Perovskite Solar Cells, a Game-Changer for Low- and Lower-Middle Income Countries?

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Figure S1. The evolution of global (a) and G7 (b) energy consumption, population and GDP between 1980 and 2016.

In contrast to the growth curves of the LICs, global energy consumption, population and GDP per Capita have seen modest growth throughout the 1980-2016 period. For example, global energy consumption has doubled since 1980, whereas energy consumption in LICs has quadrupled since 2000 alone. The difference with the G7 countries (Canada, France, Germany, Italy, Japan, United Kingdom and United States) is even starker. These countries were among the first to industrialize and show a more consolidated growth profile for the 1980-2016 period.

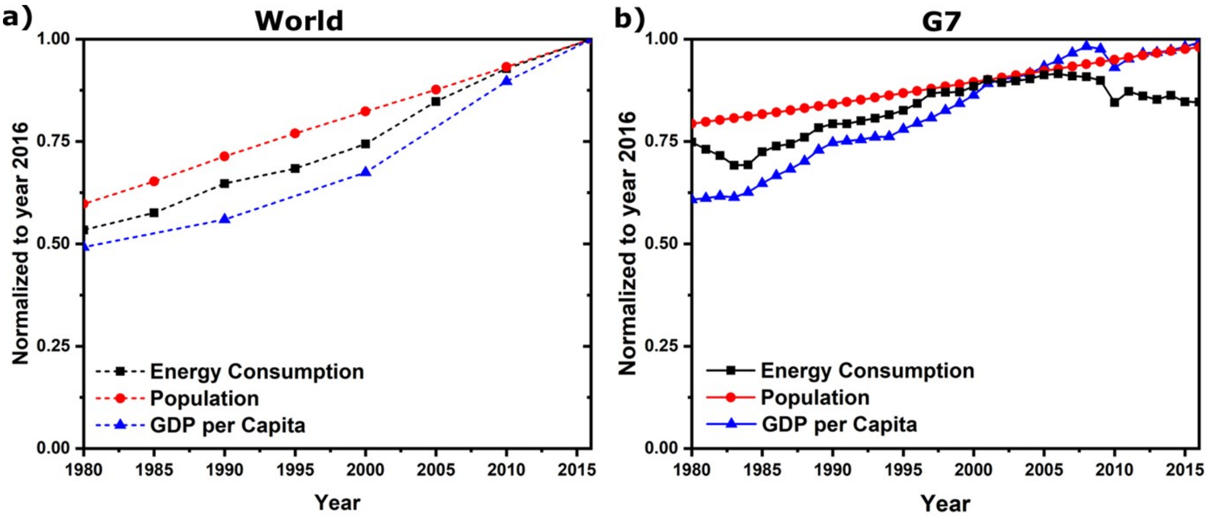

Table S2. Current and projected electricity consumption

2030 electricity consumption is based on a 15% annual growth in electricity use, which is the growth rate required to achieve the minimum threshold for modern society.[1] Of this electricity, 49% will be produced by renewables, of which solar will provide an estimated 30%.[2] We have further taken into account the practical PV power potential[3] to estimate the yearly manufacturing capacity required to meet this 2030 goal.

Country	2018 Electricity Consumption (GWh)[3]	2030 Electricity Consumption (GWh)	Required capacity for 2030 goal (GW)
Low Income Countries			
Afghanistan	6023	32223	0.18
Burkina Faso	1760	9416	0.06
Burundi	339	1814	0.01
Central African Republic	140	749	<0.01
Chad	213	1140	0.01
Democratic Republic of the Congo	8594	45978	0.30
Eritrea	408	2183	0.01
Ethiopia	8986	48075	0.28
Gambia	291	1557	0.01
Guinea	1983	10609	0.07
Guinea-Bissau	39	209	<0.01
Liberia	348	1862	0.01
Madagascar	2117	11326	0.07
Malawi	1515	8105	0.05
Mali	3040	16264	0.10
Mozambique	13390	71637	0.45
Niger	1586	8485	0.05
North Korea	12770	68320	0.49
Rwanda	764	4087	0.03
Sierra Leone	242	1295	0.01
Somalia	323	1728	0.01
South Sudan	529	2830	0.02
Sudan	11463	61327	0.35
Syria	12833	68657	0.39
Togo	1251	6693	0.05
Uganda	3534	18907	0.12
Yemen	2653	14194	0.08
Lower Middle Income Countries			
Algeria	62114	332310	1.88
Angola	10364	55447	0.33
Bangladesh	70594	377678	2.71
Belize	9417	50381	0.34
Benin	1188	6356	0.04
Bhutan	2386	12765	0.09
Bolivia	8320	44512	0.25
Cabo Verde	427	2284	0.01
Cambodia	8402	44951	0.30
Cameroon	6535	34962	0.23
Comoros	93	498	<0.01
Congo	1726	9234	0.07
Cote d’Ivoire	6690	35792	0.25
Djibouti	381	2038	0.01
Egypt	145005	775777	4.12
El Salvador	6218	33266	0.19
Eswatini	1537	8223	0.05
Ghana	11310	60509	0.42
Haiti	359	1921	0.01

Honduras	6683	35754	0.23
India	1265005	6767777	35.83
Indonesia	249042	1332375	9.84
Iran	254991	1364202	7.72
Kenya	9267	49578	0.31
Kiribati	28	150	<0.01
Kyrgyzstan	11740	62809	0.43
Laos	4059	21716	0.16
Lesotho	902	4826	0.03
Mauritania	882	4719	0.03
Mongolia	6895	36888	0.22
Morocco	28908	154658	0.86
Myanmar	18024	96428	0.65
Nepal	6562	35107	0.24
Nicaragua	3760	20116	0.14
Nigeria	25700	137495	0.89
Pakistan	101669	543929	3.22
Papua New Guinea	3662	19592	0.15
Philippines	86079	460523	3.26
Samoa	117	626	<0.01
Sao Tome and Principe	81	433	<0.01
Senegal	3842	20555	0.12
Solomon Islands	98	524	<0.01
Sri Lanka	13438	71893	0.48
Tajikistan	14213	76040	0.49
Timor-Leste	100	535	<0.01
Tunisia	15838	84733	0.50
Ukraine	127145	680226	5.74
United Republic of Tanzania	5813	31100	0.19
Uzbekistan	55285	295775	1.93
Vanuatu	60	321	<0.01
Vietnam	196829	1053035	8.26
Zambia	13097	70069	0.40
Zimbabwe	8401	44945	0.26

Table S3. Energy scenarios

To establish whether local production is technically feasible for PSCs, we studied the labour requirements for both the 18 and 41 TWh scenarios,[4] where either 20% or 100% of newly installed capacity comes from PSCs. In the 20% scenario the other 80% would come from utility scale silicon and PSCs would predominantly be used for off-grid applications. For the more ambitious 100% scenario, all new capacity would come from PSCs. Furthermore, we considered different sized production plants. Power supplied by 10 MW plants would be ~30% more expensive than for 100 MW plants, which in turn is ~20% more expensive than for 1000 MW plants.[5] The individual cost of a smaller plants is lower than for a large plant, which may make them easier to finance. The required newly installed capacity per year reaches a maximum around 2030 for all scenarios (see below), so we will focus on this year for further analysis. It is interesting to note that for both A and B scenarios, the newly installed capacity is almost identical for 2030, the main difference between the scenarios being the speed at which this production capacity is reached and for how long it is sustained. We also take into consideration the number of engineers needed to operate and maintain the production plants. The total number of required engineers cannot exceed the total number of trained engineers in the country, but also taking into consideration that there are currently more engineering graduates than jobs,[6] so job creation may be an important argument in deciding the desirable plant size. The estimated number of required engineers was extrapolated from data showing a 400 MW plant needs 350 engineers,[7] and assuming that for a 2x increase of manufacturing capacity, √2 more engineers are needed.

In the 20% scenarios, the option of building a 1000 MW plant can be discarded as it would massively overshoot demand. For the 100 MW case, three plants would be sufficient, allocated to three larger regional cities (~300,000 inhabitants) to maximise distribution. This would require an estimated combined total of 555 electrical, mechanical and chemical engineers on a total urban population of ~1 million. Twenty-five 10 MW plants could be distributed amongst the 20+ Ethiopian cities with >100,000 inhabitants. This would require 3x more engineers (~1,500), but more spread out over the country.

The 10 MW option can be discarded for the 100% scenarios, as this would require more than 100 plants and a large number of engineers (~10,000), for which the country's population centres are too thinly spread. Twelve 100 MW plants would require ~2,300 engineers. In this case a 1000 MW plant would go a long way towards providing all new capacity, requiring just 550 engineers.

The largest number of engineers required for these scenarios is ~10,000. Currently, ~27% of the 150,000 students that graduate from Universities in Ethiopia each year do so in engineering and technology,[8,9] this would yield 60,000 engineering graduates each year. Further considering that perhaps only students with a qualification higher than a bachelor degree would suffice, 5,000 (~13%)[10] engineering graduates will be looking for a job each year. Studies have further shown that as much as 35% of engineering graduates are currently unemployed, indicating that as many as 1,750 engineers per year would be available for employment in PSC plants.[11]

18 TWh scenario, 20% PSC									
				10 MW plants		**100 MW plants**		**1000 MW plants**	
Year	**Capacity (TWh)**	**New (TWh)**	**New (MW)**	**#**	**engineers**	**#**	**engineers**	**#**	**engineers**
2021	0.2	-	-	-	-	-	-	-	-
2022	0.2	0.05	30	3	180	1	185	1	550
2023	0.4	0.13	80	8	480	1	185	1	550
2024	0.5	0.13	80	8	480	1	185	1	550
2025	0.6	0.15	90	9	540	1	185	1	550
2026	0.8	0.19	110	11	660	2	370	1	550
2027	1.1	0.23	140	14	840	2	370	1	550
2028	1.3	0.29	170	17	1020	2	370	1	550
2029	1.7	0.35	200	20	1200	2	370	1	550
2030	2.1	0.42	250	25	1500	3	555	1	550

18 TWh scenario, 100% PSC									
				10 MW plants		**100 MW plants**		**1000 MW plants**	

Year	Capacity (TWh)	New (TWh)	New (MW)	#	engineers	#	engineers	#	engineers
2021	0.9	-	-	-	-	-	-	-	-
2022	1.1	0.2	140	14	840	2	370	1	550
2023	1.8	0.7	390	39	2340	4	740	1	550
2024	2.4	0.6	380	38	2280	4	740	1	550
2025	3.2	0.8	450	45	2700	5	925	1	550
2026	4.1	0.9	550	55	3300	6	1110	1	550
2027	5.3	1.2	680	68	4080	7	1295	1	550
2028	6.7	1.4	840	84	5040	9	1665	1	550
2029	8.5	1.7	1020	102	6120	11	2035	2	1100
2030	10.6	2.1	1230	123	7380	13	2405	2	1100

41 TWh scenario, 20% PSC									
				10 MW plants		100 MW plants		1000 MW plants	
Year	Capacity (TWh)	New (TWh)	New (MW)	#	engineers	#	engineers	#	engineers
2021	0.6	-	-	-	-	-	-	-	-
2022	0.8	0.2	120	12	720	2	370	1	550
2023	1.2	0.4	240	24	1440	3	555	1	550
2024	1.4	0.2	120	12	720	2	370	1	550
2025	1.8	0.4	240	24	1440	3	555	1	550
2026	2	0.2	120	12	720	2	370	1	550
2027	2.4	0.4	240	24	1440	3	555	1	550
2028	3	0.6	350	35	2100	4	740	1	550
2029	3.4	0.4	240	24	1440	3	555	1	550
2030	3.8	0.4	240	24	1440	3	555	1	550

41 TWh scenario, 100% PSC									
				10 MW plants		100 MW plants		1000 MW plants	
Year	Capacity (TWh)	New (TWh)	New (MW)	#	engineers	#	engineers	#	engineers
2021	3	-	-	-	-	-	-	-	-
2022	4	1	590	59	3540	6	1110	1	550
2023	6	2	1180	118	7080	12	2220	2	1100
2024	7	1	590	59	3540	6	1110	1	550
2025	9	2	1180	118	7080	12	2220	2	1100
2026	10	1	590	59	3540	6	1110	1	550
2027	12	2	1180	118	7080	12	2220	2	1100
2028	15	3	1760	176	10560	18	3330	2	1100
2029	17	2	1180	118	7080	12	2220	2	1100
2030	19	2	1180	118	7080	12	2220	2	1100

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