A hybrid solar photovoltaic-wind turbine-Rankine cycle for electricity generation in Turkish Republic of Northern Cyprus

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Abstract: This paper presents an energy demand model by designing a hybrid solar-wind-thermal power generation system of the Turkish Republic of Northern Cyprus, a promising substitute for the expensive battery banks. The study models the future energy demand of Turkish Republic of Northern Cyprus based on the IPCC emissions scenario A1B and A2 by designing a new hybrid solar-wind-thermal power system that satisfies the current and future requirements of firm capacity during peak periods. The study suggests an improvement in a hybrid solar-wind-thermal power system performance by predicting reliable outputs that can integrate renewable energy technologies to conventional power generation. The energy consumption prediction model emphasizes the energy requirement that has a growing demand from 300 to 400 GWh in scenario A1B and 150–450 GWh in scenario A2 from 2010 to 2050. The proposed design can meet 400 GWh of electricity demand in TRNC based on IPCC scenario A1B and 450 GWh of electricity demand in TRNC based on IPCC scenario A2. The percentage contribution of solar, wind and thermal energy for 2010, 2020, 2030, 2040 and 2050 are presented along with CO2 emissions and water consumption for each of the years.

Subjects: Energy & Fuels; Power & Energy; Renewable Energy

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PUBLIC INTEREST STATEMENT
Energy demand modelling is of much interest among scientist and engineers concerned with the issues of energy production and utilization due to its usefulness in planning and formulating energy policies. Future energy consumption in Turkish Republic of Northern Cyprus is modelled with regression analysis based on GDP and population. Due to uncertainties about the future, the study employs the Intergovernmental Panel on Climate Change scenarios to forecast the future energy demand. The output of energy demand is used to design a hybrid solar-wind-thermal power generation for Turkish Republic of Northern Cyprus. Water consumption by the proposed system and carbon dioxide emission reduction contribution are analysed, respectively. The study will provide an alternative solution to the existing battery banks used as storage for a hybrid PV-Wind energy systems and will serve as an informative tool for local and foreign investors in Turkish Republic of Northern Cyprus and also serve as a foundation for future research.
Keywords: energy conversion/recovery; IPCC scenarios, Northern Cyprus; hybrid solar-wind-thermal; power generation

1. Introduction

Clean combustion, high thermodynamic efficiency and renewable energy technologies are gaining world attention, due to their necessity to satisfy demands for CO₂ emission mitigation via the reduction of combustion generated pollution (Beér, 2000). CO₂ emissions can be mitigated if there are alternatives that are accessible, available and economical viable to replace the conventional fossil fuels (Asumadu-Sarkodie & Owusu, 2016d). Renewable energy is the cleanest and promising technology that can help mitigate CO₂ emissions (Asumadu-Sarkodie & Owusu, 2016g). The concept of sustainability demands a balance between energy availability, accessibility, economic viability, environmental impacts and social interactions (Asumadu-Sarkodie & Owusu, 2016b; Owusu & Asumadu-Sarkodie, 2016; Owusu, Asumadu-Sarkodie, & Ameyo, 2016). Security of energy supplies is of vital importance to our way of life and economic endeavours (Nakata, 2004). Solar and wind energy are some examples of renewable energy technologies that are widespread, environmentally friendly and freely available throughout the year. Wind power plants may not be viable at all sites due to low wind speed and its huge uneven variation as compared to solar energy (Nema, Nema, & Rangnekar, 2009). Likewise, due to fluctuating weather conditions, cost to integrate of solar systems may be drastically high (Dersch et al., 2004). However, combined solar wind systems are very complementary (Yang, Lu, & Burnett, 2003) in a way that, during the times and seasons where solar resources do not exist or are low in capacity, wind resources take over. Nonetheless, because of dispatchability issues (Gyuk et al., 2005) and underdevelopment of storage systems (Mohd, Ortjohann, Schmelter, Hamsic, & Morton, 2008), a heat engine should also be combined with these systems in order to supply the base load (Larson & Williams, 1987), which increases global warming due to greenhouse gases emissions. As the effects of global warming are seen in a long-term (Solomon, Plattner, Knutti, & Friedlingstein, 2009), well-defined scenarios that predict future should be investigated in order to estimate related emissions of hybrid solar-wind-thermal power plants.

Over increasing energy demand due to increasing population (Asumadu-Sarkodie & Owusu, 2016a, 2016e, 2016f; Dincer, 2000; Ehrlich & Holdren, 1971), decline of fossil fuels and global warming due to GHG emissions have led to the demand for clean, inexhaustible, environmentally friendly and renewable energy resources (Asumadu-Sarkodie & Owusu, 2016c; Demirbas, 2005; Hepbasli, 2008). The estimation of the future energy demand (Akay & Atak, 2007; Berndt & Wood, 1975; Ceylan & Ozturk, 2004; Crompton & Wu, 2005; Dunkerley, 1982; Ediger & Akar, 2007; Ediger & Tatildil, 2002; Ersel Canyurt, Ceylan, Kemal Ozturk, & Hepbasli, 2004; Haldenbilen & Ceylan, 2005; Maddala, Trost, Li, & Joutz, 1997; Murat & Ceylan, 2006; Robinson, 1988; Taal, Bulatov, Klemes, & Stehlík, 2003; Ünler, 2008) has led to the development of new energy portfolio which are more efficient, sustainable and reliable. The implementation of a hybrid solar-wind system has received a considerable attention due to its zero-emission generating capacity.

Against the backdrop, it is essential to model the future energy demand based on a well-defined scenarios from IPCC and design a hybrid solar-wind-thermal power generation for Turkish Republic of Northern Cyprus (TRNC). To the best of our knowledge, scientific studies on modelling energy demand is limited in TRNC. As a contribution to literature, our propose study will examine the case of TRNC while providing an alternative solution to the existing battery banks used as storage for a hybrid PV-Wind energy systems.

1.1. Energy demand model

Access to energy is linked to the human development (industrial production, health, agricultural output, access to water, population, education, quality of life, economic output, etc.) of every nation (Asumadu-Sarkodie & Owusu, 2016b, 2016c, 2016g). Energy forecasting is a vital input required in the conceptual framework of sustainable energy policies of every nation. Presently, energy demand modelling is of much interest among scientist and engineers concerned with the issues of energy production and utilization (Ozturk, Canyurt, Hepbasli, & Utlu, 2004). Modelling is very useful in
planning and formulating energy policies (Dincer & Dost, 1996). Modelling of energy demand is typically based on historical consumptions and the link of this consumption with altered variables such as population, gross domestic product, employment, export amount, and so on (Ceylan, Ozturk, Hepbasli, & Utlu, 2005; Kankal, Akpinar, Körnürcü, & Özşahin, 2011; Kavaklioglu, 2011). Furtado and Suslick (1993) employed the learning and translog models which indicated in their study that, GDP was the main determinant for petroleum consumption evolution in the future. Yang (2000) investigated the causality between energy consumption and GDP by using the Granger’s technique. Yoo (2006) examined the causal relationship between electricity consumption and economic growth among the Association of South East Asian Nations.

1.2. Regression analysis model

Regression analysis model is one of the numerous energy models that are developed for the sustainable progress of any country (Suganthi & Samuel, 2012). O’Neill and Desai (2005) analysed the accuracy in the projections of United States energy consumption produced by the Energy Information Administration over the period from 1982 to 2000. It was evident in their study that, GDP projections were consistently too high, while energy intensity projections were consistently too low. Suganthi and Samuel (2012) reviewed on the energy models for demand forecasting and concluded that, energy demand management is a requirement for proper allocation of the available resources of any country. A study by Kankal et al. (2011) introduced the multiple linear regression analysis models to calculate the energy consumption using GDP and population, respectively. A regression-based daily peak load forecasting method with a transformation function and reflection method was proposed by Haida and Muto (1994). Lee and Chang (2007) studied on the impact of energy consumption on economic growth using evidence from linear and non-linear models in Taiwan. They concluded in their study that, a threshold regression provides a better empirical model than the standard linear model. Al-Ghandoor, Al-Hinti, Jaber, and Sawalha (2008) studied on the electricity consumption and its associated GHG emissions of the Jordan industrial sector using a multivariate linear regression analysis to identify the main drivers behind electricity consumption and to project future electricity consumption. Jónsson, Pinson, and Madsen (2010) studied on the impact of average market price behaviour on wind energy by using a non-parametric regression model. They concluded that, the effects of wind power forecast on the average behaviour, the non-linearity and time variations in the relationship are quite substantial. Lam, Tang, and Li (2008) analysed the seasonal variations in residential and commercial sector electricity consumption in Hong Kong using a multiple regression technique. They concluded that, regression models could be a good indicator for the annual electricity consumption. Gorucu (2004) evaluated and forecast the gas consumption in Ankara, Turkey using a multivariable regression analysis. The study included an approach that understood the factors affecting gas demand in Ankara, Turkey.

1.3. Previous studies on hybrid wind-solar energy systems

A lot of studies have been done on hybrid solar PV-wind power systems (Petrakopoulou, Robinson, & Loizidou, 2016; Ribeiro, Arouco, & Coelho, 2016; Romero Rodríguez, Salmerón Lissén, Sánchez Ramos, Rodríguez Jara, & Álvarez Domínguez, 2016). Bekele and Palm (2010) investigated on the feasibility and economic viability of a hybrid solar PV-wind-diesel battery power system to meet the load requirement of 200 families in an Ethiopian community. Their research contributes to improving electricity coverage in a community in Ethiopia, compares many scenarios to enable investors make a selection and proposes diesel generator and a battery as a storage facility to ensure uninterrupted power supply in the selected community. Nonetheless, the authors doubted the outcome of their study due to the limited coverage of their study. In the same vein, their results are not certain if it can be applicable to other regions in Ethiopia with similar or different weather patterns. Their proposed hybrid system was claimed to contribute to a reduction in environmental emissions without justification from their study.

Yang, Wei, and Chengzhi (2009) investigated on the optimal design of a hybrid solar-wind power system by employing battery banks as system storage. Importantly, their study improves on battery over-discharge situations which are associated with battery banks. Their study employs the concept
of loss of power probability which eventually enables system optimum configuration. Nonetheless, battery bank storage systems are not ideal due to the occurrence of losses in storing periods, charging and discharging cycles. Their study measures a one-year field data which is somewhat difficult to be conclusive in the subject matter since the energy contribution from the various sources employed in their study varies.

In the same vein, Diaf, Belhamel, Haddadi, and Louche (2008) investigated on the assessment of a hybrid solar-wind power system by employing battery banks as system storage. Importantly, their study improves on the development of an optimum size of a system at a given load distribution that can fulfil a given energy requirement. Improving the optimal sizing of a hybrid solar-wind power system is critical to improving efficiency and economic viability of the proposed system. Their study also employs the concept of loss of power probability which enables system optimum configuration through an un-interruptible power supply from a wind generator. Nonetheless, battery bank storage systems have issues with reliability and are not ideal due to the occurrence of losses in charging, storing periods and discharging cycles. Also, assessing the optimal sizing of a hybrid solar-wind power system is location dependent, system reliability dependent and depends on the potentiality of wind and solar energy at a particular location.

Zhou, Lou, Li, Lu, and Yang (2010) investigated the control technologies for a hybrid solar-wind power system with battery storage. Their study suggested that a design for optimum resource allocation based on load demand is beneficial to reducing the initial and operation cost of a hybrid solar-wind power system. Nonetheless, probabilistic approaches are difficult to represent a changing performance of a hybrid solar-wind power system.

Cavalcanti and Motta (2015) investigated on a solar-powered-fuel-assisted Rankine cycle for power generation using an exergoeconomic analysis. Even though an economic analysis was performed in their study yet not feasible economically for investment since the cost of electricity is higher than conventional forms of power generation. Moreover, issues pertaining to water consumption and carbon dioxide emission as a result of the Rankine cycle were not assessed.

Nevertheless, our proposed study is a build-up on previous studies (Pehlivantürk, Özkan, & Baker, 2014) that mathematically modelled and simulated a concentrating solar power system in Middle East Technical University, Northern Cyprus Campus. Their micro solar power consisted of a parabolic trough collector (PTC), propane boiler, an organic Rankine cycle and a wet cooling tower. Their study was able to better the performance of the system by expanding the PTC field to burn little propane. Moreover, their study identified some non-concentrating evacuated tube collectors that possess improved thermal performance than PTCs. Nevertheless, little analysis was presented on water consumption by the Rankine cycle, their study was on a small-scale and the role of renewable energy was limited.

Majority of literature reviewed employs storage mechanisms such as battery banks that have issues with reliability and are not ideal due to the occurrence of losses in charging, storing periods and discharging cycles for hybrid solar-wind power system. Moreover, literature is limited in the scope of assessing a hybrid solar-wind-Rankine cycle power generation system that models energy demand and addresses environmental impacts by assessing water consumption and carbon dioxide emissions. Building on their research, our study models the future energy demand of TRNC based on the IPCC emissions scenario A1B and A2 by designing a new hybrid solar-wind-thermal power system that satisfies the current and future requirement of firm capacity during peak periods. Our study suggests an improvement in a hybrid solar-wind-thermal power system performance by predicting reliable outputs that can integrate renewable energy technologies (solar and wind energy) to conventional power generation (Rankine cycle based on propane) sources. To the best of our knowledge, this is the first of its kind a study combines both hybrid-solar PV-wind-Rankine cycle to meet future energy demand based on predicted IPCC scenarios. Our research will serve as an informative tool for local and foreign investors in TRNC while contributing to future research. Finally, we are aware of the
cost intensive nature and environmental unfriendliness of driving a Rankine cycle based on propane however, we opted for propane in order to accentuate the positives of renewable energy sources. In the long-run, the CO₂ emissions and water consumption for the Rankine cycle are estimated for the future electricity power demand based on the IPCC scenarios.

2. Methodology

2.1. Energy consumption and demand model

The energy consumption and demand model for the year 2004–2013 are the measured energy consumption values for TRNC from the Population Geography of the TRNC (Atasoy, 2012). However, the energy demand for year 2014–2050 was modelled using:

\[ y = a_1 x_1 + b_1 x_2 + f_1 \]  

where \( y \) is the energy demand or consumption, \( x_1 \) is the population and \( x_2 \) is the GDP. The \( a_1 \) is the population coefficient, \( b_1 \) is the GDP coefficient (for $10^{10}$) and \( f_1 \) is the intercept and the calculated values of these coefficients for TRNC are 2.18, 66.47 and 302,265, respectively. Appendix A show the analysis of future renewable energy demand, population and GDP based on IPCC scenario A1B.

IPCC scenario A1B describes a “future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies as a result of not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies” (IPCC Fourth Assessment Report on Climate Change, 2015). Based on the IPCC scenario A1B, the current study assumes a 1.01% population rise until 2030 in accordance with Atasoy (2012) and assumes a 1.005% population declines during 2030–2050. GDP increase is assumed to be 10% until 2017, in accordance to the rate of increase in GDP in the fastest increasing economies such as Brazil (Bank, http://data.worldbank.org/country/brazil), and 1% thereafter. Moreover, the heat engine efficiency is increased by 5% for every 10 years to include efficiency assumption of Scenario A1B. Finally, renewable energy contribution is assumed to immediately increase to 20%, which is stated in EU 20-20-20 plan (European Commission, 2015) and keeping the same ratio until 2050.

IPCC scenario A2 assumes that economic growth will be more evenly distributed, i.e. none of the economic factors will be rapid but stable, and so GDP increase is taken as 2.3% per annum in accordance with Intergovernmental Panel on Climate Change Report on Economic Development on Emissions Scenarios (SRES) (Change IPoC, 2015a). As the population is assumed to be rising in the same way it does at the moment, its rise is always taken as 1.01%. Moreover, in the current scenario, future is described as a delayed renewable energy sources, so renewable energy contribution is modified to be 10, 12, 15, 17.5 and 20% during 2010–2020, 2020–2030, 2030–2040, 2040–2050, respectively. Finally, as technological advances are slower than Scenario A1B, heat engine efficiency is taken as 20, 22.5, 25, 27.5 and 30%, respectively, for the periods mentioned above.

2.2. Solar resources model

Using the TMY2 data, the terrestrial solar resources model for fixed surfaces is used to calculate the maximum solar resources and hence the PV power is expressed as:

\[ E_{\text{pv}} = \eta_{\text{sys}} \eta_{\text{pv}} I_{\text{pv}} A_{\text{pv}} \]  

where \( E_{\text{pv}} \) is the energy output from the PV panel, \( \eta_{\text{sys}} \) is the system performances ratio, \( \eta_{\text{pv}} \) is the conversion efficiency of an individual PV module, \( I_{\text{pv}} \) is the hourly insolation in the plane of the PV modules and \( A_{\text{pv}} \) is the total area of PV modules (Duffie & Beckman, 1980).

\[ \eta_{\text{pv}} = \eta_{\text{ref}} \left( 1 - \rho_{\text{ref}} \left[ T_a - T_{\text{ref}} + (T_{\text{noct}} - T_a) \frac{I_{\text{pv}}}{I_{\text{noct}}} \right] \right) \]
where $\eta_{\text{ref}}$ is the PV module efficiency at reference conditions, $T_{\text{ref}}$ (25°C) and $I_{\text{noct}}$ (800 Wh.m$^{-2}$) and $T_a$ is the ambient temperature. $I_{\text{pv}}$ is the insolation for the PV panel. In the implemented model, different solar areas were used to keep constant the solar power generation from year to year.

2.3. Wind resources model

The TMY wind resources are used to calculate the hub height wind speed for the wind turbine model. The hub height wind speed ($U_h$) can calculate from 10-m height wind speed ($U_{\text{tmy}}$) data as,

$$U_h = U_{\text{tmy}} \left( \frac{Z_h}{Z_{\text{tmy}}} \right)^\alpha$$

(4)

where $Z_h$ is the wind turbine hub height and $Z_{\text{tmy}}$ is the height for the TMY wind data, wind shear constant $\alpha$ is 0.147. The electric power generated from the corresponding wind resources was calculated using the WGT model (Johnson, 2005) (Appendix B).

2.4. Thermal energy model

Moreover, Pehlivanturk’s work (Pehlivantürk et al., 2014) was used in order to model heat engine, hence CO$_2$ emission and water consumption. Although mathematical details are not given in this report for brevity, it is mandatory to state that the model flowchart is modified in a way that backup boiler is used when total electricity produced that would be generated with only solar and wind sources is not enough to supply the demand. So,

$$\dot{Q}_{\text{boiler}} = \left[ \max (W_{\text{demand}} - W_{\text{solar}} - W_{\text{wind}}, 0) \right] \div \text{(cycle thermal efficiency)} \quad (5)$$

where $\dot{Q}_{\text{boiler}}$ is the rate of heat transfer to the heat transfer fluid in the boiler, $W_{\text{demand}}$ rate of demand, $W_{\text{solar}}$ rate of work from solar and $W_{\text{wind}}$ is the rate of work from wind.

Using the work of Pehlivantürk et al. (2014), the analysis of water consumption of the heat engine is calculated as;
\[ Q_c = \rho_{H_2O} V_{H_2O} h_{fg} \]  

(6)

where the low temperature heat transfer from the Rankine cycle \( (Q_c) \) is used to evaporate water at 25°C (isothermal latent cooling), \( \rho_{H_2O} \) is the density of water, \( V_{H_2O} \) is the volumetric rate of water consumption by the cooling heat engine and \( h_{fg} \) is the enthalpy of the evaporation of water. Figure 1 shows the schematic representation of the proposed hybrid solar photovoltaic-wind turbine-Rankine cycle.

3. Results and discussion

In Table 1, the regression analysis of future renewable energy demand, population and GDP for the years 2010–2050 is given. In Table 1 (Scenario A1B), a multiple R value of 0.95 shows that there is a strong relationship between the future renewable energy generated (demand), population and GDP for the corresponding years.

In Figure 2, the electricity generation by renewable energy sources for TRNC is given. In Figure 2, the energy demand increases gradually with increasing population growth which is in line with a multitude of literature. Between the years 2015–2050 based on IPCC scenario A1B, the renewable energy demand increases from 300 to 400 GWh whilst energy consumption gradually increases from 150 to 450 GWh in IPCC scenario A2. In Figure 2(a), as it can be seen, slope changes at year 2017 and 2030 because of the storyline and corresponding assumptions mentioned in methodology. It was stated that GDP tends to increase by 10% per annum until 2017, and tends to rise by 1% thereafter which explains the change in slope at 2017. Moreover, after 2030, population is assumed to drop, explaining the change in slope at 2030. Likewise, in Figure 2(b), there are jumps in electricity generation, which is because of increasing renewable energy contribution instantly during the corresponding years. The energy demand in these two scenarios cannot be supplied by the hybrid solar photovoltaic-wind power system alone. Therefore, to compensate for future energy demand, a Rankine cycle electricity generating system was added.

In Figure 3, the contribution percentage of hybrid-solar photovoltaic-wind-Rankine cycle for TRNC is given. TRNC reaches its maximum amount of solar radiation in mid-year periods during summer months and minimum solar radiation during winter months. As a result of that the maximum PV solar energy output can be achieved during the summer period as shown in Figure 3. In this regard, the contribution of Rankine cycle power generation is minimum in mid-year periods and maximum in winter and spring season. In the presented model, the energy demand that cannot be supplied by the hybrid solar photovoltaic-wind power system during peak hours is compensated using the Rankine cycle power generation as shown in Figure 3. Nonetheless, the wind power energy output for the entire year seems constant due to the non-variability of wind speed.

The model is designed to keep a constant contribution of the solar, wind and RC for each year during the period 2010–2050 as shown in Figure 4. The contribution of solar for the energy consumption is kept constant using the corresponding different solar areas of the PV panel and wind energy is kept constant by increasing the wind turbines. The Rankine cycle contribution to the energy generation is kept at 64% for each year instead of the battery bank.

| Table 1. Regression analysis of future renewable energy demand, population and GDP for the years 2010–2050 for scenario A1B |
|---------------------------------|---------------------|
| Regression statistics            | \( p < 0.05 \)       |
| Multiple R                      | 0.953               |
| \( R^2 \)                       | 0.908               |
| Adjusted \( R^2 \)              | 0.882               |
| Standard error                  | 58,796.299          |
| Observations                    | 10                  |
In Figure 5, the hourly CO$_2$ emission from hybrid-solar photovoltaic-wind-Rankine cycle for TRNC is given. CO$_2$ emission is minimum at summer and maximum in winter and spring, which is due to increasing demand of electricity for heating purposes during the cold season and the high insolation of solar energy led to high contribution of solar PV energy for the system. In Figure 5(a), CO$_2$ emissions increase on a yearly basis due to increasing yearly energy demands.
Nonetheless, the gap between the yearly CO$_2$ decreases with respect to the increasing years as depicted in Figure 6. As the rate of CO$_2$ emissions decreases with increasing CO$_2$ emissions and increasing years which is in line with IPCC emission scenario A1B (Change IPoC, 2015b) (Appendix B). In Figure 5(b), the increasing rate of the CO$_2$ emissions increases with increasing years for scenario A2 which is confirmed by Figure 6. However, at the beginning of year 2014, CO$_2$ emissions are comparably higher in scenario A1B as compared to scenario A2, but the opposite occurs at the end of 2050 as shown in Figure 6. Another reason for having different trends of emissions in Figure 5 is the RE contribution and heat engine efficiencies. Even though both scenarios have increasing demand curves as shown in Figure 2, RE contribution is always increasing in Scenario A2 with less efficiency.
increase compared to Scenario A1B, making efficiency change unable to compensate electricity generation.

In Figure 7, the annual increase in hourly CO$_2$ emission is given. For scenario A1B model, the annual increasing rate of CO$_2$ emissions decreases until year 2040 as shown in Figure 7(a). But for scenario A2, the annual increasing rate of CO$_2$ emissions increases until year 2050 as shown in Figure 7(b). This outcome is due to IPCC scenario A2 which describes a future with delayed renewable energy.

In Figure 8, the hourly water consumption for the hybrid-solar photovoltaic-wind-Rankine cycle for TRNC is given. A substantial amount of water is a requirement for the proposed model as shown in Figure 8. The minimum amount of water is required in summer periods due to the less contribution of Rankine cycle power generating system. Same as CO$_2$, water consumption increases yearly.
With reference to scenario A1B, water consumption for power generation increases until year 2030 and begins to decrease thereafter as shown in Figure 8(a) and Figure 9. The reason is that water consumption is directly related with heat engine efficiency, and after 30% of efficiency (year 2030), even though the demand is increasing, effect of efficiency increases compensates the increase in demand, resulting in less water to be consumed at cooling tower. Notwithstanding, water consumption gradually increases in scenario A2 as shown in Figure 8(b). The water consumption at the beginning of year 2010 is comparably low in scenario A2 compared to scenario A1B.
In Figure 10, the annual increase in hourly water consumption is given. In scenario A1B, water consumption gradually decreases at an increasing rate as shown in Figure 10(a). However, water consumption gradually increases at an increasing rate in scenario A2 as shown in Figure 10(b).

4. Conclusions and future work

In this study, a multiple linear regression analysis was used to calculate the future renewable energy consumption for TRNC through a linear interpolation of GDP and population of TRNC based on the IPCC emission scenarios A1B and A2. A mathematical model for an autonomous hybrid solar-wind-heat engine was developed and CO$_2$ emissions and water consumption were calculated for years 2010–2050.

The energy consumption prediction model clearly emphasizes that the energy requirement for electricity has a growing demand from 300 to 400 GWh in scenario A1B and 150 to 450 GWh in scenario A2 during the period 2010–2050, which is impossible to meet using an autonomous hybrid solar-wind turbine. This led to a design of a hybrid-solar photovoltaic-wind turbine-Rankine cycle to compensate the future electricity demand of TRNC during peak hours. The results of the study are summarized as follows:

- The hybrid-solar photovoltaic-wind turbine-Rankine cycle can meet 400 GWh of electricity demand in TRNC based on scenario A1B.
- The hybrid-solar photovoltaic-wind turbine-Rankine cycle can meet 450 GWH of electricity demand in TRNC based on scenario A2.
- The annual increasing rate of CO$_2$ emissions decreases until year 2040 in IPCC scenario A1B.
- The annual increasing rate of CO$_2$ emissions increases until year 2050 in IPCC scenario A2.
The study can further be developed by following a probabilistic approach instead of a deterministic one. Instead of finding definite amounts of CO₂ emissions and water consumption, possible range of such values with a satisfying level of confidence interval would be handier to plan for the future. Moreover, the other IPCC scenarios such as B1 and B2 which were absent in the current study can be modelled to increase the number of strategic planning. Finally, a storage system such as a pumped hydro power system can be hybridized with the current system to store the excess amount of energy generated.

**Nomenclature**

- \( E_{pv} \): Energy output from the PV panel
- \( \eta_{sys} \): System performances ratio
- \( \eta_{pv} \): Conversion efficiency
- \( I_{pv} \): Hourly insolation in the plane of the PV modules
- \( A_{pv} \): Total area of PV modules
- \( \eta_{ref} \): PV module efficiency at reference conditions
- \( T_a \): Ambient temperature
- \( U_h \): Hub height wind speed
- \( Z_h \): Wind turbine hub height
- \( Z_{tmy} \): Height for the TMY wind data
- \( \alpha \): Wind shear constant
- \( Q_{boiler} \): Rate of heat transfer in the boiler

**Acronyms**

- RE: Renewable Energy
- TRNC: Turkish Republic of Northern Cyprus
- GDP: Gross Domestic Product
- IPCC: Intergovernmental Panel on Climate Change
- TMY2: Typical Meteorological Year 2
- HE: Heat Engine

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**Cover image**

Source: Authors.

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### Appendix A

Analysis of future renewable energy demand, population and GDP based on IPCC scenario A1B.

| Year | Energy consumption (MWh) | Population | GDP (×10^6 TL) | Demand for RE (MWh) |
|------|--------------------------|------------|----------------|---------------------|
| 2004 | 900,000                  | 218,066    | 2,456          |                     |
| 2005 | 1,025,000                | 220,289    | 3,070          |                     |
| 2006 | 1,125,000                | 256,644    | 3,988          |                     |
| 2007 | 1,200,000                | 268,011    | 4,604          |                     |
| 2008 | 1,245,000                | 270,691    | 5,080          |                     |
| 2009 | 1,230,000                | 273,398    | 5,376          |                     |
| 2010 | 1,245,000                | 276,132    | 5,614          |                     |
| 2011 | 1,275,000                | 278,893    | 6,612          |                     |
| 2012 | 1,375,000                | 281,682    | 7,425          |                     |
| 2013 | 1,375,000                | 284,499    | 7,507          |                     |
| 2014 | 1,478,013                | 287,344    | 8,258          | 295,603             |
| 2015 | 1,539,173                | 290,218    | 9,083          | 307,835             |
| 2016 | 1,605,886                | 293,120    | 9,992          | 321,177             |
| 2017 | 1,678,699                | 296,051    | 10,991         | 335,740             |
| 2018 | 1,692,463                | 299,011    | 11,101         | 338,493             |
| 2019 | 1,706,365                | 302,002    | 11,212         | 341,273             |
| 2020 | 1,720,406                | 305,022    | 11,324         | 344,081             |
| 2021 | 1,734,588                | 308,072    | 11,437         | 346,918             |
| 2022 | 1,748,911                | 311,152    | 11,552         | 349,782             |
| 2023 | 1,763,378                | 314,264    | 11,667         | 352,676             |
| 2024 | 1,777,989                | 317,407    | 11,784         | 355,598             |
| 2025 | 1,792,746                | 320,581    | 11,902         | 358,549             |
| 2026 | 1,807,651                | 323,786    | 12,021         | 361,530             |
| 2027 | 1,822,705                | 327,024    | 12,141         | 364,541             |
| 2028 | 1,837,909                | 330,295    | 12,262         | 367,582             |
| 2029 | 1,853,265                | 333,598    | 12,385         | 370,653             |
| 2030 | 1,868,775                | 336,934    | 12,509         | 373,755             |
| 2031 | 1,873,415                | 339,249    | 12,634         | 374,683             |
| 2032 | 1,878,157                | 333,573    | 12,760         | 375,631             |
| 2033 | 1,883,001                | 331,905    | 12,888         | 376,600             |
| 2034 | 1,887,948                | 330,245    | 13,017         | 377,590             |
| 2035 | 1,892,998                | 328,594    | 13,147         | 378,600             |
| 2036 | 1,898,153                | 326,951    | 13,278         | 379,631             |
| 2037 | 1,903,414                | 325,316    | 13,411         | 380,683             |
| 2038 | 1,908,780                | 323,690    | 13,545         | 381,756             |
| 2039 | 1,914,254                | 322,071    | 13,681         | 382,851             |
| 2040 | 1,919,835                | 320,461    | 13,817         | 383,967             |
| 2041 | 1,925,525                | 318,859    | 13,956         | 385,105             |
| 2042 | 1,931,323                | 317,264    | 14,095         | 386,265             |
| Year | Energy consumption (MWh) | Population | GDP ($\times 10^6$ TL) | Demand for RE (MWh) |
|------|-------------------------|------------|-------------------------|---------------------|
| 2043 | 1,937,233               | 315,678    | 14,236                  | 387,447             |
| 2044 | 1,943,253               | 314,100    | 14,379                  | 388,651             |
| 2045 | 1,949,385               | 312,529    | 14,522                  | 389,877             |
| 2046 | 1,955,629               | 310,966    | 14,668                  | 391,126             |
| 2047 | 1,961,988               | 309,412    | 14,814                  | 392,398             |
| 2048 | 1,968,460               | 307,865    | 14,962                  | 393,692             |
| 2049 | 1,975,048               | 306,325    | 15,112                  | 395,010             |
| 2050 | 1,981,753               | 304,794    | 15,263                  | 396,351             |

**Appendix B**

**Model Validation and Verification**

The wind model employed in this study is verified with third-party software RETScreen by National Resources Canada and validated with VESTAS power model as shown in Figure 11(a). The CO$_2$ emission analysis model (observed) (Figure 6) fits into IPCC’s Multi-Model Averages and Assessed Ranges for Surface Warming (expected) as shown in Figure 11(b).
