CHAPTER 5

CONCLUSION AND FUTURE SCOPE

The chapter consists of two parts, ***section 5.1*** *presents the summary of the conclusions obtained from research work in this thesis, and* ***section 5.2*** *gives some of the further work which can be carried out in line with the present work done.*

5.1 Conclusion

For precise estimation of the PV performance, it is important to analyze the factors that affect its performance such as diurnal and seasonal change of spectrum, spectral response of a solar cell, effect of cell temperature on PV module, effect of soiling, etc. So, considering the transient nature these factors, individual modules needs to be analyzed and output of those modules to be fed in the electrical model through an integrated approach for reliable estimation. In this work, a spectral model is developed to generate solar spectral irradiance using SMARTSv2.9.5, the thermal model is developed in COMSOL Multiphysics, and the electrical model is developed using MATLAB. These models are integrated using COMSOL MATLAB Livelink. The outputs from the spectral, thermal, and electrical models are experimentally validated using monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si) PV modules mounted in an open-rack inclined at 26° (latitude of the study site). The reliability or acceptance level of these models is determined using the statistical errors (such as MAE, MRE, and RMSE) and coefficient of determination (R^2). The RMSE of the short-circuit current is in the range of 0.12 A to 0.31 A for the m-Si, and ranges from 0.16 A to 0.43 A for the p-Si. The RMSE of the open-circuit voltage for m-Si and p-Si ranges from 0.53 V to 0.78 V and 0.48 V to 0.68 V, respectively. The result showed that the RMSE of cell temperature and power output for m-Si PV module ranges from 2.1-3.0°C and 1.41-3.63 W, respectively; and the same for the p-Si PV module is found to be within 2.2-3.1°C and 1.41-4.34 W, respectively. It is observed that the errors between the simulation and experimental results are in good match and within the acceptance range. Therefore, it can be concluded that the developed model provides reliable estimation of PV performance diurnally and seasonally.

Moreover, a noble method of utilizing glass coupons as proxy to PV module cover glass is used to analyze the optical (transmittance) loss of the PV module due to soiling. The effect of other environmental parameters individually and in combination is also studied. The transmittance is measured weekly for a year in dry-winter and humid subtropical locations. Such methods can be beneficial to establish best practices for the cleaning strategy of PV modules for diverse conditions worldwide. The transmittance loss (τ_{loss}) due to the soiling of horizontally mounted glass coupons is found to be (in order from high to low): winter > post-monsoon > pre-monsoon > SW monsoon seasons. The maximum average transmittance loss due to soiling for the weekly, monthly, and never cleaned glass coupons is 16.6%, 18.4%, and 24.4%, respectively, all recorded during the winter season. Based on the statistical (F- and t-test) analysis, the present study recommends weekly cleaning during winter and post-monsoon to maintain high transmittance above 80%, as well as an optimal cleaning cycle of once a month during the pre-monsoon and SW monsoon seasons to maintain high transmittance above 90%. It is observed that rain is not a complete or sufficient way of cleaning; a minimum rainfall threshold is required, depending on the cleaning strategy. The threshold rainfall required to clean the weekly cleaned glass coupon is the highest, followed by that of the monthly and never cleaned glass coupons. The rainfall thresholds for the weekly, monthly, and never cleaned glass coupons are 3.4 mm/h, 3.1 mm/h, and 2.1 mm/h, respectively. The analysis shows that adapting the cleaning cycle to the specific weather and soiling conditions of each season is essential. Linear regression analysis suggests that environmental parameters which show significance during one season do not necessarily have a strong correlation to soiling in another season. It may thus prove difficult to develop a simple empirical relationship for soiling losses. In general, the findings of this study demonstrate the usefulness of statistical analysis of experimental data in real-world conditions to elucidate the effect of environmental factors and seasonality on the soiling of solar energy conversion systems.

The energy yield analysis showed that the deviation of the simulated typical energy yield from the experimental typical energy yield is in the range of 2.40-8.06%

and 1.10-10.9% for m-Si and p-Si, respectively. The maximum reduction in energy yield of PV modules due to soiling is 26% that is, during winter, followed by 20% during post-monsoon, then pre-monsoon with 16%, and the least during monsoon with 7%. All these values are obtained when the glass surface of the PV modules (m-Si and p-Si) is left uncleaned. Therefore, the developed model can be used to obtain reliable power or energy outputs of the PV modules under seasonal variability. The novel experimental data shared in this work can significantly benefit the PV deployment and maintenance in the region and additional locations with similar environmental conditions, even though not throughout the year but at specific seasons of the year.

5.2 Future Scope

In this work, a spectrum-integrated electrical-thermal model has been developed, and investigations are made on PV soiling for the dry-winter and humid subtropical locations. However, some possible future work that can be carried out is as follows:

- Long-term outdoor experiment for validation of the spectrum-dependent model under the varying environmental parameters.
- Development of model which integrates the effect of soiling along with the spectrum dependent electrical-thermal model.
- To carry out a PV soiling study with economic analysis for cleaning cycle recommendations for maximum energy output from PV system installed in different climatic zones.
- To study the effect of anti-reflection coating on the PV surface to minimize the effect of soiling.
- To carry out economic analysis in the PV system incurred due to soiling losses.