Science to enable the circular economy

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One might think that recycling of valuable resources has always been a key facet of how advanced societies operate. For example, the use of precious metals as catalysts was usually associated with their recovery and reuse. However, a disconnect occurred when, for example, the catalytic converter for automobile exhaust treatment was introduced leading to quantities of the rare metals palladium and platinum being released and these are difficult to recover. Hence in that case, the concept of circular use recovery and reuse has been lost. There is increasing recognition of the need for responsible and efficient use (and, where possible, reuse) of all finite resources, and the potential overall benefit to society is immense: e.g. in reducing pollution and waste, resource consumption and CO_2 emissions. To some extent, awareness of the need to recover and reuse has been lost as the world economy has grown and single use disposable items now reign supreme in our everyday lives. This mode of thinking and living was given a major jolt by the BBC programme *Blue Planet II*, beautifully narrated by Sir Richard Attenborough, which dramatically showed the effects of single use plastics on the oceans. This, and the need to deal with the challenge of reducing carbon emissions to tackle climate change (https://royalsociety.org/topics-policy/projects/climate-change-evidence-causes/), has led to growing public awareness of the need to rethink our whole approach to how we use the resources available to us and how we should be better custodians of our planet. Achieving a circular economy requires redesign and reengineering of industrial processes and

products, effective capture and use of waste streams, imaginative new approaches to chemical transformations, and careful evaluation of uses and costs. All of these require developments in fundamental science. In this background, a Royal Society Discussion Meeting was held in London on the topic of '*Science to enable the circular economy*' on 24-25th June 2019. In this special issue a number of the papers presented at the meeting are collected, together with articles from early career researchers who contributed much to the discussion and are active in this broad field.

The discussion meeting was arranged into four sessions. The first concerned '*Fuels and chemicals for a circular economy*' in which the topics of fuels manufacture from both fossil and renewable resources were discussed. In this session, the first presentation by Dr Mike Muskett (BP, UK) focused on the options available for synthetic liquid fuels. Professor Michael George (University of Nottingham, UK) discussed '*Manufacturing chemicals with light: any role in the circular economy?*'. '*The mechanisms to achieve a circular economy*' was discussed by Dr John Warner (CEO & President Warner Babcock, USA) and '*Catalyst design as key elements of an efficient use of renewable carbon resources*' was presented by Professor Regina Palkowits (Institut für Technische und Makromolekulare Chemie, Germany).

The second session on '*Polymers for a circular economy*' concentrated on the pressing problem of how to reuse plastics. In session two, the topic of 'Seed and microalgae oils as feedstocks for monomers and polymers' was presented by Professor Stefan Mecking (University of Konstanz, Germany), and Professor Michael A R Meier (Karlsruhe Institute of Technology, Germany) showed that '*Renewability is not enough: sustainable synthesis of biomass-derived monomers and polymers*'. 'Polymers as a materials system in a circular economy' was introduced by Professor David Bucknall (Heriot-Watt University, UK) and Professor Charlotte Williams (University of Oxford, UK) discussed '*Circular economy plastics*'. Altogether, this provided the platform for a very lively debate and this led into a very lively poster session in which early career scientists showed new aspects of their work on circular economy research.

Biological processes can provide inspiration for developments in the circular economy. Biotechnology can provide lower energy pathways to key platform molecules, for example. The third session concentrated on 'Biotechnology in a circular economy', with a focus on the potential of biocatalysis. This session was started by Professor Nicholas Turner (University of Manchester, UK) on the topic of '*Enzyme catalysed reactions for high-value applications*'. Professor Wolfgang Zimmermann (Leipzig University, Germany) discussed '*Biocatalytic*

recycling of plastic'. '*Biocatalysis and biomass conversion: enabling a circular economy*' was the topic of the presentation by Professor Roger Sheldon (Delft University of Technology). '*Cleaner NADH recycling for biocatalytic chemical synthesis*' was described by Professor Kylie Vincent (University of Oxford, UK).

The circular economy will have have wide-ranging effects on society. The final session discussed '*Techno-economic, societal and environmental impacts of the circular economy*'. Professor Adisa Azapagi (University of Manchester, UK) discussed '*Environmental aspects of the circular economy*', emphasising the importance of a full life cycle analysis (LCA) in assessing environmental impact. Dr Kai Baldenius (BASF SE, Germany) described '*Biocatalysis: we create chemistry for a sustainable future - with a little help from enzymes!*'. '*Chemistry and catalysis: key tools for a circular economy*' was discussed by Professor Matthias Beller (Leibniz Institute for Catalysis, Germany). Sir Patrick Vallance (UK Government Chief Scientific Adviser and Head of Government Science and Engineering Profession, UK Government) gave an overview of the importance of the circular economy from the UK viewpoint. This was followed by a panel discussion which brought together the main points and themes of the overall discussion.

The discussion meeting attracted about 200 delegates and the discussion was wide ranging. It demonstrated the need for developments in basic science, the need for new processes, the role of learning from biology, and detailed consideration of environmental and social costs, benefits and impacts. The consensus, from academics, industrialists and government scientists, is that this urgent and multifaceted problem needs attention and effort now. At the heart of finding solutions to the problems identified in the discussion meeting lies catalysis as this provides the key to our way forward. The four organisers are all involved in the EPSRC UK Catalysis Hub which aims to develop and showcase catalysis research in the UK, linking to international partners. The circular economy is a central theme for the research of the Hub, with over 40 UK universities involved in this. This is a topic of intense research interest across the World, and a pressing global need. Catalysis is at the heart of the efficient transformations of molecules and materials needed for a circular economy. We can anticipate that catalytic science, working in collaboration with industry, will lead the way in providing the solutions we urgently need.

Following the discussion meeting a further satellite meeting entitled '*Scientific priorities for realising a circular economy*' was held in Chicheley Hall on 26-27th June 2020 where about

60 delegates continued and extended the discussion, and practical developments, concentrated on four topics. These were:

Systems-level science for the circular economy
Digitisation of science and the circular economy
Catalyst discovery for the circular economy
Design of materials for the circular economy

Each session was led discussion leader and each topic was discussed in detail for half a day.

The papers presented in this issue provide the reader with the key elements of the topics discussed at both meetings and highlight the cutting edge science that is helping to move society towards a circular economy as the new normal way of operating for us all.