Mathematical Modelling of Heat Transfer Physics in Sea and Air Deployed PV Systems

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Abstract: The sea provides a vast area which can be harnessed as a platform on which to install energy-harvesting technology. This is especially relevant for a small country such as Malta with a very small landmass when compared to the vast area of the surrounding sea.

Photovoltaics (PV) also become more inefficient as they heat up. When PV panels are deployed in the sun, the temperature tends to increase and the PVs become more inefficient. This is especially so in the summer months when the ambient temperatures are at their highest levels. Sea temperature in summer is lower than the air temperature. Hence deploying the PVs in the sea can contribute to keep the panel temperature lower, thereby improving its efficiency. The subject of this paper was the study of the cooling effect of the sea on the PV material. Finite Element Analysis (FEA) of PV panels deployed on land and in sea (both in submerged and surface modes) was undertaken. FEA software ANSYS was used to conduct the analysis. The FEA conducted took into consideration the physics of heat transfer through the radiation, conduction, and convection mechanisms. The conclusions of the analysis conducted demonstrated that a PV panel submerged 10 cm below the sea surface achieved the lowest temperatures of the three cases studied.

Keywords: Photovoltaics, efficiency, sea, ANSYS, heat transfer.

To study the physics of heat transfer, a Finite Element Model (FEM) was designed and simulated in three configurations. These configurations were set up to establish the temperatures which one could expect the solar panel to reach when installed in the three configurations considered for this study, namely:

Case A  – Sea deployment – Floating on the surface.
Case B  – Sea deployment – Submerged 10 cm below the sea surface.
Case C  – Land deployment.

The Finite Element Model (FEM) was set up using environmental conditions which one expects in the Maltese islands during August when the ambient temperature is at its hottest and therefore the panels would be at their most inefficient point. To maximize the inefficiency, it was therefore decided to design and set up the models incorporating the typical solar loading expected on a normal cloudless day in August. The methodology utilized in this study was to submit the model to incident solar radiation with the FEM being then set up to model the thermal heat transfer away from the model into the surrounding environment. Copper indium gallium diselenide (CIGS) panels were used for this FEM. These types of panels are flexible and suitable for sea deployment.
Theoretical Basis

In an intrinsic semiconductor, as electrons move to the conductive band they form electron-hole pairs. In this sense, an increase in temperature increases the saturation current $I_s$ due to a reduction in bandgap. Such a bandgap reduction allows photons which are low in energy to still manage to reach the conductance band thereby forming an electron-hole pair. This leads to the $I_{sc}$ typically increasing slightly (Mertens 2013).

On the other hand, the same increase in temperature reduces the open circuit voltage in a much more pronounced way. The relationship is outlined in Equations 1 and 2. Since the relationship between the open circuit voltage and the short circuit current is logarithmic, a small increase in the short circuit current brings about a large decrease in the open circuit voltage.

$$V_{oc} = m \cdot V_T \cdot \ln \left( \frac{I_{sc}}{I_S} \right) \quad \text{Equation 1}$$

$$V_{oc} = m \cdot V_T \cdot \ln \left( \frac{I_{sc}}{B} \right) + m \cdot \frac{\Delta W_G}{\alpha} \quad \text{Equation 2}$$ (Mertens 2013)

Where

- $V_{oc}$ is the open circuit voltage in volts;
- $m$ is the ideality factor which is a number between 1 and 2;
- $V_T$ is the thermal voltage in volts;
- $I_{sc}$ is the saturation current in amps.

Figure 1 shows how $I_{sc}$ and $V_{oc}$ change with temperature.

Figure 1: Variation in voltage and current with change in temperature (Mertens 2013)

Figure 1 clearly shows that operating the PV panels at the lowest temperatures enables the highest power output efficiencies to be achieved.

Heat Transfer Mechanisms Considered for the Model

To replicate real-life deployment conditions on the model, the physics of heat transfer was incorporated to include and combine the effects of convection, radiation and conduction.
Conduction

Conduction is one of the mechanisms by which heat transfers through a medium and is the predominant mode of heat transfer through solids. It is the mechanism of heat transfer through the PV panel and also through the ground in the case of the land-deployed panel Case C. The mathematical model was designed to follow the first law of thermodynamics which postulates the theory of conservation of thermal energy.

When referring to a differential control volume, one obtains Equation 3.

\[ \rho c \left( \frac{\partial T}{\partial t} + \{v\}^T \{L\} T \right) + \{L\}^T \{q\} = \ddot{q} \]

\textit{Equation 3} \hspace{2cm} \textit{(ANSYS 2015)}

Where
- \( \rho \) is the density;
- \( c \) is the specific heat;
- \( T \) is the temperature;
- \( t \) is time;
- \( \{L\} \) is the vector operator;
- \( \{v\} \) is the velocity vector for the mass transport of heat;
- \( \{q\} \) is the heat flux vector;
- \( \dot{q} \) is the heat generation rate per unit volume;
- \( \{L\}^T \{q\} \) is interpreted as \( \nabla \cdot \{q\} \) where \( \nabla \) is the divergence operator.

The first law of thermodynamics postulates that the change in the internal energy is equal to the difference between the thermal energy which is added to the PV from its surroundings to the work which is done by the system to its surroundings (Selvi and Sugumar 2018).

The heat flux vector is related to the thermal gradients through Fourier's law as outlined in Equation 4.

\[ \ast \{q\} = -\{D\} \{L\} T \]

\textit{Equation 4} \hspace{2cm} \textit{(ANSYS 2015)}

Where \( D \) would be the conductivity matrix as represented by Equation 5.

\[ \begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix} \]

\textit{Equation 5} \hspace{2cm} \textit{(ANSYS 2015)}
Where
is the conductivity in the x direction;
is the conductivity in the y direction;
is the conductivity in the z direction;
Through the combination of Equations 3 and 4, Equation 6 was obtained.

\[ \rho c \left[ \frac{\partial T}{\partial t} + [v]^T ([D] [L]^T) \right] = \{L\}^T ([D] [L]^T) + \bar{q} \quad \text{Equation 6} \quad \text{(ANSYS 2015)} \]

Equation 6 can then be expanded to Equation 7 on which the FEM was designed and set up.

\[ \rho c \left[ \frac{\partial T}{\partial t} + V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} \right] = \bar{q} + \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) \]
\[ + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) \quad \text{Equation 7} \quad \text{(ANSYS 2015)} \]

The heat transfer effects are set in a global Cartesian system. The thermal contact between the various layers making up the model were set to ‘Perfect’. This implies that no temperature drop occurs at the interfaces, thus simplifying the model.

**Convection**

Convection is a heat transfer mechanism which is driven by fluid motion. It is therefore a macroscopic mechanism through which heat is carried by the moving fluid. This motion is driven by differences in densities created by temperature gradients. Convection is the mechanism through which heat is transferred away from the PV into the sea and into the surrounding atmosphere. The model used was based on the Newton’s law of cooling as delineated in Equation 8.

\[ \{q\}^T\{n\} = h_f (T_S - T_B) \quad \text{Equation 8} \quad \text{(ANSYS 2015)} \]

Where
is the film coefficient. This is evaluated at (+)/2;
is the bulk temperature of the adjacent fluid. This is input into the model;
is the temperature at the model’s surface;
\{n\} is the unit outward normal vector.

**Convection to the surrounding sea water**

The selected film coefficient was ‘Temperature Dependent’ while the ‘Stagnant water simplified case’ was chosen. The value of convective heat losses calculated by the FEM for the panel/flotation device to water interface was 1200 W/m²°C.

**Convection to the surrounding air**

Convection heat losses to the ambient air occur from the surfaces which are in contact with air. The selected film coefficient was taken from the temperature dependent set. To give a worst-case scenario, the selected coefficient was the ‘Stagnant Air Simplified’ case. The model was set to calculate the coefficient in a temperature-dependent mode.
Radiation

Radiation is the mechanism through which heat transfer occurs via electromagnetic radiation, thereby allowing heat transfer to occur in a vacuum. While conductive and convective heat transfer rates are proportional in a linear fashion to the temperature difference, radiative heat transfer is proportional to the difference fourth power of the temperature (Modest 2013).

The radiation model follows the Stefan-Boltzmann law, as shown in Equation 9, and relates the total energy flux $q$ radiating from a body per unit time to the surroundings.

$$ q = \sigma (T_1^4 - T_2^4) \quad \text{Equation 9} \quad \text{(ANSYS 2015)} $$

Where

$\sigma$ is the Stefan Boltzmann constant or $5.670400 \times 10^{-8}$ W/m$^2$.K$^4$;

$T_1$ is the absolute temperature of the radiating surface in K;

$T_2$ is the absolute temperature of the surrounding in K.

In the FEM, radiative heat gain from the incident solar flux is modelled. Radiative losses to the environment were also included in the model. The emissivity of a material determines how much energy the material will radiate. The emissivity constant was set at 0.7.

Model Design

*Case A Sea deployment – Floating on the surface*

*The model structure*

The FEM was set up based on the internal dimensions and material properties of a specific flexible CIGS panel and was built out of these layers:

- Insulation;
- CIGS layer;
- Stainless steel.

Furthermore a layer of neoprene rubber was added to provide buoyancy in Case A only.

*Figure 2: Sectional view from the front showing the different material types*
Materials and Dimensions of the Finite Element Model

The active part of the model is made up of CuInGaSe₂ (CIGS). The length of the CIGS layer was taken at 5,744 mm. The CIGS layer was designed to be 1 mm thick and 494 mm wide as established from panel data sheets.

The thermal conductivity of the CIGS was set at 8.6 W/m.K as derived from literature (Ahmed 1995). In the model, the CIGS layer was deposited on a stainless steel layer of the same planar dimensions as the CIGS layer.

The grade of stainless steel used for the model was 316L stainless steel which has a thermal conductivity of 15.1 W/m.K. The combined CIGS and the stainless steel layer are assumed to be 1 mm thick with the stainless steel layer having a thickness of 0.46 mm.

This assumption was based on measurements taken from scaled panel diagrams. The CIGS and stainless steel layers were modelled to be contained in an Ethylene Tetrafluoro Ethylene (ETFE) jacket. This jacket is normally used by the manufacturer to impart waterproofing capabilities to the PV. As per ASTM C177, the thermal conductivity of ETFE is 0.238 W/mK. (Fluorotherm 2015). The ETFE layer was designed to be 1 mm thick in the model.

The final lower layer of the model, touching the surface of the sea, was the flotation layer which was made up of a 3 mm thick neoprene rubber layer. The thermal conductivity of neoprene rubber, also known as Polychloroprene, is 0.18W/mK at 25°C (Rubber Elastomers 1995).

Boundary Conditions

The following is the summary of the important boundary conditions:

• The connection types between each layer were set to ‘Bonded’. Throughout the simulation, one surface acted as the contact while the other acted as the target face. Heat flow occurred between the contact and the target surfaces. In this case both sides were set as contact and target thereby forming a symmetrical contact system which allowed heat flow in either direction (ANSYS 2005). The bonded connection type allowed full and unhindered heat transfer between all the parts in the contact region;
• Average peak air temperature is 31.8°C for August (Malta’s Climate 2016);
• Sea temperature for August used in the model was 26°C as found in literature (ibid.).

Case B Sea Deployment – Submerged

The Model Structure

As discussed in Case A Sea deployment – Floating on the surface, the FEM for this case was built out of these layers:

• Insulation;
• CIGS layer;
• Stainless Steel Substrate.

However in the submerged model, the layer of neoprene rubber which provides the buoyancy was not added. Figure 3 shows a cross section of the model used in Case (B).
The Case B model has 6 faces transmitting heat to the sea and one face receiving the incident heat flux.

*Case C – Land Deployment*

*The model structure*

For Case C the FEM was based on a panel which was built out of these layers:
- Insulation;
- CIGS layer;
- Stainless steel substrate.

The CIGS panels being used were designed to be deployed in a flat position on a roof (not inclined). Hence the model was set up in this way. Further to this, to simulate the roof on which the solar panels are attached in Case C, a slab of concrete was also included in the model. The slab was designed to be 150 mm thick to simplify the analysis. Thermal conduction through the concrete block was set up in the model. The temperature of the concrete slab on the side opposite to the panel (simulating the temperature inside a building) was set fixed at a room temperature of 22°C.

The model includes heat transfer via radiation and convection into and out of the panel. Figure 4 shows the geometry and model composition used for this simulation. It shows a closer view of the panel itself to show the layers making up the model. The ETFE envelope surrounding the CIGS/stainless steel layers sitting on top of each other.

*Figure 3: A section of the panel*

*Figure 4: PV installed on roof concrete slab*
The models were meshed in a way as to obtain the best balance between accuracy and performance.

**Results**

*Case A Sea deployment – Floating on surface*

The steady state temperature results obtained for Case A are shown in Figures 5, 6, and 7. These figures show various views of the panel with values of temperature outlined in the figures. Values of temperature show the maximum temperature reached.

*Figure 5: Top view of panel showing the temperature distribution – (Case A – Sea deployment – Floating on surface)*

Figure 5 shows that the highest temperature being achieved was that of 37.49°C. The temperature is highest at the centre of the PV and then reduces towards the edges which are in contact with the sea. Since most of the materials employed to construct the active area of the PV are not very good conductors of heat, such a distribution is to be expected. In this case, the border of the panel in close proximity to the water achieves a lower temperature following a gradient which achieves a max steady state panel temperature at the centre of the PV eventually reaching the sea temperature at the edge.

This can be shown more clearly in Figure 6 which is a close up of the edges of the PV.

*Figure 6: Close up section Top view of panel showing the temperature distribution*
Figure 7, on the other hand, shows a cross-sectional view of the panel indicating that the underlying structures are at a cooler level than the overlying CIGS structure. However, due to the fact that CIGS and ETFE are poor conductors of heat, the active part of the panel achieves and sustains a steady state temperature which is at least 10°C higher than the surroundings. This results in a corresponding reduction in efficiency.

**Figure 7:** Cross-sectional view showing the temperature gradients

*Case B – Sea deployment submerged*

Figure 8 show the results of the simulations and the temperatures reached by the panel at steady state. In this case the temperature achieved by the CIGS layer was 26.3°C, which was a full 10°C lower than Case A. The model basically shows that with the submerged panel the core temperature would only be a fraction of a degree higher than the surrounding sea temperature.

**Figure 8:** Top view – Case B – Submerged Panels
Again the temperature gradients at the edges can be noted in Figures 9 and 10. In the area round the edges, the temperature gradient from maximum steady state core temperature to outside sea temperature occurs in the few centimetres which constitute the outer edges of the PV.

**Figure 9:** Top view showing the edges of the panel

**Figure 10:** Section view of the PV showing thermal gradients

**Case C– Land Deployment**

Figure 11 shows the temperature gradient achieved in the land deployed model. The FEM shows that the top part of the whole concrete slab achieves a high temperature with the PV itself achieving a temperature of more than 72°C.
Figure 11: Sectional view showing temperature gradients. The top layer is the PV with the rest being the concrete slab forming the roof below.

Figure 12 is a close-up view showing the temperature of the panel surpassing a homogenous 72°C at steady state in Case C.

Figure 12: Close up sectional view of panel and concrete slab forming the roof.

In this case the edges and core of the PV panel attain the same steady state temperature. This can be seen from Figure 13 which shows the whole panel achieving a homogenous temperature value.
Figure 13: Top view of panel

The results of Case C show that the maximum temperature occurs on the CIGS semiconducting layer thereby having maximum effect on the panel efficiency.

Conclusion from Results of the Analysis Carried out on Cases A, B, and C

The results from the three cases, when compared together, provide the mathematical quantification of the sea water’s cooling effect on the PV module. This can then be combined to parameters from the PV datasheets to compute the panel’s performance efficiency and quantify the effect of different deployment methods on the power output. The PV panel used for this simulation has a maximum power coefficient $P_{\text{max}}$ of -0.43%/°C (PV Supplier 2015). From the values calculated previously, the submerged panel operates at the lowest temperature of the three panels configurations here examined. Table 1 collects the results obtained from the FEA of the three models.

<table>
<thead>
<tr>
<th></th>
<th>Temperature of panel [°C]</th>
<th>Temperature difference of panel [°C]</th>
<th>% reduction of output power compared to submerged panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Deployment</td>
<td>72</td>
<td>45.8</td>
<td>-19.7</td>
</tr>
<tr>
<td>Sea Deployment (Surface)</td>
<td>37.5</td>
<td>11.3</td>
<td>-4.8</td>
</tr>
<tr>
<td>Sea Deployment (submerged)</td>
<td>26.2</td>
<td>N/A</td>
<td>0</td>
</tr>
</tbody>
</table>

Table I: Comparison of thermal effects of land deployed, sea deployed (surface) and sea deployed (submerged)

It can be seen that the submerged panel has an improvement of 20% in power output over the land deployed panel in worst case scenario. This occurs during the summer months. The advantage would be less in the winter, spring, and autumn months.

The results of this study considers only heat flow and the sea’s cooling effect. Further work is required on other models to be able to consider the other independent variables relevant to the model such as the absorption of the incident light by the sea.
References


ANSYS n.d. *ANSYS Help manual* (n.p.).


Malta’s Climate 2016. *Malta’s Climate*. Available at www.maltaweather.com


Mathematical Modelling of Heat Transfer Physics in Sea and Air deployed PV Systems


The European Stainless Steel Development Association 2009. *Stainless Steel in Contact with Other Metallic Materials* (Dusseldorf).
