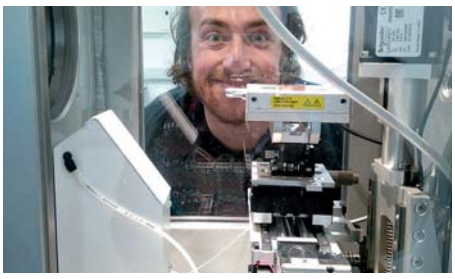
Module 2

Research Skills and PV in Action

Summary

This module aims to give students a background understanding and practical experience of experimental methods and techniques used in materials research. The core of the module is a lecture course that informs about the wide variety of thin-film deposition and characterisation techniques, including UV-Vis spectroscopy, infra-red absorption spectroscopy, Raman scattering and electron microscopy.

Students also take part in a diverse programme of practical activities that includes: the deposition of thin films via spin coating, absorption and fluorescence measurements of organic semiconductors and training to use atomic force microscopy. Industry partner Ossila also deliver workshops on enterprise and coding.



Jonathan Warby (Oxford) performing X-ray Diffraction experiments on perovskites at University of Sheffield.

Training Elements:

- Literature Review
- Lecture Course: Experimental Techniques
- Lab Practicals
- Introduction to Python for Scientists
- Visit to Ossila and Workshops

Assessments:

- Lab report
- Literature Review

University of Sheffield

Module Co-ordinator: Prof. David Lidzey (d.g.lidzey@sheffield.ac.uk)

Module 3

Mathematical Methods and Nanotechnology

Summary

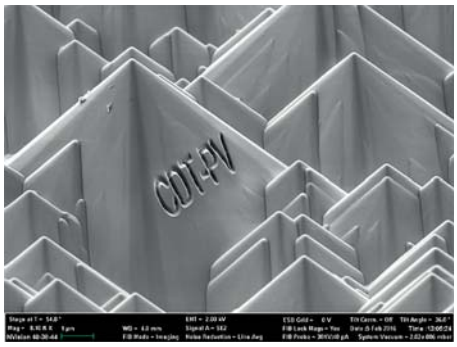
This module focuses on Mathematical Modelling and Numerical Methods in the context of PV. Students also participate in labs on cell characterisation, clean room processing and laser physics, along with a workshop on TCAD (Technology Computer Aided Design). Assessments for the module include detailed lab reports of analysis encountered during lab practicals and a team presentation.

Training Elements:

- Lecture Course: Mathematical Methods
- Labs: Nanotechnology and the Clean Room
- Team Challenge
- TCAD Workshops

Assessments:

- Lab report
- Team Challenge presentation



Nano Graffiti: CDT-PV students learn to use a focused ion beam to texture silicon surfaces during the Southampton training Module.

University of Southampton

Module Co-ordinator: Dr. Giles Richardson (g.richardson@soton.ac.uk)

Module 4

"Working closely with a group of such similarly minded people helped really ignite my passion for solar energy and sustainability, the modules laid a great foundation for in depth discussions and debates. I have thoroughly enjoyed it so far and believe I have developed into a better student, scientist and presenter than I would have been without this opportunity."

Rachael Greenhalgh, Cohort 3 student

Design, Fabrication and Characterisation for High Performance

Summary

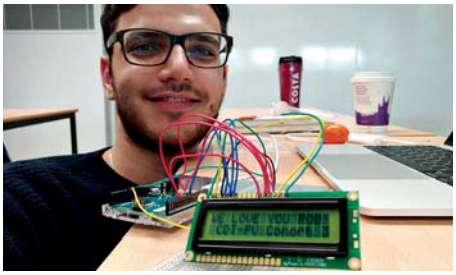
In this module students receive training in electro-chemistry characterisation, electronic structure, Kinetic Monte Carlo (KMC) simulations, materials characterisation for organic photovoltaic cells and fabrication methods for transparent coated oxides and thin film solar cells.

Training Elements:

- Electrochemistry Lectures and Labs
- Electronic Structure Workshop
- TCO and Thin-Film Deposition
- Workshop: Organic PV

Assessments:

- Organic PV lab report
- KMC report



Edris Khorani (Southampton) learning microelectronics during the Bath training module, March 2017.

University of Bath

Module Co-ordinator: Prof. Alison Walker (a.b.walker@bath.ac.uk)

Module 5

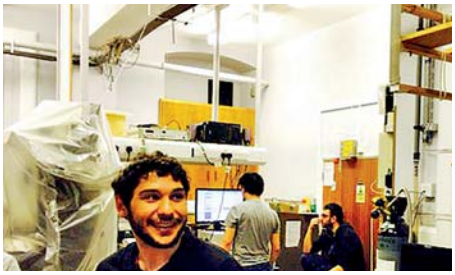
Advanced Sustainable Materials

Summary

This module begins with a comprehensive lecture course covering the following topics: Opto-electronic properties of organic semiconductors, carbon nano-tubes and graphene, polymer physics and the commercial development of organic PV (OPV). This course is assessed by a short examination.

Students then engage in a programme of lab work that aims to provide training in time resolved photoluminescence, perovskite cell characterisation and LabView for PV characterisation. Further assessment takes the form of a brief written report on these activities.

The cohort's Team Challenge consists of a presentation concerning the current status, problems and future solutions for Building Integrated Photovoltaics (BIPV). The training for this module is rounded off with a trip to Begbroke Science Park thin-film coating facility, where students receive a tour and technical presentations from industry experts.



Christos Potamialis (Loughborough) and Benjamin Freestone (Sheffield) receiving training in advanced device characterisation at the University of Oxford, April 2015.

Training Elements:

- Workshop: How to Write a Paper
- Lecture Course
- Lab Practicals: Device Making and Characterisation
- Team Challenge: BIPV
- Visit to Oxford PV, Begbroke Science Park

Assessments:

- Writing a journal style article
- Team Challenge presentation

University of Oxford

Module Co-ordinator: Prof. Henry Snaith (henry.snaith@physics.ox.ac.uk)

Module 6

System and Real PV Performance

Summary

This module aims to broaden understanding of PV from the lab-scale to full-scale operation of 'real world' PV modules. Students attend a lecture course that covers module fabrication, encapsulation and interconnect design, performance characterisation and the aspects surrounding the ageing, degradation and failure of PV modules. Guest lectures from key industry members are provided and the many aspects of commercial PV technologies discussed.

The module includes several workshops, e.g. on LabView and Matlab, aimed at providing training on useful skills for PhD investigations. Students will visit the UK's largest solar farm at Wymeswold.

Cohort 3 visiting Wymeswold Solar Farm, Leicestershire as part of the Loughborough training module, May 2017.

Training Elements:

- Workshop: PVSyst Systems Monitoring Software
- Workshop: Matlab
- Workshop: LabView
- Lecture Course: PV Systems
- Lab Practicals: Module Building and Testing
- Visit to Wymeswold Solar Farm

Assessments:

- Data analysis reporting
- Group presentation

Loughborough University

Module Co-ordinator: Dr. Jake Bowers (j.w.bowers@lboro.ac.uk)

Module 7

Highlights

CDT-PV Summer School, Uppsala, Sweden

In June 2017 CDT-PV students organised a Summer School for graduates and researchers working in the field of renewable energy and photovoltaics. The four day event was attended by over 40 students and academics within the field of PV. It offered exciting opportunities for delegates to develop their skills, interact to develop new collaborative research and build links with other research partners in Europe. Delegates received an excellent mix of talks by guest speakers from Uppsala University (UU) and local businesses and enterprises covering topics ranging from cutting edge perovskite characterisation (Gerrit Boschloo, UU) to activism in the workplace (Annika Skoglund, UU), as well as sustainability driven innovation in big business (Alex Castro, IKEA).

Interaction with other CDTs

The multifaceted nature of PV research requires an inter-disciplinary approach and the CDT-PV students have made the most of an extended network of connections with other Centres for Doctoral Training nationally. The CDT-PV's distributed structure enhances this and the table below indicates the breadth of this interaction.

CDT Name	Lead HEI
Plastic Electronics	Imperial College London
Theory and Simulation of Materials	
Diamond Science and Technologies	Universities of Warwick and Bristol
Sustainable Chemical Technologies	University of Bath
Condensed Matter Physics	University of Bristol
Quantum Engineering	
Nanoscience and Nanotechnology	University of Cambridge
Sensor Technologies and Applications	
Computational Methods for Materials Science	
Graphene	
Metamaterials	University of Exeter
Environmental Research DTP	University of Oxford
Graphene NOWNANO	
Systems Biology	
Biomedical Imaging	
Theoretical Chemistry	
Energy Storage and Applications	University of Sheffield
Polymers, Soft Matter Colloids	
Fusion	University of York

Awards

Name	Award
James Cave	CDT-PV Showcase Best Presentation 2015
Guilio Mazzotta	CDT-PV Showcase Poster Prize 2015, 2016
Lana Lee	CDT-PV Showcase Poster Prize 2015
Silvia Mariotti	PVSAT-12 Best Poster Prize 2016
Lucy Whalley	CDT-PV Showcase Best Presentation 2016
Lewis Wright	I'm a Scientist, Get Me Out of Here – Best Q&A Session Organiser 2017
Christos Potamialis	PVSAT-13 Best Poster Prize 2017
Peter Kubiak	Dalton Best Poster Prize 2017, CVD/ALD Conference, Sweden

Public Engagement and Outreach

Activity	Location	Description
How to Build A Solar Cell	Bath	A workshop delivered to Key Stage 3 school pupils by CDT-PV students based at University of Bath.
HiPy – Coding In The City	Liverpool	A series of public coding events throughout the Liverpool city region delivered by students using resources created by CDT-PV.
Solar Challenge	Liverpool	A project designed by CDT-PV to encourage teams of scientists and engineers to build an unmanned solar powered aircraft. The team entry for 2017 will compete in the national Royal Society of Arts 'Solar Challenge' and is aiming to set the world record for unmanned solar powered flight.
What Does it Mean to Decolonize Science?	Oxford	A science and philosophy talk delivered to a public audience about how particular social groups may be said to have 'colonised' science and how that could change in future.
I'm a Scientist, Get Me Out Of Here	Oxford/ Loughborough	Web-based chat competition where CDT-PV students answered questions from school children in a series of live chats.
Mathematics for Energy in the Modern World	Southampton	Exhibit for the University of Southampton's Science and Engineering Day. Over 7000 people attended this exhibit!

Claire Greenland (Sheffield) presenting her work on pervoskite materials at the CDT-PV Summer School, Uppsala, Sweden, June 2017.

A HiPy coding event at the University of Liverpool. This initiative has been spun-out of CDT-PV to provide training in coding skills across the Merseyside area.

CDT-PV Publications

2017

S.E.J. O'Kane, G. Richardson, A. Pockett, R.G. Niemann, **J.M. Cave**, N. Sakai, G.E. Eperon, H.J. Snaith, J.M. Foster, P.J. Cameron and A.B. Walker. Measurement and modelling of dark current decay transients in perovskite solar cells. J. Mater. Chem. C. 2017, 5, p452 dx.doi.org/10.1039/C6TC04964H

Michael Wong Stringer, James E. Bishop, **Joel A. Smith**, David K. Mohamad, Andrew J. Parnell, Vikas Kumar, Conny Rodenburg and David G. Lidzey, Efficient perovskite photovoltaic devices using chemically doped PCDTBT as a hole-transport material. J. Mater. Chem. A, 2017, 5, 15714 DOI: 10.1039/C7TA03103C

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L. Phillips, A.M. Rashed, R.E. Treharne, J. Kay, **P. Yates**, I.Z. Mitrovic, A. Weerakkody, S. Hall, K. Durose. Maximizing the optical performance of planar $CH_3NH_3PbI_3$ hybrid perovskite heterojunction stacks. Solar Energy Materials and Solar Cells, 2016, 147, p327

D. K. Mohamad, **B. Freestone**, R. Masters, M. Reinhardt, S. Canning, C. Rodenburg, D. Lidzey. Optimized organometal halide perovskite solar cell fabrication through control of nanoparticle crystal patterning. J. Mater. Chem. C 2016, 5, p2352 DOI: 10.1039/C6TC05189H

Chan Kyu Kwak, Gabriel E. Pérez, **B.G. Freestone**, S.A. Al-Isaee, A. Iraqi, D.G. Lidzey, and A.D.F. Dunbar. Improved efficiency in organic solar cells via conjugated polyelectrolyte additive in the hole transporting layer. J. Mater. Chem. C, 2016, 4, p10722. DOI: 10.1039/C6TC03771B

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G.E. Eperon, T. Leijtens, K.A. Bush, R. Prasanna, T. Green, J. Tse-Wei Wang, D.P. McMeekin, G. Volonakis, R.L. Milot, R. May, A. Palmstrom, D.J. Slotcavage, R.A. Belisle, J.B. Patel, **E.S. Parrott**, R.J. Sutton, Wen Ma, F. Moghadam, B. Conings, A. Babayigit, H-G. Boyen, S. Bent, F. Giustino, L.M. Herz, M.B. Johnston, M.D. McGehee, H.J. Snaith. Perovskite-perovskite tandem photovoltaics with optimized band gaps. Science, 2016, 364 (6314), p861-864

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Phillips, L.J., A. M. Rashed, R. E. Treharne, J. Kay, **P. Yates**, I. Z. Mitrovic, A. Weerakkody, S. Hall, K. Durose. Dispersion relation data for methylammonium lead triiodide perovskite deposited on a (100) silicon wafer using a two-step vapour-phase reaction process. Data in Brief, Volume 5, December 2015, p926-928

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