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Contents

Performance optimization of a photovoltaic-diesel hybrid power system for Yanbu, Saudi Arabia

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ABSTRACT

In the rural areas of Saudi Arabia, which are not connected to the national grid, electricity is supplied mainly from diesel generators. This is not just a non-renewable energy source, but it has also resulted in environmental damage and may be hazardous to human health. In order to mitigate the problem, integration with a solar photovoltaic system is proposed. A Photovoltaic-Diesel Hybrid System (PvDHS) was designed, analyzed, and optimized based on the climate data of Yanbu, Saudi Arabia. Measured local solar insolation and climate data were used in the Hybrid Optimization Model for Electric Renewables (HOMER) software with different system components and configurations in order to optimize the design that yields the best energy cost. A system consisting of a 3 kW photovoltaic system, a 2 kW diesel engine, a 1 kW converter, and 14 kWh batteries were identified to be the most cost-effective for the average daily electricity demand of 10.5 kWh. The total Net Present Cost (NPC) of this system is $17,800, a reduction of 50% over the $35,770 cost of the diesel-only system. The PvDHS useful electrical energy is found to be $0.36/kWh, while the Cost of Energy (COE) of the diesel-only system is $0.72/kWh. The system is expected to pay for itself in 2.8 years and reduce CO2 emissions by 8110 kg per year.

Keywords: hybrid systems; design optimization; arid climate; energy saving; GHG emissions

Abbreviations:

PvDHS: Photovoltaic-Diesel hybrid system; NPC: Net present cost; COE: Cost of energy; PV: Photovoltaic; DC: Direct current; AC: Alternating current; GHI: Global horizontal irradiance; CO2: Carbon dioxide; CF: Capacity factor; YF: Yield factor; PR: Performance ratio; CO: Carbon monoxide; SO2: Sulphur dioxide; NOx: Nitrogen oxides

1. Introduction

Over 6 million people, or 17 percent of the population in Saudi Arabia, live in rural areas that depend on diesel generators for electricity [1]. These regions have a limited connection to the national grid. Expanding the grid to these regions is impractical due to low energy consumption, limited economic activity, and a sparse population. On the other hand, diesel generators utilization has to overcome challenges of high fuel and maintenance costs and greenhouse gas emissions over a short life span [2,3]. Numerous studies have been performed to determine the financial, technical, and environmental feasibility of utilizing renewable energy to power rural and off-grid communities [4]. Some of these studies were carried out in Jordan [5], the east coast of Saudi Arabia [6], and Nigeria [7], which all point to significant penetrations of PV systems for electricity demands. A critical review of the state-of-art PV hybrid system shows that arid climate is the most studied region when it comes to applying PV hybrid systems [8]. Solar photovoltaic systems may be installed and configured in a variety of configurations, including stand-alone, grid-connected, or hybrid designs. Grid-connected or interactive PV systems are connected to the electrical power grid of a utility through an inverter, which converts the direct current (DC) of the power produced by the photovoltaic array to the alternating current (AC) [9,10]. Any surplus energy produced by the array is sent into the power grid, where it is credited to the consumer's account by the utility provider. When a grid-tied system has a net-metering policy in place, energy may flow both ways.

A study on stand-alone systems conducted in Iran [11] is just one example of the numerous research conducted worldwide. Stand-alone photovoltaic (PV) systems generate electricity without the need for a power grid. It is often used when a grid connection is not economically viable and accessible [12]. The photovoltaic array, inverter, charge controller, battery, and load controller are the main components of a stand-alone photovoltaic system. Solar energy becomes more cost-effective and reliable when coupled with backup power sources or integrated with another power source (hybrid system) [13,14].

In off-grid rural areas, a photovoltaic-diesel hybrid system is one of the most cost-effective options [15]. An example of a study on this can be found in [16]. Computer modeling is one technique for designing and optimizing the performance of solar photovoltaic systems. Among these modeling tools are TRANSYS [17] and Homer. HOMER modeling and simulation assists in finding the optimum design for a renewable energy system. Numerous studies have used the HOMER software to determine the optimal system confirmation and component sizing in order to improve the economics of the system [18]. HOMER has been used to predict and optimize the performance of photovoltaic systems in a variety of locales and climatic groups throughout the world, including the tropical climate of Malaysia [18], the dry climates of Libya [19] and Pakistan [20], and the humid tropical island of Sri Lanka [21]. With HOMER, the sensitivity analysis is used to evaluate a variety of operating conditions and factors, including fuel price, solar resource quality, and a variety of load sizes. Cai et al, the study of [22] examined the size of an off-grid hybrid system that included photovoltaics, a diesel generator, and a battery. The solar PV-diesel system costs 22.2 percent less than the diesel-only system and emits nearly 60 percent less greenhouse gas. In [23], the author developed the Hybrid Optimization technique, which designs and optimizes photovoltaic-diesel hybrid systems, by utilizing Genetic Algorithms. The PV and the diesel systems alone were compared, and the findings suggest that PVdiesel hybrid systems are more cost-effective and reliable. Rehman and Al-Hadhrami [24] conducted an optimization and economic analysis of a Saudi Arabian hybrid solar photovoltaic–diesel–battery system. This research demonstrates that it is technically feasible to convert some diesel generators to solar energy and positively affect rural areas.

The climatic region has significant effects on the efficiency of PV and PV hybrid systems [25]. The purpose of this research is to design and optimize a site-specific photovoltaic-diesel hybrid system (PvDHS) for usage as a power source in Yanbu, Saudi Arabia. A number of previous studies described in this section were done in Saudi Arabia, but none were done in this location. Measured local climate data fed to HOMER software is used to simulate and optimize stand-alone photovoltaic diesel hybrid systems. The aim is to identify the best system architecture to meet the typical energy demand of small residential buildings in the remote areas surrounding Yanbu.

2. Methodology

HOMER software is used with the input data of Yanbu, Saudi Arabia's climate information to optimize PV-diesel hybrid electrification. A search space sub-program was utilized to find the best number of batteries and the optimal PV, converter, and diesel generator size. The startup cost and operation are based on the International Renewable Energy Agency's 2018 Renewable Power Generation Costs. The designers and solar industry specialists recommended that the PV panels have a 25-year lifespan [26]. The deterioration rate of the PV cells is estimated to be 0.5 percent per year, and the system derating factor is 90 percent [27]. The simulation was based on a discount rate of 5% and an inflation rate of 2%.

Figure 1 shows a typical PV-diesel hybrid system in which PV arrays and batteries are linked to the system's DC side through an AC converter. The AC generator and grid extension are connected to the system AC side through the AC bus. The model also has a battery storage backup system aside from the PV and diesel generator power sources.

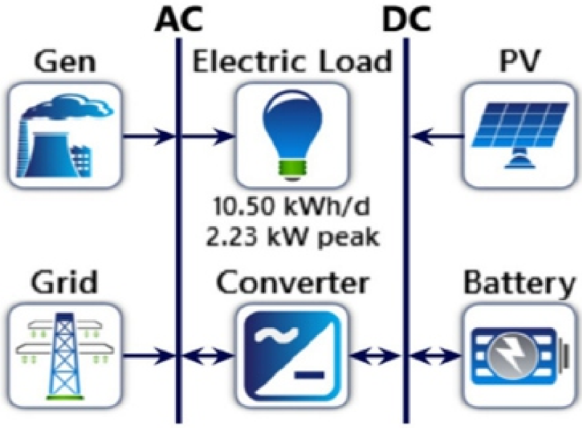

Figure 1. Proposed PV-diesel system architecture.

Figure 2 illustrates the monthly average solar Global Horizontal İrradiance (GHI) clearness index data. The highest radiation occurs during the June to September period with nearly 7.5 kWh/m2/day, while low radiation occurs between November and January. The average yearly radiation is 6.56 kWh/m2/day.

Figures 3 (a) through (d) depicts the yearly weather conditions in the Yanbu area, which include (a) the average high and low temperatures, (b) the amount of rainfall, (c) the number of sunlight hours, and (d) the relative humidity of Saudi Arabia's western region.

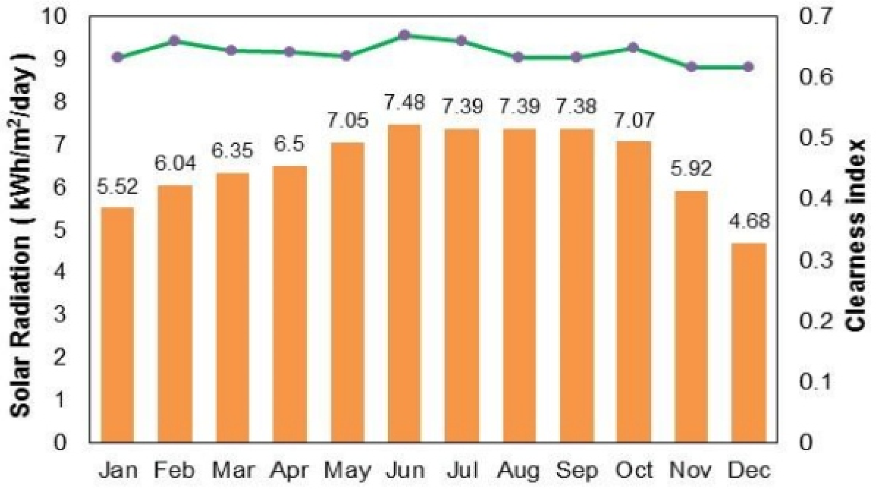

Figure 2. Monthly average solar Global Horizontal Irradiation (GHI) and Clearness Index for Yanbu.

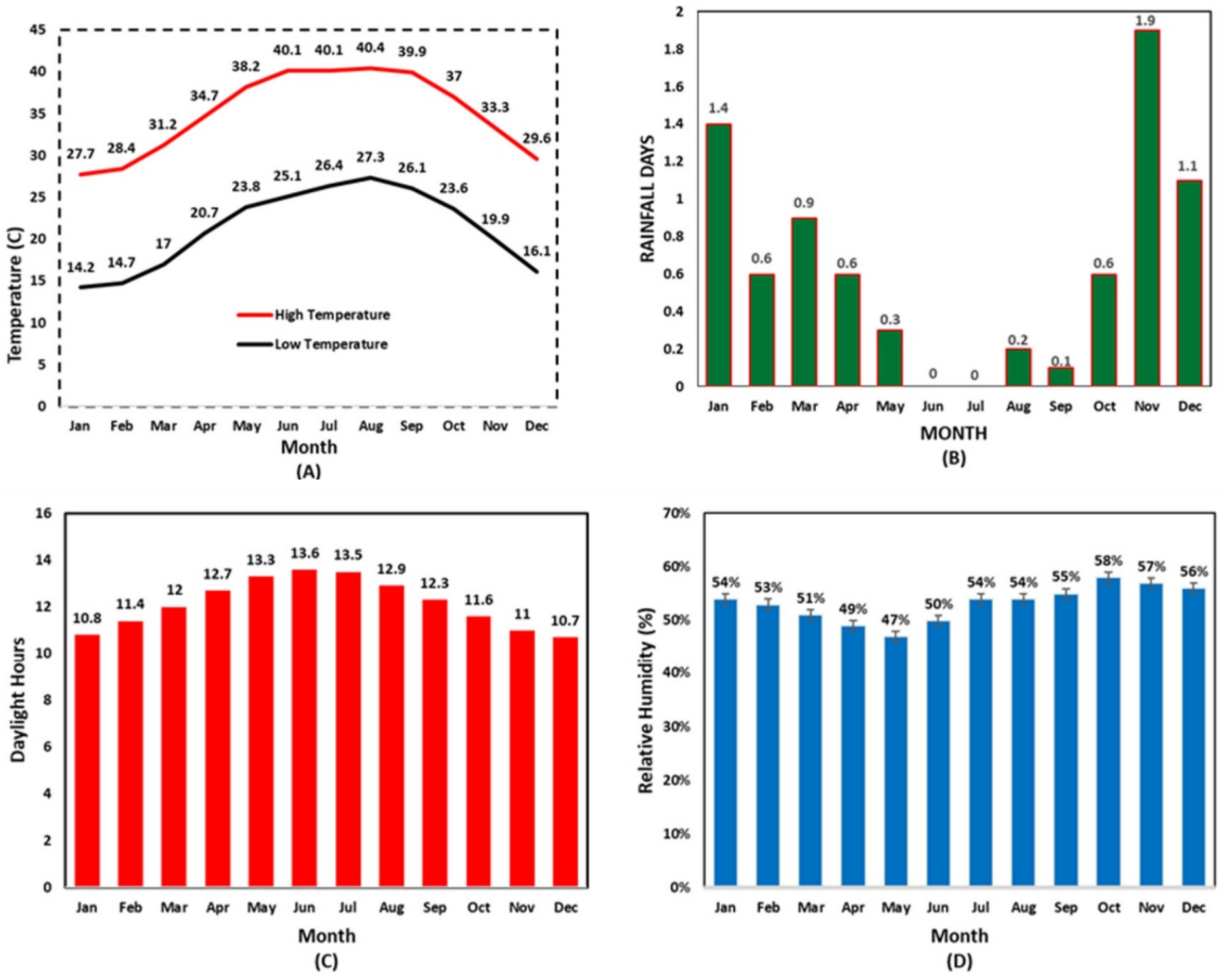

Figure 3. Yanbu annual weather data.

The solar insolation in this location is among the greatest in the country, averaging 2400 kWh/m2/year [28]. The highest and lowest air temperatures are 40.4 °C and 14.2 °C, respectively. Rainfall is very rare, with about eight days a year. Most rains happen during the cold seasons. Yanbu experiences daylight hours between 10.7 and 13.6 hours year-round. The average humidity is 545. However, during the months of high irradiation, the temperature rises, which reduces the efficiency of the PV array. As a result, the temperature of the solar cells can rise much over the standard test settings of 25 °C and can approach 70 °C, as indicated in Figure 4. This high temperature causes the voltage to drop precipitously while the current increases slightly, resulting in a reduction in the amount of power produced.

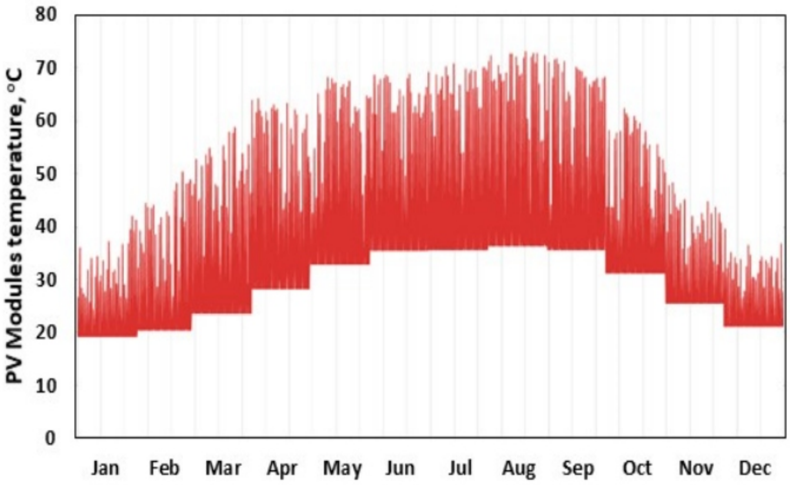

Figure 4. Day-by-day Solar PV Cell temperature fluctuation.

The optimized sizing of solar PV systems necessitates the execution of several critical processes. The energy demand, or the quantity of energy required to power the daily load, must be thoroughly analyzed. The simulation requires a number of input data, including solar radiation, energy demand, peak load, system components, and efficiency. The electrical load is the average amount of electricity consumed by a home in this area, which is 10.5 kWh per day with a peak demand of 2.21 kW. This community's load changes from month to month, as seen in Figure 5 below.

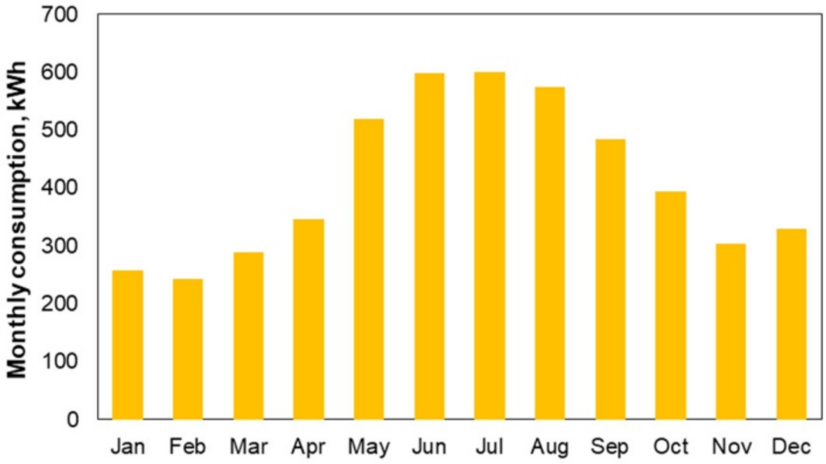

Figure 5. Electrical load profile of a rural house in Yanbu area.

The 3 kW solar PV system powers all loads during normal operating conditions and maintains the battery at full charge using an inverter/charger or conventional charger controller. When there is no solar PV output on cloudy days or at night, the inverter disconnects from PV and uses the energy stored in the batteries to power the load. If the battery has to be charged and the solar PV produces insufficient power, electricity is supplied by the diesel generator. The suggested PV module peak power output and efficiency are 335 W and 21.0%, respectively. The module specifications are listed in Table 1. The initial capital cost is $1300/kWh, whereas the replacement and maintenance costs are $1200 and $15. Table 1 shows the specifications of the solar panels utilized. An inverter is required to convert the DC power produced by the PV arrays to AC power. The inverter is stand-alone and has a 15-year lifespan with 95% efficiency for the inverter and 90% efficiency for the rectifier. This inverter's capital cost was $750/kW, while the replacement cost was $700. The operating and maintenance costs associated with the inverters were considered because they are so negligible.

Table 1. Electrical data of the PV modules.

Electrical data at standard testing conditions	
Power (P_{nom})	335 W
Panel efficiency	21.0%
Power tolerance	+5/–0%
Rated voltage (V_{mpp})	57.3 V
Rated current (I_{mpp})	5.85 A
Open-circuit voltage (V_{oc})	67.9 V
Short-circuit current (I_{sc})	6.23 A
Power temp coefficient	–0.30%/℃
Voltage temp coefficient	–167.4 mV/℃
Current temp coefficient	3.5 mA/℃

As a backup supply, the diesel generator supplements the PV power source. The generator capacity was set at 2 kW in this simulation. The initial cost was \$1000/kWh, with an \$800/kWh replacement cost and a \$0.040/kWh maintenance cost.This is because a solar PV power generation is intermittent and a generator capacity is limited, hybrid solar PV-diesel systems work best when combined with energy storage devices. This model uses Trojan 6 V deep-cycle lead-acid batteries. The nominal maximum capacity of this battery is 2.37 kWh and 396 Ah. The stage of charge is in the range of 30% to 100%, and it has a round-trip efficiency of 85%. The lifetime of the battery is ten years, and the lifetime throughput is 1075 kWh.

The PV panels must be perpendicular to the sun and clear of shadows to capture the most energy. As shown in Figure 6, several different tilt angles and azimuth angles were compared. This study employed an azimuth angle of 0° due south and a tilted angle of 25°, which is nearly equivalent to the project site's latitude (Yanbu).

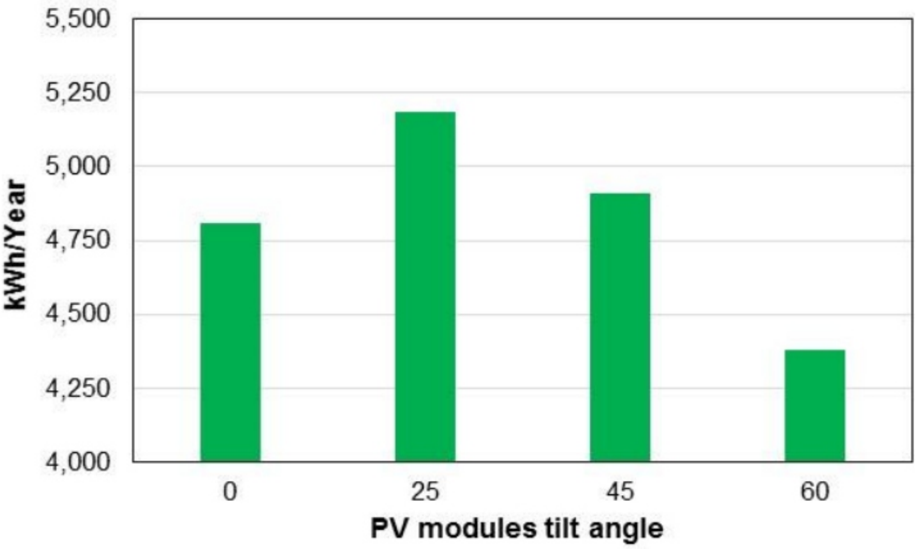

Figure 6. Average daily PV production at various tilt angles.

3. Results and discussion

The simulation results show that a hybrid solar PV-diesel with battery storage is the best solution for supplying the desired load. Three configurations were simulated; PV-diesel generator battery (PVG-B), PV battery (PV-B), and diesel generator alone (G). In order to meet the required load, the sizes of each component were varied, and the energy cost and renewable energy were calculated. As shown in Table 2, the optimum combination with the lowest net present cost consists of a 3-kW PV, 2-kW generator, six batteries, and a 1-kW converter. The optimum PV-diesel-battery hybrid system costs \$7,450.00, which includes the PV, generator, converter, and related design installations. Operational cost is \$7.60/kWh, and NPC is \$17270. These results in the lowest COE of \$0.366/kWh, while PV contributes 84% of the load demand. The annual production of the PV-G-B system up to 4,716 kWh, with a capacity factor of of around 18%

Table 2. Simulated system configurations

	PV (kW)	Gen (kW)	Battery (kWh)	Converter (kW)	Initial cost ($)	Operating cost ($/kWh)	Total NPC ($)	COE ($/kWh)	Renewable %
PV-G-B	3	2	6	1	7450	7.60	17270	0.366	84
PV-B	5		18	2	13400	5.90	21,024	0.451	100
G		2			1000	2.68	35,635	0.755	0

Figure 7 shows the average monthly electric load share of the PV and diesel generator. This graph indicated that the PV components could provide all power demand in January, February, March, April, and November. The diesel generator is needed to supplement the PV in order to meet the need for power during the other months.The renewable fraction is 84% out of the 5318 kWh produced in a year.

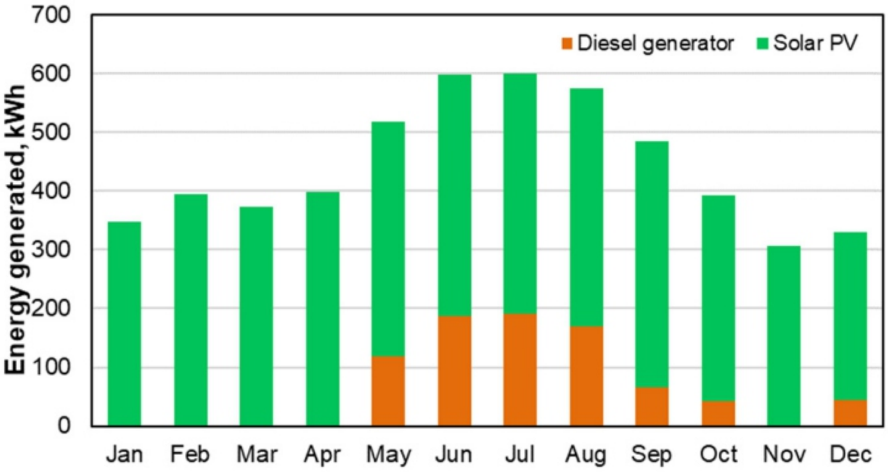

Figure 7. Monthly Electric Production by system component based on load demand.

Figure 8 shows the monthly PV electric production versus electrical load. Between January and April, and in November, the power production from PV exceeds the load. These are due to the fact that during the cold months, power demand by air-conditioning is reduced significantly, while solar radiation remains relatively high. To provide a more detailed insight of the power production consumption on a weekly basis, Figure 9 depicts a solar PV output and consumption in the last week of April and early May, where the load starts to surpass the PV power output. Additionally, it demonstrates that throughout the early and late hours of daylight, the PV power output exceeds the instantaneous loads.

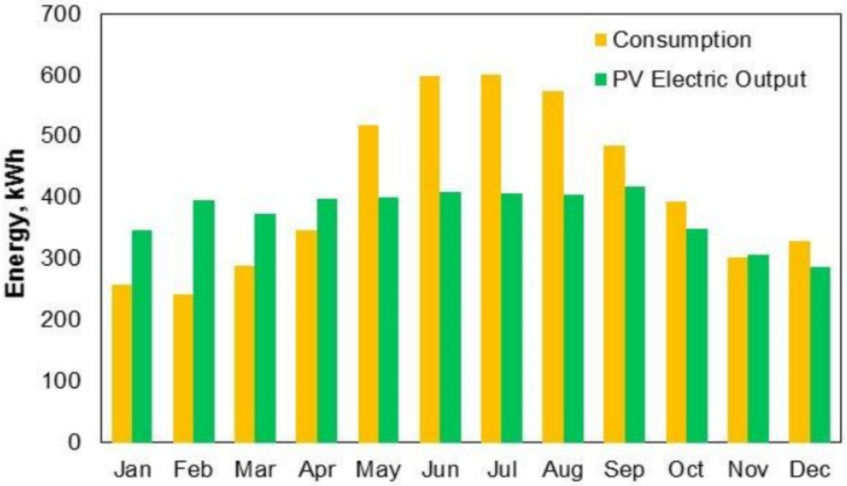

Figure 8. Monthly PV electric output and consumption.

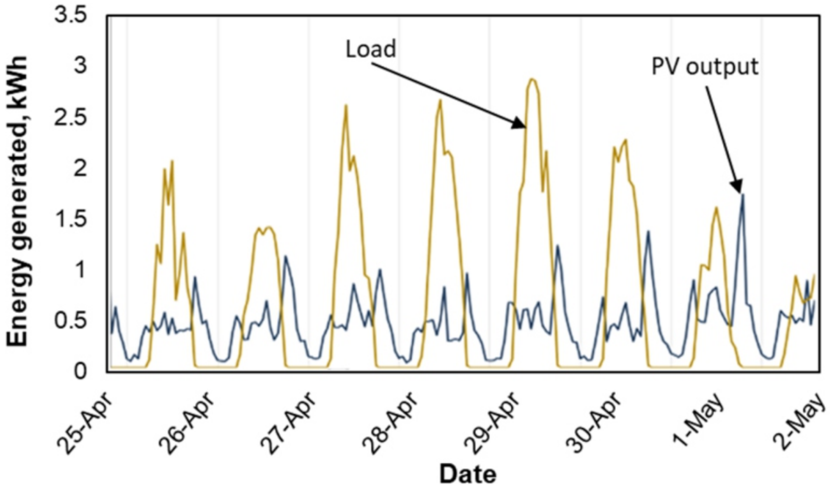

Figure 9. A 7-day PV output vs load.

Figure 10 demonstrates the system's Present Net Cost, separated down by cost category. According to this graph, the battery has the greatest net present cost of the system, followed by the PV and the diesel generator. Capital and replacement cost made up the majority of NPC. The PV panels take about 50% of the capital cost, but the replacement cost is 70% battery-related. The operating cost is less than a quarter of capital and replacement costs and mainly constitute battery and diesel generators. Fuel cost is about \$2000, and the salvage cost is at the negative spectrum. The sum of NPC for this PV-DHS is \$17800.

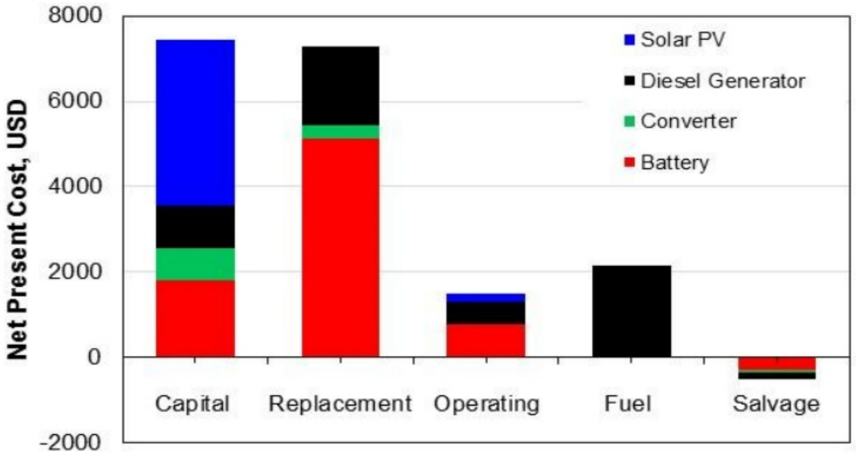

Figure 10. Net present costs.

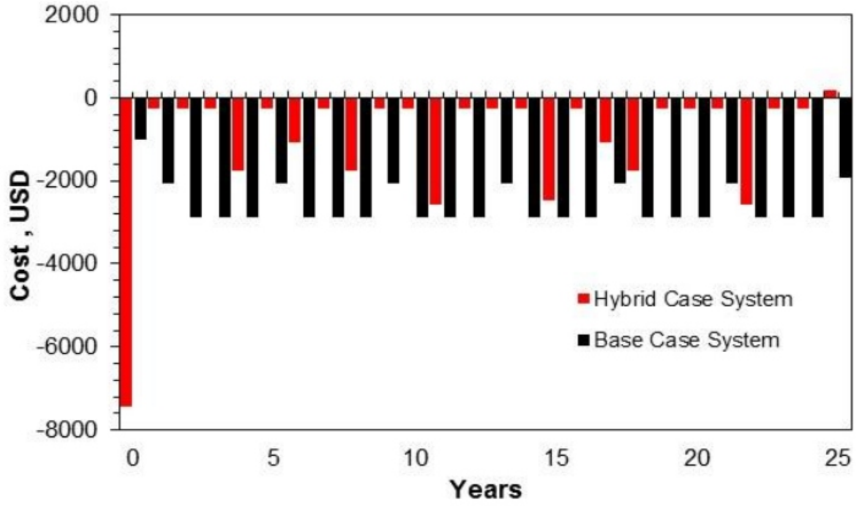

Figure 11. Cash flow comparison of hybrid and base system (Diesel only).

Figure 11 presents a cash flow comparison of the hybrid and conventional systems over the expected 25 years life span. It shows that during the infancy stage, even though the initial cost of a diesel-only system is way lower than the PVDHS, the later system is significantly less costly to run throughout the simulated period. The hybrid system's operating costs increase significantly on the fifth, tenth, and twenty-third years of life of the system due to battery and photovoltaic module replacement, although this is still less than the running expenses of a diesel-only system.

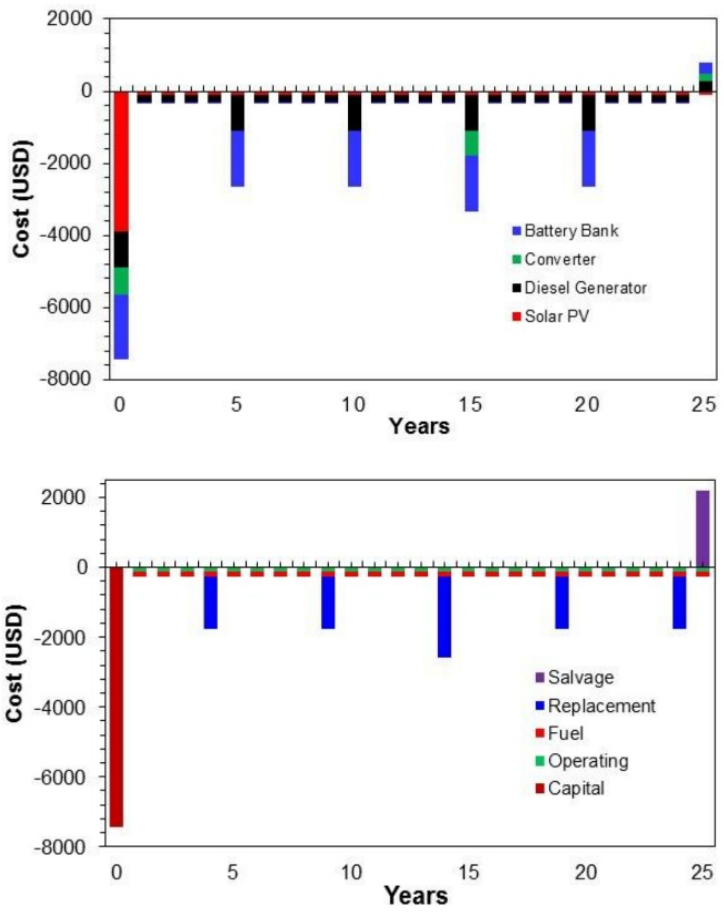

Figure 12. Cash flow summary.

Figure 12 displays a cash flow and revenue projection of the hybrid system for a period of 25 years, grouped by component and cost type. The net present cost and energy cost of the PV-diesel hybrid system are determined to be 50% cheaper than that of diesel alone. These results pointed out that the payback period is 2.8 years with a 30% internal rate of return.

Sensitivity analysis and repeated optimization were used to detect uncertainties and evaluate the simulation's unexpected behavior when fuel prices, photovoltaic efficiency losses, equipment prices, and environmental factors varied [29]. For example, high ambient temperatures decrease PV output voltage by 10%, while soiling can reduce output current by 10–30% [30]. On the other hand, Diesel generators have a cheap capital cost but a high fuel cost, which significantly impacts their adoption. In Saudi Arabia, diesel fuel prices have varied from \$0.25/Liter to \$0.58/liter [31]. A sensitivity analysis was conducted on the gasoline price, with values ranging from \$0.25/Liter to \$1.0/Liter in increments of \$0.25/Liter examined. The grid expansion costs are estimated in this study using the software's default parameters. The initial construction cost, operating, and maintenance expenses per kilometer are \$8,000 and \$45 per year, respectively, assuming a grid power purchase rate of \$0.048/kWh. A 15% tax is being considered. According to the model's assumptions, the predicted photovoltaic hybrid system will have a CF of between 18 and 25%. This means the 3 kW PV Plant would generate between 4716 and 5,524 kWh of energy per year. The optimization indicated that grid extension is preferable or break-even when the grid connecting point is within 1.07 kilometers, as shown in Figure 13.

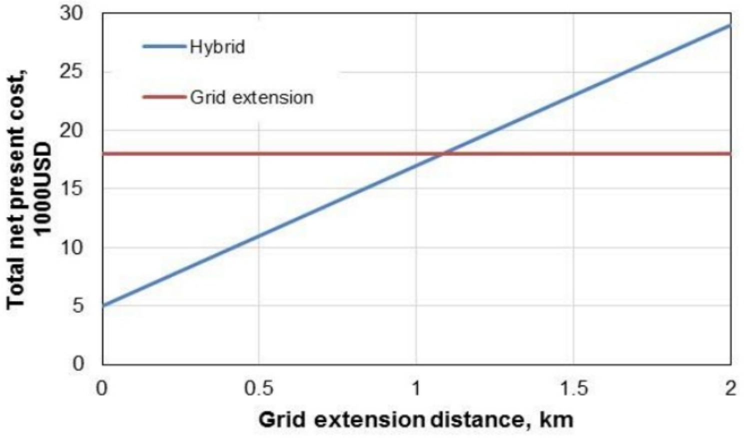

Figure 13. Break-even grid extension distance: 1.07 km.

Table 3. GHG emission of the Hybrid system and diesel system.

Emissions	Hybrid system (kg/year)	Diesel system (kg/year)
carbon dioxide	1740	9850
carbon monoxide	4.29	23.84
unburned hydrocarbons	0.476	2.66
particulate matter	0.324	17.94
sulfur dioxide	4.24	23.55
nitrogen oxides	38.3	212.77

When fossil fuels are burned, greenhouse gases are released into the Earth's atmosphere. Diesel generators use the combustion of fossil fuel. The simulation yields that PVDHS can avoid between 8110 and 11050 kg of CO2 per year. Table 3 compares the PVDHS emissions with those of a dedicated diesel generator system.

4. Conclusions

A photovoltaic-diesel hybrid electrification system was developed based on Yanbu, Saudi Arabia's climate data, to serve the grid-disconnected rural areas of this region, in which electricity is supplied mainly by diesel generators. The aim is to decrease reliance on diesel generators and increase the use of green buildings, which minimize air pollution associated with diesel combustion and provide a more reliable power system. HOMER software was utilized in the design, analysis, and optimization. The system should serve a daily electrical load of 10.5 kWh with a peak demand of 2.21 kW. The architecture of the optimized PV hybrid system incorporates 3 kW solar PV, 2 kW diesel generators, a 1 kW power converter, and 14.2 kWh batteries. The system produces 5957 kWh per year. The solar photovoltaic component can produce 80% of total energy, leaving the diesel generator component to provide 20%.

Although the hybrid system has a greater initial capital cost of $7450 than the dieselonly system ($1000), the NPC of $17,800 is much less than the diesel-only system NPC of $35,770. The system will pay for itself in less than three years, and it will reduce CO2 emissions by 8110 kg per year, which is a significant reduction.

Acknowledgements

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Design of a hybrid wind-solar street lighting system to power LED lights on highway poles

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ABSTRACT

This is an experimental study that investigates the performance of a hybrid wind-solar street lighting system and its cost of energy. The site local design conditions of solar irradiation and wind velocity were employed in the design of the system components. HOMER software was also used to determine the Levelized Cost of Energy (LCOE) and energy performance indices, which provides an assessment of the system's economic feasibility. The hybrid power supply system comprised of an integrated two photovoltaic (PV) solar modules and a combined Banki-Darrieus wind turbines. The second PV module was used to extend the battery storage for longer runtime, and the Banki-Darrieus wind turbines were used also to boost the battery charge for times when there is wind but no sunshine, especially in winter and at night. The results indicated that the hybrid system proved to be operating successfully to supply power for a street LED light of 30 watts. A wind power of 113 W was reached for a maximum wind speed that was recorded in the year 2021 of 12.10 m/s. The efficiency of the combined Banki-Darrieus wind turbine is 56.64%. In addition, based on the HOMER optimization analysis of three scenarios, of which, using either a solar PV system or the combined wind turbines each alone, or using the hybrid wind-solar system. The software results showed that the hybrid windsolar system is the most economically feasible case.

Keywords: solar energy; wind energy; hybrid system; LED streetlight; HOMER

Abbreviations: DOD: Depth of Discharge; CFL: Compact Fluorescent Lamp; LED: Light Emitting 178AIMS Energy Volume 10, Issue 2, 177–190.Diode; SCC: Short Circuit Current; PV: Photovoltaic; AD: Autonomy Days; A_ω: Rotor Wind Blades Swept Area (m^2); B_Loss: Battery Loss Factor; C_P: Wind Turbine Power Coefficient; P_Peak: Peak Power of PV Module; BAC: Battery Amperage Capacity; LCOE: Levelized Cost of Energy; O&M: Operation and Maintenance; PBP: Pay-Back Period; LF: Losses Factor; PR: Performance Ratio; CCC: The Charge Controller Current; DHL: Daily Hourly Load; DL: Daily Load; DOD: Depth of Discharge; NS: Number of Strings; NV: Nominal Voltage of the Battery; P: Wind Electrical Power (kW); PR: Performance Ratio; PVW: Solar PV Wattage; SCC: The Short Circuit Current; SDH: Sun Daily Hours; WTC: Wind Turbine Capacity; R: Radius of Banki Turbine

1. Introduction

Energy storage systems are used to help save an excess generation of clean electrical power from different renewable energy resources to be used later at periods when no adequate renewable energy resources are available. In the last three decades, hybrid energy systems were developed and innovated as a response to solar and wind energy resources utilization. For instance, hybrid energy systems can be used in places, where the electricity tariff of the electrical grid is highly expensive, and in locations, where the electrical grid is weak and intermittent, or at times when solar radiation is weak, as well as wind energy is not sufficient to generate clean electrical power.

Many papers have been published in recent years with increasing attention to hybrid systems of renewable energy.

Khare, V. et.al [1] used hybrid energy systems that are featured with their high capability to increase the rate of reliability of several renewable energy systems. They investigated experimentally the economic feasibility of a hybrid wind-solar energy system to offer clean electrical power for street lighting in low-traffic roads, in which, they sized the wind turbine, solar PV modules, batteries, charge controller, and converter. They selected metal halide lamps as they are the most appropriate light bulbs for low-traffic roads. Their results revealed that solar and wind energy resources can be utilized to operate low-consuming streetlights. In addition, findings confirmed that the annual energy generation equaled 371.7 kWh, whereas the annual energy consumption amounted to 222.8 kWh. Consequently, the remaining amount (148.9 kWh) could be exported to the electrical network making a profit from the hybrid wind-solar energy system.

Al-Tarawneh [2] focused on experimental research to calculate the annual cost savings and payback period of using LED streetlights powered via solar PV modules, Al-Tarawneh's experimental work revealed that using LED lights operated by PV power can achieve energy savings of 65% and annual energy savings of 484,261 JD, ($1 = 0.71 JD), for five major streets in Jordan. In addition, the payback period of the renewable energy system for streetlights equaled 1.47 years.

Mazzeo, H. et al., [3] examined the dynamic and energy reliability analysis of renewable hybrid system consisting of a photovoltaic solar generator, a wind micro generator and an electric generator with a storage battery to supply power for a heat pump. The heat pump is employed for heating and cooling air-conditioning of an office building environment. The dynamic simulation results identified the most contemporary load compared with the availability of the renewable source and determined the system energy reliability.

Elmorshedy, et al., [4] proposed in their study a joint and conceptual approach for technoeconomic and dynamic rule-based power control of an off-grid solar—wind renewable energy system. Their design results indicated that the hybrid renewable energy system, which integrated solar, wind,lead-acid batteries, and converter with optimal capacities of 55 kW, 18 kW, 325 kW and 42 kW, respectively, is the most cost-effective alternative with the minimum net present and energy costs of $232,423.3 and $0.3458/kWh, respectively.

Mazzeo, D. et al., [5] reviewed and made statistical analysis starting from data extracted from recent articles concerning hybrid systems. The goal of the review was to create an upgradable matrix literature database that categorizes the content of all articles into categories like geographical distribution, component configurations, operating mode and auxiliary components used to support it, intended uses, study methodologies (simulation, experimental, economic, energy, environmental, and social analysis, and so on) and software used. Furthermore, all optimization algorithms, energy, economic, environmental, and social indicators available in the literature were extracted and elaborated in order to identify the most commonly used.

Wadi, M. [6] investigated a case study of a hybrid wind-solar energy system to offer electrical power for street lighting in Turkey. He utilized a hybrid energy system and fuzzy control to control the operation and production of streetlights. The aim was to control the LED light intensity according to the battery voltage and wind speed.

Ricci, R. [7] used a hybrid renewable energy system, which integrated solar, wind, lead-acid batteries and inverter, and created optimal capacities of 55 kW, 18 kW, 325 kW and 42 kW, respectively.

The most cost-effective alternative with the minimum net current energy costs were \$232, \$423.3 and \$0.3458/kWh, respectively.

Georges, S. & Slaoui, F. [8] made a comparative study between LED and high-pressure sodium light bulbs. They made an analysis to size and design each component of a hybrid wind-solar energy system, which included wind turbines, solar PV panels, Gel batteries and charge controllers. The results indicated that using 40 kW solar PV system and 40 kW wind system for 80 Watt—1,000 LED street costs \$80,000. Moreover, replacing high-pressure sodium bulbs with 80 Watt LED can achieve \$2.66 savings in the initial installed cost of streetlights.

Al-Sarraj, et, al. [9] conducted a study aiming to assess the economic viability related to the use of a hybrid solar and wind energy system to provide clean electrical power for a facility in Iraq. They used HOMER software to estimate the hybrid system's economic feasibility. Their analysis results revealed that power produced from the solar PV system is 61.6 kW/annum, while the power from wind is 2.7 kW/annum.

This experimental study will highlight the beneficial effects and primary responsibilities of hybrid energy systems in achieving energy security, sustainability and reliability of wind PV solar systems for street lighting. The work will attempt to provide enough electric power to eliminate the need for electric power from the national electric grid, which can help save money and manpower for operation and maintenance (O&M) and reduce carbon emissions with reliable LED lighting. Moreover, HOMER software was used to analyze a similar system that uses solar and wind energy to provide electrical power for LED street lights. The LCOE, which is defined as an investment index that described the total price of energy provided by the renewable energy system by dividing the total initial cost by the annual savings, was calculated to determine the economic viability of the entire system.

2. Research methodology

The following main methodological steps were conducted in carrying out this study:

- A review, field survey, and analysis of energy demand for street lighting of past relevant applications were carried out.
- Analysis and assessment of the wind and solar radiation energy potential at the geographical location of the experimental setup were conducted.
- An estimation of the PV system size and design of the combined wind turbine system were made.
- The experiments and measurements were performed to check the success of the operation of the hybrid system in street lighting.
- The HOMER software was used in order to check the economic feasibility of the hybrid windsolar system.

3. Design and performance analysis

To calculate the clean electrical power value produced from the wind turbine, the following equation is used [10]:

$$P = {}^{1}\!/_{2}\, \rho C_P A_\omega v^3 \tag{1}$$

where *P* is the wind electrical power,*p* is the air density,*Cp* is the wind turbine power coefficient, *Aw* is the wind turbine blades swept area, and *v* is the wind speed. To calculate the wind turbine power required to feed the load of the streetlight, Eq 2 is used [11]:

$$WTC = \frac{\pi}{2} \times r^2 \times v^3 \times \rho \times \eta \tag{2}$$

where *WTC* is the wind turbine capacity, *r* is the Banki turbine's radius, and *n* is the efficiency. The needed solar PV panels power is calculated via the equation [12]:

$$PVW = \frac{DL}{SDH \times LF \times PR} \tag{3}$$

where *PVM* is the solar PV power,*DL* is the daily load, *SDH* is the sun daily hours, *LE* is the losses factor, and *PR* is the performance ratio. The PV module power capacity is computed using the formula:

$$P_{PV} = \frac{P_{Load}}{\eta_{Module} \times \eta_{Charge\ Controller} \times \eta_{Battery} \times \eta_{Cables}} \tag{4}$$

The overall watt peak needed for the PV module, P_{Peak} is computed using the formula:

$$P_{Peak} = \frac{P_{PV}}{SDH} \tag{5}$$

To calculate the battery amperage, the following equation is used [13]:

$$BAC = \frac{DHL \times AD}{B_{Loss} \times DOD \times NV} \tag{6}$$

where BAC is the battery amperage capacity, DHL is the daily hourly load, AD is the autonomy days, DOD is the depth of discharge, B_{Loss} is the battery loss factor, and NV is the battery's nominal voltage. The charge controller current, CCC, is calculated using the equation:

$$CCC = (NS)(SCC)(LF) \tag{7}$$

where NS is the number of strings, SCC is the short circuit current, and LF is the average losses.

4. Experimental procedure and setup

4.1. Systems components design

4.1.1. Wind turbine design

Based on the measured wind data at the site, the Banki-Darius wind turbine was designed. The Banki wind turbine comprised of two layers, one on top of the other. Each layer had 8 blades. The diameter of the Banki wind turbine is 39 cm, with a total height of 68.5 cm. This yielded a wing area of 0.2672 m². The response speed of the Banki wind turbines is between 5 and 25 m/s [14]. Noting that the density of air is 1.22 kg/m3at an atmospheric pressure of 101.325 kPa [15], the maximumefficiency of the combined wind turbine is estimated to be 56.64%, according to the Betz limit [16]. Substituting all values of these parameters into Eq 1 resulted in a wind power of 12.22 W and 1,528.10 W for wind speeds of 5 and 25 m/s, respectively. However, the maximum wind speed recorded in the year 2021 at the site was 12.10 m/s, which provided a maximum power of the wind turbine of about 113 W. Figure 1 shows the fabrication and design processes for the combined Banki-Darrieus wind turbine.

Figure 1. The manufacturing and designing processes of the combined Banki-Darrieus wind turbine.

To generate more efficient electrical power from wind power, three Darieus wind blades positioned between the hub height were incorporated into the Banki wind turbine to form the combined wind system, as shown in Figure 2. The capacity of the combined wind turbine can reach 300 Watt.

Figure 2. The overall system's components.

Table 1 presents the combined Banki-Darrieus wind turbine data.

Table 1. Combined Banki-Darrieus wind turbine datasheet.

Technical specifications	Numerical value
Rotor diameter	390 mm
Hub height	685 mm
Expected lifetime	20 years
Replacement cost	100 USD
Expected O&M cost	5.0 USD/annum

4.1.2. PV system

According to the solar irradiation data measured at the experimental site, the required solar PV power *(PVM)* daily load,*DL* sun daily hours, *SDH* losses factor, *LF*,and performance ratio, *PR* are estimated *DL* is 300 Watt. Hour/day (30 Watt multiplied by 10 hours), *SDH* is 5.7 hours/day [16]. *LF* is 0.8, and *PR* is 0.85. Substituting these value leads to a *PVM* of 77.4 Watt.

Table 2. 80-Watt PV module specifications.

Technical specifications	Numerical value
Maximum power	80 Watt
Number of PV panels	2
Tolerance	± 3 percent
Open circuit voltage	22 Volts
Short circuit current	4.85 Ampere
Maximum power voltage	18 Volts
Maximum power current	4.44 Ampere
PV panel efficiency	13.05 Percent
Solar cell efficiency	17.2 Percent
Series fuse rating	15 Ampere
Junction box protection	IP65
Maximum system voltage	1,000 Volt DC
Operating temperature	−40 °C to 85 °C
Dimensions	915 mm × 670 mm × 30 mm
Weight	7.31 kg

To calculate the P_{PV}, Eq 4 parameters are substituted, P_{Load} = 300 Wh/day, η_{Module} as 0.85, $\eta_{Charge\ Controller}$ as 0.95, $\eta_{Battery}$ as 0.85, and η_{Cables} as 0.97 into the previous equation leads to 450.6 Wh/day. Thus, the total power rating of the PV panels, P_{Peak}, equals 79.1 Watts.

To generate clean electricity from solar radiation, an 80 Watts solar PV polycrystalline CENTSYS module was therefore selected. However, a second 80W PV module was added in order to enhance charging of the battery for longer runtime at times of low solar irradiation.

The datasheet of the 80-Watt PV module is represented in Table 2.

4.1.3. Battery

To select the battery, Eq 6 was used to determine the amperage of the battery. Substituting the values of Eq 6 is based on DHL of 300 Wh, AD is 3 days, B_{Loss} is 0.85 according to the high temperature losses at the site weather conditions, DOD was assumed 60%, and NV of 12 V leads to BAC of 147 Ah. Thus, 150 Ah Gel battery was chosen, the specifications and datasheet of the Gel battery used in the hybrid energy system are presented in Table 3.

Table 3. 80-Watt PV panel specifications.

Technical specifications	Characterization
Model number	SB150
Storage system category	Standalone (Off-grid)
Battery type	Lithium Ion
Maximum amperage capacity	150 Ah
Nominal voltage	12 Volts
Maximum discharge current	1,500 Ampere
Battery dimensions	490.20 mm × 228.60 mm × 266.7 mm
Battery weight	295 kilograms

4.1.4. Charge controller

In this study, three charge controllers were used, one for each of the two solar PV modules and the third for the combined wind turbine. For solar PV module, the following equations present the calculations of voltage and current of the PV charge controller, which included the maximum power of PV module that is 80 Watt, the maximum voltage of PV module that is 18 Watt, and the maximum current for the PV module that is 4.44 Ampere. The open circuit voltage of the PV module is 22 Volts, and the short current circuit for the PV module is 4.85 Ampere. Substituting the previous values in Eq 7, yields:

$$CCC = (1)\ (4.85)\ (1.3) = 6.3 \text{ Ampere}$$

Therefore, the charge controller should be rated at 6.5 Ampere at the 12 Volts.

For the wind turbine, based on data on a 300 W catalogue of vertical axis wind turbine, the charge controller voltage is 12 volts, whilst the open circuit current is less than 20 Ampere.

A charge controller is used in this system to provide protection for the lithium-ion battery used to store electrical energy. Charge controller can prevent battery from high level of depth of discharge (DOD), and high level of state of charge (SOC), which can help maintain high lifespan of the battery [17]. The charge controllers used in this study for both solar PV modules and the combined Banki-Darrieus wind turbine are shown in Figure 3.

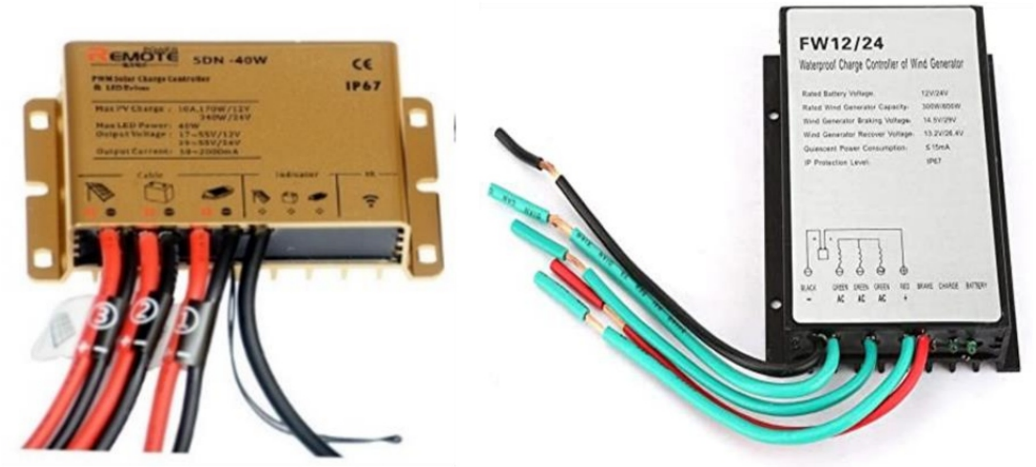

Figure 3. Charge controller used in this study for (PV panel on the left) and (wind turbine on the right).

4.2. The overall system configuration

The overall system's components are presented in Figure 3 above. Whereas, the electrical connection of the hybrid solar-wind system is shown in Figure 4, in which the PV module one and the combined wind turbine system work for providing extra electrical charge for the battery, while the PV module two is the one in charge of lighting the LED light at night by the battery and through its charge controller.

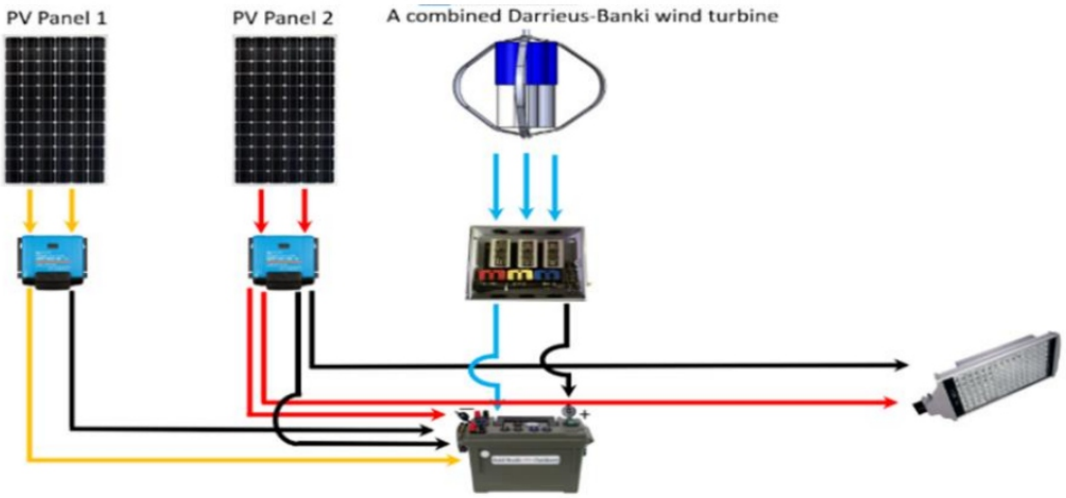

Figure 4. Configuration of PV-wind street lighting system.

5. Results and discussions

This section presents the experimental and numerical results obtained in this work.

5.1. Experimental results

Figure 5 indicates that the average power that could be obtained from the wind speed, which ranges between 30 and 120 Watt.

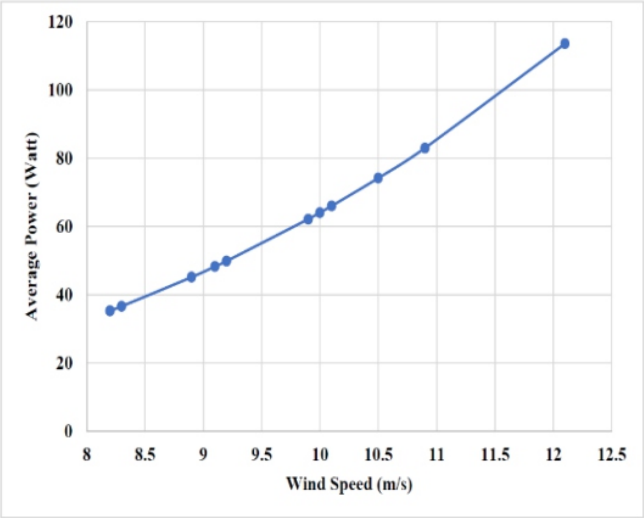

Figure 5. Average power obtained from the wind speed at Mutah University site.

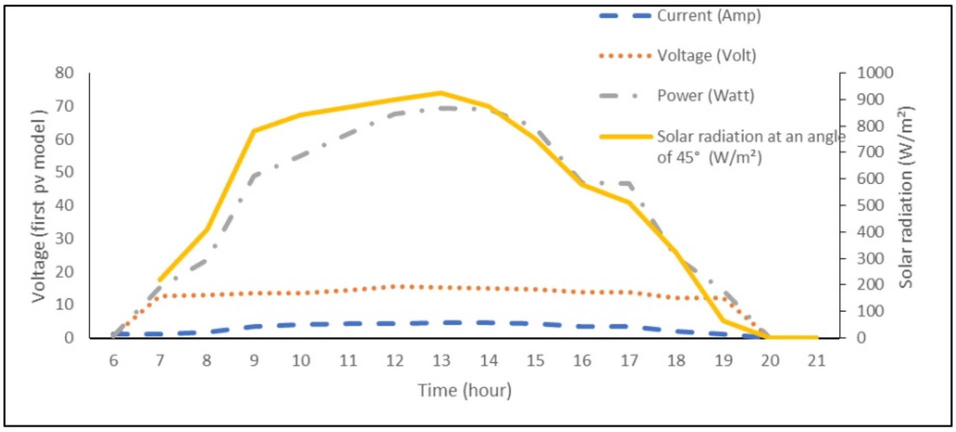

Figure 6. Solar irradiation, current, voltage, and power of the first PV module measured on August 26, 2021.

The maximum value of average power in the year 2021 was recorded at a wind speed of approximately 12 m/s, whilst the minimum average power of wind was recorded at a wind speed of approximately 8 m/s.

Figure 6 presents the solar irradiation, current, voltage, and power of the first PV module used in the experimental system.

It is indicated from the Figure 6 that the current ranged between around 0.9 (minimum value) and 4.6 Amp (maximum value), while the voltage values ranged between around 0.7 Volts and 15.34 Volts. Correspondingly, the power values ranged between a minimum value of approximately 0.6 Watt and a maximum of 70 Watt.

Figure 7 indicates that the current of the battery load was approximately constant over the day ranging between 2.2 and 2.4 Ampere. The value of voltage varied between roughly 12.2 and 12.8 Volts, providing a power that ranged between 27 and 30 Watts.

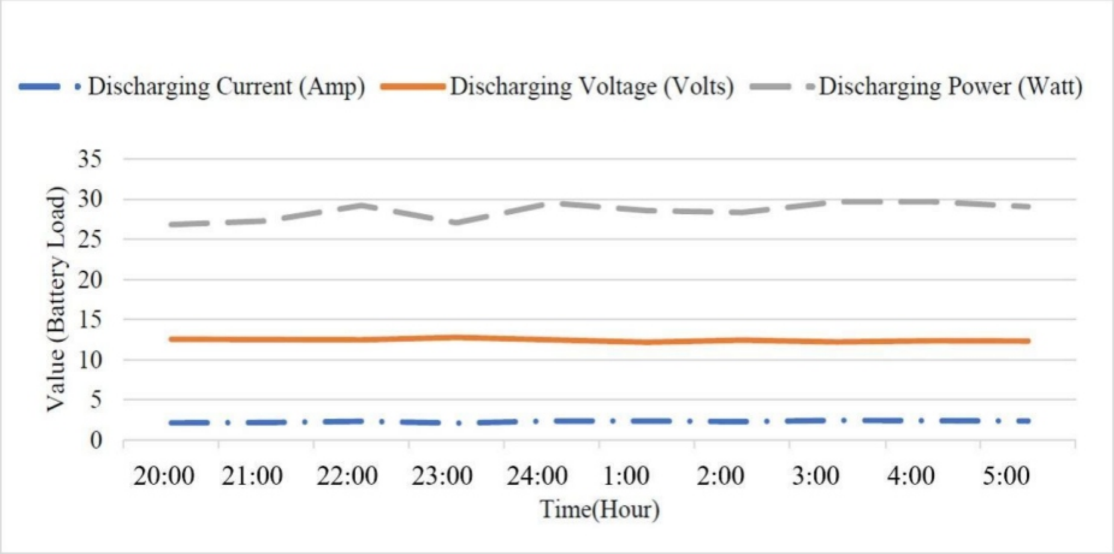

Figure 7. Battery load: current, voltage and power on August 26, 2021.

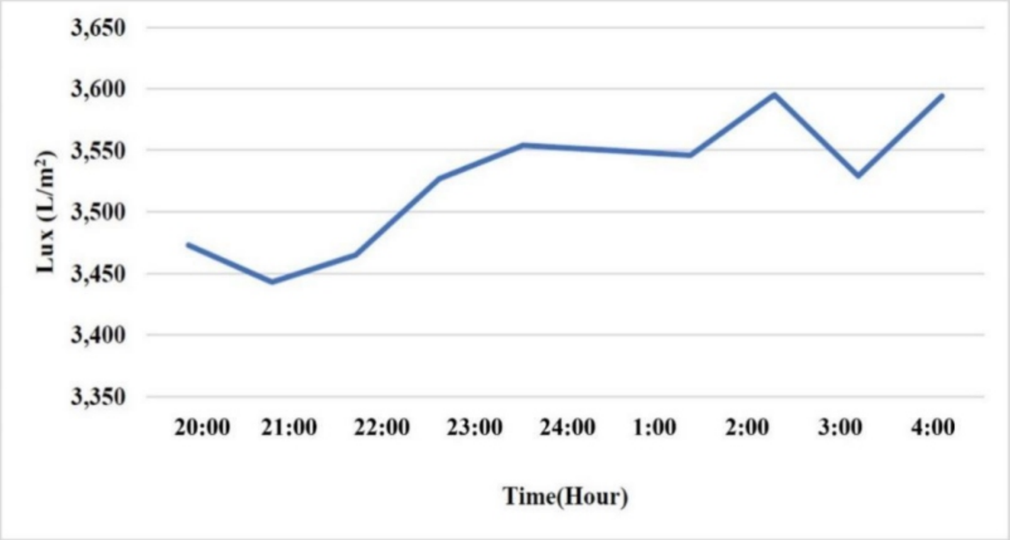

Figure 8. Light intensity at the street of the 30W LED street lamp placed at a height of 9 meters.

Figure 8 displays the light intensity at the street of the 30 W LED streetlight placed at a height of 9 meters. The figure indicates that the light intensity ranges between around 3,450 and 3,600 L/m2, which occurs between 8:00 pm and 5:00 am. Outside this range of time, the LED streetlight provides no light intensity as it is programmed not to operate.

These results have indicated that the combined Banki-Darrieus wind turbine that included three Darrieus wind blades and two layers of the Banki wind turbine, each with eight blades, and the two PV modules, each of 80 W capacity, were appropriate to light a street LED lamp of 30 Watts.

5.2.Numerical results

After conducting optimization, sensitivity analysis, and simulation through the HOMER software package for the system presented in Figure 9, it was found that there were 3 possible scenarios of the hybrid solar PV-wind system in terms of economic feasibility. The three cases are presented in Table 4.

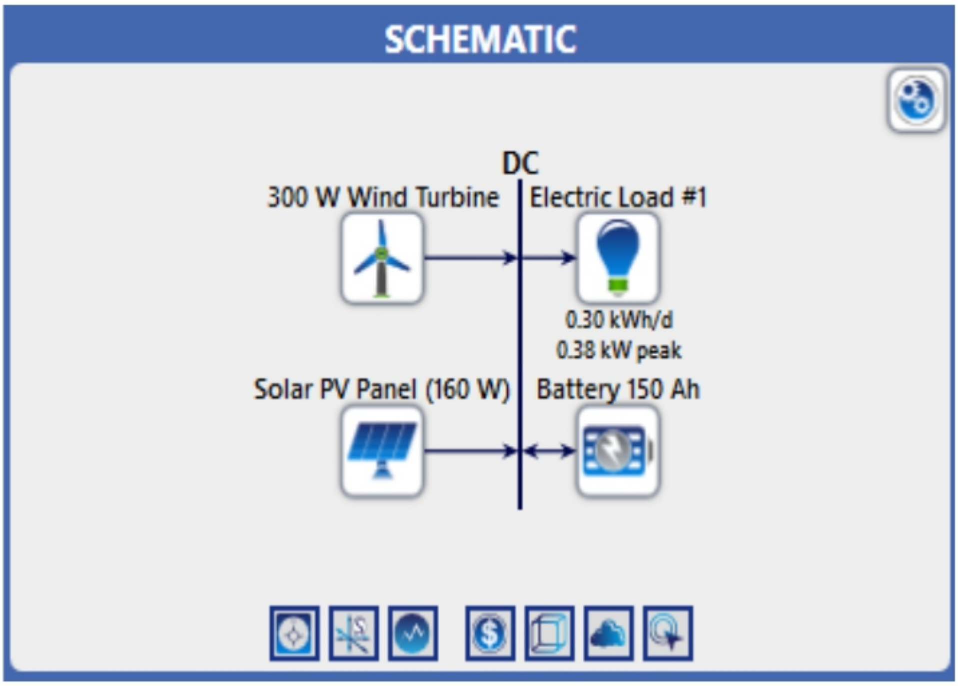

Figure 9. A schematic diagram of the hybrid solar-wind system investigated in the HOMER software.

Table 4. Scenarios defined in HOMER software.

#	Power production source	Energy storage (battery)	Layout ▦ ✢ ▭	LCOE (USD/kWh)
1	PV Panels and Wind Turbine	Yes	▦ ✢ ▭	0.5387
2	Only wind turbine	Yes	✢ ▭	0.8232
3	Only PV panels	Yes	▦ ▭	0.8791

The HOMER software numerical results revealed that the LCOE of case (1) (solar PV, wind turbine,and battery) was 0.5387 $/kWh. The net present cost of the system equals $762.09, while the system's operating cost in this scenario equals $21.24. However, the LCOE value of scenario (2) (wind turbine and battery) was 0.8232 $/kWh, with the net present cost of the system equals $1,165.22, while the system's operating price in this scenario equals $34.05. Whereas, the LCOE was 0.8791 $/kWh for scenario (3) (PV panels and battery). The system's net present cost equals $1,243.50, while the system's operating price in this scenario equals $22.22. Surely, the software results showed that the hybrid wind solar system is the most economically feasible case.

6. Conclusions

This experimental and numerical study investigated the suitability of a wind-solar hybrid system in lighting street LED lights on highway poles. The hybrid system includes a combined Banki-Darrieus wind turbine integrated with a PV solar system to provide energy to light a 30 W street lamp. The numerical part of this study included the use of HOMER software to check the levelized cost of energy of the hybrid system, which provided an assessment of the system's economic feasibility.

The main results of this experimental and theoretical study revealed the following findings:

1. The experimental results revealed that the design of the Banki-Darrieus wind turbine that included three Darrieus wind blades and two layers of the Banki wind turbine, each with eight blades and of a diameter of 39 cm and a total height of 68.5 cm, and the two PV modules, each of 80 W capacity, were adequate to light the 30 W LED street lamp.
2. The maximum wind speed recorded in 2021 at the experimental site was 12.10 m/s, which provided the wind turbine power of 113 Watts.
3. The HOMER software numerical results revealed that the hybrid wind-solar system is the most economically feasible case among using either wind or solar system alone.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conception and design of study: Nadwan Majeed Ali, Handri Ammari.
Drafting the manuscript: Nadwan Majeed Ali.
Analysis and/or interpretation of data: Handri Ammari.

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An old climate war

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ABSTRACT

During the 1990s a 'war' was fought over climate change between the author and some (not all) of his senior colleagues at the World Energy Council. There were two strands to his work: serious energy analysis and consideration of possible futures; and potential climate change. In the latter role he came up against stringent and often ill-informed criticism of his work and actions. Ill-informed because the critics did not appear to be aware of the serious and widely supported (within the WEC) published works of the WEC; and were frequently incorrect in what they claimed the author had said or written, or wrongly attributed to him actions by others outside the WEC. The record of relevant WEC publications, and the attacks made by those seeking to deny climate change or obfuscate debate on the related issues from the American Petroleum Institute, Global Climate Coalition, and US Climate Council, are related here. Everything here is based upon written records (unpublished as well as published) in the author's possession and his recollections.

Keywords: climate change; deniers; seeking objectivity; hostile responses

1. Introduction

This paper sets out the history of what usually seemed to be strident but ill-informed criticism by some individuals and their USA-based organisations in the period 1994–1998 of work conducted within the World Energy Council relating to climate change. It is based upon original documents still in the author's possession. The paper's title is a reminder of Michael Mann's remark:

"When it comes to the war on the science—that is, the old climate war—the forces of denial have all but conceded defeat. But the new climate war—the war on action is still actively being waged" [1].

There is plenty of media evidence that the old climate war still lingers on in some quarters. This paper contains elements of both the old and new climate wars, each of which continue to have relevance to current debates in the media. This paper offers the reader material to judge the passage of both wars on the ground, as Naomi Oreskes and Erik Conway have put it:

"Often we find that, in the end, it is best to let the witnesses to events speak for themselves" [2].

So first some background, then in Section 2 an outline of the work conducted relating to potential climate change at the World Energy Council (WEC) within the much broader global energy field in the period 1989 to 1998. Then in Section 3 the aftermath of hostility to that work which had emerged from June 1993 and which finally led to my removal from the WEC as recorded in various documents and quoted here.

It was September 1990 and I had greatly enjoyed over 15 years in the Royal Dutch Shell Group, initially as Group Chief Economist, then in Shell International Petroleum as Head of Planning and of Oil Supply Appraisal in mainland Europe, followed by Director of Oil Supply and Trading in Sweden, and Head of Oil Pricing in Shell International Supply and Marketing in a period of turbulence. But now it was time to move on from Shell UK, where I had first had contact with the World Energy Council (WEC) through its UK Member Committee, and attendance at its 14th Congress, held in Montreal in 1989.

I didn't fancy being Head of Crude Oil Acquisition in Shell Nigeria, certainly not at the age of 50 when I might be hanging around until late at night hoping (perhaps unsuccessfully) to see a Minister. I did not consider myself suited to being No. 2 in the Public Affairs (i.e. Public Relations) side of Shell International—what would I say if expected to speak about a policy, action or statement I disagreed with? There appeared to be internal problems at a business school where there was apparently a wish for me to become their first Director. My wife and I had just come back from this last potential post and we were out to dinner with the World Energy Council's Secretary General, Ian Lindsay, and some of his associates. My wife explained to Ian where we had been and why, Ian invited me to see him the next morning, and I became Deputy Secretary General of the WEC, on secondment from Shell for two years. I did not return to Shell.

The World Energy Council was founded in 1923, initially with Member Committees in some 40 countries (later to rise to nearly 100), including both governmental and non-governmental bodies, with the principal objective "to promote the sustainable supply and use of energy for the greatest benefit of all people." The World Energy Council claims: "Throughout history, it has never strayed from the initial concept of an organisation that is impartial, objective and realistic." Yet, as this paper will demonstrate, there was a period during the 1990s when this claim had dubious validity.

My personal background had been the University of Oxford and London School of Economics; banking and finance in the City of London; manager of an economic consultancy partnered by five professors of economics; and Deputy Director of the UK-based Industrial Policy Group composed of over twenty Chairman of major industrial companies—one of whom was Sir David Barran, Chairman of The Royal Dutch/Shell Group of Companies as it was then known. Annex 1 provides a list of people named in this paper, and their relevant affiliations at the time for ease of reference.

My interest in the weather and climate originated at a boarding school in England where I was appointed school meteorologist, was followed up by reading and following the emerging climate change debates which inter alia involved meeting leading world experts in the field during the 1970s and 1980s. While in Shell's Group Planning, I was responsible for providing inputs on global economic, geopolitical, and societal prospects among which the effects of climatic change, major volcanic eruptions, and pandemics formed a part.

At an early point in the World Energy Council (WEC) I got involved in writing the report of a WEC Commission entitled: "Energy for Tomorrow's World—the Realities, the Real Options and the Agenda for Achievement", which was published in 1993 [3]. The Commission was a body set up by the World

Energy Council's leadership which comprised nearly fifty people "eminent in his or her own field" [3, page 19)] eight regional groups (the North American Group alone comprising fifteen people), a Project Management Unit (of which I was a member), and four Special Advisers. The Commission's goal was entirely consistent with the WEC's "mission" from its beginnings in 1923.

I had not anticipated having to write "the complete document in preparation for the Publishers" but was happy to do so. Michael Schomberg (then editor of the WEC's Survey of Energy Resources) took on the formatting in what the book's Acknowledgements described as "a prodigious task completed under severe time pressures." [3, page 20]. There were many individuals and regional groups which helped in the endeavour. Topics covered included the recently formed Intergovernmental Panel on Climate Change (IPCC); and four "cases" or scenarios going out to 2020 (including "Ecologically Driven" Case C). As stated on page 308 of the WEC Commission's Report, the implications of its Cases for atmospheric concentrations of carbon dioxide and change in global-mean temperature "were calculated by the internationally respected Climate Research Unit of the University of East Anglia … work undertaken by Professor T.M.L. Wigley and Dr. M.Hulme." (page 308) The WEC Commission's Report added: "It is stressed that these Cases and estimates based upon them are for illustrative purposes only. They illustrate that if the hypothesis about enhanced global warming and potential climate change is broadly correct then, using a highly respected research unit and climate model, the consequences are likely to be as set down here."

For the purposes of this paper probably the most important aspect of the Commission's Report was its advocacy at numerous points of the need for precautionary measures to be taken to curb emissions given the risks of anthropogenic climate change. For example: "Precautionary measures to reduce the emissions of greenhouse gases should be adopted since scientific evidence does not so far justify any other policy." [3, page 304] As this paper proceeds it will be seen that my critics at that time, attacking me for what they claimed I wrote or said, or contributions from those on the WEC committee I chaired, were acting, writing, and/or speaking in flagrant contravention of what the WEC Commission had agreed and published. However, I had been warned early on by WEC Secretary General Ian Lindsay in a handwritten note dated 11th June 1993:

"The practical interpretation of the WEC's various policies and the stance likely to be taken by the major WEC supporters (Member Committee members) will not necessarily agree even with what has been written into the WEC Commission."

This was only a fortnight after WEC Chairman Gerhard Ott had congratulated me and the WEC's Commission on our excellent work. No mention was made at the time to the fact that the WEC Commission's Board was not free of views diametrically opposed to the Commission's published report. One such Board Member was the President of the US National Coal Association who, according to a handwritten note by Ian Lindsay dated July 30th 1997, regarded the Byrd/Hagel US Senate Resolution (which opposed the USA signing any protocol under the UN Framework Convention on Climate Change unless it satisfied certain conditions) as the “Ace of Spades”.

In early 1994 a WEC booklet: “Global Emissions Cases” was issued, which ended with the following paragraph:

“The WEC Commission, noting in particular the key uncertainties and further work identified by the IPCC in its Supplementary Report on Climate in 1992, took the view that on balance precautionary measures are required now in respect of potential climate change. It is against this background that the WEC Commission’s emissions cases have been outlined here” [4].

This booklet also made reference to further work using the WEC Commission’s data carried out by Gregg Marland of Oak Ridge National Laboratory which did “not produce a markedly different outcome.”

An extract was included from the IPCC’s “Climate Change 1992: The Supplementary Report to the IPCC’s Second Assessment” [5]. John Houghton was one of the three Editors of this last report, who had invited me (in my role in the World Energy Council) to join in the discussions and meetings of the IPCC back in October 1991. John became Chairman of the IPCC’s Working Group 1 (the Scientific Assessment) and drew on “Energy for Tomorrow’s World” in the first two editions of his book: “Global Warming: The Complete Briefing” [6].

A few months later I met the IPCC’s Chairman (1988–1997), Bert Bolin, whose calm approach to the subject of potential human-induced climatic change appealed to me, given some of the uncertainties with which this subject was, and still is, surrounded. As Professor Bolin wrote in his book: “A History of the Science and Politics of Climate Change”: the WEC was a “key international organisation that responded early to the potential threat of a human-induced climate change.” Here he was referring to “Energy for Tomorrow’s World” and its scenarios—“the work went beyond the IPCC efforts” (at that point of time). “The comments from the WEC on the first draft of the chapter on scenario development in the 1994 IPCC special report were sharply critical and admittedly the WEC scenarios were more informative”—than “the first draft of the chapter on scenario development in the 1994 IPCC Special Report” [7, page 93].

As Bert mentioned, these WEC “projections were later extended to 2050 and 2100 in collaboration with the International Institute for Applied Systems Analysis”, an organisation based in Laxenburg, Austria. These WEC/IIASA joint publications were: “Global Energy Perspectives to 2050 and Beyond: Report 1995” [8], and “Global Energy Perspectives”, 1998. [9] This work took up much of my time in the period 1995–1998, although the inputs of Nebojsa Nakicenovic and his IIASA colleagues was critical—Professor Nakicenovic being Study Director of the first report, and one of the three IIASA Editors of the second. I was a Lead Author for both. Interestingly, Gerhard Ott, who had been Director of the German Coal Industry Association and had become Chairman of the World Energy Council, had his name attached to both reports despite (as some of the documents referred to below indicate) clearly not being enthusiastic about the WEC discussing the subject of climate change and tending to support the hostile comments coming from some USA-based critics. This was despite the care taken to check for objectivity and care in the scenarios and related analyses.

The other major energy publication in that period had been: “New Renewable Energy Resources: A Guide to the Future”, 1994 where Jack Darnell from the World Energy Council’s US Member Committee had primary responsibility for the content, supported by over 80 specialists, and where he and I were the General Editors. Jack wrote much of the Overview and Solar Energy chapter, while I added input on environmental and efficacy aspects, especially in relation to wind and tidal energy [10].

2. Climate meeting reportage

In a history of the WEC: “From World Power Conference to World Energy Council: 90 Years of Energy Cooperation, 1923–2013” published by the WEC, it was stated:

“By the end of the 1980s, environmental concerns had moved to the centre of WEC’s agenda. ‘Environment Dominates 91-Nation Energy Talks’, the New York Times summed up the 14th Congress held in Montreal in 1989. It noted how the ‘worry at this triennial event has shifted from oil embargoes and declining reserves of fossil fuels to urban smog, acid rain and, above all, global warming” [11].

The New York Times headline was in fact slightly different but had the same meaning: “Environment Is Focus of 91-Nation Talks.” The WEC history went on:

“The 1989 meeting marked a paradigm shift. As Elihu Bergman, executive director of the Americans for Energy Independence, a conservation group, noted “you would never have heard this three years ago. This conference is symbolically legitimizing what we have known in the States: environmental policy is driving energy policy” [11].

The “catalyst” for this shift was stated to be the appearance of the Brundtland Commission report: “Our Common Future” in 1987 and the creation of the IPCC the following year. Following the subsequent Rio Earth Summit (1992) and Kyoto Protocol (1997): “In these years, sustainability came to be foregrounded at WEC.” In fact, as this paper demonstrates, this history of the WEC is rather misleading [11].

Potential climate change, induced primarily from fossil fuel use and resulting carbon dioxide and methane escape into the atmosphere, was an element in all the above work which had been primarily focussed on energy supply and usage. Now came the reports of WEC Working Group 4A: ENVIRONMENT: Potential Climate Change, of which I had been appointed Team Leader by the WEC’s Studies Committee. The purpose of these reports was to inform the WEC’s member committees (nearly 100 of them) around the world of what was taking place. Although all were written by me, some of the meetings reported on were attended by other members of the Working Group, who also had access to third party reports. The information provided came from spoken or written inputs into the various meetings covered, and responses to questions raised by me to attendees of these official meetings of inter-governmental bodies. A summary list of the WEC reports covered in this section is provided in

Annex 2 at the end of this paper to help guide the reader.

The first report: “Post-Rio ’92—Developments Relating to Climate Change” was issued in April 1994. It stated that: “The principal purpose of Working Group 4A is to monitor and report back to the WEC on all major post-Rio ’92 developments in the field of possible global warming and climate change.” The report mainly focussed upon the events leading up to the ratification of the UN Framework Convention on Climate Change (UNFCCC) in March 1994 and the work of the IPCC, but also covered recent scientific/technical findings which had appeared in leading scientific journals, the work of the UN Commission on Sustainable Development, and meetings of bodies covering bio diversity and new and renewable sources of energy (the UN Committee). The WEC report mentioned the challenges confronting climate modelling and that comments had been made by WEC Working Group 4A to the IPCC relating to “points of wording which lacked balance.”—because of an apparent unwillingness to accept the uncertainties surrounding an unknowable future [12].

In November 1994 a second draft report was circulated but, due to opposition by the WEC’s Control Panel, was not issued in that form. The draft was twelve pages in length, plus seven pages of Appendices—two pages listing countries which had ratified the UNFCCC, two pages listing the chapters and sections of the IPCC’s Second Assessment Report, and three pages listing Key Events Relating to Potential Climate Change. As the Executive Summary put it: “IPCC Reports about to go out for General Review, or recently circulated, are briefly discussed. A tendency to understate continuing uncertainties about the carbon cycle are criticised, and attention is drawn to ineffectual work on emissions scenarios” [13]. This draft report ran into strong opposition on grounds of length and content, from WEC Chairman Gerhard Ott and others. As Gerhard wrote to me on November 11th, 1994:

“I do regret, of course, that work which you undoubtedly started with all good intentions has led to such an unsatisfactory result.”

Gerhard Ott also considered the Working Group reports “too detailed and ‘for experts by experts’” which went against requests from several WEC Member Committees for plenty of detail. There was always a one-page Executive Summary.

The WEC’s Work Group had considered a question raised by one of its members, Keiichi Yokobori, as to whether the Group’s reports should include adversely critical comments on the attitudes or statements of specific individuals or organisations, but instead put forward a “more sanitised version”.

The Work Group had decided to stick with its critical comments because:

“The Work Group and its associates considered this point with care and at length. They felt that having regard to the known facts, and the poor image of business that two U.S.-based organisations were creating at a time when the INC were seeking to involve business in their deliberations, a bolder approach was justifiable. They also took note of the evidence that one U.S.-based organisation (the Climate Council) and/or its spokesman Mr. Donald Pearlman, were advising the Kuwaiti and Saudi delegations and that Mr. Pearlman had openly claimed to be campaigning for the demise of the IPCC and the removal of Prof. Bert Bolin" [14].

The Work Group's statement went on to recognise that this was a policy matter which should be drawn to the attention of the Control Panel for them to take the decision for, or against, the Work Group's recommendation for inclusion of these references.

It was clear during October 1994 that a campaign had begun from the WEC's USA Member Committee and its associates. On November 2nd 1994 William O'Keefe, Executive Vice-President of the American Petroleum Institute and close to the Global Climate Coalition of climate change deniers and sceptics wrote:

"I have serious reservations about the WEC undertaking this reporting task."

The Secretary of the WEC's US Member Committee, Barry Worthington, took exception to the response the WEC's Central Office had made to O'Keefe, referring to the exchange of "written barbs".

This was despite Worthington writing on November 3rd 1994 that the American Petroleum Institute's and Global Climate Coalition's William O'Keefe having written "the best commentary I have received regarding the WEC's Working Group on Potential Climate Change."

It was not until March 1995 that Report No. 2 was actually published, somewhat shorter (at twelve pages) than the original draft but the Executive Summary retained the sentence which had appeared in the draft Report and had aroused the strongest opposition. As was the case with the original draft version the issued report made several adversely critical comments on the recently published IPCC reports. It should not have been charged with uncritical bias in favour of the IPCC.

The WEC's next public input on climate change came as a Statement to the First Conference of the Parties to the UN Framework Convention on Climate Change (COP-1), held in Berlin March 28–April 7, 1995. It pointed out that "some 500 specialists were directly involved in this (the WEC) Commission whose findings on major energy and energy-related issues have now become authoritative within the global energy sector" and "were approved by over 4,500 delegates at the 15th WEC's Madrid Congress in 1992". However, the Statement pointed out that:

"For the majority of people, overcoming local and regional problems has a higher priority than the potential impacts of climate change. Nevertheless, given the continuing uncertainties of climate change, its potential risks must not be downplayed. A 'Minimum Regret' strategy must be adopted with a balance of precautionary measures and further studies" [15].

The precautionary measures included "the development of non-carbon fuel sources."

Report No. 3 covered the proceedings of COP-1, noting that: "There is a clear intention to arrive at a binding protocol for post-2020 anthropogenic greenhouse gas emission reductions by Annex I Parties at COP-3 in 1997". Many small island states considered the Berlin Mandate was neither clear nor urgent enough. The head of the US delegation claimed that in the USA "we are taking action both at home and abroad." Only a few US-based industry NGOs (unhappy with the performance of the U.S. delegation as they saw it) and OPEC member delegations made clear their view that COP-1 went much too far [16].

The WEC Report on COP-1 was intended to report objectively on the various positions and statements that emerged during its proceedings.

Report No. 4 (September 1995) had two objectives: to cover scientific and technical developments in the field of potential climate change since 1992; and to examine institutional developments since the Rio Earth Summit of 1992. Stress was laid on: "The need for caution in commenting upon the possible extent of future climatic change, its causes and consequences, remains unabated." Although it was recognised that modelling had improved during the 1990s particular stress was laid upon: "the predictive capacity of existing climate change (general circulation) models contain considerable uncertainty" [17]. This continues to be the case [18], but we now have much more relevant data on recent changes and their potential significance than were available twenty-seven years ago. This Report, interestingly, had benefited from Sir John Houghton (Chairman, IPCC WGI) and Bruce Callander (Hadley Climate Centre, UK) having read and commented upon it in draft.

Once again William O'Keefe complained, on November 16th 1995, that the WEC's US Member Committee "should take prompt action to resolve what I consider to be a serious conflict between his (Jefferson's) personal views and representations made on behalf of WEC." To that fax O'Keefe attached notes prepared by Bronson Gardener, Science Advisor to the Global Climate Coalition, who had been sent to an IPCC Synthesis Report drafting session in Geneva by the Global Climate Coalition's Director (John Schlaes) and two or three others (unnamed by Gardener in my subsequent discussions with him—but repeated on two successive days) "to shed the worst possible light" Gardener's words on the WEC and me. Gardener's report to O'Keefe formed the basis of the latter's claim to Worthington of my views being in "serious conflict" with the WEC.

In a Note dated January 8th 1996 to John Baker, who had become the WEC's Chairman in succession to Gerhard Ott, and Ian Lindsay as WEC Secretary General, I provided "Response to Gardener, O'Keefe and criticisms of WEC voiced to Barry Worthington":

"The attached Note refutes in detail every single criticism made of the WEC and myself. The evidence shows beyond doubt that I have (without difficulty or conflict of interest) at all times tied myself closely to WEC publications."

The Note proceeded to explain that Bronson Gardener admitted:

"he knew nothing of the WEC's publications and the views contained therein (at least until the relevant publications were given to him by Jefferson on 12 December, 1995); and that when he was asked to compare a couple of paragraphs in WEC publications with his notes he apologised profusely for not having known the WEC's position and wrongly claiming that Jefferson had failed to reflect it accurately".

There appeared to be uncertainty, even ignorance, within the WEC's US Member Committee and among those associated with the Global Climate Coalition about the WEC's published material relating to potential climate change. It was therefore deemed necessary to send this material to Barry Worthington as Secretary of that Committee (his official title was Executive Director of the US Energy Association) on 25th March 1996, attached to which was a fax which reflected concern at the US end that others might have seen the evidence of the ignorance demonstrated by faxes emanating from the Global Climate Coalition and its associates. The covering Note was copied to John Baker (WEC Chairman) and Ian Lindsay (WEC Secretary General) to alert them. But vocal opposition from within the USA nevertheless rumbled on.

Report No. 5: “Climate Change 1995; The Intergovernmental Panel on Climate Change Second Assessment Report Reviewed” appeared in March 1996 and attracted a great deal of attention. It was much longer (36 pages) than its predecessors, commenting on the contributions of all three IPCC Working Groups. The report was heavily critical of some of the IPCC’s statements and work, not least in the Policymakers’ Summaries and the content of the WGIII contribution (and to a lesser extent that of WGII). However, a close reading of many underlying chapters (particularly in the WG1 contribution) were more cautious than widely portrayed in the media. The WEC’s Press Release of April 24, 1996 stated: “the WEC warns that this lack of progress should not be allowed to encourage complacency or inaction.” The Report ended with the following sentence:

“It should be placed on record, not so much as a criticism but as a matter of fact, that most of the comments made in this review were brought to the attention of the IPCC Bureau and its Working Group Technical Support Units during the various preparatory stages of the Second Assessment Report by the WEC’s main representative in the IPCC’s deliberations” [19].

This debate roughly coincided with a fax sent to WEC Secretary General Ian Lindsay on April 1, 1996 by D.P. Bryant, Chairman of the WEC’s New Zealand Committee:

“In the words of a number of the participants, the NZWEC seminar on Carbon Dioxide Policy, Taxes and Credits was the best, and the most informative seminar they have attended. This was, in no small measure, due to Michael Jefferson setting the proper tone with a hard but fair critique of the UN Framework Convention on Climate Change Second Assessment Report. The Minister of Energy, who opened the proceedings, stayed much beyond his allotted time (absent from a Cabinet meeting) to listen to most of Michael’s presentation. As one of the industrial members of the government’s Co2 working party told me later, this objective approach enables them to wrest the pen from officials who had been drafting policy. The seminar revealed issues some members either had not been aware of, or they had not fully appreciated the consequences. Michael did us a great service for which we are properly grateful” [20].

This reference is provided, along with a later one which arose after the December 1997 meeting in Kyoto, as evidence of the quality and objectivity which I believe characterised these WEC reports. Similar support was provided over the years by several other WEC National Committees. Report No. 6 mainly focussed upon the proceedings during COP-2, held in Geneva in July 1996. The Report highlighted the statement from the US government’s delegation:

“We are not swayed by and strongly object to the recent allegations about the integrity of the IPCC’s conclusions. These allegations were raised not by the scientists involved in the IPCC, not by participating governments, but rather by naysayers and special interests bent on belittling, attacking and obfuscating climate change science” [21].

This appeared to be a significant shift in the US official position, but the mood was to change over the following months, not least with the Byrd-Hagel Senate Resolution the following July. More generally, questions arose about the reality of pushing too quickly for tough emissions targets beyond 2000 and the content of any Protocol; developing countries were in many cases unhappy about the consequences of emissions limitations for industrialised countries and their implications for developing countries’ exports; and differences remained about the wording of IPCC references to the human attribution of global climate change. WEC Secretary General Ian Lindsay commented negatively on the WEC’s Study Group report, in a handwritten note on September 9, 1996: “Frankly there is little of substance to (sic) the average reader. I had great difficulty in forcing myself to read it through.” However, Professor Bert Bolin, retiring Chairman of the IPCC, referred to the WEC in his outgoing comments relating to the IPCC’s Second Assessment:

“You will find some critical remarks in a review by the World Energy Council (WEC). The press comments focused on these critical remarks and the generally positive reception that the WEC gave to the Second Assessment Report was largely lost” [21, page 4].

Report No. 7 (May 1997) summarised the position as:

“The chances of reaching agreement in Tokyo (December 1997) on a far-reaching Protocol to curb greenhouse gas emissions beyond the year 2000 now seem remote. The negotiating text has got longer rather than shorter, as the number of proposals has multiplied. Debate, disagreement, complexity of proposals, and exhibitions of national self-interest have all intensified in recent months. Although some form of Protocol is likely, because of the powerful political interests involved, ambitious targets and tight timetables for Annex I industrialised country Parties are unlikely” [22].

This report also mentioned that: “Efforts to get non-Annex I Parties (developing countries) to accept specific commitments under the Climate Convention remain deadlocked.”

And so to the 32-page Report No. 8: “The Kyoto Conference and Protocol”, first issued in December 1997 and updated in July 1998 with more recent emissions data. Although a protocol was produced many important questions were postponed in the hope of later resolution, and it was concluded that much would hang on whether the USA would ratify the Protocol—the WEC Report considering that without US ratification a protocol would be ineffectual. The Report stated: “Circumstances surrounding the run-up to Kyoto, its outcome, and subsequent statements suggest the USA will not hurry to ratify, if it does at all” [23]. The circumstances referred to included the ByrdHagel Senate Resolution opposing US support unless Developing Country Parties accepted new specific scheduled commitments.

The Kyoto conference was widely reported at the time but few picked up (because it occurred in the early hours of the final morning of the Conference) the sudden and critical removal of an Article which was intended to provide for developing country Parties to accept the need to curb their emissions. The Conference Chair, Argentina's Ambassador to PC China (Estrada y Oyela), was responsible following intense pressure from some developing country party delegations. The move made US acceptance of the Kyoto Protocol unacceptable in the light of the Byrd-Hagel Senate Resolution. However, a fax received from John Hollins, Executive Director of the WEC's Canadian Member Committee, the Energy Council of Canada, may be found useful in assessing the contents of the next Section of this paper:

"The Honourable John Fraser, Canadian Ambassador for the Environment, addressed the Board of the Energy Council of Canada yesterday. He provided his perspective on the history leading up to Kyoto, his experience in Kyoto as a member of the Canadian delegation, and his views on where we in Canada should be going.

In preparation for this session, I had provided Mr. Fraser with, inter alia, a copy of WEC Report No.8. Mr. Fraser stated at the end of his remarks that the report was an astonishing piece of work. He vouched for the accuracy of the observations on the events that he had witnessed too, but allowed that he learned a number of very interesting details from the account! He added that the text reads very well and puts the issues objectively. He characterised it as a remarkable piece of work, that no one person on a national delegation could have done." [24].

3. The aftermath

Despite numerous favourable comments the work of WEC Working Group 4A and its Director had come under persistent attack from US-based climate change deniers and sceptics.

Report No. 10: "Instruments for Mitigating Climate Change" (September, 1998) was prepared for the 17th WEC Congress in Houston, and lies outside the main focus of this paper. It was, however, the first generally circulated evidence that I had been removed from my position as WEC Deputy Secretary General—widely considered as the result of efforts to block my work relating to potential climate change—to the post of Director of Studies and Policy Development. I had been suddenly succeeded as Deputy Secretary General by an Australian lady, who sadly died of natural causes within eighteen months. WEC Secretary General Ian Lindsay, who had fallen terminally ill shortly before he was due to retire, had been succeeded by French Canadian Gerald Doucet, who knew something about gas and had been selected by a mix of US members hostile to the work the WEC had done relating to potential climate change; French nuclear interests, it was suggested because I was cautious about nuclear energy solely on safety grounds; and by Chinese and German coal interests. It was clear that efforts to encourage my total removal from the WEC were under way. Following John Baker (later Sir John Baker) as WEC Chairman (1995–1998) was Jim Adam, Chairman and CEO of the Kansas City-based engineering company Black & Veatch.

By November 1998 news had got around that my position in the WEC had altered. However, at COP-4, held in Buenos Aires November 2–13, 1998, I was asked to join the UN Deputy Secretary General and the Head of the UN Development Programme to speak about the WEC and the Joint World Energy Assessment all three organisations were involved in. [The "World Energy Assessment: Energy and the challenge of sustainability" was published in 2000, chaired by Professor Jose Goldemberg—who proved personally very supportive then and for years afterwards, as were several other key contributors—particularly Hisham Khatib.] I was a Convening Lead Author, primarily with responsibility for the chapter: "Energy Policies for Sustainable Development". By that time I had left the WEC. I was also asked to speak about WEC's work of relevance to the proceedings at a Special Event on the last day of the conference. COP-4 itself achieved little, as Report No. 11 duly reported.

However, it may give a misleading impression to claim that in the years 1987–1997 "sustainability came to be foregrounded at WEC" [11, page 50] without mentioning it was characterised by serious dissent. Nor was it correct that in this period "the issue of sustainability has become too narrowly defined as a question of climate change and the influence of anthropogenic carbon emissions." [11, page 53]. That comment was made in 2013, long after my time, but the 1990s had seen the publication of: "Energy for Tomorrow's World", "New Renewable Energy Resources", the major WEC/IIASA works, and several WEC publications on other topics.

On December 14 1998 there was a debate at the UK's Institute of Petroleum, New Cavendish Street, London. The motion was: "This House believe that cost-effective precautionary measures should be taken, starting now, to address the climate change risk, with the requirements of the Kyoto protocol providing a sensible next step in the process." The proposer was me, as Director of Studies and Policy Development, The World Energy Council. It was opposed by William O'Keefe, as Senior Vice President, The American Petroleum Institute (there was no mention of his Global Climate Coalition role on the programme). I do not remember the outcome of the debate.

Things had been changing at the World Energy Council and continued to do so. By June 1999 I had placed my concerns in the hands of the firm of lawyers Clifford Chance as Gerald Doucet continued to be somewhat duplicitous (for instance, a fax dated 14 June 1999 referred), tried to negotiate a contract which would not permit me adequate freedom of thought or action, and then sought to end a three-year contract after one year. He had earlier informed WEC Member Committees worldwide by fax that a new Deputy Secretary General had been appointed and I had become the WEC's Director of Studies, no longer Deputy Secretary General, without consulting me either about my changed role (presumably a demotion) or the fax before it went out.

The WEC's US member committee met on 2 August 1999 and, via a fax dated 9 August 1999 from Executive Director Barry Worthington, expressed "a number of strong concerns" about a "proposed WEC GHG emissions reduction project." This too was intended to be restraining.

To bring this rendering of "An Old Climate War" to an end. Yes, those fighting for denial of anthropogenic climate change or obfuscation of the debate succeeded in getting rid of me from the World

Energy Council effectively in 1999, thereby winning that war. But John Baker (later Sir John), Honorary Chairman of the WEC, took steps to ensure I was paid my full three-year contractual financial terms and very successfully chaired the WEC study: “Living in One World” (2001), of which I was “the coordinating author and Director of the Study”. This was my last formal link with the WEC. WEC Chairman (1998–2001), Jim Adam, recognised in his Preface that we had marshalled for the reader’s attention a large volume of material and opinion about the current and future stresses on vital elements in seeking to maintain a Liveable World. Sadly, he felt it necessary to record that the opinion “represents the strongly held views of many members of The World Energy Council, but not all of them.” My successor as WEC Deputy Secretary General had died. Gerald Doucet died in 2008. Little did I know then that in 2007 I would become an academic, and subsequently senior editor of the journal Energy Policy (where I was able to draw on some of the research work with which I had been involved at the WEC as well as my earlier years in Shell), and receive a certificate from the Intergovernmental Panel on Climate Change for contributing to their award of the Nobel Peace Prize in 2007 as a lead author, contributing author, synthesis report drafting team member, editorial and expert reviewer.

4. Conclusions

It is a sad commentary on attitudes towards potential climate change during the 1990s that this war over its likely causes among others at the time, broke out and had lasting consequences. Opponents of open and hopefully objective discussion were able to silence those seeking and pursuing a balanced approach—people who recognised uncertainties but also the huge potential adverse consequences requiring effective policies, measures, and technologies (optimally located). In that Old Climate War of the 1990s hostile forces were able to do far more damage than they should have done. Their activities ran counter to the WEC’s claim that “it has never strayed from the initial concept of an organisation that is impartial, objective and realistic.” It was inevitable that the WEC’s membership would contain differing, and even conflicting, interests. Some of us made a huge effort to reflect a broader, more objective, view reflecting the full range and balance of the WEC’s global membership. The reports issued by the WEC’s Work Group on Potential Climate Change mirrored this balance of views, but this paper reflects the backlash which some climate change deniers and sceptics (mainly, but not all, in the USA) were able to inflict. Considering those who are currently responsible for the WEC’s work on energy scenarios and the needed energy transition the WEC now seems to be back on track.

Elements of both the ‘old’ climate war and the ‘new’ climate war [1] have been covered here. There have been very few published reports of attacks by climate change ‘deniers’ and those who collaborated with them where the person attacked has retained key documents and is willing to publicise them. In the interests of energy, environmental and organisational history, as well as open communication, the facts should be widely known.

The author would be happy to lodge his own holding of relevant documents with a public academic institution for open access. It is not for him to judge whether, and how far, the troubled pathway he and the WEC travelled in the 1990s had a significant impact on the energy sector.

Conflict of interest

There is no known conflict of interest on the author's part.

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Wind based hybrid systems for increased RES penetration in isolated grids: The case study of Anafi (Greece)

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ABSTRACT

The dependence of the Non-Interconnected Islands on diesel power stations increases cost of producing electricity in comparison to the mainland. This study focuses on the green energy transition of Non-Interconnected Islands, and Anafi was selected as a characteristic case. The average cost of electricity production from thermal units in Anafi was estimated to be 539 €/MWh with a peak load of 0.55 MW. Two different green energy transition scenarios are proposed for Anafi that include the addition of PV panels plus a wind turbine (scenario 1) or PV panels plus a battery (scenario 2) that would operate along the conventional diesel engines and utilized the software RETScreen program for the design and the analysis of these two proposed hybrid systems. In scenario 1, the renewable systems produced 2793 MWh, while in scenario 2 this value was simulated to be 995.51 MWh. In both proposed scenarios there is a significant penetration from Renewable Energy Sources from 68.2% (scenario 2) to 90.3% (scenario 1). In addition, in both cases there is a significant reduction in carbon dioxide emissions from 80%–95% in comparison to the baseline case which produces 2543 tons of CO2 annually. The cost of the proposed installations has been calculated to be 5.2 m € and 5.6 m € for scenarios 1 and 2, while the net present value (NPV) of the project becomes positive from the sixth year and the eleventh year respectively. The earnings of a green transition project of this nature can be allocated for the maintenance of the island's own project, as well as for the financing of new similar projects on other islands. The expected result of this work is the proposal of a system that will largely cover the energy needs of the island, reduce the cost of production per kilowatt hour and will contribute to the green energy transition of the other Non-Interconnected Islands.

Keywords: green energy transition; energy analysis; energy storage; energy economics; green islands

1. Introduction

To date, most of electricity's global demand is met by burning fossil fuels such as oil, coal and gas. In line with the European Green Deal and the EU's 2050 targets for mitigating climate change, every EU member state must aim to reduce greenhouse gas emissions to achieve climate neutrality [1]. The long-term strategy for 2050 complements the Greek National Plan for Energy and Climate (ESEK), which is the basic strategy plan of Greece for issues related to energy transition and climate adaptation [2]. One of the main goals of the existing ESEK for 2030 is to reduce greenhouse gas emissions by 42% compared to 1990 and more than 56% compared to 2005 emissions [2]. In this framework, a major goal is the elimination of the energy isolation of non-interconnected Greek islands by 2032, either through their interconnection with the mainland or through the integration Renewable Energy Sources (RES). Several islands are already moving in this direction, such as Agios Efstratios, Tilos and Ikaria. Specifically, in the

Agios Efstratios, the penetration of RES is attempted to exceed 85%, while in other small islands 60%. In this way, as well as by interconnecting the rest islands, will lead to the withdrawal of conventional stations to achieve a 77% reduction in oil use by 2030 compared to 2020 [3]. The policies that support green transition aim to counter the obstacle of high energy production process in non-interconnected islands, along with reducing the carbon footprint of the energy production sector.

With the purpose to dive deeper in the updates of green energy transition in Greek islands, Tilos island is a flagship case and has been presented by Kaldellis, 2021 [4]. Tilos is in the southeastern part of the Aegean Sea with a total area of about 63 km2 and with mountainous and rocky terrain. According to the 2021 census, its permanent population amounts to 745 inhabitants, with an annual consumption of electricity of about 3.2 GWh and an annual peak demand of about 1 MW. The island is powered by a 20 kV submarine cable that connects it to Kos diesel power station, crossing Nisyros [5]. Tilos island was the area of development for the Project T.I.L.O.S. (Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage) of the European research program, HORIZON2020, which has as its main goal the coverage of the energy needs of the island by maximizing the use of renewable energy sources [6]. The T.I.L.O.S. hybrid station, which has been in operation for three years, consists of a 800 kW medium power wind turbine, a 160 kWp photovoltaic station, inverters with a rated power of 20 kW, a built-in energy storage system with 800 kW/2.88 MWh Battery Energy Storage System (BESS) and a backup diesel generator with a power of 1.45 MW as well as additional small-scale photovoltaic installations [4]. TILOS is a project of integrated energy autonomy in order to find solutions for the electrification of unconnected islands, leading to the achievement of European goals for clean energy and mitigation of greenhouse gases by 2050. The T.I.L.O.S. facility is one of the most innovative islands microgrids in all of Europe and will set an example for the rest of the islands around the world, so that they can be transformed into green islands with clean energy free of greenhouse gas emissions and reduce costs of production of electrical power [7].

Another flagship project in the overall framework of Greek green energy transition is the Astypalea project, where the Hellenic Republic in collaboration with the Volkswagen Group aim to make Astypalea the first 'Smart and Sustainable Island'. The goal is to transform the transport system by switching to electric vehicles, including a service that will provide shared electric vehicles throughout the year with the scope of replacing conventional commercial vehicles with electric ones, and at the same time creating integrated charging infrastructures. The above will be done in conjunction with the conversion of the island, through the exploitation of RES, into an energy autonomous one, to cover the additional electricity needs that will arise from the use of electric vehicles.

In this way, the goal of zero emissions by 2030 will be achieved, also in the transport sector [8]. In respect of green energy transition, there are other ongoing projects in Greece like Chalki, Symi and Kastelorizo which are projected to be smart/green islands [9]. In addition, there are other noninterconnected islands that should accelerate their green energy transition, due to the fact that they will not be interconnected in the next decade. Such cases are the islands Anafi, Sifnos, Donousa and Gavdos [9]. Dimou and Vakalis [10] presented the first total energy green transition plan for the island of Ag. Efstratios with RES penetration that exceeded 85%. The proposed set-up included a wind turbine, PV panels and a battery and the authors highlighted the low penetration of PV and the high cost of batteries. As seen in the project of Ag. Efstratios [10], the high RES penetration can be limited by several factors and is dependent on the applied technological solutions but also to weather related constraints. On the one hand, the utilization of PV panels is clearly related to the hours of sunlight and the energy demand curve. On the other hand, wind-based solutions are subjected to the wind speed at a given moment in relation to the energy demand. Therefore, the assessment of wind potential has been in the center of attention, with Ouarda and Charron [11] highlighting that the probability density function is usually "fitted to short-term observed local wind speed data". The authors developed two-component mixture models in order to incorporate homogeneous and heterogeneous mixture distributions and incorporated statistical analysis in order to optimize their algorithm. Similarly, Mazzeo et al. [12] applied unimodal and bimodal truncated normal in order to model the extreme wind speed conditions.

There are several similarities between the characteristics of Anafi and Agios Efstratios, where the project Ai Stratis—Green island has been proposed. Both have populations of similar size, high wind potential, and are powered solely by conventional diesel engines. Therefore, Anafi could be another island that will go towards the green transition. This study focuses on the renewable technological installations, the detailed energy demand curves and the detailed yearly weather conditions for the assessment of RES penetration in green island microgrids. The study utilizes the Weibull probability density function for the calculation of the wind speed as developed by Hiester and Pennell [13] and the Klein/Theilacker algorithm for the calculation of solar radiation as presented by Duffie and Beckman [14]. The aim of this paper is to highlight the wind-based renewable energy transition as a pathway to mitigate high cost of electricity generation in the Non-Interconnected Islands and seek green energy transition solutions with lower economic and environmental costs. By using different energy analysis scenarios, the case of Anafi is presented and analyzed for a potential energy transition. The expected result is the proposal of a system that will largely cover the energy needs of the island and at the same time will significantly reduce the cost of production per kilowatt hour.

2. Materials and methods

2.1. Anafi—energy demand and climate information

Anafi was chosen as the place of study, since it is a small island, not interconnected with the mainland network and with a low population that does not fluctuate significantly throughout the year. It was also chosen because of the high wind potential that exists on the island. Anafi is a small island, with a low population that does not fluctuate significantly throughout the year. It was also chosen because of the high wind potential that exists on the island. Anafi is a small island, with a somewhat triangular shape that belongs to the Cyclades complex of the Aegean Sea, is located east of Thira, at the southeastern tip of the Cyclades and is 155 nautical miles from Piraeus. It consists of three settlements in the town of Anafi, Kleisidi and Agios Nikolaos or Gialos. According to the 2021 census it is an island with a small population of 257 inhabitants, while its area is about 39 km2. In the east of the island there is a peninsula, while in the south of Anafi there are small uninhabited islets, Ftena, Pachia, and Makria. The island has a mountainous character with the highest height being found on Vigla mountain with 579 m. In addition, it has an intense coastal division, with the length of its coasts reaching 32.4 km, without large bays [15]. Solar radiation data were retrieved from the software RETScreen-presented in the following subsection—which has incorporated the NASA climate database. Data for the wind potential were retrieved from via the Geographical Map of RAE [16], Figure 1 presents the solar radiation and Figure 2 presents the average annual wind speed on the island.

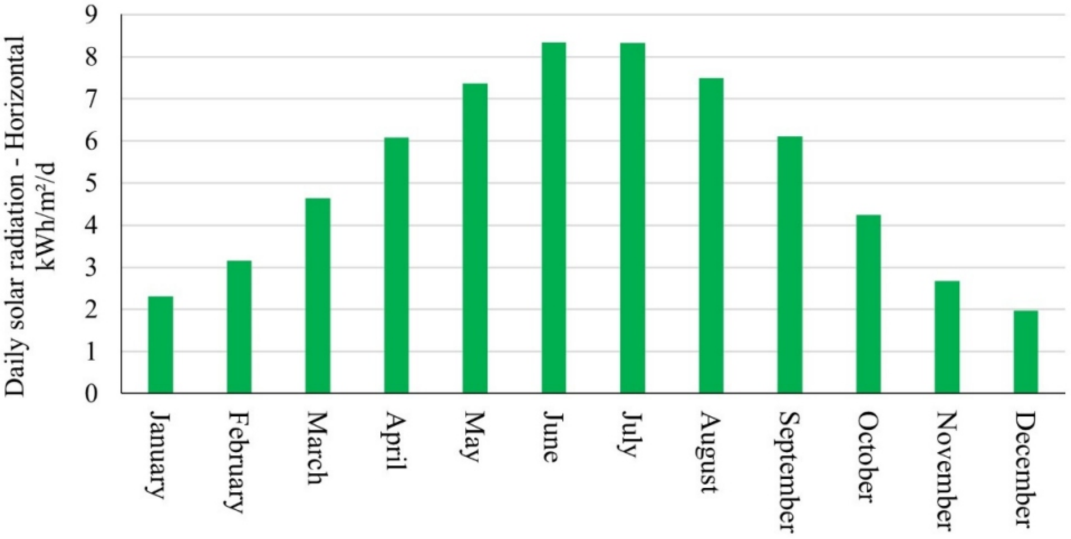

Figure 1. Monthly horizontal solar radiation of Anafi (source: RETScreen database).

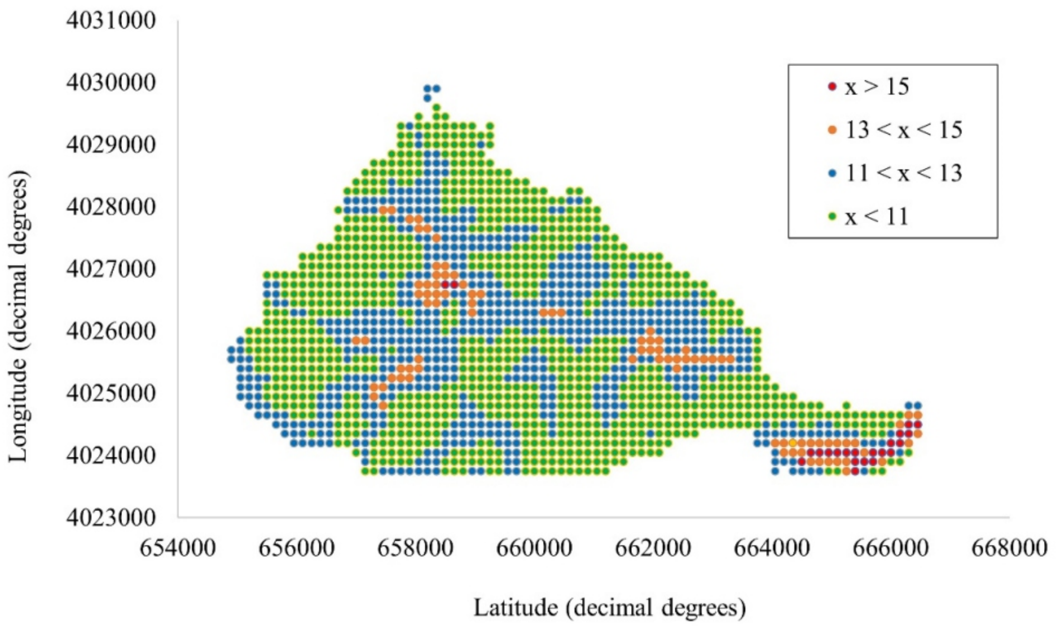

Figure 2. Average annual wind speed on Anafi island [17].

Anafi is one of the Non-Interconnected Islands (NII), and specifically belongs to the group of 'small' NIIs whose annual peak demand does not exceed 10 MW. To date, Anafi has not been connected to the mainland electricity grid but is planned to be connected within the framework of the 4th Phase interconnection of the Cyclades, through submarine cables between the Santorini-Anafi islands (Network Development Plan 2021–2025, 2020). The energy needs of its inhabitants are covered by a local power station, which includes five internal combustion engines with a total nominal power of 1.1 MW. According to the Production Data Sheets of the HEDNO [18] of NIIs that are presented in Table 1, in the last 5 years the annual peak demand ranged from 0.59 MW for the year 2017 to 0.55 MW in the year 2021. Regarding the required energy of thermal units of the island, in 2021 it fluctuated from 77.93 MWh in the month of April with a maximum price of 278.03 MWh for the month of August.

Table 1. Electricity generation and cost on Anafi for the year 2021.

Table 1. Electricity generation and cost on Anafi for the year 2021.

Year	Month	Energy of thermal units (MWh)	Average cost of production (€/MWh)	Average variable cost (€/MWh)
2021	December	82,73	493,46	309,01
2021	November	78,98	497,99	304,79
2021	October	86,56	444,78	283,01
2021	September	137,35	787,26	300,45
2021	August	278,03	184,66	121,35
2021	July	205,42	325,47	237,67
2021	June	120,6	944,02	251,31
2021	May	80,23	387,44	252,45
2021	April	77,93	650,14	260,29
2021	March	84,98	612,66	248,06
2021	February	80,53	623,07	245,81
2021	January	88,82	583,84	241,79

As seen in Table 1, the average cost of production of conventional units in Anafi for the months of January to August 2021, is approximately 539 €/MWh, with the highest price meeting in June at 944.02 €/MWh and the smallest in August with 184.66 €/MWh. The average variable production cost of conventional units of the island, is approximately 232 €/MWh with the lowest price being observed again in August (121.35 €/MWh) and the highest in April (260.29 €/MWh). It should be stated that the participation of renewable energy systems (RES) in electricity production is zero.

2.2. Software and methods of analysis

The energy analysis was implemented by means of RETScreen, a free software that has been developed in Excel environment and aims to evaluate the production of energy from potential projects with renewable energy sources and it can provide information about the emissions, the economics, and the risk of the specific project [19]. It is a useful tool in decision making and for assessing the viability of future RES projects, but also to find additional solutions for profitable energy production [19]. The Energy analysis part evaluates the generated energy from the proposed energy system. Cost Analysis calculates the initial and annual costs for the proposed project are estimated. Emission Analysis assesses the mitigated greenhouse gas emissions due to the development of RES. Financial Analysis,calculates the net present value of the project and assess the overall economic sustainability of the project.

This present study analyzed and compared two different scenarios for energy production on Anafi from one or more renewable energy sources, conventional energy sources and storage systems. In the first scenario the hybrid system used consists of a wind turbine with a nominal power of 330 kW, a photovoltaic station with a total rated power of 150 kW and a 537-kW backup diesel generator, in a manner that would resemble the energy generation set-up of Ag. Efstratios. In this scenario a wind turbine was used as the basic electric charge system, photovoltaic as the intermediate electric charge system, while a backup diesel generator was used as the peak electric charge system. More specifically, a wind turbine from the manufacturer Enercon, model Enercon 33–50 m, electric power 330 kW and with a turbine was used. The technical characteristics of the wind turbine selected are the following: pylon height 50 m, rotor diameter per turbine 33 m and scan area per turbine 876 m2. As an intermediate electric charge system, solar energy was selected using photovoltaics. More specifically, 1000 units of monocrystalline photovoltaics of the manufacturer Canadian Solar, model mono-Si-CS4A 150 W, with a total electric power of 150 kW and a power factor of 23% were used. Finally, a conventional energy source, a backup oil generator, model D2842-1103, was selected as the peak electric charge system by the manufacturer MAN Group. Then the price of the fuel is required, at which the price of 1.2 €/L was registered.

The second scenario utilized PV panels, a battery storage system and conventional energy source, i.e., a backup diesel generator. In this scenario, 2500 units of monocrystalline photovoltaics from the manufacturer Sunpower, model mono-Si-SPR-210-BLK and a total electric power of 525 kW were used. The PV station will cover a total area of 3.11 km2. The photovoltaics will be placed at an angle of 28 degrees setting the azimuth 0°, because it is preferable that their orientation is towards the equator. The efficiency of the photovoltaic system will be 16.9%. An energy storage system with Li-ion battery packs was preferred as the storage system. The battery packs will have 0.2 days of autonomy, 24 V voltage, 85% efficiency, maximum discharge depth of the battery that can be withdrawn repeatedly without abnormal loss of battery life 60%, charge controller efficiency 95% and power 45000 Ah. 'Environmental' was chosen as the temperature control method, considering that the battery will be in an uninsulated shed. A backup diesel generator was chosen as the state-of-the-art electric charge system. The model chosen here is Turbion, from the manufacturer Entropic Energy. Then the price of fuel entered was 1.2 €/L. In summary, the hybrid system used in Scenario 2 consists of a photovoltaic station with a total rated power of 525 kW, a Li-ion storage batteries or similar features 1.8 MWh, a backup diesel generator power 250 kW.

Continuing, in the next spreadsheet, in the Cost Analysis, the initial and annual costs for the proposed project were estimated. To carry out these estimates, the costs of the study, the development, the engineering of the project, as well as the costs for the power generation systems, their transmission, operation and maintenance and their spare parts were recorded. Due to the similar size and the population of Anafi with Agios Efstratios, recent financial data were used from the environmental impact study of the project Hybrid System for Production of Electricity and Thermal Energy from RES on the island of Agios Efstratios [21]. Completing the first scenario, the financial parameters were entered so that the financial analysis of the project could be calculated. It was therefore considered that the rolling tax on fuel costs is 3%, the inflation price 1.5%, the reduction rate 1% and the life of the project is 25 years. The amount of the project grant is 1.000.000 €, with 50% interest arrears, 1% loan interest rate for 25 years.

3. Results

The basic case of a power generation system was calculated by converting the monthly energy of thermal units (MWh) taken from Table 2. The peak load of the system (0.55 MW) was then calculated towards the maximum average monthly average (278 MWh = 374 kW), which represents the percentage that the peak electricity load exceeds the maximum monthly average power load during the twelve months. This percentage is 29%.

Table 2. Data on demand and production of electricity in Anafi.

Year	Month	Maximum annual point of demand (MW)	Energy of thermal units (MWh)
2021	December	0,55	82,73
2021	November	0,55	78,98
2021	October	0,55	86,56
2021	September	0,55	137,35
2021	August	0,55	278,03
2021	July	0,55	205,42
2021	June	0,55	120,6
2021	May	0,55	80,23
2021	April	0,55	77,93
2021	March	0,55	84,98
2021	February	0,55	80,53
2021	January	0,55	88,82

In scenario 1, the wind energy was set to be the main system, solar as the intermediate electric charge system and a conventional energy source as the conventional peak charge system. The energy produced by the basic load, the wind turbine, amounts to 1920 MWh, the energy produced by photovoltaics is 873 MWh, while the energy produced by the backup generator is 3124 MWh if it operates nominally. The percentage of electricity delivered to the load from each energy source is also calculated. More specifically, 86.4% is delivered through the wind turbine and 3.9% through photovoltaics. It should be mentioned that the operation of PV panels overlaps with the operation the wind turbine, which is the base system, but the PV produced electricity assists significantly to cover the mid-day peak demands with

with green energy. This result is comparable with the results that were published in a relevant study of Ag. Efstratios [10]. In this case, therefore, it is necessary to have a peak load supply system which is designed to cover the electricity consumption that has not already been covered by the main power system. This can happen when the installed capacity is not enough or to cover scheduled shutdowns. For this reason, a conventional diesel engine has been selected as the peak cargo supply system, which covers the remaining 9.7%. The results are presented in Table 3.

Table 3. Elements of electricity generated and delivered to the load in Scenario 1.

	Wind	Solar	Diesel	Total
(MWh) Electricity generated	1920	873	3124	5917
(MWh) Electricity delivered to load	1224	55	137	1416
(%) Electricity generated	68,4	31,1	111,3	210,8
(%) Electricity delivered to load	86,4	3,9	9,7	100

In Scenario 2, according to calculations in RETScreen, the electricity delivered to the load from the photovoltaics is 995.51 MWh, while the percentage of electricity delivered to the load for the proposed case of electricity use of the power system is 68.2%. And in this scenario, it is necessary to have a peak load supply system. In this scenario a diesel engine, model Turbion was used, and the electricity delivered was 464.5 MWh, and it covers 31.8% as presented in Table 4. These results highlight the ability to install battery-backed systems with lower nominal capacity than non-batterybacked systems in order to support the same load. Nonetheless, a significant parameter that need to be assessed is the RES penetration of such systems.

Table 4. Elements of electricity generated and delivered to the load in Scenario 2.

	Solar	Diesel	Total
Electricity generated (MWh)	1481,04	705,84	2186,88
Electricity delivered to load (MWh)	995,51	465,50	1461,01
(%) Electricity generated	108,90	51,90	160,80
(%) Electricity delivered to load	68,20	31,80	100,00

Summarizing, in the first proposed scenario the penetration from RES amounts to approximately 90.3%, while in the second proposed scenario 68.2%, as presented in Figure 3. The higher penetration rate from

RES, highlights that wind-based hybrid systems can be used for increased RES penetration in isolated grids in order to promote the efficient green transition. In the second scenario, the total share of RES in electricity production is lower, as is the percentage of electricity produced. This makes sense because the main system is photovoltaics using a battery. While the power of the photovoltaic exceeds the average electricity demand, it does not have the ability to meet the peak demand where it ends up being covered by the conventional engine. In this scenario, however, there is less excess energy, due to the correct dimensioning of the photovoltaic and the battery. Thus, the percentage of excess electricity produced in the first scenario is much higher than in the second. This excess energy could be exploited by other projects, such as hydrogen production systems, for electrolysis, for charging electric cars or for the conversion of the port of Anafi into a green port [21]

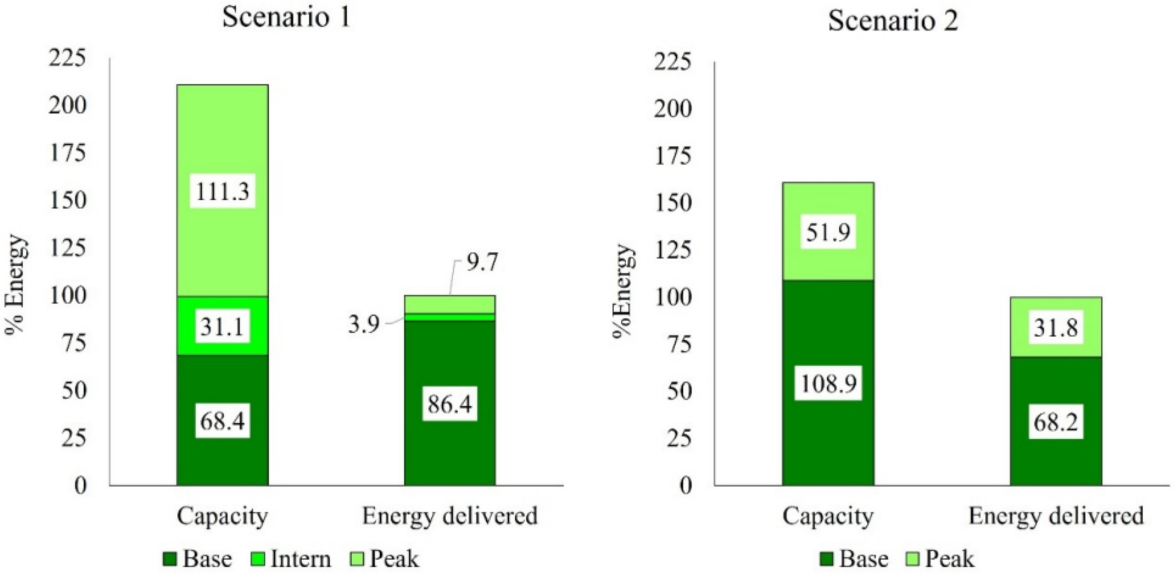

Figure 3. Energy produced and delivered by source type for both analyzed scenarios.

Regarding the greenhouse gas emissions in the first scenario, that is, taking advantage of wind, solar and a conventional energy source, there is a reduction of CO2 of about 95%. With the basic power system, it is estimated that 2051 tons of CO2 are produced, while in the proposed scenario only 95.9 tons of CO2, so there has been an annual reduction of emissions of 1956 tons of CO2. By removing the wind energy and adding a battery storage system (Scenario 2), a drop of about 80% in CO2 is observed. More specifically, with the basic power system it is estimated that 2543 tons of CO2 are produced, while in the proposed scenario only 520.9 tons of CO2, so there has been an annual reduction of CO2emissions of 2022 tons of Co2.

RETScreen calculated the total annual cost for each scenario, which represents the annual costs related to the operation, maintenance, and financing of the project. It is essentially the sum of the savings or operating and maintenance costs, the fuel costs for the proposed case and the debt payments. The total annual cost includes the repayment of the "capital" of the debt. In the first case, it was estimated by the

the program that the initial cost amounts to 5.205.720 €, of which 1% concerns the cost of the study, 2.9% the cost of development, 1.9% of the engineering of the project, 60.4% of the costs for the electricity generation systems and finally 33.8% of the costs of their transportation, spare parts, etc. In the second case it was estimated by the program that the initial cost amounts to 5.631.600 € of which 1.8% concerns the cost of the study, 2.7% the cost of development, 1.8% of its engineering, 57.2% of the costs for the electricity generation systems and finally 36.6% of the costs of their transportation, spare parts, etc. Figure 4 presents the net present value (NPV) of the two scenarios and the payback times of each scenario. It is shown that the wind-based system has a much faster payback time, i.e., 6 years in comparison to 11 years, but has an overall lower net present value with 11.13 million € vs 12.28 million € and this can be attributed to the role of the relatively big sized battery that allows the integration of a smaller diesel engine in order to meet the peak demand.

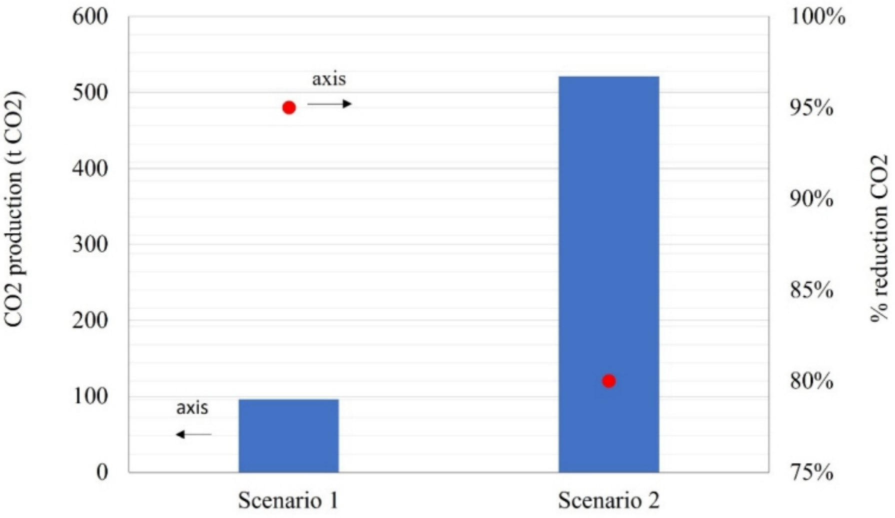

Figure 4. Reduction of emissions for both analyzed scenarios.

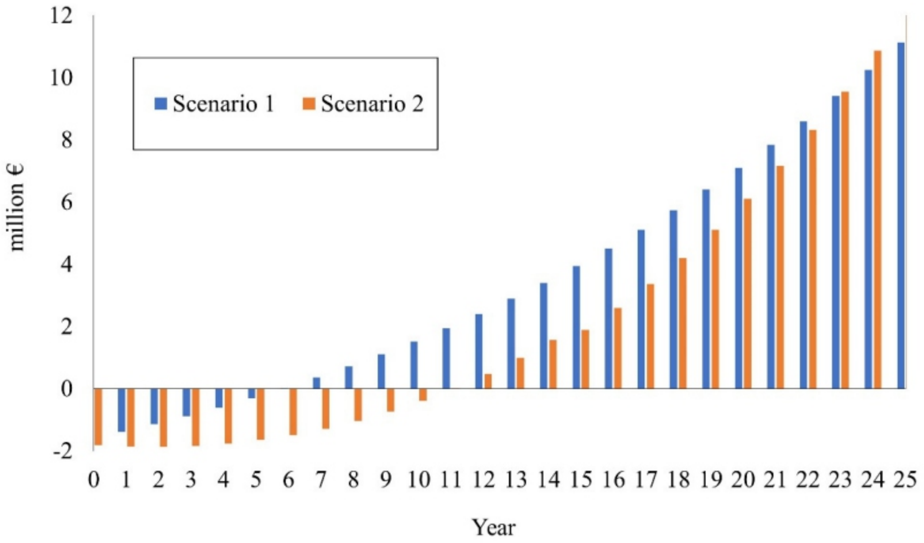

Figure 5. NPV for both analyzed scenarios.

From the sixth year onwards, it is observed that there is the possibility of revenues that can be used for the maintenance of the island's project itself, as well as for the financing of new similar projects on other islands, in order to contribute to their own green energy transition. Thus, initially, through state subsidies, sustainable, low-risk projects can be financed that will lead to the energy transition of the NIIs, which will then contribute to the islands themselves in order to achieve a rolling green transition of the remaining NIIs. This will also lead to a reduction in the greenhouse gas emissions of such islands, as shown in both scenarios, and consequently to the achievement of the goals set at national and European level. An issue that needs to be in the center of the conversation is that wind power seems to be the most efficient renewable energy system in respect of penetration, efficiency and payback time [10]. Nonetheless, photovoltaic panels have far greater acceptance when compared to other RES. More specifically, according to a research study that took place in regions of France, Germany and Switzerland in 2019, resulted in more than 85% of respondents being in favor of solar energy [22]. Thus, the pathway of efficient green energy transition should include a systematic effort to inform the public about the positive aspects of RES with low social acceptance like wind power.

4. Conclusions

In order to achieve the goals of the Greek National Energy and Climate Plan, the Long-Term Strategy 2050—LTS and the European Green Deal, regarding the reduction of greenhouse gas emissions, the green transition of the NIIs in the coming years is necessary. Through this work, two systems using RES were proposed to meet the energy needs of Anafi and to reduce its energy production costs. Using RETScreen as analysis software, it is observed that with the existing conditions, government programs and grants, in a small NII (annual demand peak <10 MW) through a relatively low self-financing it is possible to create hybrid stations where the penetration of RES can exceed 90%. This percentage is very important as it exceeds the penetration of 85% that has been set as a target in the case of Agios Efstratios, where it is a model of a green island. Finally, the green transition of the NIIs can be done more directly with the contribution of the inhabitants of the island, through the energy communities. With the help of state funding and by investing in green systems themselves, through the installation of photovoltaic panels on the roofs of their homes, or through their participation in an energy community, they can contribute to the more direct penetration of RES, the decoupling from fossil fuels and the reduction of electricity generation costs.

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Conflict of interest

Author contributions

A.O.: Writing—Original Draft, Investigation, Methodology, Validation, Data Curation, Formal Analysis; S. V.: Supervision, Visualization, Conceptualization, Methodology, Project administration, Validation, Writing—Original Draft, Writing—Review & Editing, Resources.

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