

# A Wind Energy-Based Cogeneration System for Energy and Fresh Water Production



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## Nomenclature

$A$	Area, $m^2$
$ex$	Specific exergy, $kJ/kg$
$\dot{E}x_d$	Exergy destruction rate, $kW$
$h$	Specific enthalpy, $kJ/kg$
$I_r$	Solar irradiation, $kW/m^2$
$\dot{m}$	Mass flow rate, $kg/s$
$\dot{Q}$	Heat rate, $kW$
$s$	Specific entropy, $kJ/kgK$
$\dot{S}_{gen}$	Entropy generation rate, $kW/K$
$\dot{W}$	Work rate, $kW$
$X$	Salination, $g/kg$

## Greek Letters

$\eta$	Energy efficiency
$\Psi$	Exergy efficiency
$\rho$	Density, $kg/m^3$
$\epsilon$	Effectiveness

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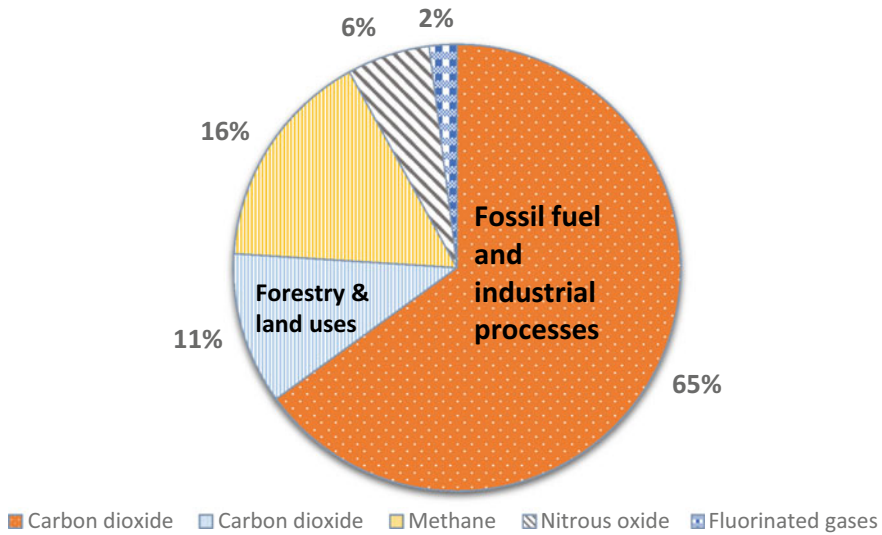
## Acronyms

CAES	Compressed air energy storage
EES	Engineering Equation Solver
HFO	Heavy fuel oil
GHG	Greenhouse gas
TES	Thermal energy storage

## 1 Introduction

Global warming and its associated impacts on nature, e.g. water scarcity, increasing fire threats, drought, salt level increase in soil, higher wildlife extinction rates and infectious diseases, is addressed as one of the primary threats to the existence of the living species by many authorities (<https://www.un.org/en/chronicle/article/health-effects-global-warming-developing-countries-are-most-vulnerable>, [https://ec.europa.eu/clima/change/consequences\\_en](https://ec.europa.eu/clima/change/consequences_en), <https://www.canada.ca/en/services/environment/weather/climatechange/causes-effects.html>). The increase in the heat-trapping greenhouse gases in the atmosphere causes temperature rise and eventually change in climate pattern on a local and global level. Due to its long residence in the atmosphere, carbon dioxide (CO<sub>2</sub>) emissions primarily from human activities are known as the main driver of the on-going global warming and its side impacts on the planet earth. Since the industrial revolution, the energy needs of humankind to sustain the life and living standards have been increasing cumulatively. Fossil fuels were and still are the main source to meet this energy demand. Today, about 80% of the global energy supply is from fossil fuels (<https://www.capp.ca/energy/world-energy-needs/>). Figure 1 shows the ratios of the greenhouse gas emissions (GHGs) for different gases. Fossil fuels and its related activities, e.g. extraction, processing and burning, are responsible from 65% of global CO<sub>2</sub> emissions. Therefore, the primary objective for mitigation of global warming is to be the development of efficient and environmentally benign energy technologies.

Conventional fossil fuel-based energy technologies cause economic and ecological problems due to unstable fuel prices and emitting large amount of CO<sub>2</sub> when combusted. On the other hand, renewable resources, i.e. wind and solar, are more than enough to make the energy supply nature-friendly. However, intermittent characteristics of these resources raise concerns in terms of reliability. This can be mitigated/avoided by correct approaches to the renewable energy systems. The most common one is to store the obtained energy when it is abundant and offer to the service when it is needed. The selection of the correct energy storage system is also critical. For instance, pumped hydro is recognized as the most commonly used method for energy storage forming almost 95% of energy storage systems operating across the globe (<https://www.hydropower.org/factsheets/pumped-storage>). On the other hand, this approach may not be feasible in every cases due to geographical



**Fig. 1** Global greenhouse gas emissions ratios (Data from <https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data>)

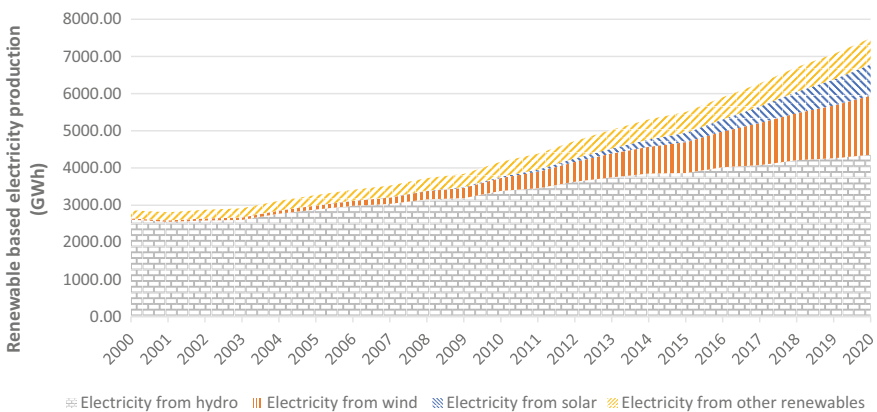
and topographical restrictions. Chemical energy storage in the form of hydrogen is another promising method to store energy effectively and nature-friendly. In this case, the excess electricity can be used in the hydrogen production via electrolysis of water, and then the produced hydrogen can be converted back to electricity via fuel cells without any harm to the nature. As a mechanical energy storage method, compressed air energy storage systems (CAESs) is an alternative nature-friendly approach that is commonly investigated. In CAES, the excess energy is used to compress the air into a storage medium, which can be an underground cavern, or a balloon located under the surface of water. When it is needed, the energy is reproduced by the expansion of the compressed air through gas turbines. Use of underwater balloons may provide the advantage of utilizing from the hydrostatic pressure; thus, the instant pressure drops and decency of the storage medium can be achieved without any extra effort. Main drivers to consider renewable energy together with energy storage can be summarized as follows:

- To provide power on demand in case renewable resources are insufficient;
- To harness more energy from renewable resources;
- To decrease CO<sub>2</sub> emission rates of power sector by penetrating more clean energy to grid;
- To manage the problems associated with intermittency of the renewable resources.

In the scope of a more sustainable planet, the production of electricity from wind energy is one of the most promising and, consequently, one of the fastest growing renewable-based electricity generation methods. In 2000, the global installed wind capacity was 17.6 GW, and global electricity production from wind was about 30

GWh (<https://www.nrel.gov/docs/fy01osti/29436.pdf>). In 2020, these ratios reached to 743 GW of global wind capacity and global wind-based electricity production of 1590 GWh (<https://ourworldindata.org/renewable-energy>). Figure 2 shows the global renewable-based electricity generations trends with respect to sources from 2000 to 2020. Wind turbine can be located as on-shore and off-shore. Off-shore wind power generation plants can enjoy higher wind speeds and larger wind blades diameters that allows to generate electricity at higher rates compared to the on-shore applications. Nonetheless, off-shore wind-based electricity production has much higher capital and operational costs. Due to this, about 93% of the global installed wind capacity is on-shore. The energy in the form of kinetic energy from moving air is converted to mechanical energy via wind turbines and eventually to electricity via generator taking place in the body of the wind turbine set-up.

The selection of site with a favorable weather pattern is critical for effective operation of wind turbines. In this regard, the minimum wind speed of 12–14 km/h, which is also known as cut-in speed, is addressed to turn turbine blades to capture energy from blowing wind and produce the useful output of electricity ([https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/WindEnergy\\_buyersguide\\_ENG.pdf](https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/WindEnergy_buyersguide_ENG.pdf)). The size of the wind turbine blades, wind speed and air density are some major parameters that define the amount of energy produced by wind turbines. Higher wind speeds mean to more energy available in the wind and electricity production via wind turbines at higher rates. However, wind turbines are designed to cope with certain wind speeds. In this regard, a cut-out wind speed is defined for safe operation of wind turbines that vary by turbine design (up to 80 km/h) (<https://www.energy.gov/eere/articles/how-do-wind-turbines-survive-severe-storms>). This is the maximum wind speed that wind turbines are capable of bearing if every single components in the system in cooperation, but in practice, wind turbines are stopped operating before reaching these ranges to remain in a safe zone.

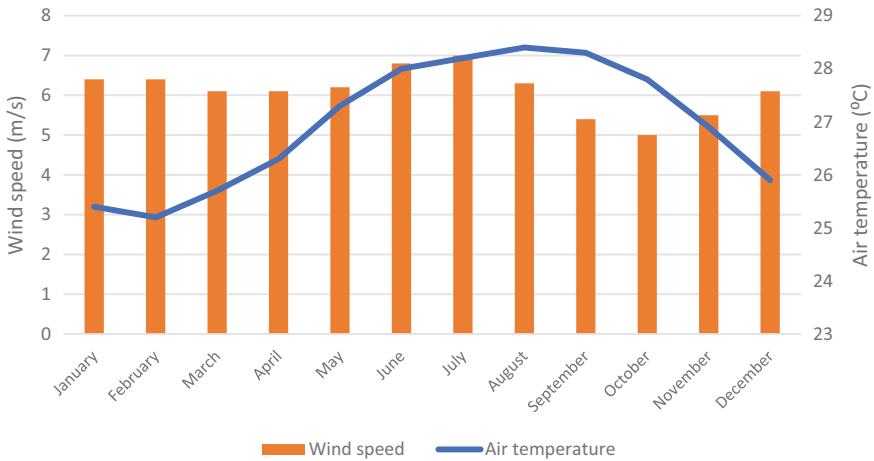


**Fig. 2** Global renewable based electricity by sources from 2000 to 2020 (Data from <https://ourworldindata.org/renewable-energy>)

Another important parameter that defines the energy extraction ratio from wind is the Betz limit. Similar to Carnot cycle efficiency in thermodynamics, stating that all energy provided to a heat engine cannot be turned into useful output and partially must be rejected to the environment, Betz limit defines the limits of extracting energy from wind. According to Albert Betz, theoretical maximum efficiency of a wind turbine cannot exceed 59.3%; meaning that only 59.3% of the kinetic energy can be used for spinning wind turbines to generate electricity (Ragheb and Ragheb 2011). In practice, wind turbines cannot reach to this efficiency, and commonly practiced wind turbine efficiencies falls between 35 and 45% range (<https://css.umich.edu/factsheets/wind-energy-factsheet>). It should be noted that the Betz limit defines the maximum kinetic energy that can be turned into mechanical energy by a wind turbine. Since the desired useful output from wind power plants is electricity, the efficiency of other system components, i.e. gearbox and generator, must be considered while calculating the electrical output of wind turbines.

In this study, the system developed is evaluated within the scope of a case study for which Antigua and Barbuda is selected as the region for the potential implementation of the system. Antigua and Barbuda is an island nation with a total population of 96,286 (<https://datacommons.org/place/country/ATG#Environment>). The country consists of two main islands and several small islands covering an area of 443 square kilometers (km<sup>2</sup>) in total (Vinet and Zhedanov 2011). For its energy, the country relies on imported fossil fuels, and heavy fuel oil is the main source used for the electricity production in the country. Due to this, the country struggles with unstable and high energy prices (0.4 US\$/kWh) as well as high CO<sub>2</sub> emission rates (<http://www.apua.ag/customer-service/rates/>). The drinking water sector in Antigua and Barbuda is reliant on seawater desalination through reverse osmosis, and fresh water production consumes about 36 GWh of electricity annually, which corresponds to around 12% of the total electricity consumption in the country (<https://www.worlddata.info/america/antigua-barbuda/energy-consumption.php>). Hydropower, geothermal, and bioenergy resources are all said to be unavailable in the country. On the other hand, the country has a good solar insolation, and the capacity of power generation from wind is reported as 400 MW for the region (Samuel 2021). Figure 3 shows the average wind speed of Antigua and Barbuda for the corresponding months. The specific objectives of the study are listed as follows:

- To design and develop a wind-based multigeneration integrated energy system;
- To conduct a thermodynamic analysis on the system and determine energy and exergy efficiencies of the system;
- To evaluate the system performance through parametric studies by considering primary design and operational parameters;
- To conduct a case study for a potential implementation of the system in Antigua and Barbuda by considering regional parameters.



**Fig. 3** Monthly average wind speed and air temperature of Antigua and Barbuda (<https://www.weather-atlas.com/en/antigua-and-barbuda/codrington-climate#wind>)

## 2 System Description

Within the scope of the current study, a wind based integrated energy systems is investigated through thermodynamic approaches. The developed system utilizes from wind as a primary energy source. The excess energy likely to occur during the off-peak time of the energy demand is stored via compressed air energy storage (CAES) system located underwater. Further, the waste heat occurring from the air compression process is stored in a thermal energy storage (TES) tank, and later introduced to the compressed air before the expansion through gas turbines. Lake/river water is utilized as a cooling agent to manage the temperature between the compression stages and store the thermal energy in the TES tank. After use in the interheaters to increase the carried energy within the compressed air before the expansion, the water is released back to its environment with acceptable temperatures to avoid any potential thermal pollution. The integrated system also comprises a thermal desalination system to produce fresh water from seawater, for which the required thermal energy is provided from the excess heat from the air compression process. The system consists of 100 wind turbines with a blade radius of 50 m. The energy analysis of the system is performed by considering an average wind speed of 8 m/s and a power coefficient of 49%. Figure 4 illustrates the system diagram. Antigua and Barbuda is selected as a region to evaluate the system as a case study. Table 1 presents the energy overview of the country. Table 2 presents the specifications considered in the analysis of the system.

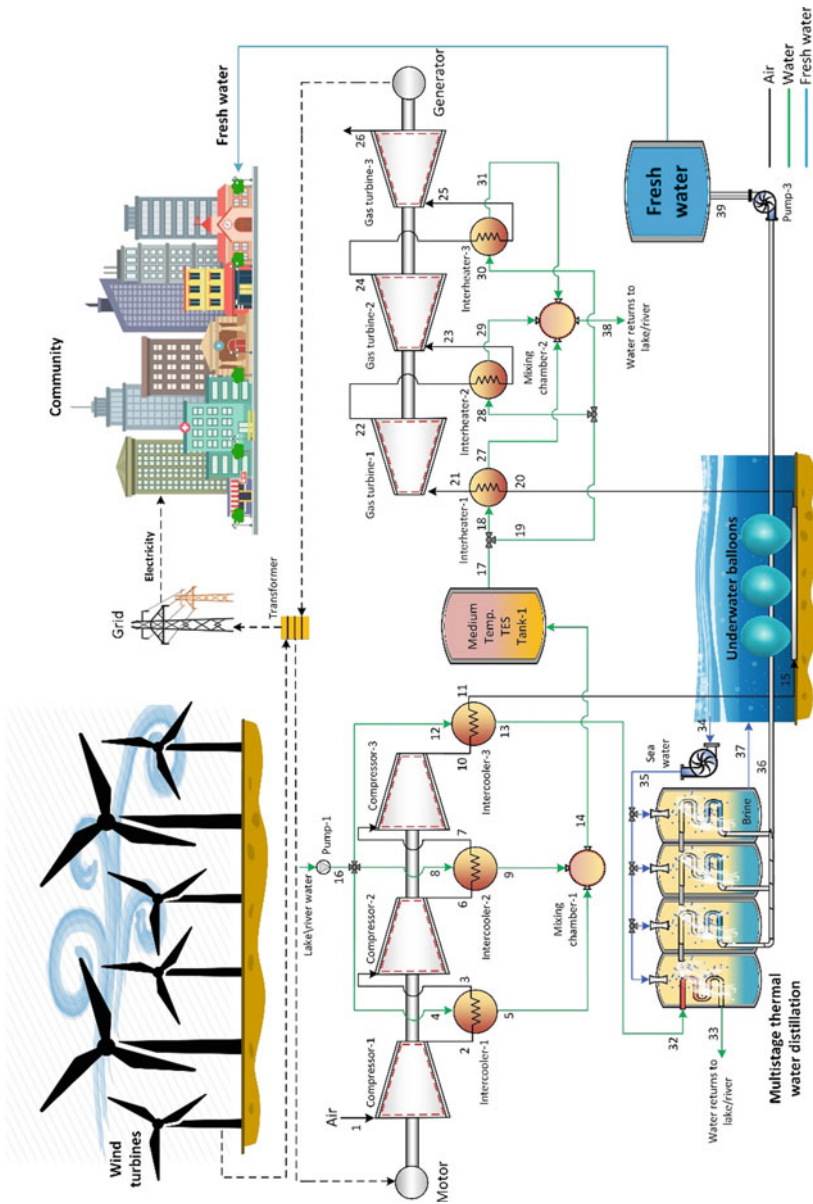


Fig. 4 A wind based integrated power system (Adapted from Karaca et al. (2021))

**Table 1** Energy overview of Antigua and Barbuda (<https://www.worlddata.info/america/antigua-barbuda/energy-consumption.php>)

Parameters	Value
Electricity consumption (GWh/year)	308
Energy source	Fossil fuel (97%)
Electricity retail price (US\$/kWh)	0.4
Main fresh water supply (HFO-powered)	Seawater reverse osmosis desalination
Fresh water electricity consumption (GWh/year)	36
CO <sub>2</sub> emission (tons/year)	557 million
CO <sub>2</sub> emission per capita (tons)	5.9

**Table 2** Specifications of the facility

Parameters	Value
Region	Antigua and Barbuda
Wind speed	8 (m/s)
Power coefficient of wind turbine ( $C_p$ )	49%
Wind turbine efficiency (Generator (90%) and gearbox (80%))	72%
Wind turbine blade radius	50 m
Number of wind turbines required (1.5 MW/turbine)	100
Required area for wind turbines (1.8 acres/MW) ( <a href="https://www.saskwind.ca/land-area">https://www.saskwind.ca/land-area</a> )	270
Pressure ratio	$r_p = 6.7$

## 2.1 System Analysis

The proposed system is evaluated through energy and exergy approaches. Thermodynamic balance equations for corresponding sub-components are presented in Table 4 in accordance with the state points as illustrated in Fig. 4. The following assumptions are considered while conducting the thermodynamic analysis of the system:

- The steady state and adiabatic operations in the pumps, compressors and turbines.
- The reference temperature and pressure for air: 25 °C and 101.3 kPa.
- The reference temperature and pressure for water: 17 °C and 101.3 kPa.
- The reference state temperature and pressure for seawater: 20 °C and 101.3 kPa.
- The isentropic efficiency of 85% for pump, compressor and turbine operations.
- The potential pressure losses throughout the system are neglected.
- The potential and kinetic energy changes are neglected.

The specific exergy of a given state point can be calculated by

$$ex_i = h_i - h_0 - T_0(s_i - s_0) \quad (1)$$



Both compressor (including pump) and turbine isentropic efficiencies can be computed by

$$\eta_{s_{comp}} = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}} \tag{2}$$

$$\eta_{s_{turbine}} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{3}$$

The exit temperature for the isentropic compressor operation can be identified by ( $k = 1.4$ )

$$\frac{T_{out,s}}{T_{in}} = \left( \frac{P_{out}}{P_{in}} \right)^{\frac{(k-1)}{k}} \tag{4}$$

For the multistage water desalination unit, mass balance equation is as follows [e.g., Demir and Dincer 2017]:

$$\dot{m}_{sw} = \dot{m}_b + \dot{m}_{des} \tag{5}$$

$$\dot{m}_{sw} X_{sw} = \dot{m}_b X_b \tag{6}$$

where  $\dot{m}_{sw}$ ,  $\dot{m}_b$ ,  $\dot{m}_{des}$ ,  $X_{sw}$ ,  $X_b$  are fed seawater mass flow rate, brine mass flow rate, desalinated product mass flow rate, fed seawater salinity, and brine salinity, respectively. Table 3 presents the values of the variables used in the analysis of the multistage water desalination unit.

The temperature increase during the air compression process is managed by inter-coolers between the stages in which lake/river water is utilized as a cold stream fluid.

**Table 3** Thermodynamic properties of desalination unit (Azhar et al. 2017)

Process	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)	Specific exergy (kJ/kg)	Salination (g/kg)
Hot water in	373.6	101.3	4.903	2572	7.07	522.8	–
Hot water out	305	101.3	4.903	133.6	0.462	1.537	–
Sea water in	293.15	101.3	65.21	78.19	0.2726	0.217	48
Brine out	304.2	4.495	61.42	120.8	0.4147	0.4812	50.96
Distilled product	304.2	4.495	3.79	2557	8.432	113	0

The thermal energy absorbed by the fluid is conveyed and stored into a thermal energy storage tank (TES). During the discharging period where wind speed is not high enough to produce enough power, the energy in the TES tank is utilized in interheaters to further increase the carried energy by the compressed air before expanding through gas turbines to generate power. The effectiveness of the heat exchangers taking place in the aforementioned cycle is written as

$$\epsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{max}} \quad (7)$$

where  $\dot{Q}_{actual}$  is the actual heat transfer, and  $\dot{Q}_{max}$  is the maximum possible heat transfer between hot and cold stream in the heat exchangers.

$$\dot{Q}_{actual} = \dot{m}_{hs}c_{p,hs}(T_{hs,in} - T_{hs,out}) = \dot{m}_{cs}c_{p,cs}(T_{cs,out} - T_{cs,in}) \quad (8)$$

where subscript of “hs” indicates the hot stream, and “cs” is for the cold stream.  $c_p$  is the specific heat capacity (kJ/kgK) of the corresponding fluid at the corresponding state properties.

$$\dot{Q}_{max} = \dot{m}_{hs}c_{p,hs}(T_{hs,in} - T_{cs,in}) \quad (9)$$

or

$$\dot{Q}_{max} = \dot{m}_{cs}c_{p,cs}(T_{hs,in} - T_{cs,in}) \quad (10)$$

Here,  $\dot{Q}_{max}$  will be the minimum value obtained from these two equation. By employing the presented equations, the effectiveness of the heat exchangers operating in the compressed air cycle is evaluated as in a range between 0.612 and 0.955. The value of the 0.612 is obtained in the intercoolers, whereas the effectiveness of the interheaters is evaluated as 0.955.

Both energy and exergy efficiencies of the system are evaluated as charging phase and discharging phase. For the charging phase, in which the energy storage is implemented, the energy efficiency can be written as

$$\eta_{charging} = \frac{\dot{W}_{net} + \dot{Q}_{ca} + \dot{Q}_{Tes}}{\dot{W}_{wind}} \quad (11)$$

where  $\dot{W}_{net}$  represents the net power output from the system,  $\dot{Q}_{ca}$  is the energy storage in the form of compressed air,  $\dot{Q}_{Tes}$  is the thermal energy storage in the TES tank and  $\dot{W}_{wind}$  is the available wind power hitting the wind turbines. Table 4 shows thermodynamic balance equations written for the each sub-components taking place in the overall system.

**Table 4** Thermodynamic balance equations of the corresponding sub-units

Component	Mass balance equation	Energy balance equation	Entropy balance equation	Exergy balance equation
Compressor-1	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1 h_1 + \dot{W}_{in} = \dot{m}_2 h_2$	$\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2$	$\dot{m}_1 ex_1 + \dot{W}_{in} = \dot{m}_2 ex_2 + \dot{E}x_d$
Intercooler-1	$\dot{m}_2 = \dot{m}_3$ $\dot{m}_4 = \dot{m}_5$	$\dot{m}_2 h_2 + \dot{m}_4 h_4 = \dot{m}_3 h_3 + \dot{m}_5 h_5$	$\dot{m}_2 s_2 + \dot{m}_4 s_4 + \dot{S}_{gen} = \dot{m}_3 s_3 + \dot{m}_5 s_5$	$\dot{m}_2 ex_2 + \dot{m}_4 ex_4 = \dot{m}_3 ex_3 + \dot{m}_5 ex_5 + \dot{E}x_d$
Compressor-2	$\dot{m}_3 = \dot{m}_6$	$\dot{m}_3 h_3 + \dot{W}_{in} = \dot{m}_6 h_6$	$\dot{m}_3 s_3 + \dot{S}_{gen} = \dot{m}_6 s_6$	$\dot{m}_3 ex_3 + \dot{W}_{in} = \dot{m}_6 ex_6 + \dot{E}x_d$
Intercooler-2	$\dot{m}_6 = \dot{m}_7$ $\dot{m}_8 = \dot{m}_9$	$\dot{m}_6 h_6 + \dot{m}_8 h_8 = \dot{m}_7 h_7 + \dot{m}_9 h_9$	$\dot{m}_6 s_6 + \dot{m}_8 s_8 + \dot{S}_{gen} = \dot{m}_7 s_7 + \dot{m}_9 s_9$	$\dot{m}_6 ex_6 + \dot{m}_8 ex_8 = \dot{m}_7 ex_7 + \dot{m}_9 ex_9 + \dot{E}x_d$
Compressor-3	$\dot{m}_7 = \dot{m}_{10}$	$\dot{m}_7 h_7 + \dot{W}_{in} = \dot{m}_{10} h_{10}$	$\dot{m}_7 s_7 + \dot{S}_{gen} = \dot{m}_{10} s_{10}$	$\dot{m}_7 ex_7 + \dot{W}_{in} = \dot{m}_{10} ex_{10} + \dot{E}x_d$
Intercooler-3	$\dot{m}_{10} = \dot{m}_{11}$ $\dot{m}_{12} = \dot{m}_{13}$	$\dot{m}_{10} h_{10} + \dot{m}_{12} h_{12} = \dot{m}_{11} h_{11} + \dot{m}_{13} h_{13}$	$\dot{m}_{10} s_{10} + \dot{m}_{12} s_{12} + \dot{S}_{gen} = \dot{m}_{11} s_{11} + \dot{m}_{13} s_{13}$	$\dot{m}_{10} ex_{10} + \dot{m}_{12} ex_{12} = \dot{m}_{11} ex_{11} + \dot{m}_{13} ex_{13} + \dot{E}x_d$
Mixing chamber-1	$\dot{m}_5 + \dot{m}_9 + \dot{m}_{13} = \dot{m}_{14}$	$\dot{m}_5 h_5 + \dot{m}_9 h_9 + \dot{m}_{13} h_{13} = \dot{m}_{14} h_{14}$	$\dot{m}_5 s_5 + \dot{m}_9 s_9 + \dot{m}_{13} s_{13} + \dot{S}_{gen} = \dot{m}_{14} s_{14}$	$\dot{m}_5 ex_5 + \dot{m}_9 ex_9 + \dot{m}_{13} ex_{13} = \dot{m}_{14} ex_{14} + \dot{E}x_d$
TES tank (charging)	$\dot{m}_{14} \times t = m_f$	$\dot{m}_{14} h_{14} \times t = m_f h_f$	$\dot{m}_{14} s_{14} \times t + S_{gen} = m_f s_f$	$\dot{m}_{14} ex_{14} \times t = m_f ex_f + Ex_d$
TES tank (discharging)	$m_i = \dot{m}_{17} \times t$	$m_i h_i = \dot{m}_{17} h_{17} \times t$	$m_i s_i + S_{gen} = \dot{m}_{17} s_{17} \times t$	$m_i ex_i = \dot{m}_{17} ex_{17} \times t + Ex_d$
Balloons (charging)	$\dot{m}_{15} \times t = m_f$	$\dot{m}_{15} h_{15} \times t = m_f h_f$	$\dot{m}_{15} s_{15} \times t + S_{gen} = m_f s_f$	$\dot{m}_{15} ex_{15} \times t = m_f ex_f + Ex_d$
Balloons (discharging)	$m_i = \dot{m}_{20} \times t$	$m_i h_i = \dot{m}_{20} h_{20} \times t$	$m_i s_i + S_{gen} = \dot{m}_{20} s_{20} \times t$	$m_i ex_i = \dot{m}_{20} ex_{20} \times t + Ex_d$
Interheater-1	$\dot{m}_{20} = \dot{m}_{21}$ $\dot{m}_{18} = \dot{m}_{27}$	$\dot{m}_{20} h_{20} + \dot{m}_{18} h_{18} = \dot{m}_{21} h_{21} + \dot{m}_{27} h_{27}$	$\dot{m}_{20} s_{20} + \dot{m}_{18} s_{18} + \dot{S}_{gen} = \dot{m}_{21} s_{21} + \dot{m}_{27} s_{27}$	$\dot{m}_{20} ex_{20} + \dot{m}_{18} ex_{18} = \dot{m}_{21} ex_{21} + \dot{m}_{27} ex_{27} + \dot{E}x_d$
Gas turbine-1	$\dot{m}_{21} = \dot{m}_{22}$	$\dot{m}_{21} h_{21} = \dot{m}_{22} h_{22} + \dot{W}_{out}$	$\dot{m}_{21} s_{21} + \dot{S}_{gen} = \dot{m}_{22} s_{22}$	$\dot{m}_{21} ex_{21} = \dot{m}_{22} ex_{22} + \dot{W}_{out} + \dot{E}x_d$
Interheater-2	$\dot{m}_{22} = \dot{m}_{23}$ $\dot{m}_{28} = \dot{m}_{29}$	$\dot{m}_{22} h_{22} + \dot{m}_{28} h_{28} = \dot{m}_{23} h_{23} + \dot{m}_{29} h_{29}$	$\dot{m}_{22} s_{22} + \dot{m}_{28} s_{28} + \dot{S}_{gen} = \dot{m}_{23} s_{23} + \dot{m}_{29} s_{29}$	$\dot{m}_{22} ex_{22} + \dot{m}_{28} ex_{28} = \dot{m}_{23} ex_{23} + \dot{m}_{29} ex_{29} + \dot{E}x_d$
Gas turbine-2	$\dot{m}_{23} = \dot{m}_{24}$	$\dot{m}_{23} h_{23} = \dot{m}_{24} h_{24} + \dot{W}_{out}$	$\dot{m}_{23} s_{23} + \dot{S}_{gen} = \dot{m}_{24} s_{24}$	$\dot{m}_{23} ex_{23} = \dot{m}_{24} ex_{24} + \dot{W}_{out} + \dot{E}x_d$

(continued)

**Table 4** (continued)

Component	Mass balance equation	Energy balance equation	Entropy balance equation	Exergy balance equation
Interheater-3	$\dot{m}_{24} = \dot{m}_{25}$ $\dot{m}_{30} = \dot{m}_{31}$	$\dot{m}_{24}h_{24} + \dot{m}_{30}h_{30} = \dot{m}_{25}h_{25} + \dot{m}_{31}h_{31}$	$\dot{m}_{24}s_{24} + \dot{m}_{30}s_{30} + \dot{S}_{gen} = \dot{m}_{25}s_{25} + \dot{m}_{31}s_{31}$	$\dot{m}_{24}ex_{24} + \dot{m}_{30}ex_{30} = \dot{m}_{25}ex_{25} + \dot{m}_{31}ex_{31} + \dot{E}x_d$
Gas turbine-3	$\dot{m}_{25} = \dot{m}_{26}$	$\dot{m}_{25}h_{25} = \dot{m}_{26}h_{26} + \dot{W}_{out}$	$\dot{m}_{25}s_{25} + \dot{S}_{gen} = \dot{m}_{26}s_{26}$	$\dot{m}_{25}ex_{25} = \dot{m}_{26}ex_{26} + \dot{W}_{out} + \dot{E}x_d$
Mixing chamber-2	$\dot{m}_{27} + \dot{m}_{29} + \dot{m}_{31} = \dot{m}_{38}$	$\dot{m}_{27}h_{27} + \dot{m}_{29}h_{29} + \dot{m}_{31}h_{31} = \dot{m}_{38}h_{38}$	$\dot{m}_{27}s_{27} + \dot{m}_{29}s_{29} + \dot{m}_{31}s_{31} + \dot{S}_{gen} = \dot{m}_{38}s_{38}$	$\dot{m}_{27}ex_{27} + \dot{m}_{29}ex_{29} + \dot{m}_{31}ex_{31} = \dot{m}_{38}ex_{38} + \dot{E}x_d$
Desalination unit	$\dot{m}_{35} = \dot{m}_{36} + \dot{m}_{37}$ $\dot{m}_{32} = \dot{m}_{33}$	$\dot{m}_{32}h_{32} + \dot{m}_{35}h_{35} = \dot{m}_{33}h_{33} + \dot{m}_{36}h_{36} + \dot{m}_{37}h_{37}$	$\dot{m}_{32}s_{32} + \dot{m}_{35}s_{35} + \dot{S}_{gen} = \dot{m}_{33}s_{33} + \dot{m}_{36}s_{36} + \dot{m}_{37}s_{37}$	$\dot{m}_{32}ex_{32} + \dot{m}_{35}ex_{35} = \dot{m}_{33}ex_{33} + \dot{m}_{36}ex_{36} + \dot{m}_{37}ex_{37} + \dot{E}x_d$

The net power of the system during the charging phase can be defined as

$$\dot{W}_{net} = \dot{W}_{wt} - \dot{W}_{comp1} - \dot{W}_{comp2} - \dot{W}_{comp3} \tag{12}$$

where  $\dot{W}_{wt}$  represents the wind turbines' power output, and  $\dot{W}_{comp}$  is for the compressor power input needed for the CAES. Power output from the wind turbine and total wind power crossing from the area swept by turbine blades can be determined by

$$\dot{W}_{wt} = \frac{1}{2} \times \pi \times r_d^2 \times C_{p_{wt}} \times N_{wt} \times V_{wt}^3 \times \rho_{air} \times \eta_{wt} \tag{13}$$

$$\dot{W}_{wind} = \frac{1}{2} \times \pi \times r_d^2 \times N_{wt} \times V_w^3 \times \rho_{air} \tag{14}$$

where  $N_{wt}$  represents the number of wind turbines,  $C_{p_{wt}}$  is the power coefficient of the wind turbine and  $\eta_{wt}$  is the wind turbine efficiency regarding the gearbox and generator efficiencies. It is important to note that wind turbines operate with wind speed in certain ranges to provide an effective and safe operation. Therefore, turbine speed ( $V_{wt}$ ) and wind speed ( $V_w$ ) are defined separately. In the analysis of the system, the maximum wind speed that the turbine can cope with is assumed as 11 m/s. Beyond this value, the turbine operates at a constant speed up until 25 m/s. After this, wind turbine stops working to avoid potential damages. Table 5 presents the thermodynamic properties of each state points shown in Fig. 4.

The exergy efficiency of the charging phase can be defined as

**Table 5** Thermodynamic properties of the corresponding state points depicted in Fig. 4

State point	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)	Specific exergy (kJ/kg)	Vapor quality
0 (air)	298.15	101.3	–	298.6	5.696	–	–
0 (water)	290.15	101.3	–	71.45	0.2534	–	–
0 (sea water)	298.15	101.3	–	97.79	0.3391	–	–
1	298.15	101.3	36.82	298.6	5.696	0	–
2	547.9	678.7	36.82	552.9	5.768	232.8	–
3	390	678.7	36.82	391.2	5.42	174.7	–
4	290	103	4.903	70.83	0.2512	0.002	0
5	373.6	103	4.903	1285	3.626	235.4	0.3862
6	708.2	4547	36.82	722.4	5.493	484.3	–
7	390	4547	36.82	391.2	4.874	337.5	–
8	290	103	4.903	70.83	0.2512	0.002	0
9	373.6	103	4.903	2552	7.034	519.8	0.954
10	708.2	30,467	36.82	722.4	4.947	647.1	–
11	390	30,467	36.82	391.2	4.328	500.2	–
12	290	103	4.903	70.83	0.2512	0.002	0
13	373.6	103	4.903	2559	7.034	519.8	0.954
14	373.6	103	9.806	1922	5.33	377.6	0.67
15	293.15	30,467	36.82	293.6	4.041	488.4	–
16	290.15	103	14.709	70.83	0.2512	0.002	0
17	373.6	101.3	9.806	1922	5.33	377.6	0.67
18	373.6	101.3	3.269	1922	5.33	377.6	0.67
19	373.6	101.3	6.538	1922	5.33	377.6	0.67
20	293	30,467	36.82	293.4	4.04	488.4	–
21	368	30,467	36.82	368.9	4.27	495.5	–
22	236.9	4547	36.82	237.1	4.373	332.9	–
23	368	4547	36.82	368.9	4.816	332.7	–
24	236.9	678.8	36.82	237.1	4.919	170.1	–
25	368	678.8	36.82	368.9	5.362	169.9	–
26	236.9	101.3	36.82	237.1	5.465	7.33	–
27	373.1	101.3	3.269	1071	3.055	187	0.2915
28	373.6	101.3	3.269	1922	5.33	377.6	0.67
29	373.1	101.3	3.269	437.4	1.356	46.02	0.009
30	373.6	101.3	3.269	1922	5.33	377.6	0.67

(continued)

**Table 5** (continued)

State point	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)	Specific exergy (kJ/kg)	Vapor quality
31	373.1	101.3	3.269	437.4	1.356	46.02	0.009
32	373.6	101.3	4.903	2559	7.034	519.8	0.954
33	305	101.3	4.903	133.6	0.462	1.537	0
34	293.15	101.3	65.21	78.19	0.2726	0.217	0
35	293.15	101.3	65.21	78.19	0.2726	0.217	0
36	304.2	4.495	3.79	2557	8.432	113	1
37	304.2	4.495	61.42	120.8	0.4147	0.4812	0
38	373.6	101.3	9.806	648.7	1.923	93	0.1032
39	293.15	101.3	3.79	84.01	0.2965	0.065	0

$$\psi_{charging} = \frac{\dot{W}_{net} + \dot{E}x_{Q_{ca}} + \dot{E}x_{Q_{Tes}} + \dot{E}x_{Q_{des}}}{\dot{W}_{wind}} \tag{15}$$

For the discharging phase, energy and exergy efficiencies can be determined by

$$\eta_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast}}{\dot{W}_{wind} + \dot{Q}_{ca} + \dot{Q}_{Tes}} \tag{16}$$

$$\psi_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast} + \dot{E}x_{Q_{des}}}{\dot{W}_{wind} + \dot{E}x_{Q_{ca}} + \dot{E}x_{Q_{Tes}}} \tag{17}$$

The integrated system’s overall energy and exergy efficiencies can be calculated by

$$\eta_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast} + \dot{Q}_{des}}{\dot{W}_{wind} + \dot{Q}_{ca} + \dot{Q}_{Tes} + \dot{Q}_{dis}} \tag{18}$$

$$\psi_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast} + \dot{E}x_{Q_{des}}}{\dot{W}_{wind} + \dot{E}x_{Q_{ca}} + \dot{E}x_{Q_{Tes}} + \dot{E}x_{Q_{dis}}} \tag{19}$$

Table 6 presents the variables taking place in the efficiency analysis. The purpose of using multiple sub-systems is to harvest more useful output from the overall energy input. Thus, the effectiveness of the renewable energy can be increased by utilizing more from abundant renewable resources. In this regard, energy efficiency of a conventional wind power plant is defined to provide a better picture of the benefit of the integrated renewable power systems. The energy efficiency for a conventional power plant can be defined as

**Table 6** Variables used in the efficiency analysis of the system

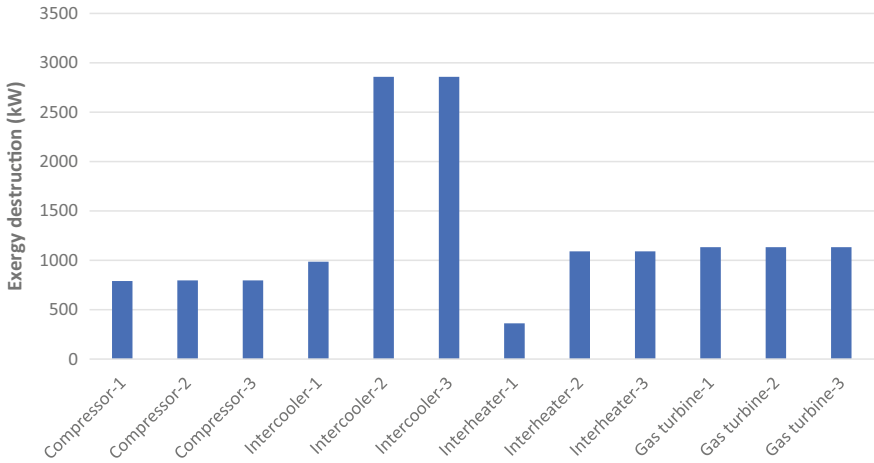
Parameters	Definition
Energy rate carried by compressed air (kW)	$\dot{Q}_{ca} = \dot{m}_{15} \times h_{15}$
Thermal energy rate carried by hot water (kW)	$\dot{Q}_{Tes} = \dot{m}_{14} \times h_{14}$
Desalinated water in energy rate form (kW)	$\dot{Q}_{des} = \dot{m}_{36}h_{36} + \dot{m}_{37}h_{37} - \dot{m}_{35}h_{35}$
Thermal energy to desalination unit (kW)	$\dot{Q}_{dis} = \dot{m}_{32} \times (h_{32} - h_{33})$
Exergy rate of $\dot{Q}_{ca}$ (kW)	$\dot{Ex}_{Q_{ca}} = \dot{m}_{15} \times ex_{15}$
Exergy rate of $\dot{Q}_{Tes}$ (kW)	$\dot{Ex}_{Q_{Tes}} = \dot{m}_{14} \times ex_{14}$
Exergy rate of $\dot{Q}_{des}$ (kW)	$\dot{Ex}_{Q_{des}} = \dot{m}_{36}ex_{36} + \dot{m}_{37}ex_{37} - \dot{m}_{35}ex_{35}$
Exergy rate of $\dot{Q}_{dis}$ (kW)	$\dot{Ex}_{Q_{dis}} = \dot{Q}_{dis} \times \left(1 - \frac{T_0}{T_s}\right)$

$$\eta_{conventional} = \frac{\dot{W}_w}{\dot{W}_{wind}} \tag{20}$$

### 3 Results and Discussion

In this section, the results of the study are presented and discussed with figures. Engineering Equation Solver (EES) software has been used in the thermodynamic, energy and exergy analysis of the system. The system performance is evaluated through various parametric studies by considering primary design and operational parameters. Antigua and Barbuda is considered as potential region to implement the system; thus wind data from the region is considered in the monthly-based analysis of the system. In the current state, the country produces its electricity from heavy fuel oil (HFO). Potential impact and performance analysis for the replacement of the existing systems with the integrated system is discussed. The total power produced by 100 wind turbines is evaluated as 85.12 MW at a wind speed of 8 m/s. On a monthly basis, the system is capable of providing 9818 tons of fresh water. Overall energy and exergy efficiencies of the system are evaluated as 39.49% and 37.62%, respectively. Figure 5 shows the exergy destruction rates in the major system components. Total exergy destruction rate throughout the system is evaluated as 15,033 MW. According to the thermodynamic analysis results, the highest exergy destruction rates are observed in the interheaters 1 and 2 with a value of 2858 MW. Exergy destruction is the loss of work potential. Therefore, it is possible to extract more useful output by decreasing the exergy destruction rates. In this specific case, high exergy destruction in intercoolers can be mitigated by lowering the temperature difference between hot and cold stream. Table 7 presents the performance results of the developed integrated renewable energy system.

Figure 6 shows the monthly basis electricity production of the integrated system. July and January are evaluated as the most productive period of the year in this regard.



**Fig. 5** Exergy destruction rates in the major system components

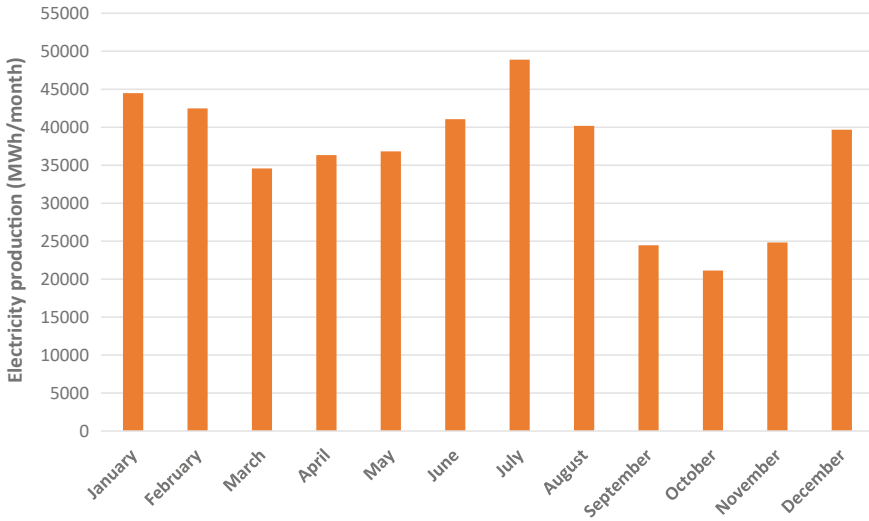
**Table 7** The summary of the integrated system performance results

Parameters	Value
Number of wind turbines	100
Average wind speed	8 m/s
Power coefficient of wind turbine ( $C_p$ )	49%
Wind turbine efficiency (Generator (90%) and gearbox (80%))	72%
Wind turbine blade radius	50 m
Power capacity of the system (Wind)	85.12 MW
Power capacity of energy storage system	14.55 MW
Net power production of the system during charging phase	51.36 MW
Monthly fresh production	9818
Overall energy efficiency of the system	39.49%
Overall exergy efficiency of the system	37.62%

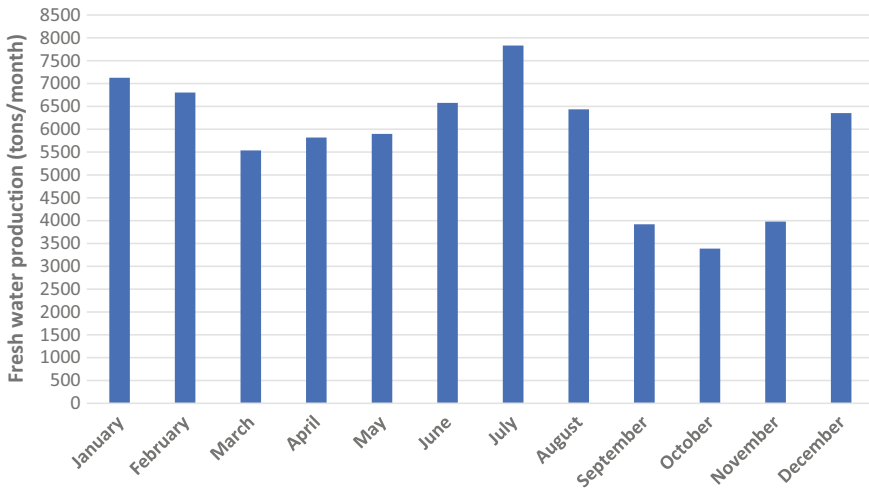
For the corresponding periods, the electricity productions become 48.9 MWh and 44.5 MWh per month, respectively. The similar result is expected for energy storage ratios since higher electricity production via wind may allow to dedicate higher portion of the produced electricity to energy storage via CAES. September, October and November are the least productive period of the year in the region.

Figure 7 presents the potable water production in accordance with monthly basis average wind speed (see Fig. 1). In this regard, the most productive period of the year is evaluated as July with a total fresh water production of 7833 tons, where the average wind speed of the region is reported as 7.42 m/s. The lowest fresh water production rates are obtained for October with a value of 3386 tons. It should be





**Fig. 6** Monthly-based electricity production



**Fig. 7** Monthly potable water production rates

noted that thermal energy for water desalination process is from the excess heat occurring during the period of energy storage via CAES. For off-peak time, 60% of electricity produced by wind turbine is considered as excess power and utilized for the energy storage. Therefore, average wind speed for the corresponding periods of the year greatly impacts the freshwater production ratios.

Note that integrated systems allow to harness more energy from renewable resources. In this regard, comparative assessment of the integrated system with a

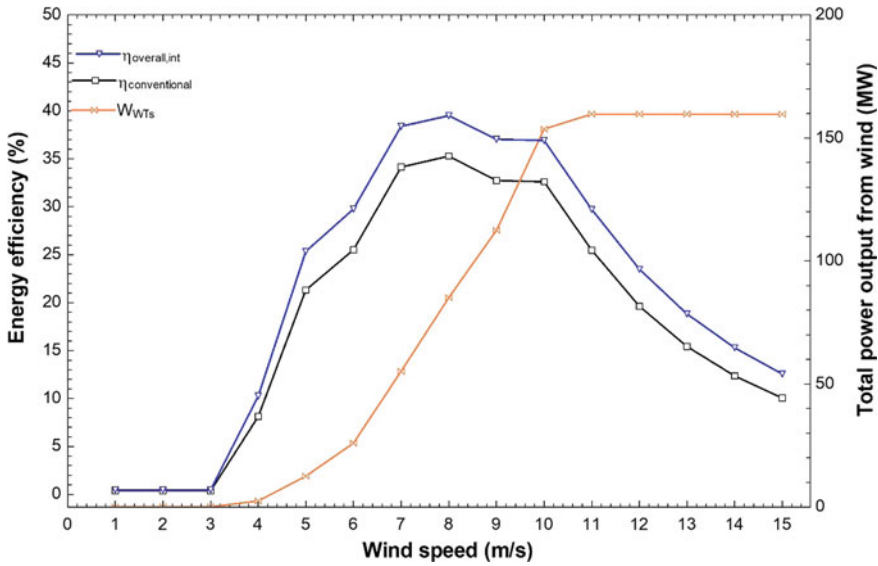


Fig. 8 Integrated system versus conventional wind power plant

conventional wind power plant is presented in Fig. 8 to provide a better understanding. Up to 11 m/s, it is considered that the wind turbine operates with the wind speed. Then, the turbine operates with a constant speed 11 m/s up until the wind speed 15 m/s. After this, the turbine stops working to avoid potential damages. The power coefficient factor is varied for different wind speeds, for which the  $C_p$  values provided in Neill and Hashemi (2018) for corresponding wind speeds are used. Due to the determined operational limit of the wind turbine, the power production becomes stable after the wind speed of 11 m/s. However, the efficiency of the plant decreases since the output from the system becomes stable while the wind energy increases with higher wind speeds. At a wind speed of 11 m/s, the system is capable of producing 156 MW of electrical power. On the other hand, it is found that integrated system performs higher energy efficiency (39.49%) than that of a conventional wind power plant (35.28%). According to this results, it is evaluated that the integrated system offers around 12% increase in the harnessing energy from the wind compared conventional wind power plant. Figure 9 presents the energy and exergy efficiencies of the integrated system for different operational phases with respect to wind speeds. Exergy efficiency of the discharging phase becomes slightly higher than the energy efficiency due to the decrease in the denominator of the exergy efficiency definition for the corresponding phase.

The annual electricity need of Antigua and Barbuda is reported as 308 GWh (See Table 1, which totally relies on imported heavy fuel oil. The country also produces its potable water from seawater via reverse osmosis where electricity required is from HFO-based power plants. The analysis of the proposed system indicates that the system is capable of 745.66 GWh clean energy production for the region, which is

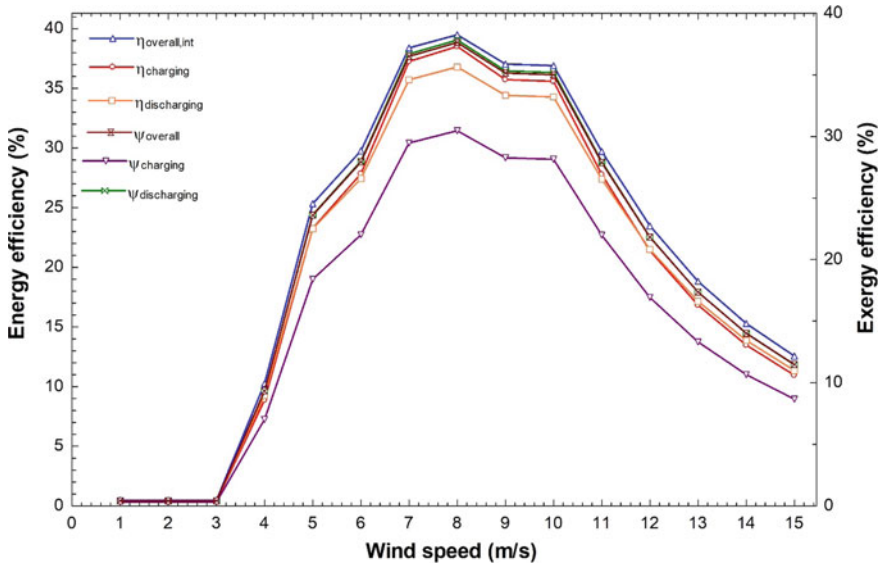


Fig. 9 Energy and exergy efficiencies of the system at various wind speeds

well above the country’s annual electricity demand. Beyond making the country totally energy independent and consuming clean energy, the potential implementation of the proposed system may make Antigua and Barbuda an energy exported in the Caribbean region.

### 4 Conclusions

In the scope of the current study, thermodynamic analysis of a wind-based integrated energy system is conducted. The performance of the study is investigated through various parametric studies. The findings of the conducted study can be summarized with couple bulleted points as follows:

- At a wind speed of 11 m/s, the electrical power output of the system 156 MW;
- At an average wind speed of 8 m/s, the potable water production is about 9618 tons/month;
- Overall energy and exergy efficiencies of the system are evaluated as 39.49% and 37.62%, respectively;
- Compared to conventional wind power plant, the integrated system is capable of harnessing 12% more energy from wind.

In closing, conventional fossil fuel-based energy production and consumption activities are the primary contributors to global warming and its devastating impacts on the planet. Furthermore, having depleting sources and unstable prices make

fossil fuel and energy relying on these sources even more problematic. Therefore, renewable-based effective and nature-friendly energy systems become a necessity for all if a cleaner, safer, and more stable environment is demanded.

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