Sustainable Energy Transition of an Island in the Mediterranean

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Introduction **—** This report provides a detailed analysis of the present energy scenario on a small Mediterranean island and explores the feasibility of transitioning to a 100% renewable energy system. The study covers the island's reliance on diesel-driven generator sets, the potential integration of photovoltaic (PV) panels, and the implementation of diurnal energy storage **[1]**. The results, generated through MATLAB analysis, offer insights into carbon emissions, electricity generation, costs, and the impact of storage losses on the island's energy landscape. The MATLAB code showing the full calculation steps and workings is submitted with this report.

Keywords — Energy, Electricity, Power, Storage, PV.

A. PRESENT ELECTRICITY GENERATION

At present, all generation on the island is provided using existing diesel-driven generator sets (gensets). The island consumes 900 metric tonnes (900,000kg) of diesel fuel each year in these gensets.

i. The CO_2 emission per year is calculated as follows.

Density of diesel: 0.85 kg/m^3 [2]

Emission per litre: 2.55 kgCO_2/m^3 [3]

Mass of diesel: 900,000 kg

$$Volume\ of\ the\ Diesel\ Used = \frac{mass\ of\ diesel}{Density\ of\ Diesel} = 1{,}058{,}823.5294\ litre(m^3)$$

$$CO_2\ Emission\ on\ the\ Diesel\ Used = Volume\ of\ the\ Diesel\ Used \times Emission\ per\ litre = \mathbf{2{,}700{,}000\ kgCO_2/year}$$

ii. Electricity Produced on the Island each year with 30% efficiency and diesel calorific values of 43.6MJ/kg is calculated as follows.

$$Diesel\ Energy\ Content = \frac{mass\ of\ diesel \times Diesel\ Calorific}{3.6} = 10{,}900{,}000\ kWh$$

$$Total\ Electricity\ Produced = Efficiency \times Diesel\ Energy\ Content = \mathbf{3270\ MWh}$$

iii. The cost of electricity from the diesel gensets is $500/tonne of the cost to import diesel fuel is calculated as follows.

$$Total\ diesel\ cost = mass\ of\ diesel \times diesel\ cost\ in\ \$/kg = \$450{,}000$$

$$Electricity\ cost = \frac{Total\ diesel\ cost}{Total\ Electricity\ Produced \times 1000} = \$\mathbf{0.14/kWh}$$

iv. The Line Rated Current when rated line to line voltage is 6.4kV

$$Island\ Average\ Power = \frac{Total\ Electricity\ Produced \times 1000}{8760} = 373.287671\ kW$$

$$Line\ Rated\ Power = 2 \times Island\ Average\ Power = 746.575342\ kW$$

$$Line\ Rated\ Current = \frac{Line\ Rated\ Power}{3 \times V_{Ph}} = \mathbf{67.35\ A}$$

v. The rated power of a genset running a synchronous generator at 1500rpm.

$$Genset\ Rated\ Power = \frac{2.5 \times Island\ Average\ Power}{4} = \mathbf{233.305\ kW}$$

vi. The moment of inertia (J) of a genset.

$$KE = Genset\ Rated\ Power \times 12 \times 1000 = 2{,}799{,}657.534247\ Joules$$

$$J = \frac{2 \times KE}{\omega^2} = \mathbf{226.93\ kgm^2}$$

vii. The diameter (D) of the genset cylinder if the steel density is 7800kg/m^3.

$$D = \sqrt[5]{\frac{8 \times 40 \times J}{\pi \times Steel\ Density}} = \mathbf{1.24m}$$

B. REPLACING THE GENERATION WITH PV PANELS

i. The power output of 200m^2 panel set was calculated using the following code segment in the MATLAB. Figure 1 shows the plot of power output of a 200m^2 panel set.

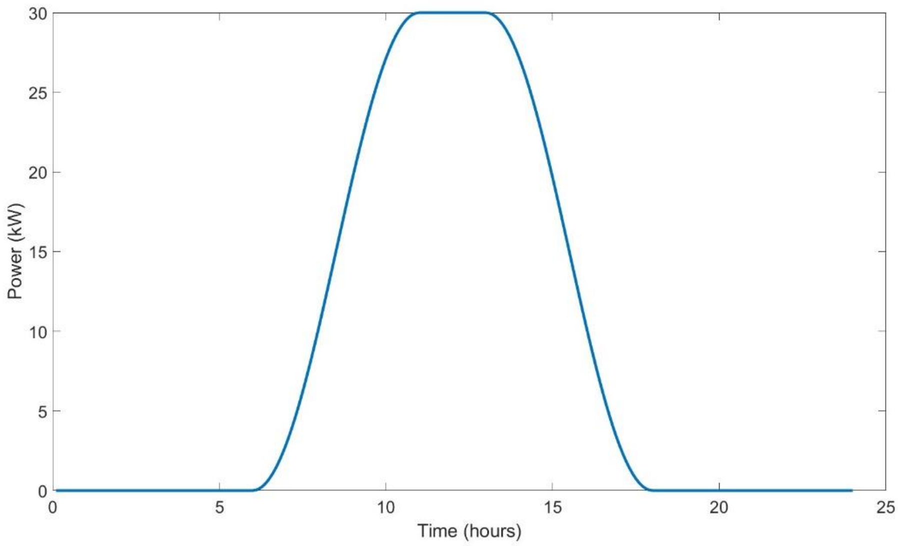

Figure 1: 200m^2 PV panel set - Output Power on an average day

The total energy produced by a set of PV panel is calculated as follows.

$$Pav = \frac{\sum_{t=0.1}^{24} P(t)}{lenght(t)} = 8.75kW$$

$$Total\ Energy\ Produced\ by\ a\ set\ of\ PV\ Panel = Pav \times 24 = \mathbf{210kWh}$$

ii. The number of Panel sets that will be delivered with 115% of the electrical energy presently consumed on the Island is calculated as follows.

$$Solar\ Energy = 1.15 \times Total\ Electricity\ Produced \times 1000 = 3{,}760{,}500kWh$$

$$Number\ of\ Panel = \frac{Solar\ Energy}{Total\ Energy\ produced\ by\ a\ set\ of\ PV\ Panel \times 365} \cong \mathbf{50\ sets}$$

iii. The total sum of installation cost that would be spent by the islanders over 10year before transfer of ownership from the installer with an agreed \$20/MWh is calculated as follows.

$$Amount\ of\ Yearly\ Energy\ from\ Solar\ Energy = \frac{Solar\ Energy \times 20}{1000} = \$75{,}210$$

$$Total\ Amount\ in\ 10 years = Amount\ of\ Yearly\ Energy\ from\ Solar\ Energy \times 10 = \$\mathbf{752,100}$$

iv. The following outline the reasons why the islanders should sign the contract for the PV panels.

- The diesel cost $450,000 per year while PV panels cost $75,210: the is a real bargain saving 83.29% of the current expenditure per year.
- Initial cost from the islanders is zero since the installer is paying for everything: <u>No initial installation cost.</u>
- Cost per kWh for diesel gensets is $0.14 while that of PV panels is $0.02: <u>Low running cost</u>.
- Zero CO^2 emissions
- Sustainability

C. USING DIURNAL ENERGY STORAGE

i. Dmax is calculated as follows.

$$Daily\ Demand = \frac{Total\ Electricity\ Produced \times 1000}{365} = 8958.90411kW$$

$$Daily\ Demand = \int_0^7 0.4D_{max}dt + \int_7^9 D_{max}(0.4 + \frac{0.6(t-7)}{2})dt + \int_9^{10} D_{max}(1 - 0.15(t-9))dt + \int_{10}^{16} 0.85D_{max}dt + \int_{16}^{18} D_{max}(0.85 + \frac{0.15(t-16)}{2})dt + \int_{18}^{21} D_{max}(1 - \frac{0.6(t-18)}{3})dt + \int_{21}^{24} 0.4D_{max}dt$$

$$implies\ D_{max} = \mathbf{582.69kW}$$

ii. Figure 2 shows plot of power output of the completed collection of PV panel sets and electrical power demand.

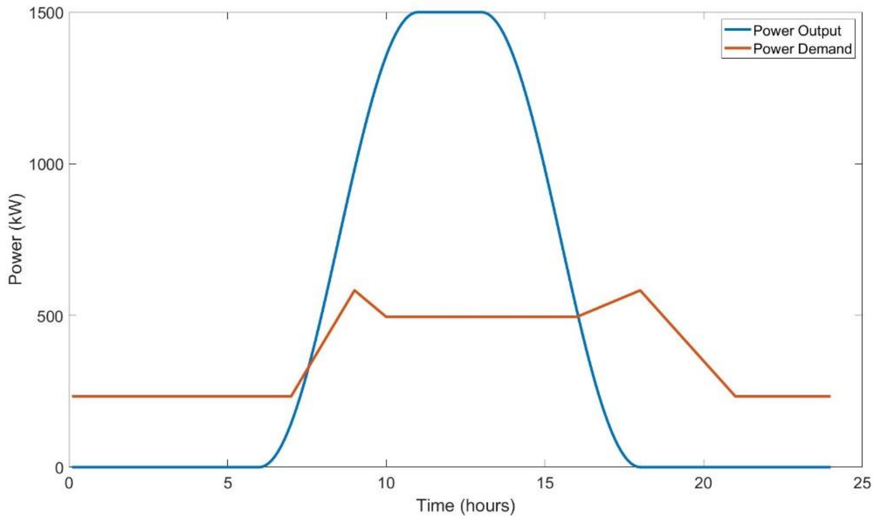

Figure 2: Power Output and Demand over an average day

iii. The minimum energy storage capacity, input and output power were calculated using the following MATLAB code segment. Figure 3 shows the graph of the storage energy capacity with time while allowing negative.

```
%initialize variables - storage, net power, input and output power
Storage = zeros(size(t));
Max_Storage = 0;
Net_Power = zeros(size(t));
Input_Power = zeros(size(t));
Output_Power = zeros(size(t));
%iteration in 240 steps of time from 6th minutes to 24 hours
for i = 2:length(t)
    Net_Power(i) = Pout(i) - D(i); % in kW
    Storage(i) = Storage(i - 1) + Net_Power(i) * 0.1; % 0.1 (6 minutes) factor convert
power (kW) to energy (kWh)
    Max_Storage = max(Max_Storage, abs(Storage(i)));
    Input_Power(i) = max(Net_Power(i), 0);
    Output_Power(i) = max(-Net_Power(i), 0);
end

fprintf('    Minimum Energy Storage Capacity: %f kWh\n', Max_Storage);
fprintf('    Input Power Rating: %f kW\n', max(Input_Power));
fprintf('    Output Power Rating: %f kW\n', max(Output_Power));
```

$$Minimum\ Energy\ Storage\ Capacity = \mathbf{4212.94\ kWh}$$
$$Input\ Power\ Rating = \mathbf{41004.71\ kW}$$
$$Output\ Power\ Rating = \mathbf{582.69\ kW}$$

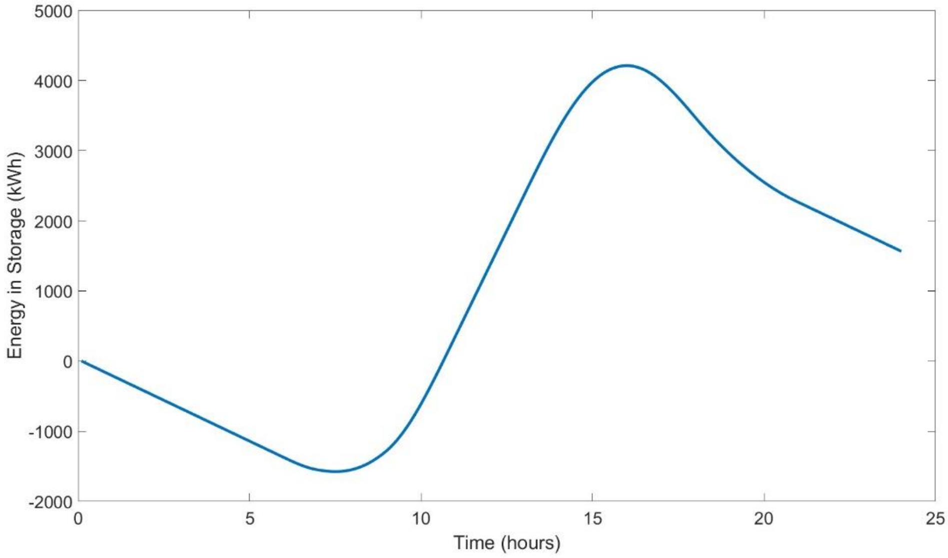

Figure 3: Energy in Storage over the day (allowing negative)

The initial value of the storage above was set to zero (0). Now, adjusting the initial value of the storage to the minimum value of the storage above using the MATLAB code below will ensure that the stored energy will never cross negative. Figure 4 in (iv) depict this graphically.

```
% b. Adjusting the initial energy in store to not crossover to negative
Storage_NonNegative = zeros(size(t));
Net_PowerNN = zeros(size(t));

% Initialize storage considering the initial energy
Storage_NonNegative(1) = abs(min(Storage));

% Iteration in 240 steps from 6th minutes to 24 hours
for i = 2:length(t)
    Net_PowerNN(i) = Pout(i) - D(i); % in kW
    Storage_NonNegative(i) = max(min(Storage_NonNegative(i - 1) + Net_PowerNN(i) * 0.1,
Max_Storage), 0);
end
```

iv. Figure 4 shows the graph of energy store over an average day assuming a 100% roundtrip efficiency. It also shows that the energy store was emptied at 7:30AM just about the sun rises.

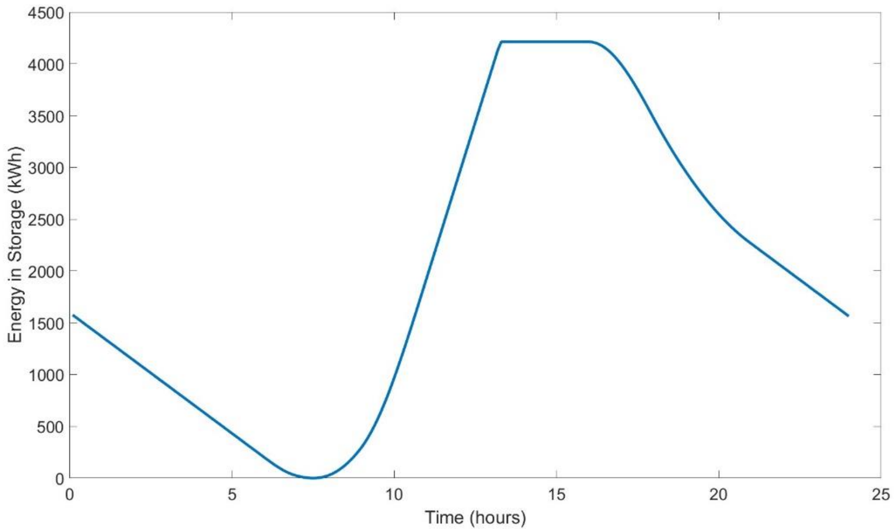

Figure 4: Energy in Storage over the day (100% Efficiency)

46.85% of energy used directly from the **PV panel** while **53.15%** from **storage energy**. The following code segment shows the calculating method used from the MATLAB code.

```
% b. Fraction of total amount of energy consumed from Solar and Storage
% Total energy consumed
Total_Consumption = sum(D) * 0.1;  % kWh
% Energy directly used from solar
Direct_Use = sum(D.* (D <= Pout)) * 0.1;  % kWh. If Pout (PV power) is greater than or
equal to D (demand), corresponding D array element will be multiply by 1 (true) else the
corresponding element will be multiply by zero (false). Then sum all the element in the
array
% Energy used from storage
Storage_Used = Total_Consumption - Direct_Use; % kWh
% Fractions Used
Fraction_Direct = Direct_Use / Total_Consumption;
Fraction_Storage = Storage_Used / Total_Consumption;
```

D. Dealing with storage losses

Considering a 20% of all energy put into storage is lost at the moment that it is being put in, the following code segment shows the calculation.

```
Storage_D = zeros(size(t));
Max_Storage_D = 0;
Net_Power_D = zeros(size(t));
loss_factor = 0.8;
%iteration in 240 steps of time from 6th minutes to 24 hours
for i = 2:length(t)
    Net_Power_D(i) = Pout(i) - D(i); % in kW
    Storage_D(i) = Storage_D(i - 1).*loss_factor + Net_Power_D(i) * 0.1; % 0.1 time to
convert power to energy (kWh)
    Max_Storage_D = max(Max_Storage_D, abs(Storage_D(i)));
end
fprintf('   Part D - Minimum Energy Storage Capacity: %f kWh\n', Max_Storage_D);
% Plot energy in storage - allowing negative
figure;
plot(t, Storage_D,"LineWidth",3);
xlabel('Time (hours)','FontSize',24);
ylabel('Energy in Storage (kWh)','FontSize',24);
title('Part D - Energy in Storage over the Day (Allowing Negative)','FontSize',24);
% b. Adjusting the initial energy in store to not crossover to negative
Storage_NonNegative_D = zeros(size(t));
Net_PowerNN_D = zeros(size(t));
% Initialize storage considering the initial energy
Storage_NonNegative_D(1) = abs(min(Storage_D));
% Iteration in 240 steps from 6th minutes to 24 hours
for i = 2:length(t)
    Net_PowerNN_D(i) = Pout(i) - D(i); % in kW
    Storage_NonNegative_D(i) = max(min(Storage_NonNegative_D(i - 1).*loss_factor +
Net_PowerNN_D(i) * 0.1, Max_Storage_D), 0);
end
% ii. a. Plot energy in storage with 80% roundtrip efficiency of the storage
figure;
plot(t, Storage_NonNegative_D,"LineWidth",3);
xlabel('Time (hours)','FontSize',24);
ylabel('Energy in Storage (kWh)','FontSize',24);
title('Part D - Energy in Storage over the Day (80% Efficiency)','FontSize',24);
```

Figures 5 and 6 show the graphs of energy in storage while allowing to cross negative and not cross negative respectively. From the figures the minimum storage capacity of ***4212.94 kWh*** is required to meet the demand when PV panels are not producing. To mitigate non availability of supply, the storage minimum capacity must select at least 20% of the minimum designed value above.

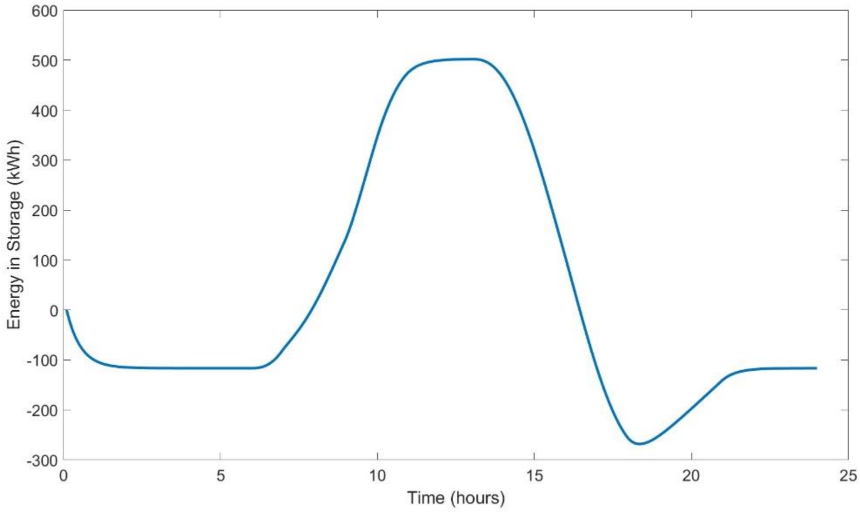

Figure 5: Energy in Storage over the day (allowing negative)

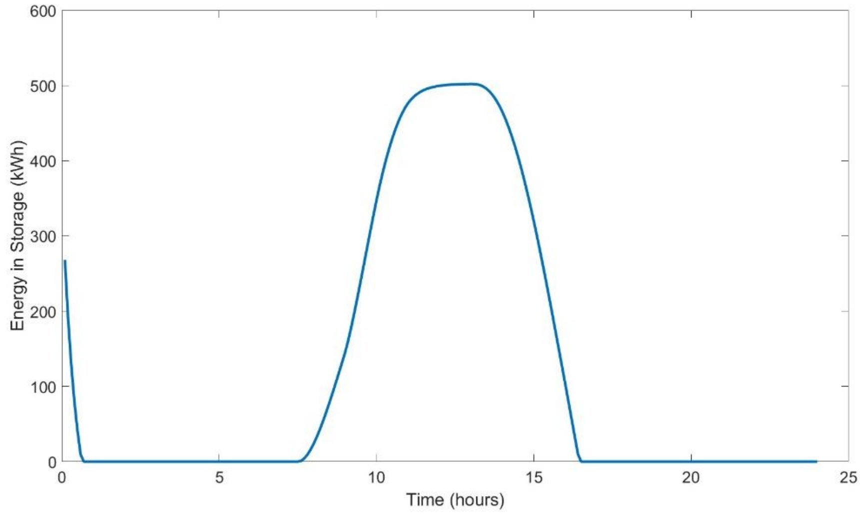

Figure 6: Energy in Storage over the day (20% losses)

The turned-down energy = **97197.38 kWh**. This is calculated as in the following code segment.

```
for i = 2:length(t)
    Net_Power_D(i) = Pout(i) - D(i); % in kW. Removing demand from the generation
    % Modified storage calculation
    Storage_TDE(i) = Storage_TDE(i - 1) + Net_Power_D(i) * 0.1;
    if Net_Power_D(i) > Storage_TDE(i) / 0.1
        excess_power = Net_Power_D(i) - Storage_TDE(i) / 0.1; % remove storage
        turned_down_energy = turned_down_energy + excess_power * 0.1;
    end
end
```

E. References

[1] P. S. GARVEY, Writer, *ENGR4004: Energy Storage Coursework.* [Performance]. University of Nottingham, 2024.

[2] E. M. Mark J. Kaiser, "Specifications," in *Pipeline Rules of Thumb Handbook - A manual of quick, accurate solutions to everyday pipeline engineering problems*, ScienceDirect, 2022, pp. 1089-1146.

[3] A. Q. Jakhrani, A. R. H. Rigit, A.-K. Othman, S. R. Samo and S. A. Kamboh, "Estimation of carbon footprints from diesel generator emissions," in *IEEE - 2012 International Conference on Green and Ubiquitous Technology*, Bandung, Indonesia, 2012.