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Energy Sustainability on an Offshore Island: A Case Study in Taiwan

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Abstract: This study determines the energy usage pattern for Penghu, which is an island in the Taiwan Strait, for which electricity is the major energy source. There is an increase in electricity consumption as the number of inhabitants and tourists increases. Water supply from desalination plants represents another major electricity demand. To reduce energy consumption and carbon emissions, subsidy programs are used to encourage the use of LED lighting and energy-efficient appliances (air conditioners and refrigerators), but not for common appliances, such as chest freezers. Abundant solar radiation in summer and the northeast monsoon in autumn/winter make Penghu an ideal location to take advantage of solar energy and wind power. An undersea cable between Penghu and Taiwan is now available and can be used to stabilize the isolated grid system in Penghu. The target for a low-carbon island can be achieved by installing PV systems and onshore and offshore wind turbines to fulfill the energy demand for the tourism industry.

Keywords: Penghu; tourism; electricity; desalination

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Citation: Huang, C.-Y.; Yu, T.-T.; Lin, W.-M.; Chung, K.-M.; Chang, K.-C. Energy Sustainability on an Offshore Island: A Case Study in Taiwan. *Energies* **2022**, *15*, 2258. https://doi.org/10.3390/en15062258

Academic Editor: Iqbal M. Mujtaba

Received: 1 March 2022
Accepted: 17 March 2022
Published: 19 March 2022

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1. Introduction

The use of fossil fuels causes greenhouse gas (GHG) emissions and climate change worldwide. The Paris Agreement of 2015 aims to limit carbon emissions and to limit the increase in the global average temperature to less than 2 °C above pre-industrial levels [1]. Low-carbon development is an important measure to reduce environmental degradation due to increased economic activity [2–4]. The European Union is expected to be the first climate-neutral continent by 2050 [5].

Tourism is the major economic activity for most countries, but it also results in an increase in energy consumption and GHG emissions [6,7]. Hotels are diverse in terms of building type, in order to provide the best facilities for guests, and they are among the most energy-intensive in terms of end-use. The number of rooms, the services, and the outdoor temperature are key variables that affect the use of electricity for lighting, air conditioning, and heating [8,9]. Previous studies of the tourism industry in Spain show that electricity consumption progressively increases as tourism increases, particularly for hotels with higher star ratings [10,11]. There are similar results for hotels in Taiwan [12]. The respective average carbon emissions for international tourist hotels, standard tourist hotels, general hotels, and homestay facilities are 28.9, 19.2, 12.5, and 6.3 kg-CO_2/person-night (0.623 CO_2/kWh) [13].

Maintaining the energy supply to offshore islands is challenging and most of the electricity generation depends on imported fossil fuels. Dornan [14] showed that government-funded off-grid rural electrification projects are rarely sustainable. Output-based subsidies to energy service companies (ESCOS) are effective. A survey of electricity consumption for Lampedusa Island in Italy was conducted by Beccalia et al. [15]. The study showed

that energy demands during the summer period are strongly correlated to the number of private houses and hotels (tourist flow). Seasonal oscillations are correlated to the number of tourists. The energy demand increases significantly if the number of overnight stay rates increases [16]. To ensure the sustainable development of tourism, a specific island development model for energy demand is required, such as long-term investments by using energy-efficient appliances and renewable energy sources. Tax credits for the installation of energy-saving devices and equipment also represent an effective strategy [17].

The 2030 Agenda for Sustainable Development was adopted by all United Nations Member States in 2015. There are 17 Sustainable Development Goals (SDGs) to end poverty and other deprivations (health, education, inequality, and economic growth). The application of the SDGs is a foundation for a more sustainable future. SDG 7 aims to ensure universal access to affordable, reliable, and modern energy services while tackling climate change and working to preserve oceans and forests [18].

In Taiwan, the "Guidelines on Energy Development" was activated in 2017 to promote a green economy, environmental sustainability, and social equity. The overall carbon emission coefficient for power will be reduced from 0.529 kg of CO_2/kWh in 2016 to 0.394 kg of CO_2/kWh in 2025. Raw coal consumption for coal-fired units is restricted. and the policy aims to develop low-carbon and clean energy, including a 20% energy generation using renewable sources (photovoltaic, wind power generation, geothermal power generation, hydraulic power generation, biomass energy power generation, and hydrogen energy fuel cell) by 2025 [19].

Penghu is an island in the Taiwan Strait. Electricity generation and transportation are the major sources of GHG emissions. Penghu was a pilot (2011–2015) for a low-carbon society. The project included the use of renewable energy, energy savings, green transportation, low-carbon buildings, forestation, resource recycling, low-carbon life, and low-carbon education. The northeast monsoon during autumn and winter is a local phenomenon and wind energy can be used to reduce total GHG emissions by about 50% [20]. A 4-year project (2015–2018) subsidized the use of energy-efficient appliances to reduce energy consumption. Another subsidy program for LED lights, energy-saving air conditioners, and energy management systems (EMS) in the domestic and commercial sectors was enacted in 2018–2020. Public awareness of energy savings is another major strategy [21]. Lu et al. [22] reported that chest freezers are common electric appliances in Penghu. There are no national standards for energy-efficient chest freezers, so these are not covered by subsidy programs.

Fisheries used to be the largest industry in Penghu, but the local environment and activities (Penghu ocean fireworks festival, POFF, and Penghu seafood festival) are attracting more tourists. This study determines the outcomes of government-funded projects and the impact of the tourist flow on energy supply and demand.

The literature shows a lack of studies related to the analysis of energy sustainability for an offshore island. The present paper aims to bridge this gap by analyzing the energy supply and demand for a low-carbon island. A specific island development model for energy demand is correlated with the tourism industry, energy consumption pattern, and water supply. The key variables for electricity consumption are determined, followed by perspectives for sustainable development (a low-carbon island). This study is a reference for other countries to formulate a low-carbon island.

2. Methodology

Principal component analysis [23] and the index decomposition approach [7] can be used to determine which factors affect electricity consumption. On an offshore island, energy supply, and demand are less complicated. This study analyzes data that is collected from published articles, technical reports, and databases. Historical data for ambient temperature, global solar radiation, wind [24], water supply [25], tourists [26], and electrical energy supply/consumption [27] in Penghu is used. This approach is considered to be simple and effective.

Cross-correlation is used to measure information between the two time series. The correlation coefficient, γ, as shown in Equation (1), ranges from -1.0 to 1.0. The data sets are identical when the value of γ is 1.0.

$$\gamma = \frac{1}{N}\sum_{1}^{N}\frac{V1'V2'}{\sigma_{V1}\sigma_{V2}} \quad (1)$$

where $V1'$ and $V2'$ are fluctuating components for the two time series while σ_{V1} and σ_{V2} are standard deviations.

2.1. Background Information on Penghu

The Penghu archipelago (23°12′ N−23°47′ N and 119°19′ E−119°43′ E) is located in the Taiwan Strait between Mainland China and Taiwan. There are 90 isles, 19 of which are populated. The total area is approximately 127 km^2. There are five townships (Husi, Siyu, Wangan, Cimei, and Baisha) and a city (Magong) with 42,427 households and 2.51 persons per household [26]. The monthly average temperature in 2018–2020 is shown in Figure 1. It ranges between 16.4 °C (February 2018) and 29.8 °C (July 2020). Air conditioning and water heating are the major sources of power consumption in summer and winter, respectively [22].

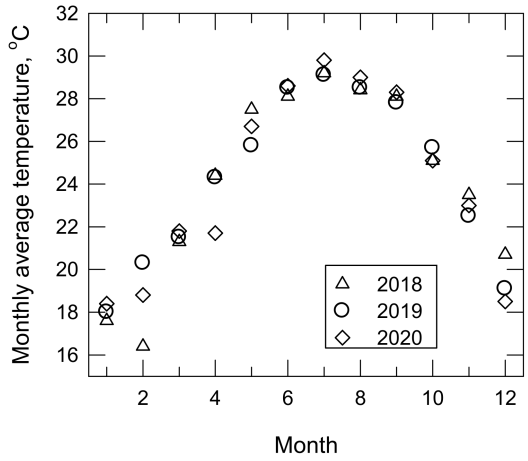

Figure 1. Monthly average temperature.

Solar energy allows sustainable development and a reduction in GHG emissions and environmental crises in rural areas. The production of hot water using solar water heaters (SWHs) is one of the most important applications for solar energy [28]. An energy system consisting of solar thermal collectors, a stirring engine thermoelectric generator, was proposed by Dong et al. [29] for energy production and storage. A solar PV-powered air conditioning unit with a battery system was studied using simulations and experiments [30].

Penghu straddles the Tropic of Cancer and is ideally suited to the use of solar energy technologies. The monthly average solar radiation and duration of sunshine in Penghu (2011–2020) is shown in Figure 2. The maximum monthly solar radiation is 667 MJ/m^2 (July), so the monthly duration of sunshine is 270 h. In winter, solar radiation is less than 300 MJ/m^2/month [24]. The northeast monsoon during autumn and winter is a natural phenomenon in Penghu. The average wind speed is between 4.1 m/s and 5.8 m/s, with a wind direction of 10–30°, as shown in Figure 3, and thus, Penghu is an ideal wind field for wind power generation. Li et al. [20] showed that wind turbines can operate at full capacity for about 3800 h every year. Therefore, PV and wind power are renewable energy sources for summer and autumn/winter, respectively.

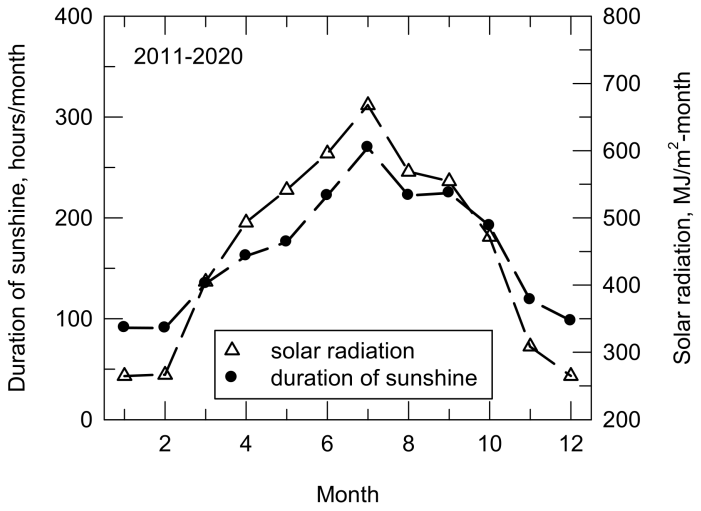

Figure 2. Monthly average solar radiation and duration of sunshine (2011–2020).

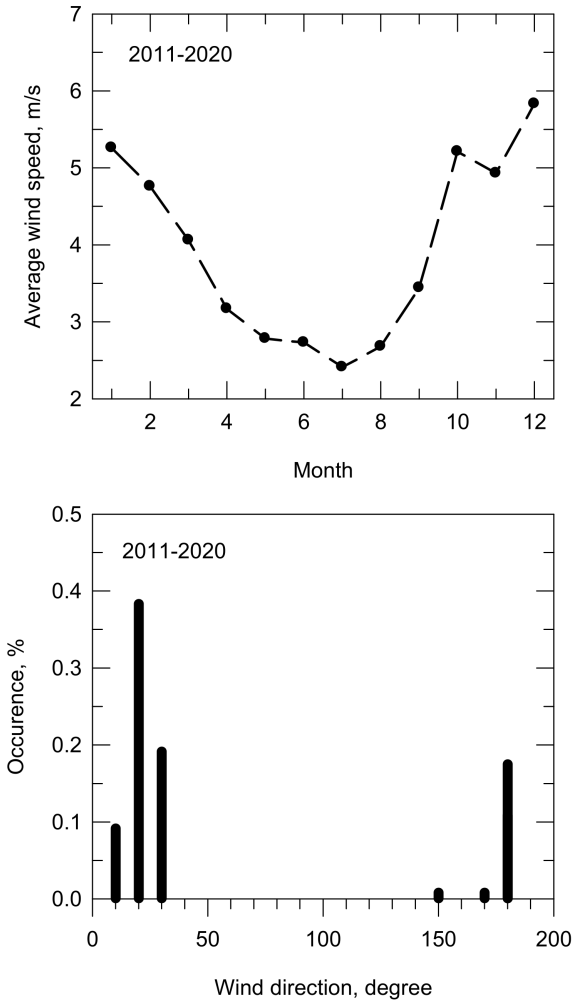

Figure 3. Average wind speed and wind direction (2011–2020).

2.2. Tourism Industry

The coastline of Penghu is approximately 448 km long. Natural attractions include the common cape bays, wave-erosion platforms, wave-erosion cliffs, wave-erosion cavities, and sandy and rocky coast. Basalt, in pillar-shaped joints, is a unique feature of Penghu. In recent years, more tourists have visited the island [26].

Tourist accommodation in Taiwan is divided into four main types: international tourist hotels, standard tourist hotels, general hotels, and homestay facilities (bed & breakfast, B&B) [31]. In Penghu, there is only one international tourist hotel (331 guest rooms in operation since 2016) and one standard tourist hotel (78 guest rooms). The historical record (2011–2021) for general hotels is shown in Figure 4. The figure ranges between 50 and 60. There were 2727 guest rooms available in 2021 (51.45 guest rooms/general hotel). The B&B industry has experienced rapid growth in the last ten years. Figure 5 shows that the number of B&Bs has increased from 190 in 2011 to 1061 in 2021, and the number of guest rooms has increased from 841 to 4983 (4.69 guest rooms/B&B in 2021).

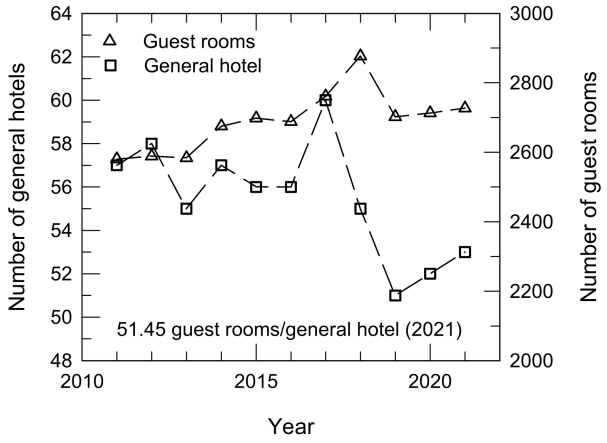

Figure 4. General hotels in Penghu (2011–2021).

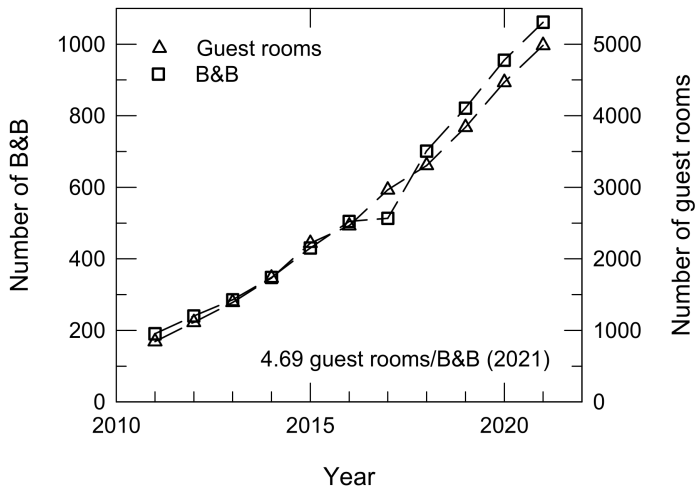

Figure 5. Bed & Breakfast establishments in Penghu (2011–2021).

Natural attractions and activities feed the tourism industry in Penghu. The yearly tourist flow (2011–2021) is shown in Figure 6. POFF has been held in the summer since 2003. Excellent night views and different scenery and cultural tours are features of the island. The number of tourists was approximately 0.87 million in 2011 and 1.28 million in 2019. A decrease in numbers in 2021–2022 corresponds to the COVID-19 pandemic. In 2021, only 0.62 million tourists visited Penghu. The new coronavirus outbreak in 2020 had a significant effect on Penghu's tourism industry. Following epidemic eases, there was an increase in the tourist flow from June to October, as shown in Figure 7. In 2021, a new coronavirus scare began in Taiwan in late April and almost no visitors came to Penghu in June–July, due to strict local regulations.

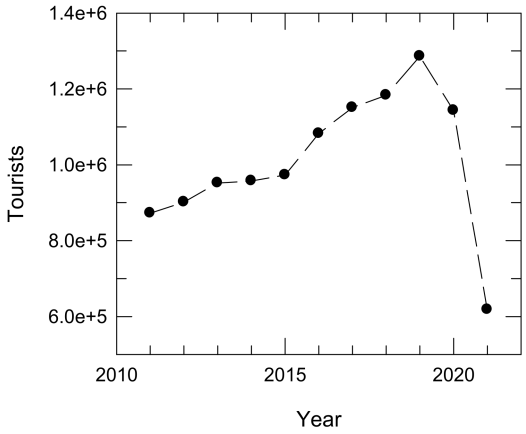

Figure 6. Yearly tourist flow (2011–2021).

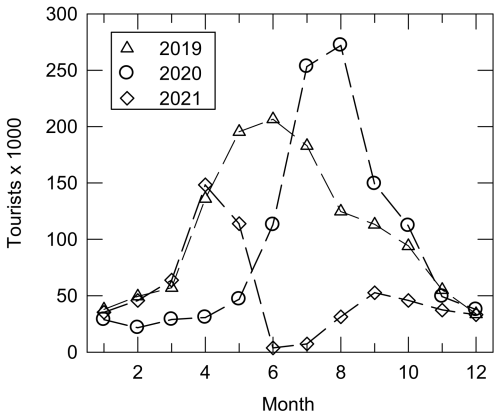

Figure 7. Monthly tourist flow (2019–2021).

2.3. Electricity Supply and Consumption

Electricity is the major source of energy consumption in Penghu [22] and is generated using independent power systems. The power plants of the Taiwan Power Company (TPC) are shown in Table 1. The largest power plant is located in Huxi Township (Chienshan power plant). It uses 12 diesel engines that consume heavy oil with a total capacity of about 130 MW. Ten diesel engines using diesel oil (the total capacity = 2.3 MW) are operated in Wangan, Hujing, and Cimei. On small isles, the governmental offices on each isle operate diesel engines to generate electricity. The "Million solar PV roof program" and "Low-carbon society project" were activated by the Bureau of Energy of the Ministry of Economic Affairs [19]. The capacity of solar PV and wind power (14 wind turbines) is now 16 MW and 10.2 MW, respectively.

Table 1. Electricity generation on Penghu.

Power Plant	Units	Capacity, MW	Fuel
Chienshan	4	10.433	heavy oil
Chienshan	8	11.0	heavy oil
Wangan	4	1.0	premium diesel oil
Hujimg	2	0.3	premium diesel oil
Cimei	4	1.0	premium diesel oil
PV		16	
Wind	14	10.2	

Electricity is the dominant energy source in Penghu. The historical record for electricity consumption for the domestic, commercial, and public sectors is shown in Figure 8. Electricity consumption by the domestic sector (households) was 153,754 MWh in 2012

and 173,928 MWh in 2019 [27]. This is associated with an increase in the number of local residents, from 988,843 to 105,952 [26]. In terms of the commercial sector, electricity consumption has progressively increased as the tourism industry has grown during the period of 2012–2019. The electricity consumption for each sector has been re-categorized so the data for 2020–2021 cannot be compared with the historical data for 2012–2019 [27]. There is a difference of approximately 11,700 MWh between 2020 and 2021 using the new database. This corresponds to a decrease in the number of tourists. The public sector has benefited from subsidy programs. Long-term investments for LED lights and energy-efficient appliances (air conditioners and refrigerators) have resulted in a decrease in electricity consumption in schools and governmental facilities between 2012 and 2020.

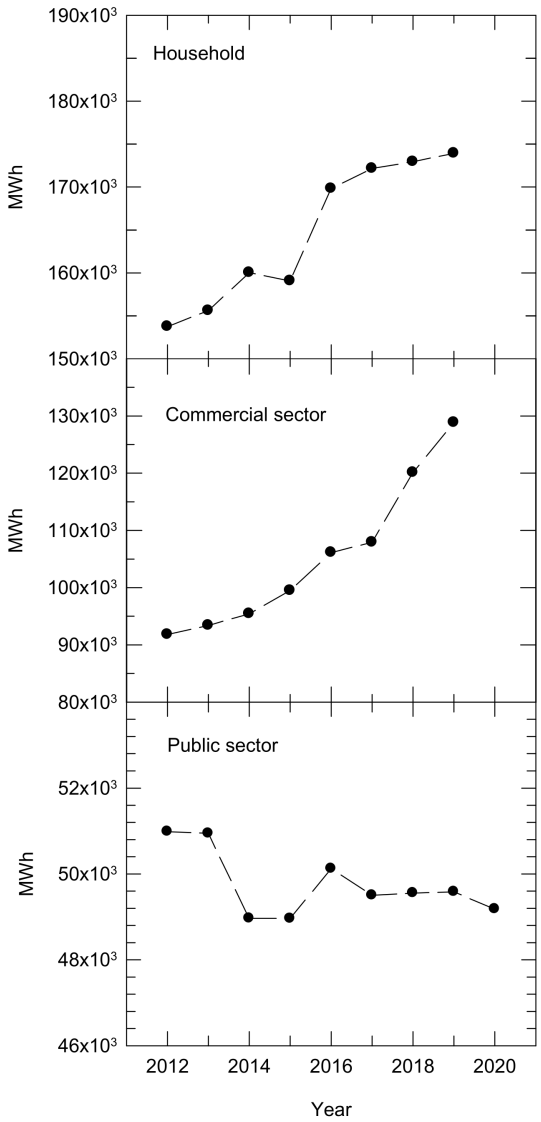

Figure 8. Electricity consumption.

In terms of the commercial sector, there are three groups of end-users based on the contract capacity, ≥800 kW, 50–800 kW, and <50 kW. The electricity consumption for each group is shown in Figure 9. For the group with a contract capacity greater than 800 kW, the electricity consumption was about 4940 MWh in 2014 and 23,676 MWh in 2019. There was an opening for an international tourist hotel in 2016 (5900 MWh in 2019) and a shopping mall in 2018 (11,660 MWh in 2019). The increase in electricity consumption for the other two groups is accounted for by the hotel industry because there is a significant increase in the number of B&Bs.

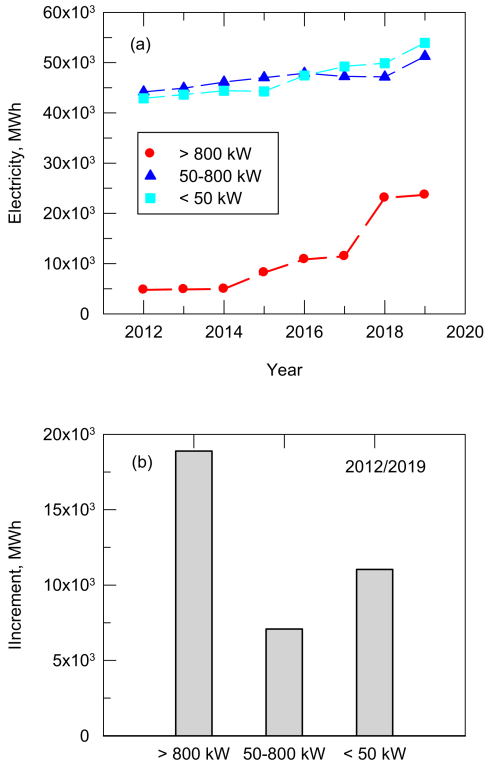

Figure 9. Electricity consumption for the commercial sector (**a**) historical record; (**b**) an increment in electricity consumption between 2012 and 2019.

Outdoor temperature is a key variable that affects the use of electricity for air conditioning. In Figure 1, the monthly average temperature (July–September) for 2020 was greater than that for 2018 and 2019, as was the monthly electricity consumption, which is shown in Figure 10. Water heating was required in winter and spring. To reduce electricity consumption in summer, energy-saving air conditioners are required.

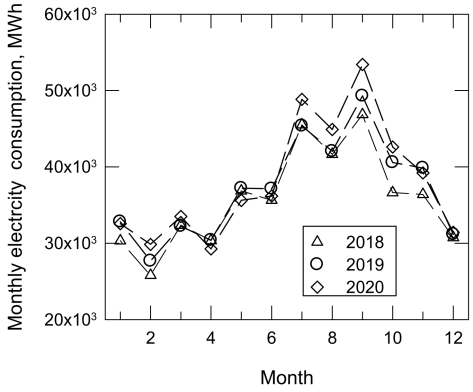

Figure 10. Monthly electricity consumption.

2.4. Water Supply

The terrain on Penghu is flat and there is a long dry period (October-March) and high water vaporization. The annual precipitation is about 1000 mm, thus the seven reservoirs are often empty. Groundwater used to account for about half the volume of the daily water supply [32]. This results in seawater intrusion and groundwater salinization [33]. Fan et al. [34] used four water quality indices to determine the degree of scaling and corrosion in SWHs on Penghu. There is a significantly higher chloride ion concentration and significant corrosion.

Penghu has access to unpolluted seawater, thus desalination plants are a practical alternative. The first desalination plant using reverse osmosis was built at Magong and the locations of the other plants are listed in Table 2. Seven use seawater (capacity = 100–10,000 m^3/day, CMD) and four plants (capacity = 180–4000 CMD) use brackish groundwater. In 2020, 6,950,000 m^3 (or 18,989 CMD) of fresh water was produced, thus approximately 60% of the fresh water supply comes from the desalination plants. Penghu has not experienced a water shortage during the last ten years.

Table 2. Desalination plants using reverse osmosis (RO) in 2020.

Desalination	CMD	10,000 m^3
Tongpan	100	2.25
Hoojing	200	4.31
Wangan	400	14.64
Siyu	750	27.45
Baisha	1200	22.11
Magong	3000	126.14
Magong	10,000	415.36
Brackish groundwater		
Cimei	1000	11.21
Siyu	1200	35.38
Chenggong	4000	36.10
Jiangjyun	180	0.08

A desalination plant using RO requires high-pressure pumps to force the water through the membrane and to remove unwanted substances. The process is energy-intensive. The monthly electricity consumption for three desalination plants is shown in Figure 11. The plant in Magong (13,000 CMD) produced 5,415,000 m^3 fresh water in 2020. The monthly electricity consumption was between 1496 MWh and 1811 MWh (or about 20,147 MWh annually). In Wangan and Siyu, the annual fresh water production is 146,400 m^3 and 274,500 m^3, with an electricity consumption of 873 MWh and 918 MWh, respectively. The electricity consumption for these three desalination plants accounts for more than 5% of all electricity consumption on Penghu.

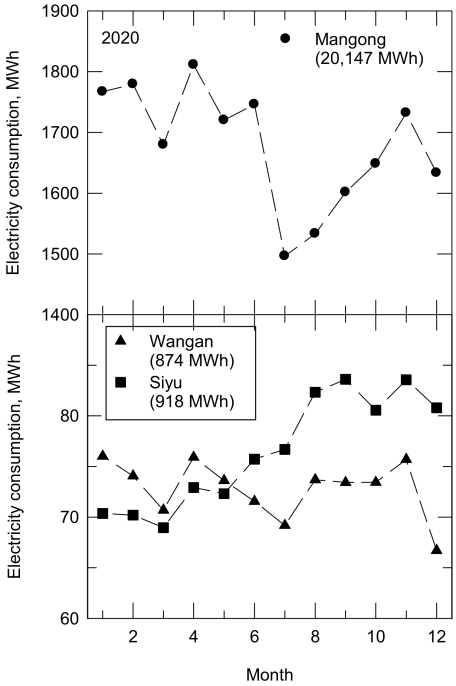

Figure 11. Monthly electricity consumption for three desalination plants in 2020.

3. Results

As shown in Figure 8, the electricity consumption by the domestic sector increases as the number of local residents increases. Figure 12 shows a progressive increase in the number of local residents, but the daily electricity consumption for each person increased in 2015–2016. The mean value is 4.269 for 2011–2015 and 4.525 kWh/person/day for 2016–2019. As shown in Figure 6, the number of tourists was 0.973 million in 2015 and 1.082 million in 2016. More B&B establishments were founded. However, some of them are not registered [31] so daily electricity consumption for each person increases.

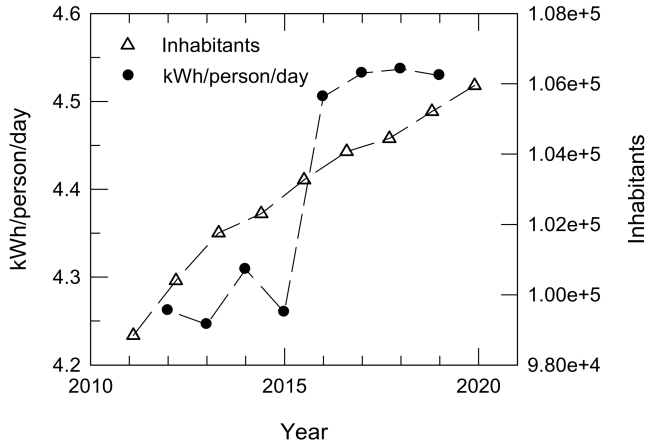

Figure 12. Electricity consumption in the domestic sector.

The annual electricity consumption is plotted against the number of tourists shown in Figure 13. They are closely correlated, which agrees with previous studies [15,16]. The value of γ is 0.91 in 2017–2019. This indicates that the number of tourists is the key variable for annual electricity consumption. The subsidy programs for energy-efficient appliances and lighting [21] are effective and result in a decrease in annual electricity consumption (γ = 0.78 in 2012–2016). The annual increase is approximately 2.4% for the period 2012–2019.

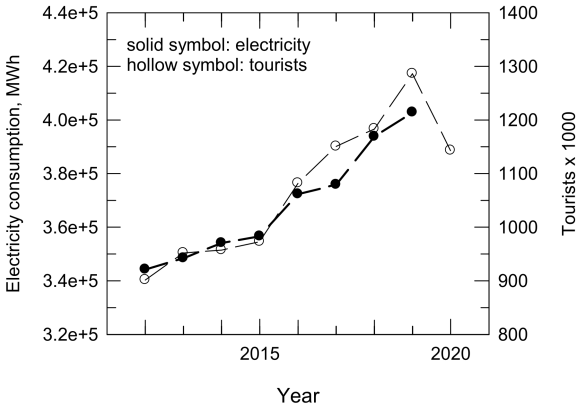

Figure 13. Electricity consumption and the number of tourists.

The ratio of electricity consumption to the number of tourists is shown in Figure 14. There is a gradual decrease in the ratio in terms of annual electricity consumption (γ = 0.86). This is not the case for the use of electricity consumption by the commercial sector (γ = 0.85). The ratio is 99.4 $\pm$ 2.8 kWh/tourist. Therefore, the number of tourists is a key parameter for electricity consumption by the commercial sector, and also for annual electricity consumption. Figure 15 shows the effect of tourism on electricity consumption. If the electricity consumption for tourism is excluded (99.4 kWh $\times$ the number of tourists), there is a very

gradual increase in the electricity consumption from 252,386 MWh in 2012 to 273,969 MWh in 2019. The annual increase is approximately 1.2%.

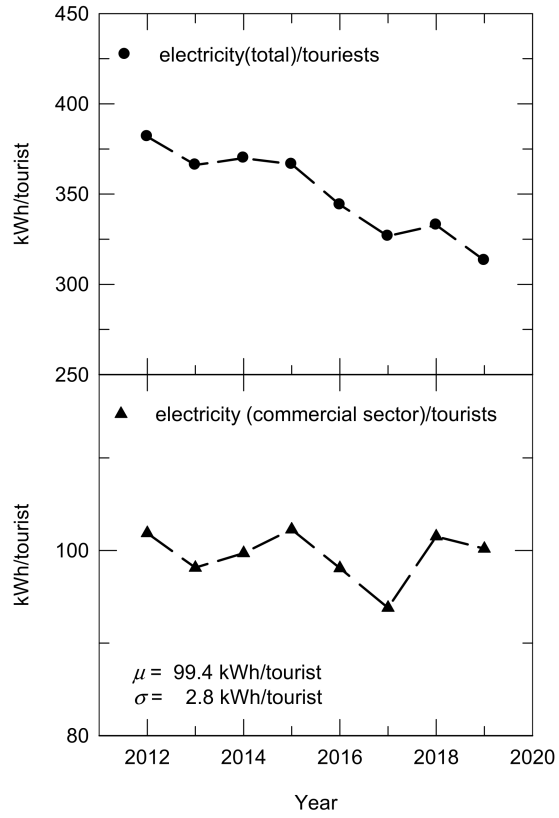

Figure 14. The ratio of electricity consumption to the number of tourists.

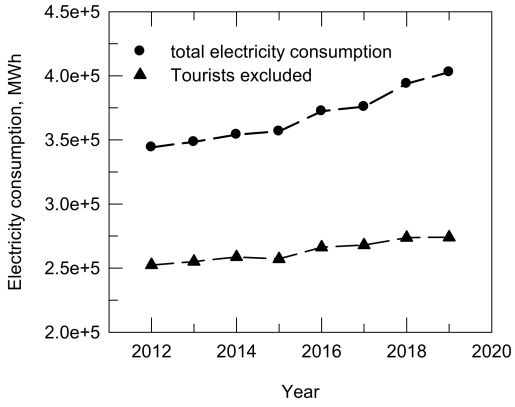

Figure 15. The effect of tourism on electricity consumption.

As shown in Section 2.3, more than 5% of electricity in Penghu is used for desalination. The daily volume of fresh water supply in 2020 and 2021 is shown in Figure 16. The average value is 32,083 m^3 in 2020 and 27,000 m^3 in 2021. The peak value during August–September (2020) corresponds to an end to restrictions due to the COVID-19 epidemic and an increase in tourist flow from June to October. In 2021, the low value for June–August corresponds to a period of strict local regulations due to an outbreak of COVID-19. Figure 6 shows that the number of tourists is 1,142,920 in 2020 and 618,013 in 2021. The water consumption per tourist is estimated to be 3.53 m^3. This figure is considerably greater than that for the domestic sector (0.25–0.28 m^3/person/day) [25].

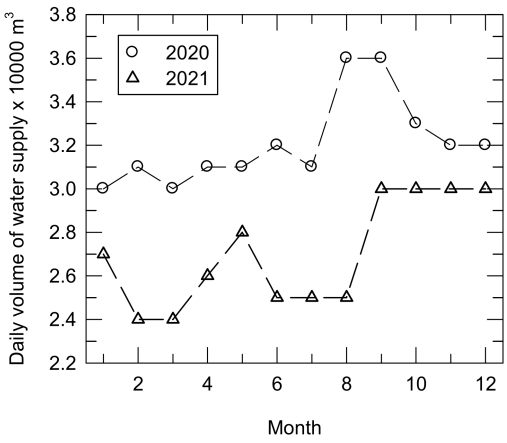

Figure 16. The daily volume of fresh water supply for 2020 and 2021.

Figure 13 shows that there is an increase in electricity consumption of 58,597 MWh between 2012 and 2019. This is due to an increase in the number of inhabitants/tourists and the fresh water demand (desalination), as shown in Figure 17. Other than in the domestic sector (18.9%), the tourism industry (65.2%) is the major cause of the increase in electricity consumption, and desalination plants account for 7.8% due to an increase in the number of tourists.

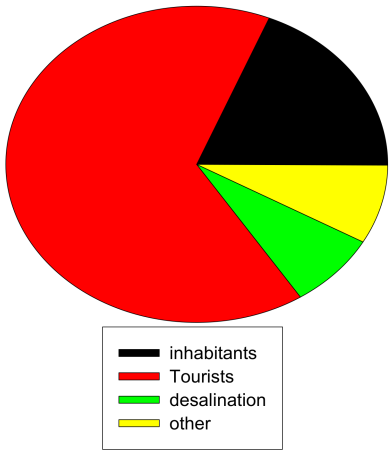

Figure 17. Key variables for the increase in electricity consumption.

4. Discussion

Penghu is an offshore island, thus it is inconvenient to transport liquefied petroleum gas to the island and the gas price is slightly higher. Therefore, local residents consume excessive amounts of electrical energy [22]. Long-term investment in LED lights and energy-efficient appliances (refrigerators and air conditioners) reduces electricity consumption but subsidy programs must include energy-efficient chest freezers. Lu et al. [22] also reported that there is a fixed monthly charge for electricity for small isles so there is excessive consumption of electrical power by local residents and this policy incentive should be terminated.

Hotels are among the most energy-intensive end-users. EMS is a system of computer-aided tools that reports energy that is used by individual pieces of equipment. B&Bs are a major part of the hotel industry in Penghu. Therefore, there is only one demonstration project for EMS. Chang and Chung [21] conducted face-to-face interviews with hoteliers (450 samples) to determine the energy usage for the hotel industry. LED lighting is a common feature of all hotels (98%). In terms of energy-efficient appliances, only 70% of air conditioners and 53% of refrigerators are rated as energy-efficient, so more incentives are required. A power regenerative system for an elevator is another approach.

Water demand for the hospitality service, kitchens, dining areas, swimming pools, and landscape requires excessive electricity (desalination). Water must be used efficiently for daily operation by the hotel industry, thus public awareness of water conservation must be increased. Water should also be recycled completely for many tourism businesses.

A low-carbon island requires the use of renewable energy. The area of solar collectors that is installed per thousand inhabitants in Penghu is smaller because the groundwater has a higher chloride ion concentration, thus there is pitting corrosion in SWHs [28]. The development of local desalination plants that produce water of a better quality will increase the use of SWHs. The capacity of the solar PV systems is 16 MW and generated 20,000 MWh in 2019 [27] after the "Million solar PV roof program". Land occupancy limits the installation of larger-scale ground-mounted PV systems. Revised regulations for PV systems on farms are required. An offshore PV system floating on a pontoon is also an alternative [35,36].

The northeast monsoon during autumn and winter makes Penghu an ideal wind field for wind power generation. Fourteen wind turbines (capacity = 10.2 MW) were built as part of the low-carbon island project. These generated 32,000 MWh in 2019 [27]. Eleven new wind turbines are proposed, with a capacity of 33 MW, so total electricity generation will be about 135,500 MWh. BEMOEA [37] has a "Four-Year Plan for the Promotion of Wind Power". The offshore wind power facility will have a capacity of 14 MW.

Penghu has an isolated grid system. Furthermore, 500,000 MWh of electrical power will be generated annually using onshore and offshore wind turbines and this will exceed the annual electricity consumption. Wind power is intermittent in nature and creates an unstable grid system. An undersea cable connects the grid in Penghu to the larger grid in Taiwan [19]. Any electricity surplus in winter is sent to the main grid in Taiwan. Penghu will be one of the lowest carbon islands in the world.

5. Conclusions

Natural attractions and activities in Penghu have created rapid growth in the tourism industry. Energy and water supplies face challenges. The analyses of the data collected from published articles, technical reports, and databases are useful to determine key variables for electricity consumption, but the approach may not be applicable in urban regions due to complicated energy supply and demand. Subsidy programs for energy-efficient appliances are effective. Local common appliances should also be included.

An increase in the number of inhabitants and tourists has created a gradual increase in annual electricity consumption. In the commercial sector, the opening of an international tourist hotel and a shopping mall has resulted in a large increase in demand for electricity. Desalination plants account for more than 5% of annual electricity consumption. Awareness of water conservation by local residents and tourists could be increased using a well-designed campaign.

A specific strategy for energy supply and demand is required for a small island. Tourism is now the major industry in Penghu. The tourist flow produces a seasonal oscillation in the demand for energy and water. In summer, revised regulations for PV systems on farms are required for the installation of larger-scale ground-mounted PV systems. Wind power is available due to the monsoon in autumn and winter. The isolated grid system can be stabilized using an undersea cable between Penghu and Taiwan. Surplus electricity can be sent to the main grid. Renewables can make Penghu a low-carbon island and allow sustainable development of the tourism industry.

Author Contributions: Conceptualization, W.-M.L. and K.-M.C.; methodology, C.-Y.H. and T.-T.Y.; formal analysis, C.-Y.H. and W.-M.L.; investigation, C.-Y.H. and T.-T.Y.; resources, K.-C.C.; data curation, C.-Y.H. and W.-M.L.; writing—original draft preparation, C.-Y.H. and W.-M.L.; writing—review and editing, K.-M.C.; project administration, K.-M.C.; funding acquisition, K.-C.C. and K.-M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Penghu County Authority, Taiwan, China, grant number YC-1081001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The technical support by the staff of Energy Research Center, National Cheng Kung University is appreciated.

Conflicts of Interest: The authors declare no conflict of interest.

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