Appendix. Formula and Facts

Energy Sources

$P = \sigma T^4$	(1)
$E_{g,SJ}^{opt} \cong 2.55\, kT_s$	(2)

Solar cell (Single Junction) [M. Alam & M. Khan, https://arxiv.org/abs/1205.6652]

$qV_{oc,SJ} = E_G\left(1-\frac{T_D}{T_S}\right) - kT\, ln\left(\frac{\theta_D}{\theta_S}\right) - kT_D \ln\left(\frac{\gamma(T_D)}{\gamma(T_S)}\right)$	(3a)
$qV_{oc,SJ} = 0.95 \times E_g - 0.232$ (AM0, Cell at T=300K)	(3b)
$qV_{oc,SJ} = E_G\left(1-\frac{T_D}{T_S}\right) - kT\, ln\left(\frac{\theta_D}{\theta_S}\right) - kT_D \ln\left(\frac{\gamma(T_D)}{\gamma(T_S)}\right)$ $-k\, T_D\, ln\left(\frac{1}{\eta_{ext}}\right) -$ $kT_D\, ln\,(1-\Delta)$ (With non-radiative recombination and imperfect absorption)	(3c)
$qV_{mp,SJ} = E_G\left(1-\frac{T_D}{T_S}\right) - kT\, ln\left(\frac{\theta_D}{\theta_S}\right)$	(4a)
$qV_{mp,SJ} = 0.95 \times E_g - 0.31$ (AM0, Cell at T=300K)	(4b)
$J_{sc,SJ} = J_0\left(1-\beta E_g\right)$ (AM1.5, $J_0 = 83.75, \beta = 0.428$).	(5a)
$J_{sc}^{\max} \sim 70\, mA/cm^2$ (AM1.5); $J_{sc}^{\max} \sim 100\, mA/cm^2$ (AM0)	(5b)
$FF \sim (v_{oc}/v_{oc} + 4.7)$ (within 2% for $v_{oc} > 10$) with $v_{oc} \equiv V_{oc}/(nkT/q) = (v_{oc} - ln(v_{oc} + 0.72))/(V_{oc} + 1)$	(6a)
$FF = (E_g - 10 \times nkT/q)/(E_g - 5 \times nkT/q)$	(6b)
$E_{g,SJ}^{\rm opt} = (0.95 + 0.31 \times \beta)\, /\, (2 \times 0.95 \times \beta)$ Note. $\left(1-\frac{T_D}{T_S}\right) = 0.95$	(7a)
$\eta_{T.SJ} = -26.45E_g^2 + 70.77E_g - 14.42$ (AM1.5, empirical)	(7b)

Solar Cell (Tandem and bifacial) [M. Alam & M. Khan, https://engineering.purdue.edu/~alamgrp/papers-pdf/2016_Alam_Bifacial-Tandem-Limits.pdf]

$\eta_{T,DJ}(R=0) = 20 + 47E_{g,b} - 24E_{g,b}^2$ ($E_{g,b}..E_{g,t}$ bottom & top bandgaps)	(8a)
$E_{g(t)}^{opt}\,(N=2) = 0.33\,(2+R)E_{g(b)} + (1-R)$	(8b)
$J_{sc}(N) = \frac{2}{N+1} J_{sc}(\langle E_g \rangle)$ $\langle E_g \rangle$ ... Average of bandgaps of the N cells	(9)
$qV_{mp}/N = \langle E_g \rangle \left(1 - \frac{T_D}{\langle E_g \rangle}\frac{E_{g,max}}{T_s}\right) - k_B\, T_D\, ln \frac{\theta_D}{\theta_S}$ [N-junctions]	(10a)
$V_{mp,N} = N\left[V_{mp\,,SJ} - \left(\frac{N-1}{N+1}\right)\left(E_{g,SJ} - \frac{1}{\beta}\right)\frac{T_D}{T_S}\right]$ $\beta = 0.428$, $E_{g,SJ} = 1.33$ for AM1.5	(10b)
$P_{out} = J_{sc} \times V_{mp} = 2N/(N+1)\, J_{sc,SJ}\,[\,V_{mp,1} - \ldots\ldots]$	(11)
$E_{g,\max} = \frac{N-1}{\beta\, N} + \frac{\beta(1+R)E_0 - R}{\beta \times N}$	(12a)
$E_0^{opt} = \left[E_{g,SJ}^{opt} - \left\{\frac{(N-1)(1-R)}{2\beta\, N}\right\}\right] \frac{2N}{\{N(1+R) + (1-R)\}}$	(12b)

$E_0^{opt}\,(N \to \infty) \sim \left(E_{SJ} - \frac{1-R}{2\beta}\right)\left(\frac{2}{1-R}\right)$	(12c)

Module temperature dependence

$(T - T_a) = P/h = 1000(1 - \eta - R)/h$	(13)

Temperature dependence **for silicon**

$dV_{oc}/dT \sim\ 2.2\, mV/C$	(14a)
$dI_{sc}/dT \sim\ 0.0006 \times\ I_{sc}$	(14b)
$dFF/dT\ \sim 0.0015 \times\ FF$	(14c)
$dP_M/dT \sim\ -0.005 \times\ P_M$ (a-Si – 0.0021, CdTe – 0.0025, CIGS – 0.0033)	(14d)