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Techno-economic analysis of a PV–wind–battery–diesel standalone power system in a remote area

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Abstract: The global acceptance of solar and wind resources for power generation has continued to increase due to the fluctuation of world oil and gas prices, recent advances in technology, high prices of fossil fuels, no direct greenhouse gas emission from solar and wind resources and government policies to support utilisation of renewable energy resources (RESs). In recent times, RESs have become a potential alternative to supply electricity to the rural communities where the extension of transmission and distribution lines is difficult due to technical and financial barriers. In view of this, this study deals with the optimisation of net present cost (NPC), fuel cost, operation cost and cost of energy (COE) of the hybrid system which consists of photovoltaic (PV), wind turbine generator (WTG), diesel generator and battery storage system. A hybrid power system is designed in this research work to serve a remote community. The optimisation of the key performance indicators of the proposed hybrid power system is done by using the hybrid optimisation model for electric renewable (HOMER). The results obtained from this research work are analysed to select the best options among the available configurations based on the lowest NPC and COE produced by each configuration. The simulation results from several case studies show that incorporation of PV and WTG have reduced the operating cost of the system.

1 Introduction

The rapid increase in population and industrialisation has necessitated an important role that electrical power plays in economic and well-being of a country. The availability of power supply has been reported in many kinds of literature to be the basic requirement for the developmental program of any nation. This can be achieved if the power utilities can harness all the available renewable resources as the prerequisites to meet the daily power demand of consumers [1]. The technical, economic and environmental benefits of renewable energy resources (RESs) have encouraged the utilities to maximise utilisation of photovoltaic (PV) and wind turbine generator (WTG) for power generation at all segments of power system [2]. In addition to this, the rapid innovation in the technological development of renewable energy modules coupled with the government policies, high price of fossil fuels and high pollution from the conventional power plants has shifted the attention of the power utilities towards the application of RESs for power generation [3]. This has necessitated an urgent replacement of convectional power plants with the renewable energy technologies.

Due to the benchmarks set by many international organisations, several countries have been encouraged to construct microgrid power generation facilities to power the remote locations that cannot be connected to the grid due to economic and technical constraints. By using the economies of scale, it is advisable to utilise RESs to meet the load demand at the rural communities than to spend millions of dollars for extension of transmission and distribution lines to such areas without any financial benefits [4]. This has prompted utilisation of renewable hybrid system to provide electricity in the remote areas where grid connection is highly expensive [5]. Caballero *et al.* [6] have presented a method for the optimal design of a grid-connected PV–wind hybrid energy system. Bilil *et al.* [7] have presented a multi-objective genetic algorithm for optimisation of the annualised renewable energy cost and the reliability indices of a power system. Meanwhile, de Souza *et al.* [8] have presented a pseudo-dynamic planning approach to estimate the impact of reliability assessment on the distribution system. The aforementioned body of literature shows that little work has been done in the integration of RERs into the power system to reduce the greenhouse gas (GHG) emissions and operating cost.

In view of this, this paper presents a techno-economic analysis of a hybrid system that consists of wind, PV, battery and diesel generator. The techno-economic simulation is carried out on the proposed hybrid system by using HOMER software package to determine the optimal configuration of the system based on the minimum cost of energy (COE) and net present cost (NPC). HOMER is an efficient software that allows the optimal combination of various RESs based on the energy source models, load profile, solar irradiation data, wind speed data and fuel price of the diesel generator. The optimal configuration of the hybrid system allows the system to be designed in such a way that it will reduce the operating cost of the system [2].

The paper aims at designing a sustainable optimised hybrid system that will improve the utilisation of RESs at reduced fuel cost, maintenance cost and GHG emissions [9]. The operating cost, energy cost, and NPC have been used as the performance metrics to compare different configurations of a hybrid system. The impacts of RESs on a standalone power system are investigated and the comparative analysis of the system is based on different benefits that can be derived from a hybrid system [10]. A hybrid optimisation program is utilised in the proposed power system to ensure that energy cost, operating cost and NPC are minimised while meeting the load demand and the system constraints.

This research work presents a techno-economic analysis of a hybrid system that consists of PV–wind–battery–diesel generator. Finally, the economic and environmental benefits of the hybrid system over the conventional standalone diesel generator show that PV–wind–battery–diesel system is more viable based on the minimal operating cost, cost of energy, GHG emission, and NPC. The results obtained from this study show the acceptability of a hybrid system as a practical means to meet the power demand of the rural communities.

2 Hybrid system

The basic components of the hybrid system that is utilised in this paper include the WTG, PV system, diesel generator and battery storage system (BSS), as shown in Fig. 1. These components allow the hybrid power system to function effectively without any power interruption. The combination of two or more resources in a hybrid power system is cost effective and reliable than using a single power source [11]. The strength of one power source can be used to overcome the weakness of another source. The trade-off solutions can be achieved with the integration of multiple RESs in a hybrid power system [12]. A hybrid power system is an important option to meet the power requirements of the rural dwellers and this will invariably improve the quality of life and well-being of people in remote areas. The models of each component of the hybrid system are discussed briefly in the following section.

2.1 Modelling of wind system

The wind system has been reported in many kinds of literature to be one of the RESs that has a huge potential for power generation application. The global acceptance of wind system is caused by the uncertainty that is associated with the future policy changes, environmental concerns, cost effectiveness, high prices of fossil fuels and other factors [13]. The wind system has been playing a proactive role in power generation of many countries as well as a prime mover for many mechanical devices [14]. It can be utilised by the power utilities and independent power producers to generate electrical power from the wind resources at the commercial level. The wind system can be used for a standalone or grid connected power system because of the following characteristics, i.e. low maintenance and operating cost, low capital cost, no fuel cost, no direct GHG emission and so on. The output power of a WTG depends on the wind characteristic, tower height, wind shear and so on. The power output of a wind system can be expressed as [15]

$$PWTG_{\text{output}} = \begin{cases} 0 & \text{if } v < v_{\text{ci}} \\ P_{\text{r}} \cdot \dfrac{(v^k - v_{\text{co}}^k)}{v_{\text{co}}^k - v_{\text{r}}^k} & \text{if } v_{\text{ci}} \le v \le v_{\text{r}} \\ P_{\text{r}} & \text{if } v_{\text{r}} \le v \le v_{\text{co}} \\ 0 & \text{if } v > v_{\text{co}} \end{cases} \quad (1)$$

where P_r is the rated power output of the wind turbine, v_{ci} is the cut-in wind speed, v_r is the rated wind speed, v_{co} is the cut-out wind speed, v is the actual wind speed and $PWTG_{output}$ is the power output of a wind system.

The WTG with the nominal rating of 65 kW and model number AOC 15/50 is used in this study. The power curve for the wind turbine based on the manufacturer's specifications is shown in Fig. 2.

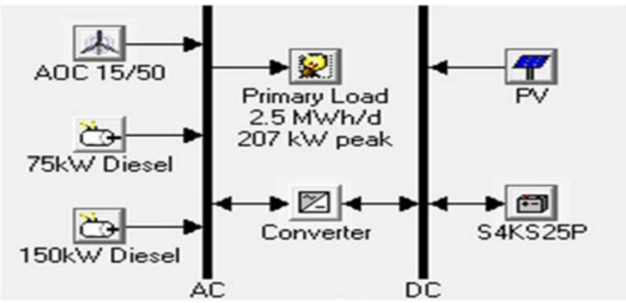

Fig. 1 *Hybrid power system*

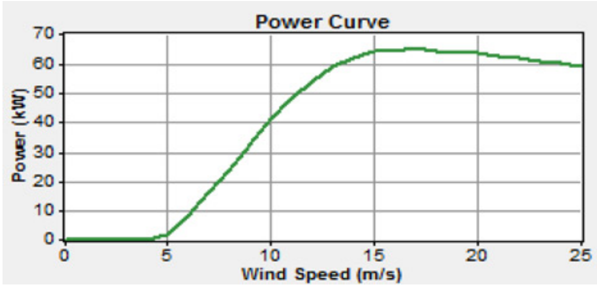

Fig. 2 *Wind turbine power curve*

2.2 Modelling of PV system

A PV system consists of solar panels that convert sunlight directly into electricity for standalone and grid connected power applications. The universal acceptance of PV system in recent years for power generation is due to the government policies to encourage utilisation of PV system, high demand of electricity, environmental concerns, low operating cost and no fuel cost [16]. The best places to use the PV system for reduction of fuel cost of the diesel generator is the rural areas that are not connected to the grid and where the transportation of diesel from the urban centres to the rural areas is too expensive due to long distances [17, 18]. For this reason, the PV system can be used in conjunction with other RESs to reduce the fuel consumption and GHG emissions of the conventional generating units. The output power of PV system depends on solar irradiance, ambient temperature and the conversion efficiency of PV panel. The output power of PV system can be estimated by using the following expressions [15]:

$$T_{\text{ct}} = T_{\text{at}} + s(t) \times \left\{ \frac{\text{NOCT} - 20}{0.8} \right\} \quad (2)$$

$$I = s(t) \times \{ I_{\text{sc}} + K_{\text{ct}} \times (T_{\text{ct}} - 25) \} \quad (3)$$

$$V = \{ V_{\text{oc}} + K_{\text{vt}} \times T_{\text{ct}} \} \quad (4)$$

$$\text{FF} = \frac{V_{\text{mp}} \times I_{\text{mp}}}{V_{\text{oc}} \times I_{\text{sc}}} \quad (5)$$

$$P_{\text{pv}}(s(t)) = \eta_{\text{cells}} \times \text{FF} \times V \times I \quad (6)$$

where T_{ct} is the cell temperature [°C], T_{at} is the ambient temperature [°C], $s(t)$ is the random irradiance, NOCT is the nominal cell operating temperature [°C], I_{sc} is the short-circuit current [A], K_{ct} is the current temperature coefficient [mA/°C], V_{oc} is the open-circuit voltage [V], K_{vt} is the voltage temperature coefficient [mV/°C], V_{mp} is the voltage at maximum power [V], I_{mp} is the current at maximum power [A], FF is the fill factor, η_{cells} is the number of PV cells, V is the terminal voltage, I is the current (A) and $P_{pv}(s(t))$ is the PV power output (W).

2.3 Modelling of BSS

BSS coverts electricity generated from PV and WTG into a form that could be stored at an off-peak period when power demand is usually low and feed back into the system during the peak period. In this paper, the role of BSS is to mitigate the fluctuation effect that is associated with the renewable resources due to their stochastic characteristics. The effect can be smoothened out with the application of BSS. The capacity of the BSS depends on the maximum load demand, amount of renewable energy generation, daily energy usage, renewable energy input, the reliability of power supply, cost of the battery, the condition of operation, average temperature and so on. The optimal operation of BSS is subject to the charge and discharge limits based on the depth of discharge and availability of the local RERs. The BSS must operate between the minimum and maximum allowable state of charge (SOC). The SOC lower and upper limits of the BSS are presented as follows [15]:

$$\mathrm{SOC}^{\min}(t) \le \mathrm{SOC}(0) - \frac{\eta \Delta t}{\mathrm{NCB}_n} \sum_{t=1}^{n} P_{\mathrm{bss}(\tau)} \le \mathrm{SOC}^{\max}(t) \quad (7)$$

$$\mathrm{SOC}^{\min}(t) \le \mathrm{SOC}(t) \le \mathrm{SOC}^{\max}(t) \quad (8)$$

The optimal operation of the battery by considering the depth of discharge (DOD) can be expressed as

$$\mathrm{SOC}^{\min}(t) = (1 - \mathrm{DOD}) \times \mathrm{SOC}^{\max}(t) \quad (9)$$

The SOC of the battery system can be expressed in the discrete-time domain used by the following equation:

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) - \frac{\eta \Delta t}{\mathrm{NCB}_n} P_{\mathrm{bss}}(t-1) \quad (10)$$

The SOC can be expressed in terms of its initial value by the following expression:

$$\mathrm{SOC}(t) = \mathrm{SOC}(0) - \frac{\eta \Delta t}{\mathrm{NCB}_n} \sum_{\tau=1}^{k} P_{\mathrm{bss}}(\tau) \quad (11)$$

where NCB_n is the nominal capacity of the battery system, Δt is the step time and η charge efficiency of the BSS.

2.4 Modelling of diesel generator

The diesel generator is integrated into a power system for the purpose of meeting the load requirements of the consumers. Diesel generator sets offer durable and reliable power solutions that range from prime power, continuous power, and standby power applications [19]. The diesel generators can be used as a back-up generator, emergency/standby units, and peak shaving because of their operating characteristics such as fast start up, availability, reliability, durability and black start capability. These have made diesel generators preferred choice in some locations despite their numerous setbacks. The fuel consumption rate of the diesel generator with its output power at time t can be expressed as [20]

$$F = F_0 \cdot Y_{\mathrm{dg}} + F_1 \cdot P_{\mathrm{dg}} \quad (12)$$

where F_0 is the fuel curve intercept coefficient (units/h/kW), F_1 is the fuel curve slope (units/h/kW), P_{dg} is the electrical output of the generator (kW) and Y_{dg} is the rated capacity of the generator (kW).

2.4 Modelling of converter

The role of a bi-directional converter in a power system is to convert the DC voltage from PV units and battery to AC voltage that can be used at the load points. Similarly, a bi-directional converter can be used to convert AC voltage from a diesel generator and WTG to DC voltage to charge the battery. The efficiency of a converter is defined by the following equation [21]:

$$\eta_{\mathrm{cov}} = \frac{P_{\mathrm{output}}}{P_{\mathrm{input}}} \quad (13)$$

where P_{output} is the AC output power, P_{input} is the DC input power to the converter and η_{con} is the converter efficiency.

3 Economic modelling of the hybrid system

The most important benchmark to determine if the RESs that have been integrated into a power system are financially worthwhile can be analysed by using the following parameters: the annualised cost of the system (ACS), NPC, and COE. The aforementioned operating parameters are used in this study as the economic criteria to evaluate the feasibility of renewable hybrid system configurations. These key performance indicators are used to investigate the impacts of PV, WTG and BSS on the hybrid system.

3.1 Cost of energy

The COE is the monetary value of the energy produced per kWh by the power generating units. The COE is primarily derived from the annualised cost of the system and the annual energy served (AES). The COE of the hybrid system can be estimated by using the ratio of ACS to AES [22]

$$\mathrm{COE} = \frac{\mathrm{ACS}}{\mathrm{AES}} \quad (14)$$

3.2 Annualised cost of the system

The ACS is calculated by using the following operating parameters, i.e. annualised capital cost (ACC), annualised fuel cost (AFC), annualised replacement cost (ARC), annualised maintenance cost (AMC) and capital recovery factor (CRF) [22]. The CRF of a power system is estimated with the aid of the life span and interest rate of the system. The ACS for the hybrid system can be expressed as

$$\mathrm{ACS} = \sum_{i=1}^{n} [\mathrm{ACC} + \mathrm{ARC} + \mathrm{AMC} + \mathrm{AFC}] \quad (15)$$

The CRF for each component of the hybrid system can be expressed as

$$\mathrm{CRF}(i, P_{\mathrm{proj}}) = \frac{i \cdot (1+i)^{P_{\mathrm{proj}}}}{(1+i)^{P_{\mathrm{proj}}} - 1} \quad (16)$$

The annual interest rate can be estimated by using the following equation:

$$i = \frac{\left(i^{\mathrm{nom}} - f\right)}{(1+f)} \quad (17)$$

where f is the annual inflation rate, i^{nom} is the nominal interest rate and i is the annual interest rate (%)

3.3 NPC of the hybrid system

The NPC of the hybrid power system is a summation of the NPC of the capital cost, maintenance cost, fuel cost and replacement cost of each component of the power system [22]. The NPC can be expressed as

$$\mathrm{NPC} = \frac{\mathrm{ACS}}{\mathrm{CFR}} (\$/\mathrm{yr}) \quad (18)$$

4 Results and discussions

The economic and environmental analysis of the hybrid power system is carried out in this research work by considering ACC, ARC, AFC, AMC and a lifetime of each component of the

Table 1 Configuration of the case studies

Description	Case 1	Case 2	Case 3	Case 4
first diesel generator, kW	75	75	75	75
second diesel generator, kW	150	150	150	150
WTG kW	65	65	0	0
PV, kW	15	15	15	15
battery, kWh	24	0	24	0
inverter, kW	200	200	200	200

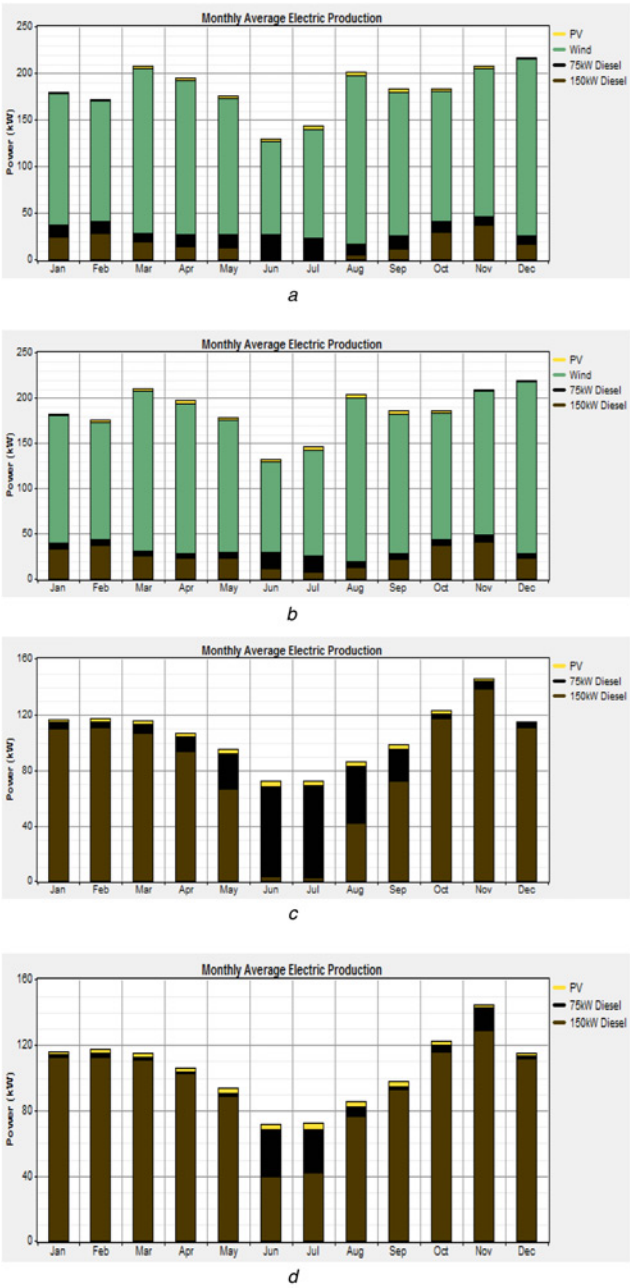

Fig. 3 *Share of electrical power generation for each component of the hybrid system for*
a Case study 1
b Case study 2
c Case study 3
d Case study 4

system. These performance indicators are utilised in the paper to select the optimal solution among the numerous configurations of the hybrid system. In this study, the economic and environmental performance of different combinations of hybrid system that consists of PV, WTG, battery, and diesel generator has been carried out by using HOMER simulation software. This is achieved by using the case studies present in Table 1.

4.1 *Analysis of the results*

A number of case studies have been investigated and analysed in this study as a measure to get a clear insight of the impacts of RESs in a power system. The power contribution from PV, WTG, and diesel generator for each case study is presented in Figs. 3*a*–*d*. The WTG system contributes 82% of the total power produced in the hybrid system as shown in Fig. 3*a*. The contribution of PV and diesel generator in the first case study is insignificant when compared with WTG and the system has a renewable fraction of 83%. The second case study as presented in Fig. 3*b* also shows that WTG contributes as much as 81% of the total power produced by the hybrid system. The second case study has a renewable fraction of 82%. The results obtained from the third and fourth case studies as presented in Figs. 3*c* and *d* indicate that diesel generators produced 98% and 97% of the total power generated by the hybrid system. The third and fourth case studies have 2 and 3% renewable fractions, respectively.

The effects of renewable technologies on the optimal operation of a standalone power system are categorised based on the economic and emission considerations summarised in Tables 2 and 3 and Figs. 4*a*–*c*. The cost analysis of different case studies is used in this paper to select the optimal option among the numerous combinations of the hybrid system. Having compared the four case studies, it can be seen that case study 1 is the best option among the numerous configurations of the hybrid system. The COE of the system is $0.127/kWh, which is the least among the four case studies. The NPC is $1,484,973/yr, fuel consumption is 82,407 l/yr, annualised cost of the system is $116,922/yr and the operating cost of the system is $100,302/yr as presented in Table 2 and Fig. 4*c*. It can be established from the results presented in Table 3 that case study 1 has the least GHG emissions when compared with other case studies. The reason for this is the high level of the renewable fraction which is estimated to be 83% as presented in Table 2. Furthermore, the system is economically and

Table 2 Economic analysis of different case studies

Description	Case 1	Case 2	Case 3	Case 4
COE, $/kWh	0.127	0.137	0.264	0.264
NPC, $/yr	1,484,973	1,594,049	3,079,962	3,144,486
renewable fraction	0.83	0.82	0.02	0.03
operating cost, $/yr	100,302	111,651	231,022	238,885
fuel consumption, l/yr	82,407	95,994	269,167	276,915

Table 3 Environmental analysis of different case studies

Pollutant	Emissions, kg/yr			
	Case 1	Case 2	Case 3	Case 4
carbon-dioxide	217,004	252,785	708,805	729,208
carbon-monoxide	536	624	1750	1800
unburned hydrocarbons	59.3	69.1	194	199
particulate matter	40.4	47	132	136
sulphur-dioxide	436	508	1423	1464
nitrogen-oxides	4780	5568	15,612	16,061

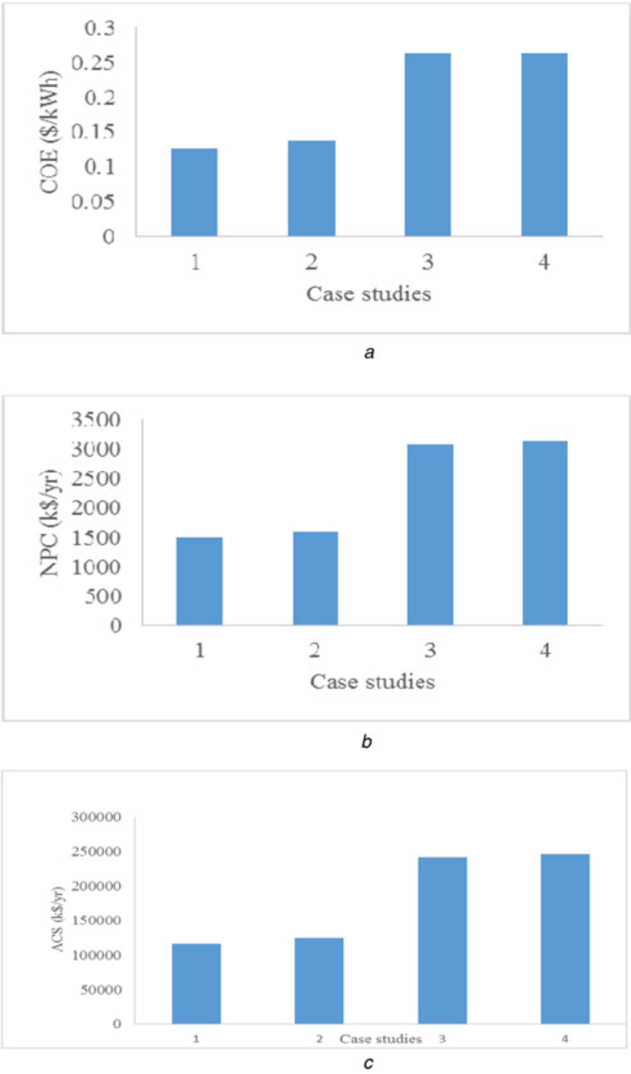

Fig. 4 *Different case studies of*
a COE
b NPC
c ACS

environmentally feasible based on the lowest values of COE, NPC, ACS, operating cost and fuel consumption.

5 Conclusion

In this paper, the HOMER software is used to optimised the operation and environmental cost of the PV, WTG, and BSS that served as a standalone power system. The comparison of the economic and environmental performance of the system was analysed by using different case studies. The case study 1 has shown better performance because of lowest COE, NPC, operating cost, fuel consumption, ACS and GHG emissions among the four case studies. Hence the system is economically and environmentally feasible when compared with other case studies. The results obtained from this study have established that RESs are potential alternatives to meet the power demand of the rural dwellers due to a number of benefits.

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