Wind gravity: A novel gravity based energy storage system for wind energy

Technical report
Energy Storage and Transport project
Group 32
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October 23, 2021	Group 32

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Wind gravity

SUMMARY:

The report will focus on the created model of an energy storage, made to store the difference of energy between supply and demand by the usage of gravitational energy. The supply consists of wind turbines not providing a consistent amount of energy and households not using a consistent amount of energy. The idea of the created energy storage will be explained in chapter 2, the model of this system, including the supply and demand, will be explained in chapter 3, chapter 4 and 5 will focus on the experimental set-up and plan, chapter 6 is about the results of the model and experiment, valdidating the model, and chapter 7 is the conclusion and what can be improved for follow-up research.

Contents

1 Introduction

Due to the changing climate the United Nations (UN) came up with an agenda for sustainable Development, the agenda's aim is to transform the world by 2030. Within this report 17 sustainable Development Goals are set. For many of these goals it is important that a more clean kind of energy is being created. However, clean energy is difficult to make sustainable. Because of this it is of importance that a storage system is created to store this energy.

The goal of this project is to come up with an energy storage and transport system. This system will have a certain sustainable supply and a certain demand group. There will be a difference in energy between the supply and demand. The storage system should be able to fill this gap. For this system a mathematical-physical model will be made and this model will be validated by an experiment.

A storage system has been developed that works by the use of storing energy in the form of gravitational energy. For the energy supply wind turbines will be used, because this a clean form of energy. This will be explained more extensively in the report.

2 The energy storage and transport system

As stated in the introduction, the system is going to be created by making use of wind turbines as supply side. In total 60 windmills are going to be used, with each windmill having a 2 MW capacity. For the demand side 125000 standard dutch households are going to be used, which, on average, have an equal energy demand as the windmills supply.

The way the system will store the oversupplied energy, is by pulling train carts over rails up a mountain. This is done by making use of chains and a motor. This way the energy gets stored as gravitational energy. For this a mountain with a not to steep incline needs to be used. For this reason a mountain in Switzerland would be used. The particular mountain is 2 km high, which it reaches over 20 km in length. When the supply is not able to keep up with the demand, the train carts will be lowered down the mountain. By making use of a regenerative motor the lowering of the carts will generate energy to supply to the households.

To be able to store the energy in the system if there is a lot of oversupply, the train carts will be able to be stored at the top of the mountain. Doing this will make it possible to store a lot more energy. Every train cart will be able to theoretically store 400 KWh of energy per kilometer of height difference. With more carts it will be possible to store more energy in the system, this shows that the storage system is changeable and therefore can be scaled up if necessary. However for scaling the system up more space needs to be created at the top of the mountain because the carts have to be able to be stored somewhere. The amount of carts that would be needed for 125000 households to store energy needed for 24 hours would come to 1500 carts. These carts are needed to be able to supply energy the whole year round. But also to be able to keep supplying energy in case of to low or too high wind speeds, in both circumstances no energy will be generated and the storage will be unloaded quite a lot. To make sure that the system can output the energy that is needed, two factors are going to be used, the first one being the speed with which the carts go down the slope. This is because the faster the carts are moving the quicker the gravitational energy releases and is turned into electricity. The second way to regulate the output is by adding carts to the tracks going down, this will add more weight and therefor more energy will be generated per second if that is needed.

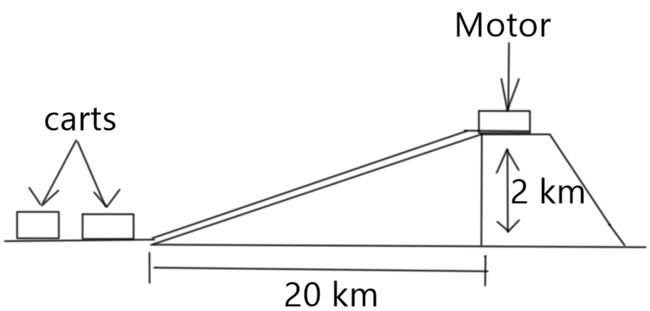


Figure 1: schematic drawing of the storage system

3 The model

3.1 Design/validation strategy of model

To validate the model the results need to be carefully designed/analysed and the model might need to be tweaked afterwards. Particular attention should be paid to the physical correctness of the model (energy conservation, no weird behavior, the results need to make sense, suitable time-steps, etc), the decisions of the controller should be carefully inspected, the boundary conditions (amount of carts, maximum speed, maximum acceleration/force, energy neutral in the long term, etc) should be kept and in general the model should be made professionally (neat readable code, good output, etc).

3.2 Supply and demand

The supply and demand is based on usage data for households by NEDU [4] and the supply side is based on wind speed data by KNMI [2]. This data is imported, then scaled and converted to the actual output of the group of households and the wind farm (with easy adjust-ability). To make the data continuous (since the model should be able to do arbitrary time-steps) interpolation is done. To see more details on the supply and demand can be viewed in appendix B.1.

3.3 Storage

The storage is modeled by a set of train carts (with a certain mass), which are all connected to each other on a straight rail with a certain slope and length. This has the result that the carts on the track can be regarded as one giant cart (which chances in mass, positions and velocity), which makes doing the physics and control easier.

This giant cart experiences gravity, friction (equal to the sum of the friction of the individual carts) and the force from the generator/regenerative braking to make power. This is then modeled using Newtonian physics. These Newtonian forces can be found in appendix B.2.

The force of the generator is set by the controller (and must be a positive number) and relates to the power generated as such

$$P_{storage} = \eta F_G v \tag{1}$$

where $P_{storage}$ is the power (note that a positive power means energy is being stored and a negative power means power is being released), F_G is the force of the generator and η is the efficiency of the generator (in this case is 0.9 when storing [5] and 0.7 when releasing [1]). Finally, the sum of all these forces determines the acceleration of the carts.

On the top and bottom of the track there is a storage for the carts. Going into this storage is simplified by assuming that arriving carts brake (regenerative). Their (or part of their) kinetic energy gets converted into power. When carts are added they are assumed to be "hooked" into the chain of carts and thus the total kinetic energy/momentum gets redistributed across all the carts. The new carts get the same speed as the rest). The kinetic energy of a single cart is

$$E = \frac{1}{2}mv^2 \tag{2}$$

where m is the mass of a cart and v is its velocity, when regenerating an efficiency factor needs to be taken into account. When this equation and conservation of energy is used to calculate how a “hook” of a new cart changes the velocity of the carts it becomes

$$v_{new} = \sqrt{\frac{Nv_{old}^2}{N+1}}\hat{\boldsymbol{v}}_{old} \tag{3}$$

where N is the amount of carts and v_{old} is the previous velocity. It is interesting to note that this immediately (re)sets the velocity to zero if it starts with zero carts.

The system for the storage also needs to be controlled to make sure the amount of power that is put in or pulled out satisfies the differences between supply and demand. For this a controller was made. The details of this controller and the control aspects of the system can be found in appendix B.3.

4 The experimental set-up

To get an understanding of the physical properties of the system, an experiment needs to be conducted. The experiment will give results that can later be used to validate the model. Also, one of the result of the experiment would be getting an efficiency factor, so there is a rough understanding of what the storage system will do. To get an efficiency factor the in- and output have to be measured. The second result will be a better understanding of all components needed to create a gravity based storage system on a large scale.

To conduct the experiment an experimental setup has to be created. The setup should replicate the real system as close as possible, to ensure as little deviation to the scaled up version as possible. Because of this, the setup will look like the following: a model train will be put on a model train track. These train tracks are of type H0. By putting this track on a straight piece of wood and laying it down at an incline, the mountain side is simulated. To pull the train up the track a stepper motor will be used. The reason for using a stepper motor is the accuracy of the motor and its ability to be used as a generator when rotated by and external source. The stepper motor also has the advantage of generating voltage at low RPM. A normal DC motor would need gears to achieve the same output voltage for the same input RPM. This is important, because a measurement is needed when the train is rolling down the incline. To calculate the efficiency factor a couple of strategies need to be used. First of all, the in- and output voltage have to measured. Measuring voltage will be done by using a Multi-meter.

The stepper motor has two coils, coil A and coil B. To measure the total power output of the motor, both coils need to be connected. This can be done using two full bridge rectifiers. These are schematically represented below:

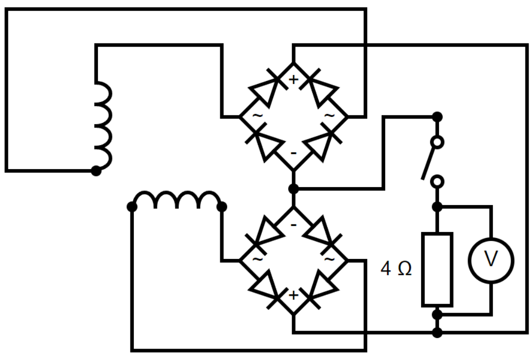


Figure 2: Schematic representation of the full bridge rectifiers

By placing a resistor at the output and measuring the voltage across the resistor, the output power can be calculated using the formula 4:

$$P = \frac{V^2}{R} \tag{4}$$

where P is the power output in Watt, V is the voltage across the resistor in volt and R is the resistance of the resistor in Ohm. By using the in- and output of the system, an efficiency factor can be calculated. However, this efficiency factor can only be used for the total system. The total efficiency can be split up into multiple different factors for pulling up the train carts, and one for the letting down of the carts. For this, the gravitational energy can be calculated. With this a comparison can be made between the amount of energy that was put into the system, and the amount of energy that theoretically needed to be inputted into the system. The same goes for the output. For calculating the gravitational energy formula 5 can be used:

$$U = mgh \tag{5}$$

where U is the gravitational energy in Joule, M is the mass of the train in kg, g is the gravitational constant and h is the height in meter. By using this method it can be seen where most energy will be lost.

Different motors will be used for the experiment than in the real system, meaning that there will be different efficiencies for these motors. By taking this into account, a better estimation of the real storage system can be produced. To subtract the efficiency for the stepper motor in the experiment, the following calculation has to be done:

$$\eta_{without-stepper-motor} = \frac{\eta_{total}}{\eta_{stepper-motor}} \tag{6}$$

Part/Component/Service	**Quantity**	**Supplier**	**Price**
Steppermotor: NEMA 17	1	TinyTronics	€11,00
Bracket voor Stappenmotor	1	TinyTronics	€2,50
Stepper controller: TB6600	1	TinyTronics	€12,99
Arduino: Uno	1	Marktplaats	€10,00
Rails: H0	7	Marktplaats	€3,50
Train cart: PIKO H0	1	Markplaats	€2,00
Wood/building material	1	Praxis	€15,00
3D printing: Pulley	1	Own 3D printer	€2,00
		Total	€58,99

5 The measurement plan

The most important part of the experiment is the setup.To get accurate results the wiring diagram in figure 3 should be used.

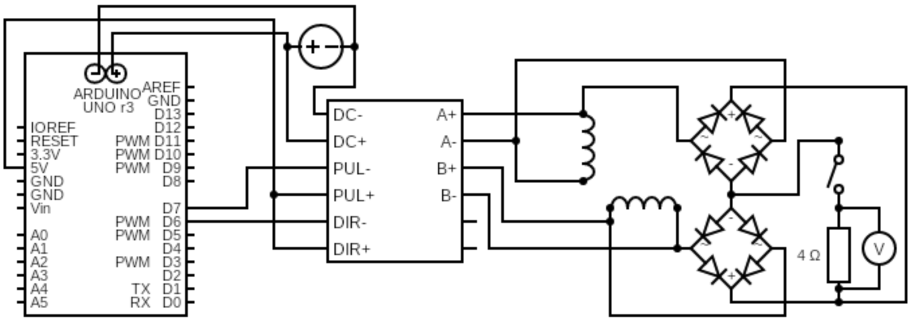


Figure 3: Schematic representation of the full circuit diagram

The power supply for the stepper motor controller should be set to 8v. A plank of wood is needed with a length of at least 130cm. On this plank, 8 pieces of track can be placed and screwed or glued into place. At the top of the plank the stepper motor should be screwed down together with the bracket. Make sure that the output shaft of the stepper motor is at 90 degrees compared to the track and that the centre of the shaft is aligned with the centre of the track. This alignment is important to keep the string from slipping and inducing extra friction. A 3D printed pulley should then be fitted over the shaft. This pulley increases the torque arm of the string, making it easier for the train to rotate the stepper motor. The string can then be tied to the pulley. the other end of the string should be attached to the front of the cart. The point of attachment should be in line with the centre of gravity in order for the cart not to tip when pulled. The 6-pin connector can now be attached to the stepper motor. The plank should be put at an angle such that the force on the string is high enough to turn the stepper motor. If the motor does not turn when releasing the cart, the angle or the weight on the model train should be increased. The angle and weight should be measured to later be used in calculations.
The next step is to upload the code to the Arduino. This code can be found using the in attachment 2. After uploading the code, connect the power supply to the stepper motor controller. Using the power supply and a timer, the power consumption can be measured. Once the train is at the top the power supply should be turned of, which will cause the train to start rolling down the track. The voltage can now be measured across the resistor, as well as the time it takes for the train to roll down.

6 Validation results

6.1 Results of the experiment

From conducting the experiment the following data has been gathered. The power input and output of the storage system, the speed of the carts and the theoretical energy amount of the storage system. In order to compute the input and output of the storage system, the current and voltages during the storing and unloading of the system had to be computed. In order to do this a multi meter was used, this way the amount of energy can be computed.

To make sure that the data that is gathered is accurate and reliable, it would be important to run the experiment multiple times. However due to a malfunction of the stepper motor after the first run, it was not possible to do more runs after this. Resulting in just one data set.

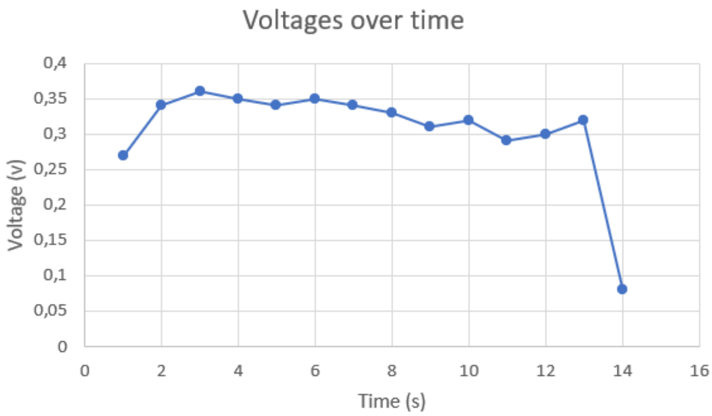


Figure 4: Voltages over time.

With the use of this data the amount of energy that the storage outputs can be calculated, because the current over the system is uniform the amount of energy can be computed. When the carts are going down the slope this is equal to 4.16 J. The last part of the graph is going steep down, this is due to the carts being at the bottom of the slope. To compute the amount of energy that needs to be put into the storage system in order to get the carts to the top, is equal to 55.02 J this is because the current and voltages do not change when the cart is pulled up.

This means that in the experiment the efficiency is less than 10 percent.

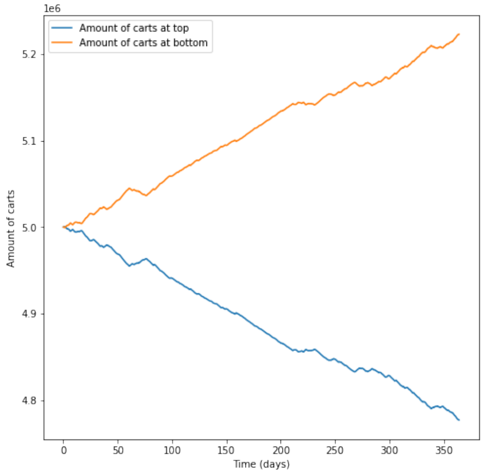
6.2 Validation of the model

In order to validate the model it is important that the experiment gathers a lot of data. However, due to malfunctioning of some parts of the experiment the model can not be validated. The way the model could have been validated, would be by using different speeds for the carts and seeing how the curve of the energy in and output would have changed. Comparing this data to the data out of the model should have resulted into the same curvature in the graphs. If this was the case the model would have been correct and thereby validated. The only thing that can be said about the model when looking at the experiment, would be that the efficiency factor would not be accurate. However this is most probably due to the kind of motor that was used.

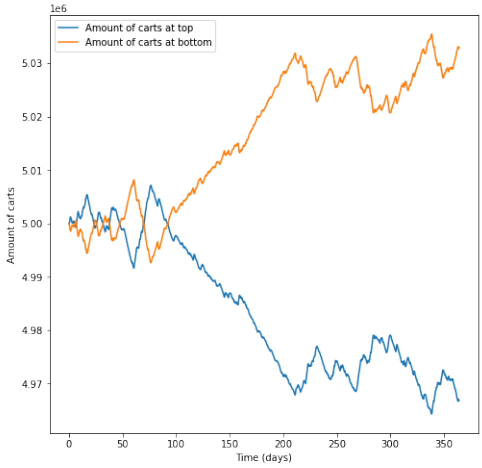
6.3 Validating the model on model

6.3.1 Finding the real efficiency and maximum amount of households

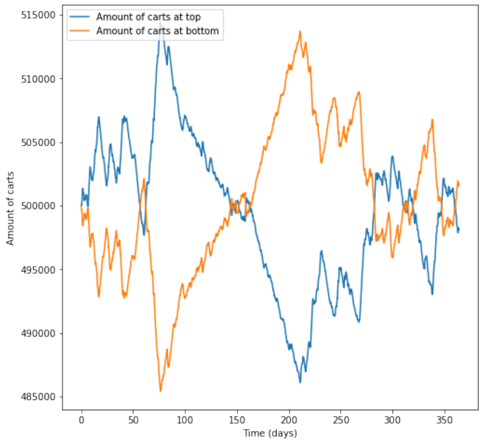
The goal of this project is to power 125000 households with a certain wind park which provides exactly the required amount of energy. With hind sight this was a unrealistic goal since of course there will be losses due to friction, efficiency of the generator and motor, etc. Thus the real amount of households that can be supported (and thus the real efficiency) needs to be found. This was done by assuming a very high amount of carts. The amount of households can than be adjusted until at the end of the year the same amount of carts are in the same positions. In figure 5 several graphs can be seen which display the amount of carts during the year. It can be seen that around 66500 households has long term equilibrium with the amount of carts. From this it can concluded that the total working efficiency is around $\eta \approx \frac{66500}{125000} \approx 55\%$ is found.



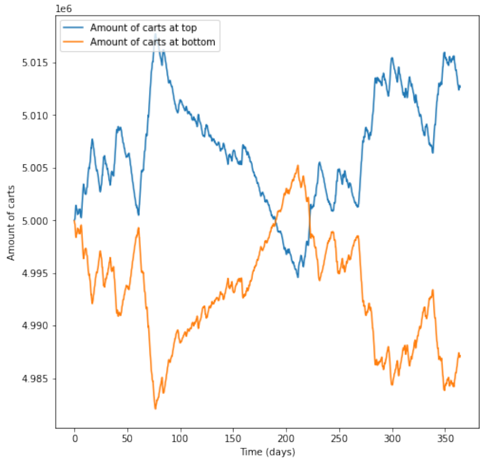
(a) 125000 households.



(b) 75000 households.



(c) 66500 households.



(d) 62500 households.

Figure 5: Amount of carts on top and bottom for various amount of carts during the year.

Besides the efficiency, the the amount of carts needed can be concluded by looking at the maximum difference in carts. When powering 66500 household around 30000 carts are needed. In the most optimal case (pretty much no space between each cart) this would require an area of around 1.35 square kilometer to store all carts on top of the mountain.

7 Conclusion

A mathematical-physical model of the energy storage and transport system has been obtained and describes the working of this system. Both the supply and demand also have been modeled with the use of real data. A controller, controls the in and output of the storage system by comparing the supply and demand. The efficiency according to the model is around 55 percent. To validate this efficiency an experiment has been carried out. The results of the experiment gave an efficiency of around 10 percent. Due to some major issues during the experiment this efficiency is not very representative. The motor used in the experiment did not work very well, which may have caused the low efficiency during this experiment. Also, not enough data was obtained to properly validate the model, because after a short time the motor did not work anymore.

The results of the model suggest that the system can storage enough energy to power 66500 households. The system will fill the energy gap between the supply (60 wind turbines) and demand (66500 households) without any problems. The maximum load of the system is also high enough to deliver enough power when there are peaks in the demand. Although, the storage system will work properly for these 66500 households, it is a rather expensive system for this amount of households. The system will also take in a lot of space, since the track is 20 kilometers long and around 30000 carts have to be stored at both the top and the bottom. So this storage system has potential, but because it can 'only' power 66500 households it will be a rather expensive solution. Although it is important to note that with a more stable power source (for example by combining it with a European wide network of wind turbines instead of only local) this could be significantly better.

A couple of things can be done as follow-up steps for this project. The most obvious thing to improve is the experiment, because there were some problems with the experiment during this project. The reason why the results of the experiment lacked, was mostly the quality of the electronics that were used. Because of the low budget, the electronics that were used did not function good enough to get proper results. So to improve the experiment a proper stepper-motor and stepper-motor controller needs to be purchased to be able to get the wanted results from the experiment. Another way to improve the experiment is by using a longer track, so more data per test can be obtained. Next to that, the mathematical-physical model can still improve, because for example the losses from transporting the electrical energy from the wind turbines to the storage system and back to the household are left out in the model.

References

[1] Vasco DE Janeiro Jean-Guy Bartaire, Rolf Bauerschmidt. Efficiency in electricity generation, July 2003. *Available at* https://wecanfigurethisout.org/ENERGY/Web_notes/Bigger_Picture/Where_do_we_go_Supporting_Files/Efficiency%20in%20Electricity%20Generation%20-%20EURELECTRIC.pdf *(2021-10-10).*

[2] KNMI. Uurwaarden van weerstations. *Available at* https://www.daggegevens.knmi.nl/klimatologie/uurgegevens *(2021-10-03).*

[3] Ron Kurtus. Coefficient of rolling friction. *Available at* https://www.school-for-champions.com/science/friction_rolling_coefficient.htm *(2021-10-10).*

[4] NEDU. Verbruiksprofielen elektriciteit 2019. *Available at* https://www.nedu.nl/documenten/verbruiksprofielen/ *(2021-09-28).*

[5] US Department of Energy. Determining electric motor load and efficiency, April 2014. *Available at* https://energy.gov/sites/prod/files/2014/04/f15/10097517.pdf *(2021-10-10).*

A Attachments

1. The (code for) the time dependent model, https://github.com/TimHeiszwolf/MTDS_Gravity_storage
2. Arduino code for stepper motor, https://canvas.tue.nl/groups/163730/files/folder/report%20attachments?preview=3535407
3. The raw data from the simulations/modeling with controller, https://drive.google.com/drive/folders/1m_1F7pYJhCL4BRyzPlB71FJS9FXrpZb2?usp=sharing

B Extra information model

First of all the code for the model (which is properly commented) can be found at https://github.com/TimHeiszwolf/MTDS_Gravity_storage (also see attachment 1).

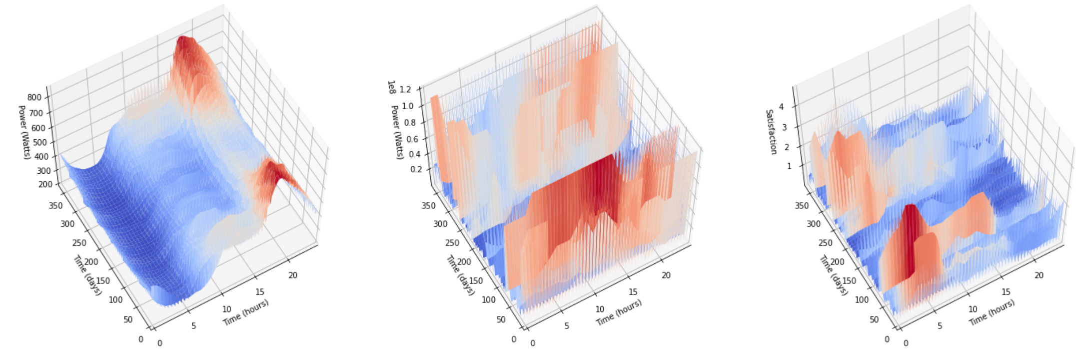
B.1 Supply and model

The model of the demand is based on "verbruiksprofielen" data by NEDU [4], which describes the amount of usage per (type of) household for each 15 minutes in a year. The demand model specifically uses the data from 2019 (2020 was discarded due to the impact COVID-19 might have had). It imports this data and converts it into power usage based on the consumption of each type of household. Then, using interpolation, it can also give data for each minute/second of the year. Using interpolation is important, since the data is not continues. There potentially could be big fluctuations in demand for the storage to handle. These are only due to the way the data was interpreted. For the end result of the model, a single type of consumers was chosen simplify the model. In figure 6a the load profile of an average household during the year can be seen.

The supply by the windmills is calculated in a similar way, but includes some physical aspects. First of all, data on wind speed from the KNMI is gotten [2]. The power can then be calculated as

$$P_{wind} = C_p R^2 v_{wind}^3 \rho \quad \text{with a maximum of 2MW} \tag{7}$$

where R is the radius of the windmill, v_{wind} is the wind speed from the KNMI data, ρ is the air density and C_p is a coefficient, which originally took into account the efficiency and other losses of the windmill, but since the data did not line up with the real output of the windmill it was turned into a normalization factor, which forces the total output of the windmill over a year to be the same as that of the real windmills. The results of this method can be found in figure 6b.



(a) Load profile of a single house.

(b) Load profile of the wind park.

(c) Satisfaction for only the supply and total demand.

Figure 6: Load profiles of and satisfaction by households and windmills. The x-axis is the time during the day and the y-axis is the day during the year.

Even though the difference between supply and demand can easily be seen in the figures, another graph was created for further results and analysis. For this a dimensionless metric was defined: the satisfaction of the demand

$$S = \frac{P_{supply} - P_{storage}}{P_{demand}} \tag{8}$$

where P_{supply} is the amount of power supplied by the power source, $P_{storage}$ is the power taken or supplied by the storage system (negative power is outgoing power, see chapter 3.3 for more details) and P_{demand} is the power demanded. In figure 6c this metric can be seen, assuming there is no storage system.

B.2

The gravity is

$$F_g = -\sin(\theta)Nmg \tag{9}$$

where θ is the angle of the track, N is the amount of carts on the track, m is the mass per cart and g is the gravitational acceleration. Please note that moving to the top of the track is the positive direction, while going down is the negative direction. The friction consists of air friction, which can be modeled in a simplified way with the drag equation

$$F_d = -\frac{1}{2}N\rho v^2 C_D A\hat{\boldsymbol{v}} \tag{10}$$

where ρ is the density of the air (this is assumed to be constant), v is the velocity of the carts, C_D is the drag coefficient (in this case 1.05) and A is the frontal area of each cart. Rolling friction of the cart with the tracks can be modeled with

$$F_r = -\mu F_n\hat{\boldsymbol{v}} \tag{11}$$

where μ is the coefficient of rolling friction, which is somewhere between 0.001 and 0.002 for trains and F_n is the normal force (in this case $F_n = \cos(\theta)Nmg$) [3].

B.3 Controller

To control the amount of power output by the storage system there are only two factors which can be controlled: the force applied to the carts by the generator and the amount of carts on the track. The velocity can also be controlled (although indirectly mainly by the force). First some very basic scenarios are made to see what the options are. Afterwards a more complex controller system can be made.

First of all let's try to get constant power. This is the case if both the force of the generator and the velocity remain constant (of course there are also non-trivial cases where the force is changed while the velocity changes in the opposite direction). For that to be true the acceleration needs to be zero and thus the total force remains zero

$$F_{G,const} = -(F_g + F_d + F_r) \tag{12}$$

from this we can conclude that the force of the generator must be the opposite of the gravitational and friction force. In fact the friction force even acts as a restoring force/-dampers in the case that the velocity is different from the desired value. It is important to note that this a very weak restoring force and thus it is better to do active control. To then calculate the constant power that is inputted/outputted equation 1 can be used.

The second case is increasing or decreasing the power. From equation 1 and 12 it can be seen that this can be done by changing the amount of force by the generator, changing the amount of carts (thus increasing the gravity and friction forces) or changing the velocity. From this a interesting almost paradoxical phenomena becomes apparent: increasing the amount of power in the short term results in decreased power in the long term and vice versa. For example when taking power out of the system you can increase the generator force to increase power output, but this will result in a lower speed and thus a lower power output in the long term. To increase power the velocity can also be increased but to do with you need to have the generator force decrease so that results in a lower output in the short term.

While this may seem like a big problem the severity is not that high. That is because the border between "short-term" and "long term" is tens of seconds and since the modeling/-control problem is only really relevant in the tens of minutes and thus the focus can be put on the "long term" solution (changing the velocity and the amount of carts).

Eventually a working controller was found. It is simple, ignoring the short term control aspects but it does work well. First of all it always tries to add new carts, it does this because this is a simple way of controlling the system. After testing the controller with always adding new carts if possible the results were good. So there was no reason to make the controller over complex by adding an other variable.

Next, the other thing to control is the force of the generator which indirectly controls the velocity. This is what had an active control scheme. The model starts by calculating the force needed for having no acceleration and the power associated with it. The difference between the power this generates and the difference between demand and supply is then calculated. Based on that a needed change in velocity is calculated which then gets translated into an acceleration (with a maximum of 1 m/s^2). This then gets translated into the desired force of the generator (with a minimum of 0 N).

B.3.1 Maximum power load

Another interesting aspect to look at might be the maximum load on and investigate what the theoretical maximum in that regard may be (again assuming no shortage of carts). For that there is one obvious limiting case: the velocity of the carts (with a maximum of 10 meter per second. If we look at the speed for the 66500 households and 60 windmills case in figure 7 it can be seen that the maximum speed reached is around 2.5 meter per second (mainly when the wind is at maximum output). From this we can conclude that in theory our system (with one track) has a maximum at 266000 households, 240 windmills and 120000 carts (requiring 5.4 square kilometer of storage minimally).

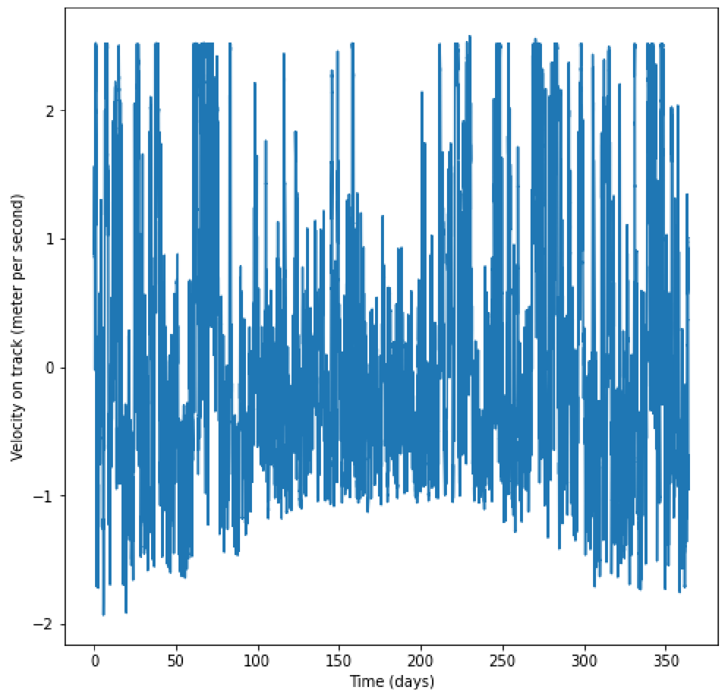


Figure 7: Velocity of the carts during the year.

Of course this is in theory, in practice it might differ since the system and controller might have more difficulties with sudden peaks (getting carts on the track).