PRELIMINARY OPERATION ASSESSMENT OF A TWO-STAGE ORC ENGINE COMBINED WITH EVACUATED TUBE SOLAR COLLECTORS THROUGHOUT GREECE

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ABSTRACT

A solar two-stage Organic Rankine Cycle (ORC) engine designed, constructed and experimentally tested in authors' previous work, is hereby evaluated for operation in a wide set of representative locations distributed throughout Greece. The simulation model gathers daily meteorological data for the areas of interest for a thirty-four years reference period. The produced power and operational efficiency of the integrated system that includes the solar collectors combined with the ORC engine is then calculated, with the use of already existing experimental data. The installation, operational and maintenance cost of the integrated system is calculated at current prices for its lifespan and the cost of every produced kWh is presented in maps for the entire country. Finally, the effect of climate variability on energy production performance and the presence of trends were investigated as well. The results show that there is a great spatial variability on the received solar radiation, the thermal energy and the power production in comparison to the relatively small size of the country and this variation is not only a function of the latitude. The energy cost varies considerably between 0.41 and 0.7 €/kWh throughout the country. The great variance and the complexity of the factors influencing the cost of the produced energy highlight the importance of geospatial analysis approaches to assess renewable energy potential and to support technoeconomic analysis and feasibility studies. The proposed approach was proven to be an effective tool for the assessment of the feasibility and potential of a solar heat-to-power engine for Greece and to be expanded in other regions as well.

1 INTRODUCTION

The Organic Rankine Cycle (ORC) technology has been a field of intense research and development for the last decades, as numerous theoretical and experimental investigations have proven that it is a very promising technology for efficient conversion of low-grade heat into useful work or electricity (Lecompte et al., 2015; Mago et al., 2008; Zhao et al., 2019).

Proper planning and technoeconomic analysis have a key role in the growth and development of renewable energy. Renewable energy potential however depends on many variables that vary both in space and time. Therefore, several studies used geospatial analysis approaches to assess renewable energy potential and to support technoeconomic analysis and feasibility studies (Soulis et al., 2016; Tamm & Tamm, 2020; Wang et al., 2018). For example, several researchers used geographical information systems (GIS) based approaches and geospatial analysis to evaluate hydropower potential, site selection and sizing of hydropower and pumped hydropower storage projects (Punys et al., 2019; Tamm & Tamm, 2020; Wang et al., 2018). Many other studies used GIS for the spatial estimation of wind energy potential (Cellura et al., 2008; Veronesi et al., 2016) as well as solar energy resources assessment (Mccandless et al., 2016; Ortiz et al., 2020; Wu et al., 2013)

In the case of solar ORC systems, the operation efficiency and the power production potential at any given site depend on the meteorological conditions temporal variability and especially solar irradiation and temperature. Both these variables are characterized by temporal and spatial variability within short distances, especially in countries characterized by steep relief, long coast lines, and a great number of mountain ridges, islands and peninsulas such as the Mediterranean countries (Mancosu et al., 2014; Mardikis et al., 2005; Soulis et al., 2018). In this context, geostatistical analysis and solar prediction modeling approaches are used for the estimation of solar radiation spatial distribution based on the available ground measurements (Fathizad et al., 2017; Mccandless et al., 2016; Rehman & Ghori, 2000; Soulis et al., 2018). In most relevant applications, the methodologies used for geostatistical prediction are variations of kriging-based models (Soulis et al., 2018; Zagouras et al., 2015).

In this study, a simulation model of a two-stage ORC engine combined with evacuated tube solar collectors was developed and applied throughout Greece. The model uses daily meteorological data including temperature and solar irradiation for the areas of interest for a thirty-four years reference period. These data are downscaled in hourly time step and then are used to predict the evacuated tube solar collectors' (ETC) performance for the entire reference period in spatially distributed form. The produced power and operation efficiency of the system is then calculated. A set of ranking maps presenting various aspects of the performance of the integrated system throughout the country is created using spatial interpolation techniques. The installation, operational and maintenance cost of the integrated system is calculated and the cost of every produced kWh is presented in maps for the entire country. Finally, the effect of climate variability and the presence of trends are investigated as well.

2 MATERIALS AND METHODS

2.1 Solar-ORC system description and simulation.

The system evaluated in this study is an autonomous solar two-stage Organic Rankine Cycle (ORC) engine of nominal power of 10kWe at 100kWth that was constructed and experimentally tested in authors' previous work (Ntavou et al., 2017). The integrated system includes an evacuated solar collectors' field of 100kWth capacity, a two-stage ORC engine for operation in full and partial heat load (one or two expanders accordingly) and a RO system with three identical sub-units operating with electricity produced from the ORC engine towards fresh water production. The two-stage ORC test rig is configured as a single circuit with R-245fa organic fluid and two scroll expanders installed in-series, operating at subcritical conditions. According to (Kosmadakis et al., 2010), the two-in-series expanders' configuration experiences superior performance in a wide range of thermal load variation but also cost and control simplicity are favorable aspects.

In the current analysis the two-stage ORC engine is coupled with a solar field that consists of vacuum tube solar collectors (Thermomax DF 100 30). The technical specifications of the solar field are presented in Table 1.

Table 1: Technical specifications of collectors' field

Model	**Thermomax DF 100 30**
No. of collectors, N_{col}	60
Absorber area, A_{col} (m^2)	3.02
Tilt angle, ^{o}	45
Zero-loss efficiency, η_0, -	0.832
First order coefficient, a_1, W/m^{2}K	1.14
Second order coefficient, a_2, W/m^{2}K^2	0.0144

The thermal efficiency (η_{th_col}) of the solar collector is expressed as:

$$\eta_{th\_col} = \eta_0 - a_1 \cdot \frac{T_m - T_{amb}}{G_t} - a_2 \cdot \frac{(T_m - T_{amb})^2}{G_t} \tag{1}$$

where T_m and T_{amb} are the mean inlet-outlet temperature of the collector and the ambient temperature, respectively, G_t is the global radiation on tilted surface and the coefficients η_0, a_1 and a_2 are defined in Table 1. The heat generated by the solar collectors' field (Q_{ev}) is expressed by the following equation:

$$Q_{ev} = N_{col} \cdot A_{col} \cdot G_t \cdot \eta_{th\_col} \tag{2}$$

where N_{col} and A_{col} are the number of collectors and the absorber area (Table 1). The maximum ORC net power generation (P_{ex}) is expressed as a polynomial that correlates the maximum net power generation with Q_{ev} and operation temperature (T_h). These variables are the independent ones and the net power generated by the ORC can be expressed as a function of them. The correlation is extracted from the elaboration of the experimental data derived to map the ORC engine performance, where the fluctuation of the net power generation P_{ex} is measured as Q_{ev} varies in a range at a predefined T_h value. The minimum Q_{ev} is the heat flow limit that ORC starts operating while the maximum is the 120 kWth. The corresponding equation that correlates the maximum P_{ex} with Q_{ev} and T_h is:

$$P_{ex} = 1.941 + 0.2437 \cdot Q_{ev} - 0.00058 \cdot Q_{ev}^2 - 0.0756 \cdot T_h + 0.000504 \cdot T_h^2 + 0.00072 \cdot Q_{ev} \cdot T_h \quad (3)$$

The coefficient of determination achieved with eq. (3) is very high ($R^2 = 91.8$) showing the strength of the relationship among the three variables.

The thermal efficiency of the ORC engine is expressed as:

$$\eta_{th\_orc} = \frac{P_{ex}}{Q_{ev}} \quad (4)$$

The integrated Solar-ORC system is modelled so as the maximum net power to be achieved under the varied operational conditions. The maximum net power is observed when the total efficiency (eq. 5) of the entire process is maximized as a function of T_h.

$$\eta_{th\_t} = \eta_{th\_col} \cdot \eta_{th\_orc} \quad (5)$$

The maximization of η_{th_t} is obtained by applying the optimization features of EES software and concludes to a T_h value for which η_{th_t} is maximized under different values of Q_{ev}. It should also be mentioned that the pinch point T_{pp} temperature difference in the evaporator is set at 10 ^{o}C and η_{th_col} is calculated based on this assumption.

2.2 Case Study Site and Data

Greece has an area of about 132,000 km^2, it is located in Southeast Europe and it is characterized by huge spatial variability of meteorological conditions within short distances as is the case in most Mediterranean countries (Figure 1). At the same time, the meteorological information available is generally scarce, especially for some of the required weather variables such as solar radiation (Soulis et al., 2018, 2020). The above characteristics make Greece a representative example for the analysis of the most important challenges and limitations and the identification of feasible solutions for the spatial estimation of the operation efficiency and the power production potential of solar ORC systems.

The required meteorological variables for the current analysis were temperature and solar irradiation in hourly time step for a representative reference period. To this end, historical meteorological data coming from the meteorological stations of the Hellenic National Meteorological Service (HNMS) of Greece (Figure 1) were used. In total, 140 stations were used, corresponding to a density of 1 station per 950 km^2, which can be considered adequate. However, an important limitation is that many stations' data-series had serious gaps or did not record all the required weather parameters (Figure 1). The available historical data used in this study were daily maximum, minimum and mean temperature and daily sunshine hours for 34 years (1 January 1971 to 31 December 2004) exceeding the minimum World Meteorological Organization (WMO) reference period requirements. This period can be considered adequate to reflect climate variability and to investigate possible trends in power production potential (Soulis et al., 2018).

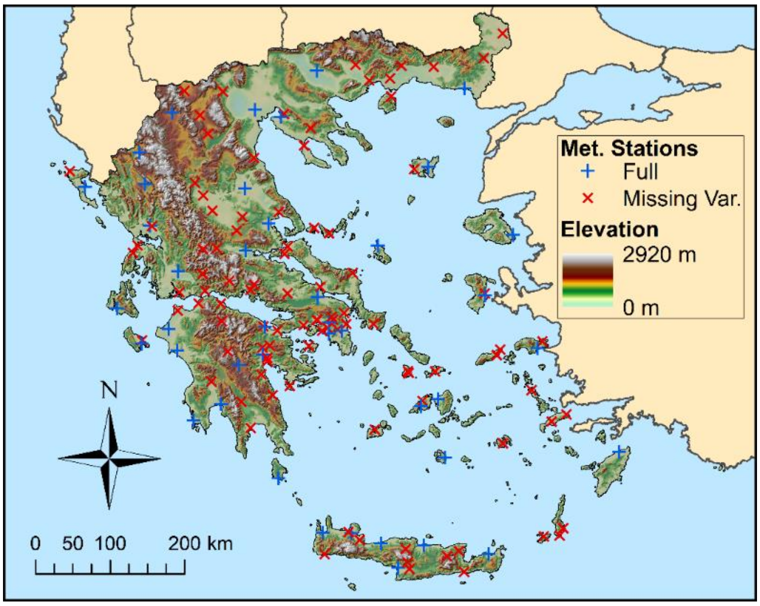

Figure 1: Topography of the study area (Greece) and positions of available meteorological stations with complete datasets and with missing variables.

The first step of the meteorological data processing was to assess the available data for integrity and consistency, and to fill the existing gaps as described by (Soulis et al., 2018). Especially for the case of solar radiation, a solar radiation modeling approach was attempted to fill the corresponding gaps in the data series. The estimation of solar radiation was attempted using the models of (Valiantzas, 2013) and (Hargreaves & Samani, 1982).

2.3 Solar ORC performance simulation

The simulation of the solar ORC was implemented in Microsoft Excel using VBA programming language. The main steps followed in the developed algorithm were: i) downscaling of the daily temperature and global solar radiation data to hourly time step, which is required for the simulation of the Solar-ORC system; ii) estimating the diffuse and the direct solar radiation fractions for each data point; iii) estimating the direct solar radiation on the tilted surface considering the collectors' field characteristics and the coordinates of each station; iv) estimating the global solar radiation on the tilted surface; v) estimating the heat generated by the solar collectors' field (Q_{ev}) and the net power generated by the ORC (P_{ex}), and the corresponding efficiencies in hourly time step; vi) integration of the obtained results at daily time step; calculate monthly, annual and interannual statistics; and vii) calculating the cost of every produced kWh for each station for the entire period and for each year. A process flow diagram presenting the main steps of the applied methodology is provided in Figure 2.

Temperature data were downscaled using the CISBE method (Chow & Levermore, 2007) based on *Tmax* and *Tmin*. The global solar radiation for each hour was calculated from the respective daily global solar radiation based on the ratio between the corresponding daily and the hourly extraterrestrial radiation that were calculated based on the solar constant, the solar declination, the time of the year, and the solar time angles at the beginning and end of each hour interval. As it is very rare to have measurements of diffuse sky radiation, several researchers have established empirical relationships estimating diffuse sky radiation from the global solar radiation based on the clearness index (kt), which is the ratio of the global to the extraterrestrial radiation (Berrizbeitia et al., 2020). In the current study, the method developed by Soares et al. (Soares et al., 2004) based on measurements from Athens Greece was used as the most representative of the available methods for the conditions prevailing in Greece.

Direct global radiation on a horizontal surface was estimated as the global radiation minus the diffuse radiation. The direct solar radiation on the tilted surface was then estimated based on the solar angles at the middle of each hour interval. Finally, the global radiation on tilted surface was the sum of the direct solar radiation on the tilted surface and the diffuse radiation (Kalogirou, 2009). It should be noted that ground reflected solar radiation was assumed to be negligible. The hourly air temperature and global solar radiation on the tilted surface data were used for the estimation of the thermal power of the solar collectors (Q_{ev}) and the net power generated by the ORC (P_{ex}), and the corresponding efficiencies in hourly time step for the entire study period (1971-2004) and for all the available meteorological stations with the methodology described in section 2.1. The obtained results were integrated at daily time step and the monthly, annual and interannual statistics were calculated for all the involved quantities.

The cost of every produced kWh was estimated considering the present value of all the installation, operational and maintenance costs of the integrated system for the lifespan of the project, which was assumed to be 20 years for the entire system except of the ORC that should be replaced after 10 years. The total cost was calculated equal to 83,160€ assuming a maintenance cost equal to 1% of the total cost for each year of operation. The total cost was divided by the total electricity production for the entire lifespan of the system based on the interannual daily average power production of the system for the entire study period for each examined location in order to consider the variability of the meteorological conditions. Estimations of the cost per produced kWh considering the daily average power production of each studied year were also made in order to investigate the temporal variability and possible trends.

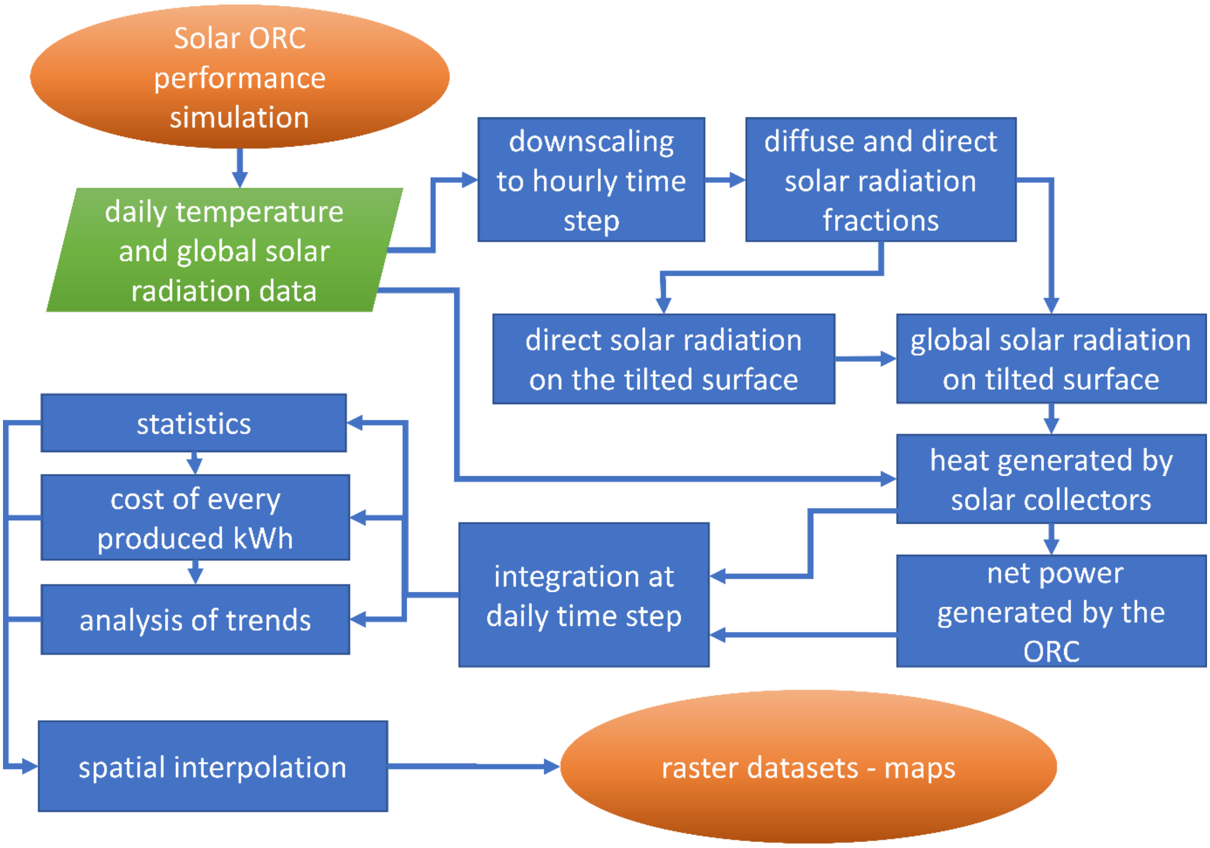

Figure 2: Process flow diagram of the developed algorithm.

2.4 Spatial Interpolation

Kriging-based models are typically used for geostatistical prediction of variables related to renewable energy resources development (Cellura et al., 2008; Lee et al., 2014; Rehman & Ghori, 2000; Wu et al., 2013). In the current study simple kriging was used for the spatial interpolation of the obtained results for the global solar radiation, the thermal power production by the collectors' array, the net power production by the ORC and the cost per produced kWh. This method was selected because it performed better than all the other kriging-based models. The co-kriging method, which is able to utilize the covariance between two or more regionalized variables that are related to provide improved results, was also tested using as secondary information the elevation. However, the correlations between the variables of interest and the elevation were proven to be very weak. Then after establishing normality of the data (via log transformation), the most suitable semivariogram modeling functions and parameters were evaluated. The stable semivariogram model fitted adequately well in the studied datasets. All the above analysis was made using ESRI's ArcGIS software package (version 10.5.1, Environmental Systems Research Institute, Redlands, CA, USA).

2.5 Analysis of Trends

The effect of climate variability on energy production performance and the presence of trends were investigated to consider the potential impact of shifts in weather conditions. To this end, the areal statistics for the net power production and the cost per kWh were calculated for each year in the studied period and then their variability and possible trends were analyzed. Linear regression lines were fitted to the areal mean, minimum and maximum values of the annual net power production, while the corresponding 95% confidence bands and the significance of the difference of the corresponding slope values from 0 at the 0.05 confidence level were evaluated.

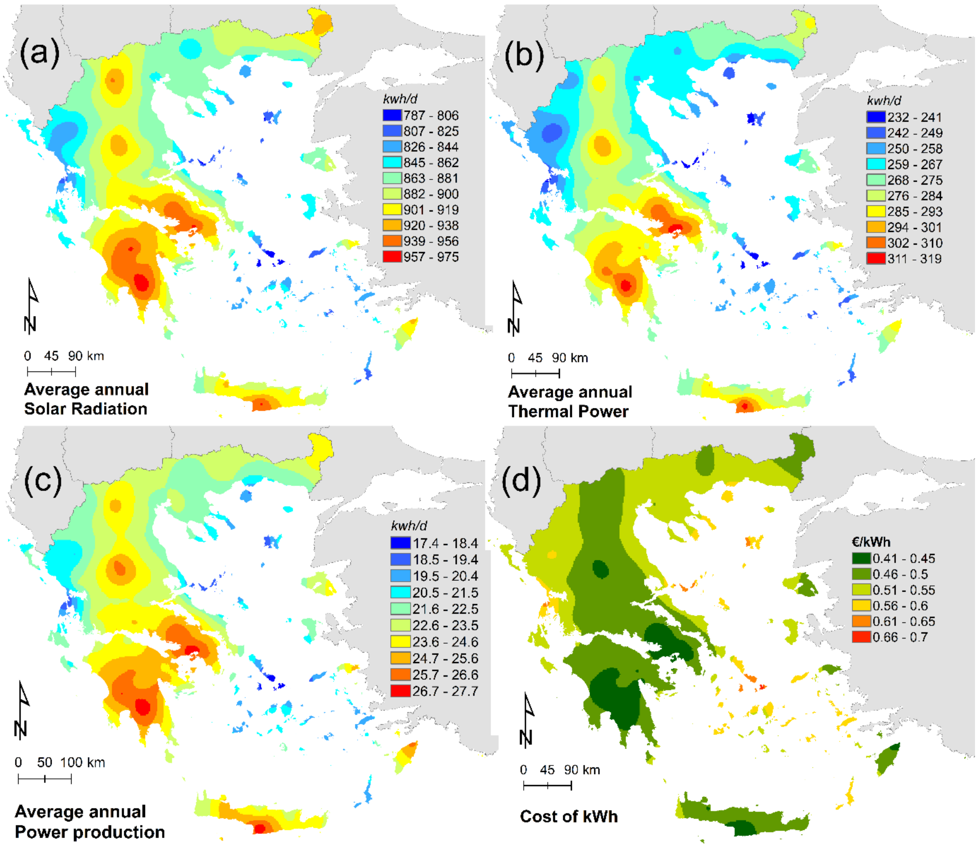

Figure 3: Mean interannual solar radiation per day received by the solar collectors array (a); mean interannual thermal power production from the solar collectors' array per day (b); mean interannual net power production per day (c); and cost per produced kWh (d) spatial distribution for the entire study period (1971-2004).

3 RESULTS AND DISCUSSION

The accuracy of the interpolated surfaces and the cross-validation of all the obtained results indicated that the obtained performance was adequate with RMSSE ranging 0.91 and 1.16. The spatial distribution of the mean interannual solar radiation received by the collectors' array per day, the mean interannual thermal power production from the solar collectors' array per day and the mean interannual net power production per day are presented in Figure 3a, b, c respectively. As shown in these figures, there is a profound spatial variability as the respective values of received solar radiation range from 787 to 985 kWh/d, Q_{ev} ranges between 232 and 319 kWh/d and P_{ex} ranges between 17.4 and 27.7 kWh/d. This is a considerable variation for the performance of the same system taking into account the relatively small size of the country. An interesting finding is also that the received solar radiation variation is not solely a function of the latitude (Figure 3a). Furthermore, higher values are observed both in areas with lower elevation and in mountainous areas as it is revealed comparing Figures 1 and 3a. The considerable spatial variability and the complexity of the involved process highlight the importance of reliable and dense monitoring networks and efficient geostatistical analysis and solar prediction modeling methods (Fathizad et al., 2017; Mccandless et al., 2016; Rehman & Ghori, 2000).

Thermal and power production generally follow the spatial pattern of the solar radiation (Figure 3c); however, the net power production depends additionally on the ambient temperature and the optimization of the ORC engine operation according to the available thermal power and the ambient temperature (Ntavou et al., 2017). These factors influence the thermal efficiencies of the solar collector and the ORC engine complicating further the assessment of power production potential. As it is also reported by Roumpedakis et al. (2020), the correlation between the solar field area and the optimization parameters is complicated and directly connected to the climatic conditions of each considered location.

The corresponding interannual thermal efficiency of the solar collectors ranges between 0.29 and 0.33, of the ORC engine between 0.075 and 0.089 and the total efficiency between 0.022 and 0.028. As it is presented in Figure 3d, the cost varies considerably between 0.41 and 0.7 €/kWh in the various regions. This cost is a function of the estimation of the total cost of the system (123.910€, of which 48.700€ is the cost of the heat production circuit and 15.600€ is the cost of the ORC engine) and reductions on the total cost will result in analogous reductions on the cost per kWh. The great variance and the complexity of the factors influencing the estimated cost of the produced energy highlight the importance of geospatial analysis approaches to assess renewable energy potential and to support technoeconomic analysis and feasibility studies as it was also indicated by several other studies (Rojanamon et al., 2009; Soulis et al., 2016; Tamm & Tamm, 2020; Wang et al., 2018).

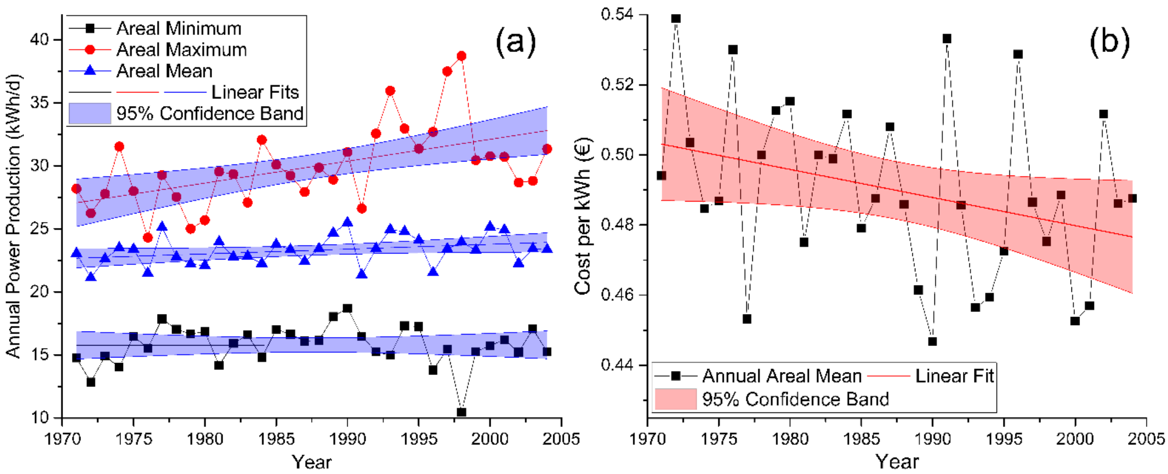

Figure 4: Areal mean, minimum and maximum annual net power production (a) and cost per produced kWh (b) for each year of the studied period and the corresponding linear regression lines.

The effect of climate variability and the possible presence of trends in the studied period is summarized in Figure 4, where the areal mean, minimum and maximum annual net power production, the corresponding cost per unit of produced energy for each year of the studied period and the best fitted linear regression lines are presented. As can be seen, climate variability and possible trends are important factors and should be thoroughly further investigated.

4 CONCLUSIONS

The results indicate that there is a profound spatial variability on the received solar radiation, the thermal energy and the power production in comparison to the relatively small size of the country. This variation is not solely a function of the latitude. The energy cost varies considerably spatially between 0.41 and 0.7 €/kWh in the various regions. The great variance and the complexity of the factors influencing the cost of the produced energy highlight the importance of geospatial analysis approaches to assess renewable energy potential and to support technoeconomic analysis and feasibility studies. The obtained results reveal that the proposed approach comprises an effective tool for the assessment of the feasibility and potential of a solar heat-to-power engine for Greece and for broader regions as well.

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