47330 Energy Storage and Conversion
Assignment 2

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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, $V_{max} = (500/3)\pi\ m^3$
- Buoyant force is defined as ($V_{max}\ m^3$)($Acceleration_{gravity}\ m/s^2$)($Density_{fluid} - Density_{sphere}\ kg/m^3$) $= (500/3)(\pi)(9.8)(1030 - 5000) =$ **$-6.49\pi \times 10^6$ N**
- Potential energy is calculated by multiplying the net force with the maximum potential depth, 100 meters. Total PE = (100 m)($-6.49\pi \times 10^6$ N)(10 spheres) = -6.484π GNm = **5.66 MWh**

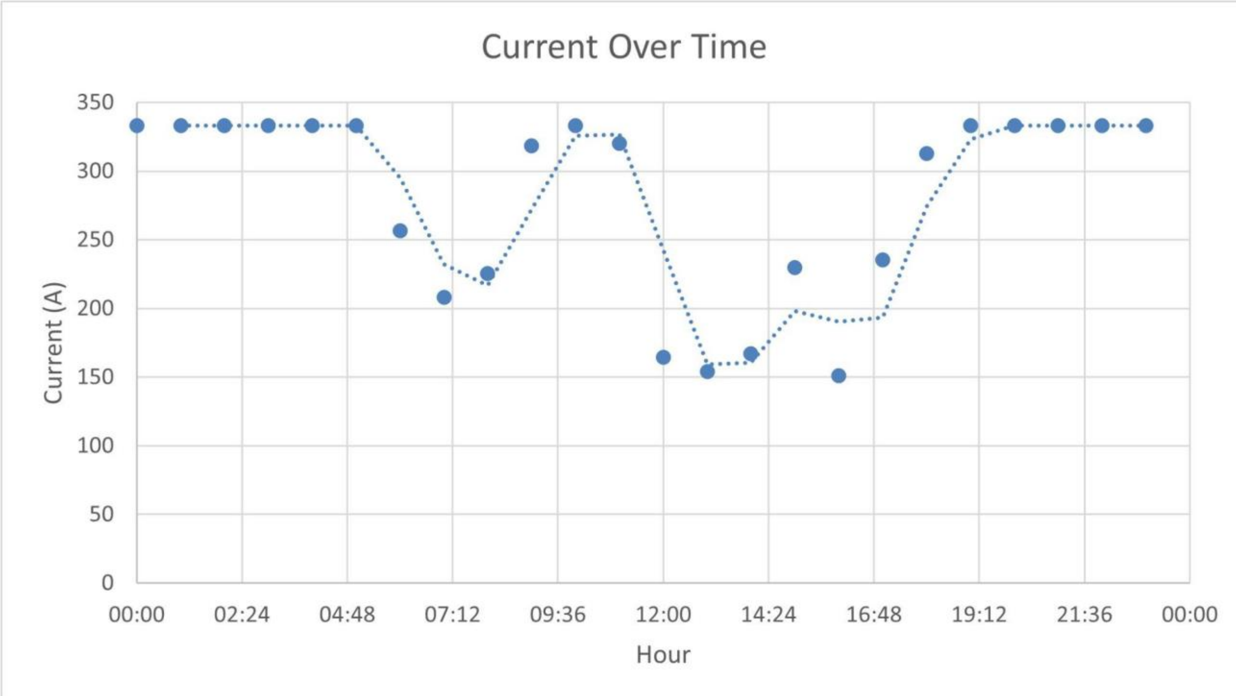
The round trip efficiency of the heat storage system $\eta_{round\ trip} = \eta_{dis}\ \eta_{2nd}\ \eta_{carnot} = \eta_{dis}\eta_{2nd}(1-T_A/T_C) = (0.96)(0.70)[1- 101+273/(600+273)] =$ **45.42%**

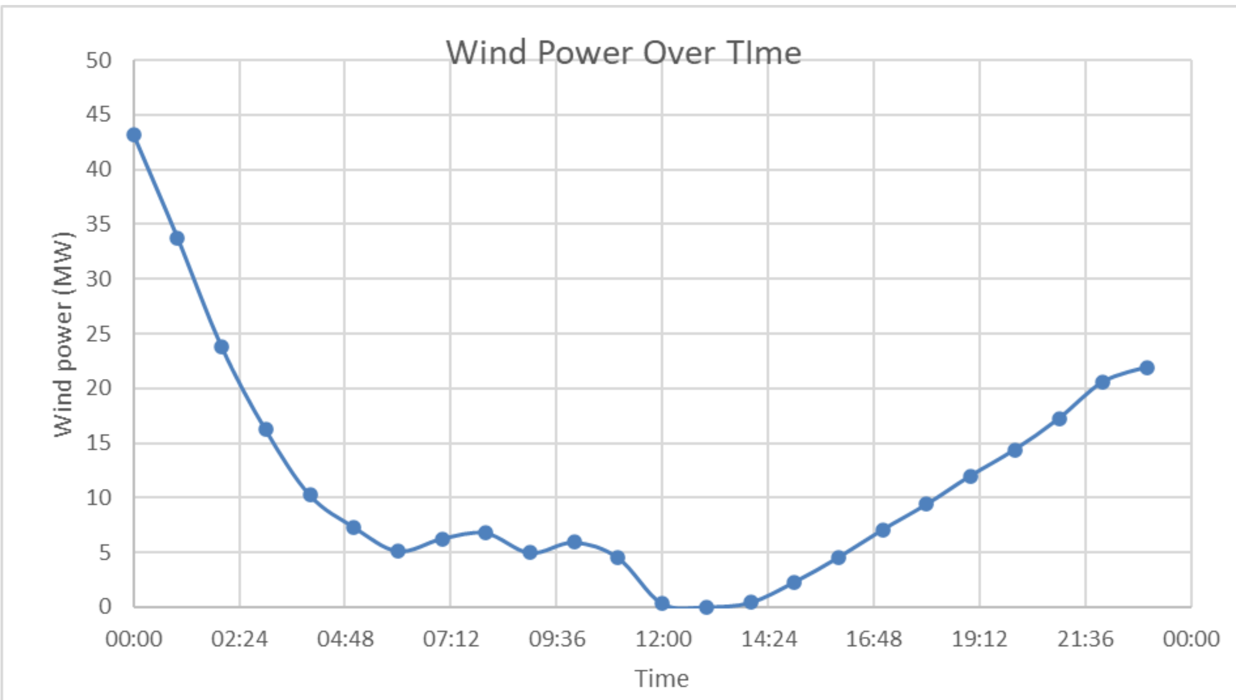
Task Two

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

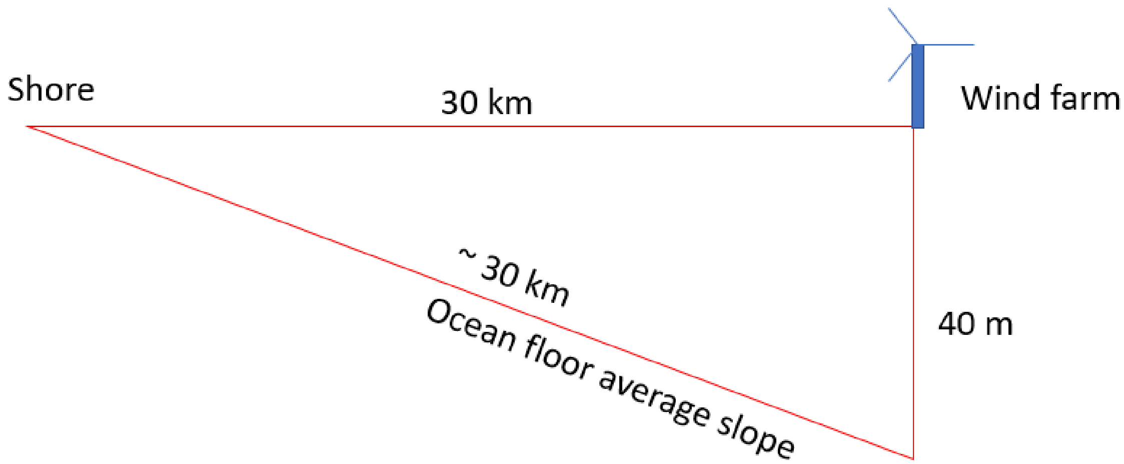
The energy through the cable was maximized using a Python script. When the power from the farm is greater than 10MW, excess energy is first used to charge the potential storage. If the potential storage is full, the excess energy will charge thermal. It is assumed that the thermal storage can charge 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 BBC Science Focus, 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):

Starting at 07:00

Hour \ Energy	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
0	172.664	172.764	172.864	172.964	173.064	173.164	173.264	173.364	173.464	173.564	173.664	173.764	173.858	173.945	174.031	174.118	174.204	174.291	174.377	174.464	174.55	174.637	174.723	174.81	174.896	174.983	175.069	175.156	175.242	175.329	175.415	175.502	175.588	175.675
1	175.264	175.464	175.664	175.864	176.064	176.264	176.464	176.655	176.841	177.028	177.214	177.401	177.582	177.755	177.928	178.101	178.274	178.447	178.62	178.793	178.966	179.139	179.312	179.485	179.658	179.831	180.004	180.176	180.349	180.522	180.695	180.868	181.041	181.214
2	177.864	178.164	[illegible]	[illegible]	179.064	179.364	179.664	179.959	180.252	180.545	180.838	181.131	181.421	181.707	181.993	182.267	182.533	182.799	183.065	183.331	183.597	183.863	184.129	184.395	184.661	184.924	185.183	185.443	185.702	185.962	186.221	186.481	186.74	187
3	180.464	180.864	[illegible] Chart Area	[illegible]	182.064	182.464	182.864	183.259	183.652	184.045	184.438	184.831	185.221	185.607	185.993	186.367	186.719	187.071	187.424	187.776	188.129	188.481	188.834	189.186	189.539	189.888	190.234	190.58	190.926	191.272	191.467	191.467	191.467	191.467
4	183.064	183.564	184.064	184.564	185.064	185.564	186.064	186.559	187.052	187.545	188.038	188.531	189.021	189.507	189.993	190.479	190.958	191.437	191.9	192.346	192.791	193.236	193.682	194.127	194.573	195.015	195.454	195.893	196.332	196.77	196.955	196.955	196.955	196.955
5	185.664	186.264	186.864	187.464	188.064	188.664	189.264	189.859	190.452	191.045	191.638	192.231	192.821	193.407	193.993	194.579	195.158	195.737	196.316	196.895	197.474	198.053	198.632	199.211	199.79	200.365	200.937	201.499	196.332	196.77	196.955	196.955	196.955	196.955
6	188.264	188.964	189.664	190.364	191.064	191.764	192.464	193.159	193.852	194.545	195.238	195.931	196.621	197.307	197.993	198.679	199.358	200.037	200.716	201.395	202.074	198.053	198.632	199.211	199.79	200.365	200.937	201.499	196.332	196.77	196.955	196.955	196.955	196.955
7	190.864	191.664	192.464	193.264	194.064	194.864	195.664	196.459	197.252	198.045	198.838	199.631	200.421	201.207	201.993	198.679	199.358	200.037	200.716	201.395	202.074	198.053	198.632	199.211	199.79	200.365	200.937	201.499	196.332	196.77	196.955	196.955	196.955	196.955
8	193.464	194.364	195.264	196.164	197.064	197.964	198.864	199.759	200.652	201.545	198.838	199.631	200.421	201.207	201.993	198.679	199.358	200.037	200.716	201.395	202.074	198.053	198.632	199.211	199.79	200.365	200.937	201.499	196.332	196.77	196.955	196.955	196.955	196.955
9	196.064	197.064	198.064	199.064	200.064	201.064	202.064	199.759	200.652	201.545	198.838	199.631	200.421	201.207	201.993	198.679	199.358	200.037	200.716	201.395	202.074	198.053	198.632	199.211	199.79	200.365	200.937	201.499	196.332	196.77	196.955	196.955	196.955	196.955

Starting at 08:00

Hour \ Energy	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
0	172.664	172.764	172.864	172.964	173.064	173.164	173.264	173.355	173.441	173.528	173.614	173.701	173.787	173.874	173.96	174.047	174.133	174.22	174.306	174.393	174.479	174.565	174.652	174.738	174.825	174.911	174.998	175.084	175.171	175.257	175.344	175.43	175.517	175.603
1	175.264	175.464	175.664	175.864	176.064	176.264	176.464	176.659	176.852	177.045	177.238	177.431	177.624	177.817	178.01	178.203	178.393	178.572	178.752	178.931	179.111	179.29	179.47	179.649	179.829	180.005	180.178	180.351	180.524	180.697	180.87	181.043	181.216	181.389
2	177.864	178.164	178.464	178.764	179.064	179.364	179.664	179.959	180.252	180.545	180.838	181.131	181.424	181.717	182.01	182.302	182.578	182.844	183.11	183.376	183.642	183.908	184.174	184.44	184.706	184.969	185.228	185.488	185.747	186.007	186.266	186.526	186.785	187.045
3	180.464	180.864	181.264	181.664	182.064	182.464	182.864	183.259	183.652	184.045	184.438	184.831	185.224	185.617	186.01	186.403	186.789	187.175	187.561	187.945	188.304	188.663	189.022	189.381	189.74	190.096	190.449	190.801	191.154	191.505	191.851	192.197	192.543	192.889
4	183.064	183.564	184.064	184.564	185.064	185.564	186.064	186.559	187.052	187.545	188.038	188.531	189.024	189.517	190.01	190.503	190.989	191.475	191.961	192.447	192.933	193.419	193.905	194.391	194.877	195.359	195.838	196.317	196.796	197.274	197.736	198.175	198.614	199.053
5	185.664	186.264	186.864	187.464	188.064	188.664	189.264	189.859	190.452	191.045	191.638	192.231	192.824	193.417	194.01	194.603	195.189	195.775	196.361	196.947	197.533	198.119	198.705	199.291	199.877	200.459	201.038	201.617	196.796	197.274	197.736	198.175	198.614	199.053
6	188.264	188.964	189.664	190.364	191.064	191.764	192.464	193.159	193.852	194.545	195.238	195.931	196.624	197.317	198.01	198.703	199.389	200.075	200.761	201.447	202.133	198.119	198.705	199.291	199.877	200.459	201.038	201.617	196.796	197.274	197.736	198.175	198.614	199.053
7	190.864	191.664	192.464	193.264	194.064	194.864	195.664	196.459	197.252	198.045	198.838	199.631	200.424	201.217	202.01	198.703	199.389	200.075	200.761	201.447	202.133	198.119	198.705	199.291	199.877	200.459	201.038	201.617	196.796	197.274	197.736	198.175	198.614	199.053
8	193.464	194.364	195.264	196.164	197.064	197.964	198.864	199.759	200.652	201.545	198.838	199.631	200.424	201.217	202.01	198.703	199.389	200.075	200.761	201.447	202.133	198.119	198.705	199.291	199.877	200.459	201.038	201.617	196.796	197.274	197.736	198.175	198.614	199.053
9	196.064	197.064	198.064	199.064	200.055	201.042	202.028	199.759	200.652	201.545	198.838	199.631	200.424	201.217	202.01	198.703	199.389	200.075	200.761	201.447	202.133	198.119	198.705	199.291	199.877	200.459	201.038	201.617	196.796	197.274	197.736	198.175	198.614	199.053

Starting at 09:00 : Winning Sweep

Hour \ Energy	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
0	172.664	172.764	172.864	172.964	173.064	173.164	173.264	173.364	173.464	173.564	173.664	173.764	173.864	173.964	174.064	174.164	174.264	174.364	174.464	174.564	174.664	174.764	174.864	174.964	175.064	175.157	175.244	175.33	175.417	175.503	175.59	175.676	175.763	175.849
1	175.264	175.464	175.664	175.864	176.064	176.264	176.464	176.664	176.864	177.064	177.264	177.464	177.664	177.864	178.064	178.263	178.449	178.636	178.822	179.009	179.195	179.382	179.568	179.755	179.941	180.121	180.294	180.467	180.64	180.813	180.986	181.159	181.332	181.505
2	177.864	178.164	178.464	178.764	179.064	179.364	179.664	179.964	180.264	180.564	180.864	181.164	181.464	181.764	182.064	182.363	182.656	182.949	183.242	183.535	183.828	184.121	184.414	184.696	184.975	185.248	185.514	185.78	186.046	186.311	186.571	186.83	187.09	187.349
3	180.464	180.864	181.264	181.664	182.064	182.464	182.864	183.264	183.664	184.064	184.464	184.864	185.264	185.664	186.064	186.463	186.856	187.249	187.642	188.035	188.428	188.821	189.214	189.607	190	190.39	190.776	191.162	191.548	191.933	192.312	192.691	193.07	193.449
4	183.064	183.564	184.064	184.564	185.064	185.564	186.064	186.564	187.064	187.564	188.064	188.564	189.064	189.564	190.064	190.563	191.056	191.549	192.042	192.535	193.028	193.521	194.014	194.507	195	195.49	195.976	196.462	196.948	197.433	197.912	198.391	198.87	199.349
5	185.664	186.264	186.864	187.464	188.064	188.664	189.264	189.864	190.464	191.064	191.664	192.264	192.864	193.464	194.064	194.663	195.256	195.849	196.442	197.035	197.628	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
6	188.264	188.964	189.664	190.364	191.064	191.764	192.464	193.164	193.864	194.564	195.264	195.964	196.664	197.364	198.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
7	190.864	191.664	192.464	193.264	194.064	194.864	195.664	196.464	197.264	198.064	198.864	199.664	200.464	201.264	202.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
8	193.464	194.364	195.264	196.164	197.055	197.942	198.828	199.715	200.601	201.488	198.864	199.664	200.464	201.264	202.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
9	194.078	194.978	195.878	196.778	197.617	198.417	199.217	199.715	200.601	201.488	198.864	199.664	200.464	201.264	202.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349

Starting at 10:00

Hour \ Energy	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
0	172.664	172.764	172.864	172.964	173.064	173.164	173.264	173.364	173.464	173.564	173.664	173.764	173.864	173.964	174.064	174.164	174.264	174.364	174.464	174.564	174.664	174.764	174.864	174.964	175.064	175.157	175.244	175.33	175.417	175.503	175.59	175.676	175.763	175.849
1	175.264	175.464	175.664	175.864	176.064	176.264	176.464	176.664	176.864	177.064	177.264	177.464	177.664	177.864	178.064	178.263	178.449	178.636	178.822	179.009	179.195	179.382	179.568	179.755	179.941	180.121	180.294	180.467	180.64	180.813	180.986	181.159	181.332	181.505
2	177.864	178.164	178.464	178.764	179.064	179.364	179.664	179.964	180.264	180.564	180.864	181.164	181.464	181.764	182.064	182.363	182.656	182.949	183.242	183.535	183.828	184.121	184.414	184.696	184.975	185.248	185.514	185.78	186.046	186.311	186.571	186.83	187.09	187.349
3	180.464	180.864	181.264	181.664	182.064	182.464	182.864	183.264	183.664	184.064	184.464	184.864	185.264	185.664	186.064	186.463	186.856	187.249	187.642	188.035	188.428	188.821	189.214	189.607	190	190.39	190.776	191.162	191.548	191.933	192.312	192.691	193.07	193.449
4	183.064	183.564	184.064	184.564	185.064	185.564	186.064	186.564	187.064	187.564	188.064	188.564	189.064	189.564	190.064	190.563	191.056	191.549	192.042	192.535	193.028	193.521	194.014	194.507	195	195.49	195.976	196.462	196.948	197.433	197.912	198.391	198.87	199.349
5	185.664	186.264	186.864	187.464	188.064	188.664	189.264	189.864	190.464	191.064	191.664	192.264	192.864	193.464	194.064	194.663	195.256	195.849	196.442	197.035	197.628	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
6	188.264	188.964	189.664	190.364	191.064	191.764	192.464	193.164	193.864	194.564	195.264	195.964	196.664	197.364	198.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
7	190.864	191.664	192.464	193.264	194.064	194.864	195.664	196.464	197.264	198.064	198.864	199.664	200.464	201.264	202.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
8	193.464	194.364	195.264	196.164	197.055	197.942	198.828	199.715	200.601	201.488	198.864	199.664	200.464	201.264	202.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349
9	194.078	194.978	195.878	196.778	197.617	198.417	199.217	199.715	200.601	201.488	198.864	199.664	200.464	201.264	202.064	198.763	199.456	200.149	200.842	201.535	202.228	198.221	198.814	199.407	200	200.59	201.176	201.762	196.948	197.433	197.912	198.391	198.87	199.349

Hour \ Energy	4.4	4.41	4.42	4.43	4.44	4.45	4.46	4.47	4.48	4.49	4.5	4.51	4.52	4.53	4.54	4.55	4.56	4.57	4.58	4.59	4.6	4.61	4.62	4.63	4.64	4.65	4.66	4.67	4.68	4.69	4.7
4	192.042	192.091	192.141	192.19	192.239	192.289	192.338	192.387	192.437	192.486	192.535	192.584	192.634	192.683	192.732	192.782	192.831	192.88	192.93	192.979	193.028	193.077	193.127	193.176	193.225	193.275	193.324	193.373	193.423	193.472	193.521
5	196.442	196.501	196.561	196.62	196.679	196.739	196.798	196.857	196.917	196.976	197.035	197.094	197.154	197.213	197.272	197.332	197.391	197.45	197.51	197.569	197.628	197.687	197.747	197.806	197.865	197.925	197.984	198.043	198.103	198.162	198.221
6	200.842	200.911	200.981	201.05	201.119	201.189	201.258	201.327	201.397	201.466	201.535	201.604	201.674	201.743	201.812	201.882	201.951	202.02	202.09	202.159	202.228	202.297	197.747	197.806	197.865	197.925	197.984	198.043	198.103	198.162	198.221
7	200.842	200.911	200.981	201.05	201.119	201.189	201.258	201.327	201.397	201.466	201.535	201.604	201.674	201.743	201.812	201.882	201.951	202.02	202.09	202.159	202.228	202.297	197.747	197.806	197.865	197.925	197.984	198.043	198.103	198.162	198.221

Max Energy	202.297
Power	4.61 MW
Hours	6

Start at 09:00 and run for 6 hours

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 for i 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 - 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 - 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-electrical-lines/#:~:text=High%20voltage%20transmission%20lines%20deliver,exceeds%20supply%2C%20a%20blackout%20occurs.