Institution: University of Sussex		
Unit of Assessment: 9 – Physics		
Title of case study: The impact of quantum computing research on the adoption of public policy directed towards developing quantum computing and its economic benefits		
Period when the underpinning research was undertaken: 2007 – 2017		
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:**
Winfried K. Hensinger	Professor	2005 – present
Sebastian Weidt	Lecturer	2013 – present
Period when the claimed impact occurred: 2013 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research by Winfried Hensinger and his team at the University of Sussex demonstrated the viability of building quantum computers that can solve important real-world problems, most notably via the creation of the first industrial blueprint to build practical quantum computers. Hensinger advised governments in the UK, Germany and USA about policy implications of his research. His work has also been highlighted in major reports informing public policy. The findings of the research and his associated advice have been used as evidence aiding the adoption of new public policies, directed to develop and enhance the economic benefit of quantum computing for each country. The resulting multi-billion-pound total investment has given rise to outcomes such as the creation of a national quantum computing hub and a national quantum computing centre in the UK, three quantum computing testbeds in the USA and numerous funded collaborative industry projects to build practical quantum computers showcasing the emergence of a new industry sector.

2. Underpinning research

Practical quantum computers have been described as one of the holy grails of science due to their disruptive capabilities across a wide range of sectors such as finance, drug discovery, and breaking encryptions to name a few. Yet the challenge to build such a machine has been viewed as vast, and possibly insurmountable.

Trapped ions have been considered as one of the most promising hardware platforms to build practical machines. However practical quantum computers, capable of solving the most interesting problems, would require millions of qubits. While trapped ion systems have been viewed as promising because of the ability to implement the required quantum operations with small errors, the actual scalability of the platform had been questioned. Traditionally trapped ion quantum computing makes use of laser beams to execute quantum gates where the number of laser beams required scales with the number of qubits (ions) used in the quantum computer. While this is easily achievable with tens or hundreds of quantum bits, it is very difficult to imagine building a quantum computer with millions or billions of quantum bits where millions or billions of pairs of laser beams would need to be aligned with an accuracy of 10μm. Research at Sussex focussed on developing an alternative solution, namely to use global microwave fields (instead of laser beams) for quantum gate execution, therefore avoiding having to align millions or even billions of laser beams in a practical quantum computer (R2, R4, R5). Instead of using laser beams for quantum gate execution, their approach makes use of proven microwave technology. Quantum gates are executed by applying semi-static voltages to a microchip in a manner very similar in nature to the operation of classical transistors (R5).

Another challenge for building a trapped ion quantum computer is the proposed architecture for such machine. Early ion traps were constructed from metal rods. A practical quantum computer would require millions of trapping zones so it is inconceivable a quantum computer could be constructed in this way. A much more suitable approach consists of silicon microchips as a fully scalable architecture. The Sussex group made significant breakthroughs in the practical realisation and operation of such an ion microchip (R1, R3). This includes the creation of a chip allowing the application of the largest voltage applied to an ion microchip allowing for very deep trapping potentials capable of holding ions for extended periods of time, giving confidence in the use of such chips for the operation of a quantum computer (R3).

Any practical quantum computer would require a modular architecture since it would likely be impossible to fit sufficiently many qubits onto a single module. A known approach for modularity consisted of connecting modules via a technique referred to as photonic interconnects. However, even after 15 years of development, the connection speed is extremely slow while the required engineering is very difficult. The Sussex group invented a new approach to modularity, where electric field links between modules are used to allow for ion transport, giving rise to orders of magnitude improvement in connection speed while dramatically reducing the engineering difficulty required for implementation (R6).

In 2017, Hensinger led an international team consisting of scientists from Google, Aarhus University, Riken and Siegen University in publishing the world's first blueprint for a Quantum Computer (QC) capable of solving real-world problems (R6). This blueprint showed that it is now possible to build a practical quantum computer featuring millions of qubits, substantially advancing the credibility of producing a commercial device. The work was published in Science Advances, received extensive media attention and achieved an Altmetric score of 634, placing it in the top 5% of papers of the same age in this journal. Hensinger made a live appearance on prime-time Sky News and the paper was covered by all major news agencies.

3. References to the research

R1: Versatile ytterbium ion trap experiment for operation of scalable ion-trap chips with motional heating and transition-frequency measurements, J.J. McLoughlin, A.H. Nizamani, J.D. Siverns, R.C. Sterling, M.D. Hughes, B. Lekitsch, B. Stein, Seb Weidt, and W.K. Hensinger, Phys. Rev. A 83, 013406 (2011), DOI: 10.1103/PhysRevA.83.013406 – 49 citations

R2: Simple Manipulation of a Microwave Dressed-State Ion Qubit, S.C. Webster, S. Weidt, K. Lake, J.J. McLoughlin and W.K. Hensinger, Phys. Rev. Lett. 111, 140501 (2013), DOI: 10.1103/PhysRevLett.111.140501 – 63 citations

R3: Fabrication and operation of a two-dimensional ion-trap lattice on a high-voltage microchip, R.C. Sterling, H. Rattanasonti, S. Weidt, K. Lake, P. Srinivasan, S.C. Webster, M. Kraft & W.K. Hensinger, Nature Communications 5:3637 (2014) DOI: 10.1038/ncomms4637, preprint published in 2013: https://arxiv.org/abs/1302.3781v1 – 70 citations

R4: Ground-state cooling of a trapped ion using long-wavelength radiation, S. Weidt, J. Randall, S.C. Webster, E.D. Standing, A. Rodriguez, A.E. Webb, B. Lekitsch and W.K. Hensinger, Phys. Rev. Lett. 115, 013002 (2015), DOI: 10.1103/PhysRevLett.115.013002 – 25 citations

R5: Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S.C. Webster, K. Lake, A.E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker and W.K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016), DOI: 10.1103/PhysRevLett.117.220501 – 79 citations

R6: Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich and W.K. Hensinger, Science Advances 3, e1601540 (2017), DOI: 10.1126/sciadv.1601540; *author contributions explained in manuscript*; preprint published in 2015: https://arxiv.org/abs/1508.00420v1 – 203 citations

(Citations from Google Scholar; R3, R5 and R6 were collaborative work with majority of work carried out at Sussex; R1 – R6 were all led and planned by W.K. Hensinger).

4. Details of the impact

4.1 The 1st phase of the UK National Quantum Technology Programme (2015-2019)

In November 2013, Hensinger was invited to join a group of 20 leading academics, industry stakeholders and policymakers to prepare advice for David Willetts, Minister of State for Universities and Science, to deliver a coherent strategy on future directions in Quantum Technology (QT) towards developing a national vision maximising QT's scientific and economic benefit to the UK (S1). [text removed for publication]. Hensinger stressed the importance of a sustained, targeted funding program in order to allow quantum computing (QC) to progress beyond the proof of principle demonstrations. [text removed for publication]. The 2013 autumn budget statement (S3, p.56) allocated GBP270,000,000 for the development of QT over 5 years, invested in part in the development of quantum computing by enhancing capability, product development, growing a skilled workforce and facilitating exploitation of research (S4). Indeed, ion trap technology was chosen to sit at the heart of UK's first quantum computing hub (S4, p.20) tasked with the development of QC.

4.2 The 2nd phase of the UK National Quantum Technology Programme (since 2019)
In 2016, Hensinger was invited to a meeting to finalise plans for the second phase of the UK National Quantum Technology Programme (NQTP). At the meeting, Hensinger outlined his blueprint for a practical, scalable trapped-ion quantum computing architecture. [text removed for publication] explains '*The blueprint paper gave a credible description of how a practical quantum computer could be constructed. An updated strategic landscape document (S5) and evidence base for NQTP Phase 2 funding was produced from this meeting containing key results from the blueprint article.*' (S1). [text removed for publication] explains '*[The document] used your research as evidence that it should be possible to build practical quantum computers; as such, it provided compelling evidence to continue government support of quantum computing as part of the NQTP.*'

In July 2018, Hensinger was invited to give evidence to the UK Parliament Science and Technology Select Committee as part of their inquiry exploring the opportunities and challenges for QT. In his testimony Hensinger said '*Last year, we published the first construction plan on how to build such a quantum computer. With the technology innovations we made as part of the national quantum technology programme, we are now able to say that it is possible to build such a machine'* (S6 p.4). Hensinger not only provided the Committee with evidence for the continuation of the NQTP (S6, p.15,16) based on his research but also pointed to a severe skills shortage of qualified quantum engineers (S6, pp.8, 13) that would need to be addressed in order to build practical quantum computers designed according to his blueprint. The Committee adopted Hensinger's recommendations (S7, p.43,61), additionally highlighting Hensinger's suggestion that QC has the potential to inspire young people to study STEM subjects (S7, p.47) and his view concerning the breadth of applications of quantum computing (S7,11). The Government Response to the Committee's Report (S8) proves that the UK government has adopted Hensinger's advice: for example, to allocate more funding and continue the NQTP (S8, pp.1,3) and to expand the NQTP's current training programmes (S8, p.8-9). [text removed for publication] *further UKRI funding of GBP315,000,000 was announced in the 2018 Autumn Statement. As a result, the second phase of the NQTP will see a substantial increase in UK investment in quantum computing [text removed for publication] and very significant funding will be channelled into UK quantum computing development via the Industrial Strategy Challenge Fund (a total of GBP153,000,000 grant funding plus at least GBP205,000,000 matched funding from industry).* [text removed for publication]

The UK Industrial Strategy Challenge Fund (ISCF) can be considered as the most significant enhancement in the second phase of the NQTP. Together with a venture capitalist partner, Hensinger made a submission to Innovate UK to propose an ISCF quantum computing challenge. The document's introduction made reference to Hensinger's research as evidence that it is now time for the UK government to financially support subsystems development for the commercial production of large-scale quantum computers via the ISCF. This proposal was accepted and Hensinger was invited to help develop a policy proposal (S9) that was submitted to relevant committees at Innovate UK and Treasury. This proposal made a case for the full second phase of the NQTP. [text removed for publication]. Between October and December 2018, the UK Government implemented its own Industrial Strategy Future Sectors Review jointly run by Department for Digital, Culture, Media & Sport (DCMS) & Department for Business, Energy & Industrial Strategy (BEIS). Hensinger was invited to participate as part of their challenge panel of six QT specialists (S10), where he explained the level of technology readiness for quantum computing, referencing his research, and recommended developing a skilled work force and increased funding to aid commercialisation of this technology (S10). In June 2019, the Government confirmed a GBP153,000,000 funding boost through the Industrial Strategy Challenge Fund, including the provision of a national quantum computing centre with a budget of GBP35,000,000, as well as spelling out a further investment of GBP235,000,000 in the development of QT (S11). This allocation has created significant impact already; for example, 90 businesses are collaborating with 40 universities, including industry projects developing practical quantum computers and their applications [text removed for publication]. [text removed for publication].

4.3 Quantum computing public policy in Germany

In May 2018, the German Federal Office of Information Policy published a report concerning the state of the art in quantum computing flagging Hensinger's blueprint to build a quantum computer (R6) as being capable of factorizing 2048 bit numbers and as such able to break RSA encryption (RSA is the commonly used encryption protocol) (S12, p.114).

The following month, Hensinger was one of seven experts invited to testify about quantum computing (QC) to the German parliamentary select committee 'Digitale Agenda' (S13) as well as to provide a written set of recommendations (S14). Hensinger testified that, based on his research (R6), it is now possible to build a practical quantum computer, provided government supports such an effort with appropriate means (S13, p.16). He explained that machines constructed according to his trapped-ion blueprint would provide opportunities to simulate chemical reactions or biological systems (S13, p.25). In order to realize such a machine, he stressed the necessity of qualified human resources (S13, pp.16, 22), sufficient investment (S13, p.30-31) and the importance of creating a new industry sector (S13, p.22). Based in part on the evidence provided to the parliamentary select committee, the Federal Government formulated its strategy to promote QC with its framework policy program on quantum technologies (S15). The report identifies ion trapping as a suitable hardware platform (S15, p.9) and flags simulating chemical reactions as an application (S15, p9). It also includes other recommendations made by Hensinger, such as the importance of skilled labour (S15, p.30-31), funding (S15, p32) and industry involvement (S15, pp.14, 22). Following Hensinger's and the other experts' recommendations, the German government announced EUR650,000,000 investment in QT in August 2018 (S15, p.8). Further strengthening the development of QC in Germany, in June 2020, German chancellor Angela Merkel announced a further EUR2,000,000,000 for the construction of two quantum computers and announced the ambition of creating a new QC industry sector (S16, pp.11,12).

4.4 Quantum computing public policy in the USA

In 2016, Hensinger was invited to the US Department of Energy (DOE) to discuss his research in developing practical quantum computers. He gave a lecture to more than 600 government officials (S17), the then Secretary of Energy Moniz requested a copy of Hensinger's presentation, and the visit included a number of meetings with high-level officials at the Department [text removed for publication]. These meetings covered the applications and technical readiness of quantum computing. [text removed for publication] '*[text removed for publication] Dr. Hensinger's input to critical policymaker discussions helped substantiate the Departments' prioritization of quantum technology […] Examples include the Quantum Testbeds for Science with a total volume of approximately USD45,000,000 in 2018.'* (S18).

[text removed for publication] of the White House organised a number of meetings at the Executive Office of the President's Office of Science and Technology Policy, where Hensinger held discussions with government officials involved in quantum policymaking, national security, and science policy in general. The function of these meetings was to advise US government officials on the state of the art in quantum computing. Hensinger's engagement included meetings with key members of the Interagency Working Group on Quantum Information Science, who at the time were involved in a formal consultation process to develop the US National Strategic Computing Initiative. [text removed for publication] explains '*This work [the formal consultation process] has since culminated in the development and signing into law of the National Quantum Initiative Act (21 Dec 2018). Through this bill, the US has launched its National Quantum Initiative Program which establishes the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications. To facilitate this, the US Government has committed to invest USD1,200,000,000, of which USD625,000,000 over five years has been earmarked for the establishment of 5 quantum research centres.*' [text removed for publication] (S18).

More recently, in 2019, the US National Academies of Sciences, Engineering, and Medicine commissioned an influential consensus report on the state of quantum computing. Hensinger's approach was highlighted as a suitable approach to build practical large-scale quantum computers (S19, p.122) constituting evidence for the technology readiness of QC.

5. Sources to corroborate the impact

S1: Testimony letter [text removed for publication]
S2: UK Quantum Technology Landscape 2014
S3: HM Treasury, Autumn Statement, 2013
S4: UK National Quantum Technologies Programme, A roadmap for quantum technologies in the UK, 2015
S5: UK Quantum Technology Landscape 2016
S6: Science and Technology Committee, Oral evidence: Quantum technologies, HC 820, 2018
S7: Science and Technology Committee, Quantum technologies, Report, December 2018
S8: Science and Technology Committee Quantum technologies: Government Response to the Committee's Twelfth Report (2018), Eleventh Special Report of Session 2017–19, 2019
S9: Testimony letter [text removed for publication]
S10: [text removed for publication]
S11: HM Treasury BUDGET 2018
S12: Federal Office of Information Security: Status of quantum computer development, 2018
S13: German select committee Digitale Agenda 2018: press release, minutes and video (in German)
S14: Invited written submission to the German Parliament Select Committee Digitale Agenda by Winfried Hensinger 2018 (in German)
S15: German government framework programme Quantum Technologies, September 2018
S16: German government announcement on economic recovery 2020 (in German)
S17: Distinguished speaker lecture at the US Department of Energy given by Winfried Hensinger (2016)
S18: Testimony letter [text removed for publication]
S19: The National Academies Press: Quantum Computing: Progress and Prospects (2019)