

DSC SOLAR TECHNOLOGIES: GLOBAL MARKETS



EGY105A
July 2016

Juan Toribio Bueso
Project Analyst

ISBN: 1-62296-327-X



BCC Research
49 Walnut Park, Building 2
Wellesley, MA 02481 USA
866-285-7215 (toll-free within the USA),
or (+1) 781-489-7301
www.bccresearch.com
information@bccresearch.com

TABLE OF CONTENTS

TOPIC	PAGE NO.
CHAPTER 1 INTRODUCTION	2
STUDY GOALS AND OBJECTIVES	2
REASONS FOR DOING THE STUDY	2
SCOPE OF REPORT	3
INTENDED AUDIENCE	3
METHODOLOGY	4
INFORMATION SOURCES	4
ANALYST'S CREDENTIALS	4
RELATED BCC RESEARCH REPORTS	5
BCC RESEARCH WEBSITE	5
DISCLAIMER	5
CHAPTER 2 EXECUTIVE SUMMARY	7
<i>SUMMARY TABLE GLOBAL MARKET FOR INSTALLED PHOTOVOLTAIC POWER BY TECHNOLOGY, THROUGH 2020 (MW/YEAR)</i>	7
<i>SUMMARY FIGURE GLOBAL MARKET SHARE OF INSTALLED PHOTOVOLTAIC POWER BY TECHNOLOGY, 2014-2020 (%)</i>	8
CHAPTER 3 OVERVIEW	10
THE SUN AS AN INEXHAUSTIBLE SOURCE OF ENERGY	11
PHOTOELECTROCHEMICAL CONVERSION OF SOLAR ENERGY	11
<i>TABLE 1 SOLAR CONVERSION EFFICIENCY FOR VARIOUS PHOTOVOLTAIC SYSTEMS (SINGLE JUNCTION)*</i>	11
MOLECULAR ENGINEERING OF SENSITIZERS FOR CONVERSION OF SOLAR ENERGY INTO ELECTRICITY	12
<i>TABLE 2 HIGHEST POWER-CONVERSION EFFICIENCIES OBTAINED USING DIFFERENT POLYPYRIDINE COMPLEXES OF RUTHENIUM</i>	13
<i>TABLE 3 PHOTOELECTROCHEMICAL PARAMETERS OF NATURAL DYE-BASED DSC</i>	13
OPTIMIZATION OF REDOX MEDIATORS AND ELECTROLYTES	15
<i>TABLE 4 PUBLICATIONS DEVOTED TO TiO₂ AND ZnO FOR PHOTOVOLTAIC CONVERSION, 1995-2014 (NUMBER OF PUBLICATIONS)</i>	15
SOLID-STATE DYE-SENSITIZED SOLAR CELLS INCORPORATING MOLECULAR HOLE-TRANSPORTERS	16
USE OF GRAPHENE IN DYE SOLAR CELLS	16
<i>TABLE 5 DSC PERFORMANCE OF DEVICES WITH GRAPHENE MATERIALS IN THE TiO₂ LAYER COMPARED WITH CONTROL CELLS</i>	17
PACKAGING OF DYE SOLAR CELLS	18
<i>TABLE 6 COMPARISON OF PMPP DROP LOSSES BETWEEN DSC AND SI FOR TWO TEMPERATURE RANGES</i>	19
SCALING UP TO COMMERCIAL DSC PRODUCTION LEVELS	19
<i>TABLE 7 N719 DYE COST AS A FUNCTION OF VOLUME (\$/G, KG)</i>	20
DYE	20
<i>TABLE 8 RUTHENIUM PRICE PER OZ PER YEAR, JANUARY 1999-MAY 2016 (\$/OZ)</i>	21
<i>TABLE 9 GLOBAL DEMAND FOR RUTHENIUM, 2003-2013 (TONS/YEAR)</i>	22
TiO ₂	22
ELECTROLYTE SYSTEMS	22
SUBSTRATES AND SUPERSTRATES	23

TOPIC	PAGE NO.
ELECTROCATALYST	23
TABLE 10 PLATINUM PRICE PER OZ PER YEAR, JANUARY 1999-MAY 2016 (\$/OZ)	24
TABLE 11 GLOBAL DEMAND FOR PLATINUM, 2003-2013 (TONS/YEAR)	25
SEALANTS, CURRENT COLLECTORS AND BUSBARS	25
TABLE 12 SILVER PRICE PER OZ PER YEAR, APRIL 2005-APRIL 2016 (\$/OZ)	26
TABLE 13 MATERIAL REQUIREMENTS AND COSTS FOR 100,000 M2 (7 MWP) DSC	26
LONG-TERM STABILITY - THE KEY TO INDUSTRIAL SUCCESS	27
TABLE 14 PRODUCTION OF ELECTRICITY (YEO) FOR A VIRTUAL ROOF-TOP DSC PHOTOVOLTAIC SYSTEM INSTALLED IN CENTRAL EUROPE (20-YEAR TIME SPAN)	27
MANUFACTURING OF DYE SOLAR CELLS	28
COMMERCIAL APPLICATIONS OF DYE SOLAR CELLS	30
BUILDING INTEGRATED APPLICATIONS (BIPV)	30
TABLE 15 GLOBAL MARKET FOR SILICON MONOCRYSTALLINE-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	31
TABLE 16 GLOBAL MARKET FOR SILICON POLYCRYSTALLINE-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	32
TABLE 17 GLOBAL MARKET FOR AMORPHOUS SILICON-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	32
TABLE 18 GLOBAL MARKET FOR CIGS-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	33
TABLE 19 GLOBAL MARKET FOR DSC-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	33
FIGURE 1 GLOBAL MARKET SHARE OF INSTALLED PHOTOVOLTAIC POWER IN BIPV SECTOR BY TECHNOLOGY, 2014-2020 (%)	34
GRID-CONNECTED SOLAR FARMS	35
TABLE 20 GLOBAL MARKET FOR SILICON MONOCRYSTALLINE AND POLYCRYSTALLINE TECHNOLOGY USED IN POWER GRID-CONNECTED SOLAR FARMS BY REGION, THROUGH 2020 (GW)	35
TABLE 21 GLOBAL MARKET FOR AMORPHOUS SILICON TECHNOLOGY USED IN POWER GRID-CONNECTED SOLAR FARMS BY REGION, THROUGH 2020 (GW)	36
TABLE 22 GLOBAL MARKET FOR CIGS TECHNOLOGY USED IN POWER GRID-CONNECTED SOLAR FARMS BY REGION, THROUGH 2020 (GW)	36
TABLE 23 GLOBAL MARKET FOR ACCUMULATED POWER OF GRID-CONNECTED SOLAR FARMS OF DSCS TECHNOLOGY BY REGION, THROUGH 2020 (MW)	37
FIGURE 2 PRICES OF PV TECHNOLOGIES BY TECHNOLOGY, 2014-2020 (\$/W)	37
FIGURE 3 GLOBAL MARKET SHARE OF INSTALLED PHOTOVOLTAIC POWER OF GRID-CONNECTED SOLAR FARMS SECTOR BY TECHNOLOGY, 2014-2020 (%)	38
CONSUMER PRODUCTS	39
TABLE 24 GLOBAL MARKET FOR DSC-INTEGRATED CONSUMER PRODUCTS BY REGION, THROUGH 2020 (\$ MILLIONS)	40
FIGURE 4 GLOBAL MARKET SHARE OF DSC-INTEGRATED CONSUMER PRODUCT CONSUMPTION BY REGION, 2014-2020 (%)	41
REMOTE INDUSTRIAL APPLICATIONS	41
TABLE 25 GLOBAL MARKET FOR DSC-INTEGRATED REMOTE INDUSTRIAL APPLICATIONS BY REGION, THROUGH 2020 (\$ MILLIONS)	43
FIGURE 5 GLOBAL MARKET SHARE FOR DSC-INTEGRATED REMOTE INDUSTRIAL APPLICATIONS BY REGION, 2014-2020 (%)	43
REMOTE COMMUNITY APPLICATIONS	44
TABLE 26 GLOBAL MARKET FOR DSC CONSUMPTION IN REMOTE COMMUNITY APPLICATIONS BY REGION, THROUGH 2020 (\$ MILLIONS)	44

TOPIC	PAGE NO.
<i>FIGURE 6 GLOBAL MARKET SHARE OF DSC CONSUMPTION FOR REMOTE COMMUNITY APPLICATIONS BY REGION, 2014-2020 (%)</i>	44
FUTURE MARKET	45
HOW TO MAKE HIGH-EFFICIENCY DYE-SENSITIZED SOLAR CELLS	46
TiCl ₄ TREATMENTS	46
<i>TABLE 27 CHARACTERISTICS OF NANOCRYSTALLINE TiO₂ LAYERS WITH AND WITHOUT TiCl₄ TREATMENT</i>	47
Effect of the Light-scattering TiCl ₄ Layer	47
<i>TABLE 28 EFFECTS OF THE LIGHT-SCATTERING TiCl₄ LAYER</i>	47
THICKNESS OF THE NANOCRYSTALLINE TiO ₂ LAYER	48
<i>TABLE 29 CONVERSION EFFICIENCY OF DSC WITH TiO₂ ANTI- REFLECTING FILM (%/UM)</i>	48
ANTI-REFLECTING FILM	48
REPRODUCIBILITY OF DSC PHOTOVOLTAICS	48
<i>TABLE 30 EFFICIENCIES OF 12 DSCS MADE WITH TECHNIQUES TO IMPROVE THE CONVERSION EFFICIENCY (NO./%)</i>	49
CONCLUSION	49
SCALE-UP AND PRODUCT DEVELOPMENT STUDIES OF DSC IN ASIA AND EUROPE	49
<i>TABLE 31 DSC APPLICATION AREAS UNDER DEVELOPMENT IN VARIOUS COUNTRIES</i>	50
SCALING UP OF LABORATORY CELLS TO MODULES AND PANELS	50
Module Design Considerations	52
DSC DEVELOPMENT STUDIES IN VARIOUS EUROPEAN LABORATORIES	53
Energy Research Centre of the Netherlands (ECN)	53
Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE)	54
<i>TABLE 32 FRAUNHOFER ISE'S EFFICIENCY PARAMETERS FOR GLASS FRIT-BASED DSC</i>	55
Dye Solar Modules for Façade Applications: Results from Project ColorSol	56
G24 Innovation	57
3GSolar	58
DSC DEVELOPMENT STUDIES IN VARIOUS LABORATORIES IN JAPAN	58
<i>TABLE 33 EFFICIENCY OF DSC LABORATORY CELLS, SUB-MODULES AND MODULES OBTAINED IN VARIOUS INDUSTRIAL LABORATORIES</i>	58
Aisin Seiki Co. Ltd. and Toyota Central R&D Laboratories	59
Fujikura Ltd.	60
Peccell Technologies Inc.	61
Sharp Co. Ltd.	62
Sony Corp. Ltd.	63
Shimane Institute for Industrial Technology	63
TDK Co. Ltd.	63
Eneos Co. Ltd.	64
NGK Spark Plug Co. Ltd.	64
Panasonic Denko Co. Ltd.	66
Taiyo Yuden Co. Ltd.	66
Dai Nippon Printing Company	66
Mitsubishi Paper Mills and Sekisui Jushi Corp.	67
J-Power Co. Ltd. (Japan)	67

TOPIC	PAGE NO.
DSC DEVELOPMENT WORK IN SOUTH KOREA AND TAIWAN	68
Korean Institute of Science and Technology	68
Electronics and Telecommunications Research Institute, South Korea	68
Samsung SDI, South Korea	69
Industrial Technology Research Institute of Taiwan (ITRI)	69
JTouch, Taiwan	70
DSC DEVELOPMENT WORK IN AUSTRALIA AND CHINA	70
Dyesol, Australia	70
Military Applications of DSCs	71
Institute of Plasma Physics, Chinese Academy of Science	71
CHAPTER 4 GLOBAL MARKET FOR SOLAR TECHNOLOGY	74
SOLAR TECHNOLOGY: THE GLOBAL MARKET	74
TABLE 34 EVOLUTION OF WORLD TRADE IN SOLAR TECHNOLOGY, 2011-2014 (\$ MILLIONS)	74
TABLE 35 GLOBAL TRADE IN SOLAR TECHNOLOGY VS. GLOBAL TRADE, 2011-2014 (%)	74
TABLE 36 MAJOR IMPORTERS OF SOLAR TECHNOLOGY BY COUNTRY, 2011-2014 (\$ MILLIONS)	75
TABLE 37 GLOBAL MARKET SHARE OF THE MAIN SOLAR TECHNOLOGY IMPORTERS BY COUNTRY, 2014 (%)	75
TABLE 38 JAPAN'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	76
TABLE 39 GLOBAL MARKET SHARE OF JAPAN'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	76
TABLE 40 CHINA'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	77
TABLE 41 GLOBAL SHARE OF CHINA'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	77
TABLE 42 U.S.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	77
TABLE 43 GLOBAL SHARE OF U.S.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	78
TABLE 44 HONG KONG'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	78
TABLE 45 GLOBAL SHARE OF HONG KONG'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	79
TABLE 46 U.K.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	79
TABLE 47 GLOBAL SHARE OF U.K.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	80
TABLE 48 MAJOR GLOBAL IMPORTERS OF SOLAR TECHNOLOGY BY COUNTRY, 2011-2014 (%)	80
TABLE 49 VIETNAM'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	81
TABLE 50 GLOBAL SOLAR TECHNOLOGY EXPORT SALES BY COUNTRY, 2011-2014 (\$ MILLIONS)	81
TABLE 51 GROWTH OF THE TOP 10 SOLAR TECHNOLOGY EXPORTERS BY COUNTRY, 2011-2014 (%)	82
TABLE 52 GLOBAL SHARE OF THE TOP 10 SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	82

TOPIC	PAGE NO.
CHAPTER 5 DSC VERSUS ALTERNATIVE PV TECHNOLOGIES	85
TABLE 53 PERFORMANCE COMPARISON OF DSCS WITH OTHER PHOTOVOLTAIC TECHNOLOGIES ON A SUNNY DAY (WH)	85
TABLE 54 PERFORMANCE COMPARISON OF DSCS WITH OTHER PHOTOVOLTAIC TECHNOLOGIES ON A CLOUDY DAY (WH)	85
DSM MANUFACTURING COSTS	86
TABLE 55 MARKET PRICES OF DIFFERENT PHOTOVOLTAIC TECHNOLOGIES (% , \$)	87
TABLE 56 ESTIMATED COSTS FOR LARGE-SCALE MANUFACTURING OF 20 MW DSMS (%)	88
TABLE 57 ESTIMATED COSTS FOR VARIOUS MATERIALS USED TO FABRICATE 20 MW DSMS (%)	88
ADVANTAGES OF DSC TECHNOLOGY VS PREVIOUS TWO GENERATIONS	88
TABLE 58 EFFICIENCY COMPARISON OF VARIOUS TYPES OF DSCS (%)	90
CHAPTER 6 DYE SOLAR MODULES-FROM LABORATORY TO COMMERCIAL DEVELOPMENT	92
TABLE 59 NUMBER OF PAPERS PUBLISHED ON MONOCRYSTALLINE SILICON TECHNOLOGY, JANUARY 2010-JUNE 2015 (NUMBER)	92
TABLE 60 NUMBER OF PAPERS PUBLISHED ON POLYCRYSTALLINE SILICON TECHNOLOGY, JANUARY 2010-JUNE 2015 (NUMBER)	92
TABLE 61 NUMBER OF PAPERS PUBLISHED ON AMORPHOUS SILICON TECHNOLOGY, JANUARY 2010-JUNE 2015 (NUMBER)	93
TABLE 62 NUMBER OF PAPERS PUBLISHED ON CIGS, JANUARY 2010-JUNE 2015 (NUMBER)	93
TABLE 63 NUMBER OF PAPERS PUBLISHED ON DSC, JANUARY 2010-JUNE 2015 (NUMBER)	93
FIGURE 7 GLOBAL DISTRIBUTION OF PAPERS ON DIFFERENT PV TECHNOLOGIES, JANUARY 2010-JUNE 2015 (NUMBER OF PAPERS)	94
TABLE 64 NUMBER OF PAPERS PUBLISHED ON DSMS	95
DYE SOLAR CELL/MODULES AS ELECTROCHROMIC WINDOWS	95
EMERGENCE OF DYE SOLAR MODULE BUSINESSES	96
TABLE 65 GLOBAL COMMERCIAL COMPANIES AND RESEARCH CENTERS THAT DEVELOP DYE SOLAR CELLS/MODULES	96
CHAPTER 7 CURRENT RESEARCH ON DYE SOLAR MODULES	101
TABLE 66 EVOLUTION OF DYE-SENSITIZED SOLAR MODULES, 1996-2015	101
FABRICATION PROCESSES OF DYE SOLAR MODULES	102
DESIGN CONFIGURATIONS OF DYE SOLAR MODULES	102
SERIES CONNECTIONS	103
Monolithic Design (S-type)	103
Z-type and W-type Interconnections	104
PARALLEL CONNECTION	105
BALL-GRID DSC	106
COMBINED SERIES AND PARALLEL CONNECTED DSMS	106
TABLE 67 COMPARISON OF PV PERFORMANCE AND DEVICE DESIGNS OF DSMS	107
CHAPTER 8 EMERGING TECHNOLOGIES AND PATENT EVALUATION	112
FABRICATION OF FLEXIBLE MODULES	112
EMERGENCE OF SOLID-STATE DSMS	113

TOPIC	PAGE NO.
DYE SOLAR PANELS (DSPS)	114
EMERGENCE OF ALTERNATIVE DESIGNS	115
DYE SOLAR MODULE DESIGNS WITH IMPROVED FF	115
AREA DEPENDENT CHARGE COLLECTION IN DSMS	116
<i>TABLE 68 RELATION BETWEEN EFFICIENCY OF DSC WITH DEVICE AREA* (%/CM2)</i>	117
DSM Stability Tests	117
THERMAL STABILITY OF DYES AND ELECTROLYTES	118
LONG-TERM STABILITY OF DSMS	119
REVERSE BIAS DEGRADATION OF DSMS	120
STANDARDS FOR DSMS	120
PEROVSKITE SOLAR CELLS	121
ASCENSION OF PEROVSKITE SOLAR CELLS	121
ENGINEERING THE DEPOSITION PROCESS	122
OPEN ISSUES AND PITFALLS	123
Stability	123
Toxicity	123
PLANAR VERSUS MESOSCOPIC ARCHITECTURES	123
OUTLOOK	124
<i>TABLE 69 PEROVSKITE SOLAR CELLS PERFORMANCE PARAMETERS AND ROLE OF PEROVSKITE</i>	124
TECHNOLOGY PATENT EVALUATION	127
CURRENT STATE OF TECHNOLOGY	127
<i>TABLE 70 FUNCTIONALITY FOR THE SUCCESSFUL INDUSTRIAL PRODUCT DEVELOPMENT OF DYE SOLAR CELL MODULES</i>	127
PATENTS ON PV TECHNOLOGIES	129
By Region	129
<i>TABLE 71 GLOBAL DISTRIBUTION OF PATENTS FILED FOR MONOCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	129
<i>FIGURE 8 GLOBAL DISTRIBUTION OF PATENTS FILED FOR MONOCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	130
<i>TABLE 72 GLOBAL DISTRIBUTION OF PATENTS FILED FOR POLYCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	130
<i>FIGURE 9 GLOBAL DISTRIBUTION OF PATENTS FILED FOR POLYCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	131
<i>TABLE 73 GLOBAL DISTRIBUTION OF PATENTS FILED FOR AMORPHOUS SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	131
<i>FIGURE 10 GLOBAL DISTRIBUTION OF PATENTS FILED FOR AMORPHOUS SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	132
<i>TABLE 74 GLOBAL DISTRIBUTION OF PATENTS FILED FOR CIGS TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	132
<i>FIGURE 11 GLOBAL DISTRIBUTION OF PATENTS FILED FOR CIGS TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	133
<i>TABLE 75 GLOBAL DISTRIBUTION OF PATENTS FILED FOR DSC TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	133
<i>FIGURE 12 GLOBAL DISTRIBUTION OF PATENTS FILED FOR DSC TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)</i>	134
<i>FIGURE 13 GLOBAL DISTRIBUTION OF PATENTS FILED FOR PV TECHNOLOGIES BY TYPE, 2004-2014 (NUMBER OF PATENTS)</i>	134
By Manufacturer/Research Institute	135

TOPIC	PAGE NO.
<i>TABLE 76 NUMBER OF PATENTS FILED FOR DSC TECHNOLOGY BY COMPANY, 2004-2014</i>	136
CHAPTER 9 COMPANY PROFILES	138
3G SOLAR PHOTOVOLTAICS LTD.	138
COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION (CSIRO)	138
<i>PRINTABLE SOLAR CELLS</i>	139
PEROVSKITE SOLAR CELLS	139
DYEPOWER	140
DYESOL LTD.	140
MILITARY APPLICATIONS OF DSCS	141
DYENAMO AB	141
ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE (EPFL)	142
ENEOS CO. LTD.	143
ENERGY RESEARCH CENTER OF THE NETHERLANDS (ECN)	144
EXEGER SWEDEN AB	144
FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS (ISE)	145
FUJIKURA LTD.	146
G24 POWER LTD.	147
GUNZE LTD.	148
INDUSTRIAL TECHNOLOGY RESEARCH INSTITUTE OF TAIWAN (ITRI)	149
INSTITUTE OF PLASMA PHYSICS, CHINESE ACADEMY OF SCIENCES	149
JTOUCH CORP.	150
KOREA INSTITUTE OF SCIENCE AND TECHNOLOGY (KIST)	151
MERCK KGAA	151
MITSUBISHI PAPER MILLS CO. LTD.	152
NGK SPARK PLUG CO. LTD.	153
OXFORD PHOTOVOLTAICS	154
SOLAR FARM	155
BIPV	155
PECCELL TECHNOLOGIES INC.	155
RICOH LTD.	157
SAMSUNG SDI	157
SHARP CORP.	158
SHIMANE INSTITUTE OF TECHNOLOGY	159
SOLARONIX SA	159
SONY U.K. TECHNOLOGY CENTRE	161
TAIYO YUDEN CO. LTD.	161
TATA STEEL EUROPE LTD.	162
TOYOTA/AISIN SEIKI CO. LTD.	162

LIST OF TABLES

TABLE HEADING	PAGE NO.
SUMMARY TABLE GLOBAL MARKET FOR INSTALLED PHOTOVOLTAIC POWER BY TECHNOLOGY, THROUGH 2020 (MW/YEAR)	7
TABLE 1 SOLAR CONVERSION EFFICIENCY FOR VARIOUS PHOTOVOLTAIC SYSTEMS (SINGLE JUNCTION)*	11
TABLE 2 HIGHEST POWER-CONVERSION EFFICIENCIES OBTAINED USING DIFFERENT POLYPYRIDINE COMPLEXES OF RUTHENIUM	13
TABLE 3 PHOTOELECTROCHEMICAL PARAMETERS OF NATURAL DYE-BASED DSC	13
TABLE 4 PUBLICATIONS DEVOTED TO TIO ₂ AND ZNO FOR PHOTOVOLTAIC CONVERSION, 1995-2014 (NUMBER OF PUBLICATIONS)	15
TABLE 5 DSC PERFORMANCE OF DEVICES WITH GRAPHENE MATERIALS IN THE TIO ₂ LAYER COMPARED WITH CONTROL CELLS	17
TABLE 6 COMPARISON OF PMPP DROP LOSSES BETWEEN DSC AND SI FOR TWO TEMPERATURE RANGES	19
TABLE 7 N719 DYE COST AS A FUNCTION OF VOLUME (\$/G, KG)	20
TABLE 8 RUTHENIUM PRICE PER OZ PER YEAR, JANUARY 1999-MAY 2016 (\$/OZ)	21
TABLE 9 GLOBAL DEMAND FOR RUTHENIUM, 2003-2013 (TONS/YEAR)	22
TABLE 10 PLATINUM PRICE PER OZ PER YEAR, JANUARY 1999-MAY 2016 (\$/OZ)	24
TABLE 11 GLOBAL DEMAND FOR PLATINUM, 2003-2013 (TONS/YEAR)	25
TABLE 12 SILVER PRICE PER OZ PER YEAR, APRIL 2005-APRIL 2016 (\$/OZ)	26
TABLE 13 MATERIAL REQUIREMENTS AND COSTS FOR 100,000 M ² (7 MWP) DSC	26
TABLE 14 PRODUCTION OF ELECTRICITY (YEO) FOR A VIRTUAL ROOF-TOP DSC PHOTOVOLTAIC SYSTEM INSTALLED IN CENTRAL EUROPE (20-YEAR TIME SPAN)	27
TABLE 15 GLOBAL MARKET FOR SILICON MONOCRYSTALLINE-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	31
TABLE 16 GLOBAL MARKET FOR SILICON POLYCRYSTALLINE-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	32
TABLE 17 GLOBAL MARKET FOR AMORPHOUS SILICON-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	32
TABLE 18 GLOBAL MARKET FOR CIGS-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	33
TABLE 19 GLOBAL MARKET FOR DSC-BASED BIPV TECHNOLOGY BY REGION, THROUGH 2020 (\$ MILLIONS)	33
TABLE 20 GLOBAL MARKET FOR SILICON MONOCRYSTALLINE AND POLYCRYSTALLINE TECHNOLOGY USED IN POWER GRID-CONNECTED SOLAR FARMS BY REGION, THROUGH 2020 (GW)	35
TABLE 21 GLOBAL MARKET FOR AMORPHOUS SILICON TECHNOLOGY USED IN POWER GRID-CONNECTED SOLAR FARMS BY REGION, THROUGH 2020 (GW)	36
TABLE 22 GLOBAL MARKET FOR CIGS TECHNOLOGY USED IN POWER GRID-CONNECTED SOLAR FARMS BY REGION, THROUGH 2020 (GW)	36
TABLE 23 GLOBAL MARKET FOR ACCUMULATED POWER OF GRID-CONNECTED SOLAR FARMS OF DSCS TECHNOLOGY BY REGION, THROUGH 2020 (MW)	37
TABLE 24 GLOBAL MARKET FOR DSC-INTEGRATED CONSUMER PRODUCTS BY REGION, THROUGH 2020 (\$ MILLIONS)	40
TABLE 25 GLOBAL MARKET FOR DSC-INTEGRATED REMOTE INDUSTRIAL APPLICATIONS BY REGION, THROUGH 2020 (\$ MILLIONS)	43
TABLE 26 GLOBAL MARKET FOR DSC CONSUMPTION IN REMOTE COMMUNITY APPLICATIONS BY REGION, THROUGH 2020 (\$ MILLIONS)	44
TABLE 27 CHARACTERISTICS OF NANOCRYSTALLINE TIO ₂ LAYERS WITH AND WITHOUT TiCl ₄ TREATMENT	47
TABLE 28 EFFECTS OF THE LIGHT-SCATTERING TiCl ₄ LAYER	47

TABLE HEADING	PAGE NO.
TABLE 29 CONVERSION EFFICIENCY OF DSC WITH TIO2 ANTI- REFLECTING FILM (%/UM)	48
TABLE 30 EFFICIENCIES OF 12 DSCS MADE WITH TECHNIQUES TO IMPROVE THE CONVERSION EFFICIENCY (NO./%)	49
TABLE 31 DSC APPLICATION AREAS UNDER DEVELOPMENT IN VARIOUS COUNTRIES	50
TABLE 32 FRAUNHOFER ISE'S EFFICIENCY PARAMETERS FOR GLASS FRIT-BASED DSC	55
TABLE 33 EFFICIENCY OF DSC LABORATORY CELLS, SUB-MODULES AND MODULES OBTAINED IN VARIOUS INDUSTRIAL LABORATORIES	58
TABLE 34 EVOLUTION OF WORLD TRADE IN SOLAR TECHNOLOGY, 2011-2014 (\$ MILLIONS)	74
TABLE 35 GLOBAL TRADE IN SOLAR TECHNOLOGY VS. GLOBAL TRADE, 2011-2014 (%)	74
TABLE 36 MAJOR IMPORTERS OF SOLAR TECHNOLOGY BY COUNTRY, 2011-2014 (\$ MILLIONS)	75
TABLE 37 GLOBAL MARKET SHARE OF THE MAIN SOLAR TECHNOLOGY IMPORTERS BY COUNTRY, 2014 (%)	75
TABLE 38 JAPAN'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	76
TABLE 39 GLOBAL MARKET SHARE OF JAPAN'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	76
TABLE 40 CHINA'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	77
TABLE 41 GLOBAL SHARE OF CHINA'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	77
TABLE 42 U.S.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	77
TABLE 43 GLOBAL SHARE OF U.S.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	78
TABLE 44 HONG KONG'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	78
TABLE 45 GLOBAL SHARE OF HONG KONG'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	79
TABLE 46 U.K.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	79
TABLE 47 GLOBAL SHARE OF U.K.'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	80
TABLE 48 MAJOR GLOBAL IMPORTERS OF SOLAR TECHNOLOGY BY COUNTRY, 2011-2014 (%)	80
TABLE 49 VIETNAM'S MAIN SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2011-2014 (\$ MILLIONS)	81
TABLE 50 GLOBAL SOLAR TECHNOLOGY EXPORT SALES BY COUNTRY, 2011-2014 (\$ MILLIONS)	81
TABLE 51 GROWTH OF THE TOP 10 SOLAR TECHNOLOGY EXPORTERS BY COUNTRY, 2011-2014 (%)	82
TABLE 52 GLOBAL SHARE OF THE TOP 10 SOLAR TECHNOLOGY SUPPLIERS BY COUNTRY, 2014 (%)	82
TABLE 53 PERFORMANCE COMPARISON OF DSCS WITH OTHER PHOTOVOLTAIC TECHNOLOGIES ON A SUNNY DAY (WH)	85
TABLE 54 PERFORMANCE COMPARISON OF DSCS WITH OTHER PHOTOVOLTAIC TECHNOLOGIES ON A CLOUDY DAY (WH)	85
TABLE 55 MARKET PRICES OF DIFFERENT PHOTOVOLTAIC TECHNOLOGIES (% , \$)	87

TABLE HEADING	PAGE NO.
TABLE 56 ESTIMATED COSTS FOR LARGE-SCALE MANUFACTURING OF 20 MW DSMS (%)	88
TABLE 57 ESTIMATED COSTS FOR VARIOUS MATERIALS USED TO FABRICATE 20 MW DSMS (%)	88
TABLE 58 EFFICIENCY COMPARISON OF VARIOUS TYPES OF DSCS (%)	90
TABLE 59 NUMBER OF PAPERS PUBLISHED ON MONOCRYSTALLINE SILICON TECHNOLOGY, JANUARY 2010-JUNE 2015 (NUMBER)	92
TABLE 60 NUMBER OF PAPERS PUBLISHED ON POLYCRYSTALLINE SILICON TECHNOLOGY, JANUARY 2010-JUNE 2015 (NUMBER)	92
TABLE 61 NUMBER OF PAPERS PUBLISHED ON AMORPHOUS SILICON TECHNOLOGY, JANUARY 2010-JUNE 2015 (NUMBER)	93
TABLE 62 NUMBER OF PAPERS PUBLISHED ON CIGS, JANUARY 2010-JUNE 2015 (NUMBER)	93
TABLE 63 NUMBER OF PAPERS PUBLISHED ON DSC, JANUARY 2010-JUNE 2015 (NUMBER)	93
TABLE 64 NUMBER OF PAPERS PUBLISHED ON DSMS	95
TABLE 65 GLOBAL COMMERCIAL COMPANIES AND RESEARCH CENTERS THAT DEVELOP DYE SOLAR CELLS/MODULES	96
TABLE 66 EVOLUTION OF DYE-SENSITIZED SOLAR MODULES, 1996-2015	101
TABLE 67 COMPARISON OF PV PERFORMANCE AND DEVICE DESIGNS OF DSMS	107
TABLE 68 RELATION BETWEEN EFFICIENCY OF DSC WITH DEVICE AREA* (%/CM ²)	117
TABLE 69 PEROVSKITE SOLAR CELLS PERFORMANCE PARAMETERS AND ROLE OF PEROVSKITE	124
TABLE 70 FUNCTIONALITY FOR THE SUCCESSFUL INDUSTRIAL PRODUCT DEVELOPMENT OF DYE SOLAR CELL MODULES	127
TABLE 71 GLOBAL DISTRIBUTION OF PATENTS FILED FOR MONOCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	129
TABLE 72 GLOBAL DISTRIBUTION OF PATENTS FILED FOR POLYCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	130
TABLE 73 GLOBAL DISTRIBUTION OF PATENTS FILED FOR AMORPHOUS SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	131
TABLE 74 GLOBAL DISTRIBUTION OF PATENTS FILED FOR CIGS TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	132
TABLE 75 GLOBAL DISTRIBUTION OF PATENTS FILED FOR DSC TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	133
TABLE 76 NUMBER OF PATENTS FILED FOR DSC TECHNOLOGY BY COMPANY, 2004-2014	136

LIST OF FIGURES

FIGURE TITLE	PAGE NO.
SUMMARY FIGURE GLOBAL MARKET SHARE OF INSTALLED PHOTOVOLTAIC POWER BY TECHNOLOGY, 2014-2020 (%)	8
FIGURE 1 GLOBAL MARKET SHARE OF INSTALLED PHOTOVOLTAIC POWER IN BIPV SECTOR BY TECHNOLOGY, 2014-2020 (%)	34
FIGURE 2 PRICES OF PV TECHNOLOGIES BY TECHNOLOGY, 2014-2020 (\$/W)	37
FIGURE 3 GLOBAL MARKET SHARE OF INSTALLED PHOTOVOLTAIC POWER OF GRID-CONNECTED SOLAR FARMS SECTOR BY TECHNOLOGY, 2014-2020 (%)	38
FIGURE 4 GLOBAL MARKET SHARE OF DSC-INTEGRATED CONSUMER PRODUCT CONSUMPTION BY REGION, 2014-2020 (%)	41
FIGURE 5 GLOBAL MARKET SHARE FOR DSC-INTEGRATED REMOTE INDUSTRIAL APPLICATIONS BY REGION, 2014-2020 (%)	43
FIGURE 6 GLOBAL MARKET SHARE OF DSC CONSUMPTION FOR REMOTE COMMUNITY APPLICATIONS BY REGION, 2014-2020 (%)	44
FIGURE 7 GLOBAL DISTRIBUTION OF PAPERS ON DIFFERENT PV TECHNOLOGIES, JANUARY 2010-JUNE 2015 (NUMBER OF PAPERS)	94
FIGURE 8 GLOBAL DISTRIBUTION OF PATENTS FILED FOR MONOCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	130
FIGURE 9 GLOBAL DISTRIBUTION OF PATENTS FILED FOR POLYCRYSTALLINE SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	131
FIGURE 10 GLOBAL DISTRIBUTION OF PATENTS FILED FOR AMORPHOUS SILICON TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	132
FIGURE 11 GLOBAL DISTRIBUTION OF PATENTS FILED FOR CIGS TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	133
FIGURE 12 GLOBAL DISTRIBUTION OF PATENTS FILED FOR DSC TECHNOLOGY BY REGION, 2004-2014 (NUMBER OF PATENTS)	134
FIGURE 13 GLOBAL DISTRIBUTION OF PATENTS FILED FOR PV TECHNOLOGIES BY TYPE, 2004-2014 (NUMBER OF PATENTS)	134