Externalities of clean energy technologies: A study

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Abstract. The sustainability of any system can be explained Carnot principle. The manmade devices / systems are consuming natural resources mass, R, combination of air, water and fuel. After proper operations, the devices / systems rejected waste mass, W into the eco-system. Applications of Carnot principle indicated that ecological efficiency (\(\eta_{\text{Eco}}\)) in this case is \(\left[1 - \frac{W}{R}\right] \times 100\%\) and if W is not digested or recycled through natural system, then \(\eta_{\text{Eco}}\) has a tendency towards zero and will trigger back to the ecological system and raised the question for sustainability of eco-systems. One of the consequences of W on the eco-system is the smog formation at the beginning of winter morning over the urban surroundings. The smog causes major problems in respiration, visibility and ultimately affects mobility. The possible reason behind smog formation is the condensation of gas and particulates at dawn time emitted from burning of bio-mass and fossil fuels. The condensation gets delayed due to the urban heat islanding (UHI) effect generated by the built-in-systems. The condensation diffuses with raise in ambience temperature from sun shine. This paper delves an analysis on the cause and effect of UHI and impact of clean mobility in diffusing the smog effect.

1. Introduction
Sustainable development is an often-used term but one that requires the user to associate it with a defined problem. It was reported by the United Nation’s report that in 1950 about 30% of the world’s population lived in urban areas and 70% lives in rural areas but by the year 2030 the phenomenon will reverse with about 70% of the world’s population will live in cities. The rapid urbanization is quickly transitioning communities from the natural rural vegetation to man-made urban engineered infrastructure. The anthropogenic induced change has manifested itself in micro scale and meso scale increases in temperatures in comparison to adjacent rural regions which are known as the urban heat island (UHI) effect and results in potentially adverse consequences for local and global communities. In conjunction with the released of greenhouse gases (GHGs) the UHI effect enhanced the negative impact to the climate change. Thus, efforts have to be given to explore the sources of UHI apart from its origination from anthropogenic sources. Building density is one of the possible causes in developing UHI effect. The question arises whether photovoltaic (PV) in building have any role in developing additional UHI effect or not. The main aim of the present paper is to explore the impact of PV on the built-in-systems on UHI. Solar energy is possibly converted in two useful forms one is by thermal route and other by PV route. The advances in the technology and the concerns about global warming are encouraging both utilities and customers to expand the use of grid-connected PV systems. Thus, PV power is now a reality and it has entered into the power budget in many countries in general and sun rich countries in particular. The PV power systems are installed on the following sites and it is necessary to examine their impact on the specific site such that precautionary measurement can be taken. The sites are; i. open land, ii. built-in-
systems and iii. water surface. Apart from the installation in remote rural areas in standalone mode the PV systems are now entered into the city region, where PV is installed as the building component marked as Building Integrated PV (BiPV) systems or these are coupled over the rooftop as the roof mounted PV (RmPV) or roof integrated PV (RiPV) systems. However, whatever may be the integration technique one requires to explore the impact of PV systems as the cause for enhancing the negative impact on climate change.

It was reported that the growth rates PV installed capacities have been high for the last decades and may remains in the decades to come [1-3]. A major driver for this increasing share of PV in the global power supply is the ecological limit of our planet, the Earth [4]. The GHG emissions have been identified as the major threat for a collapse of the globalized human civilization in this century [5, 6]. The absolute amount of annually emitted anthropogenic GHGs has steadily increased also during the previous decade. If the mitigation efforts are delayed, achieving low longer term emissions becomes more difficult, and mitigation options are narrowed. For keeping the climate change impacts more or less under control, the 2°C target has now been commonly accepted, i.e. temperature increase due to human activities needs to be limited according to this fundamental threshold [5].

As a consequence, GHGs emissions need to be radically reduced, in particular those of the power generation system. A zero GHG emitting economy needs to be realized, the sooner the better [7]. Renewable energies exhibit very low specific GHG emissions, the major fraction thereof is still caused by the conventional energy system and will be automatically reduced alongside the progress of the global energy transformation. For the special case of PV two factors are decisive. Firstly, the cumulative energy demand for PV systems is steadily decreasing by about 14% per each doubling of historic cumulated capacity according to the energy learning curve [8]. Secondly, by using an increasing fraction of low carbon energy sources in the production of PV systems, one can reach a considerable progress in reducing the specific GHG emissions of PV systems [9]. Alongside the renewable energy technologies PV had been commonly considered as the most expensive power generation option [10]. The latest dramatic decrease in PV prices has changed this and PV is now competitive among other renewable and conventional power systems [11]. The high competitive edge of solar PV for end users had previously been expected and is now confirmed by the market.

Initially the PV systems were first used in the stand-alone mode in providing electricity to the rural remote areas where no other sources of energy were present. As the PV power systems require large surface area they are installing on the building surface, rooftop, open ground space and even over the surface of the water bodies. Installations of PV module in each of the above places have specific environmental impact. Thus, while planning for installing PV power systems it is essential to evaluate the impact of PV power systems on land, water and building. In the present paper efforts have been given to assess the impact of PV systems on various places and to explore the externalities of PV systems in enhancing the negative impact on climate change.

2. Assessment of externalities

Earth, the planet where we live has finite material resources and biological capacity and the manmade systems are consuming this finite resource and emitting waste that is loading the natural ecosystems and the electric power projects are of no exception. These are in turn degrading the biological capacity of the natural ecosystems and raising the question on sustainability of the power projects. Thus, to bring sustainability, the manmade systems must operate within the carrying capacity of the earth and its ecology. If operations of the manmade systems exceed the limit of carrying capacity of the earth’s ecosystems, overtime it will be stressed, then go into decline, and finally reach to the collapse stage. To address this issue one needs to evaluate the level of integration between the power generating systems and with the earth’s ecosystems for bringing sustainability.

In general the fossil fuel based power generating systems are the major polluters to the ecosystems and efforts were given to the use of renewable energy (RE) resources to have the possibilities in overcoming constraints. In addition, use of RE resources can bring security to the energy flow pattern and at the same time it reduces the load on the ecosystems. Thus, more effort is required for accessibility to the RE
resources for bringing energy security, that in turn emerged in the sustainable development (SD) process. Moreover, proper use of RE resources offers the opportunities to improve accessibilities to the modern energy services to the underdeveloped and developing communities, which is crucial for the achievement towards the sustainable developmental goals. Sustainable development addresses the concerns about the relationships between human society and the nature. This can be correlated from the Carnot principle of thermodynamics and is presented in fig. 1 below.

Figure 1: Carnot Cycle in the nature

It is well known that in order to run any man made systems the basic inputs are air, water and fuel. All of these inputs are resources ‘R’ is consumed from the ecological systems. After the operation of the man made the system the waste ‘W’ is to the ecological systems. Thus, use of the net input mass is ‘(R-W)’ which is converted into useful form of work. The waste ‘W’ is required to digest by the ecological system. If this waste ‘W’ is not digested properly it will load the ecological systems and will have negative impact to the natural phenomenon, even sometimes it triggers back to the ecological systems. Applications of Carnot principle on this phenomenon indicated about the ecological efficiency, \( \eta_{eco} = \frac{(W-R)}{R} \times 100\% = [1 - \frac{W}{R}] \times 100\% \). The above phenomenon can be presented in fig. 2 with ecological efficiency \( \eta_{eco} = [1 - \frac{W}{R}] \times 100\% \), ---- (3.1) and term \( [1 - \frac{W}{R}] \) represent as the ecological Carnot Factor (CF). For operation of PV cells the input natural resources is solar radiation and the wastes are reflected and transmitted radiation from the PV modules. Thus, radiation balance over the PV module surface will indicate about the ecological efficiency of PV power systems.

The radiation balance over the PV cell is represented in figs. 3 & 4. The input resources, R for PV cells is incoming solar radiation or insolation (kWh/m²/d) and the non converted radiation is W (either transmitted or reflected) is returning back to the environment. Thus, (R-W) (kWh/m²/d) is the effective radiation absorbed by the solar PV modules and this is converted into useful form of energy like heat and electricity. By substituting the values of R and W in the above equation one can find out the ecological efficiency of PV module. Experimentally it has been observed that a 230Wp, 24 V PV module generate 1.15 kWh of energy per day at an insolation level of 4.5 -5.5 kWh/m²/day. The insolation level on a 230
Wp PV module having the dimension of 1.7 x 1 m² is about 8.5 kWh. Thus, the Carnot efficiency of the 230 Wp module is 
\[
1 - \frac{7.35}{8.5} \times 100\% = 86.4\%.
\]

Thus, rest radiation 13.6% is converted into electricity and some of its part is converted into heat. The waste 86.4% of energy is the combination of reflected, transmitted and absorbed heat energy. The waste heat is accumulating into the surroundings of the atmosphere and has the tendency to develop the heat islanding (HI) effect. This is typically integrating the problem in urban areas where high rise structure is the responsible for developing heat islanding effect and is known as urban heat islanding (UHI) effect. The HI effect has a prominent role in smog formation particularly in urban areas. The vehicle density in urban areas are comparatively is higher than the rural areas. The input fuel for the vehicles is of organic compounds (H-C) and after burning they emit oxides of hydrogen, nitrogen, carbon and black carbon / shoot. Combination of these reacts in air initiated by UV spectrum of sunlight, resulting in formation Ozone, aldehyde and Perox acetyl nitrides (PANs). These ingredients are colorless and under the influence of temperature, dust and humidity they form smog presented in figure 3 below.
The infrared emission from multi-storied built-in-systems in conjunction with heat pumping from air-conditioning units enhances the temperature of the surroundings the built-in-systems. The BiPV systems play a positive role in reducing the UHI effect.

3. Energy Balance of PV module surface.

For trapping the maximum solar radiation the solar PV modules are placed at an inclination of latitude ±5° at the roof / ground / water surface. In order to calculate the energy balance over the PV module surface let us assume that to be horizontal one as presented in fig. 4. However, when calculating the radiative heat exchange with the other elements like exchanges between the surface of roof / ground, the solar module and the sky above are considered to be purely vertical as presented in fig. 4. The module placed at specific inclination to calculate their radiance for power production. The energy balance equation of the solar PV module surface can be written as:

\[
\text{SkySW} + \text{AtmLW} + \text{SrfLW} = \text{PVSW} + \text{PVLW} + \text{PVH} + \text{PV}E
\]  

The terms on the left hand side is incoming solar radiation over the PV module surface. The term SkySW↓ is the incoming short wave radiation, both direct and diffuse, from the sun. The term AtmLW↓ is the incoming long wave radiation (diffuse) from the atmosphere. The term SrfLW↑ is the long wave radiation coming up from the surface of roof / ground and being intercepted by the PV module. Its value is computed from the roof emissivity and surface temperature and the long wave radiation received by the surface of roof / ground. The value of the term SrfLW↑ can be computed as:

\[
\text{SrfLW} = \varepsilon_{\text{Srf}} \sigma T^4 + (1 - \varepsilon_{\text{Srf}}) \text{SrfLW}\downarrow
\]

The terms on the right hand side of eqn.1 are outgoing energy from the PV module. The term PVSW↑ is the short wave radiation reflected by the PV module. It is classically parameterized using the albedo of the PV module (αPV). Thus, PVSW↑ = αPV PVSW↓ and assuming that it is going back to the sky. Here we have neglected the effect of the inclination of the PV module on the direction of the reflected light. The researchers [12] indicated that the value of the albedo of the PV module (αPV) ranges from 0.06 to 0.1. The albedo of PV module is measured by integrating the hemispheric directional reflectance measured with a goniometer.

\[
\text{PVH} + \text{PV}E
\]

The PVLW↑ is the long-wave radiation emitted as well as reflected by the PV module to the sky. It depends on the surface temperature of the PV module (\(T_{\text{PV}}\)), which is estimated as;
TPV = T_{Air} + kT_{Irr} \tag{3}

where T_{Air} is the air temperature, \( T_{Irr} \) is the irradiance received by the PV module and \( kT \) is a constant coefficient equal to 0.05K / (W/m²). In this formulation, then nocturnal dependency of the module surface temperature on the sky temperature proposed by [13] is not used. The emissivity of the PV module (\( \epsilon_{PV} \)) is also taking a major role for the upward long wave radiation; \( ^{PV}LW^{↑} \) can be presented as:

\[
^{PV}LW^{↑} = \epsilon_{PV}\sigma T_{4} + (1 - \epsilon_{PV}) \, SkyLW_{↓} \tag{4}
\]

The PVLW\(_{↓}\) is the long-wave radiation emitted by the PV module towards the downwards direction either on the roof or ground surface. It is computed under the hypothesis that the temperature of the downward face of the PV module is always approximately equal to the air temperature. However, even if the temperature of the downwards face of the PV module is underestimated due to the warming of the PV module and the heat diffusion inside it, this temperature will still be higher than the sky temperature. So, from the point of view of the roof / ground below the PV module, the incoming radiation will be higher. This captures at least the first order of an effect of the PV module on the roof / ground. Given the uncertainties we also neglect the dependency in emissivity for this face of the PV module and this gives as:

\[
^{PV}LW_{↓} = \sigma T_{4}^{\text{Air}} \tag{5}
\]

The term \( ^{PV}E \) is the amount of electricity produced by the PV module and it depends on the nature and characteristics of the PV module, the irradiance level on the module, its inclination and the air temperature. The term \( ^{PV}H \) is the sensible heat flux from the solar module to the atmosphere. We assume that the PV module is thin enough, has no significant thermal mass and hence is in quasi-equilibrium. This means that the sensible heat flux, the only term that is not parameterized, is taken to be equal to the residue of the solar panel energy budget. Besides the fact that it is difficult to have a parameterization of this term, this ensures conservation of energy balance.

3.1. Modification of energy balance on the roof / ground / water surface.

For the energy balance on the roof or the ground surface, the most important key parameter will, of course, be the proportion of roof / ground area occupied by the solar modules. As mentioned above, that here only consideration comes from the projection of the module on to the horizontal surface. The fraction of the roof covered by solar PV modules is considered as \( f_{\text{Mod}} \). The following simplifying assumptions are made in this respect:

- Average temperature is still calculated for the roof / ground / water, without distinguishing between the parts of the roof / ground / water under or beside the PV module. This is reasonable, in particular for flat roofs with inclined panels, because the shadows cast by the panels can modify the radiative contribution to the roof beside as well as below the modules.
- The coefficient for heat transfer from the roof / ground / water surface to the sensible heat flux is not changed.
- The effect of humidity level during the studies was neglected. The water interception reservoir treating rain water and evaporation concerns the whole surface of the roof / ground / water. These assumptions allow us to change only the radiative contributions to the energy balance of the roof / ground. Assuming that the surface area of the shadows is equal to the surface area of the solar panels, the incoming solar radiation on the roof is:

\[
^{\text{Srf}}SW_{↓} = (1 - f_{\text{Mod}}) \, ^{\text{Sky}}SW_{↓} \tag{6}
\]

The incoming long wave radiation on the roof / ground surface is modified by the long wave radiation emitted downwards by the solarPV modules and this can be represented as;
\[ S_{\text{rf}} \text{LW}_i = (1 - f_{\text{Mod}}) S_{\text{Sky}} \text{LW}_i + f_{\text{Mod}} S_{\text{PV}} \text{LW}_i \] (7)

The above methods were conceived and implemented in order to quantify the interactions between the PV modules and the roof / ground surface.

4. Radiation characteristics and energy conversion of PV modules.

In order to assess the energy balance of the PV power systems implemented in the building of the urban areas it is necessary to have the knowledge of the urban albedo due to the building structures. It was reported [12] that the albedo in the urban road, roofs, facades, glazing is varying in between 0.4 and 2.5\( \mu \text{m} \) and the infrared thermal emissivity is in between 5 - 12\( \mu \text{m} \). The researchers reported about the specific measurements in different cities using the goniometer. The researchers further reported that the measurement process is fully automated in the ranges of 0.4–2.5\( \mu \text{m} \) spectral domain. The albedo of the solar modules was then computed by integrating the radiance in all directions over the entire spectral range.

In the urban areas it has been observed that both solar thermal (ST) and photovoltaic systems were implemented in the building. The ST modules were used to supply hot water and the PV systems were used to generate electricity. As the present work is confined into electricity production efforts have been given to estimate the role of the PV modules in producing electricity. The electrical energy produced from a PV module is usually parameterized as;

\[ P_{\text{VE}} = \frac{\text{Module rating in Wp}}{1000} \times \text{Irr} \times \text{T}_{\text{Cof}} \] (8)

The \( P_{\text{VE}} \) is the electricity produced in kWh by the PV systems and the module rating Wp is the rated module used in the system. The T_{\text{Cof}} the temperature co-efficient of the PV module as the PV modules are rated at standard test condition (STC) where the temperature and radiation level are maintained at 25 \( ^{\circ} \text{C} \) and 1000 W/m\(^2 \). The T_{\text{Cof}} is a function of temperature level and it is very sensitive in case of Si PV module but comparatively less sensitive in case of thin film modules like CdTe and amorphous Si.

The insolation received by the PV module \( S_{\text{SkySW}_i} \) is calculated by estimating on the relative position of the sun and PV module or by applying a correction factor (\( C_F \)) as follows;

\[ \text{Irr} = C_F \times S_{\text{SkySW}_i} \] (9)

The correction factor \( C_F \) is typically 1.09 – 1.11 on annual average for a south facing modules in Indian cities. Assuming that the PV modules are placed with an approximately 23 ± 5° tilt and oriented between south-east and south-west direction, the value of \( C_F \) is about 1.09 [14]. The correction factor due to raise in module temperature can be written as;

\[ \text{T}_{\text{Cof}} = [1 - 0.005 \times (T_{\text{Mod}} - 298)] \] (10)

Finally, incorporating all the perturbing factors estimation on electricity production of the PV module is parameterized as;

\[ P_{\text{VE}} = \frac{\text{Module rating in Wp}}{1000} \times C_F \times S_{\text{SkySW}_i} \times [1 - 0.005 \times (T_{\text{Mod}} - 298)] \] (11)

5. Results of studies on the Externalities of PV Modules.

The impact of the solar PV modules on the environment of building / ground / water in Indian condition was studies using the formulation developed in the previous sections. The studies indicated that the impact of PV modules on air temperature is relatively small but the module surface temperature has impact on the mounting condition. Field studies were conducted at the same place where the PV modules
are installed on i. Ground mounted (GmPV), ii. Roof mounted (RmPV) iii. Roof integrated (RiPV) and water surface mounted (WsPV) to observe the variation of local temperature and their influence in heat islanding (HI) effect. The experimental results were round the clock in a particular month and are presented in the fig. 5 below.

Figure 5: Variation of module surface temperature over module mounting systems

Measurements were conducted round the year and data for a particular month was presented to observe the trend of variation.

Studies further showed that the module surface temperature in all the system and the local air temperature are equal up to 7.00 am in the morning. As the sun shines sharply the module temperature increases rapidly than that of air temperature and it reach at higher value around 12.00 noon in all the cases. The air temperature at the site remains steady up to 5.00 pm then it starts falling and stabilizes at 10.00 pm in the night as indicated in fig. 5. However, the module starts cooling after 4.00 pm and stabilizes after 11.00 pm. Similarly the power generated from the module falls also with raise in temperature. Among the four cases it has been observed that the temperature profile of the ground mounted and roof integrated PV system follow the same trend however, the roof mounted showed the highest module surface temperature and the water mounted showed the lowest surface temperature. These observations are about the atmospheric heat delivery by the three types of mounting combinations. The addition of the heat generated by the PV module enhances the heat islanding effect. This will be more prominent in urban areas rather than in rural areas as the density of building in urban areas is more than that in rural areas and there are meagre convective windows for reducing the locally generated heat in anthropogenic activities.

The temperature effect has also bad impact on the power generation. In the urban areas PV modules were mounted either by RmPV condition or RiPV condition. As the module surface temperature of the RmPV system is higher than that of RiPV system consequently the open circuit voltage in RiPV system is higher than that of RmPV system. A typical study in this respect is presented in fig. 6 presented below.

It has been observed from the fig.6 that RiPV modules of offering more power than that of the modules mounted in RmPV structures. The possible reason behind this is that RiPV modules mounted over the insulated surface and the roof is under the shadow. On the other hand the RmPV systems the modules are placed over the open roof systems without any insulation and mounting structures is providing partial shadow over the roof resulting in heat transmission to the entire roof surface and reflected back over the
back surface of the module. Moreover, the convective heat flow added with the reflected long wave radiation in the case.

![Figure 6: Variation of open circuit voltage with module surface temperature](image)

6. Discussion and concluding remarks
As mentioned in the earlier section that PV modules over the building either in RmPV mode or in RiPV mode absorb solar radiation falling on the building surface and able to convert them in useful form of energy.

Table 1. Externalities of PV power systems.

| Externalities   | Ground Surface | Roof Surface | Water Surface |
|-----------------|----------------|--------------|---------------|
|                 | Mounted        | Integrated   |               |
| Thermal         |                |              |               |
| i. Conduction   | Low            | High         | Very low      | Very low      |
| ii. Convection  | Reasonable     | Reasonable   | Low           | Low           |
| iii. Radiation  | Low            | High         | High          | High          |
| Electrical      |                |              |               |
| i. Generation   | Fairly good    | Moderate     | Fairly good   | Very good     |
| ii. Conservation| Not applicable | Low          | Good          | Not applicable|

The converted energy is usable in buildings, either directly in the form of heat through solar thermal application or as electricity to meet the building demand. However, while integrating this it has the possibility in modifying the energy balance of the urban surface in contact with the atmosphere. So this effect may have possibly influence the urban micro-climate. The additional RmPV or RiPV structure also change the radiation received by the roof and the building canopy and hence modified the building energy balance. This parameterization simulates their production in a relatively precise way, as it depends on the evolving meteorological conditions, rather than simply using a rule of thumb annual production as is often done in building design. The PV modules also influence the building energy systems and allow the heat fluxes both radiative and convective to the atmosphere. Thus, this chapter has provided a possible
method to evaluate the influence of PV module implementation strategies on the assessment of urban heat islanding effect. Thus, to deploy the solar PV modules in urban sectors of sun rich countries require attention to mitigate the additional UHI developed due to the application of PV power the urban canopy. This effect has the direct impact on the hot countries as they reduce the domestic cooling load developed by putting the air conditioning (AC) systems. On the other hand, this effect has direct impact on the power consumption pattern of the AC systems. Moreover, the reduction in UHI effect may have a direct impact on reduction of smog formation. It can be further that introduction of electrical mobility and the BiPV systems may have direct impact in diffusing the smog formation.

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