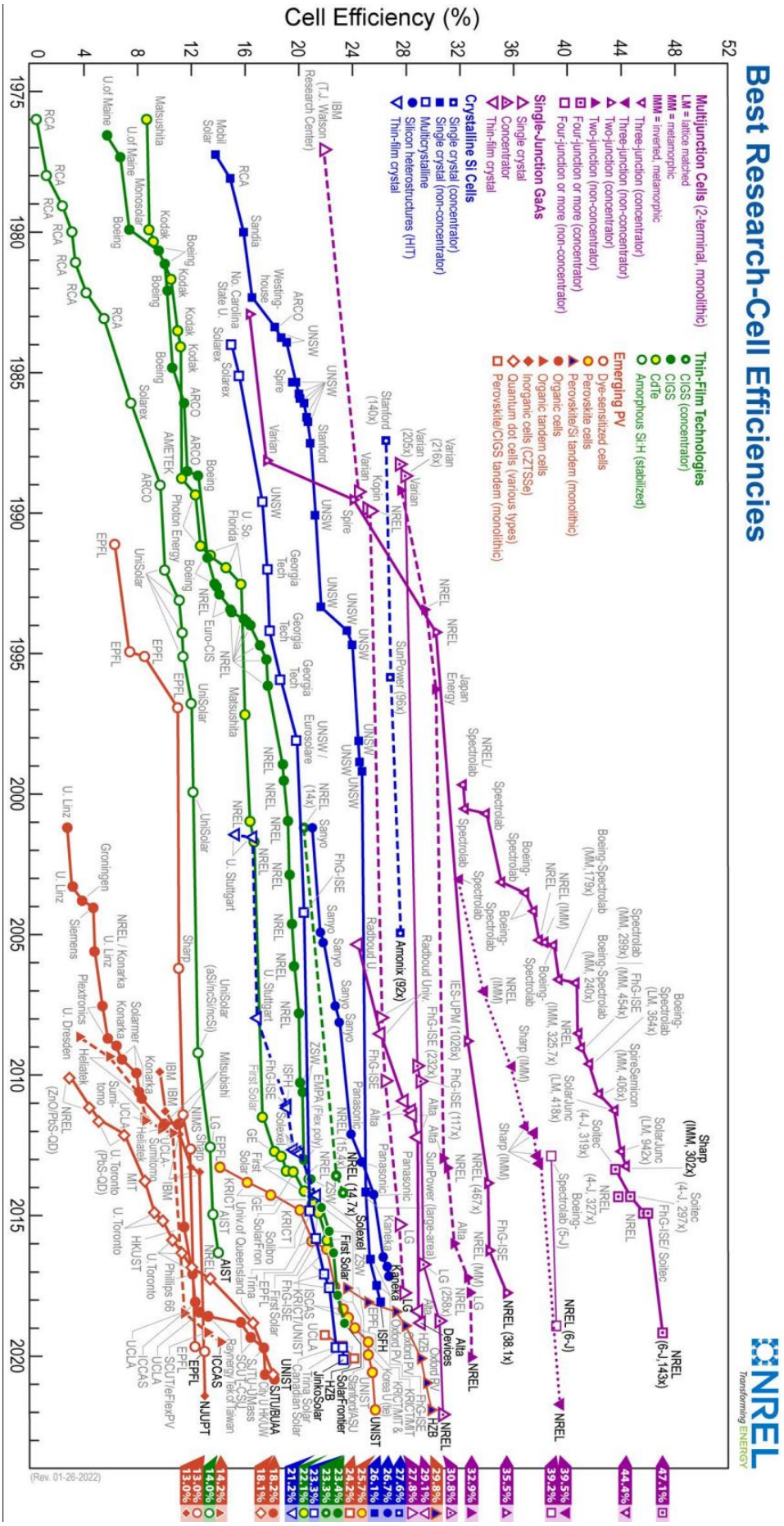
7 Appendices

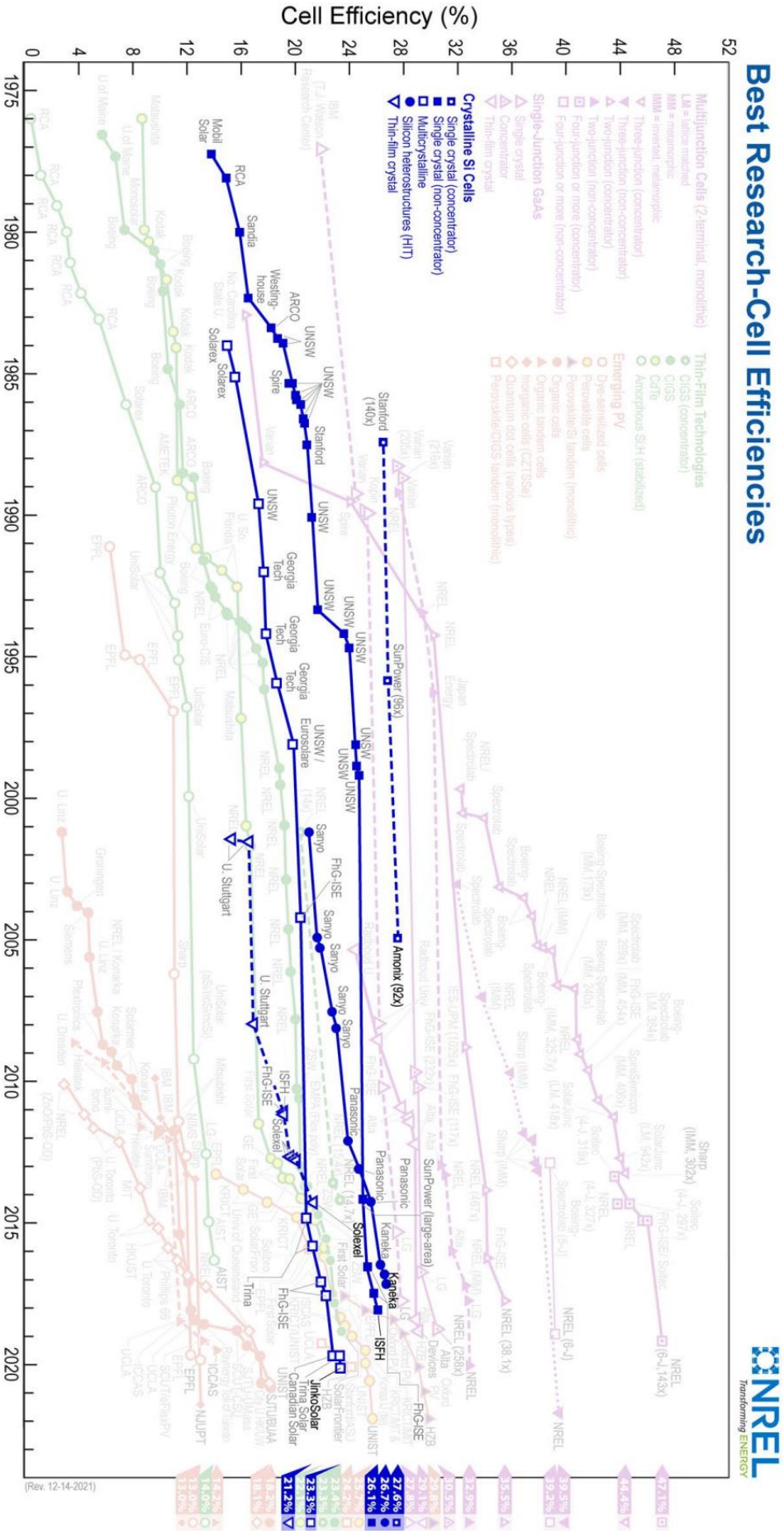
Appendix A

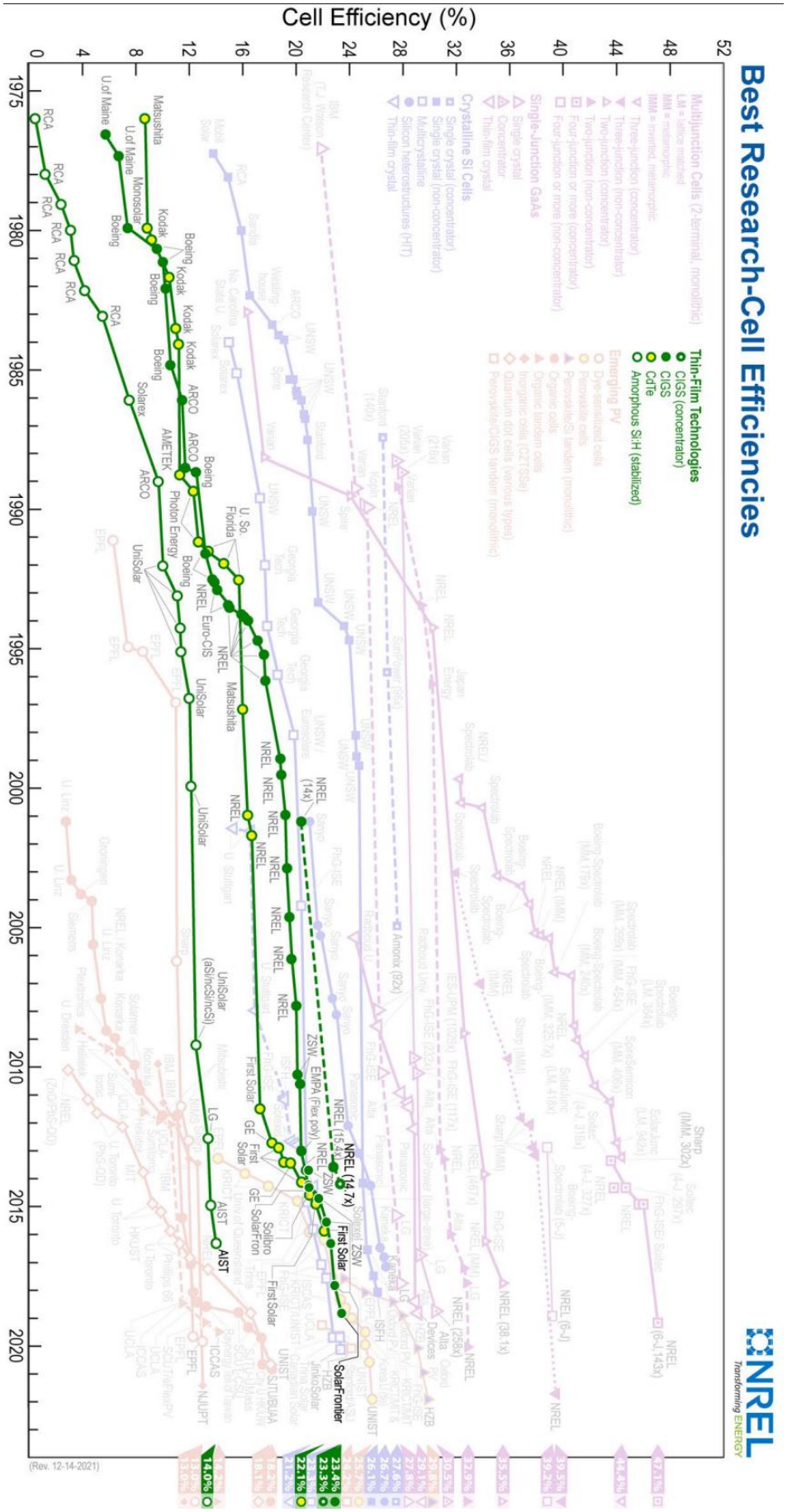
System element	System type				
	Grid tied	Grid tied with storage	Grid tied with storage and backup	Mini-grid	Micro-grid
PV array (DC)				√	√
PV array (AC)	√	√	√	√	√
Energy storage (DC)		√	√	√	√
PCU (GCI)	√	√	√	√	√
PCU (BDI)		√	√	√	√
Utility grid line	√	√	√		√
Load(s) (DC)		√	√	√	√
Load(s) (AC)		√	√	√	√
Back-up sources (DC)			√	√	√
Other RNE sources (DC)		√		√	√
Back-up sources (AC)			√	√	√
Other RNE sources (AC)		√		√	√

Table 5. Elements of different PV systems.

Appendix B


Best Research-Cell Efficiencies
Cell Efficiency (%)
NREL
Transforming ENERGY
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Perovskite/CIGS tandem (monolithic)
(Rev. 01-26-2022)


Best Research-Cell Efficiencies
Cell Efficiency (%)
NREL
Transforming ENERGY
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
Emerging PV
Single-Junction GaAs
Multijunction Cells (2-terminal, monolithic)
Mobil Solar
RCA
Sandia
Westing-house
ARCO
UNSW
Spire
Solarex
Stanford
Georgia Tech
Sanyo
FhG-ISE
U. Stuttgart
Amonix (92x)
SunPower (96x)
Panasonic
Kaneka
Solexel
ISFH
Trina
JinkoSolar
Canadian Solar
(Rev. 12-14-2021)

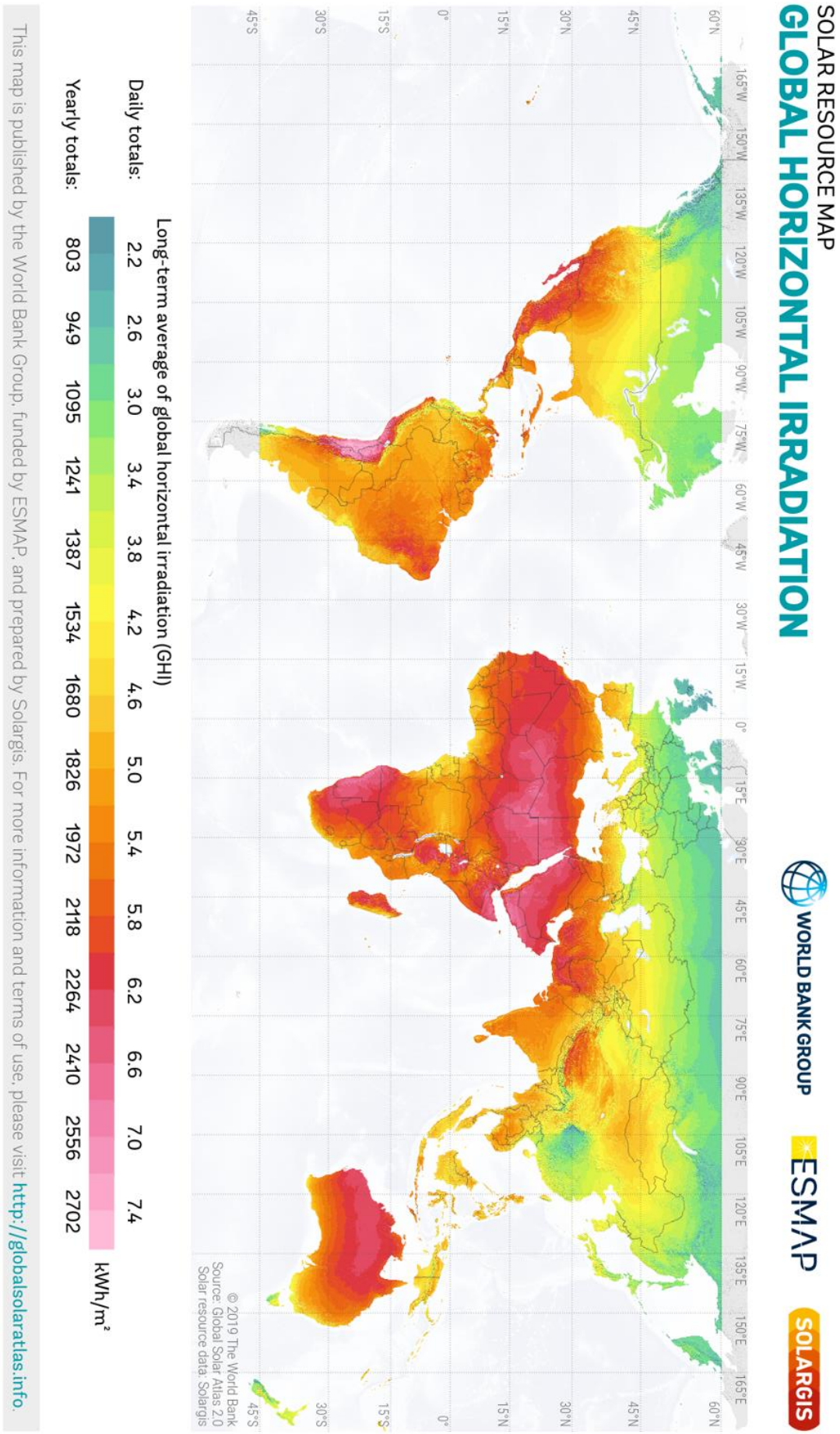

Best Research-Cell Efficiencies
Cell Efficiency (%)
NREL
Transforming ENERGY
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
NREL (14.7x)
First Solar
SolarFrontier
AIST
(Rev. 12-14-2021)

Appendix C

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	26.7 ± 0.5	79.0 (da)	0.738	42.65[a]	84.9	AIST (3/17)	Kaneka, *n*-type rear IBC[4]
Si (DS wafer cell)	**24.4 ± 0.3**	**267.5 (t)**	**0.7132**	**41.47[b]**	**82.5**	**ISFH (8/20)**	**Jinko Solar, *n*-type**
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 μm thick)[5]
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c,e]	72.1	FhG-ISE (8/07)	CSG Solar (<2 μm on glass)[6]
III–V cells							
GaAs (thin-film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78[f]	86.7	FhG-ISE (10/18)	Alta Devices[7]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[8]
InP (crystalline cell)	24.2 ± 0.5[g]	1.008 (ap)	0.939	31.15[a]	82.6	NREL (3/13)	NREL[9]
Thin-film chalcogenide							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	0.734	39.58[h]	80.4	AIST (11/18)	Solar Frontier[10]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass[11]
CZTSSe (cell)	11.3 ± 0.3	1.1761 (da)	0.5333	33.57[f]	63.0	Newport (10/18)	DGIST, Korea[12]
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77[a]	65.1	NREL (3/17)	UNSW[13]
Amorphous/ microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[i,g]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST[14]
Si (microcrystalline cell)	11.9 ± 0.3[g]	1.044 (da)	0.550	29.72[a]	75.0	AIST (2/17)	AIST[15]
Perovskite							
Perovskite (cell)	21.6 ± 0.6[j,k]	1.0235 (da)	1.193	21.64[l]	83.6	CSIRO (6/19)	ANU[16]
Perovskite (minimodule)	**18.6 ± 0.2[j,m]**	**29.539 (da)**	**1.089[c]**	**22.64[c,b]**	**75.4**	**NREL (6/20)**	**UNCarolina, eight cells**
Dye sensitized							
Dye (cell)	11.9 ± 0.4n	1.005 (da)	0.744	22.47[o]	71.2	AIST (9/12)	Sharp[17]
Dye (minimodule)	10.7 ± 0.4n	26.55 (da)	0.754[c]	20.19c,p	69.9	AIST (2/15)	Sharp, seven serial cells[18]
Dye (submodule)	8.8 ± 0.3n	398.8 (da)	0.697[c]	18.42c,q	68.7	AIST (9/12)	Sharp, 26 serial cells[19]
Organic							
Organic (cell)	**15.2 ± 0.2g,r**	**1.015 (da)**	**0.8467**	**24.24[b]**	**74.3**	**FhG-ISE (10/20)**	**Fraunhofer ISE**
Organic (minimodule)	12.6 ± 0.2r	26.129(da)	0.8315[c]	21.32[c,l]	71.1	FhG-ISE (9/19)	ZAE Bayern (12 cells)[20]
Organic (submodule)	11.7 ± 0.2r	203.98 (da)	0.8177[c]	20.68[c,l]	69.3	FhG-ISE (10/19)	ZAE Bayern (33 cells)[20]

Figure 17. Confirmed single-junction terrestrial cell and submodule efficiency measured under STC. (Green, et al., 2020)

Appendix D


SOLAR RESOURCE MAP
GLOBAL HORIZONTAL IRRADIATION
WORLD BANK GROUP
ESMAP
SOLARGIS
Long-term average of global horizontal irradiation (GHI)
Daily totals: 2.2 2.6 3.0 3.4 3.8 4.2 4.6 5.0 5.4 5.8 6.2 6.6 7.0 7.4
Yearly totals: 803 949 1095 1241 1387 1534 1680 1826 1972 2118 2264 2410 2556 2702
kWh/m²
© 2019 The World Bank
Source: Global Solar Atlas 2.0
Solar resource data: Solargis
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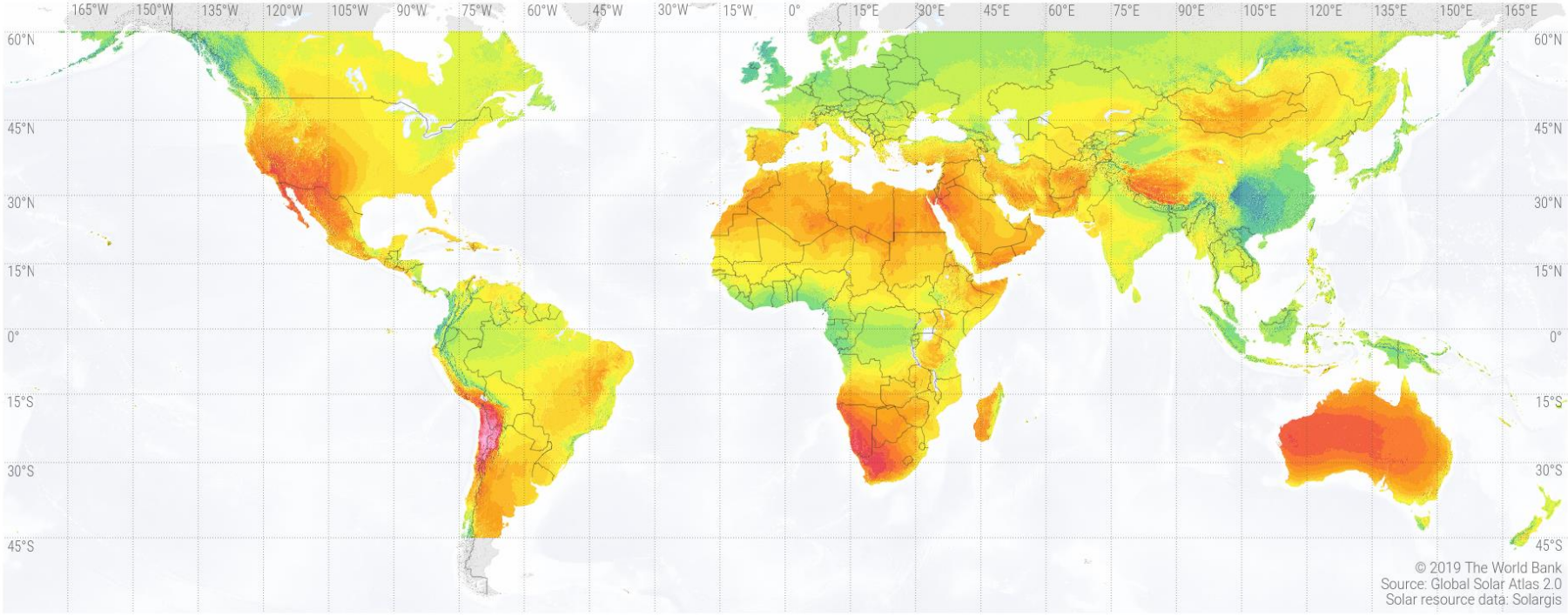
SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION



Long-term average of direct normal irradiation (DNI)

Daily totals:	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
										kWh/m²
Yearly totals:	365	730	1095	1461	1826	2191	2556	2922	3287	3652

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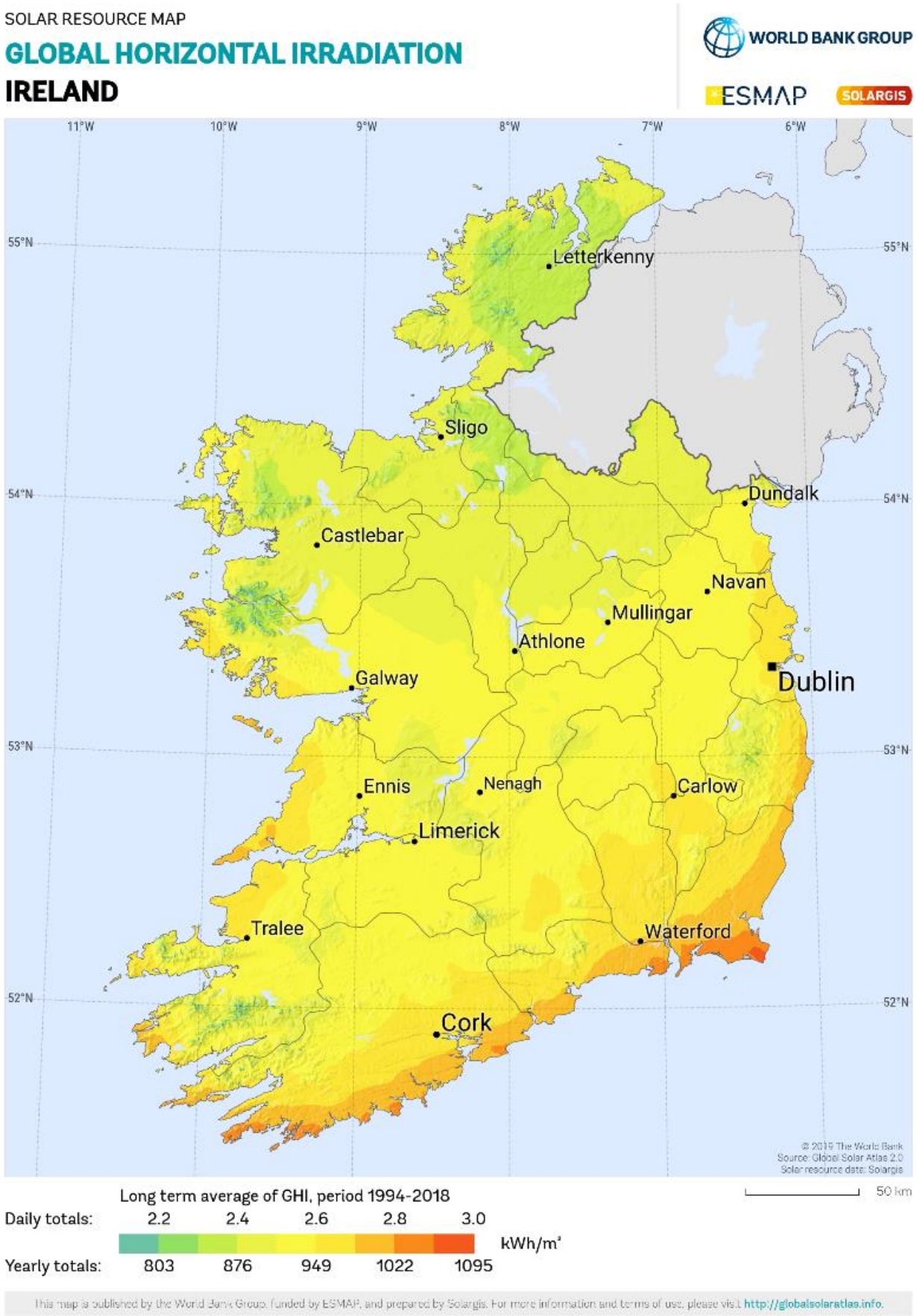
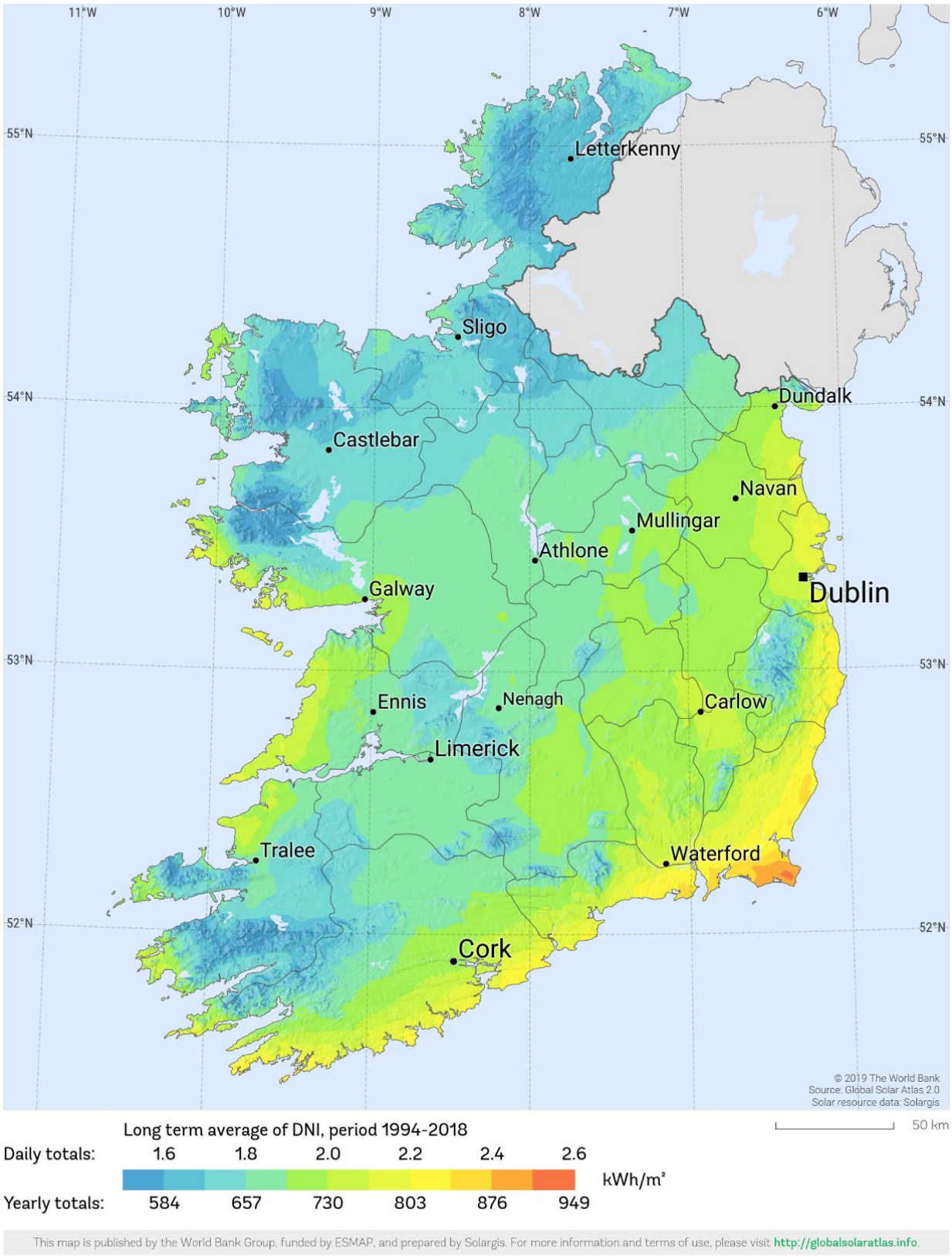

SOLAR RESOURCE MAP
GLOBAL HORIZONTAL IRRADIATION
IRELAND
WORLD BANK GROUP
ESMAP
SOLARGIS
11°W
10°W
9°W
8°W
7°W
6°W
55°N
54°N
53°N
52°N
Letterkenny
Sligo
Dundalk
Castlebar
Navan
Mullingar
Athlone
Galway
Dublin
Ennis
Nenagh
Carlow
Limerick
Tralee
Waterford
Cork
© 2019 The World Bank
Source: Global Solar Atlas 2.0
Solar resource data: Solargis
50 km
Long term average of GHI, period 1994-2018
Daily totals: 2.2 2.4 2.6 2.8 3.0 kWh/m²
Yearly totals: 803 876 949 1022 1095
This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info.


SOLAR RESOURCE MAP
DIRECT NORMAL IRRADIATION
IRELAND
WORLD BANK GROUP
ESMAP
SOLARGIS
11°W
10°W
9°W
8°W
7°W
6°W
55°N
54°N
53°N
52°N
Letterkenny
Sligo
Dundalk
Castlebar
Navan
Mullingar
Athlone
Galway
Dublin
Ennis
Nenagh
Carlow
Limerick
Tralee
Waterford
Cork
© 2019 The World Bank
Source: Global Solar Atlas 2.0
Solar resource data: Solargis
50 km
Long term average of DNI, period 1994-2018
Daily totals: 1.6 1.8 2.0 2.2 2.4 2.6
kWh/m²
Yearly totals: 584 657 730 803 876 949
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Appendix E

Parameter	Symbol	Units	Monitoring purpose	Required?			Number of sensors
				Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy	
Irradiance (see 7.3)							
In-plane irradiance (POA)	G_i	W·m^{-2}	Solar resource	√	√ or E	√ or E	Table 4 column 1
Global horizontal irradiance	GHI	W·m^{-2}	Solar resource, connection to historical and satellite data	√	√ or E		Table 4 column 1
Direct normal irradiance	DNI	W·m^{-2}	Solar resource, concentrator	√ for CPV	√ or E for CPV		Table 4 column 1
Diffuse irradiance	G_d	W·m^{-2}		√ for CPV with < 20× concentration	√ or E for CPV with < 20× concentration		Table 4 column 1
Circumsolar ratio	CSR						
Environmental factors (see 7.3)							
PV module temperature	T_{mod}	°C	Determining temperature-related losses	√	√ or E		Table 4 column 2
Ambient air temperature	T_{amb}	°C	Connection to historical data, plus estimation of PV temperatures	√	√ or E	√ or E	Table 4 column 1
Wind speed		m·s^{-1}	Estimation of PV temperatures	√	√ or E		Table 4 column 1
Wind direction		degrees		√			Table 4 column 1
Soiling ratio	SR		Determining soiling-related losses	√ if soiling losses expected to be >2 %			Table 4 column 1
Rainfall		cm	Estimation of soiling losses	√	√ or E		Table 4 column 1
Snow			Estimation of snow-related losses				

Parameter	Symbol	Units	Monitoring purpose	Required?			Number of sensors
				Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy	
Humidity			Estimation of spectral variations				
Tracker system (see 7.4)							
Error in dual-axis tracker primary angle	$\Delta\phi_1$	degrees	Tracker system fault detection, dual-axis	√ for CPV with >20× concentration			Table 4 column 1
Error in dual-axis tracker secondary angle	$\Delta\phi_2$	degrees		√ for CPV with > 20× concentration			Table 4 column 1
Single-axis tracker tilt angle	ϕ_T	degrees	Tracker system fault detection, single-axis	√ for single-axis tracker			Table 4 column 1
Electrical output (see 7.5 and 7.6)							
Array voltage (DC)	V_A	V	Energy output, diagnostics and fault localization	√			At each inverter (optionally at each combiner box or each string)
Array current (DC)	I_A	A		√			
Array power (DC)	P_A	kW		√			
Output voltage (AC)	V_{out}	V	Energy output	√	√		At each inverter and at system level
Output current (AC)	I_{out}	A		√	√		
Output power (AC)	P_{out}	kW		√	√	√	
Output energy	E_{out}	kWh		√	√	√	
Output power factor	λ		Utility request compliance	√	√		At each inverter and at system level
Reduced load demand			Determine utility or load request compliance and impact on PV system performance	If applicable	If applicable		At system level
System output power factor request	λ_{req}			If applicable	If applicable		At system level

Table 6. Requirements for monitoring.

System size (AC)	Number of sensors	
	Column 1	Column 2
< 5 MW	1	6
≥ 5 MW to < 40 MW	2	12
≥ 40 MW to < 100 MW	3	18
≥ 100 MW to < 200 MW	4	24
≥ 200 MW to < 300 MW	5	30
≥ 300 MW to < 500 MW	6	36
≥ 500 MW to < 750 MW	7	42
≥ 750 MW	8	48

Table 7. Relation between system size and number of sensors (this is also known as Table 4 by the Table above).

✓ means a required parameter to measure on site. The symbol "E" indicates that might be estimated based on regional or local meteorological or satellite data, instead of measuring on site.

Appendix F

(Pavkovic, 2013) Properties of several refrigerants.

Substance	R number	Chemical formula	M kg/kmol	NBP °C	CRT °C	CRP bar	Safety group	ODP	GWP_{100}
Carbon dioxide	R-744	CO_2	44,01	-55,6[1]	31,6	73,77	A1	0	1
Ammonia	R-717	NH_3	17,03	-33,3	132,25	113,33	B2 (B2L[2])	0	0
Sulfur dioxide	R-764	SO_2	64,06	-10,0	157,49	78,84	B1	0	0
Ethylether	R-610	$C_4H_{10}O$	74,12	35	194,0	36	-	0	0
Dimethylether	E-170	C_2H_6O	46,07	-25	126,9	53,7	A3	0	0
Methyl chloride	R-40	CH_3Cl	50,49	-24,2	143,1	66,77	B2	0,02	16

[1] – tripple point

[2] – new class introduced since 2010

Substance	R number	Chemical formula	M kg/kmol	NBP °C	CRT °C	CRP bar	Safety group	ODP	GWP_{100}
Trichlorofluoromethane	R-11	CCl_3F	137,4	23,71	197,96	44,1	A1	1	4000
Dichlorodifluoromethane	R-12	CCl_2F_2	120,91	-29,75	111,97	41,4	A1	1	8500
Chlorotrifluoromethane	R-13	$CClF_3$	104,5	-81,3	29,2	39,2	A1	1	11700
chlorodifluoromethane	R-22	$CHClF_2$	86,47	-40,81	96,15	49,9	A1	0,055	1700
R22/R115	R-502	$CHClF_2 + CF_3CClF_2$	111,6	-45,3	80,73	40,2	A1	0,33	5600

R number	Chemical formula / composition	M kg/kmol	NBP [°C]	CT [°C]	CP bar	Temp. glide [°C]	Safety group	GWP_{100}
R-32	CH_2F_2	-52,02	-51,65	78,11	57,8	0	A2L[1]	580
R-134A	CH_2FCF_3	102,03	-26,07	101,06	40,6	0	A1	1300
R-404A	R143A/125/134A (52/44/4)	97,6	-46,6	72,14	37,4	0,46	A1	3800
R-407C	R32/125/134A (23/25/52)	86,2	-43,8	86,05	46,3	5,59	A1	1600
R-410A	R32/125 (50/50)	72,59	-51,6	70,17	47,7	0,1	A1	1900
R-507	R143A/125 (50/50)	98,86	-47,1	70,75	37,2	0	A1	4000
R-508A	R23/116 (39/61)	100,1	-87,4	11,01	37,0	0	A1	13000
R-717 ammonia	NH_3	17,03	-33,3	132,25	113,33	0	B2L[1]	0
R-744 Carbon dioxide	CO_2	44,01	-55,6	31,6	73,77	0	A1	1
R-600A isobutane	$CH(CH_3)_3$	58,12	-11,6	134,66	36,29	0	A3	20
R-290 propane	C_3H_8	44,1	-42,11	96,74	42,51	0	A3	20
R-1270 propylene	C_3H_6	42,08	-47,62	91,06	45,55	0	A3	20

[1] – new safety classes introduced since 2010

Appendix G

Temp [°C]	Pressure	Volume [m^3/kg]		Density [kg/m^3]		Enthalpy [kJ/kg]			Entropy [kJ/(kg)(K)]	
	kPa (abs)	Liquid v_f	Vapor v_g	Liquid $1/v_f$	Vapor $1/v_g$	Liquid h_f	Latent h_{fg}	Vapor h_g	Liquid s_f	Vapor s_g
22	608.49	0.0008	0.0338	1217.0	29.549	230.4	180.7	411.0	1.1060	1.7182
23	627.25	0.0008	0.0328	1213.3	30.462	231.8	179.8	411.6	1.1107	1.7178
24	646.44	0.0008	0.0318	1209.6	31.399	233.2	178.9	412.1	1.1155	1.7175
25	666.06	0.0008	0.0309	1205.9	32.359	234.6	178.0	412.6	1.1202	1.7171
26	686.13	0.0008	0.0300	1202.1	33.344	236.1	177.0	413.1	1.1250	1.7168
27	706.66	0.0008	0.0291	1198.3	34.354	237.5	176.1	413.6	1.1297	1.7165
28	727.64	0.0008	0.0283	1194.4	35.389	238.9	175.2	414.1	1.1345	1.7161
29	749.04	0.0008	0.0274	1190.6	36.451	240.4	174.2	414.6	1.1392	1.7158
30	771.02	0.0008	0.0266	1186.7	37.540	241.8	173.3	415.1	1.1439	1.7155
31	793.43	0.0008	0.0259	1182.8	38.657	243.3	172.3	415.6	1.1487	1.7151
32	816.28	0.0008	0.0251	1178.8	39.802	244.8	171.3	416.1	1.1534	1.7148
33	839.66	0.0009	0.0244	1174.9	40.975	246.2	170.3	416.6	1.1581	1.7145
34	863.53	0.0009	0.0237	1170.8	42.179	247.7	169.3	417.0	1.1628	1.7142
35	887.91	0.0009	0.0230	1166.8	43.413	249.2	168.3	417.5	1.1676	1.7138
36	912.80	0.0009	0.0224	1162.7	44.679	250.6	167.3	418.0	1.1723	1.7135
37	938.20	0.0009	0.0218	1158.6	45.977	252.1	166.3	418.4	1.1770	1.7132
38	964.14	0.0009	0.0211	1154.5	47.308	253.6	165.3	418.9	1.1817	1.7129
39	990.60	0.0009	0.0205	1150.3	48.672	255.1	164.2	419.3	1.1864	1.7125
40	1017.61	0.0009	0.0200	1146.1	50.072	256.6	163.2	419.8	1.1912	1.7122
41	1045.16	0.0009	0.0194	1141.9	51.508	258.1	162.1	420.2	1.1959	1.7119
42	1073.26	0.0009	0.0189	1137.6	52.980	259.6	161.0	420.6	1.2006	1.7115
43	1101.93	0.0009	0.0184	1133.3	54.490	261.1	159.9	421.1	1.2053	1.7112
44	1131.16	0.0009	0.0178	1128.9	56.040	262.7	158.8	421.5	1.2101	1.7108
45	1161.01	0.0009	0.0174	1124.5	57.630	264.2	157.7	421.9	1.2148	1.7105
46	1191.41	0.0009	0.0169	1120.0	59.261	265.7	156.6	422.3	1.2195	1.7101
47	1222.41	0.0009	0.0164	1115.6	60.934	267.3	155.4	422.7	1.2242	1.7097
48	1253.95	0.0009	0.0160	1111.0	62.652	268.8	154.3	423.1	1.2290	1.7093
49	1286.17	0.0009	0.0155	1106.4	64.415	270.4	153.1	423.5	1.2337	1.709
50	1319.00	0.0009	0.0151	1101.8	66.225	271.9	151.9	423.8	1.2384	1.7086
51	1352.44	0.0009	0.0147	1097.1	68.084	273.5	150.7	424.2	1.2432	1.7082
52	1386.52	0.0009	0.0143	1092.4	69.992	275.1	149.5	424.6	1.2479	1.7077
53	1421.23	0.0009	0.0139	1087.6	71.952	276.6	148.3	424.9	1.2527	1.7073
54	1456.58	0.0009	0.0135	1082.8	73.966	278.2	147.0	425.3	1.2574	1.7069
55	1492.59	0.0009	0.0132	1077.9	76.035	279.8	145.8	425.6	1.2622	1.7064
56	1529.26	0.0009	0.0128	1072.9	78.162	281.4	144.5	425.9	1.2670	1.7059
57	1566.61	0.0009	0.0124	1067.9	80.348	283.0	143.2	426.2	1.2717	1.7055
58	1604.63	0.0009	0.0121	1062.8	82.596	284.6	141.9	426.5	1.2765	1.705
59	1643.35	0.0009	0.0118	1057.7	84.908	286.3	140.5	426.8	1.2813	1.7044
60	1682.76	0.0010	0.0115	1052.5	87.287	287.9	139.2	427.1	1.2861	1.7039
61	1722.88	0.0010	0.0111	1047.2	89.735	289.5	137.8	427.4	1.2909	1.7033
62	1763.72	0.0010	0.0108	1041.8	92.255	291.2	136.4	427.6	1.2957	1.7028
63	1805.28	0.0010	0.0105	1036.4	94.851	292.9	135.0	427.9	1.3006	1.7021
64	1847.47	0.0010	0.0103	1030.9	97.526	294.5	133.6	428.1	1.3054	1.7015

Table 8. Freon 134a (R-134a) thermodynamics properties.