Mechanical Mass-Energy Storage Systems: Making Clean, Renewable Energy Work

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Abstract

We are facing a major energy crisis today. Our current electrical energy system is dependent on methods that are harmful to the environment, producing greenhouse gasses that are a major contributor to climate change. One solution to this is the implementation of clean, renewable energy sources such as solar and wind, but these sources lack consistency and predictability. We propose using mechanical mass-energy storage systems to make them viable. Mechanical mass-energy storage would allow for clean, renewable energy to be produced and stored at optimal times and then be dispatched when needed. We developed software to simulate energy production, consumption, and storage to determine if mechanical mass-energy storage can maintain a city's energy demand over a day. Multiple trials show that we were able to meet a city's energy demand, but it would require much more infrastructure than a city is accustomed to.

1 Introduction

1.1 The Core Problem

The main cause of climate change is a natural phenomenon known as the greenhouse effect. The planetary consequence of the greenhouse effect is that when more gases, such as carbon dioxide and methane, are in the atmosphere, the planet will trap more heat from the Sun.

There are many things that human society does that add greenhouse gases to Earth's atmosphere and thus contribute to climate change. We are targeting just one of those things, and that is the burning of fossil fuels for electricity. For reference, in 2016 about 65% of electricity generated in the United States came from burning fossil fuels [1]. This is problematic because burning these fossil fuels releases greenhouse gases into the atmosphere, which in turn warms the planet.

The goal that we, and many others, want to attain is to have an electrical energy system that is both *clean* and *renewable*. The word "clean" refers to there being net *zero* greenhouse gas emissions, and the word "renewable" refers to the idea that the source is not able to be depleted (at least while the Sun still shines). There are a handful of tools we can use to achieve this goal and thus solve the problem of using unclean or non-renewable energy sources to generate electricity.

1.2 Non-Solutions

There are a few things that we are not considering as long-term solutions even though they may have a lot of promise or short-term benefits. Documenting these things and why we are not considering them is helpful in the understanding of the problem and how we came to our proposed solution.

One tool that may be very helpful in minimizing carbon emissions quickly is nuclear power. Nuclear power is technically clean by our definition, as it does not have long-term greenhouse gas emissions [2]. However since it results in radioactive waste, it does not fit a more natural definition of the word clean. Regardless that is not why we are disqualifying it; we are dismissing it because it is debatable as to whether it is renewable or not. Some argue that it is not renewable because uranium and other elements that could theoretically be used for fission are finite while others argue that it could theoretically be just as renewable as the Sun [3]. Since nuclear power is so controversial, we decided to exclude it in our proposed solution. As a consequence of excluding nuclear power, we make our problem significantly harder to solve because nuclear power is responsible for 20% of electricity generation in the United States, according to 2016 numbers [1].

Another tool not included in our solution is biomass burning. Biomass energy involves converting material derived from plants and animals into electricity by burning it in a similar way we burn coal or natural gas [1]. This energy source is unsurprisingly renewable because life is renewable. The problem with biomass is that it is controversial as to whether it should be considered as clean or not. Some claim that it is not clean because burning it obviously produces carbon dioxide. On the other hand, it is argued that it is clean because by growing the fuel in the first-place carbon dioxide is being pulled out of the air; therefore, assuming perfect efficiency, the cycle has net zero emissions [4]. Again due to controversy we are excluding it as an energy source in our proposed solution. This only slightly hardens the problem, as biomass accounted for just 2% of United States electricity generation in 2016 [1].

By excluding nuclear energy, biomass, and of course fossil fuels in our solution, we are eliminating 87% of the total electricity generated. Or in other words, the energy sources we are considering only made up 13% of the United States electricity generation in 2016 [1]. Due to this huge discrepancy, our solution is rather cumbersome.

1.3 A Solution

The solution we are exploring is to build an electrical energy system using only sources that are not disqualified in the sections above. The energy sources that are currently in our vision are wind power, photovoltaic solar power, concentrated solar-thermal power, hydroelectric power, tidal power, and geothermal power. While no energy source is environmentally perfect, we are considering all these sources to be both clean and renewable. However, simply having a lot of devices to harness these energy sources will not work; we must dig into why these energy sources are incompatible with our electrical energy system.

Our electrical energy system requires a constant, exact flow of energy to exactly meet the electricity demand, but clean, renewable energy sources lack the consistency and predictability in energy output to meet that requirement [2]. For example, solar power is only available during the day, and when it is available, it is hit or miss; some days are cloudy, and some days are sunny. The same is true for wind power; wind speed is ever-changing. This unreliability will simply not work for our electricity needs. So the question is, how do we make these clean, renewable energy systems reliably work with our electrical energy system?

One solution to the inconsistency of these energy sources is the implementation of mass-energy storage systems; such systems would allow clean, renewable energy to be produced and stored at optimal times and then be used consistently throughout time. It should be noted that not all mass-energy storage systems are created equally. Our goal is to design a storage system that is both able to accommodate our electrical energy system and be as environmentally friendly as possible. For these reasons and other reasons, we are excluding certain types of storage devices.

We are not considering any storage device that stores energy chemically. The reason being that many chemical batteries have other environmental concerns, namely the concern of toxic waste [5]. To be clear, we do believe chemical batteries have their place in the energy system as a whole but just not in the scope of the electrical energy system.

We are focusing on mechanical mass-energy storage systems for supplementing clean, renewable energy in the electrical grid. Mechanical mass-energy storage systems have a high efficiency and do not cause excessive hazardous waste [2]. In fact, our current electrical energy system already uses some mechanical storage systems reliably. The big application of these systems are as part of hydroelectric dams [2]. When a hydroelectric dam produces more power than the grid needs, it can use that extra electricity to power pumps to transport water back upstream, which effectively stores the energy produced from the water falling; this mechanism is known as *pumped-storage* [2]. One other current application of mechanical storage is using *flywheels* for "balancing momentary mismatches between power being generated and power being used [6]." We think these mechanical mass-energy storage systems show a lot of promise, and that is why we want to explore them.

Our solution is to design an electrical energy system that uses only clean, renewable energy sources. To address imbalances between energy produced by these sources and electrical energy demand, we are designing a mechanical mass-energy storage system to store previously produced energy. To dynamically test our designs, we are developing a software simulation to evaluate the viability of our solution.

2 The Software

2.1 Overview

We are developing software to simulate real-time electricity demand and real-time energy production from clean, renewable energy sources. Additionally, the software has a virtual mechanical mass-energy storage system that addresses the imbalances between energy production and consumption. We of course do not have the tools, resources, or level of expertise to develop a comprehensive software simulation; therefore, we had to opt to solve a smaller iteration of the problem and simplify the components of our software.

2.2 Repackaging the Problem

We chose to change the scope of our solution and solve a simpler problem. Rather than constructing a solution for the entire electrical energy system, we built a solution just on the scale of a single city's electricity demand; our city of choice is Des Moines, Iowa. By doing this repackaging, our clean, renewable energy sources only have to be built to power the Greater Des Moines Area, and our virtual mechanical mass-energy storage system only has to supplement power on that scale. Also by using a single city, the problem is easier to conceptualize, and the solution is easier to package.

2.3 The Components and their Corresponding Simplifications

The simplification of software components comes from the fact that we do not have all the disciplinary backgrounds necessary on our team nor the academic time to develop all-encompassing software. These simplifications are detailed below.

2.3.1 Simulating Real-Time Electricity Demand for the Greater Des Moines Area

The electrical energy system does not operate in the scope of individual cities but rather in the scope of continent-wide energy grids. This is problematic because there is no public data available for the electrical energy consumption for just the Greater Des Moines Area, let alone real-time data. This means that we have to calculate approximations for energy consumption in some way.

In a previous version of the software we used a bottom-up calculation for approximating energy consumption. This is done by summing the total number of houses, small businesses, companies, etc. multiplied by their average corresponding energy uses. We ended up not liking this approach because it was too hard to discover all sources for consumption and how much each of those sources uses. How much energy does this data center use? How much energy does ethanol production use? How much energy does that skyscraper use? How does consumption change throughout seasons? These questions exemplify the difficulty of calculating energy consumption this way.

What we do now is calculate in a top-down fashion using source data from the Energy Information Administration. As previously stated, electricity works in continent-wide energy grids, so we figured to find the grid Des Moines is a part of and take a percentage of that grids energy demand and call that Des Moines's electrical energy consumption.

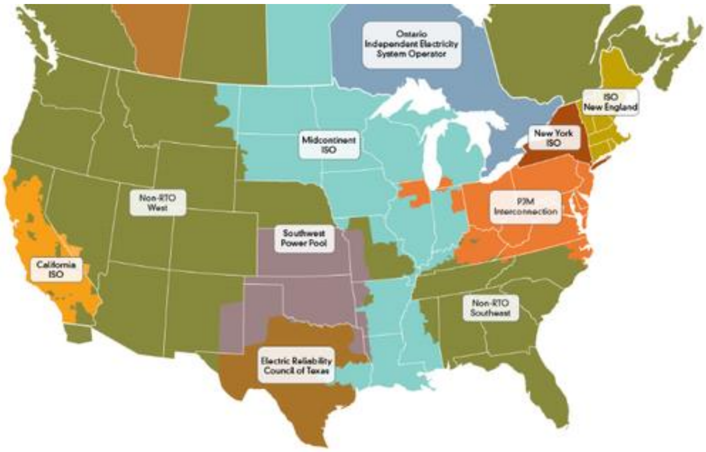

Figure 1: Energy grids in and around the United States. [7]

As seen in figure 1, Des Moines is within the Midcontinent Independent System Operator (MISO). On the Energy Information Administration's website, they have live and historical hourly energy consumption data available by energy grid; the MISO is one of those energy grids. From that data, we are able to derive the data seen in table 1 using a SQL database.

	HOUR	AVG	MIN	MAX	RANGE
1	00:00:00.0000000	76204	70417	79592	9175
2	01:00:00.0000000	73560	67747	78215	10468
3	02:00:00.0000000	72473	66559	77468	10909
4	03:00:00.0000000	72011	65757	77321	11564
5	04:00:00.0000000	72292	65462	78225	12763
6	05:00:00.0000000	73509	65945	80930	14985
7	06:00:00.0000000	77005	66809	86188	19379
8	07:00:00.0000000	82213	68898	92610	23712
9	08:00:00.0000000	84158	70831	93826	22995
10	09:00:00.0000000	84151	72723	92169	19446
11	10:00:00.0000000	83659	73913	90065	16152
12	11:00:00.0000000	82668	73998	87590	13592
13	12:00:00.0000000	81449	74025	85429	11404
14	13:00:00.0000000	80363	74185	83846	9661
15	14:00:00.0000000	79576	74097	82446	8349
16	15:00:00.0000000	78846	74254	81292	7038
17	16:00:00.0000000	78672	74711	81324	6613
18	17:00:00.0000000	79789	76170	82983	6813
19	18:00:00.0000000	82718	78654	86830	8176
20	19:00:00.0000000	84818	80617	89956	9339
21	20:00:00.0000000	84219	79616	89632	10016
22	21:00:00.0000000	82853	77765	88157	10392
23	22:00:00.0000000	80452	75497	85098	9601
24	23:00:00.0000000	77566	73222	81471	8249

Table 1: Hourly energy consumption for the MISO derived from source data located on the Energy Information Administration's Website [8]. Source data is pulled from between February 1st, 2018 and February 9th, 2018. Unit of energy is Megawatt Hours.

The "MIN" column in table 1 gives us a *base load* of energy that will be required for the corresponding hour, the "MAX" column gives us the highest *peak load* experienced for the corresponding hour, and the "RANGE" column gives us the amount of positive deviation from the base load that can be experienced in the total energy required for the corresponding hour. See figure 2 for a graphical representation of this data.

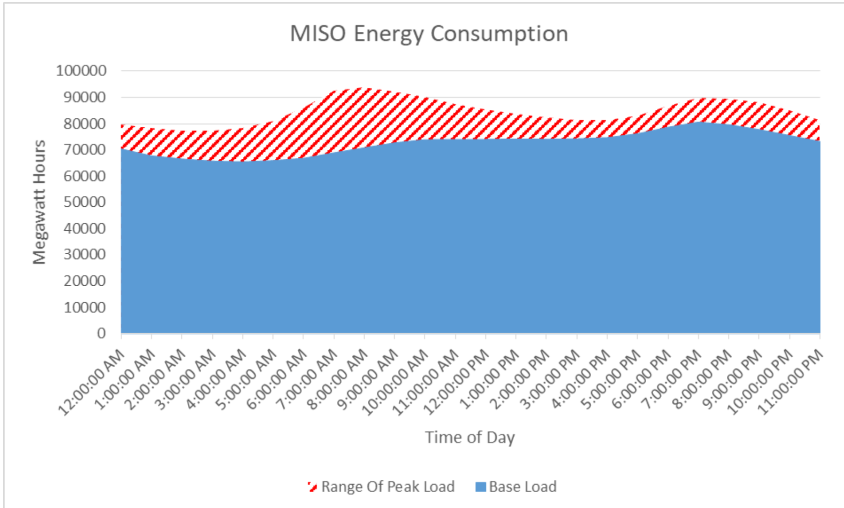

Figure 2: Graph of MISO energy consumption over a day derived from data available between February 1st, 2018 and February 9th, 2018. Blue area is the base load. Red area is the range of the peak load. [8]

The data above is for the MISO, but we want information for just Des Moines to use in our simulation. The best way we currently have of getting this data is by taking the population of the Greater Des Moines Area, dividing it by the population that the MISO serves, and then multiplying our figures by this decimal. We are aware that this is crude because different populations of the MISO may use different amounts of electricity based on the local industry, local businesses, temperature, etc. Still, we like this method better because it gives real hourly data and can be adjusted to get simulation data for different times of the year.

2.3.2 Simulating Real-Time Energy Produced from Clean, Renewable Energy Sources

Currently we only have two clean, renewable energy sources implemented in our software; they are wind power and photovoltaic solar power. Both sources are significantly simplified for various reasons. One mutual reason is because they are both dependent on the weather and simulating weather patterns accurately is something we have yet to look into.

2.3.3 Simulating Real-Time Energy Produced from Wind Power

There are some key ideas that go into our energy output calculation for wind turbines. One idea is that wind turbine manufacturers state the *max capacity* of their turbines. The max capacity is the most amount of watts a turbine can produce at a given time [9]. For example if a turbine has a max capacity of three megawatts, then that means the most energy that the wind turbine can produce is three mega joules every second; of course, this is only possible if the wind is blowing at an optimal speed.

Unfortunately, most of the time the wind is not at optimal speed. To express this, there is a number called the *capacity factor*. The capacity factor is the percentage of max capacity that is produced over a time frame; this percentage will change based on how windy a location is [9]. For instance if we have a three megawatt wind turbine and the capacity factor is 30%, the effective wattage produced would be 0.9 megawatts.

For the simulation, we set up a wind turbine to follow the capacity factor calculation (max capacity * capacity factor * time frame). However since we are trying to simulate real-time energy production we cannot just use a fixed capacity factor because different times of the day will have different wind speeds and thus different capacity factors. To solve this problem, we developed a tier system to represent capacity factors at different hours of the day; a generic example of our tier system and their corresponding capacity factors can be seen in table 2.

Tier	Average Capacity Factor
Tier 1	0%
Tier 2	5%
Tier 3	25%
Tier 4	50%
Tier 5	75%

Table 2: Wind energy tiers to accommodate an average daily capacity factor of 25%.

We map the capacity factors seen in table 2 to correspond with certain hours of the day. We plot the capacity factors so that the average capacity factor for the whole day is equal to a capacity factor between 25 and 40 percent; the exact average capacity factor for a single day will depend on what month it is and the location of the turbine. See figure 3 for a generic plot of the tiers by hour.

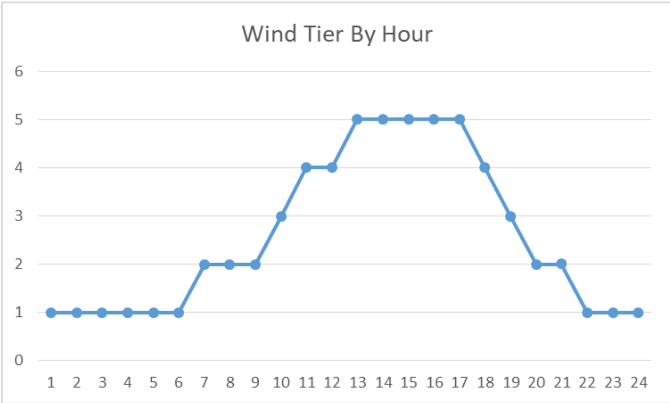

Figure 3: Generic wind tiers plotted by hour. This plot does not consider North-South wind movement.

Iowa is an ideal place for wind energy production, as it had an average capacity factor of 34.3% in 2012 [10]. Therefore, we base our tier system to have an average daily capacity factor of 33%. Our tiers for Iowa wind turbines can be seen in table 3.

Tier	Average Capacity Factor
Tier 1	4%
Tier 2	13%
Tier 3	33%
Tier 4	58%
Tier 5	83%

Table 3: Wind tiers adjusted to represent wind speed in Iowa.

Lastly, we include random deviations in our capacity factors to simulate weather. This is a simple way to represent the fact that wind speeds vary day by day, hour by hour, and second by second.

This tier system is not perfect, but it is an effective way to simplify weather patterns. Furthermore, it allows us to easily modify our simulation to use different tier mappings based on the time of year and location of each wind farm.

2.3.4 Simulating Real-Time Energy Produced from Photovoltaic Solar Power

Daily photovoltaic solar energy production can be calculated with:

$$E = A \times CE \times SE, \qquad (1)\ [11]$$

where E represents the total energy produced per day in kWh, A represents the area of solar panels in m^2, CE represents the conversion efficiency as a percent of the sun's energy that is able to be converted to electricity, and SE represents the available solar energy in kWh beamed onto a m^2 of solar panel per day. A typical CE is 20 percent [11]. SE is based on the location of the land, the month of the year, the weather that day, and the angle of the solar panel.

To get the average daily available solar energy for land around Des Moines, we used NASA's Atmospheric Science Data Center. This data center allows one to enter in coordinates and other parameters, and it will spit back information specific to those coordinates. The key information we used from this data center is shown in table 4.

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m^2/day)													
Lat 41.6 Lon - 93.609	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
OPT	3.58	3.75	4.40	4.84	5.47	6.13	6.08	5.55	5.15	4.47	3.47	3.29	4.69
OPT ANG	63.0	53.0	40.0	24.0	12.0	4.00	9.00	19.0	36.0	51.0	60.0	66.0	36.3

Table 4: Solar energy available per square meter per day for land around Des Moines. [12]

From table 4 we get the average daily available solar energy per square meter of optimally angled, stationary, equator-facing solar panels. Then to simulate daily weather changes, we randomly deviate this number. Lastly, we plug that number into equation 1 to get the actual energy output for a day.

Since we want real-time data for our simulation, we must break down our daily energy produced into hourly segments because not all hours will produce the same amount of energy. To do this, we use another tier system. See table 5 for our tier levels and their corresponding values. Then see figure 4 to observe how these tiers are plotted throughout the time of day.

Tier	Percent of Daily Energy
1	0%
2	1%
3	8%
4	12%
5	16%

Table 5: Generic solar energy tiers for equator-facing solar panels.

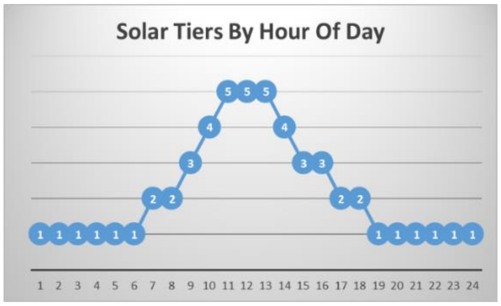

Figure 4: Generic solar tiers throughout time of day.

2.3.5 Implementing a Virtual Mechanical Mass-Energy Storage System

We have two types of mechanical storage devices in our mass-energy storage system. One is the Heindl Battery, which is used to supplement base load energy demands. The other is a flywheel, which is used to supplement variable peak load energy demands. Review figure 2 to see the base load and peak load for the MISO.

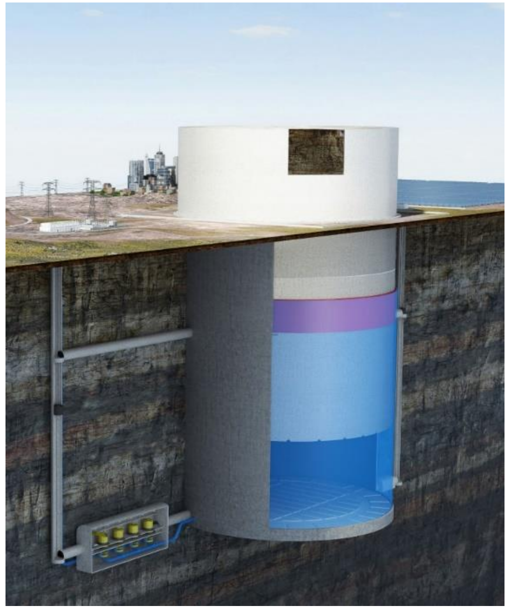

Figure 5: Mechanical energy storage system capable of storing large amounts of energy through hydraulic potential energy. Developed by Heindl Energy. [13]

The Heindl Battery is shown above in figure 5. It stores energy using hydraulic potential energy on a large scale. The idea of the Heindl Battery is to use pumps to lift a large mass to store gravitational potential energy; the mass is mostly composed of the pre-existing land. When there is excess energy created by our energy sources, the Heindl system uses that energy to power electric pumps to move large amounts of water from a reservoir to beneath the mass. The mass can then be released to move the water through a turbine back to the reservoir [13].

A Heindl Battery's energy storage can be calculated with:

$$E = (2\rho_r - 3/2\rho_w)\pi g r^3 h, \qquad (2)\ [13]$$

where E represents the energy storage in joules, ρ_r and ρ_w represents the density of the mass and water in kg/m^3, g represents the acceleration due to gravity in m/s^2, r represents the radius of the mass in meters, and h represents the lift height in meters. It is assumed that the maximum lift height is equal to the radius to ensure hydrostatic stability [13]. Thus equation 2 tells us that the maximum energy capacity increases by a power of four with the radius. This means that if the radius of a Heindl Battery increases from 100m to 125m, the maximum energy capacity will increase from 3 GWh to 8 GWh [13].

Even though a single, large Heindl Battery could theoretically store enough energy for the base load energy demands, the fill time would be an issue. Our simulation assumes that the Heindl Battery cannot release energy while it is charging. Due to the lack of consistency from our energy sources, the Heindl Battery must always be able to handle the base load. Having multiple Heindl Batteries would allow us to deal with the base load even if one battery is empty or charging. To maintain consistency, these batteries were designed so that if one depletes and must charge, another will stop charging to cover the demand.

Maintaining enough energy to deal with the base load was important to keep in mind when implementing the Heindl Batteries. If the batteries release too much energy, they will drain leading to energy shortages. But on the other hand if they release too little, the base load will not be covered, and our *highly variable storage* will deplete. The Heindl Batteries were designed to have a maximum output rate to achieve this balance. The maximum output rate was calculated using a flat percentage of the base load. Some of the base load is covered by the energy production, so this ensures that energy demands are met.

A flywheel stores energy as rotational kinetic energy, which is a mechanical process; however, a large array of flywheels is necessary in order to handle mass-energy storage. We are using these flywheels to hold highly variable storage, which is storage that is able to provide within a fraction of a second. We assume that a flywheel array will be able to effectively address the volatile nature of peak load energy demands since they are already used in electrical grids for both dealing with the inconsistency of renewables and for grid balancing [6].

We use standard rotational physics equations to calculate energy storage within a flywheel. We assume all flywheels are hollow, having all their mass on the outer edge and currently have carbon fiber, steel, titanium, and aluminum available for flywheel mass materials. Additionally, we have both mechanical and magnetic bearings as options; the type of bearing will affect how much energy is lost due to heat and friction. We allow a flywheel to spin just up to the speed that the tensile strength of the given material allows for and thus assume the flywheel's motor can handle that speed; this max speed is the only limitation to how much energy a flywheel of a given mass and radius can hold. Lastly, we assume a flywheel can charge and discharge at any rate. We are aware that there are some technical limitations that we are not addressing at this time, but we had to assume an individual flywheel was entirely volatile in order to make it exactly follow consumption. In reality, there would likely have to be a tightly knitted system of flywheels in order to handle exact volatility.

2.4 System Explanation and Diagram

The driver of our system keeps track of the time of day and how fast the simulation iterates through a day. At each hour of the day, the driver will gather the hourly energy consumption and production data. The driver also has the ability to gather data on intervals smaller than an hour as long as the interval evenly goes into an hour. For example, the driver can pull data in four 15 minute segments or 3600 one second segments as opposed to pulling the whole hour at once. After the driver pulls the energy production and consumption for a time of day, it routes those figures to the Energy Commander. The Energy Commander will determine the difference between the energy produced and consumed and act accordingly. If the energy produced is larger than the energy consumed, the amount needed from the energy produced will be sent to the city to fulfill the demand,

and the extra energy produced will be sent to storage. If the energy consumed is greater than the energy produced, all of the energy produced will be sent to fulfill a portion of the city's demand, and the rest of the city's demand will be fulfilled by energy out of storage.

When surplus energy gets to storage, the storage system will check to see if the flywheels are holding a minimum threshold of energy; if they are not, they will be filled to the minimum threshold. Then the remaining surplus will be used to charge Heindl Batteries.

When energy is needed from storage, the storage system will first look at the Heindl Batteries. Since the Heindl Batteries are geared to only supplement the base load, they will only fulfill a certain amount of the energy needed. The remaining energy needed will be part of the peak load and thus have to be fulfilled by the array of flywheels. If the energy needed is not able to be fulfilled, either because storage is dry or because there is not enough energy in the flywheels to address the peak load, a power outage will be documented along with the amount of energy the system was short by.

See figure 6 for a visual representation of our system diagram and explanation.

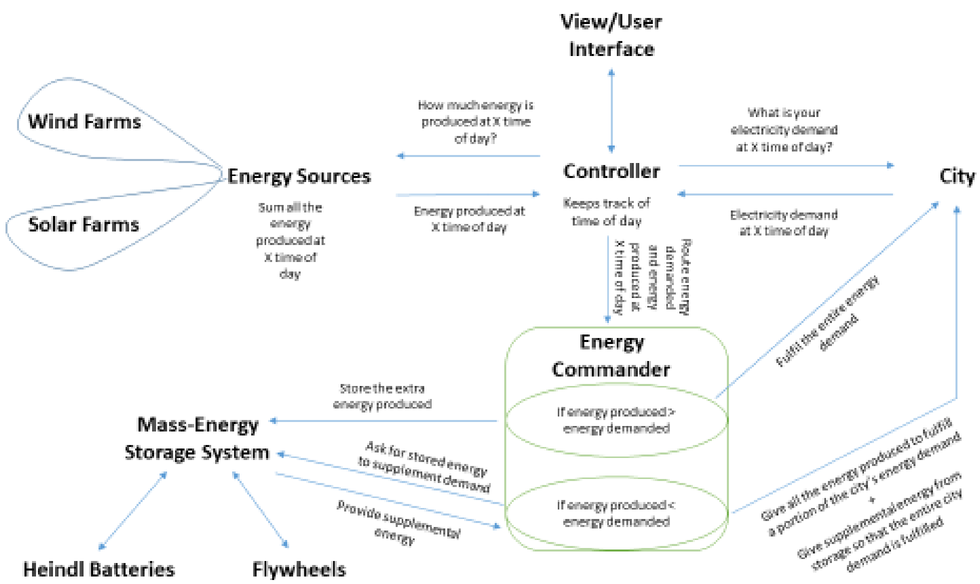

Figure 6: System diagram for our simulation.

3 Results

3.1 The Goal

We are trying to find a set of wind turbines, solar panels, and storage devices that can reliably supplement the city's energy demand for one day. A successful result will be a set that can, over multiple trials, address all of the city's demands with no power outages and end the day with at least as much stored energy as it started with. Due to the nature of the simulation, each trial will have unpredictable variations of energy produced and energy demanded; some trials will favor the set, and some trials will not. A successful set will be able to pass at least 80% of its trials.

3.2 Parameters

As discussed above, energy production and consumption will vary by time of year. We will be using the MISO's real-time consumption data from the first ten days of March 2018. Then we will take Des Moines's estimated percentage of that consumption and use it to approximate the city's consumption data. Our solar farms will deviate production using the average daily available solar energy for March in the Des Moines area, see table 4 for reference. Our wind turbines will deviate from an average daily capacity factor of 35%, which is reasonable for the month of March in Iowa [10], [14]. We will run ten trials for every set of wind turbines, solar panels, and storage devices.

3.3 Tested Sets

Set	Number Of Turbines	Area Of Solar Panel	Number Of Flywheels	Average Number Of Shortages	Average Shortage Amount In MWh	Pass Rate
1	800	6,500,000	3750	46.7	355.406	0%
2	1000	6,500,000	3750	0	0.000	100%
3	800	8,125,000	3750	47.4	352.581	0%
4	800	6,500,000	4688	47.1	337.672	0%
5	926	3,500,000	4300	2.4	11.751	40%
6	950	3,500,000	4300	0.2	0.707	90%

Table 6: Simulation results. Each turbine has a 3MW max capacity. The conversion efficiency for solar energy is 20%. The flywheels are made of carbon fiber, have a magnetic bearing, have a radius of 0.5m, and have a mass of 400kg.

3.4 Analysis

The goal of the different sets was to find which parameters affect the pass rate most significantly and to find a passing set with minimal storage and production. We started with a baseline set that was bound to fail. Then we individually increased each parameter by 25% for the next three sets. Increasing the amount of wind turbines allowed the simulation to pass every time because the extra turbines were able to pick up enough of the peak load during the night, which helped the highly variable storage. Even though the wind is not necessarily strong at night, the small amount of extra production went a long way in terms of aiding the highly variable storage. Increasing the amount of solar panels was not that helpful because it was completely unable to supplement the highly variable storage at night. Increasing the amount of flywheels helped at the end of the day because a lot of highly variable storage could be built up over time, but it failed to supplement the long stretch of day before the wind speed picked up.

Sets 5 and 6 were trial and error runs to find a set with minimal storage and production. Set 5 increased the number of turbines and flywheels to get a 40% passing rate, and set 6 increased the number of turbines a little more to achieve a 90% passing rate. We have yet to configure an optimal set.

4 Future Work

Adding a more diverse selection of clean, renewable energy sources would have the biggest impact in designing a comprehensive energy system. This would both increase the reliability of energy production and reduce the ecological impact of the system. One reason the reliability improves is because different energy sources have different production values based on the time of year.

It would also be valuable to add a more diverse selection of mechanical mass-energy storage devices. For example, the Heindl Battery works well on flat land, but it would not work well on terrain intensive area. Looking into other mechanical storage types will make this methodology more accessible to other regions of the world.

Modifying the software to simulate for different cities would significantly help its applicability. For example, coastal cities would have different electrical energy consumption and need to rely on different energy sources, such as tidal power. Configuring the software to be able to easily add consumption and production data would allow for users to modify it for a more diverse selection of cities.

Lastly reducing the amount of simplifications in the software would improve its accuracy by a large degree. More precise physics models, energy infrastructure implementation, and weather simulation are all things that could improve accuracy.

References

[1] United States Energy Information Administration, "Energy in the United States", Energy Information Administration, Washington, DC, 2017.

[2] P. Singer, R. Singer and R. Warnet, "Sustainable Germany", Simpson College, 2017.

[3] N. Chowdhury, "Is Nuclear Energy Renewable Energy?", *Large.stanford.edu*, 2012. [Online]. Available: http://large.stanford.edu/courses/2012/ph241/chowdhury2/. [Accessed: 09- Mar- 2018].

[4] R. Rehmeier, "Environmental Issues", Simpson College, 2018.

[5] J. Heelan, E. Gratz, Z. Zheng, Q. Wang, M. Chen, D. Apelian and Y. Wang, "Current and Prospective Li-Ion Battery Recycling and Recovery Processes", *JOM*, vol. 68, no. 10, pp. 2632-2638, 2016.

[6] "Applications - Temporal Power", Temporal Power, 2018. [Online]. Available: http://temporalpower.com/what-we-do/applications/. [Accessed: 08- Mar- 2018].

[7] J. Moore, *Energy Grids in the U.S.*. 2013.

[8] United States Energy Information Administration, "U.S. Electric System Operating Data", Energy Information Administration, Washington, DC.

[9] "Output From Industrial Wind Power", *National Wind Watch*. [Online]. Available: https://www.wind-watch.org/faq-output.php. [Accessed: 09- Mar- 2018].

[10] United States Energy Information Administration, "Electric Power Monthly", Energy Information Administration, Washington, DC, 2018.

[11] "NASA Atmospheric Science Data Center: Solar Power Potential According to Location", *The Grid*, 2018. [Online]. Available: https://thegrid.rexel.com/en-us/energy_efficiency/w/solar_renewable_and_energy_efficiency/70/nasa-atmospheric-science-data-center-solar-power-potential-according-to-location. [Accessed: 11- Mar- 2018].

[12] United States National Aeronautics and Space Administration, "NASA Surface meteorology and Solar Energy - Available Tables", Atmospheric Science Data Center, Washington, DC, 2018.

[13] "Technical Concept - Heindl Energy", *Gravity Storage*. [Online]. Available: https://heindl-energy.com/technical-concept/. [Accessed: 11- Mar- 2018].

[14] "U.S. Average Annual Capacity factors by project and State", *windAction*, 2013. [Online]. Available: http://www.windaction.org/posts/37255-u-s-average-annual-capacity-factors-by-project-and-state#.Wqb0wujwbIU. [Accessed: 10- Mar- 2018].