

This content has been downloaded from IOPscience. Please scroll down to see the full text.

Download details:

IP Address: 3.137.209.225

This content was downloaded on 26/04/2024 at 14:36

Please note that [terms and conditions apply](#).

You may also like:

[Exocytosis: From Molecules to Cells](#)

[Artificial Intelligence Strategies for Analyzing COVID-19 Pneumonia Lung Imaging, Volume 1](#)

[Big Science in the 21st Century](#)

[ICRU Report 64: Dosimetry of High-Energy Photon Beams Based on Standards of Absorbed Dose to Water](#)
D W O Rogers

[Collins Advanced Sciences: Physics](#)
R Q Hackett

[Influence of volute section form on hydraulic performance and pressure fluctuation in double suction centrifugal pump](#)
D Zhu and R Xiao

[Handbook of Physics in Medicine and Biology](#)
Slavik Tabakov

Commercialising Fusion Energy

How small businesses are transforming big science

Commercialising Fusion Energy

How small businesses are transforming big science

Edited by

William J Nuttall

School of Engineering and Innovation, The Open University, Milton Keynes, UK

Satoshi Konishi

Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto, Japan

Shutaro Takeda

Urban Institute, Kyushu University, 744 Motoooka, Nishi, Fukuoka, Japan

David Webbe-Wood

School of Engineering and Innovation, The Open University, Milton Keynes, UK

IOP Publishing, Bristol, UK

© IOP Publishing Ltd 2020

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publisher, or as expressly permitted by law or under terms agreed with the appropriate rights organization. Multiple copying is permitted in accordance with the terms of licences issued by the Copyright Licensing Agency, the Copyright Clearance Centre and other reproduction rights organizations.

Certain images in this publication have been obtained by the authors from the Wikipedia/Wikimedia website, where they were made available under a Creative Commons licence or stated to be in the public domain. Please see individual figure captions in this publication for details. To the extent that the law allows, IOP Publishing disclaim any liability that any person may suffer as a result of accessing, using or forwarding the image(s). Any reuse rights should be checked and permission should be sought if necessary from Wikipedia/Wikimedia and/or the copyright owner (as appropriate) before using or forwarding the image(s).

Permission to make use of IOP Publishing content other than as set out above may be sought at permissions@iopublishing.org.

William J Nuttall, Satoshi Konishi, Shutaro Takeda and David Webbe-Wood have asserted their right to be identified as the authors of this work in accordance with sections 77 and 78 of the Copyright, Designs and Patents Act 1988.

ISBN 978-0-7503-2719-0 (ebook)
ISBN 978-0-7503-2717-6 (print)
ISBN 978-0-7503-2720-6 (myPrint)
ISBN 978-0-7503-2718-3 (mobi)

DOI 10.1088/978-0-7503-2719-0

Version: 20201201

IOP ebooks

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, Temple Circus, Temple Way, Bristol, BS1 6HG, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

In memory of Stephen N P Smith

Contents

Preface	xiii
Editor biographies	xiv
List of contributors	xv
1 Introduction	1-1
<i>William J Nuttall, Satoshi Konishi, Shutaro Takeda and David Webbe-Wood</i>	
1.1 Background	1-1
1.2 What is nuclear fusion?	1-3
1.3 Purpose and structure of this book	1-5
References	1-6
Section I Private fusion primer	
2 Review of approaches to fusion energy	2-1
<i>Richard J Pearson and Shutaro Takeda</i>	
2.1 Introduction	2-1
2.2 Three key conceptual spaces for fusion reactors: MCF, ICF and MIF	2-3
2.2.1 Magnetic confinement fusion	2-3
2.2.2 Inertial confinement fusion (ICF)	2-6
2.2.3 Magneto-inertial fusion (MIF)	2-7
2.3 Concept-specific engineering challenges for MCF, ICF and MIF	2-10
2.3.1 Plasma production and control	2-10
2.3.2 Fuelling and exhaust systems	2-13
2.3.3 Diagnostics	2-16
2.4 Summary	2-19
References	2-27
3 Considerations for commercialization strategies for fusion energy	3-1
<i>Shutaro Takeda and Sehila M Gonzalez de Vicente</i>	
3.1 Introduction	3-1
3.1.1 Background	3-1
3.1.2 Content of this chapter	3-2
3.2 Future market	3-2
3.2.1 Energy demand forecasts	3-2

3.2.2	The role of nuclear fusion in climate change mitigations	3-3
3.2.3	Future market for fusion energy systems	3-3
3.3	Commercialization pathways	3-4
3.3.1	Four commercialization pathways	3-4
3.3.2	The benefits and the risks of spinoff businesses	3-7
3.3.3	Technology readiness level	3-7
3.3.4	Investment strategies for fusion enterprises	3-8
3.4	Fusion power core design methodology	3-9
3.5	Constraints	3-10
3.6	Conclusions	3-11
	Acknowledgment	3-12
	References	3-12

4 Funding and financing commercial fusion power plants 4-1

David Webbe-Wood

4.1	Introduction	4-1
4.2	Possible sources of funding	4-2
4.2.1	Provision of funds by a commercial operator	4-2
4.2.2	Funds provided by a bank or similar investor	4-3
4.2.3	Funding provided by government	4-3
4.2.4	Funds provided by the consumer	4-4
4.3	Sources of income	4-6
4.3.1	Income from sale of electricity	4-6
4.3.2	Income from other uses of the energy	4-6
4.4	Conclusions	4-6
	Acknowledgment	4-7
	References	4-7

Section II Progress in the private sector

5 Tokamak Energy 5-1

Melanie Windridge

5.1	The case for fusion energy	5-2
5.2	The Tokamak Energy approach—spherical tokamaks and high temperature superconductors	5-3
5.3	The combination of spherical tokamaks and high temperature superconductors	5-5
5.4	Progress so far	5-7
5.5	Future plans and business overview	5-10

5.6	Summary	5-12
	References	5-12
6	Laser fusion CANDY GPI/Hamamatsu	6-1
	<i>Y Mori</i>	
6.1	Introduction	6-1
6.2	Laser fusion activities in the world	6-2
	6.2.1 How the laser fusion reactor generates power	6-2
	6.2.2 Laser fusion activities and trends	6-3
6.3	Laser fusion activities in Hamamatsu	6-4
	6.3.1 Why laser fusion in Hamamatsu?	6-4
	6.3.2 Strategy of GPI	6-5
6.4	Laser fusion mini-reactor CANDY	6-6
	6.4.1 Concept of CANDY	6-6
	6.4.2 Laser technology	6-7
	6.4.3 Plasma fuel physics	6-7
	6.4.4 Target injection	6-9
6.5	Summary	6-10
	Acknowledgments	6-10
	References	6-11
7	Pioneers of commercial fusion	7-1
	<i>Richard J Pearson and William J Nuttall</i>	
7.1	Introduction	7-1
7.2	Private investment in fusion	7-3
	7.2.1 Private investment into clean energy technology	7-3
	7.2.2 Private investment in fusion: same but different	7-4
7.3	Private fusion companies	7-7
	7.3.1 TAE Technologies	7-9
	7.3.2 General Fusion	7-10
	7.3.3 Lawrenceville Plasma Physics	7-11
	7.3.4 MIFTI Fusion	7-13
	7.3.5 First Light Fusion Ltd	7-14
	7.3.6 Proton Scientific Inc.	7-14
	7.3.7 Helion Energy	7-15
	7.3.8 Lockheed Martin's Skunk Works	7-15

7.3.9	CTFusion	7-17
7.3.10	Agni Fusion	7-17
7.3.11	Commonwealth Fusion Systems	7-18
7.3.12	Compact Fusion Systems	7-19
7.3.13	Hyperjet Fusion	7-19
7.3.14	HB11 Energy	7-20
7.3.15	ZaP Energy	7-21
7.3.16	Marvel Fusion	7-22
7.3.17	Renaissance Fusion	7-22
7.4	Discussion: the prospect of private fusion success	7-23
	References	7-24

Section III Public sector push to commercialization

8	STEP—on the pathway to fusion commercialization	8-1
	<i>Howard Wilson, Ian Chapman, Tris Denton, William Morris, Bhavin Patel, Garry Voss, Chris Waldon and the STEP Team</i>	
8.1	Introduction	8-1
8.2	Three components towards fusion commercialization	8-3
8.3	The role of private fusion companies	8-4
8.4	STEP—spherical tokamak for energy production	8-5
8.5	Fusion power from a spherical tokamak plasma	8-8
8.6	Technical risks to commercial viability of a spherical tokamak	8-12
8.7	Conclusions	8-15
	Acknowledgments	8-15
	References	8-15
9	DEMO design activities and helical initiatives in Japan	9-1
	<i>Takuya Goto</i>	
9.1	Japan’s policy on fusion research and development	9-1
9.2	Status of tokamak DEMO design in Japan	9-4
9.3	Helical reactor design as alternatives	9-7
9.4	Issues towards commercialization	9-10
	References	9-12

Section IV Challenges and future opportunities

10	Fusion innovation: understanding the engineering challenges to commercial fusion	10-1
	<i>Richard J Pearson</i>	
10.1	Introduction	10-1
10.2	Engineering challenges to commercial fusion	10-4
	10.2.1 Fusion reactor materials	10-4
	10.2.2 Blankets for tritium breeding and power generation	10-8
	10.2.3 Tritium handling systems	10-14
	10.2.4 Waste management and remote handling	10-17
	10.2.5 Balance of plant systems	10-22
10.3	Fusion innovation	10-26
	10.3.1 Seeking successful fusion innovation	10-26
	10.3.2 Commercial drivers for fusion	10-27
	10.3.3 An innovation strategy for cooperative public and private sector fusion development	10-30
10.4	Conclusions	10-31
	References	10-33
11	Commercial opportunities for nuclear fusion	11-1
	<i>William J Nuttall</i>	
11.1	Introduction and historical origins	11-1
	11.1.1 Fusion energy ambitions live in the shadow of nuclear fission success—1960s and 1970s	11-1
	11.1.2 Atomic energy—the allure of electricity	11-2
	11.1.3 Fusion follows fission’s footsteps	11-4
11.2	Civil fusion’s first success	11-5
11.3	The painful story of ‘cold fusion’	11-8
11.4	Looking ahead: fusion’s potential commercial attributes	11-10
11.5	Fusion can do better than electricity generation	11-11
11.6	The importance of net-zero and deep decarbonization	11-15
11.7	Non-electricity commercialization	11-15
	11.7.1 Process heat applications	11-16
11.8	Conclusions	11-18
	Acknowledgements	11-19
	References	11-19

12	Fusion energy and carbon management	12-1
	<i>Satoshi Konishi, Hoseok Nam and Shutaro Takeda</i>	
12.1	Fusion and carbon-based chemistry	12-1
12.2	Pyrolysis and gasification of biomass	12-1
12.3	Market for biofuel	12-4
12.4	Electricity generation by SOFC	12-5
12.5	Effect of subsidy	12-5
12.6	Fusion charcoal production	12-6
12.7	Market in carbon credits	12-7
12.8	Economic analyses of CCS	12-8
12.9	Carbon credit trading	12-11
12.10	Biomass feedstock and supply chain	12-12
	12.10.1 Residential garbage and its collection	12-12
	12.10.2 Agricultural by-products and their characteristics	12-14
12.11	Summary	12-17
	References	12-17
13	Conclusions	13-1
	<i>William J Nuttall, Satoshi Konishi, Shutaro Takeda and David Webbe-Wood</i>	
	References	13-4

Preface

Disclaimer: This book contains information obtained from scientific and trustable sources, and all chapters are peer-reviewed by experts to increase its reliability. Reprinted material is quoted with permission, and sources are clearly indicated. A wide variety of references are listed at the end of each chapter. Reasonable efforts have been made to publish reliable data and information, but the editors, authors and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use. This book contains no advice or guidance and should not be used as the basis of any investment or other decision.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Images: Efforts have been made to establish and contact copyright holders for all images presented in this book. We are most grateful to all the various rights holders who have kindly granted permission for reproduction. Despite our best endeavours there may be instances where the rights of third parties have been overlooked. In such cases, we apologize and we ask that rights holders make contact and we will endeavour to resolve matters.

Editor biographies

William J Nuttall



Corresponding Editor William Nuttall CPhys FInstP is Professor of Energy at The Open University, UK. He is also a Fellow of the Payne Institute for Public Policy at the Colorado School of Mines, USA and a Fellow of the Construction Engineering Masters programme at the University of Cambridge, UK. He is an Affiliated Lecturer in Cambridge University Engineering Department and a Fellow of Hughes Hall, University of Cambridge. He holds a PhD in Physics (1993) from the Massachusetts Institute of Technology, USA, where he was a Fulbright scholar (1987–1988).

Satoshi Konishi



Editor Satoshi Konishi is a Professor at the Institute of Advanced Energy, Kyoto University. He was previously the Director of the Fusion Reactor Systems Laboratory at the Japan Atomic Energy Research Institute. He earned his PhD from the University of Tokyo.

Shutaro Takeda



Editor Shutaro Takeda is a Fellow of the Urban Institute, Kyushu University. He conducts research on energy sustainability, energy economy and renewable energy policy in developing nations. He is also the Research Representative of the Public Outreach Initiative for Nuclear Fusion at the National Institute for Fusion Science. In 2018, he was named the International Young Energy Professional of the Year by the Association of Energy Engineers.

David Webbe-Wood



Editor David Webbe-Wood is a PhD Student in the School of Engineering and Innovation at The Open University. He previously earned his Master of Research qualification in Nuclear Energy from Imperial College London. He is a member of The Society for Radiological Protection and a former Radiological Protection Specialist.

List of contributors

Ian Chapman

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

Tris Denton

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

Sehila M Gonzalez de Vicente

The International Atomic Energy Agency, Wagramer Strasse 5. A-1400 Vienna,
Austria

Takuya Goto

National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu, Japan

Yoshita Mori

The Graduate School for the Creation of New Photonics Industries, Hamamatsu,
Shizuoka, 431-1202, Japan

William Morris

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

Hoseok Nam

Graduate School of Energy Science, Kyoto University, Yoshidahonmachi,
Sakyo, Kyoto: 606-8317, Japan

Bhavin Patel

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK
York Plasma Institute, Department of Physics, University of York, Heslington,
York YO10 5DD, UK

Richard J Pearson

Kyoto Fusioneering Ltd, 5-24 Gokashohirano, Uji, Kyoto, Japan

Garry Voss

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

Chris Waldon

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

Howard Wilson

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy,
Culham Science Centre, Abingdon, Oxon OX14 3DB, UK

York Plasma Institute, Department of Physics, University of York, Heslington,
York YO10 5DD, UK

Melanie Windridge

Tokamak Energy Ltd. 173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD,
UK