

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY 34

- 1.1 Graphene properties 34
- 1.2 Commercialization 35
- 1.3 The graphene market to date 36
- 1.4 The graphene market in 2021 37
- 1.5 The graphene market in 2022 39
- 1.6 Graphene commercial market developments 2020-2022 40
- 1.7 Graphene funding and investments 2020-2022 45
- 1.8 Publicly listed graphene companies 47
- 1.9 Graphene global production capacities, in tons and by type 48
- 1.10 Global demand for graphene 50
 - 1.10.1 Global graphene demand, to 2033, tons 50
 - 1.10.2 Global graphene demand, by end user market to 2033 53
 - 1.10.3 Graphene market, by region 56
 - 1.10.3.1 Asia-Pacific 56
 - 1.10.3.2 North America 59
 - 1.10.3.3 Europe 61
- 1.11 Graphene products 62
- 1.12 Industrial collaborations and licence agreements 65
- 1.13 Graphene market challenges 73

2 OVERVIEW OF GRAPHENE 75

- 2.1 History 75
- 2.2 Properties 76
- 2.3 Types of graphene 77
 - 2.3.1 Graphene materials 78
 - 2.3.1.1 CVD Graphene 78
 - 2.3.1.2 Graphene nanoplatelets 80
 - 2.3.1.3 Graphene oxide and reduced Graphene Oxide 81
 - 2.3.1.4 Graphene quantum dots (GQDs) 82
 - 2.3.2 Intermediate products 97
 - 2.3.2.1 Graphene masterbatches 97
 - 2.3.2.2 Graphene dispersions 97

3 GRAPHENE PRODUCTION 99

- 3.1 Quality 100
- 3.2 Assessment of graphene production methods 101

4 REGULATIONS 106

- 4.1 Environmental, health and safety regulation 106
 - 4.1.1 Europe 106
 - 4.1.2 United States 107
 - 4.1.3 Asia-Pacific 108
- 4.2 Workplace exposure 109

5 GRAPHENE PATENTS AND PUBLICATIONS 111

6 GRAPHENE PRODUCTION 113

- 6.1 Commercial production capacities 114
- 6.2 Graphene oxide and reduced Graphene Oxide production capacities 115
 - 6.2.1 By producer 115
- 6.3 Graphene nanoplatelets production capacities 116
 - 6.3.1 By producer 117
- 6.4 CVD graphene film 118
 - 6.4.1 By producer 118
- 6.5 Graphene production issues and challenges 119
 - 6.5.1 Oversupply 119
 - 6.5.2 Quality 119
 - 6.5.3 Large-volume markets 120
 - 6.5.4 Commoditisation 120
 - 6.5.5 Industrial end-user perspective 121

7 GRAPHENE PRICING 122

- 7.1 Pristine graphene flakes pricing/CVD graphene 124
- 7.2 Few-Layer graphene pricing 125
- 7.3 Graphene nanoplatelets pricing 126
- 7.4 Graphene oxide (GO) and reduced Graphene Oxide (rGO) pricing 127
- 7.5 Graphene quantum dots pricing 129
- 7.6 Multilayer graphene (MLG) pricing 130
- 7.7 Graphene ink 131

8 MARKETS FOR GRAPHENE 132

- 8.1 3D PRINTING 132
 - 8.1.1 Graphene in 3D printing 132
 - 8.1.2 Market outlook 132
 - 8.1.3 Market drivers, trends and applications 133
 - 8.1.4 Global market in tons, historical and forecast to 2033 136

○	8.1.5	Product developers	138	
•	8.2	ADHESIVES	140	
○	8.2.1	Graphene in adhesives	140	
○	8.2.2	Market outlook	141	
○	8.2.3	Market drivers, trends and applications	141	
○	8.2.4	Global market in tons, historical and forecast to 2033	144	
○	8.2.5	Product developers	145	
•	8.3	AEROSPACE	147	
○	8.3.1	Market overview	147	
○	8.3.2	Market prospects	147	
○	8.3.3	Market assessment	148	
○	8.3.4	Applications Map	150	
○	8.3.5	Global market in tons, historical and forecast to 2033	151	
○	8.3.6	Product developers	152	
•	8.4	AUTOMOTIVE	155	
○	8.4.1	Graphene in the automotive sector	155	
○	8.4.2	Market outlook	156	
○	8.4.3	Market drivers, trends and applications	157	
○	8.4.4	Global market in tons, historical and forecast to 2033	160	
○	8.4.5	Product developers	161	
•	8.5	BATTERIES	165	
○	8.5.1	Graphene in batteries	165	
▪	8.5.1.1	Battery market megatrends	166	
○	8.5.2	Market outlook	171	
▪	8.5.2.1	Flexible and stretchable batteries	173	
○	8.5.3	Market drivers, trends and applications	174	
○	8.5.4	Global market in tons, historical and forecast to 2033	179	
○	8.5.5	Product developers	180	
•	8.6	COMPOSITES	186	
○	8.6.1	Graphene in composites	186	
○	8.6.2	Fiber-based polymer composite parts	186	
▪	8.6.2.1	Market outlook	186	
▪	8.6.2.2	Market drivers, trends and applications	187	
○	8.6.3	Metal-matrix composites	191	
▪	8.6.3.1	Market drivers, trends and applications	191	
○	8.6.4	Global market in tons, historical and forecast to 2033	192	
○	8.6.5	Product developers	193	
•	8.7	CONDUCTIVE INKS	199	
○	8.7.1	Graphene in conductive inks	199	
○	8.7.2	Market outlook	199	
○	8.7.3	Market drivers, trends and applications	200	
○	8.7.4	Global market in tons, historical and forecast to 2033	204	
○	8.7.5	Product developers	206	
•	8.8	CONSTRUCTION AND BUILDINGS	209	
○	8.8.1	Graphene in construction and buildings	209	
○	8.8.2	Market outlook	209	
○	8.8.3	Market drivers, trends and applications	210	
▪	8.8.3.1	Cement	210	
▪	8.8.3.2	Asphalt bitumen	212	
▪	8.8.3.3	Aerogels	213	
○	8.8.4	Global market in tons, historical and forecast to 2033	214	
○	8.8.5	Product developers	215	
•	8.9	ELECTRONICS	218	
○	8.9.1	WEARABLE ELECTRONICS AND DISPLAYS	218	

▪	8.9.1.1	Graphene in wearable electronics and displays	218
▪	8.9.1.2	Market outlook	219
▪	8.9.1.3	Market drivers, trends and applications	219
▪	8.9.1.4	Global market, historical and forecast to 2033	222
▪	8.9.1.5	Product developers	223
○	8.9.2	TRANSISTORS AND INTEGRATED CIRCUITS	225
▪	8.9.2.1	Graphene in transistors and integrated circuits	225
▪	8.9.2.2	Market outlook	226
▪	8.9.2.3	Market drivers, trends and applications	226
▪	8.9.2.4	Global market, historical and forecast to 2033	229
▪	8.9.2.5	Product developers	230
○	8.9.3	MEMORY DEVICES	232
▪	8.9.3.1	Graphene in memory devices	232
▪	8.9.3.2	Market outlook	232
▪	8.9.3.3	Market drivers, trends and applications	233
▪	8.9.3.4	Global market in tons, historical and forecast to 2031	234
▪	8.9.3.5	Product developers	236
•	8.10	FILTER MEDIA	237
○	8.10.1	Graphene in filter media	237
○	8.10.2	Market prospects	237
○	8.10.3	Market drivers, trends and applications	238
○	8.10.4	Global market in tons, historical and forecast to 2033	242
○	8.10.5	Product developers	244
•	8.11	FUEL CELLS	247
○	8.11.1	Graphene in fuel cells	247
○	8.11.2	Market outlook	247
○	8.11.3	Market drivers, trends and applications	248
○	8.11.4	Global market in tons, historical and forecast to 2033	252
○	8.11.5	Product developers	253
•	8.12	LIFE SCIENCES AND MEDICINE	254
○	8.12.1	Graphene in life sciences and medicine	254
○	8.12.2	Market outlook	255
▪	8.12.2.1	Drug delivery	255
▪	8.12.2.2	Imaging and diagnostics	256
▪	8.12.2.3	Implants	256
▪	8.12.2.4	Medical biosensors	257
▪	8.12.2.5	Woundcare	258
▪	8.12.2.6	Medical wearables	258
▪	8.12.2.7	Gene delivery	259
○	8.12.3	Market drivers, trends and applications	260
○	8.12.4	Global market in tons, historical and forecast to 2033	264
○	8.12.5	Product developers	266
•	8.13	LIGHTING	270
○	8.13.1	Graphene in lighting	270
○	8.13.2	Market outlook	270
○	8.13.3	Market drivers, trends and applications	271
○	8.13.4	Global market in tons, historical and forecast to 2033	273
○	8.13.5	Product developers	274
•	8.14	LUBRICANTS	276
○	8.14.1	Graphene in lubricants.	276
○	8.14.2	Market outlook	277
○	8.14.3	Market drivers, trends and applications	278
○	8.14.4	Global market in tons, historical and forecast to 2033	280
○	8.14.5	Product developers	281

- 8.15 OIL AND GAS 284
 - 8.15.1 Graphene in oil and gas 284
 - 8.15.2 Market outlook 284
 - 8.15.3 Market drivers, trends and applications 285
 - 8.15.4 Global market in tons, historical and forecast to 2033 287
 - 8.15.5 Product developers 288
- 8.16 PAINTS AND COATINGS 290
 - 8.16.1 Graphene in paints and coatings 290
 - 8.16.2 Market outlook 290
 - 8.16.3 Market drivers, trends and applications 291
 - 8.16.4 Global market in tons, historical and forecast to 2031 294
 - 8.16.5 Product developers 296
- 8.17 PHOTONICS 301
 - 8.17.1 Graphene in paints and coatings. 301
 - 8.17.2 Market outlook 301
 - 8.17.3 Market drivers, trends and applications 302
 - 8.17.4 Global market in tons, historical and forecast to 2031 305
 - 8.17.5 Product developers 307
- 8.18 PHOTOVOLTAICS 308
 - 8.18.1 Graphene in photovoltaics 308
 - 8.18.2 Market outlook 309
 - 8.18.3 Market drivers, trends and applications 309
 - 8.18.4 Global market in tons, historical and forecast to 2031 312
 - 8.18.5 Product developers 313
- 8.19 RUBBER AND TIRES 315
 - 8.19.1 Graphene in rubber and tires. 315
 - 8.19.2 Market outlook 315
 - 8.19.3 Market drivers, trends and applications 316
 - 8.19.4 Global market in tons, historical and forecast to 2031 319
 - 8.19.5 Product developers 321
- 8.20 SENSORS 324
 - 8.20.1 Graphene in sensors. 324
 - 8.20.2 Market outlook 325
 - 8.20.3 Market drivers, trends and applications 325
 - 8.20.4 Global market in tons, historical and forecast to 2031 329
 - 8.20.5 Product developers 331
- 8.21 TEXTILES AND APPAREL 335
 - 8.21.1 Graphene in textiles and apparel. 335
 - 8.21.2 Market outlook 335
 - 8.21.3 Market drivers, trends and applications 336
 - 8.21.4 Global market in tons, historical and forecast to 2031 341
 - 8.21.5 Product developers 342
- 8.22 SUPERCAPACITORS 347
 - 8.22.1 Graphene in supercapacitors. 347
 - 8.22.2 Market outlook 347
 - 8.22.3 Market drivers, trends and applications 348
 - 8.22.3.1 Flexible and stretchable supercapacitors 350
 - 8.22.4 Global market in tons, historical and forecast to 2031 351
 - 8.22.5 Product developers 352
- 8.23 OTHER MARKETS 355
 - 8.23.1 Audio equipment 355
 - 8.23.2 Sporting goods and apparel 355

9	GRAPHENE PRODUCER ASSESSMENT	357
• 9.1	Types of graphene produced, by producer	357
• 9.2	Markets targeted, by producer	361
• 9.3	Graphene product developers target markets	364
10	GRAPHENE COMPANY PROFILES	368
11	GRAPHENE EX-PRODUCERS AND PRODUCT DEVELOPERS	624
12	OTHER 2-D MATERIALS	639
• 12.1	Comparative analysis of graphene and other 2D materials	642
• 12.2	2D MATERIALS PRODUCTION METHODS	644
○ 12.2.1	Top-down exfoliation	644
▪ 12.2.1.1	Mechanical exfoliation method	645
▪ 12.2.1.2	Liquid exfoliation method	645
○ 12.2.2	Bottom-up synthesis	646
▪ 12.2.2.1	Chemical synthesis in solution	646
▪ 12.2.2.2	Chemical vapor deposition	646
• 12.3	TYPES OF 2D MATERIALS	648
○ 12.3.1	Hexagonal boron-nitride (h-BN)/Boron nitride nanosheets (BNNSs)	648
▪ 12.3.1.1	Properties	648
▪ 12.3.1.2	Applications and markets	649
○ 12.3.2	MXenes	652
▪ 12.3.2.1	Properties	652
▪ 12.3.2.2	Applications	653
○ 12.3.3	Transition metal dichalcogenides (TMD)	654
▪ 12.3.3.1	Properties	655
▪ 12.3.3.2	Applications	657
○ 12.3.4	Borophene	659
▪ 12.3.4.1	Properties	659
▪ 12.3.4.2	Applications	660
○ 12.3.5	Phosphorene/ Black phosphorus	661
▪ 12.3.5.1	Properties	662
▪ 12.3.5.2	Applications	663
○ 12.3.6	Graphitic carbon nitride (g-C ₃ N ₄)	666
▪ 12.3.6.1	Properties	666
▪ 12.3.6.2	C ₂ N	666
▪ 12.3.6.3	Applications	667
○ 12.3.7	Germanene	668
▪ 12.3.7.1	Properties	668
▪ 12.3.7.2	Applications	669
○ 12.3.8	Graphdiyne	670
▪ 12.3.8.1	Properties	671
▪ 12.3.8.2	Applications	671
○ 12.3.9	Graphane	673

▪	12.3.9.1	Properties	674	
▪	12.3.9.2	Applications	674	
○	12.3.10	Rhenium disulfide (ReS ₂) and diselenide (ReSe ₂)		675
▪	12.3.10.1	Properties	675	
▪	12.3.10.2	Applications	675	
○	12.3.11	Silicene	676	
▪	12.3.11.1	Properties	676	
▪	12.3.11.2	Applications	677	
○	12.3.12	Stanene/tinene	679	
▪	12.3.12.1	Properties	679	
▪	12.3.12.2	Applications	680	
○	12.3.13	Antimonene	681	
▪	12.3.13.1	Properties	681	
▪	12.3.13.2	Applications	681	
○	12.3.14	Indium selenide	682	
▪	12.3.14.1	Properties	682	
▪	12.3.14.2	Applications	682	
○	12.3.15	Layered double hydroxides (LDH)		683
▪	12.3.15.1	Properties	683	
▪	12.3.15.2	Applications	683	
•	12.4	2D MATERIALS PRODUCER AND SUPPLIER PROFILES		686 (19 company profiles)

13 RESEARCH METHODOLOGY 703

•	13.1	Technology Readiness Level (TRL)	703
---	------	----------------------------------	-----

14 REFERENCES 706

List of Tables

•	Table 1.	Graphene commercial market developments 2020-2022.	40
•	Table 2.	Graphene funding and investments 2020-2022.	45
•	Table 3.	Publicly listed graphene companies.	47
•	Table 4.	Main graphene producers by country, annual production capacities, types and main markets they sell to.	48
•	Table 5.	Demand for graphene (tons), 2018-2033.	51
•	Table 6.	Main graphene producers in North America.	59
•	Table 7.	Main graphene producers in Europe.	61
•	Table 8.	Commercial products incorporating graphene.	63
•	Table 9.	Graphene industrial collaborations, licence agreements and target markets.	66
•	Table 10.	Graphene market challenges.	73
•	Table 11.	Properties of graphene, properties of competing materials, applications thereof.	76
•	Table 12.	Applications of GO and rGO.	82
•	Table 13.	Comparison of graphene QDs and semiconductor QDs.	84

- Table 14. Advantages and disadvantages of methods for preparing GQDs. 87
- Table 15. Applications of graphene quantum dots. 88
- Table 16. Markets and applications for graphene quantum dots in electronics and photonics. 89
- Table 17. Markets and applications for graphene quantum dots in energy storage and conversion. 90
- Table 18. Markets and applications for graphene quantum dots in sensors. 91
- Table 19. Markets and applications for graphene quantum dots in biomedicine and life sciences. 92
- Table 20. Markets and applications for graphene quantum dots in electronics. 93
- Table 21. Market and technology challenges for graphene quantum dots. 94
- Table 22. Prices for graphene quantum dots. 96
- Table 23. Assessment of graphene production methods. 103
- Table 24. Regulations and rulings related to graphene in Europe. 106
- Table 25. Regulations and rulings related to graphene in North America. 107
- Table 26. Regulations and rulings related to graphene in Asia-Pacific. 108
- Table 27. Accumulated number of patent publications for graphene, 2004-2021. 111
- Table 28. Demand for graphene (tons), 2018-2033. 113
- Table 29. Graphene oxide production capacity by producer, 2014-2022. 115
- Table 30. Graphene nanoplatelets capacity in tons by producer, 2010-2022. 117
- Table 31. CVD graphene film capacity by producer, 2014-2022 in 000s m2. 118
- Table 32. Types of graphene and typical prices. 122
- Table 33. Pristine graphene flakes pricing by producer. 125
- Table 34. Few-layer graphene pricing by producer. 126
- Table 35. Graphene nanoplatelets pricing by producer. 126
- Table 36. Graphene oxide and reduced graphene oxide pricing, by producer. 127
- Table 37. Graphene quantum dots pricing by producer. 129
- Table 38. Multi-layer graphene pricing by producer. 130
- Table 39. Graphene ink pricing by producer. 131
- Table 40. Market overview for graphene in 3D printing. 132
- Table 41. Market outlook for graphene in 3D printing. 132
- Table 42. Market and applications for graphene in 3D printing. 133
- Table 43. Demand for graphene in 3-D printing (tons), 2018-2033. 136
- Table 44. Product developers in graphene 3D printing. 138
- Table 45. Market overview for graphene in adhesives. 140
- Table 46. Market outlook for graphene in adhesives. 141
- Table 47. Market and applications for graphene in adhesives. 141
- Table 48. Demand for graphene in adhesives (tons), 2018-2033. 144
- Table 49. Product developers in graphene adhesives. 145
- Table 50. Market overview for graphene in aerospace. 147
- Table 51. Scorecard for graphene in aerospace. 147
- Table 52. Market and applications for graphene in aerospace. 148
- Table 53: Demand for graphene in aerospace (tons), 2018-2030. 151
- Table 54: Product developers in graphene for aerospace. 152
- Table 55. Market overview for graphene in the automotive market. 156
- Table 56. Market outlook for graphene in automotive. 156
- Table 57. Market and applications for graphene in automotive. 157
- Table 58. Demand for graphene in automotive (tons), 2018-2033. 160
- Table 59. Product developers in the graphene automotive market. 161
- Table 60. Applications of nanomaterials in batteries. 165
- Table 61. Market overview for graphene in batteries. 170
- Table 62. Market outlook for graphene in batteries. 171

- Table 63. Market drivers for use of nanomaterials in batteries. 171
- Table 64. Applications of nanomaterials in flexible and stretchable batteries, by materials type and benefits thereof. 174
- Table 65. Market and applications for graphene in batteries. 174
- Table 66. Estimated demand for graphene in batteries (tons), 2018-2033. 179
- Table 67. Product developers in graphene batteries. 180
- Table 68. Market overview for graphene in composites. 186
- Table 69. Market outlook for graphene in fiber-based polymer composite parts. 186
- Table 70. Market and applications for graphene in fiber-based composite parts. 187
- Table 71. Market and applications for graphene in metal matrix composites. 191
- Table 72. Global market for graphene in composites 2018-2033, tons. 192
- Table 73. Product developers in graphene composites. 193
- Table 74. Market overview for graphene in conductive inks. 199
- Table 75. Market outlook for graphene in conductive inks. 199
- Table 76. Market and applications for graphene in conductive inks. 200
- Table 77. Comparative properties of conductive inks. 203
- Table 78. Demand for graphene in conductive ink (tons), 2018-2033. 204
- Table 79. Product developers in graphene conductive inks. 206
- Table 80. Market overview for graphene in construction and buildings. 209
- Table 81. Market outlook for graphene in construction. 209
- Table 82. Graphene for concrete and cement. 210
- Table 83. Graphene for asphalt bitumen. 212
- Table 84. Demand for graphene in construction (tons), 2018-2033. 214
- Table 85. Graphene product developers in construction. 215
- Table 86. Market overview for graphene in wearable electronics and displays. 218
- Table 87. Market outlook for graphene in wearable electronics and displays. 219
- Table 88. Market and applications for graphene in electronics. 219
- Table 89. Comparison of ITO replacements. 221
- Table 90. Demand for graphene in wearable, flexible and stretchable electronics, 2018-2033. 222
- Table 91. Product developers in graphene-based electronics. 223
- Table 92. Market overview for graphene in transistors and integrated circuits. 225
- Table 93. Comparative properties of silicon and graphene transistors. 225
- Table 94. Market outlook for graphene in transistors and integrated circuits. 226
- Table 95. Market and applications for graphene in transistors and integrated circuits. 226
- Table 96. Demand for graphene in transistors and integrated circuits, 2018-2033. 229
- Table 97. Product developers in graphene transistors and integrated circuits. 230
- Table 98. Market overview for graphene in memory devices. 232
- Table 99. Market outlook for graphene in memory devices. 233
- Table 100. Market and applications for graphene in memory devices. 233
- Table 101. Demand for graphene in memory devices, 2018-2033. 235
- Table 102. Product developers in graphene memory devices. 236
- Table 103. Market overview for graphene in filtration. 237
- Table 104. Market outlook for graphene in filtration. 237
- Table 105. Market and applications for graphene in filtration. 238
- Table 106. Demand for graphene in filtration (tons), 2018-2033. 242
- Table 107. Graphene companies in filtration. 244
- Table 108. Market overview for graphene in fuel cells. 247
- Table 109. Market outlook for graphene in fuel cells. 247
- Table 110. Market and applications for graphene in fuel cells. 248
- Table 111. Demand for graphene in fuel cells (tons), 2018-2033. 252

- Table 112. Product developers in graphene fuel cells. 253
- Table 113. Market overview for graphene in life sciences and medicine. 255
- Table 114. Market outlook for graphene in drug delivery. 255
- Table 115. Scorecard for graphene in imaging and diagnostics. 256
- Table 116. Scorecard for graphene in medical implants. 256
- Table 117. Scorecard for graphene in medical biosensors. 257
- Table 118. Scorecard for graphene in woundcare. 258
- Table 119. Market and applications for graphene in life sciences and medicine. 260
- Table 120. Demand for graphene in life sciences and medical (tons), 2018-2033. 264
- Table 121. Product developers in graphene life sciences and biomedicine. 266
- Table 122. Market overview for graphene in lighting. 270
- Table 123. Market outlook for graphene in lighting. 270
- Table 124. Market and applications for graphene in lighting. 271
- Table 125. Demand for graphene in lighting, 2018-2033. 273
- Table 126. Product developers in graphene lighting. 274
- Table 127. Market overview for graphene in lubricants. 276
- Table 128. Nanomaterial lubricant products. 276
- Table 129. Market outlook for graphene in lubricants. 277
- Table 130. Market and applications for graphene in lubricants. 278
- Table 131. Demand for graphene in lubricants (tons), 2018-2033. 280
- Table 132. Product developers in graphene lubricants. 281
- Table 133. Market overview for graphene in oil and gas. 284
- Table 134. Market outlook for graphene in oil and gas. 284
- Table 135. Market and applications for graphene in oil and gas. 285
- Table 136. Demand for graphene in oil and gas (tons), 2018-2033. 287
- Table 137. Product developers in graphene oil and gas. 288
- Table 138. Market overview for graphene in paints and coatings. 290
- Table 139. Market outlook for graphene in paints and coatings. 290
- Table 140. Market and applications for graphene in paints and coatings. 291
- Table 141. Demand for graphene in paints and coatings (tons), 2018-2033. 294
- Table 142. Product developers in graphene paints and coatings. 296
- Table 143. Market overview for graphene in paints and coatings. 301
- Table 144. Market outlook for graphene in photonics. 301
- Table 145. Market and applications for graphene in photonics. 302
- Table 146. Demand for graphene in photonics, 2018-2033. 305
- Table 147. Product developers in graphene photonics. 307
- Table 148. Market overview for graphene in photovoltaics. 308
- Table 149. Market outlook for graphene in photovoltaics. 309
- Table 150. Market and applications for graphene in photovoltaics. 309
- Table 151. Demand for graphene in photovoltaics (tons), 2018-2033. 312
- Table 152. Product developers in graphene solar. 313
- Table 153. Market overview for graphene in rubber and tires. 315
- Table 154. Market outlook for graphene in rubber and tires. 315
- Table 155. Market and applications for graphene in rubber and tires. 316
- Table 156. Demand for graphene in rubber and tires (tons), 2018-2033. 319
- Table 157. Product developers in rubber and tires. 321
- Table 158. Market overview for graphene in sensors. 324
- Table 159. Market outlook for graphene in sensors. 325
- Table 160. Market and applications for graphene in sensors. 325
- Table 161. Demand for graphene in sensors (tons), 2018-2033. 329
- Table 162. Product developers in graphene sensors. 331
- Table 163. Market overview for graphene in smart textiles and apparel. 335

- Table 164. Market outlook for graphene in smart textiles and apparel. 335
- Table 165. Market and applications for graphene in smart textiles and apparel. 336
- Table 166. Demand for graphene in textiles (tons), 2018-2033. 341
- Table 167. Graphene product developers in smart textiles and apparel. 342
- Table 168. Market overview for graphene in supercapacitors. 347
- Table 169. Market outlook for graphene in supercapacitors. 347
- Table 170: Comparative properties of graphene supercapacitors and lithium-ion batteries. 348
- Table 171. Market and applications for graphene in supercapacitors. 348
- Table 172. Demand for graphene in supercapacitors (tons), 2018-2033. 351
- Table 173. Product developers in graphene supercapacitors. 352
- Table 174. Graphene audio equipment producers and products. 355
- Table 175. Graphene sporting goods producers and products. 356
- Table 176. Graphene producers and types produced. 357
- Table 177. Graphene producers target market matrix. 361
- Table 178. Graphene product developers and end users target market matrix. 364
- Table 179. Performance criteria of energy storage devices. 619
- Table 180. 2D materials types. 641
- Table 181. Comparative analysis of graphene and other 2-D nanomaterials. 642
- Table 182. Comparison of top-down exfoliation methods to produce 2D materials. 644
- Table 183. Comparison of the bottom-up synthesis methods to produce 2D materials. 647
- Table 184. Properties of hexagonal boron nitride (h-BN). 649
- Table 185. Electronic and mechanical properties of monolayer phosphorene, graphene and MoS₂. 662
- Table 186. Properties and applications of functionalized germanene. 669
- Table 187. GDY-based anode materials in LIBs and SIBs 671
- Table 188. Physical and electronic properties of Stanene. 680
- Table 189. Technology Readiness Level (TRL) Examples. 704

List of Figures

- Figure 1. Demand for graphene, by market, 2021. 38
- Figure 2. Demand for graphene, 2018-2033, tons. 52
- Figure 3. Global graphene demand by market, 2018-2033 (tons), conservative estimate. 53
- Figure 4. Global graphene demand by market, 2018-2033 (tons). Medium estimate. 54
- Figure 5. Global graphene demand by market, 2018-2033 (tons). High estimate. 55
- Figure 6. Demand for graphene in China, by market, 2021. 56
- Figure 7. Demand for graphene in Asia-Pacific, by market, 2021. 57
- Figure 8. Main graphene producers in Asia-Pacific. 58
- Figure 9. Demand for graphene in North America, by market, 2021. 60
- Figure 10. Demand for graphene in Europe, by market, 2021. 62
- Figure 11. Graphene layer structure schematic. 75
- Figure 12. Illustrative procedure of the Scotch-tape based micromechanical cleavage of HOPG. 75
- Figure 13. Graphite and graphene. 76
- Figure 14. Graphene and its descendants: top right: graphene; top left: graphite = stacked graphene; bottom right: nanotube=rolled graphene; bottom left: fullerene=wrapped graphene. 78
- Figure 15. Types of CVD methods. 79
- Figure 16. Schematic of the manufacture of GnPs starting from natural graphite. 81

- Figure 17. Green-fluorescing graphene quantum dots. 83
- Figure 18. Schematic of (a) CQDs and (c) GQDs. HRTEM images of (b) C-dots and (d) GQDs showing combination of zigzag and armchair edges (positions marked as 1–4). 83
- Figure 19. Graphene quantum dots. 86
- Figure 20. Top-down and bottom-up graphene QD synthesis methods. 87
- Figure 21. Revenues for graphene quantum dots 2019-2033, millions USD 95
- Figure 22. Fabrication methods of graphene. 99
- Figure 23. TEM micrographs of: A) HR-CNFs; B) GANF@ HR-CNF, it can be observed its high graphitic structure; C) Unraveled ribbon from the HR-CNF; D) Detail of the ribbon; E) Scheme of the structure of the HR-CNFs; F) Large single graphene oxide sheets derived from GANF. 100
- Figure 24. (a) Graphene powder production line The Sixth Element Materials Technology Co. Ltd. (b) Graphene film production line of Wuxi Graphene Films Co. Ltd. 101
- Figure 25. Schematic illustration of the main graphene production methods. 102
- Figure 26. Published patent publications for graphene, 2004-2021. 112
- Figure 27. Demand for graphene, 2018-2033, tons. 114
- Figure 28. CVD Graphene on Cu Foil. 124
- Figure 29. Applications of graphene in 3D printing. 136
- Figure 30. Demand for graphene in 3-D printing (tons), 2018-2033. 137
- Figure 31. CNCTArch lightweight mounting for digital signalling. 138
- Figure 32. Applications of graphene in adhesives. 144
- Figure 33. Demand for graphene in adhesives (tons), 2018-2033. 145
- Figure 34. Graphene Adhesives. 146
- Figure 35. Applications of graphene in aerospace. 151
- Figure 36: Demand for graphene in aerospace (tons), 2018-2033. 152
- Figure 37. Orbex Prime rocket. 153
- Figure 38: Graphene enhanced aircraft cargo container. 153
- Figure 39: Graphene aircraft. 154
- Figure 40. Summary of graphene in automobiles. 156
- Figure 41. Applications of graphene in automotive. 159
- Figure 42. Demand for graphene in automotive (tons), 2018-2033. 161
- Figure 43. Supercar incorporating graphene. 161
- Figure 44. Graphene anti-corrosion primer. 163
- Figure 45. Graphene-R Brake pads. 163
- Figure 46. Antistatic graphene tire. 163
- Figure 47. Graphene engine oil additives. 164
- Figure 48. Annual cobalt demand for electric vehicle batteries to 2031. 167
- Figure 49. Annual lithium demand for electric vehicle batteries to 2031. 168
- Figure 50. Costs of batteries to 2031. 170
- Figure 51. Applications of graphene in batteries. 178
- Figure 52. Demand for graphene in batteries (tons), 2018-2033. 179
- Figure 53. Apollo Traveler graphene-enhanced USB-C / A fast charging power bank. 181
- Figure 54. Exide Graphene Lead Acid Battery. 181
- Figure 55. 6000mAh Portable graphene batteries. 182
- Figure 56. Real Graphene Powerbank. 184
- Figure 57. Graphene Functional Films - UniTran EH/FH. 185
- Figure 58. Applications of graphene in composites. 190
- Figure 59. Demand for graphene in composites (tons), 2018-2033. 193
- Figure 60. Graphene bike. 194
- Figure 61. Graphene lacrosse equipment. 195
- Figure 62. Graphene-based suitcase made from recycled plastic. 195

- Figure 63. Aros Create. 196
- Figure 64. Grays graphene hockey sticks. 198
- Figure 65. Applications of graphene in conductive inks. 204
- Figure 66. Demand for graphene in conductive ink (tons), 2018-2033. 205
- Figure 67. BGT Materials graphene ink product. 206
- Figure 68. Printed graphene conductive ink. 207
- Figure 69. Textiles covered in conductive graphene ink. 207
- Figure 70. Comparison of nanofillers with supplementary cementitious materials and aggregates in concrete. 210
- Figure 71. Demand for graphene in construction (tons), 2018-2033. 215
- Figure 72. Graphene asphalt additives. 216
- Figure 73. OG (Original Graphene) Concrete Admix Plus. 216
- Figure 74. Demand for graphene in wearable, flexible and stretchable electronics, 2018-2033. 223
- Figure 75. Moxi flexible film developed for smartphone application. 224
- Figure 76. Applications of graphene in transistors and integrated circuits. 229
- Figure 77. Demand for graphene in transistors and integrated circuits, 2018-2033. 230
- Figure 78. Graphene IC in wafer tester. 231
- Figure 79. Schematic cross-section of a graphene based transistor (GBT, left) and a graphene field-effect transistor (GFET, right). 231
- Figure 80. Demand for graphene in memory devices, 2018-2033. 235
- Figure 81. Layered structure of tantalum oxide, multilayer graphene and platinum used for resistive random-access memory (RRAM). 236
- Figure 82. Applications of graphene in filtration. 242
- Figure 83. Demand for graphene in filtration (tons), 2018-2033. 243
- Figure 84. Graphene anti-smog mask. 244
- Figure 85. Graphene filtration membrane. 245
- Figure 86. Graphene water filter cartridge. 245
- Figure 87. Applications of graphene in fuel cells. 251
- Figure 88. Demand for graphene in fuel cells (tons), 2018-2033. 252
- Figure 89. Graphene-based E-skin patch. 254
- Figure 90. Flexible and transparent bracelet that uses graphene to measure heart rate, respiration rate etc. 259
- Figure 91. Applications of graphene in life sciences and medicine 264
- Figure 92. Demand for graphene in life sciences and medical (tons), 2018-2033. 265
- Figure 93. Graphene medical biosensors for wound healing. 267
- Figure 94. Graphene Frontiers' Six™ chemical sensors consists of a field effect transistor (FET) with a graphene channel. Receptor molecules, such as DNA, are attached directly to the graphene channel. 267
- Figure 95. GraphWear wearable sweat sensor. 268
- Figure 96. BioStamp nPoint. 269
- Figure 97. Applications of graphene in lighting. 273
- Figure 98. Demand for graphene in lighting, 2018-2033. 274
- Figure 99. Graphene LED bulbs. 275
- Figure 100. Applications of graphene in lubricants. 280
- Figure 101. Demand for graphene in lubricants (tons), 2018-2033. 281
- Figure 102. Tricolit spray coating. 282
- Figure 103. Graphenoil products. 282
- Figure 104. Applications of graphene in oil and gas. 287
- Figure 105. Demand for graphene in oil and gas (tons), 2018-2033. 288
- Figure 106. Directa Plus Grafysorber. 289

- Figure 107. Applications of graphene in paints and coatings. 294
- Figure 108. Demand for graphene in paints and coatings (tons), 2018-2033. 295
- Figure 109. Cryorig CPU cooling system with graphene coating. 296
- Figure 110. Four layers of graphene oxide coatings on polycarbonate. 297
- Figure 111. 23303 ZINCTON GNC graphene paint. 298
- Figure 112. Graphene-enhanced anti-corrosion aerosols under their Hycote brand. 298
- Figure 113. Scania Truck head lamp brackets ACT chamber 6 weeks, equivalent to 3y field use. Piece treated with GO to the left together with different non-GO coatings. 299
- Figure 114. Schematic of graphene heat film. 300
- Figure 115. Applications of graphene in photonics. 305
- Figure 116. Demand for graphene in photonics, 2018-2033. 306
- Figure 117. All-graphene optical communication link demonstrator operating at a data rate of 25 Gb/s per channel. 307
- Figure 118. Applications of graphene in photovoltaics. 312
- Figure 119. Demand for graphene in photovoltaics (tons), 2018-2033. 313
- Figure 120. Graphene coated glass. 314
- Figure 121. Applications of graphene in rubber and tires. 319
- Figure 122. Demand for graphene in rubber and tires (tons), 2018-2033. 320
- Figure 123. Eagle F1 graphene tire. 321
- Figure 124. Graphene floor mats. 322
- Figure 125. Vittoria Corsa G+ tire. 322
- Figure 126. Graphene-based sensors for health monitoring. 324
- Figure 127. Applications of graphene in sensors. 329
- Figure 128. Demand for graphene in sensors (tons), 2018-2033. 330
- Figure 129. AGILE R100 system. 331
- Figure 130. Graphene fully packaged linear array detector. 332
- Figure 131. GFET sensors. 332
- Figure 132. Graphene is used to increase sensitivity to middle-infrared light. 334
- Figure 133. Applications of graphene in smart textiles and apparel. 340
- Figure 134. Demand for graphene in textiles (tons), 2018-2033. 341
- Figure 135. 878 Project One jacket display. 342
- Figure 136. Colmar graphene ski jacket. 343
- Figure 137. Graphene dress. The dress changes colour in sync with the wearer's breathing. 343
- Figure 138. G+ Graphene Aero Jersey. 344
- Figure 139. Inov-8 graphene shoes. 344
- Figure 140. Graphene Functional Membranes - UniTran GM. 345
- Figure 141. Graphene jacket. 346
- Figure 142. Applications of graphene in supercapacitors. 351
- Figure 143. Demand for graphene in supercapacitors (tons), 2018-2033. 352
- Figure 144. KEPCO's graphene supercapacitors. 353
- Figure 145. Skeleton Technologies supercapacitor. 354
- Figure 146. Zapgo supercapacitor phone charger. 354
- Figure 147. Callaway Chrome Soft golf and Chrome Soft X golf balls. 356
- Figure 148. Graphene heating films. 368
- Figure 149. Graphene flake products. 374
- Figure 150. ALKA Black-T. 378
- Figure 151. Printed graphene biosensors. 387
- Figure 152. Brain Scientific electrode schematic. 408
- Figure 153. Graphene battery schematic. 433
- Figure 154. Dotz Nano GQD products. 435
- Figure 155. Graphene-based membrane dehumidification test cell. 441

- Figure 156. Proprietary atmospheric CVD production. 452
- Figure 157. Wearable sweat sensor. 485
- Figure 158. InP/ZnS, perovskite quantum dots and silicon resin composite under UV illumination. 492
- Figure 159. Sensor surface. 507
- Figure 160. BioStamp nPoint. 524
- Figure 161. Nanotech Energy battery. 543
- Figure 162. Hybrid battery powered electrical motorbike concept. 545
- Figure 163. NAWASStitch integrated into carbon fiber composite. 546
- Figure 164. Schematic illustration of three-chamber system for SWCNH production. 547
- Figure 165. TEM images of carbon nanobrush. 548
- Figure 166. Test performance after 6 weeks ACT II according to Scania STD4445. 563
- Figure 167. Quantag GQDs and sensor. 565
- Figure 168. The Sixth Element graphene products. 579
- Figure 169. Thermal conductive graphene film. 580
- Figure 170. Talcoat graphene mixed with paint. 592
- Figure 171. T-FORCE CARDEA ZERO. 595
- Figure 172. Structures of nanomaterials based on dimensions. 639
- Figure 173. Schematic of 2-D materials. 641
- Figure 174. Diagram of the mechanical exfoliation method. 645
- Figure 175. Diagram of liquid exfoliation method 646
- Figure 176. Structure of hexagonal boron nitride. 648
- Figure 177. BN nanosheet textiles application. 651
- Figure 178. Structure diagram of Ti₃C₂T_x. 652
- Figure 179. Types and applications of 2D TMDCs. 655
- Figure 180. Left: Molybdenum disulphide (MoS₂). Right: Tungsten ditelluride (WTe₂) 656
- Figure 181. SEM image of MoS₂. 656
- Figure 182. Atomic force microscopy image of a representative MoS₂ thin-film transistor. 658
- Figure 183. Schematic of the molybdenum disulfide (MoS₂) thin-film sensor with the deposited molecules that create additional charge. 659
- Figure 184. Borophene schematic. 660
- Figure 185. Black phosphorus structure. 662
- Figure 186. Black Phosphorus crystal. 662
- Figure 187. Bottom gated flexible few-layer phosphorene transistors with the hydrophobic dielectric encapsulation. 663
- Figure 188: Graphitic carbon nitride. 666
- Figure 189. Structural difference between graphene and C₂N-h₂D crystal: (a) graphene; (b) C₂N-h₂D crystal. Credit: Ulsan National Institute of Science and Technology. 667
- Figure 190. Schematic of germanene. 668
- Figure 191. Graphdiyne structure. 671
- Figure 192. Schematic of Graphane crystal. 673
- Figure 193. Schematic of a monolayer of rhenium disulfide. 675
- Figure 194. Silicene structure. 676
- Figure 195. Monolayer silicene on a silver (111) substrate. 677
- Figure 196. Silicene transistor. 677
- Figure 197. Crystal structure for stanene. 679
- Figure 198. Atomic structure model for the 2D stanene on Bi₂Te₃(111). 680
- Figure 199. Schematic of Indium Selenide (InSe). 682
- Figure 200. Application of Li-Al LDH as CO₂ sensor. 684
- Figure 201. Graphene-based membrane dehumidification test cell. 693

