Institution: University of Cambridge		
Unit of Assessment: UoA 9 Physics		
Title of case study: Sustainable energy - without the hot air		
Period when the underpinning research was undertaken: 2012-2016		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Sir David MacKay	Professor of Natural Philosophy and Regius Professor of Engineering	Jan 1995 to Apr 2016
Period when the claimed impact occurred: 1 August 2013 to 31 July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Professor David MacKay's research in the Department of Physics at the University of Cambridge applied his background in information theory and statistical inference to the issues of climate change and sustainability. His book *Sustainable energy – without the hot air* (2008) has sold over 75,000 hardcopies, been downloaded over 557,300 times, and translated into 22 languages. The sustained impacts of MacKay's research include:

1. Providing the blueprint for the 2050 Calculator tool which has been used by the UK Government to formulate energy policy, and internationally to determine realistic climate-change mitigation targets for the Paris Climate Agreement (2016) and new energy policies (India 2017)
2. Increasing public understanding of and support for clean energy. In 2014, MacKay was the first winner of the Science Communication Medal of the Göttinger Literaturherbst (with Max Planck Institute) *"for his outstanding achievements to communicate environmental science… to the broad public as well as to politicians"*.

2. Underpinning research (indicative maximum 500 words)

David MacKay (1967–2016) was a true polymath. Whilst in the Department of Physics at the University of Cambridge, he made pioneering contributions to information theory, inference, and learning algorithms. His rigorous approach to inference, comprehensively described in his landmark book *Information theory, inference, and learning algorithms* [R1], informed his many research areas which included Bayesian probability theory, error-correcting codes, machine learning, human-computer interface and the public understanding of science, especially sustainable energy. He used this background in information theory to move beyond what he saw as the limitations of the sustainable energy debate:

> 'when people talk about life after fossil fuels and climate change action, I think there's a lot of fluff, a lot of greenwash, a lot of misleading advertising, and I feel a duty as a physicist to try to guide people around the claptrap and help people understand the actions that really make a difference.' (TED talk 'A Reality check on Renewables', 2012).

His response to this challenge was his highly influential book *Sustainable Energy - without the Hot Air* [R2, 2008], as well as his subsequent publications in which he analysed the possibility of powering energy-intensive industries by carbon-free electricity [R3, 2013] and the role that solar energy can play in meeting energy demand [R4, 2013]. The origins of the research content of his book can be traced to his deep interest in the teaching of physics – he had strong reservations about the traditional mode of teaching which did not promote deep understanding and physical insight into physics. This was illustrated by his research into the success of students in solving physical insight problems. In tackling nine such problems, students in the first, second, third and fourth years averaged less than 50% success and their performance did not improve from the first to the fourth year, a sobering conclusion [R5, 2000].

In his book, MacKay adopted and developed the 'physical insight' approach, making the issues involved in the sustainability agenda understandable by those without the necessary technical background in the vast array of different types of science which had to be understood and mastered. MacKay's research for the book involved understanding the details of energy generation, consumption and loss involved in essentially all aspects of everyday life and then reducing them to models which were compared with the hard data. This involved a huge amount of original analysis and research. For example, in his analysis of tidal energy, he showed that the published approach underestimated the amount of available energy by a factor of ten, calculations he presented in the book (see further details in [R6], 2007).

The book splits into two parts. The first 250 pages read like a popular exposition and can be easily understood by the non-expert. In the final technical chapters, he derives energy budgets for all sorts of contributions to the global environment: cars, wind, planes, solar energy, heating, waves, tide and 'stuff'. This section illustrates how to convert extremely complex non-linear problems into a form which can be used to make realistic estimates of their impact on global sustainability. The compelling type of analysis in the book is illustrated in Figure 1, the pink (left) stack showing the energy requirement and the green (right) stack the maximum energy which could be derived from renewable resources. Every element of the stacks were the subject of detailed research. The analysis shows the magnitude of the challenge facing the UK.

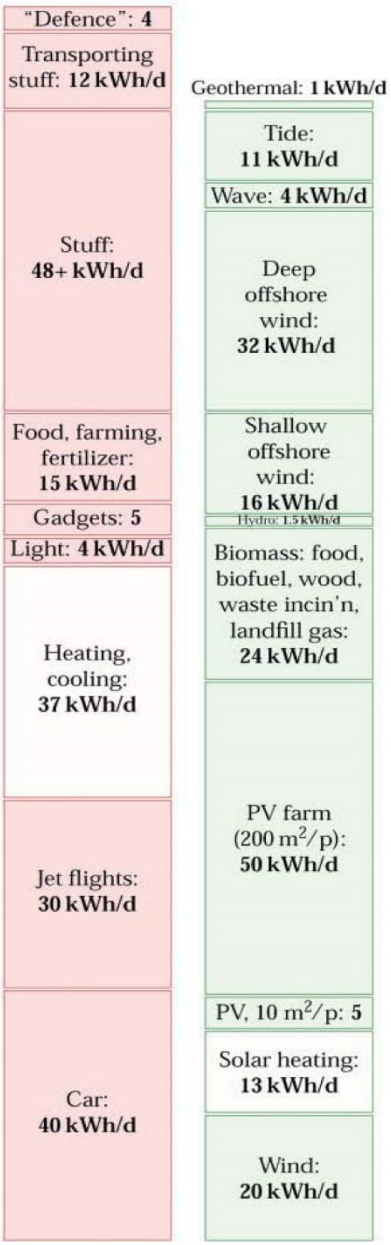

Figure 1.

MacKay made *Sustainable energy – without the hot air* available to the public with a free downloadable version. Prof Martin Hoffert, NYU physicist who has researched climate models over decades, reviewed the book for *Science* magazine. He said of MacKay in reference to the book: *"His calculations are always thought-provoking even when his assumptions had me banging the table in disagreement. My objections often faded as his analysis unfolded. The author dug out a lot of hard-to-find data"*, testifying to the depth of MacKay's research.

The analytical framework which MacKay developed in *Sustainable energy – without the hot air* has subsequently become the blueprint for the 2050 Calculator tool, used in the UK and worldwide to influence and formulate government policy (see section 4).

3. **References to the research** (indicative maximum of six references)

R1. 'Information theory, inference, and learning algorithms' (2003). Cambridge: Cambridge University Press. Google scholar citations >11,000
R2. 'Sustainable energy - without the hot air', David J C MacKay, Cambridge: UIT Publications, 2008. ISBN 978-0-9544529-3-3, Google scholar citations: 2,044. Available free at http://www.inference.org.uk/sustainable/book/tex/sewtha.pdf Prof Martin Hoffert's review can be found here Can Civilization (at Least the U.K.) Run Sustainably? | Science (sciencemag.org)
R3. MacKay DJC. 'Solar energy in the context of energy use, energy transportation and energy storage' Philosophical Transactions of the Royal Society **A371** Article number ARTN 20110431 13 Aug 2013 https://royalsocietypublishing.org/doi/10.1098/rsta.2011.0431 Google scholar citations 51
R4. MacKay DJC. 'Could energy-intensive industries be powered by carbon-free electricity?' Philosophical Transactions of the Royal Society **A371** Article number ARTN 20110560 13 Mar 2013 http://dx.doi.org/10.1098/rsta.2011.0560 Google scholar citations 20
R5. Physics Teaching Survey, March 2000. S. Mahajan and D. MacKay. http://www.inference.org.uk/teaching/survey/
R6. MacKay, D. J. C. (2007). Under-estimation of the UK tidal resource. http://www.inference.phy.cam.ac.uk/mackay/abstracts/TideEstimate.html.

This case study is unusual in that it involves a huge amount of detailed research and data analysis, but much of this on its own would not be suitable for publication in research or pedagogical journals. R1 was rigorously peer reviewed and has over 11,000 Google scholar citations. R2 has over 2,000 Google scholar citations, is recommended reading for 48 different university courses at 44 universities in 16 countries, and has been cited by the House of Commons and in the UN World Economic survey 2013. The high quality of the research involved is also supported by expert reviews (see evidence file E10). R3 and R4 update the research described in the book. R5 illustrates MacKay's focus on teaching and his desire to improve students' ability to solve physics problems using 'physical insight', which underpinned the development of R2. R6 develops MacKay's analysis of the models used to estimate the UK's tidal resource.

4. Details of the impact (indicative maximum 750 words)

A consequence of the success and impact of *Sustainable energy – without the hot air* was that MacKay became well known in policy making circles, and in 2009 was appointed as Chief Scientific Advisor to the Department of Energy and Climate Change (DECC), a post he held for the next five years [E1a]. This was followed by his appointment as a Knight Bachelor in the 2016 New Year's Honours List 'for services to Scientific Advice in Government and Science Outreach' [E1b].

Global impact on government energy policies

As Chief Scientific Advisor to DECC, MacKay was awarded an unusually high level of resourcing - a budget of tens of millions of pounds and a team of around 50 people – as well as a level of seniority (Director General level) which meant that he sat on the department board (extremely rare for Chief Scientific Advisors). As a result, he was 'a voice in the room at every important decision that DECC made between 2010 and 2014' [E2a], and was instrumental in convincing the UK government to publish a carbon plan in December 2011 that drew extensively on his quantitative approach to energy and climate change. The UK became the first country in the world to set a legally binding target for carbon emissions.

A major impact while he was at DECC was the development of a computational tool known as the 2050 Calculator. The team that developed the calculator was created as a result of MacKay's book and the desire of senior staff at DECC to be able to analyse energy options using a similar framework [E2a]. Every member of the team studied the book in preparation for the task [E2a]. The programme manager of the 2050 Calculator at the Department of Business Energy and Industrial Strategy (BEIS) describes it as:

> 'an interactive version of what David did in 'sustainable energy without the hot air'. In it he set out all the possible sources of low carbon energy in the UK on one side, and all the demand we have for energy on the other and looked at how much we could decrease our demand and increase our supply and saw whether or not these actually lined up, so was it possible to meet our target and have a sustainable energy system' [E2b].

Users of the calculator quickly gain the perspective of policy-makers by modelling the effect of different policy decisions on the reduction of UK emissions. Research published in *Nature Energy* (2017) shows that calculator engagement increases users' preparedness to reduce energy use and pushes energy preferences away from fossil fuels towards renewable energy sources [E3]. As an interactive version of the book, the calculator carried the same high standards of clarity. The open-source calculator work was praised in the Macpherson report (2013) into government analytical modeling as setting a 'new standard for transparency' [E4]. The Guardian described it as 'probably one of the most open and transparent pieces of policy-making ever undertaken by the British government' [E4].

The calculator became a tool for consensus-based decision making within the UK government. The head of a UK Government Programme on International Climate Finance said in 2020: 'It was the calculator that drove the cross-government climate strategy, and from that we identified the key sectors that we needed to decarbonise' [E2b]. The shared thinking which emerged from use of the calculator: 'led to the restructuring of the electricity market in July 2011, which in turn paved the way for mass renewable energy auctions and a huge increase in UK renewable energy capacity' [E2a,b]. In 2019, the UK National grid announced 'a clean energy milestone as zero carbon electricity outstrips fossil fuels in 2019' [E5]. Over the last decade, the UK energy sector has had the '"fastest rate of decarbonisation in the world' [E6]. BEIS is planning a new UK calculator for 2020 (The MacKay Calculator) in order to maintain the UK's leadership on climate action.

During the impact period, DECC, and its successor BEIS, have supported governments in countries including China and India to develop their own calculators based on the original DECC version, which is now used in over 30 countries. A global version of the calculator was launched in 2015. By the end of March 2016, it had been accessed more than 22,000 times [E7a]. Four countries (India, Vietnam, Colombia and Nigeria) used their calculators to formulate mitigation targets (Nationally Determined Contributions - NDCs) for the Paris Climate Agreement (2016) [E7b]. India further used their calculator to develop a new National Energy Policy (2017) in accordance with their NDCs [E8].

Increasing public understanding of and support for clean energy

MacKay's TED (Technology, Entertainment and Design) talk, 'A Reality Check on Renewables' (2012), has been viewed over 1.45 million times [E9]. His book, *Sustainable energy – without the hot air* (2008), has sold over 75,000 hardcopies, been downloaded over 557,300 times, and translated into more than 22 languages. It is recommended reading for 48 different courses at 44 universities in 16 countries [E10a] and is used as training material for the Yale National Teachers initiative [E10b], a nationwide initiative to support high-need public schools in the US.

The book has been cited by the House of Commons [E10c] and in the UN World Economic survey 2013 [E10c], and has won accolades from all sides of the climate change debate as a clear and unbiased reference work. Reviews in the opening pages of the book include those from the Former Chairman of Royal Dutch Shell, the former Executive Director of Friends of the Earth, Environment Ministers and Secretaries of State for the Environment, Chief Scientific Advisers, the Director of Sustainable Development at EDF Energy, and Professors of climate science [E10e]. Duncan McLaren, Chief Executive of Friends of the Earth Scotland, said the book 'provides a solid foundation to help us make well-informed choices, as individuals and more importantly as societies' [E10e].

Bill Gates, who in 2016 invested USD1 billion in a clean energy fund [E11a], blogged about the book's impact on him: 'If someone is going to read just one book [on energy] I would recommend this one' [E11b]. 'The book 'really shaped my thinking…To this day, if you want to understand the opportunities for clean energy, nothing else comes close. I still go back and re-read parts of it myself' [E11c]. In 2010, Gates bought 2000 copies of the book to give to the audience at his TED talk on renewable energy [E11c].

In 2014, MacKay was the first winner of the Science Communication Medal of the Göttinger Literaturherbst (with Max Planck Institute) honored: 'for his outstanding achievements to communicate environmental science with clear texts, facts and figures, backed up by empirical data and explanations of limitations – to the broad public as well as to politicians' [E1c]. In 2016, MacKay won a Breakthrough Paradigm Award from the Breakthrough Institute 'In recognition of his path-breaking scholarship and public service on clean energy, energy systems, and innovation' [E1d].

5. Sources to corroborate the impact (indicative maximum of 10 references)

E1. **David MacKay Awards, Appointments and Honours: (a)** Appointment as Chief Scientific Advisor to the Department of Climate Change (2009) – page 2 of PDF **(b)** Knighthood (2016) - page 6 of PDF **(c)** Science Communication Medal of the Göttinger Literaturherbst/Max Planck Institute (2014) – page 12 of PDF **(d)** Breakthrough Paradigm Award (2016) – page 14 of PDF

E2. **Evidence of David MacKay's contribution to the 2050 calculator and of the link between the calculator and the electricity market reform which enabled rapid decarbonisation of the UK energy sector**: **(a)** Email Correspondence from Former Deputy Director in charge of the DECC's 2050 team **(b)** Article ***"The calculator that Could Save the World"***, Engineering Matters (Reby Media/Mott MacDonald Consultancy), Jun 2020. See pages 2, 3 and 4 of PDF.

E3. **Research Article: *"Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool",*** Demski *et al.***,** NATURE ENERGY 2, 17027 (2017). See pages 4 and 5 of PDF.

E4. **MacPherson Report into Government Analytical Modelling (2013).** See page 17 of PDF (page 13/47 of publication).

E5. **National Grid Press Release *"Britain hits historic clean energy milestone as zero carbon electricity outstrips fossil fuels in 2019"* (2019)**

E6. **Drax Electric Insights Quarterly Report (Oct - Dec 2019)** See page 4 of PDF.

E7. **Department of Business Energy and Industrial Strategy (BEIS) Reports: (a)** Report on 2050 Calculator Work, March 2016. See page 7 of PDF (page 6/12 of publication). **(b)** Summary of the case to renew support for the 2050 Calculator Work. See Pages 19 and 30 of PDF (pages 5/59 and 16/59 of publication).

E8. **Draft National Energy Plan, Government of India (2017).** See pages 1, 12 and 20 of PDF.

E9. **David MacKay's TED talk** viewed over 1.45 million times. 560,000 times on TED https://www.ted.com/talks/david_mackay_a_reality_check_on_renewables and over 907,000 times on YouTube MacKay Youtube TED

E10. **Sustainable Energy - Without the Hot Air (SEWTHA) References and Reviews: (a)** List of university courses with SEWTHA as a recommended/reference reading **(b)** Article outlining the Yale Teacher Training initiative (see pages 2 and 5 of PDF). **(c)** UK House of Commons Environmental Audit Committee Members Report Tue 14 July 2009 & UN World Economic Survey 2013 (see pages 9, 10, 11, 14, 59, 94 of PDF) **(d)** Review of SEWTHA for science magazine by Prof Martin Hoffert, NYU physicist who worked on climate models. See page 108 of PDF **(e)** Reviews of SEWTHA included in the preface – see pages 110 and 111 of PDF.

E11. **Bill Gates Blog Entries:** Bill Gates Blog entries **(a)** announcing $1 billion investment fund to support clean energy technologies (2016). **(b)** 2010 and **(c)** 2016 commenting on the impact of "Sustainable Energy - Without the Hot Air" **(c)**