47330 Energy Storage and Conversion Assignment 2

Peter Krepkiy s221664 Solomon Leo s221577 Vardhan Koripally s221407

Task One

The maximum storage capacity of the potential energy storage system is found by calculating the buoyant force of the sphere assembly, and multiplying by the maximum potential depth that the spheres can be submerged to, for the overall potential energy of the system. Potential energy follows the (Force)x(Distance) formula, or the potential to do work:

- The maximum volume per sphere is $V_{max, sphere} = (4/3)(\pi)(r^3)$. Using 5 meters for the maximum possible radius, $V_{max} = (500/3)\pi \text{ m}^3$
- Buoyant force is defined as ($V_{max} m^3$)(Acceleration_{gravity} m/s²)(Density_{fluid} Density_{sphere} kg/m³) = (500/3)(π)(9.8)(1030 5000) = -6.49 π x 10⁶ N
- Potential energy is calculated by multiplying the net force with the maximum potential depth, 100 meters. Total PE = $(100 \text{ m})(-6.49\pi \text{ x} 10^6 \text{ N})(10 \text{ spheres}) = -6.484\pi \text{ GNm} = 5.66 \text{ MWh}$

The round trip efficiency of the heat storage system $\eta_{round trip} = \eta_{dis} \eta_{2nd} \eta_{carnot} = \eta_{dis} \eta_{2nd} (1-T_A/T_C) = (0.96)(0.70)[1-101+273/(600+273)] = 45.42\%$

Task Two

The maximized energy through the cable is achieved through the following configuration:

- The maximum potential energy storage will be used, 10 spheres with a diameter of 10 meters and depth of 100 meters. The maximum power used in the motors is 5.66 MW.
- The thermal energy storage will have a capacity of 68.33 MWh to match the maximum storage in 04:00. The electrical heater will have a power of 27.12 MW to match the maximum power to the thermal storage at 00:00. The generator will constantly output 4.61 MW starting at 09:00 and run for 6 hours

With this configuration, the total energy transported will be 202.2975 MWh. The following graphs give the current through the cable and the power from the wind farm each hour:



It can be seen that the energy island reduces the variability of the power output from the wind farm.

The following table gives the state of the system each hour:

Time at start of period	WindPower (MW)	Electrical power (MW)	Cable Power	Potential Storage	Power to Potential	Thermal Storage	Power to Thermal	Current
00:00	43.210709	43.210709	10	5.66	6.086022	26.039700	27.124687	333
01:00	33.772972	33.772972	10	5.66	0	48.861753	23.772972	333
02:00	23.822029	23.822029	10	5.66	0	62.130901	13.822029	333
03:00	16.212851	16.212851	10	5.66	0	68.095238	6.212851	333
04:00	10.245285	10.245285	10	5.66	0	68.330712	0.245285	333
05:00	7.319994	7.319994	10	2.778273	-3.098631	68.330712	0.000000	333
06:00	5.111728	5.111728	7.695522	0	-2.987390	68.330712	0.000000	257
07:00	6.239247	6.239247	6.239247	0	0	68.330712	0.000000	208
08:00	6.766367	6.766367	6.766367	0	0	68.330712	0.000000	226
09:00	4.948337	4.948337	9.558337	0	0	58.586471	-10.150250	319
10:00	5.90621	5.90621	10	0.480075	0.516210	48.842231	-10.150250	333
11:00	4.511831	4.511831	9.6019063	0	-0.516210	39.097991	-10.150250	320
12:00	0.325445	0.325445	4.935445	0	0	29.353751	-10.150250	165
13:00	0.0103	0.0103	4.6203	0	0	19.609511	-10.150250	154
14:00	0.403922	0.403922	5.013922	0	0	9.865271	-10.150250	167
15:00	2.275905	2.275905	6.885905	0	0	0.121031	-10.150250	230
16:00	4.53401	4.53401	4.53401	0	0	0.121031	0.000000	151
17:00	7.060792	7.060792	7.060792	0	0	0.121031	0.000000	235
18:00	9.385717	9.385717	9.385717	0	0	0.121031	0.000000	313
19:00	11.999616	11.999616	10	1.859643	1.999616	0.121031	0.000000	333
20:00	14.381846	14.381846	10	5.66	4.086406	0.404654	0.295440	333
21:00	17.210197	17.210197	10	5.66	0	7.326443	7.210197	333
22:00	20.572283	20.572283	10	5.66	0	17.475834	10.572283	333
23:00	21.933485	21.933485	10	5.66	0	28.931980	11.933485	333

The energy through the cable was maximized using a Python script. When the power from the farm is greater than 10MW, excess energy is first used to charge the potential storage. If the potential storage is full, the excess energy will charge thermal. It is assumed that the thermal storage can charge at any time, including while discharging. If the wind power dips below 10MW we discharge potential first. At a specified time thermal will begin discharging at a constant rate for several hours and during this time, potential will be discharged and charged accordingly.

A parametric sweep was performed with the two changing variables as the power output of thermal and the number of hours discharged. Each sweep has a corresponding calculated total energy, 4 large sweeps are performed, each one starting at a different hour from 07:00 to 10:00. It was found that starting at 09:00 produced the highest energy output. Then, a smaller sweep is performed starting at 09:00, with the step size of the thermal output as 0.01 instead of 0.1 to produce a more accurate power output for the generator. When the best combination of a 4.61MW discharge rate for 6 hours was found, it was simulated in python to show the complete state of the system at all times.

Task Three

The purpose is to reduce the cost of the cable. A few details go into calculating the cost of the cable, namely distance and power rating, which influences weight and armor sheathing.

According to Alexandra Franklin-Cheung at <u>BBC Science Focus</u>, fixed (non-floating) wind farms can only be built on a sea depth of up to 40 meters, which translates to roughly a maximum distance of 30 km from the shoreline. We assume that a conventional wind farm is used (given that the only current floating wind farms in operation are located in either Scotland or Portugal, and we assume this project is located in the Danish exclusive economic zone). Given that power cables run on or just beneath the ocean floor, a pythagorean-model right-triangle approximation can be used to average the terrain on the ocean floor. The maximum possible length of the power cable is also about 30 km.*



*The difference in maximum depth between jacket or monopile foundations is negligible assuming a 30 km maximum distance when calculating the maximum possible submarine cable length.

This is a relatively low-distance cable setup.

With a fixed voltage and variable current, up to 333 A, the only way to reduce the power rating and thus the cost of the cable is to reduce the current draw. Similarly to above-ground ultra-high voltage transmission lines, loss of energy due to conductor resistance is minimized with high voltages.

With the energy island, the minimum resistance is 90.09 Ω , and the maximum power through the cable is (30 kV)(333 A) = 9.99 MW or 10 MW. Without the energy island, the maximum power through the cable during the 24 hour cycle is about 43.21 MW ~ 44 MW. The average power output of the wind farm without the energy island is exactly 12 MW.

Is there a large-enough difference in those two power outputs to warrant all of the costs associated with the construction of the energy island?

Three options are assessed:

- 1. Build (and endure all of the construction, maintenance, operations costs of) the energy island, with an attached cable of distance 30 km and power rated to 10 MW.
- 2. Do not build the energy island and use a cable of distance 30 km and power rated to ~44 MW.
- 3. Do not build the energy island and instead use a dual cable setup, one rated to 12 MW, the average wind farm power output in the 24 hour cycle, and a secondary (offload) cable to which is distributed the remaining (44-12 = 32 MW) peak power.

Judging by the small distance (30 km), the associated costs with building a high power cable are negligible. Thus, it can be concluded that options 2 or 3 make the most sense, and the difference in power ratings of the cable setups are negligible in the scope of the short-distance shoreline application. In fact, the 30km estimate is the theoretical maximum, so the true distance could be even shorter. In addition, using a higher power-rated cable instead of an energy island will allow all 268 MWh of the energy from the wind farm to be transported per day, there will be no loss due to inefficiency. This means a higher profit per day because that energy can be sold or used for production. In conclusion, given the relatively short distance, it is cheaper to build a higher power-rated cable setup than an entire offshore energy storage platform. If the scale and distances were larger, then an energy storage platform could be considered.

Appendix

Excel Sweeps (4 large and 1 small):

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```
Python Script:
import numpy as np
import pandas as pd
import openpyxl
# Energy Storage and Conversion Assignment 2 Simulation Code
# Solomon Leo
wind = [43.210709]
, 33.772972
, 23.822029
, 16.212851
, 10.245285
, 7.319994
, 5.111728
, 6.239247
, 6.766367
, 4.948337
, 5.90621
, 4.511831
, 0.325445
, 0.0103
, 0.403922
, 2.275905
, 4.53401
, 7.060792
, 9.385717
, 11.999616
, 14.381846
, 17.210197
, 20.572283
, 21.933485]
discharge rates = [i for i in np.arange(4.4, 4.71, 0.01)]
time steps = [i \text{ for } i \text{ in } range(4, 8, 1)]
# Runs a sweep of the daily power simulation for many values of discharge
rate and time with thermal storage running
def run sim (rates, times):
    # Make a data frame where each column is a discharge rate and each row
is a time
    sims = [[0 for i in range(len(rates))] for i in range(len(times))]
    for i in range(len(times)):
        for j in range(len(rates)):
            sims[i][j] = (power sim(rates[j], times[i])[1])
    df = pd.DataFrame(sims, columns = rates)
    return df
# Iterate through wind powers, returns a tuple with a list of the powers
through the cable at each hour and the sum of them
def power sim (tdischarge, hours):
    # Current storage of thermal and potential
    thermal = 0
```

```
potential = 0
    # Lists of power values for each hour
    lcable = []
    lthermal = []
    lpotential = []
    # Time parameters
    hour = 0
    start = 9
    for i in wind:
        # We will use the generator between these hours and when thermal
can discharge
        if hour >= start and hour <= start + hours and thermal >
tdischarge/0.4731:
            # If there is not enough energy from thermal and farm
discharge potential
            if tdischarge + i < 10:
                # If potential is already discharged we cant do anything
                if potential == 0:
                    lcable.append(tdischarge+i)
                    thermal = thermal - tdischarge/0.4731
                    lthermal.append(thermal)
                    lpotential.append(potential)
                # If potential has charge discharge
                elif potential != 0:
                    needed = 10 - (i + tdischarge)
                    # If the needed energy is greater than potential
stored release all potential
                    if needed >= potential:
                        lcable.append(i + tdischarge + potential)
                        potential = 0
                        thermal = thermal - tdischarge/0.4731
                        lthermal.append(thermal)
                        lpotential.append(potential)
                    # If needed energy is less than potential stored
release some potential
                    elif needed < potential:
                        lcable.append(10)
                        potential -= needed
                        thermal = thermal - tdischarge/0.4731
                        lthermal.append(thermal)
                        lpotential.append(potential)
            # If we have excess energy charge storages
            elif i + tdischarge > 10:
                lcable.append(10)
                thermal = thermal - tdischarge/0.4731
                excess = i + tdischarge - 10
                # If potential is not full fill potential and excess goes
to thermal
                if potential < 5.66:
                    free = (5.66 - \text{potential})/0.93
                    if excess >= free:
```

```
thermal = thermal + (excess - free) *0.96
                        potential = 5.66
                        lpotential.append(potential)
                        lthermal.append(thermal)
                    elif excess < free:
                        potential = potential + excess*0.93
                        lpotential.append(potential)
                        lthermal.append(thermal)
            # Thermal will discharge at constant rate through hours and
can be charged while discharging
        # If the power from the farm is greater than 10 we send 10 through
the cable and the excess charges the storages
        elif i > 10:
            power = i - 10
            lcable.append(10)
            # If potential is not full we fill potential and excess goes
to thermal
            if potential < 5.66:
                free = (5.66 - \text{potential})/0.93
                if power >= free:
                    thermal = thermal + (power - free) *0.96
                    potential = 5.66
                    lpotential.append(potential)
                    lthermal.append(thermal)
                elif power < free:
                    potential = potential + power*0.93
                    lpotential.append(potential)
                    lthermal.append(thermal)
            # If potential is full we put all into thermal
            elif potential == 5.66:
                thermal += power*0.96
                lpotential.append(potential)
                lthermal.append(thermal)
        # If power from farm is less than 10, we take from the potential
storage first
        elif i < 10:
            needed = 10 - i
            if potential > needed/0.93:
                potential = potential - needed/0.93
                lpotential.append(potential)
                lthermal.append(thermal)
                lcable.append(10)
            elif potential < needed/0.93:
                lcable.append(i + potential*0.93)
                potential = 0
                lpotential.append(potential)
                lthermal.append(thermal)
        hour += 1
    return lcable, sum(lcable), lpotential, lthermal
```

```
df = run_sim(discharge_rates, time_steps)
# Puts data into an excel file
#df.to_excel(r'\Users\solomon\Desktop\Energy Storgae\Results.xlsx',
sheet_name = 'Sheet2', index = False)
print(df)
dic = power_sim(4.61, 6)
final = pd.DataFrame(i for i in range(24))
final['Cable Power'] = dic[0]
final['Potential Storage'] = dic[2]
final['Thermal Storage'] = dic[3]
print(final)
print(dic[1])
##
#final.to_excel(r'\Users\solomon\Desktop\Energy Storgae\Results.xlsx',
sheet name = 'Sheet3', index = False)
```

Non-European number convention is used, meaning a comma (,) is used for thousands-place and a period (.) is used before the decimals place.

https://elek.com.au/articles/submarine-power-cable-ratings/ https://powerlinesinc.com/high-voltage-electricallines/#:~:text=High%20voltage%20transmission%20lines%20deliver,exceeds%20supply%2C%20a%20b lackout%20occurs.