Supplementary information

DEVELOPMENT OF THE LIFE-CYCLE ECONOMIC AND ENVIRONMENTAL ASSESSMENT MODEL FOR ESTABLISHING THE OPTIMAL IMPLEMENTATION STRATEGY OF THE ROOFTOP PHOTOVOLTAIC SYSTEM

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Table S1. Geographical description of the 78 weather stations in South Korea (Lee *et al.* 2014)

No.	Region	Longitude (E˚)	Latitude (N˚)	Altitude (m)	No.	Region	Longitude (E˚)	Latitude (N˚)	Altitude (m)
1	Daegwallyoug	128.43	37.4	772.6	40	Yeosu	127.44	34.44	64.6
2	Chuncheon	127.44	37.54	77.7	41	Wando	126.42	34.23	35.2
3	Bukgangneung	128.51	37.48	78.9	42	Jindo	126.19	34.28	476.5
4	Gangneung	128.53	37.45	26	43	Seongsan	126.52	33.23	17.8
5	Seoul	126.57	37.34	85.8	44	Seogwipo	126.33	33.14	49
6	Incheon	126.37	37.28	68.2	45	Ganghwa	126.26	37.42	47
7	Wonju	127.56	37.2	148.6	46	Yangpyeong	127.29	37.29	48
8	Suwon	126.59	37.16	34.1	47	Icheon	127.29	37.15	78
9	Seosan	126.29	36.46	28.9	48	Inje	128.1	38.03	200.2
10	Cheongju	127.26	36.38	57.2	49	Hongcheon	127.52	37.41	140.9
11	Daejeon	127.22	36.22	68.9	50	Taebaek	128.59	37.1	712.8
12	Chupungnyeong	127.59	36.13	244.7	51	Jecheon	128.11	37.09	263.6
13	Andong	128.42	36.34	140.1	52	Boeun	127.44	36.29	175
14	Pohang	129.22	36.01	2.3	53	Cheonan	127.07	36.46	21.3
15	Daegu	128.37	35.53	64.1	54	Boryeong	126.33	36.19	15.5
16	Jeonju	127.09	35.49	53.4	55	Buyeo	126.55	36.16	11.3
17	Gwangju	126.53	35.1	72.4	56	Geumsan	127.28	36.06	170.4
18	Busan	129.01	35.06	69.6	57	Buan	126.42	35.43	12
19	Mokpo	126.22	34.49	38	58	Imsil	127.17	35.36	247.9
20	Heuksando	125.27	34.41	76.5	59	Jeongeup	126.51	35.33	44.6
21	Gochang	126.35	35.2	52	60	Namwon	127.19	35.24	90.3
22	Jeju	126.31	33.3	20.4	61	Jangsu	127.31	35.39	406.5
23	Gosan	126.09	33.17	74.3	62	Juam	127.14	35.04	74.6
24	Jinju	128.02	35.09	30.2	63	Jangheung	126.55	34.41	45
25	Sokcho	128.33	38.15	18.1	64	Haenam	126.34	34.33	13
26	Cheorwon	127.18	38.08	153.7	65	Goheung	127.16	34.37	53.1
27	Dongducheon	127.03	37.54	109.1	66	Bongwhoa	128.54	36.56	319.8

End of Table S1

No.	Region	Longitude (E°)	Latitude (N°)	Altitude (m)	No.	Region	Longitude (E°)	Latitude (N°)	Altitude (m)
28	Munsan	126.45	37.53	29.4	67	Yeongju	128.31	36.52	210.8
29	Baengnyeongdo	124.37	37.57	144.9	68	Mungyeong	128.08	36.37	170.6
30	Donghae	129.07	37.3	39.9	69	Yeongdeok	129.24	36.31	42.1
31	Ulleungdo	130.53	37.28	222.8	70	Uiseong	128.41	36.21	81.8
32	Yeongwol	128.27	37.1	240.6	71	Gumi	128.19	36.07	48.9
33	Chungju	127.57	36.58	115.1	72	Yeongcheon	128.57	35.58	93.6
34	Uljin	129.24	36.59	50	73	Geochang	127.54	35.4	221
35	Sangju	128.09	36.24	96.2	74	Hapcheon	128.1	35.33	33.1
36	Gunsan	126.45	36	23.2	75	Miryang	128.44	35.29	11.2
37	Ulsan	129.19	35.33	34.6	76	Sancheong	127.52	35.24	138.1
38	Changwon	128.34	35.1	37.2	77	Geoje	128.36	34.53	46.3
39	Tongyeong	128.26	34.5	32.7	78	Namhae	127.55	34.48	45

Table S2. Estimated MADSR at the 54 unmeasured locations in South Korea by using an advanced CBR model (Lee *et al.* 2014)

No.	Region	Monthly average daily solar radiation (kWh/m^2/day)											
		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	Sokcho	2.95	2.81	4.30	4.75	4.23	5.31	3.24	4.05	4.06	3.36	1.88	2.27
2	Cheorwon	2.79	3.08	4.42	4.52	5.00	5.14	3.35	3.72	4.28	3.40	2.05	2.12
3	Dongducheon	2.75	3.11	4.47	4.54	4.96	5.11	3.22	3.58	4.24	3.58	2.13	2.25
4	Munsan	2.81	3.08	4.48	4.63	4.93	4.83	3.20	3.65	4.21	3.53	2.17	2.34
5	Baengnyeongdo	2.19	3.02	4.82	4.84	5.20	4.97	3.77	4.00	4.40	3.70	2.05	1.74
6	Donghae	2.94	2.92	4.41	4.58	4.40	5.25	3.72	4.07	3.82	3.38	2.03	2.32
7	Ulleungdo	1.97	2.68	3.91	4.81	4.27	5.33	4.32	4.25	3.60	3.14	2.00	1.85
8	Yeongwol	2.82	3.00	4.44	4.69	4.87	5.17	3.60	3.70	3.83	3.26	2.09	2.33
9	Chungju	2.76	2.95	4.54	4.67	5.02	5.08	3.71	3.68	4.18	3.44	2.14	2.25
10	Uljin	3.01	2.98	4.64	4.86	4.47	5.29	4.36	4.38	3.94	3.56	2.26	2.32
11	Sangju	2.87	3.16	4.84	4.91	4.89	5.04	3.71	3.50	3.86	3.33	2.13	2.41
12	Gunsan	2.76	3.13	4.66	5.14	4.95	4.82	3.61	3.69	4.59	3.61	2.27	1.84
13	Ulsan	2.96	2.95	4.90	5.23	4.84	4.88	4.66	4.03	4.24	3.59	2.21	2.58
14	Changwon	3.00	3.25	4.78	5.36	4.88	4.62	4.37	3.86	4.35	3.65	2.23	2.54
15	Tongyeong	3.02	3.26	4.83	5.41	4.67	4.55	4.85	3.81	4.66	3.68	2.30	2.62
16	Yeosu	2.97	3.39	4.93	5.44	4.80	4.61	4.71	3.92	4.81	3.84	2.45	2.38
17	Wando	2.61	3.46	4.79	5.39	4.82	4.55	4.62	3.75	4.57	3.90	2.11	2.03
18	Jindo	2.36	3.43	4.81	5.44	5.08	4.36	3.77	3.93	4.81	3.86	2.10	1.84
19	Seongsan	2.21	3.09	4.65	5.39	4.69	3.84	4.65	3.84	4.80	3.74	2.17	1.79

End of Table S2

No.	Region	Monthly average daily solar radiation (kWh/m^2/day)											
		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
20	Seogwipo	2.69	3.27	4.62	5.32	4.73	3.89	4.35	3.98	4.81	3.89	2.32	2.06
21	Ganghwa	2.71	3.02	4.59	4.66	4.81	4.83	3.25	3.90	4.18	3.55	2.05	2.28
22	Yangpyeong	2.71	2.93	4.43	4.44	4.69	4.89	3.00	3.77	4.03	3.32	2.09	2.21
23	Icheon	2.69	2.94	4.43	4.67	5.08	5.13	3.32	3.71	4.06	3.33	2.22	2.25
24	Inje	2.56	2.87	3.93	4.27	4.62	4.94	3.32	3.74	3.52	3.10	2.05	2.20
25	Hongcheon	2.76	2.89	4.35	4.44	4.92	5.03	3.41	3.78	3.94	3.24	2.10	2.19
26	Taebaek	2.83	3.21	4.53	4.61	5.14	5.03	3.56	3.53	3.57	3.47	2.05	2.23
27	Jecheon	2.87	3.13	4.50	4.57	4.92	5.05	3.72	3.70	3.88	3.33	2.09	2.32
28	Boeun	2.82	3.21	4.56	4.87	5.00	5.16	3.44	3.78	4.22	3.46	2.06	2.21
29	Cheonan	2.76	3.13	4.67	4.92	4.96	5.11	3.53	3.70	4.31	3.51	2.11	2.10
30	Boryeong	2.48	3.10	4.54	4.79	4.94	4.83	3.36	3.53	4.44	3.62	2.30	2.00
31	Buyeo	2.75	2.98	4.56	4.81	4.84	4.93	3.49	3.42	4.19	3.50	2.14	1.94
32	Geumsan	2.91	3.15	4.63	5.04	4.86	5.20	3.85	3.51	3.79	3.33	2.11	2.10
33	Buan	2.54	3.06	4.59	5.18	4.98	4.95	4.15	3.67	4.53	3.62	2.13	1.80
34	Imsil	2.81	3.15	4.77	5.20	5.00	4.99	3.70	3.49	4.37	3.60	2.10	2.04
35	Jeongeup	2.48	3.04	4.72	5.20	4.92	5.01	4.15	3.36	4.39	3.64	2.08	1.78
36	Namwon	2.97	3.13	4.87	5.24	5.00	5.05	4.09	3.72	4.32	3.68	2.36	2.21
37	Jangsu	2.81	3.34	4.83	5.07	5.16	5.09	3.71	3.49	4.24	3.50	2.11	2.07
38	Juam	2.74	3.25	4.75	4.91	4.84	4.68	4.00	3.68	4.06	3.45	2.05	2.04
39	Jangheung	2.94	3.47	4.91	5.28	4.82	4.54	4.23	3.65	4.38	3.91	2.21	2.06
40	Haenam	2.70	3.31	4.63	5.20	4.85	4.55	4.58	3.75	4.57	3.90	2.12	2.04
41	Goheung	2.74	3.39	4.69	5.37	4.89	4.62	4.20	3.69	4.40	3.77	2.24	2.19
42	Bongwhoa	2.90	3.17	4.49	4.70	4.93	5.08	3.56	3.75	3.54	3.24	2.11	2.38
43	Yeongju	2.83	3.19	4.85	4.90	5.07	5.17	3.67	3.58	4.02	3.33	2.06	2.31
44	Mungyeong	2.55	3.20	4.92	4.95	5.02	5.17	3.64	3.43	4.08	3.49	2.03	2.24
45	Yeongdeok	2.89	2.87	4.72	4.97	4.49	5.42	4.52	4.07	3.82	3.56	2.15	2.26
46	Uiseong	2.91	3.15	4.66	4.74	4.86	5.26	4.19	3.75	3.95	3.42	2.09	2.41
47	Gumi	2.69	3.12	4.79	5.02	4.93	5.29	4.05	3.68	3.81	3.40	2.10	2.28
48	Yeongcheon	2.88	3.01	4.89	5.02	4.87	5.05	4.16	3.77	3.64	3.41	2.14	2.25
49	Geochang	2.99	3.27	4.85	5.27	5.30	5.06	3.96	3.72	4.06	3.59	2.13	2.48
50	Hapcheon	2.98	3.17	4.78	5.31	4.94	5.16	4.26	3.62	4.20	3.63	2.05	2.40
51	Miryang	2.91	3.20	4.92	5.16	4.79	4.86	4.23	3.69	4.12	3.63	2.12	2.48
52	Sancheong	2.75	3.24	4.93	5.24	5.16	5.06	3.92	3.57	4.05	3.54	2.07	2.09
53	Geoje	2.80	3.15	4.75	5.40	4.69	4.40	4.43	3.51	4.24	3.54	2.10	2.25
54	Namhae	2.96	3.33	4.70	5.39	5.01	4.66	4.46	3.70	4.35	3.65	2.15	2.54

Table S3. Key elements for the life cycle cost and life cycle CO_2 analyses

	Classification	Detailed description
Analysis approach		Present worth method
Real discount rate	Interest growth rate	3.30%
	Electricity price growth rate	0.66%
	KCERs [a] growth rate	2.66%
Analysis period		25 years
Starting point of analysis		2012
Significant cost of ownership	Initial investment cost (IIC)	US$1,410/kW (based on market research)
	Initial benefit	Government subsidy (40% of the IIC)
	Operation & maintenance cost	Repair cost (1% of the IIC/yr.)
	Operation & maintenance benefits	Electricity savings
		Benefit from KCERs (US$11.12/$tCO_2$)

Where: [a]KCERs stands for the Korea Certified Emission Reductions (US$11.12/$tCO_2$); and the exchange rate (KRW/USD) is 1,079 won to a U.S. dollar (as of 7 May, 2013).

Table S4. Regional climate in Seoul (Northern part of South Korea)

Region	Geographical factors		Meteorological factors	
	Latitude (°N)	Monthly meridian altitude (°)	Monthly average daily solar radiation (kWh/m^2/day)	Monthly average temperature (°C)
Jan.	37.30	37.03	2.76	–7.2
Feb.		44.87	3.01	1.2
Mar.		52.7	4.54	3.6
Apr.		60.53	4.68	10.7
May		68.37	4.75	17.9
Jun.		76.20	4.56	22
Jul.		68.37	3.07	24.6
Aug.		60.53	3.4	25.8
Sep.		52.70	4.16	21.8
Oct.		44.87	3.26	14.2
Nov.		37.03	1.76	10.7
Dec.		29.20	1.93	–0.9

Table S5. Regional climate in Daejeon (central part of South Korea)

Region	Geographical factors		Meteorological factors	
	Latitude (°N)	Monthly meridian altitude (°)	Monthly average daily solar radiation (kWh/m^2/day)	Monthly average temperature (°C)
Jan.	36.22	38.13	2.91	–5.7
Feb.		45.97	3.18	1.8
Mar.		53.80	4.89	4.5
Apr.		61.63	5.06	11.6
May		69.47	5.00	18.1
Jun.		77.30	5.23	22.7
Jul.		69.47	3.78	25.7
Aug.		61.63	3.74	25.8
Sep.		53.80	4.25	21.2
Oct.		45.97	3.63	13.5
Nov.		38.13	2.28	11.2
Dec.		30.30	2.22	0.4

Table S6. Regional climate in Busan (southern part of South Korea)

Region	Geographical factors		Meteorological factors	
	Latitude (°N)	Monthly meridian altitude (°)	Monthly average daily solar radiation (kWh/m^2/day)	Monthly average temperature (°C)
Jan.	35.06	39.23	3.15	–0.7
Feb.		47.07	3.18	6.1
Mar.		54.90	5.03	7.4
Apr.		62.73	5.40	13.1
May		70.57	4.76	17.3
Jun.		78.40	4.66	21.3
Jul.		70.57	5.11	25.1
Aug.		62.73	4.00	25.8
Sep.		54.90	4.29	23.3
Oct.		47.07	3.60	17.6
Nov.		39.23	2.29	14.1
Dec.		31.40	2.54	4.4

Table S7. Profile of the unit panels in the rooftop photovoltaic system

No.	Product name	Power capacity(w)	Efficiency (%)	Miscellaneous losses (%)	Unit Size(mm)		
					Width	Length	Thickness
1	SM-42KSM	42	14.00	5.00	505	680	38
2	SM-48KSM	48	14.00	5.00	560	680	38
3	SM-63KSM	63	14.00	5.00	715	680	38
4	SM-70KSM	70	14.00	5.00	795	680	38
5	SM-83KSM	83	14.00	5.00	920	680	38
6	SM-165PA0	165	14.00	3.00	1587	790	38
7	SM-200PD0	200	14.00	3.00	1460	980	38
8	SM-200PJ0	200	14.00	3.00	1460	980	50
9	SM-200PK0	200	14.00	3.00	1460	980	50
10	SM-220PK0	220	14.05	3.00	980	1620	50
11	SM- 224 MHO	224	14.21	3.00	980	1620	50
12	SM- 232 MHO	232	14.75	3.00	980	1620	50
13	SM- 240 MHO	240	15.20	3.00	980	1620	50
14	HIS·M188SF	188	13.00	3.00	983	1476	35
15	HIS·M191SF	191	13.20	3.00	983	1476	35
16	HIS·M194SF	194	13.40	3.00	983	1476	35
17	HIS·M197SF	197	13.60	3.00	983	1476	35
18	HIS·M200SF	200	13.80	3.00	983	1476	35
19	HIS·M203SF	203	14.00	3.00	983	1476	35
20	HIS·M206SF	206	14.20	3.00	983	1476	35
21	HIS·M209SF	209	14.40	3.00	983	1476	35
22	HIS·M212SF	212	14.60	3.00	983	1476	35
23	HIS-S197SF	197	13.60	3.00	983	1476	35
24	HIS-S200SF	200	13.80	3.00	983	1476	35
25	HIS-S203SF	203	14.00	3.00	983	1476	35
26	HIS-S206SF	206	14.20	3.00	983	1476	35
27	HIS-S209SF	209	14.40	3.00	983	1476	35
28	HIS-S212SF	212	14.60	3.00	983	1476	35
29	HIS-S215SF	215	14.80	3.00	983	1476	35
30	HIS-S218SF	218	15.00	3.00	983	1476	35
31	HIS-S221SF	221	15.20	3.00	983	1476	35
32	HIS-M209SG	209	12.90	3.00	983	1645	35
33	HIS-M212SG	212	13.10	3.00	983	1645	35
34	HIS-M215SG	215	13.30	3.00	983	1645	35
35	HIS-M218SG	218	13.50	3.00	983	1645	35
36	HIS-M221SG	221	13.70	3.00	983	1645	35
37	HIS-M224SG	224	13.90	3.00	983	1645	35
38	HIS-M227SG	227	14.00	3.00	983	1645	35
39	HIS-M230SG	230	14.20	3.00	983	1645	35
40	HIS-M233SG	233	14.40	3.00	983	1645	35
41	HIS-S218SG	218	13.50	3.00	983	1645	35
42	HIS-S221SG	221	13.70	3.00	983	1645	35
43	HIS-S224SG	224	13.90	3.00	983	1645	35
44	HIS-S227SG	227	14.00	3.00	983	1645	35
45	HIS-S230SG	230	14.20	3.00	983	1645	35
46	HIS-S233SG	233	14.40	3.00	983	1645	35
47	HIS-S236SG	236	14.60	3.00	983	1645	35
48	HIS-S239SG	239	14.80	3.00	983	1645	35
49	HIS-S242SG	242	15.00	3.00	983	1645	35

Table S8. Profile of the unit panel and inverter in the rooftop photovoltaic system

Classification		Photovoltaic panel (No. 7)	Photovoltaic inverter
Model name		SM-200PD0	HPC-500SL-K
Power capacity (w)		200	500,000
Module efficiency (%)		14.0	98.0
Miscellaneous losses (%)		3.0	3.0
Size	Width (B)	1,460 mm	–
	Length(A)	980 mm	–
	Thickness	38 mm	–

Table S9. Life-cycle economic and environmental performance of the rooftop photovoltaic system according to the slope of the installed panel (SoP)

Optimization parameters				Optimization results				
SoP[a] (°)	ILP[b] (m)	NoP_L[c] (EA)	NoP[d] (EA)	AEG/unit[e] (kWh/EA)	Total AEG[f] (kWh)	IIC[g] (US$)	NPV_{25}[h] (US$)	SIR_{25}[i]
0	0.980	40	1,080	231.59	250,120	182,736	342,427	1.983
5	1.129	35	945	239.53	226,355	159,894	321,324	2.055
10	1.270	31	837	246.31	206,163	141,620	301,117	2.116
15	1.400	28	756	251.91	190,442	127,915	284,403	2.167
20	1.521	26	702	256.31	179,933	118,778	273,303	2.207
25	1.629	24	648	259.54	168,180	109,642	258,629	2.238
30	1.725	23	621	261.50	162,390	105,073	251,758	2.257
35	1.809	22	594	262.19	155,739	100,505	242,437	2.266
40	1.878	21	567	261.60	148,328	95,936	230,947	2.263
45	1.933	20	540	259.75	140,264	91,368	217,582	2.250
50	1.973	20	540	256.64	138,583	91,368	213,304	2.225
55	1.998	20	540	252.29	136,237	91,368	207,169	2.190
60	2.009	19	513	246.82	126,620	86,800	189,341	2.145
65	2.003	19	513	240.22	123,231	86,800	180,225	2.090
70	1.983	20	540	232.48	125,539	91,368	178,391	2.025
75	1.947	20	540	223.65	120,770	91,368	165,402	1.950
80	1.897	21	567	213.82	121,237	95,936	158,422	1.867
85	1.832	21	567	203.12	115,167	95,936	141,756	1.775
90	1.754	22	594	191.60	113,809	100,505	129,646	1.677

Where: [a]SoP stands for the slope of the installed panel; [b]ILP stands for the installed length of the panel; [c]NoP_L stands for the number of installed panels along the length of the rooftop area; [d]NoP stands for the number of installed panels; [e]AEG/unit stands for the annual electricity generation per unit panel; [f]Total AEG stands for the total annual electricity generation; [g]IIC stands for the initial investment cost (including the government subsidy); [h]NPV_{25} stands for the net present value at year 25; and [i]SIR_{25} stands for the savings-to-investment ratio at year 25.

Table S10. Optimization results in the first scenario

Rank	Optimization parameters					Optimization results				
	ToP[a]	SoP[b] (°)	NoP_W[c]	NoP_L[d]	NoP[e]	AEG/unit[f] (kWh)	Total AEG[g] (kWh)	IIC[h] (US$)	NPV_{25}[i] (US$)	SIR_{25}[j]
1	30	36	40	14	560	285.77	160,030	103,280	249,213	2.266
2	41	34	40	13	520	285.74	148,587	95,903	231,195	2.265
3	19	33	40	14	560	265.99	148,957	96,173	231,621	2.264
4	45	40	40	12	480	300.84	144,404	93,398	224,843	2.263
5	19	32	40	15	600	265.86	159,513	103,043	247,826	2.262
6	41	41	40	12	480	284.85	136,729	88,525	212,796	2.261
7	24	31	40	15	600	261.74	157,042	101,520	243,748	2.260
8	9	42	27	21	567	261.01	147,994	95,936	230,203	2.259
9	11	30	40	14	560	292.88	164,011	106,122	254,279	2.257
10	9	43	27	20	540	260.64	140,746	91,368	218,758	2.256

Where: [a]ToP stands for the panel type; [b]SoP stands for the slope of the installed panel; [c]NoP_W stands for the number of installed panels along the width of the rooftop area; [d]NoP_L stands for the number of installed panels along the length of the rooftop area; [e]NoP stands for the number of installed panels; [f]AEG/unit stands for the annual electricity generation per unit panel; [g]Total AEG stands for the total annual electricity generation; [h]IIC stands for the initial investment cost (including the government subsidy); [i]NPV_{25} stands for the net present value at year 25; and [j]SIR_{25} stands for the savings-to-investment ratio at year 25.

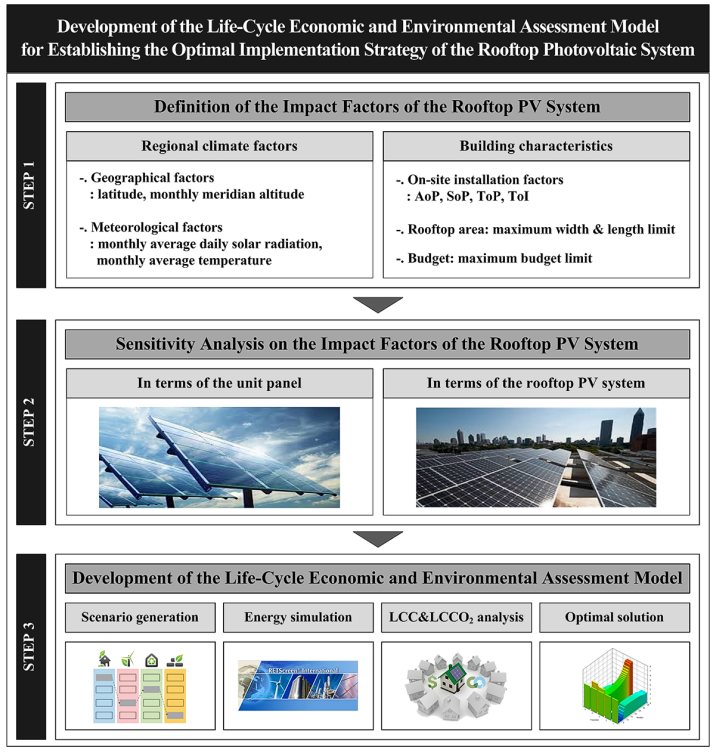

Fig. S1. Research framework

Fig. S2. 78 weather stations in South Korea (Lee *et al.* 2014)

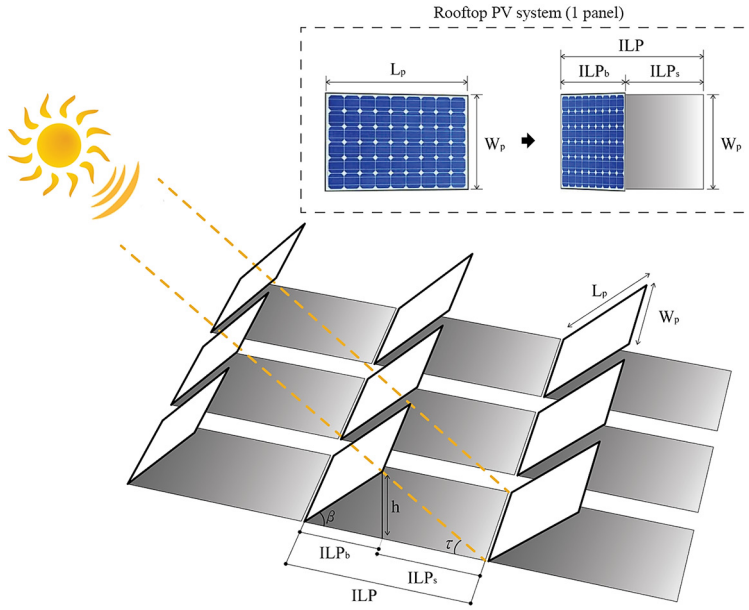

Fig. S3. Standard for calculating the installation area of the rooftop PV system

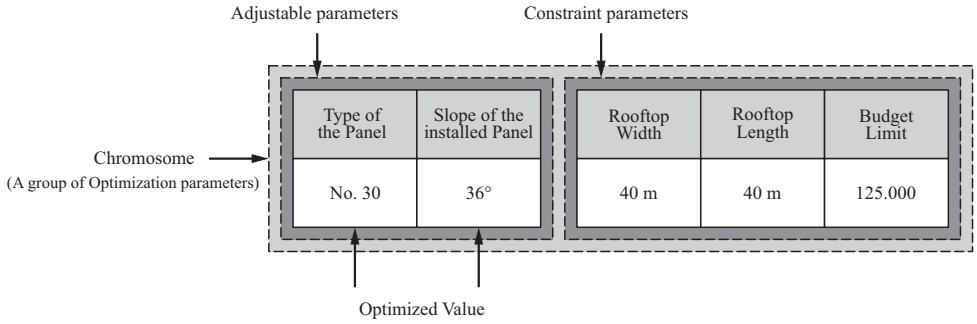

Fig. S4. Description of chromosomes in a genetic algorithm

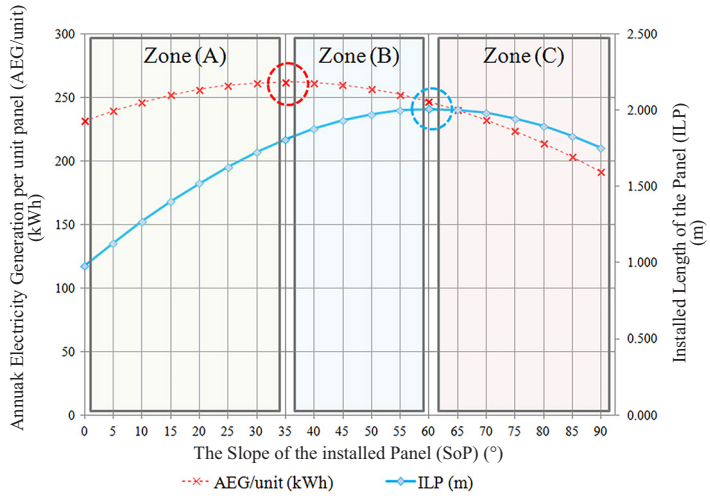

Fig. S5. AEG/unit and ILP according to the SoP

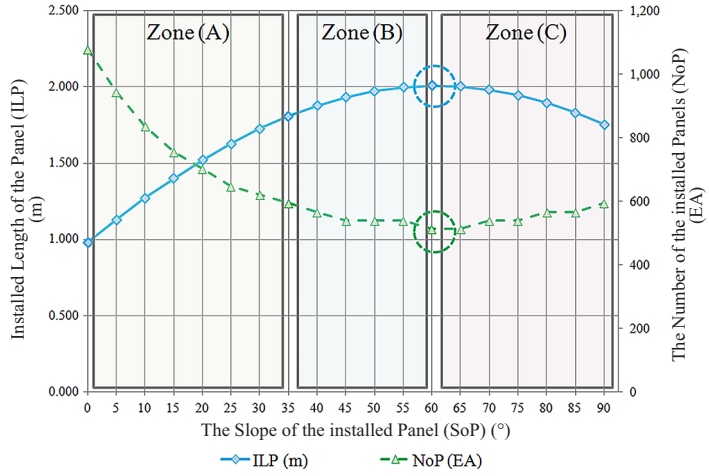

Fig. S6. The correlation between the ILP and the NoP

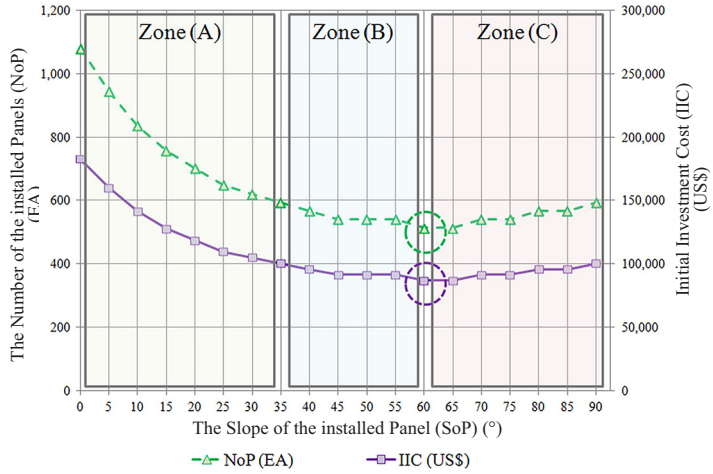

Fig. S7. The correlation between the NoP and the IIC

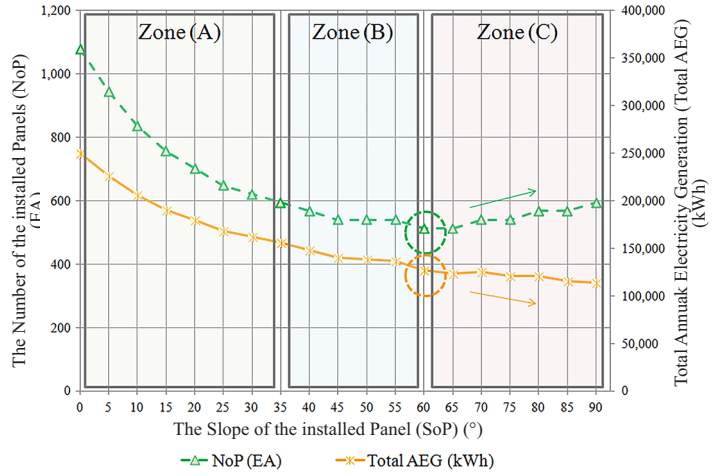

Fig. S8. The correlation between the NoP and the total AEG

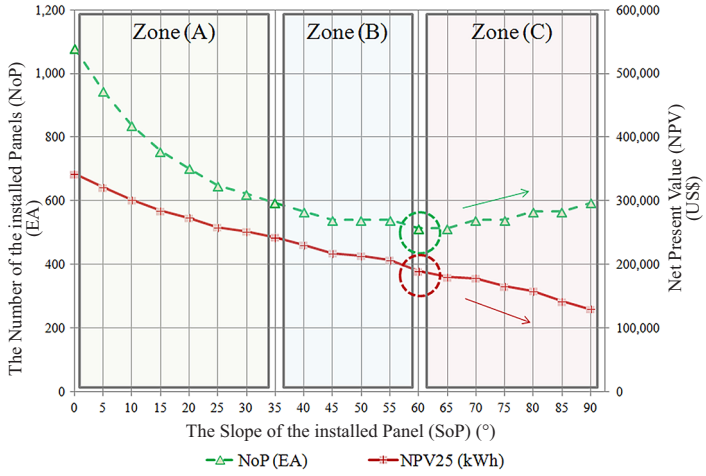

Fig. S9. The correlation between the NoP and the NPV

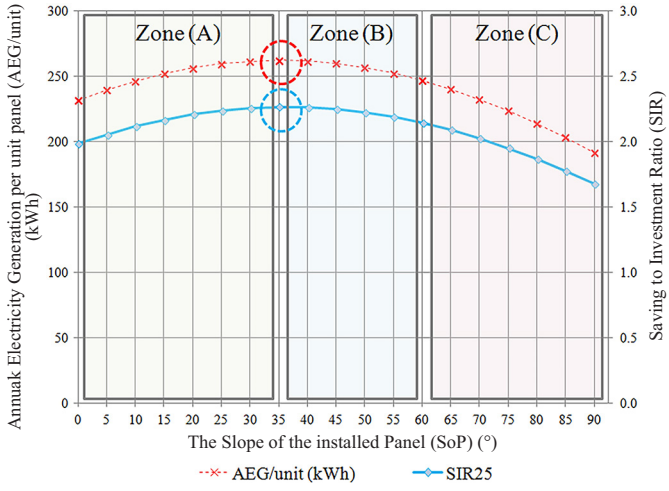

Fig. S10. The correlation between the AEG/unit and the SIR