Annexure A
MATLAB Code for Detailed Balance Study

Detailed balance code has been simulated in MATLAB at IIT Jodhpur. Following sections contain different part of MATLAB code utilized.

A.1 MATLAB Code to Generate Ultimate Efficiency in Ideal Case and Limited E_{diff} Case

```
% this section generate ultimate efficiency for both ideal and non-ideal
% case
clear all;clc;
ec = 1.60217662e-19;% electron charge
Eg_cutt = 4.428; % cutt off energy of photon in solar spectrum
Eg = 0.8:0.01:4; % range of bandgap to plot ultimate efficiency
Ediff=0.8; % difference between electrochemical potential of ETM and HTM
h = 6.62607004*10^(-34); %plank constant in mks unit
h_cut = h/(2*pi); % reduced plank constant
c = 2.99792458*10^8; % velocity of light
k = 1.38064852*10^(-23);% boltzman constant
Ta = 300;% ambient temperature in kelvin
Ts = 5778; % source temperature of sun in kelvin
Et = (k*Ta)/ec; % thermal energy in electron volt at ambient
Rs= 2.16*10^(-5);% solar light dilution factor for earth
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
w_cutt = (Eg_cutt.*ec)./h_cut; % frequency corresponding to cutt off energy of photon
w_min = (0.001.*ec)/h_cut; % minimum energy of photon to be considered
Pin_c=1000;% incident AM1.5 energy consideration for practical purpose
fun = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))); % integral function to
%calculate Generation rate
fun_u = @(x) ((h_cut.*x).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1)))); %
%integral to calculate incident energy
[m n]=size(wg);
%fun1 = @(x) ((h_cut^3).*(x.^2))./(((k*Ts)^3).*(exp((h_cut*x)./(k*Ts))-1));% function
%defined with change of parameter in integral
% fun1 = @(x) ((x.^2)./(exp(x)-1)); % function defined according to auxilary parameter
% calculation of generation rate
Gs=zeros(m,n);
for i=1:n
Gs (m,i)= Rs.*quadgk(fun,wg(m,i),w_cutt); % Generation rate for frequency
%corresponding to bandgap to maximum photon energy
end
figure
plot(Eg,Gs,'r');
hold on
xlabel('Eg(eV)')
ylabel('exciton pair generated')
```

```
title('Generation rate')
hold off
%calculation of ultimate efficiency
% ideal ultimate efficiency N0 and non-ideal ultimate efficiency N
Pin=0;% total incident energy initilization
Pin= Rs.*quadgk(fun_u,0,w_cutt); % total incident energy from zero photon energy to
%cutt off energy of photon
N0 = ((Eg.*Gs.*ec)./(Pin));% multiplied by charge to get in eV ultimate efficiency ideal
%ETM HTM
N = ((Ediff.*Gs.*ec)./(Pin));% multiplied by charge to get in eV ultimate efficiency
%practical ETM HTM
figure
plot(Eg,N0,'r+');
hold on
xlabel('Eg(eV)')
ylabel('efficiency/100')
title('ultimate efficiency')
axis([0.1 4 0 0.7])
hold off
figure
plot(Eg,N,'g+');
hold on
xlabel('Eg(eV)')
ylabel('efficiency/100')
title('Ultimate efficiency with E_diff')
axis([0.1 4 0 0.7])
hold off
```

A.2 MATLAB Code to Generate Staircase Internal Quantum Efficiency

```
clear all;clc;% this part demonstrate step function used to generate generate CM effect with
%staircase CM
 ec=1.6e-19;
h = 6.62607004*10^(-34); %plank constant in mks
h_cut = h/(2*pi); % reduced plank constant
Eg = 0.8; %Enegy level to plot VOC and m
Eg_cutt=4.28;
Eg_range=0:0.01:8*Eg;
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
w_cutt = (Eg_cutt.*ec)/h_cut; % frequency corresponding to cutt off energy
[m n]=size(Eg_range);
IQE=zeros(m,n);
for k=1:n
p=floor(Eg_range(m,k)./Eg);% number of unit step to be considered
 if p == 2
    fun_u = @(x) ((UnitStep(x-Eg))+ (UnitStep(x-2*Eg)));
```

```
elseif p == 3
  fun_u = @(x) ((UnitStep(x-Eg))+ (UnitStep(x-2*Eg))+(UnitStep(x-3.*Eg)));
elseif p == 4

  fun_u = @(x) ((UnitStep(x-Eg))+ (UnitStep(x-2*Eg))+(UnitStep(x-3.*Eg))+(UnitStep(x-4*Eg)));
elseif p == 5
  fun_u = @(x) ((UnitStep(x-Eg))+ (UnitStep(x-2*Eg))+(UnitStep(x-3.*Eg))+(UnitStep(x-4*Eg))+(UnitStep(x-5*Eg)));
elseif p == 6
  fun_u = @(x) ((UnitStep(x-Eg))+ (UnitStep(x-2*Eg))+(UnitStep(x-3.*Eg))+(UnitStep(x-4*Eg))+(UnitStep(x-5*Eg))+(UnitStep(x-6*Eg)));
elseif p == 7
  fun_u = @(x) ((UnitStep(x-Eg))+ (UnitStep(x-2*Eg))+(UnitStep(x-3.*Eg))+(UnitStep(x-4*Eg))+(UnitStep(x-5*Eg))+(UnitStep(x-6*Eg))++(UnitStep(x-7*Eg)));
else
  fun_u = @(x) ((UnitStep(x-Eg)))    ;
end
IQE(m,k)=fun_u(Eg_range(m,k)) ;
end
plot(Eg_range./Eg,IQE,'r+');
```

A.2.1 MATLAB Code for Unit Step Function

```
function Y = UnitStep(X)
Y = zeros(size(X));
Y(X > 0) = 1;
eng = symengine;
if strcmp(eng.kind,'maple')
  Y(X == 0) = nan;
else
  Y(X == 0) = 0;
end
```

A.3 MATLAB Code to Generate Finite Slope Internal Quantum Efficiency

```
clear all;clc;% this part demonstrate step function used to generate generate CM effect with %slope
ec=1.6e-19;
h = 6.62607004*10^(-34); %plank constant in mks
h_cut = h/(2*pi); % reduced plank constant
Eg = 1.2 ;%Enegy level to plot VOC and m
Eg_cutt=4.28;
Eg_range=0:0.01:4*Eg;
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
```

```
w_cutt = (Eg_cutt.*ec)/h_cut; % frequency corresponding to cutt off energy
 Eg_CM=2.85.*Eg;
 slope=1.14./Eg;
[m n]=size(Eg_range);
IQE=zeros(m,n);
for k=1:n
  fun_u = @(x) ((UnitStep(x-Eg))+ (slope.*(x-Eg_CM)).*(UnitStep(x-Eg_CM))); % integral to
calculate ultimate generation rate
  IQE(m,k)=fun_u(Eg_range(m,k)) ;
end
plot(Eg_range./Eg,IQE,'b+');
```

A.4 MATLAB Code to Generate Ultimate Efficiency with Ideal V_{oc} and Finite V_{oc} Approximation with Staircase Carrier Multiplication

```
%% This section generate ultimate efficiency with CM stair case
clear all; clc;
ec = 1.60217662e-19;% electron charge
Eg_cutt = 4.428; % cutt off energy of photon in solar spectrum
Eg = 0.8:0.01:4; % range of bandgap to plot ultimate efficiency
Ediff=0.8;
h = 6.62607004*10^(-34); %plank constant in mks
h_cut = h/(2*pi); % reduced plank constant
c = 2.99792458*10^8; % velocity of light
k = 1.38064852*10^(-23);% boltzman constant
Ta = 300;% ambient temperature in kelvin
Ts = 5778; % source temperature of sun in kelvin
Et = (k*Ta)/ec; % thermal energy in electron volt at ambient
Rs= 2.16*10^(-5);% solar light dilution factor for earth
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
w_cutt = (Eg_cutt.*ec)./h_cut; % frequency corresponding to cutt off energy
w_min = (0.1.*ec)/h_cut; % minimum energy of photon to be considered
Pin_c=1000;% incident AM1.5 energy consideration for practical purpose
fun_1 = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))); % integral function
%to calculate Generation rate
fun_u = @(x) ((h_cut.*x).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1)))); %
%integral to calculate incident solar energy
[m n]=size(wg);
% calculation of generation rate with stair case CM
```

```
Gs=zeros(m,n);% generation rate with No CM
Gs_CM=zeros(m,n);% generation rate with CM
for i=1:n
  %Eg_CM_=Eg_CM(m,i);
   p(m,i)=floor(4.28/Eg(m,i));% number of unit step to be considered


  if   p(m,i) == 2
        fun   =   @(x)    ((UnitStep(((x.*h_cut)./ec)-Eg(m,i))+    (UnitStep(((x.*h_cut)./ec)-
2*Eg(m,i)))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
      elseif   p(m,i) == 3
        fun   =   @(x)    ((UnitStep(((x.*h_cut)./ec)-Eg(m,i))+    (UnitStep(((x.*h_cut)./ec)-
2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
3.*Eg(m,i)))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
     elseif   p(m,i) == 4
        fun   =   @(x)    ((UnitStep(((x.*h_cut)./ec)-Eg(m,i))+    (UnitStep(((x.*h_cut)./ec)-
2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-3.*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
4*Eg(m,i)))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
      elseif   p(m,i) == 5
        fun   =   @(x)    ((UnitStep(((x.*h_cut)./ec)-Eg(m,i))+    (UnitStep(((x.*h_cut)./ec)-
2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-3.*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
4*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
5*Eg(m,i)))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
      elseif   p(m,i) == 6
        fun   =   @(x)    ((UnitStep(((x.*h_cut)./ec)-Eg(m,i))+    (UnitStep(((x.*h_cut)./ec)-
2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-3.*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
4*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-5*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
6*Eg(m,i)))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
     else
        fun = @(x) (((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))))    ;
  end
   Gs_CM(m,i)= Rs.*quadgk(fun,wg(m,i),w_cutt); % generation term
Gs (m,i)= Rs.*quadgk(fun_1,wg(m,i),w_cutt); % Generation rate
end
figure
plot(Eg,Gs_CM./Gs,'r');
hold on
xlabel('Eg(eV)')
ylabel('exciton pair generated')
title('Generation rate comparision with stair case CM')
hold off
%calculation of ultimate efficiency
```

```
% ultimate ideal efficiency N0 with stair case CM and N non-ideal ultimate efficiency
Pin=0;% total incident energy

Pin= Rs.*quadgk(fun_u,0,w_cutt); % total incident energy
%Pin_c=1000;
N0 = ((Eg.*Gs_CM.*ec)./(Pin));% multiplied by charge to get in eV ultimate efficiency ideal ETM HTM with CM stair case
N = ((Ediff.*Gs_CM.*ec)./(Pin));% multiplied by charge to get in eV ultimate efficiency practical ETM HTM with CM stair case
figure
plot(Eg,N0,'r+');
hold on
xlabel('Eg(eV)')
ylabel('efficiency/100')
title('ultimate efficiency with stair case CM')
axis([0.1 5 0 1])
hold off
figure
plot(Eg,N,'g+');
hold on
xlabel('Eg(eV)')
ylabel('efficiency/100')
title('Ultimate efficiency with E_diff with stair case CM')
axis([0.1 5 0 1])
hold off
```

A.5 MATLAB Code to Generate Ultimate Efficiency with Ideal V_{oc} and Finite V_{oc} Approximation with Finite Slope Carrier Multiplication

```
clear all; clc;
ec = 1.60217662e-19;% electron charge
Eg_cutt = 4.428; % cutt off energy of photon in solar spectrum
 Eg = 0.8:0.01:4; % range of bandgap to plot ultimate efficiency
 Eg_CM=2.85.*Eg;
 Ediff=0.8;
 slope=1.14./Eg;
h = 6.62607004*10^(-34); %plank constant in mks
h_cut = h/(2*pi); % reduced plank constant
c = 2.99792458*10^8; % velocity of light
```

```
k = 1.38064852*10^(-23);% boltzman constant
Ta = 300;% ambient temperature in kelvin
Ts = 5778; % source temperature of sun in kelvin
Et = (k*Ta)/ec; % thermal energy in electron volt
Rs= 2.16*10^(-5);% solar light dilution factor
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
w_cutt = (Eg_cutt.*ec)./h_cut; % frequency corresponding to cutt off energy
w_min = (0.1.*ec)/h_cut; % minimum energy of photon to be considered
fun_1 = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))); % integral function
%to calculate Generation rate
fun_u = @(x) ((h_cut.*x).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1)))); %
%integral to calculate incident energy
[m n]=size(wg);
Gs_CM=zeros(m,n);% generation rate with finite slopt CM
Gs=zeros(m,n); % generation rate with no CM
IQE_test=zeros(m,n);
for i=1:n
 Eg_CM_=Eg_CM(m,i);
 fun = @(x) (((UnitStep(((x.*h_cut)./ec)-Eg(m,i)))+(slope(m,i).*(((x.*h_cut)./ec)-
Eg_CM_)).*UnitStep(((x.*h_cut)./ec)-
Eg_CM_)).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
Gs_CM(m,i)= Rs.*quadgk(fun,wg(m,i),w_cutt); % generation term
Gs (m,i)= Rs.*quadgk(fun_1,wg(m,i),w_cutt); % Generation rate
end
figure
plot(Eg,Gs_CM./Gs,'r');
hold on
xlabel('Eg(eV)')
ylabel('exciton pair generated')
title('Generation rate with slope case CM')
hold off
%calculation of ultimate efficiency
% ultimate efficiency N0 and ultimate generation term G0
Pin=0;% total incident energy
Pin= Rs.*quadgk(fun_u,0,w_cutt); % total incident energy
Pin_c=1000;
N0 = ((Eg.*Gs_CM.*ec)./(Pin));% multiplied by charge to get in eV ultimate efficiency
%ideal ETM HTM with CM stair case
```

```
N = ((Ediff.*Gs_CM.*ec)./(Pin));% multiplied by charge to get in eV ultimate efficiency
%practical ETM HTM with CM stair case
figure
plot(Eg,N0,'r+');
hold on
xlabel('Eg(eV)')
ylabel('efficiency/100')
title('ultimate efficiency with slope case CM')
axis([0.1 5 0 1])
hold off
figure
plot(Eg,N,'g+');
hold on
xlabel('Eg(eV)')
ylabel('efficiency/100')
title('Ultimate efficiency with E_diff with slope case CM')
axis([0.1 5 0 1])
hold off
```

A.6 MATLAB Code to Generate Photovoltaic Performance Parameter with Detailed Balance Consideration with Ideal V_{oc} and Limited V_{oc} Case

```
clear all;clc;
ec = 1.60217662e-19;% electron charge
%Eg=1.5;
Eg_cutt = 4.428; % cutt off energy of photon
 %Eg = 0.27:0.01:Eg_cutt; %Enegy level to plot VOC and m
Eg = 0.8:0.01:4; %Enegy level to plot VOC and m
 Eg_ = Eg-0.26; % bandgap shift of QD
 Ediff=Eg; % for limited Voc case comment it
%Ediff=0.8; % for ideal Voc case comment it
h = 6.62607004*10^(-34); %plank constant in mks
h_cut = h/(2*pi); % reduced plank constant
c = 2.99792458*10^8; % velocity of light
k = 1.38064852*10^(-23);% boltzman constant
Ta = 300;% ambient temperature in kelvin
Ts = 5778; % source temperature of sun
Et = k*Ta./ec; % thermal energy in electron volt
Rs= 2.16*10^(-5);% solar light dilution factor
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
w_cutt = (Eg_cutt.*ec)/h_cut; % frequency corresponding to cutt off energy
w_min = (0.1.*ec)/h_cut; % minimum energy of photon to be considered
fun = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))); % integral function to
calculate Generation rate
```

```
fun_1 = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ta))-1))); % integral function to blackbody radiation at room temperature
fun_u = @(x) ((h_cut.*x).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1)))); % integral to calculate incident energy
[m n]=size(wg);
% generation rate in ideal QDSSC
 Gs=zeros(m,n);
for i=1:n
Gs (m,i)= Rs.*quadgk(fun,wg(m,i),w_cutt); % Generation rate with density of states
end
 Fe=zeros(m,n);%black dody radiation at room temperature
for i=1:n
Fe (m,i)= 2.*quadgk(fun_1,wg(m,i),w_cutt); % blackbody radiation at room temperature
end
F=Gs./(exp(Ediff/Et)-1); % when radiative recombination is considered
% open circuit potential and short circuit current
Voc=(Et).*(log((Gs+F)./(F+Fe)));
Isc = 0.0001.*ec.*(Gs-Fe);
figure
plot(Eg, Voc,'g+:')
hold on
title('Voc')
axis([0.8 4 0 4])
xlabel('Eg(eV)')
ylabel('Voc,m')
% finding fill factor
hold off
Vm=zeros(m,n);
Pm=zeros(m,n);
% Energy lost due to energy difference between ETM and HTM
Eloss=zeros(m,n);
for k=1:n
   fun2=@(V) (-V.*(0.0001.*ec.*(Gs(m,k)+F(m,k)-Fe(m,k).*exp(V./Et)-F(m,k).*exp(V./Et))));

        [Vm(m,k) Pm(m,k)]= fminbnd(fun2,0.25.*Voc(m,k),Voc(m,k));
   Eloss(m,k)=Rs.*quadgk(fun_u,wg(m,k),w_cutt);
end
X=Fe(m,k).*exp(-Vm./Et);
Im = 0.0001.*ec.*(Gs+F-Fe.*exp(Vm./Et)-F.*exp(Vm./Et));
M = (Vm.*Im)./(Isc.*Voc);
% Energy lost due to energy difference between ETM and HTM
figure
plot(Eg,M,'g+:');
hold on
 title('Fill factor')
 axis([0.4 2.4 0 1])
 hold off
 figure
Pin=0;% total incident energy
Pin= Rs.*quadgk(fun_u,0,w_cutt); % total incident energy
Ps=Pin;% input power
 N1= (Isc.*Voc.*M)./(0.0001.*Ps);
  plot(Eg,N1,'g+:');
  hold on
```

```
 xlabel('Eg(eV)')
ylabel('efficiency/100')
title('detailed balance efficiency')
axis([0.1 5 0 0.4])
hold off
```

A.7 MATLAB Code to Generate Photovoltaic Performance Parameter with Detailed Balance Consideration with Ideal V_{oc} and Limited V_{oc} Case with Carrier Multiplication

```
clear all;clc;
ec = 1.60217662e-19;% electron charge
%Eg=1.5;
Eg_cutt = 4.428; % cutt off energy of photon
 %Eg = 0.27:0.01:Eg_cutt; %Enegy level to plot VOC and m
Eg = 0.8:0.01:4; %Enegy level to plot VOC and m
 Eg_ = Eg-0.26; % bandgap shift of QD
 Eg_CM=2.*Eg;
Ediff=0.8;
h = 6.62607004*10^(-34); %plank constant in mks
h_cut = h/(2*pi); % reduced plank constant
c = 2.99792458*10^8; % velocity of light
k = 1.38064852*10^(-23);% boltzman constant
Ta = 300;% ambient temperature in kelvin
Ts = 5778; % source temperature of sun
Et = k*Ta./ec; % thermal energy in electron volt
Rs= 2.16*10^(-5);% solar light dilution factor
wg = (Eg.*ec)./h_cut; % frequency corresponding to bandgap
w_cutt = (Eg_cutt.*ec)/h_cut; % frequency corresponding to cutt off energy
w_min = (0.01.*ec)/h_cut; % minimum energy of photon to be considered
fun = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))); % integral function to
calculate Generation rate
fun_1 = @(x) ((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ta))-1))); % integral function to
blackbody radiation at room temperature
fun_b = @(x) ((h_cut.*x).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1)))); % integral to
calculate incident energy
[m n]=size(wg);
 Gs=zeros(m,n);
for i=1:n
Gs (m,i)= Rs.*quadgk(fun,wg(m,i),w_cutt); % Generation rate with density of states
end
Gs_CM=zeros(m,n);% generation term with CM
p=zeros(m,n);
for i=1:n
   Eg_CM_=Eg_CM(m,i);
   p(m,i)=floor(4.28/Eg(m,i));% number of unit step to be considered
  if   p(m,i) == 2
         fun_u = @(x) ((1+ (UnitStep(((x.*h_cut)./ec)-
2*Eg(m,i)))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
       elseif   p(m,i) == 3
```

```
        fun_u   =   @(x)   ((1+   (UnitStep(((x.*h_cut)./ec)-2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
3.*Eg(m,i))))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
      elseif   p(m,i) == 4

        fun_u   =   @(x)   ((1+   (UnitStep(((x.*h_cut)./ec)-2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
3.*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
4*Eg(m,i))))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
       elseif   p(m,i) == 5

        fun_u   =   @(x)   ((1+   (UnitStep(((x.*h_cut)./ec)-2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
3.*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-4*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
5*Eg(m,i))))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
       elseif   p(m,i) == 6

        fun_u   =   @(x)   ((1+   (UnitStep(((x.*h_cut)./ec)-2*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
3.*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-4*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
5*Eg(m,i)))+(UnitStep(((x.*h_cut)./ec)-
6*Eg(m,i))))).*((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))));
      else
         fun_u = @(x) (((x.^2./(c^2*4*pi^2)).*(1./(exp((h_cut.*x)./(k*Ts))-1))))    ;
  end
   Gs_CM(m,i)= Rs.*quadgk(fun_u,wg(m,i),w_cutt); % generation term
end
figure
plot(Eg,Gs_CM./Gs,'g+');
hold on
title('Ratio of generation rate with CM')
xlabel('Eg(eV)')
ylabel('ratio of ganeration term')
 Fe=zeros(m,n);%black dody radiation at room temperature
for i=1:n
Fe (m,i)= 2.*quadgk(fun_1,wg(m,i),w_cutt); % blackbody radiation at room temperature
end
Voc=(Et).*(log((Gs_CM+F)./(F+Fe)));
Isc = 0.0001.*ec.*(Gs_CM-Fe);
figure
plot(Eg, Voc,'g+:')
hold on
title('Voc with CM')
axis([0.8 2 0 1])
xlabel('Eg(eV)')
ylabel('Voc/Eg,m')
hold off
Vm=zeros(m,n);
Pm=zeros(m,n);
for k=1:n

   fun2=@(V)  (-V.*(0.0001.*ec.*(Gs_CM(m,k)+F(m,k)-Fe(m,k).*exp(V./Et)-F(m,k).*exp(V./Et))));

        [Vm(m,k) Pm(m,k)]= fminbnd(fun2,0.25.*Voc(m,k),Voc(m,k));


end
X=Fe(m,k).*exp(-Vm./Et);
```

```
Im = 0.0001.*ec.*(Gs_CM+F-Fe.*exp(Vm./Et)-F.*exp(Vm./Et));
M = (Vm.*Im)./(Isc.*Voc);
figure
plot(Eg,M,'g+:');
hold on
 title('Fill factor with CM')
 axis([0.4 2.4 0 1])
 hold off
 figure
Pin=0;% total incident energy
Pin= Rs.*quadgk(fun_b,0,w_cutt); % total incident energy
Ps=Pin;% input power
 N1= (Isc.*Voc.*M)./(0.0001.*Ps);
  plot(Eg,N1,'g+:');
  hold on
 xlabel('Eg(eV)')
ylabel('efficiency/100')
title('detailed balance efficiency with CM')
axis([0.1 5 0 0.5])
hold off
```

...