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Modelling and comparison between lithium-ion energy storage and flywheel energy storage for households.

Comparison and mathematical modelling of two different energy storage system technologies through Matlab Simulink. The aim of this work is to compare lithium-ion batteries and flywheel kinetic energy storage systems in a household application connected to a solar panel installation.

Archibald De Kepper

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Thesis advisor: Francisco Díaz Gonzàlez

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Acknowledgments

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Sincerely,

Archibald De Kepper

Chapter 1

Introduction

1.1 Overall context

“Right here, right now is where we draw the line. The world is waking up. And change is coming whether you like it or not.” quoting Greta Thunberg [1]. The young climate activist has understood the consequences of climate change, and is asking each and every one of us, to take action today to give our children a livable world tomorrow.
This shocking quote gives every student of our generation the aim of helping the society towards a more sustainable future. As an electrical engineer, my best addition could mostly be in the energy market. Many interesting researches and projects have been done in the past few years and the development of this sector is encouraging regarding to the aim of reducing CO2 emissions.
The idea of doing a research about mechanical storage for households was driven by the huge infatuation given around producing greener energy to get to the objectives in terms of climate changes.

1.1.1 History and future

The first idea of global warming came in Joseph Fourier’s head in 1820. But at this time, there were little reactions. In 1837, the first differences on glaciers are studied by Louis Agassin without knowing why and how those glaciers were losing ice volume.
The start of real interest of the scientific population about global warming came in 1896 when well known chemist Svante August Arrhenius found a direct link between CO2 emissions and global earth warming. He received the nobel price in 1903 for this research. We have to wait until the seventies for this idea to be widespread in the population. [2, 10, 15]
Since then everything has gone really fast:

- First COP in 1979
- First assesment that concludes a rise of more than 0.3 degrees due to human emissions in 1990
- First protocol to try to reduce global earth warming in 1997
- We reach the 8 billions tonnes per year of from fossil feul burning in 2006
- Developed countries start contributing to a 30bn, three-year deal on "Fast Start Finance" to help them "greener" their economies and adapt to climate impacts in 2010
- A new analysis of the Earth’s temperature record by scientists concerned over the "Climate-Gate" allegations proves the planet’s land surface really has warmed over the last century in 2011
- Researchers find collapse of West Antarctic ice sheet may be irreversible, bringing meters of sea-level rise over future centuries in 2015.
- Solar electricity and wind power become economically competitive with fossil fuels in some regions in 2016

- IPCC report on 1.5°C warming in 2018 says that to avoid dangerous climate change, the world's greenhouse gas emissions must be in sharp decline by 2030.
- In 2020 the mean global temperature is 14.8°C, the warmest in tens of thousands of years. The level of CO2 in the atmosphere is 418 ppm, the highest in millions of years.

Since the industrialisation of the human society the temperature has risen by 1 degree. The consequences will be seen on different points in the next few years. The equilibrium created by the nature through billions of years will be broken. Different species will not be able to adapt to such a fast change and in the worst case, it could be fatal for humanity.
It is essential to reduce the emissions in the next years to avoid, from a short-term point of view, natural disaster and lost of certain species, and from a long-term point of view, the disappearance of the human specie.
During the years different agreements have tried to be set to avoid this climate change but it is only in the last decade that things have been accelerating and that the objectives, especially in Europe, have been set with really high expectations.

1.1.2 UE main objectives for reducing CO2

Since a few years the UE has a real aim of lowering the gas emissions around the continent. But last years, they really went to an other level of expectations with high-level objectives and strategies to finally become a climate neutral continent in 2050.

The offical strategie of the EU through the "Accords de Paris" in 2016 [8, 9]:

- Renewable energy target at least 32% by 2030
- Cutting green house gas emissions by at least 55% in 2030 (Compared to 1990)
- Facilitate administrative procedures to encourage green energy
- Add more flexibility in the energy mix
- Limit the global warming below 2 degrees
- Become a climate neutral continent by 2050

The energy sector is responsible for 75% of the EU's gas emissions. It is also a sector that is growing up really fast and new solutions to create greener energy are discovered every year. This sector is clearly the one with the most expectations to become greener in the next couple of years. The rise of green energy production installations and energy storage is very encouraging and many doors are open for new ideas and technologies. As we can see the EU counts a lot on this sector and will invest enormous amounts of money to achieve it's high expectation objectives.

Since the main barrier for greener energy supply is the capacity of storage to supply peak demands and not the capacity of generation, the idea of having a research in this sector merged. While many big tech companies are trying to find different ways to store large quantities of electricity, the idea of this work was to find out if storage technologies for lower capacities that are needed in other applications could help to make the step to greener energy. This is why the main question for this work is the next one:

" Is it possible to design a mechanical battery, made for private households, connected to solar panels, that can be attractive financially or at least ethically?"

1.2 Contribution

The aim of this project is to model a flywheel that can be used as mechanical energy storage in little volumes to make it able to fit into private homes or gardens.
The flywheel technology will be compared to the classic lithium-ion battery.
The final objective will be, if possible, to have a theoretical product that could be manufactured and sold to private entities to make each private family or business able to completely be self-sufficient in terms of energy thanks to a solar panels system linked with this energy storage capacity.

1.3 Motivation

As a student from the generation I am born in, I have been educated in the issues of global warming all my life an this affects and interests me a lot.
As an engineering student in Energy, I am really focusing on the future of energy and all the new technologies that are coming up in the last years to reduce our carbon footprint. My interest for the course given by Sr Francisco Diaz Gonzalez named Energy Storage at the UPC has given me an extra interest about the importance of finding financially attractive possibilities to store energy if we want to go to fully green energy production. While my idea is to make a career into renewables, this work is a first step to try to one day, be one of the many actors in charge of going green for our future power system.

This research fits well in time thanks to many different actors.
First of all, nowadays the overall population is being educated about the idea of becoming sustainable. Mentalities have changed and the aim of particulars to become self-sufficient is growing. A demand for storage capacities at home is growing and the chemical batteries are not always a good option.
Secondly, the European Union and many others governments are investing big amounts to avoid global warming. There is an aim of helping financially the population the get self-sufficient in the coming years.
Thirdly, many NGOs and climate activist are fighting against the processes that are needed to obtain a chemical battery. Other alternatives are studied and mechanical batteries could be an option.
And lastly, it is easy to notice that the market of home-batteries is exponentially growing since the last decade. This market is open to expand with new products and the demand will not stop raising in the coming years.

1.4 Structure

To achieve the objective of finding a product that could end up into our houses to store the energy mechanically, a clear structure has been set.

The next chapter will start by explaining how this idea merged during the years to finally decide to write a full document on this subject. It will explain the aim of going to little entities and work on non-chemical batteries. The idea of little entities will be clarified with the exact public audience of this product explained.

In the third chapter, a model of the flywheel and the chemical battery will be done through the use of Matlab Simulink. This section will show how the models have been done and why it has been done in this way. These models will make the comparison between both technologies.

The fourth chapter will contain all the results represented with charts and graphs. This will make comparisons easier between the technologies. The models are tested on 24 hours every time and three different days of the year have been chosen to test them.

The last chapter is the conclusion of this thesis. It will analyze the real feasibility of each technology. It will answer the main question of the thesis and show clearly if it could be possible to manufacture a product in real life.

Chapter 2

Context

For multiple years the cost of production of green electricity has been higher then it's competitors that are producing with non-renewable energy resources but in the last few years it lowered a lot and it is expected to continue it's decline. This is a great opportunity, but if we want to increase the part of green energy in the mix we will have to find non-expensive technologies that are able to store the energy. The need of energy storage capacity will be explained in the next few sections.

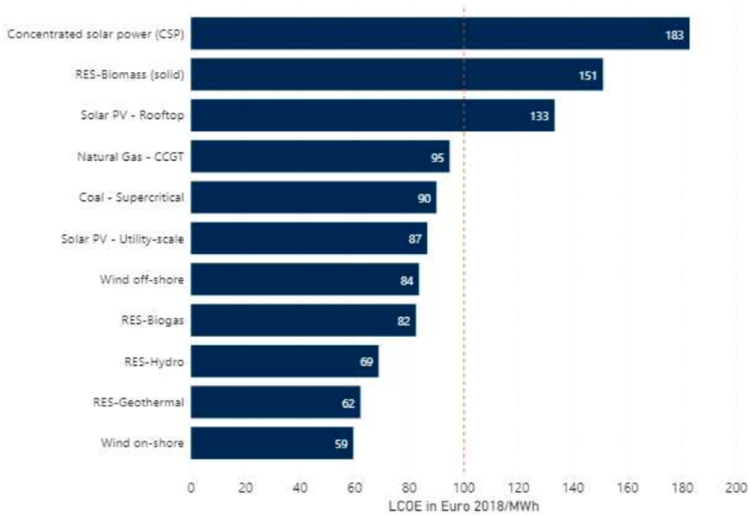

Figure 2.1: LCOE renewables [16]

2.1 Future of energy

Nowadays, energy is one of the main subjects in the newspapers. It is changing, and really fast. The world wants to make it's energy greener and tries to find solutions to achieve it.
The European Union is one of the main consumers in the world and has a clear view on what they want their energy production to become. Through different treaties and accords they established a clear strategy and view about the energy of tomorrow.
The better integration of cost-effective green energy in the mix is the main objective of the UE in the next years. Linking various energy carriers and sectors is a way to get there. It is also important to make the energy flow more circularly and not only from the producer to the consumer. Multi-directional directions of flows could help for having flexibility and thus possible to integrate more easily renewable energy productions.
The storage of energy is a way to make the mix more flexible and multi-directional. It will also make the non-reliable but cost-effective energy productions more reliable. This is really important to make the use of solar and wind possible in the energy mix.
The competitiveness has been and will continue to be boosted by the UE. Multiple big tech companies are making research's and this is why the prices for production of green energy and storage

of energy are lowering.

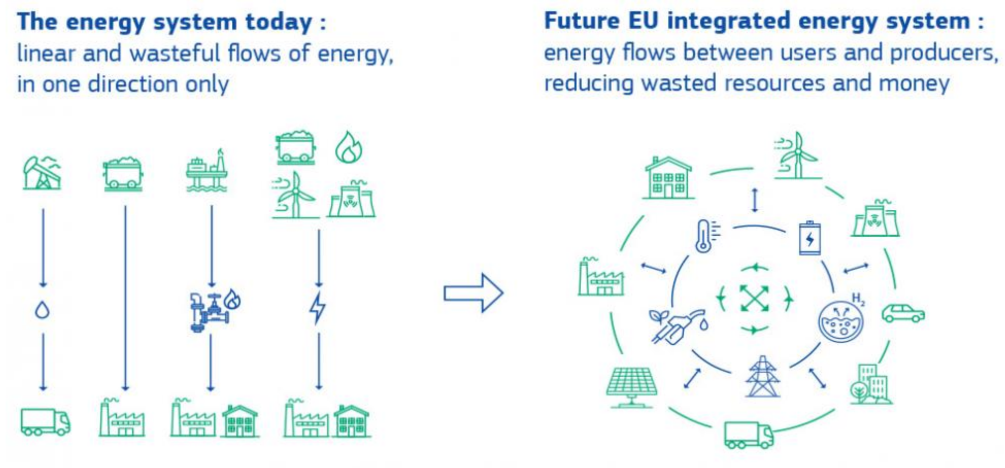

Figure 2.2: Energy integrated system [8]

2.2 Mechanical energy storage for little entities

In this section some explanations will be given about the reasons that made this work to be about mechanical storage for little entities. It will clarify why mechanical is preferred to electro-chemical storage and why little entities have been the subject in front of big storage projects.

2.2.1 Why do we need storage

Having storage capacity is really important for many different reasons. First of all it can be usefull in locations that are not connected to the grid and that can only rely on one or a few different electricity production technologies. In places where the only source of energy is the sun, the need of storage is essential to supply with energy during nigh time.
Energy storage can also be used as security to avoid black-out problems, some people will also use this technology to take profit from the different energy prices during the day in countries where varied pricing is introduced.
The most important aspects of energy storage is it's capacity to stabilise the differences between production and demand. And this is the reason why energy storage is main pathway to decarbonization. Many green energy productions are not stable or non variable compared to polluting energy production technologies. The only possibility to make them stable is to connect them with an energy storage capacity.
Adding storage to the mix is the only possibility to be able to extend the part of green energy production into he grid without losing in stability.

The next few figures will show the lack of stability of carbonless energy production technologies. To get these numbers the European country France has been taken as example, who is especially partisan of nuclear [7, 6].

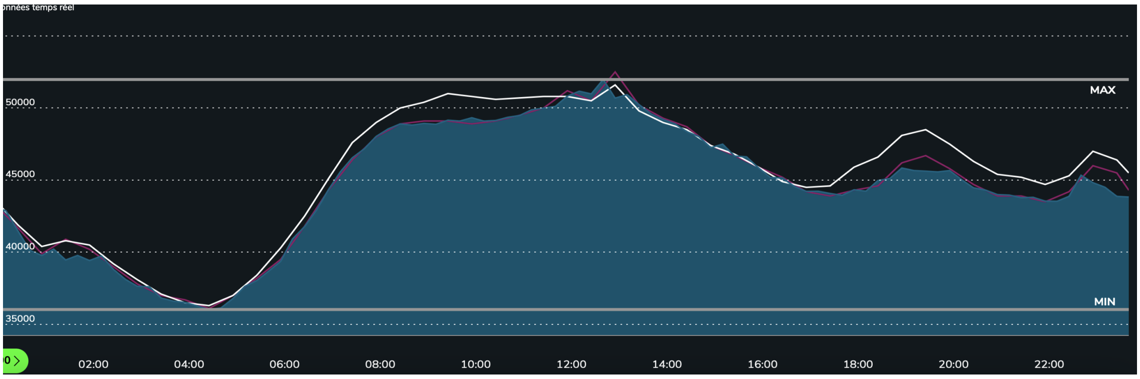

Figure 2.3: Energy demand France 16/05/2023 [3]

The demand is as expected higher during the morning, average during the day with a second peak in the late afternoon and then goes back down for the night.

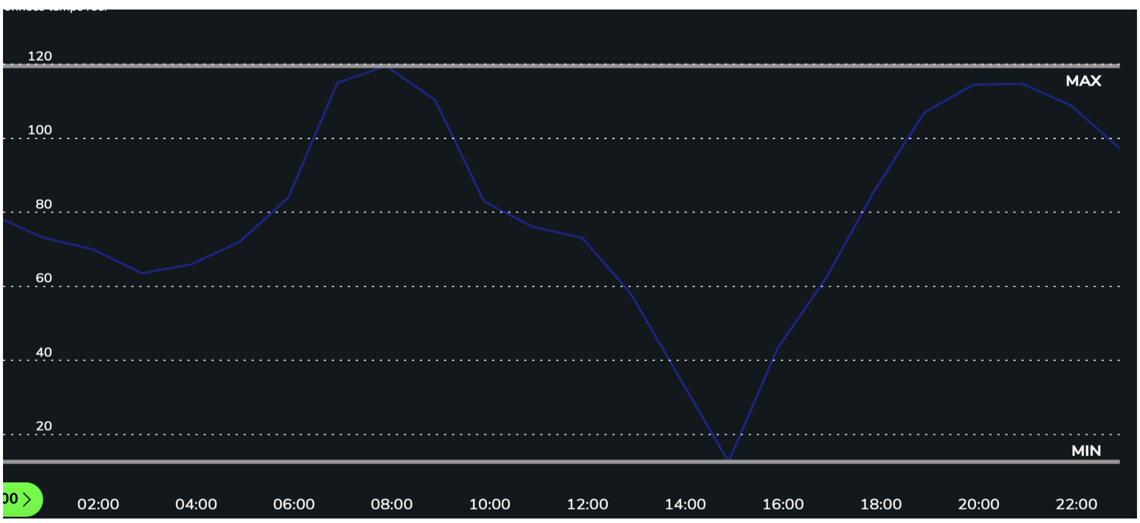

Figure 2.4: Energy price France 16/05/2023 [3]

The price of the energy in France will depend on the demand, this is why prices are really high in peak hours. The prices are especially low in the middle of the day and this is certainly due to good sun and wind production at this moment of the day.

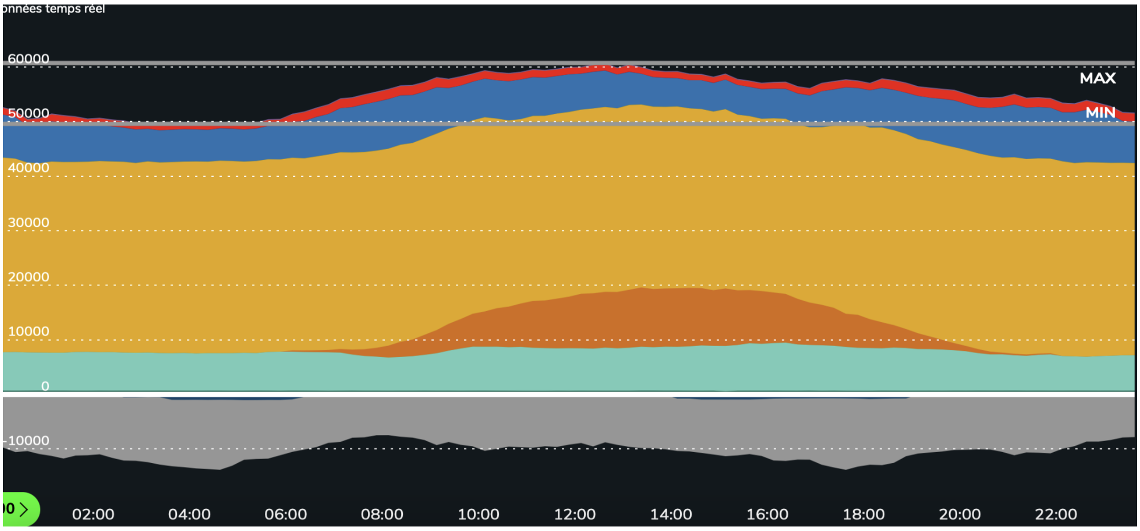

Figure 2.5: Energy mix France 16/05/2023 [3]

In this figure we can see the classic behavior of every different energy production technology:

- Red: Gas
- Dark blue: Hydraulic
- Yellow: Nuclear
- Orange: Solar
- Cyan: Wind
- Other colors: Pumping,carbon, fuel, bio-energies etc.

Nuclear is very constant during the 24 hours. It is not able to adapt in seconds of minutes to supply more or less demand. Solar and sun variate much more but it is not controllable, it depends on the behavior of the wheather. Hydro will be most of the time constant while gas is the only bigger energy production in the mix that can be controlled easily and can change his production debit in minutes or even seconds. It is also the one that rejects the most CO2.

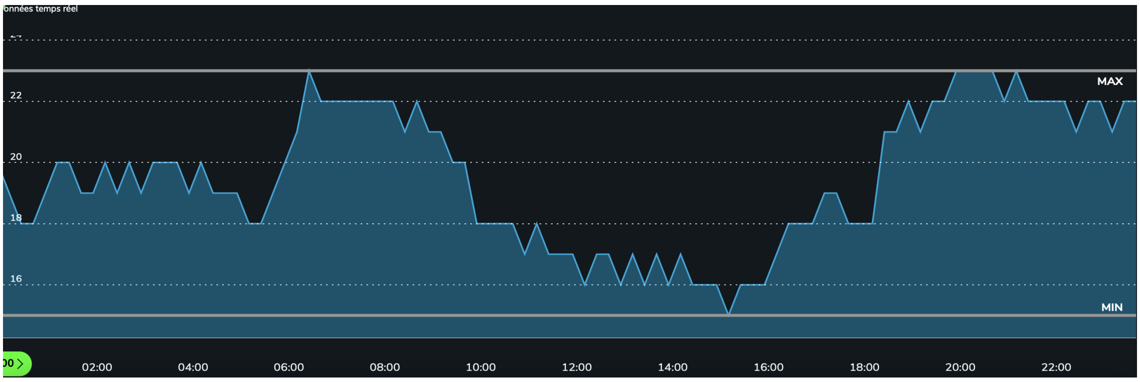

Figure 2.6: Carbon density in energy production [CO2/KW] France 16/05/2023 [3]

The carbon density per kW depends a lot on the part of gas that is used in the energy mix, especially for France that do not use a lot of carbon and fuel for their production.

As we can see in the example of the energy mix of France is that the biggest issue toward greener energy is the gas part of the grid. The gas is very flexible and thus can be used when the demand is higher. When the demand is raising the price also goes up thus the energy created by gas can be sold at higher prices. This means gas is financially profitable while it is the most CO2 consuming because it is only working when prices are high. Only batteries that can be charged during the day thanks to wind and solar could replace the gas part of the mix without emitting large amounts of CO2.

If we want to avoid using nuclear, we will have to do the same thing. Increase solar and wind production but especially increase the capacity of the storage to supply by night when there is no sun nor wind

Today, by far the most of our energy storage capacity are pumped hydro power plants. It exceeds 94%. The 6 other percents are a set of thermal storage, electrochemical storage, compressed air and flywheels.
Lithium-ion batteries and many other electrochemical batteries are more and more used for new projects as well as flywheels and compressed air. Big companies know that the market of energy storage is a very strategic one for the next years and are investing massive budgets in research and development.

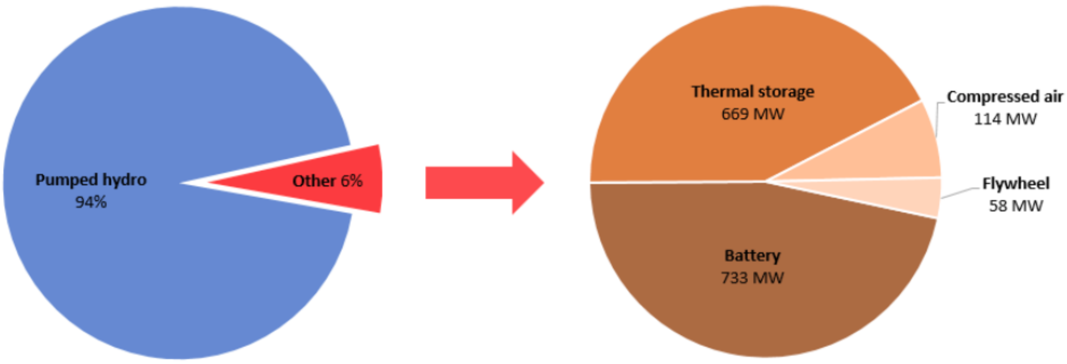

Figure 2.7: Storage capacity distribution world [5]

2.2.2 Why mechanical

The document takes a focus on mechanical storage and not elechtrochemical storage for multiple reasons.
Most of the storage systems nowadays are done with lithium-ion elechtrochemical batteries. Other types of batteries are also used like Sodium-sulfur or Nickel-Cadmium. The explanations that will be given for Lithium-ion batteries are similar for the other two battery types. Lets focus on Lithium-ion[11].

As we know lithium-ion batteries are unbeatable in terms of efficiency and especially energy density (around 75 W/kg). Each year new technologies make them better and the costs are going down.
But it also has his cons. As it is known, lithium is a rare metal that is not unlimited. At the moment we are able to extract enough to supply the demand but it may not last forever. We could one day have the same problem of rarity than we have today with oil. Which means, dependency to other countries, very variable prices and more and more polluting technologies to extract this metal.
While the objective to add energy storage to the grid is to limit CO2 emissions for the health of our earth, maybe this kind of batteries are not the solution for the future. Even if, at short term they are the most efficient.
The very low cyclability, very burnable characteristic and the difficulties to recycle those kind of batteries are a brake to count on them for the long future.
It is not possible to forget the many scandals all around the world but especially in Africa about the conditions of work of the workers that are extracting those materials in deep mines.

As said above, many different types of elechtrochemical batteries exists but most of them have the same cons as the lithium-ion one. Although I hope one day a new technology will be found to make them more eco-responsible. But nowadays it is not the case. For this reason the focus is on mechanical and not chemical in this work.

Because of the non-chemical character of the mechanical batteries, those have always been more sustainable for the nature. No chemical reactions, means longer cyclability and easier recyclable. The energy density of a chemical battery will never be matched (Minimum 5 times heavier for the same storage for mechanical batteries), and this is why it is not adapted for many applications like electric cars or planes where the weight is really important. But the objective is to find the right applications and take advantage of the LCOE that could maybe beat a chemical battery in certain apploications (Example: Basic flywheel: 3.8c/kWh vs Lithium-ion battery: 11c/kWh [17].)

2.2.3 Why private

This section will explain why the aim of this project was to focus only on little entities and households. The objective is to have a theoretical product that can be sold to a target market that are private houses, or small buildings.

Nowadays, more than 91% of the storage capacity is made of pumped-hydro power stations. The other sectors are low but are growing up really fast.
To achieve the EU-objectives for 2030 a lot of budget has been given to big projects all around Europe with multiple technologies. All these projects are mega projects led by big multinational companies that have the aim of adding storage to the grid through big capacity storages. The purpose of this project is to add storage to the grid, but not through big projects. Through a small theoretical product that could be sold to private houses on a large scale and have an impact on the grid storage thanks to a large number of mini-storage systems.

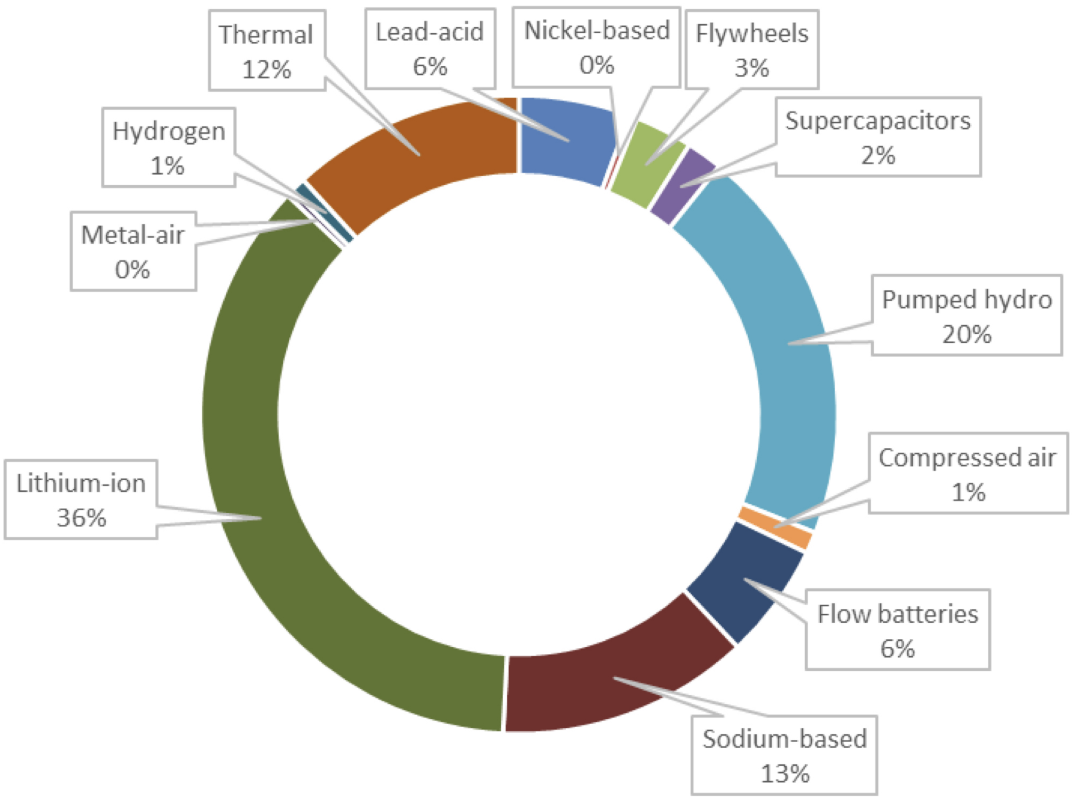

Figure 2.8: Energy storage projects EU by type [11]

The idea is to compare it with the solar panels market around the years 2005. At this moment, electricity generation through solar panels was only done in big solar panels farms or on big industry roof's. Having solar panels at home was financially not profitable. When the technology efficiency increased and the tax credits helped to make it financially attractive many people added solar panels on their roof. Today nearly 25% of the solar energy production is private.

[4].

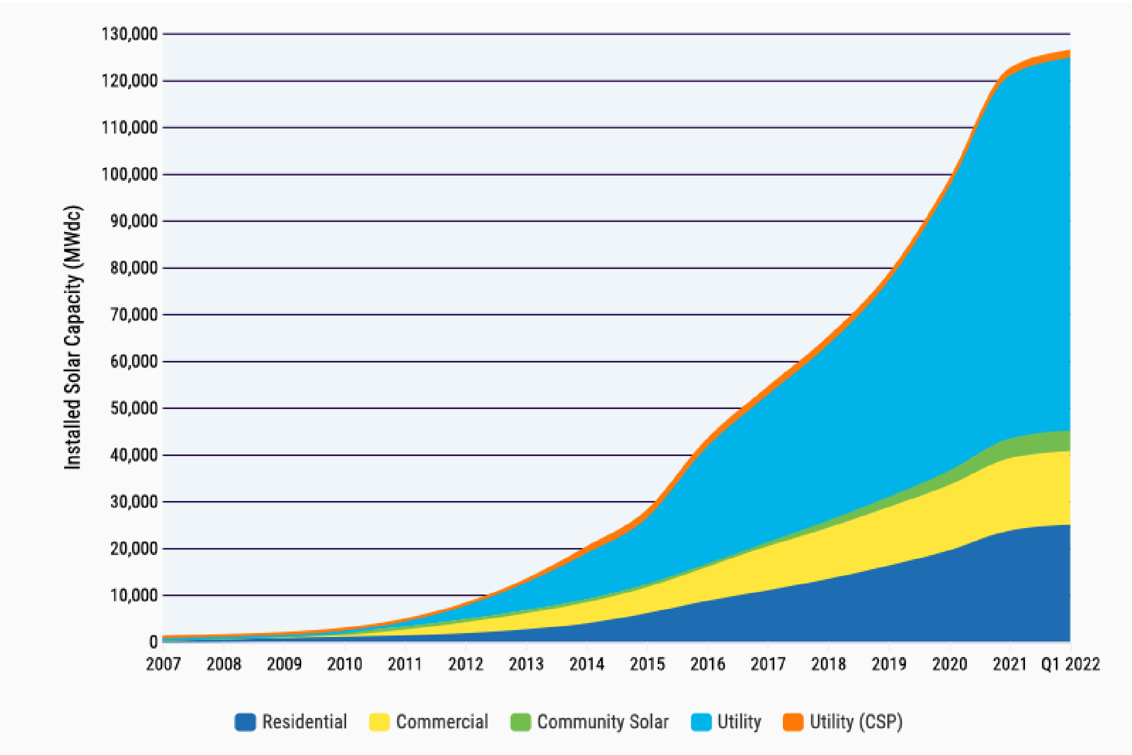

Figure 2.9: Solar panels distribution USA [4]

The idea is to copy the growth of the solar production market in the 2000's with the energy storage market today.

First it has to become financially profitable for the consumer. This has to be done thanks to better technologies but can also be helped later with tax credits given by the state. Then it should become a "hipe" of having his own storage at home. It has to be something exciting to feel self-sufficient in terms of energy for each of us. This could make an even not-financially profitable product still be interesting to put on the market.
Finally with large numbers the private sector could have a positive impact on the energy mix thanks to the total added energy storage.

Since a few years the idea of being green and sustainable is well seen especially in Europe and the United States. Even with a non-financially attractive product many middle-class people could be interested by becoming completely self-sufficient and having a good feeling about their footprint on earth. Although it is clear that people care about money and it would be a great point to achieve this financial attractiveness.

For these multiple reasons, and also because there is no option on the market to store our own energy at home mechanically at the moment. The idea is to create this product that could make every house or building self-sufficient in terms of energy while not using chemical reactions and rare metals.

2.3 Context conclusion

All the previous points of this chapter are leading to the next research that will be about the modelling of a flywheel and a lithium-ion battery. The aim is to make a model of both to facilitate the comparison. The model will be done on Matlab Simulink and should answer the question of the possibility for a flywheel to compete with an elechtro-mechanical battery in the aim of storing energy for a household on a 24 hours sample.

Chapter 3

Models implementation

The complete model is formed by four main blocks: The solar panel installation (production), the household (demand), the grid and the Energy storage device.

The main structure can be seen in the scheme below:

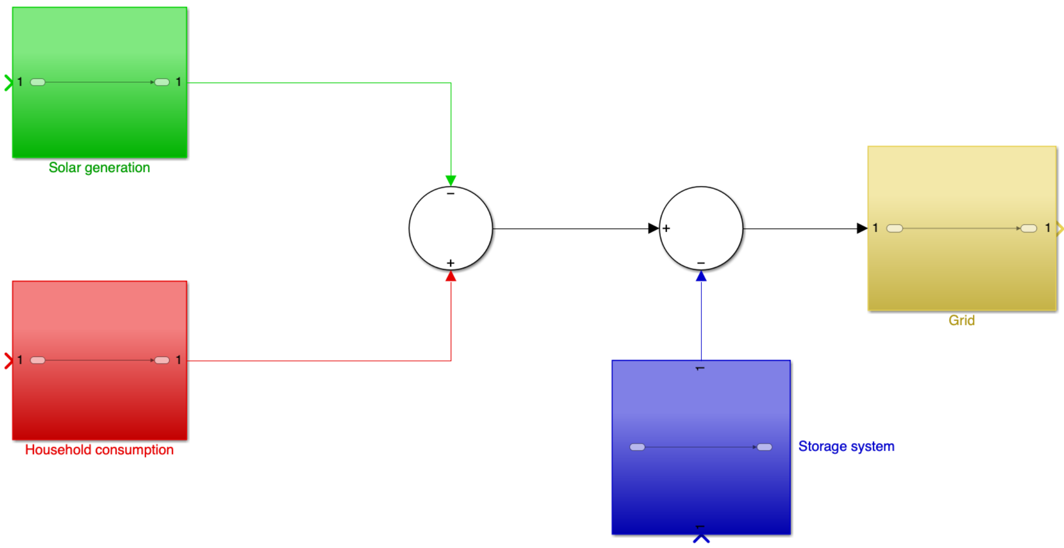

Figure 3.1: Simplified model structure Simulink

As explained before, the aim of the storage system is to contribute to the energy supply when the solar panels are not producing more than the demand. For this reason the storage system will always try to supply the difference between the demand and the production.

The part of energy that could not be supplied neither by the solar panels neither the storage system is supplied by the grid. A positive value on the graph of the grid means a need of supply from the grid.

3.1 Data

The data used in the simulations for the power and demand has been taken from an existing solar power installation used to power a private household in Belgium near Brussels (50.700374, 4.471177). This power installation is large compared to regular installations but it fits perfectly in the application of connecting it with a storage system.
Specific information about the solar panel installation:

- Type of panel : Trina Solar 415Wc Black Frame

- Number of panels : 42
- Geographical coordinates : 50.700374, 4.471177
- Inclination : 48°
- Maximum power of the full installation : 10kW

The demand used has been taken from the same household during the same days than the generation. This data is a good representation of the most probable public to be able to take profit of energy storage at home. It is important to note that this house is not heated with electricity but that it is a really energy-consuming house compared to a classic household, nearly twice the average of the country.

To simplify, the prices have been taken for the one day in Spain with as date 16/06/2022. The motivations of taking the prices of a random day and not the corresponding are the following: First of all, as the energy prices are very volatile and mostly depend on geopolitics since the last few years, the correlation between the day of the year and the electricity price is not really high especially in this geopolitical tensional moments that we are facing. The day has been chosen to support the thesis results without exaggeration.
The second reason of not taking the electricity price of the day and location of the demand and electricity production have been taken is because, in Belgium, the prices for electricity are constant during the whole day or can have, as a maximum, two different prices in 24 hours. While this is not beneficial for using energy storage. For this reason taking the location of Spain had more sense, knowing also that the Belgian government is pushing to obtain variable electricity prices for the next years in the country.

The main idea of the next models is to supply the demand as best as possible. The models are energy storage systems so their objective is to be able to supply the energy used in the household that is not directly supplied by the solar panels. For this reason most of the graphs will contain "ConMinusGen" that represents the consumption of the house minus the generation in real time. The graph that represents the excess or lack of energy is the energy given by the house, seen by the grid. For this reason this graph will often be named "Grid"

It is important to note that the simulations have been done with sample of 8640 seconds what represents 24h. The graphs are going from midnight until midnight of the next day.

The next sections will give a more technical explanation of every of the models that have been made to simulate the energy storage installation of the household.

3.2 Lithium-ion battery

In this section the model of the Lithium battery will be explained, the model will be shown and the assumptions will be given and justified.

3.2.1 Battery used

The battery used as model for the simulation is the Resu 16h Prime designed and manufactured by HPchem and available on the market [12].

The important specifications for the simulation are the next once:

- Capacity : 16kWh
- Maximum power : 11kWh
- Minimum power : 0,1kWh
- Internal resistance : 0,1Ω

- Efficiency : 0,9

It is important to note that in all the models the initial state of charge of the battery is put a 0.5.
No information about the SOC-Voltage graph could be found so a the pattern of another lithium-ion battery SOC-Voltage graph has been used and adapted to fit into the Resu 16h Prime.

It is assumed that the minimum and maximum SOC for this type of battery are respectively 10% and 90%.

3.2.2 General explanation model

In this section an explanation will be given about the model of the battery that in this case, is the storage system of the scheme seen above.

The Battery model is divided in two big subsystems:
The Energy management system (EMF) and the Storage device. The EMF will give an information about the power delivered by the battery while the Storage device will inform the EMF about SOC and Voltage.

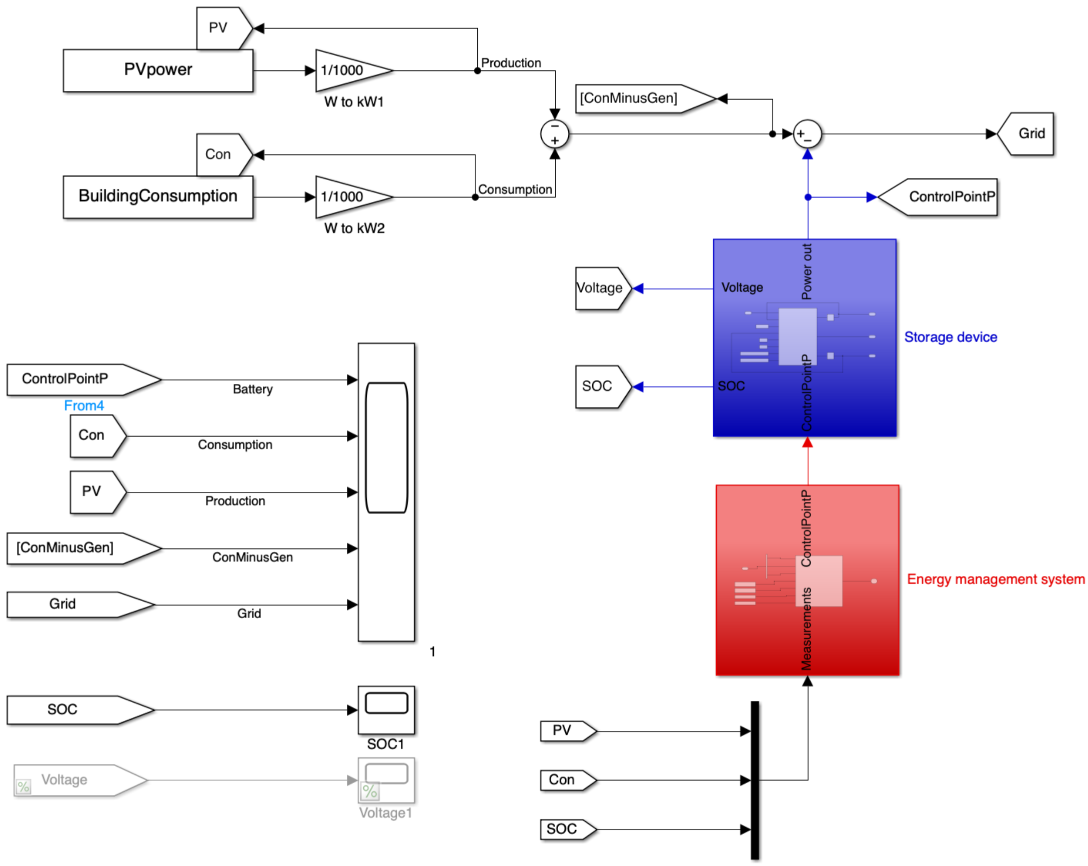

Figure 3.2: Battery model structure Simulink

3.2.3 EMS

The EMS is responsible for the managing of the power delivered or received by the battery. With a couple of inputs it will calculate the output of the power that will be positive in case of discharging and negative in case of charging the device.
The code is mainly a code that imposes the battery to try to supply the difference between the

demand and production while not exceeding maximum and minimum power nor maximum and minimum SOC.

Inputs of the Energy management system

- Solar panel generation
- Household consumption
- SOC
- Maximum power battery
- Minimum power battery
- Maximum SOC
- Minimum SOC

Outputs of the Energy management system

- Power delivered by battery

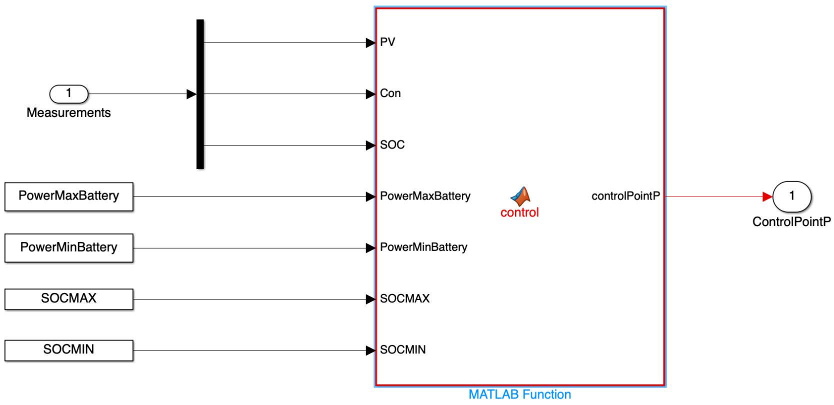

Figure 3.3: EMF battery model structure Simulink

3.2.4 Storage device

The main role of the storage device is to recalculate the SOC and voltage at every iteration to give this information back to the EMS.

Inputs of the Storage system

- Power delivered by battery
- SOC
- Capacity of the battery
- Efficiency
- Internal resistance
- SOC-Voltage graph
- Voltage

Outputs of the Storage system

- Power delivered by battery
- SOC

- Voltage

The power delivered by the battery doesn't change in the Storage system, it is the same at the input than at the output. The SOC and Voltage are needed as input and output to recalculate them at every iteration of the simulation.

The formula used to recalculate the SOC:

$$SOC = SOC - \eta * I/C$$

With:

- η the efficiency
- I the current found with the formula: $I = P/V$
- C the capacity of the battery

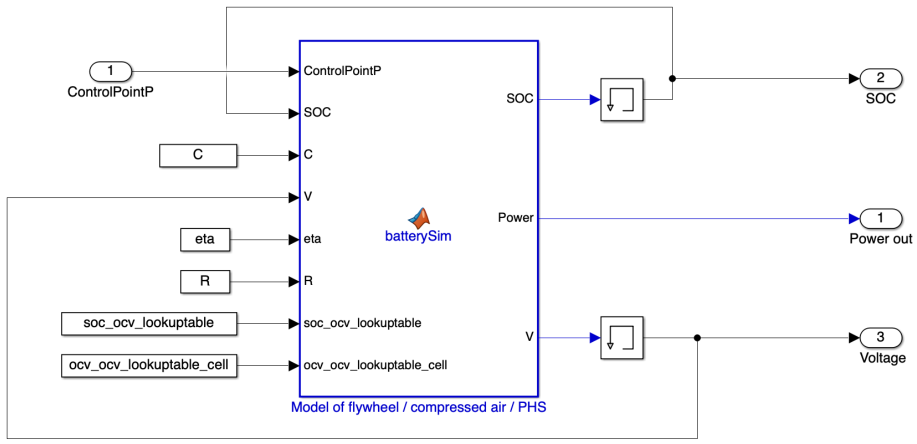

Figure 3.4: Storage device battery model structure Simulink

3.3 Flywheel

In this section the model of the flywheel is explained, the model will be shown and the assumptions will be given and justified.

3.3.1 Flywheel used

The flywheel that has been used as model for the simulation is the Flywheel Punch Power 200 from the brand [13].

The important specifications for the simulation are the next once:

- Capacity : 5 kWh
- Maximum speed : 424 rad/sec
- Minimum speed : 100 rad/sec
- Maximum power : 85kWh
- Minimum power : 0,1kWh
- Voltage : 400-415

- Efficiency : 0,9
- Inertia : 212,044

It is important to note that the initial speed of the flywheel is put at 300 rad/sec. The frictions are considered constant and not related to the speed of the flywheel. The ideal speed for the flywheel is considered at 254 rad/sec and this is the ideal speed used by the controller. In this applications two flywheels will be used side by side and it is assumed that the they are not related to each other and that the energy capacities can be summed.

3.3.2 General explanation model

In this section an explanation will be given about the model of the flywheel that in this case, is the storage system of the scheme .

The flywheel model is divided into three subsystems. The energy management system, the controller and the storage system. The EMS will give the information about the power that has to be delivered to supply the demand, the controller will smoothen this signal and try to keep the flywheel at it's ideal speed with a certain strength of action depending on a constant k. The storage device is in charge of the calculations of the current, voltage and speed at every step.

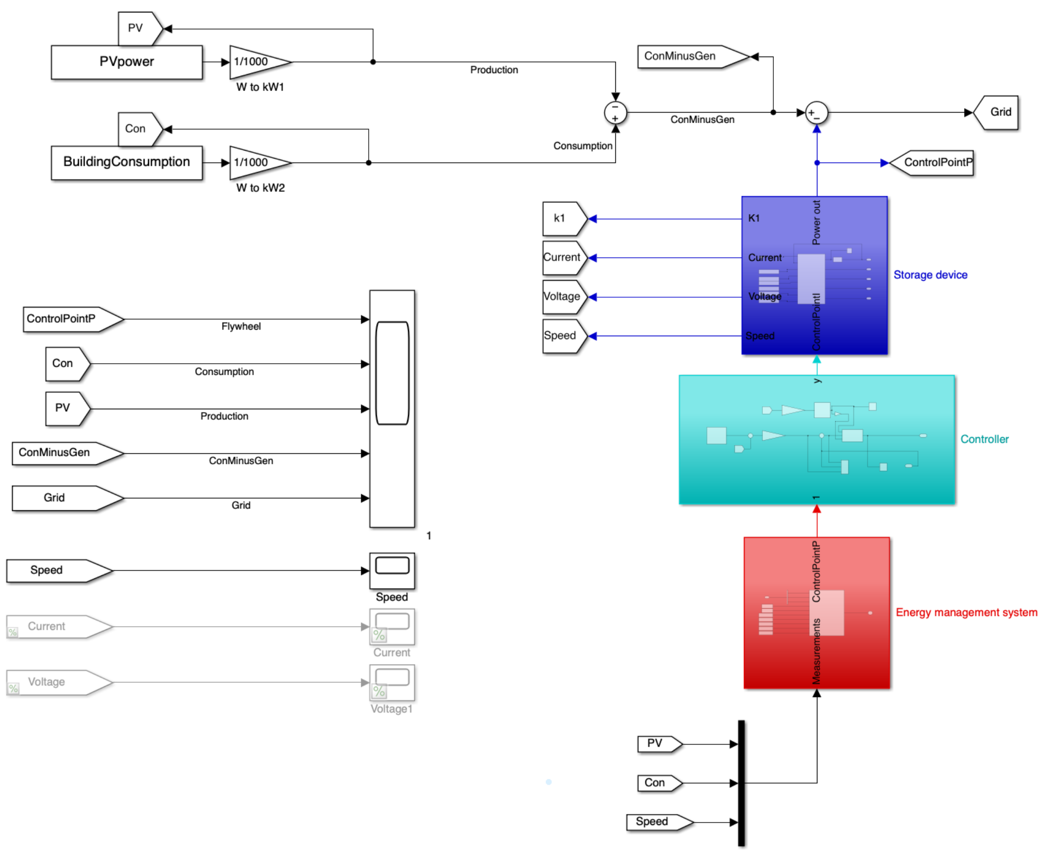

Figure 3.5: Flywheel model structure Simulink

3.3.3 EMS

The EMF is responsible of the calculations of the power needed by the system to supply the demand respecting the conditions of the maximum and minimum speed and power of the flywheel. With a couple of inputs it will calculate the output of the power that will be positive in case of discharging and negative in case of charging the device.

To avoid being to close to the maximum or minimum speed this block contains an if function that works as followed: Once the speed gets between the MAX-MARGIN/MIN+MARGIN the power delivered by the the flywheel will increase/decrease to decrease/increase the rotating speed. This power increase/decrease is done in an exponential way getting closer to the limits to ensure that the speed never reaches the maximum/minimum speed. The MARGIN is a constant number mostly determined with simulation trials

Inputs of the energy management system:

- Solar panel generation
- Household consumption
- Speed
- Maximum/minimum power flywheel
- Maximum/minimum speed flywheel
- Margin constant for speed limits controller

Outputs of the energy management system:

- Power EMF

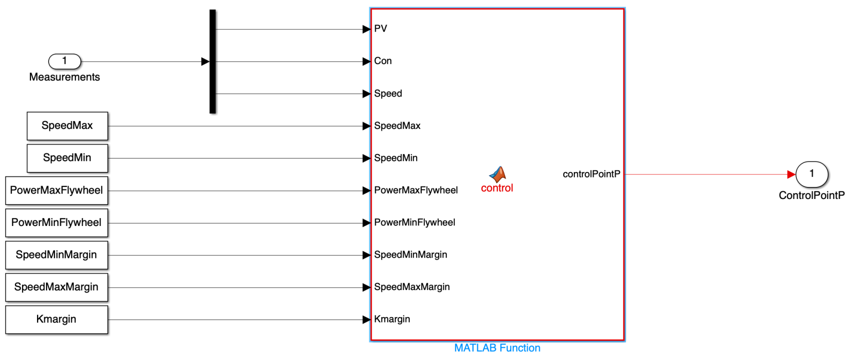

Figure 3.6: EMF flywheel model structure Simulink

3.3.4 Controller

The controller or control system has as objective to keep the flywheel speed close to it's optimal speed. Doing this, it will also smooth-en the power delivered with certain strength that will depend on a constant k.
The controller will adapt the input power coming from the EMF with a linear controller depending on the constant k. This means that the power added or subtracted to the input power will be equal to Speed*k.
The controller also contains a power limitation part that depends on the speed of the flywheel. As the power delivered by the flywheel is directly proportional to the rotational speed of the device, a lookup-table could be done bu using only two points: (0,0) y (W_{mas},P_{max}).
The new power supply of the flywheel calculated in controller is the output of this block and goes to the input of the next block that is the storage system.

Inputs of the controller:

- Power EMF
- Speed

Outputs of the controller:

- Power delivered flywheel

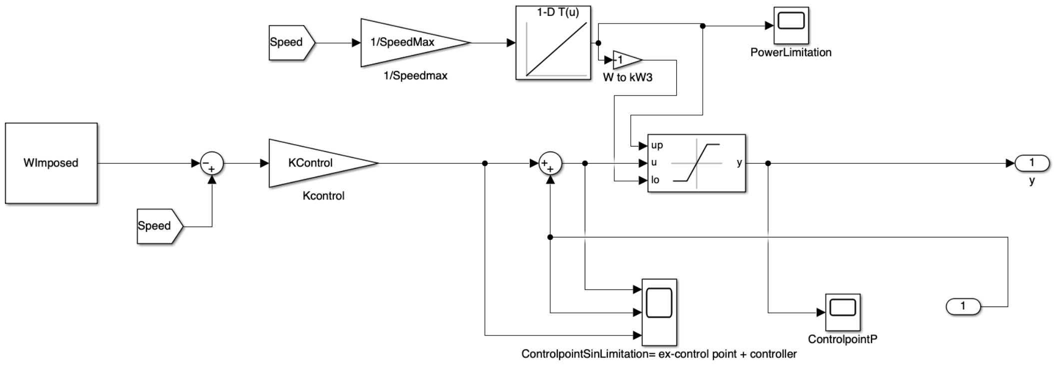

Figure 3.7: Controller flywheel model structure Simulink

3.3.5 Storage device

The main role of the storage device is to recalculate the speed, current and voltage at every iteration to give this information back to the EMF.
The speed and voltage are linearly related to a constant k_r that can be found by dividing the maximum speed with the maximum voltage.
The current can be found by dividing the power by the tension and the variation of the rotational speed ($\partial\omega$ is explained with the next formulas:

$$V = Speed * k2$$

$$I = P/V$$

$$\partial\omega == -(Te + T1)/J$$

with
$T_e = P/speed$
T_1 a friction constant
J the inertia

The friction constant is based on a 30% loss of energy of a flywheel in 2 hours, what is a usually used number for flywheel losses. The inertia is found with the next formula:

$$E = \frac{1}{2}\dot{J}\omega^2$$

with
E the energy of the flywheel
J the inertia of the flywheel
ω the speed of the flywheel

The energy E is coming from the calculations for the sizing of the flywheel that will be explained next in the next subsection.

This block will also be responsible for the adding of the efficiency of the flywheel. The recovered speed for the flywheel (When power is negative) will be multiplied by the efficiency that equal to 0.90 according to the Power Punch 200 flywheel.

The speed derivative will be integrated with an integration block to obtain the new speed of the flywheel after each iteration.

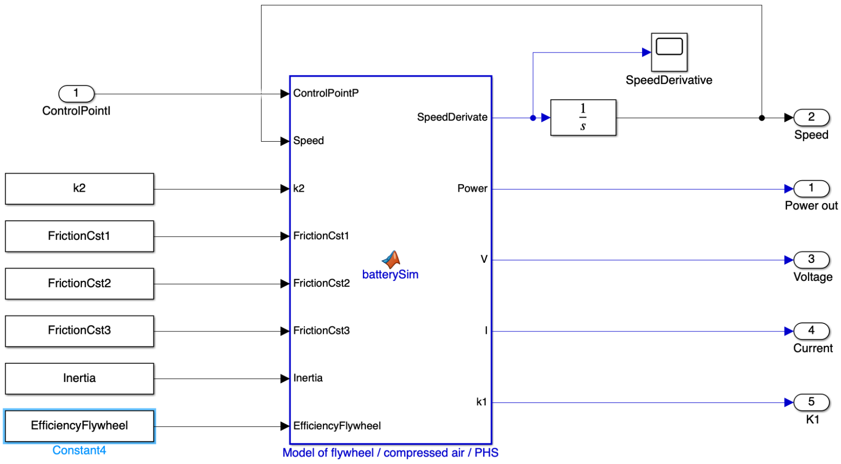

Figure 3.8: Storage device model structure Simulink

3.3.6 Sizing flywheel

The values used for the flywheel has been found thanks to a mix of, using values coming from the model Punch Power 200, and calculations about the flywheel. All the values taken from the Punch Power 200 have been explained above. The calculations for the sizing of the flywheel are the next once:
The aim was to have a 10kW capacity storage system divided in two different flywheels. It is assumed that the capacities can be summed together. The next numbers have been fixed:

- Capacity : 5kWh $(5.4 \cdot 10^7)$
- Volumic mass : 7900 (Steel)
- Height : 1m

Knowing

$$E = \frac{1}{2} \cdot E_k(\omega_{max}^2 - \omega_{min}^2)$$

With E_k the capacity and ω the speed max and min.
It is possible to calculate the inertia J

$$J = \frac{(2 * E_k)}{(\omega^2 - \omega^2)}$$

knowing

$$J = \frac{1}{2}mr^2$$

$$J = \frac{1}{2}\rho V r^2$$

With m the mass and r the radius
It is possible to compute the radius r

$$r = \sqrt[4]{2\frac{\rho\pi d}{J}}$$

The value computed for radius is 36cm. This chape of flywheel is possible and manufacturable.

3.4 Lithium-ion and flywheel combined

In this section a combined model of the sized flywheel connected to battery we be used as energy storage system for the household. The connection of those two models together will be explained.

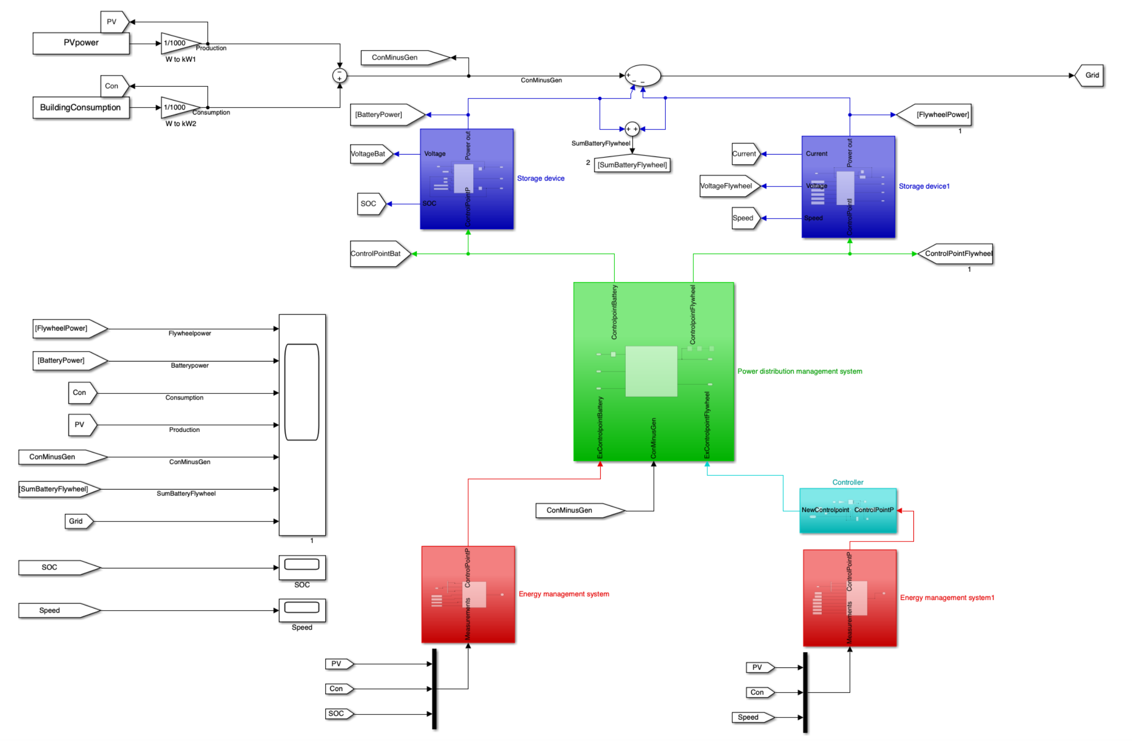

Figure 3.9: Combined model structure Simulink

3.4.1 EMS

The EMS system of both the flywheel and the battery will be separated. The function of this block will be exactly the same as in the separated models. This means that each storage system will act exactly like it has to supply the demand without taking into account the other storage system. This issue will be fixed in the next block, the Combined controller.
It is important to note that the controller of the flywheel also acts in the exact same way as in the separate model of the flywheel.

3.4.2 Combined controller

The combined controller is responsible to determine which storage system has to supply in priority the demand before the other one. The inputs of this block will come from both EMF's and the consumption minus the generation who is basically the energy to supply for the complete storage system.

The idea for the distribution of the supply is to work with a couple of points where point one is has I priority in front of point two, two in front of three etc.

1. The main objective is to supply as best possible the demand to try to rely the least possible on the grid, to save money, and avoid gas emissions.

2. Then there is the idea of longevity of the full storage system. The longer the system can work wiithout need of replacement the better the LCOE and impact on the nature. As the flywheels are wellknown to have really large life expectancies in terms of number of cycles. This is not the case for the battery. The life expectancy of the battery can vary depending on multiple factors. One of them is the use of power deliveries of with high ramp, big derivatives

of the power. For this reason the combined controller will limitate the ramp of the battery and prioritize the flywheel when ramps are to heavy and could damage the life expectancy of the battery.

3. The last point in this list is a general prioritizing of the battery before the flywheel because the capacity of the battery is bigger.

Many other points could have been implemented depending on the exact application and use of the storage system.

The main idea of this block, is to use a ramp limiter in the derivative of the power of the battery. In the code a couple of if functions will be used to make the battery supply, and if the ramp limits it full supply or the battery has it's SOC close to 0 then the flywheel will power the part that has to be powered. The outputs are the final supply of the battery and flywheel seperated.

Inputs of the combined controller:

- Power battery
- Power flywheel
- Consumption minus generation

Outputs of the combined controller:

- Power battery
- Power flywheel

3.4.3 Storage device

The storage device of both parts of the complete storage systemn will have the exact same function as in the separated models. This means, for the battery, with a couple of inputs it will recalculate the SOC, voltage and current at every iteration. For the flywheel, it will recalculate the speed, voltage and current at every iteration.
The informations calculated at every iteration are used in both EMF to determine the power of each storage system.

3.5 Prices and consumption computations

Each of the previous models has a block that is in charge to calculate different usefull values for the general research of this doxument. This block is basically the same in each model and will make computation about consumption, money saved, co2 avoided etc.

The main idea of this block is to take as input the generation, consumption, energy given to the grid and energy prices to be able to give many different information about prices, grid dependency and CO2 rejection avoided.

The values computed are integrated values for the 24 hours of calculation. It means that for example the general consumption of the household will be the integration of the consuption during the whole day.

It is important to note that when the price paid to the distributor is calculated, only the positive values of the energy given the grid are integrated because we consider no money recieved for energy given to the grid.

The CO2 production is calculated with a mean CO2/kWh of energy rejected in Belgium in 2021. The energy prices are the prices of one specific day in Spain. This is explained in point 3.1.

Inputs of prices and consumption computations :

- Solar panel generation
- Household consumption
- energy given to the grid
- CO2 production constant

Outputs of the prices and consumption computations:

- Total consumption
- Total production
- Total consumption minus production
- Total energy taken from the grid without storage system
- Total energy taken from the grid with sorage system
- Price of the day (Scope)
- Average price of the day
- Price energy supply of the day without energy storage system neither solar panels
- Price energy supply of the day without energy storage system
- Price energy supply of the day with energy storage system
- Money saved with storage system
- Money saved with total installation (Solar installation plus storage system)

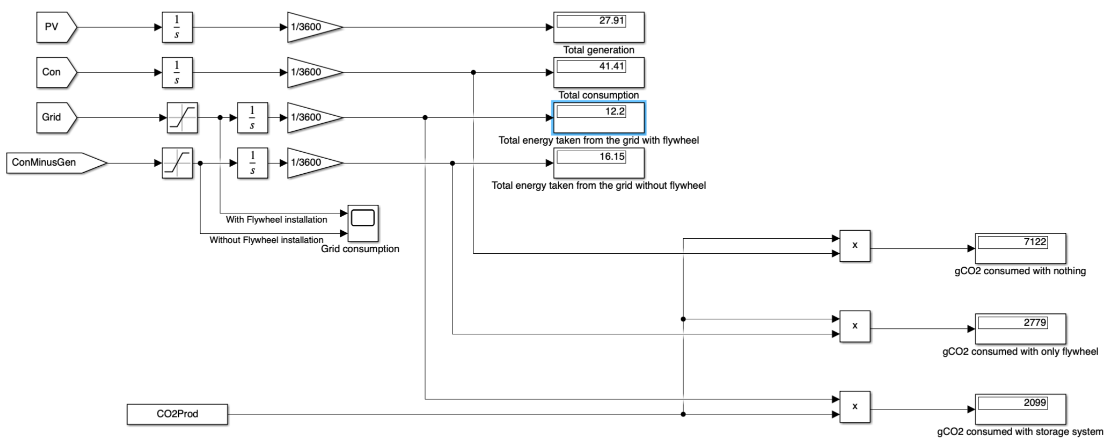

Figure 3.10: Consumption computations model structure Simulink

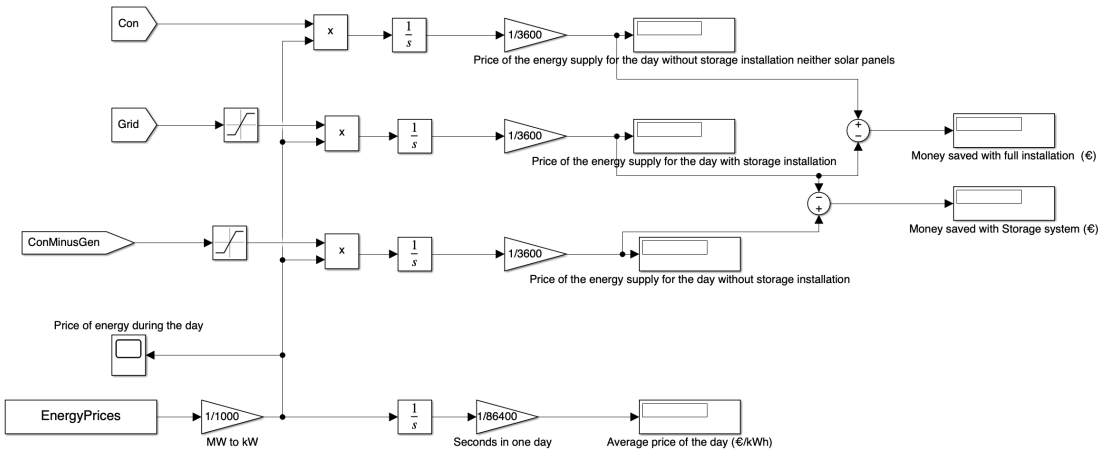

Figure 3.11: Finanacial computations model structure Simulink

3.6 List of assumptions

This section is a full list of all the assumptions that have been used for the model. Most of them have been explained in this chapter but are listed once again here:

- The model is a 8640 seconds model (24h) with a 1 second iteration
- The friction of the flywheel is independent with the speed
- Production and consuption values are taken from a private solar panel installation in Belgium near Brussels (50.700374) 4.471177)
- The prices for the energy are taken from Spain the 16/06/2022
- The initial SOC is 0.5 and initial speed of the flywheel is 300 rad/s
- The lookup table for the SOC-Voltage link is taken from another lithium-ion battery and adapted to fit in the right numbers for this application
- The Maximum and minimum SOC are fixed at 85% and 10%
- The roundup efficiency of the flywheel has been set at 90%
- The kinetic energies of two flywheels are summed
- The formula for the inertia of a cylinder is used for the flywheel
- The minimum speed for the flywheel is fixed at 100 rad/s
- The maximum ramp for the battery is fixed at $30 * 10^{-4}$ kW/s
- The minimum power of the flywheel is fixed at 0.1kW
- The minimum power of the flywheel is fixed at 0.1kW

Chapter 4

Analysis and Overall feasibility

In this section the results of the models will be computed and explained. Comments will be given about the feasibility and financial aspect of every of the model tested. A big chart will compare all the numbers obtained to have a clear view about the performances of every technology tested.

4.1 Initial investment

Investment prices of solar generation and energy storage are varying a lot since a few years. It is difficult to determine how prices will vary in the future. The prices are especially high at the moment and this is due to raw material market prices. With covid and political tensions in Europe these raw materials became really expensive while it looks to go down to a more stable price in the future.

The prices for the investing needed for the different models and solar panel installation have been inspired by a document written by The Italian Association of Chemical Engineering [14]. Making an own more complex computation with the Capex, Opex, LCOE etc would have been interesting but goes beyond the boarders of this document. The values use will be the next one:

- CAPEX Solar panel installation : 1120€/kW
- CAPEX Lithium-ion battery : 280€/kWh
- CAPEX Flywheel storage : 560€/kWh

Knowing this it is possible to calculate the initial investment needed for the three technologies.

Solar panel installation

The solar panel installation is a 10kW installation.

$$1120 * 10 = 11200$$

Battery

The battery installation is supposed to be able to store 16kWh of energy

$$280 * 16 = 4480$$

Flywheel

The flywheel installation is composed of two flywheel that both can store 5kWh of kinetic energy.

$$560 * 10 = 5600$$

It is important to note that as this technology is still under research, it is possible that in a few years this value doesn't look relevant at all.

Full model

$$11200 + 2280 + 5600 = 19080$$

4.2 Performance comparison

In this section a chart with all the main results of the models for the different test-days will be given to make comparisons between the technologies.

Day 1

DATE	Grid consumption [kWh]	Electricity costs [€]	Investment costs [€]	CO2 consumption [g]
No installation	50,42	8,911	0	8672
Solar panels	29,35	5,563	11200	5048
Panels + Battery	10,78	2,122	15680	1854
Panels + Flywheel	17,28	3,417	16200	2971
Full installation	7,268	1,41	20680	1250

- Total solar panel production : 36,34[kWh]
- Average price of energy : 0,1704[€/kWh]

Day 2

DATE	Grid consumption [kWh]	Electricity costs [€]	Investment costs [€]	CO2 consumption [g]
No installation	43,84	7,17	0	7540
Solar panels	11,07	2,042	11200	1905
Panels + Battery	0,007552	0,001377	15680	1,299
Panels + Flywheel	0,6932	0,1219	16200	119,2
Full installation	0,00651	0,001215	20680	1,121

- Total solar panel production : 74,32[kWh]
- Average price of energy : 0,1704[€/kWh]

Day 3

DATE	Grid consumption [kWh]	Electricity costs [€]	Investment costs [€]	CO2 consumption [g]
No installation	41,41	6,834	0	7122
Solar panels	16,51	2,796	11200	2779
Panels + Battery	6,55	1,205	15680	1127
Panels + Flywheel	12,2	2,153	16200	2099
Full installation	5,48	1,085	20680	942,6

- Total solar panel production : 27,91[kWh]
- Average price of energy : 0,1704[€/kWh]

4.3 Analysis

The different numbers seen in the charts are giving interesting information about the usefullness of each of the technologies in this application. The values given mainly show the financial attractiveness and the CO2 consumption avoided. With the investment costs on the side it is possible to do easy calculations to obtain the time needed to recover this investment depending on your specific application.

The first day that represents a classic day that is not fully sunny shows that each technology is diminishing a lot the consumption and energy budget of the day. Nevertheless none of the storage systems are able to fully supply the demand. It can be important to note that with a 20k € investment the energy costs of the day are going from 9 to 1,5€. If every day of the year would be like this one 2737€ would be saved each year. Would mean that in this favorable situation only 7 years would recover the total investment. It is also interesting to note that the two other investments like only battery or only flywheel could be interesting in terms of time of recovery on the investment in this situation, 6.3 years and 8 years respectively. Even if it looks like the battery is the best investment it may not be because the battery has the lowest cyclability. The best in terms of life expectancy is the flywheel while the complete model has a better cyclability than the battery thanks to the imposed ramp in the power of the battery in the model.

The second day shows that the three different storage systems are bringing the consumption close to 0. This means that the dependence to the grid is very low in this kind of situation with good sun and appropriated consumption during the day. Even if the flywheel looks to not be the best in terms of pure results it could be considered better thanks to it's long life expectancy and ethical advantages compare to the full model or lithium-ion battery model.

The last day that represents a day with a lower sun production shows that the model adapted well to this lack of sun and the grid dependancy stayed quite low. The performance of the lithium-ion battery is nearly two times better than the flywheel while the full model isn't really perfoming better than the battery.

It is important to note that the flywheel starts the day with a speed of 300 rad/s and the battery with a SOC at 0.5. To be more precise a simulation should be done on multiple days to represent better the initial charge that depends on the day before

4.4 Graphs

This section will show you all the informations obtained with the models through all the interesting graphs that the model is plotting.
It is important to note that Battery power is the power delivered by the battery. The limited ramp can be seen in the fullmodel.
The flywheel power is the energy exchanged with the flywheel.
A positive value for these powers means a discharge for the battery/flywheel and a negative power means a charge.
The energy exchanged with the grid represents the energy taken from the grid when it is positive and given to the grid when it is negative.
The consumption minus the generation (ConMinusGen) represents the energy that the storage system has to supply.
In the fullmodel, the Battery power plus the flywheel power (SumBatteryFlywheel) represents the energy given from the complete energy storage system.

4.4.1 Day 1

Generation-demand

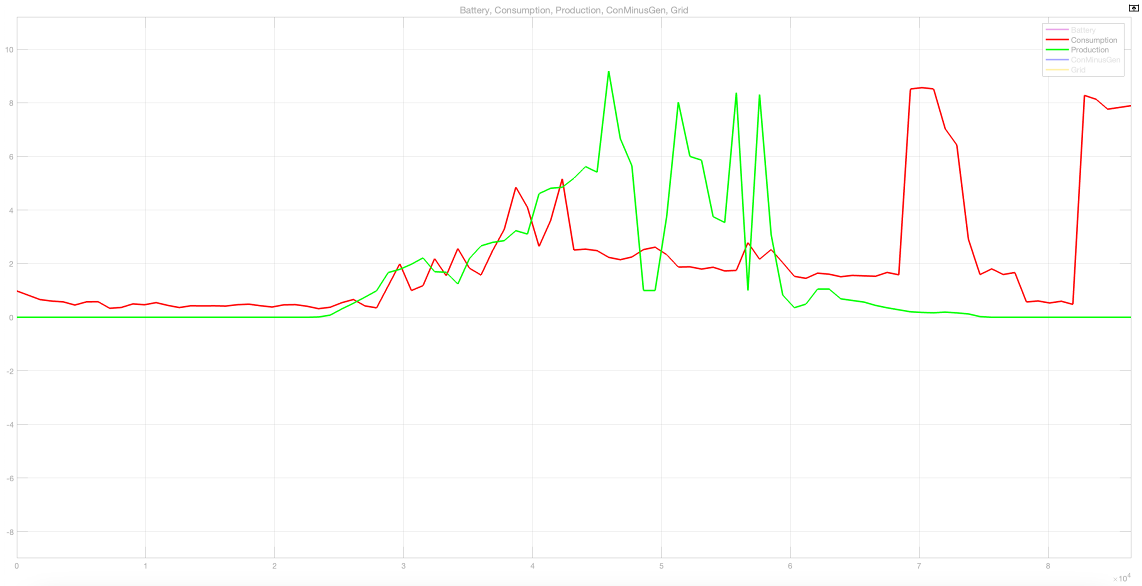

Figure 4.1: Generation(red)-Demand(green)

Battery model

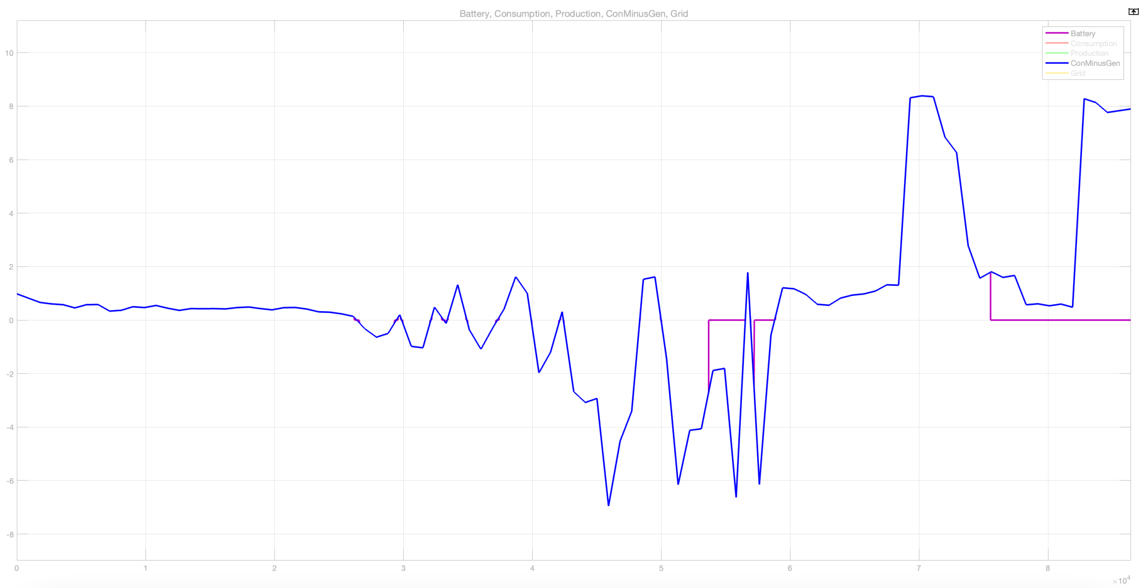

Figure 4.2: Battery power(purple)-Consumption minus generation(blue)

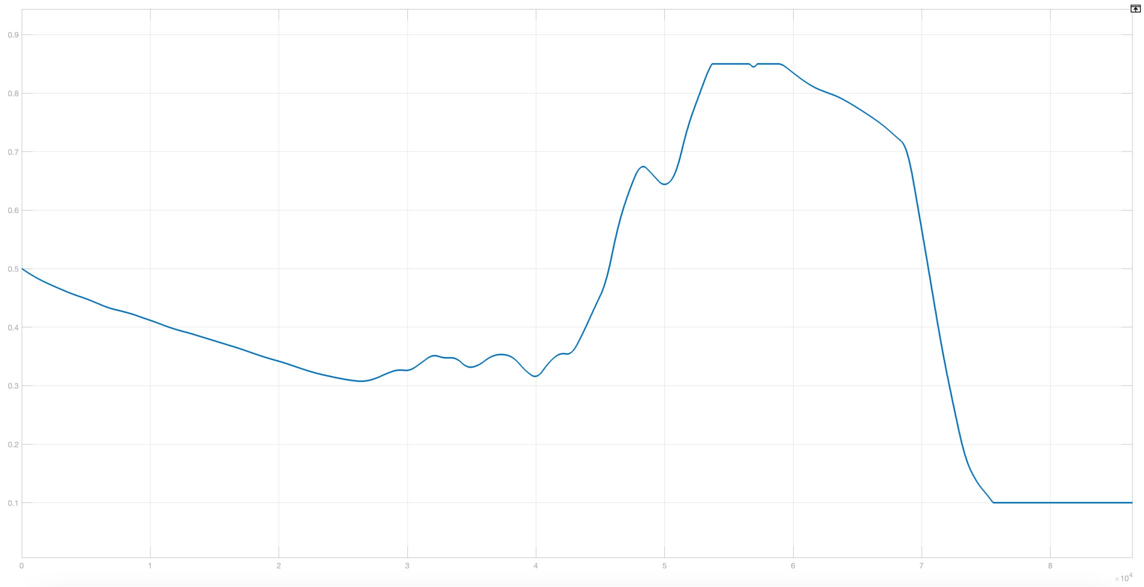

Figure 4.3: SOC(blue)

Figure 4.4: Energy exchanged with the grid(yellow)

Flywheel model

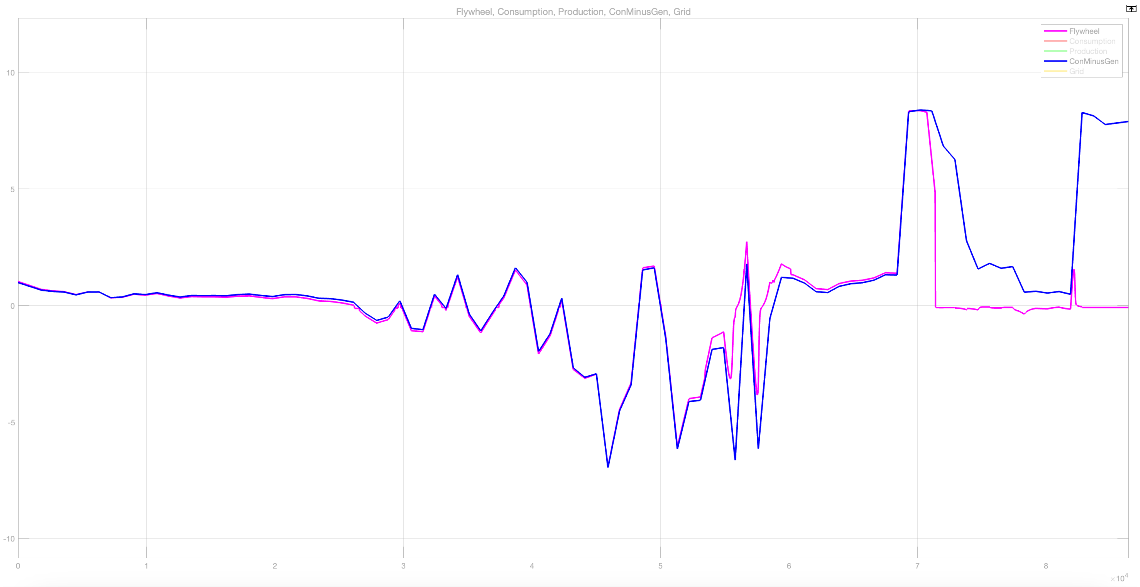

Figure 4.5: Flywheel power(purple)-Consumption minus generation(blue)

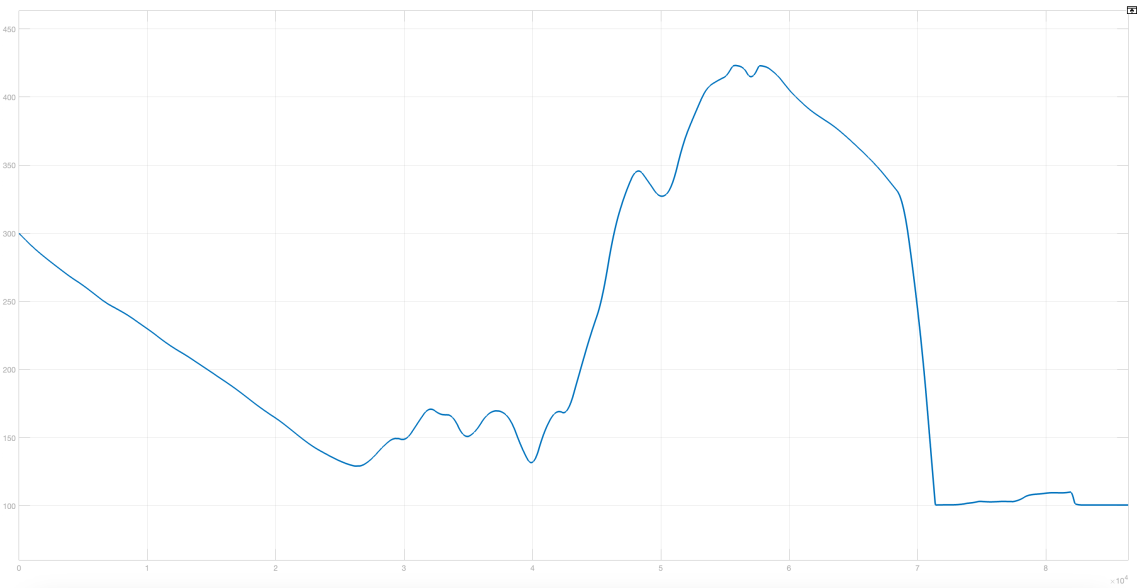

Figure 4.6: Speed(blue)

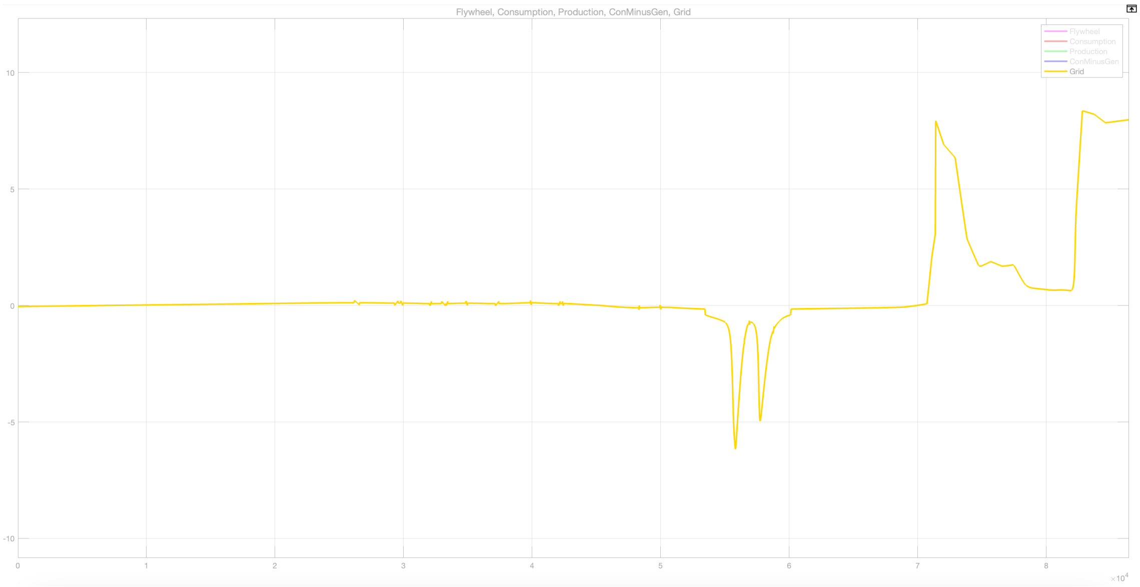

Figure 4.7: Energy exchanged with the grid(yellow)

Full model

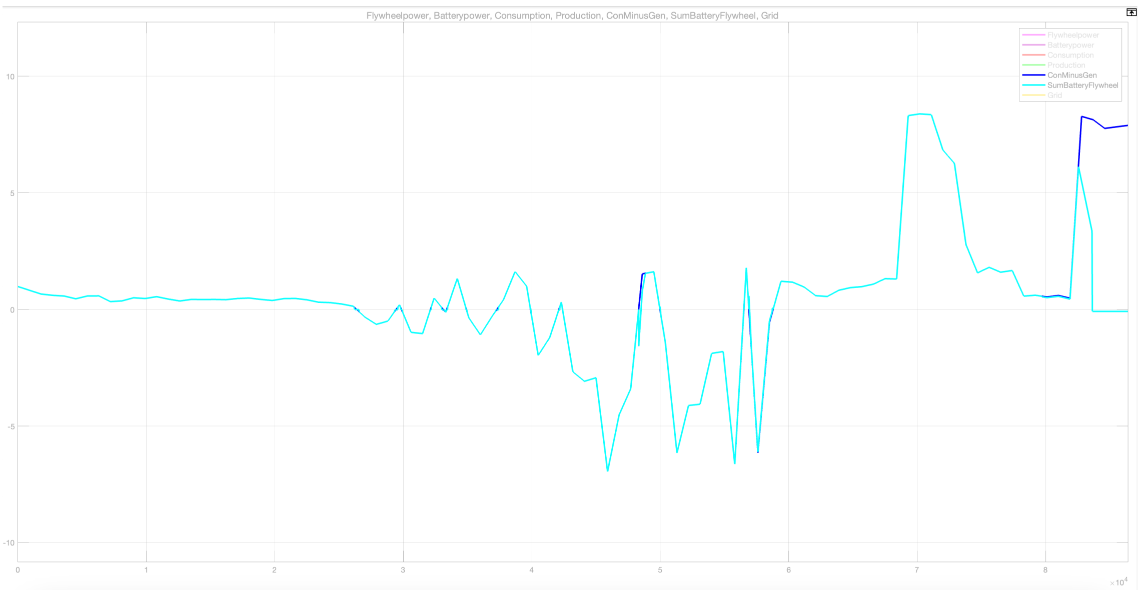

Figure 4.8: Battery power plus flywheel power(cyan)-Consumption minus generation(blue)

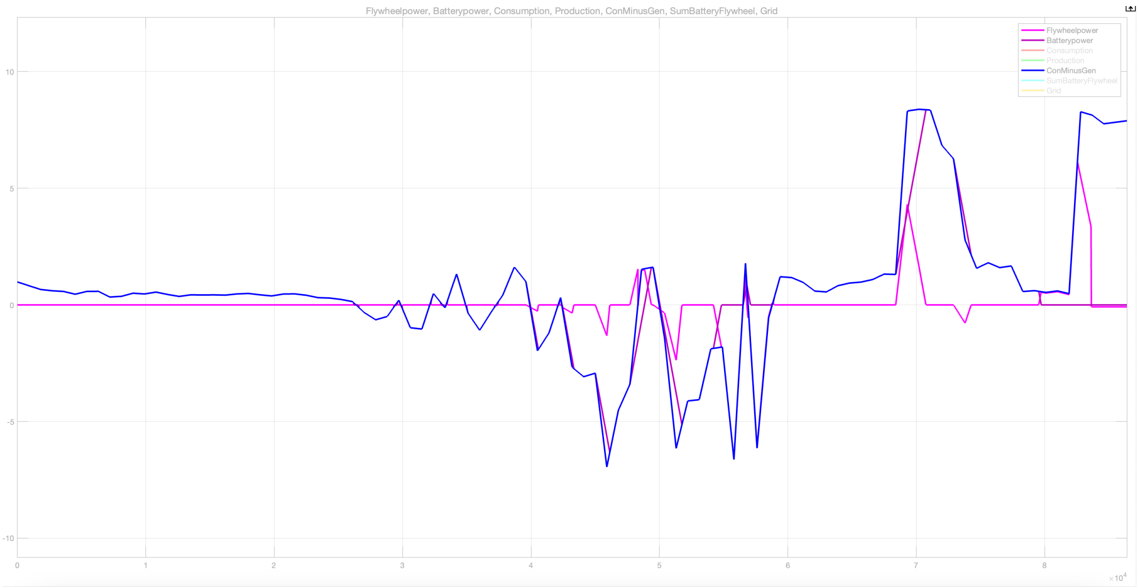

Figure 4.9: Battery power(purple)- Flywheel power(pink)-Consumption minus generation(blue)

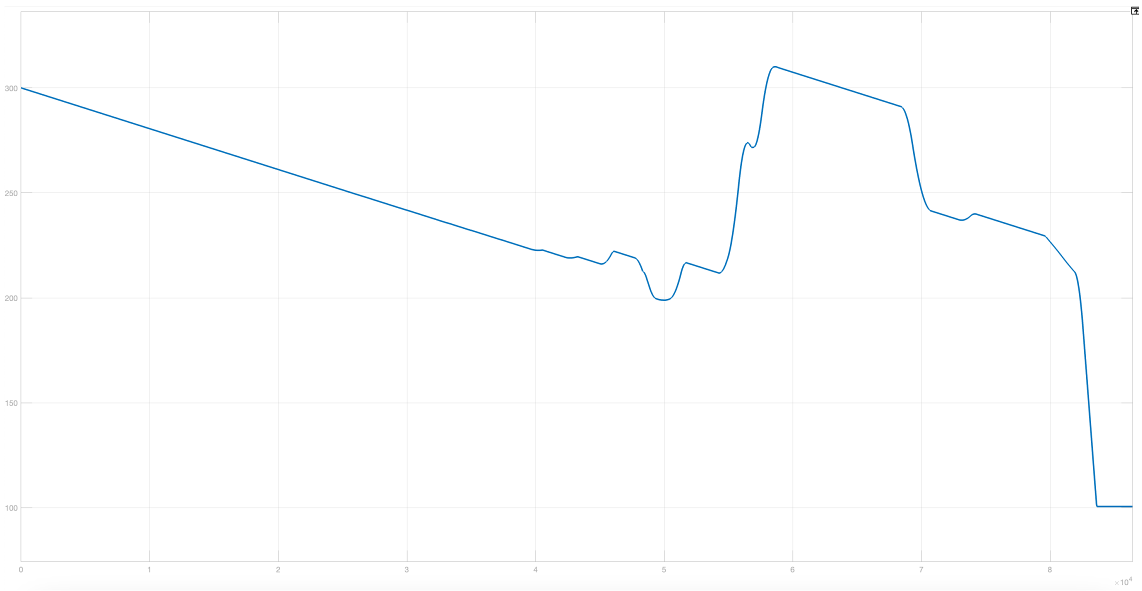

Figure 4.10: Speed(blue)

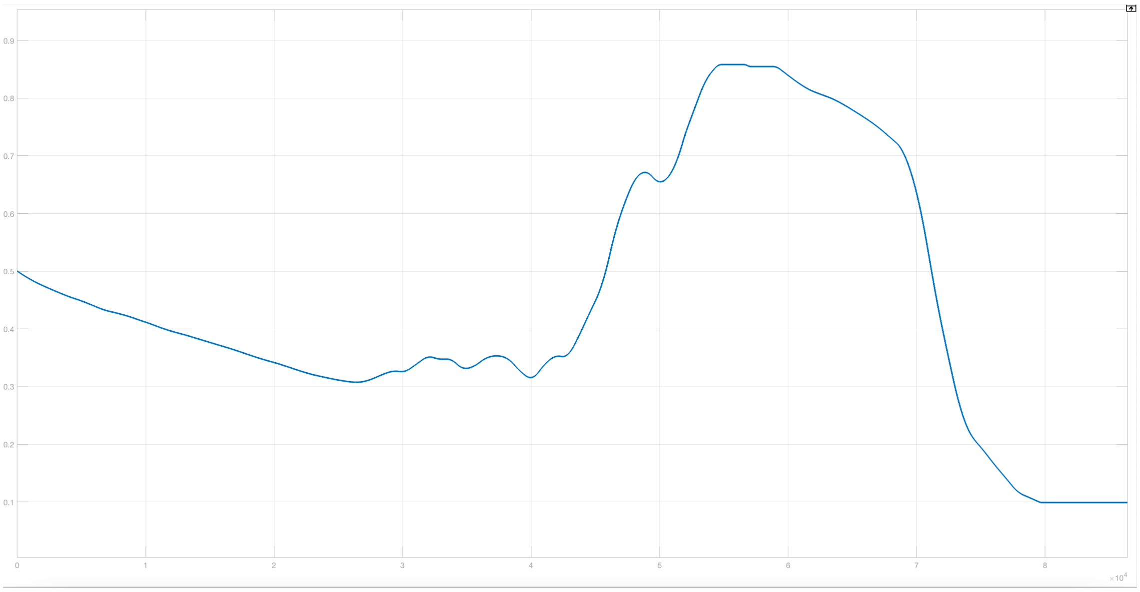

Figure 4.11: SOC(blue)

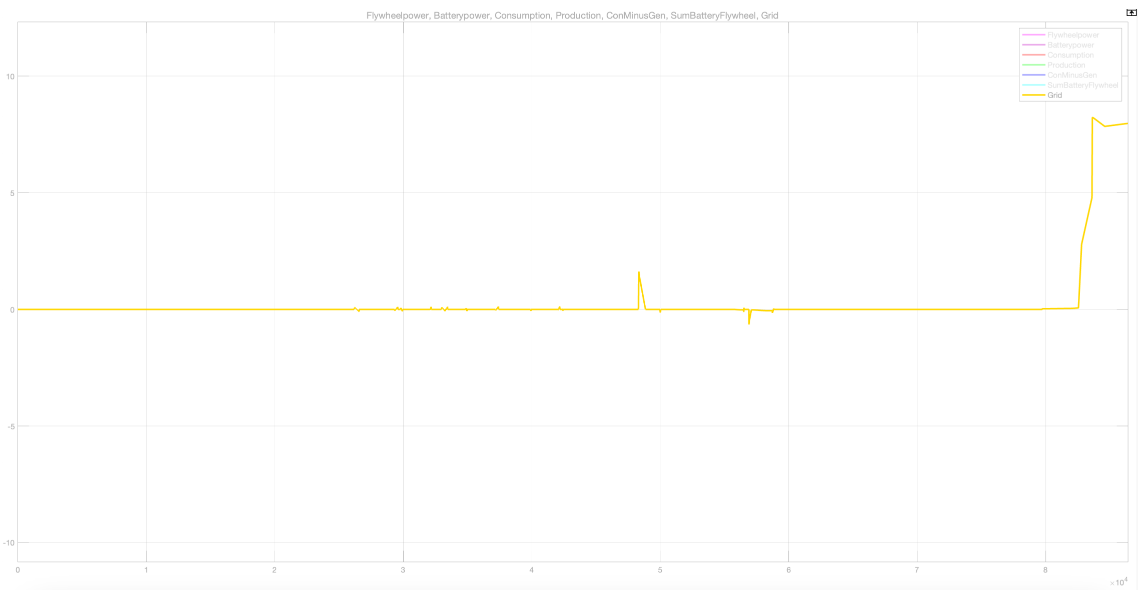

Figure 4.12: Energy exchanged with the grid(yellow)

4.4.2 Day 2

Generation-demand

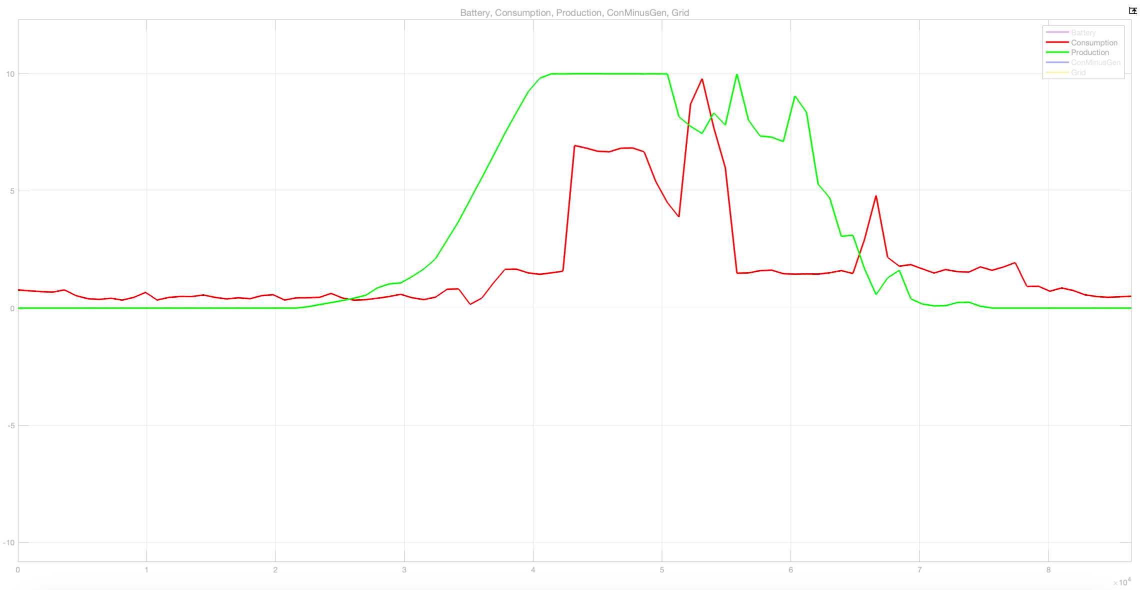

Figure 4.13: Generation(red)-Demand(green)

Battery model

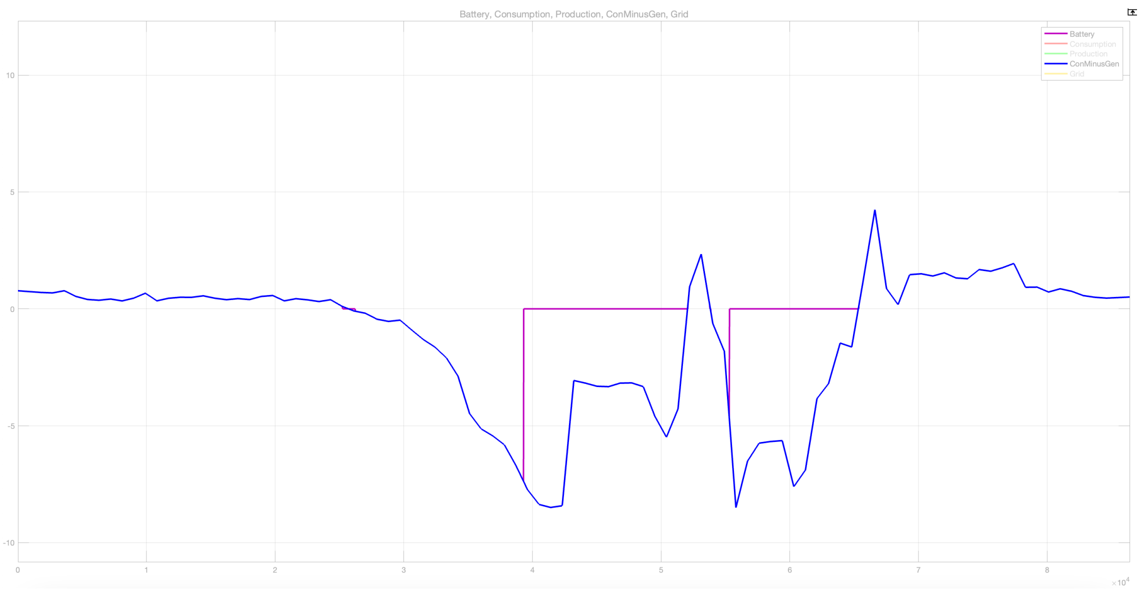

Figure 4.14: Battery power(purple)-Consumption minus generation(blue)

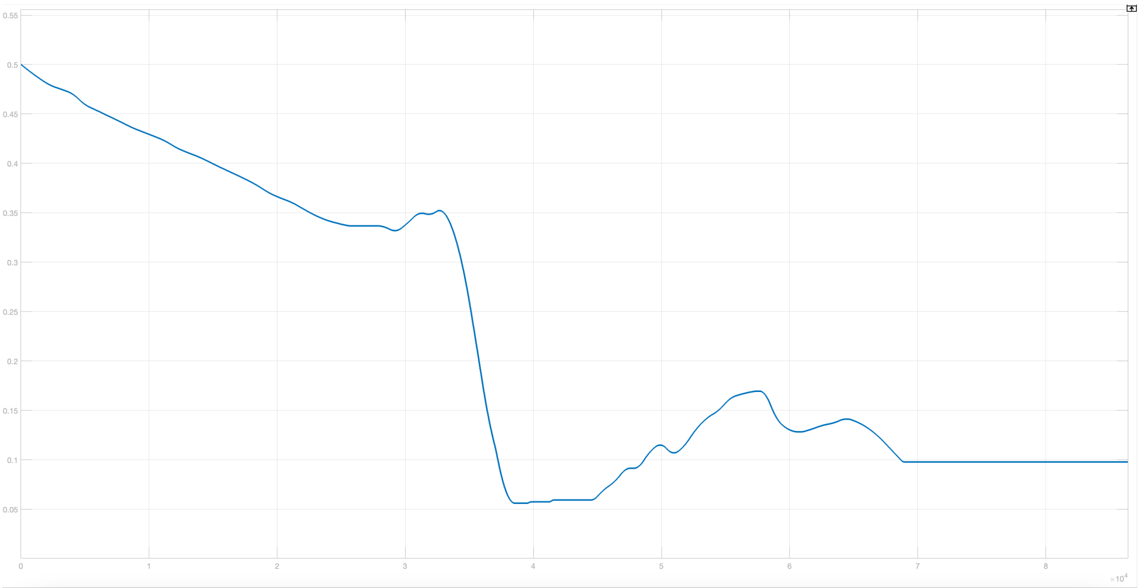

Figure 4.15: SOC(blue)

Figure 4.16: Energy exchanged with the grid(yellow)

Flywheel model

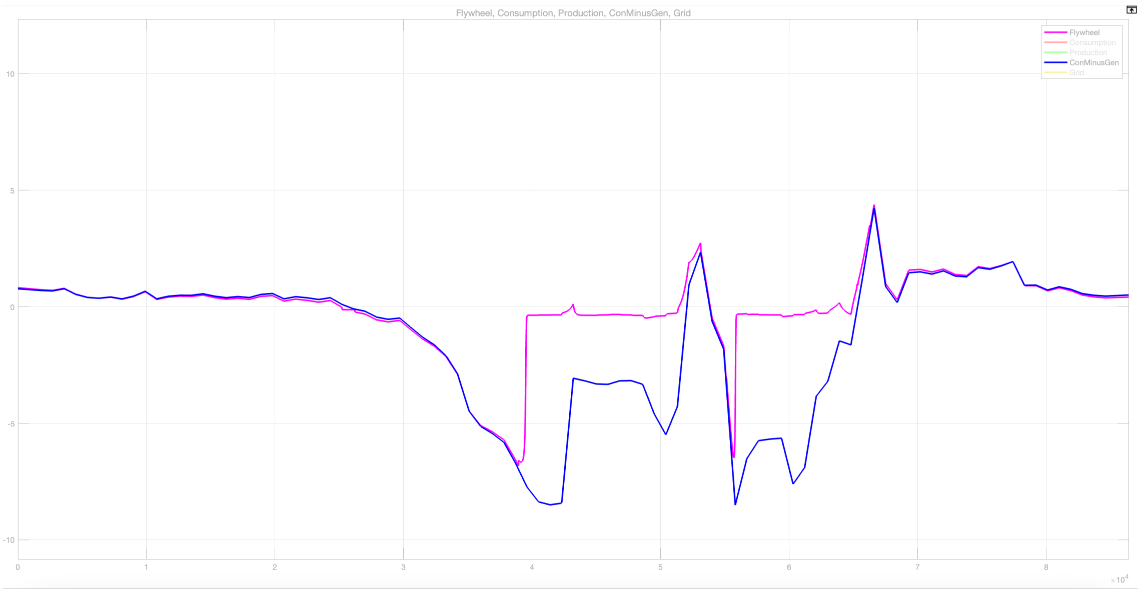

Figure 4.17: Flywheel power(purple)-Consumption minus generation(blue)

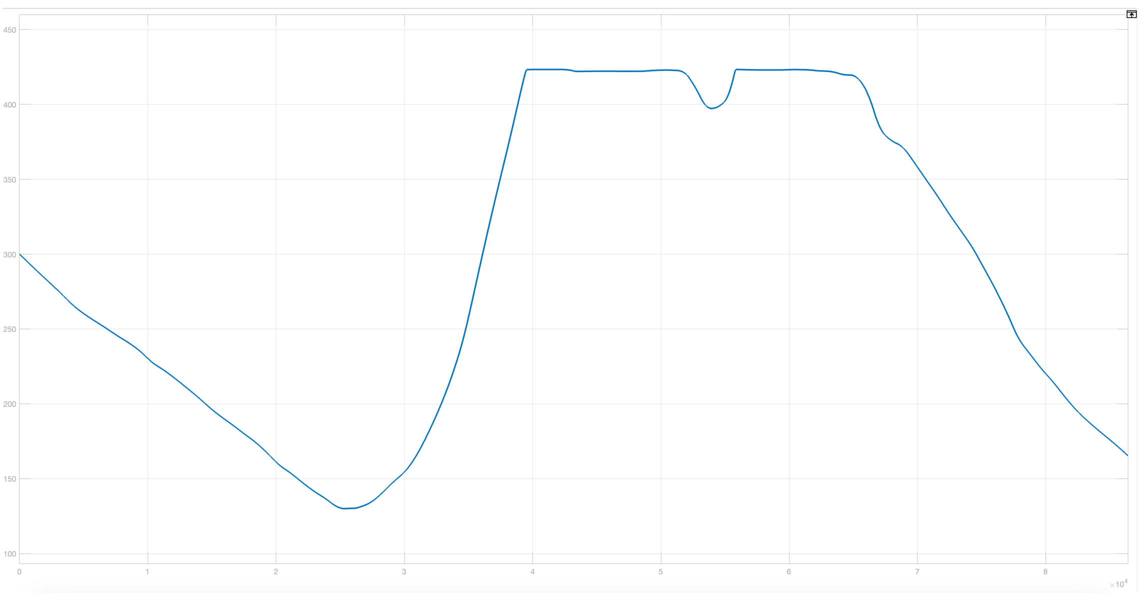

Figure 4.18: Speed(blue)

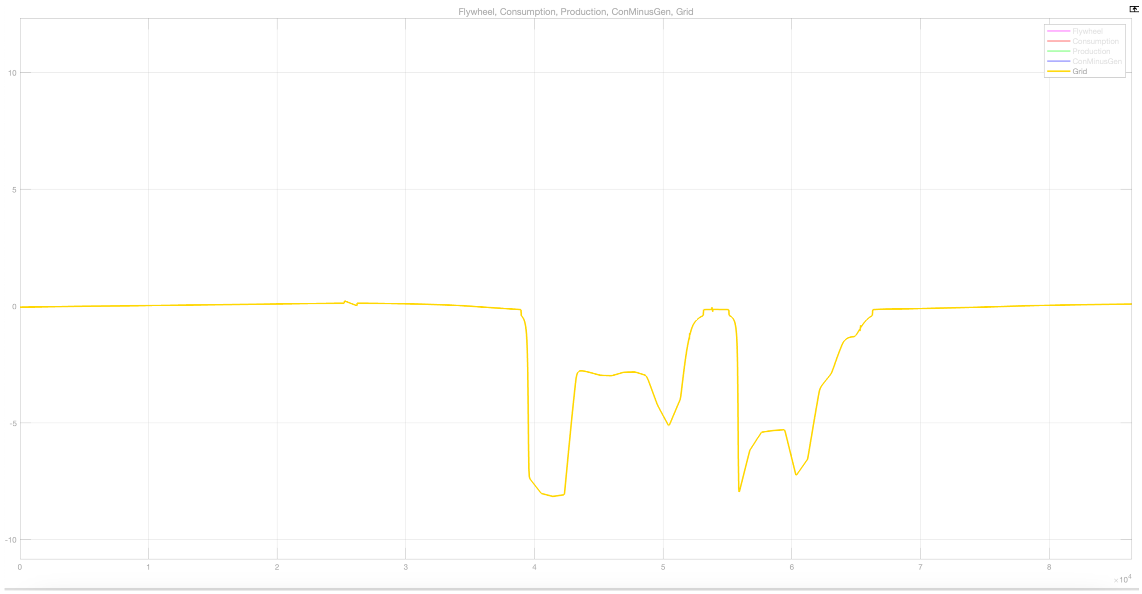

Figure 4.19: Energy exchanged with the grid(yellow)

Full model

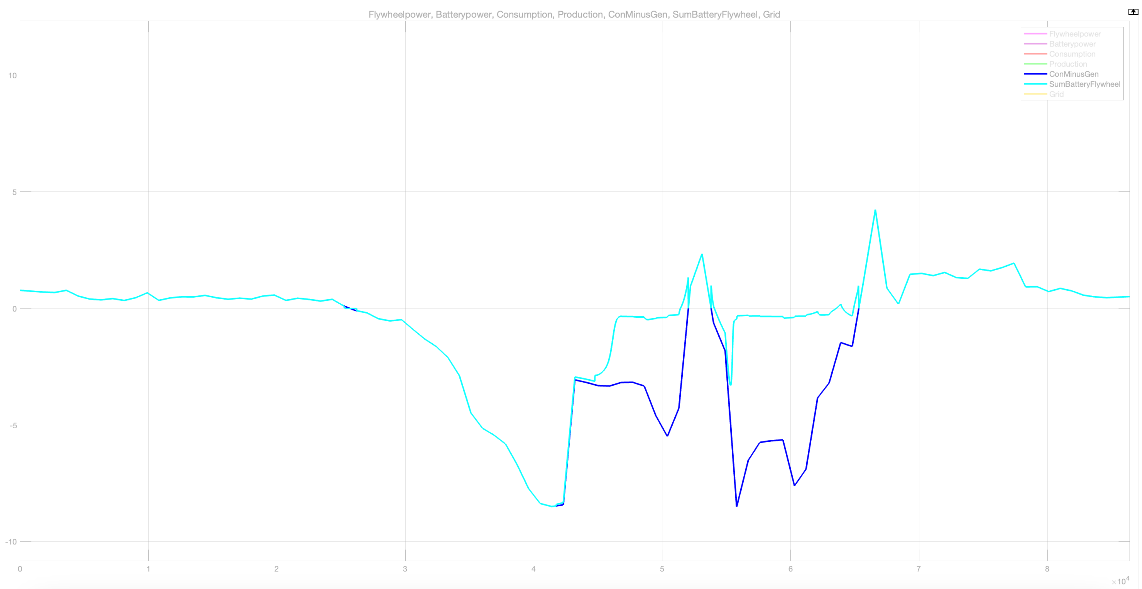

Figure 4.20: Battery power plus flywheel power(cyan)-Consumption minus generation(blue)

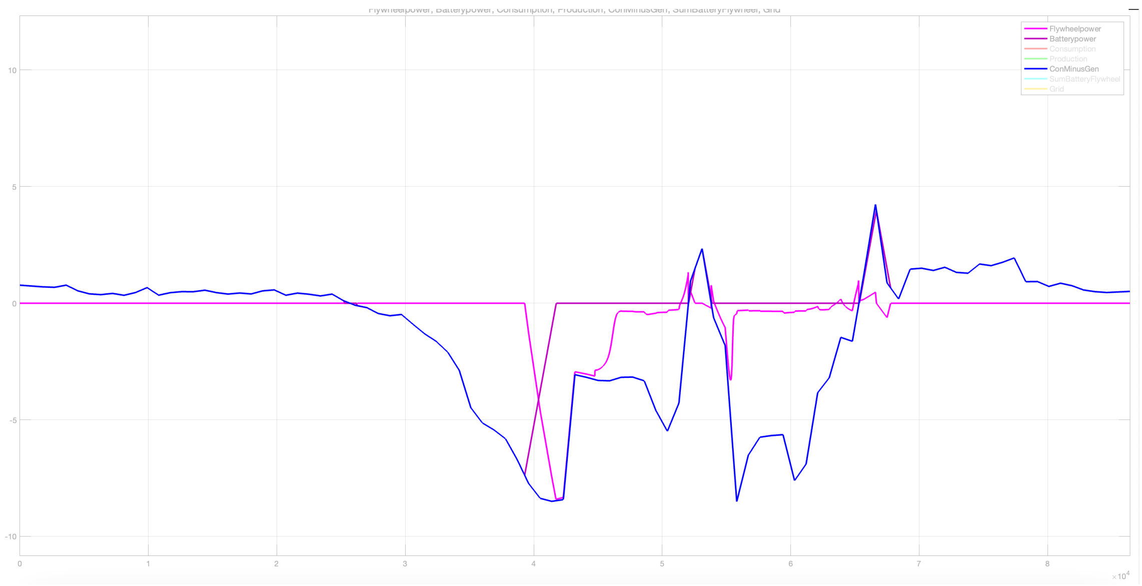

Figure 4.21: Battery power(purple)- Flywheel power(pink)-Consumption minus generation(blue)

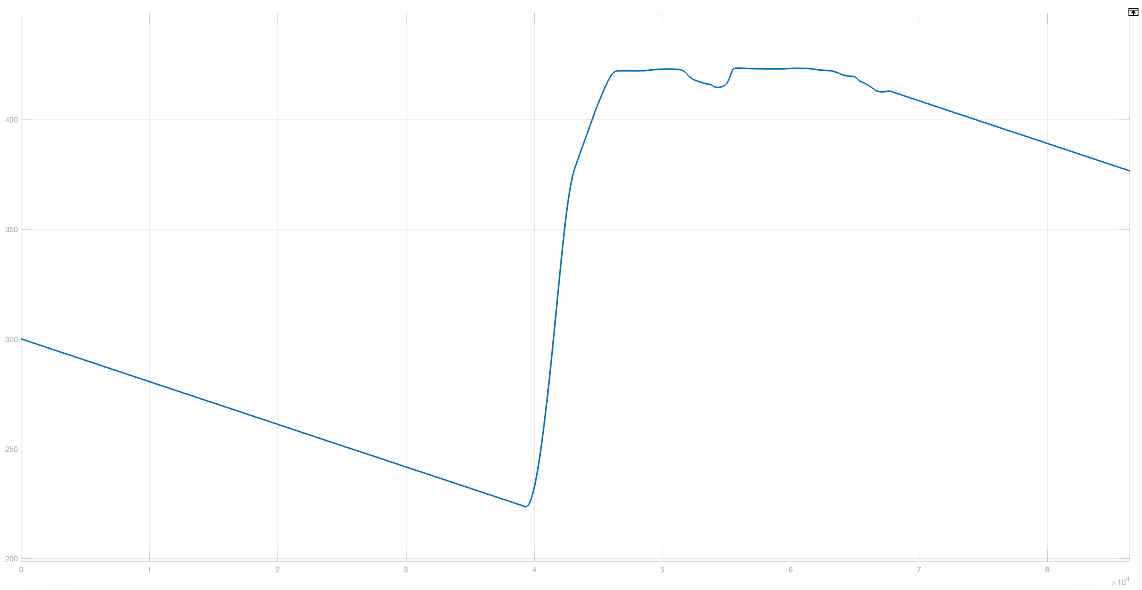

Figure 4.22: Speed(blue)

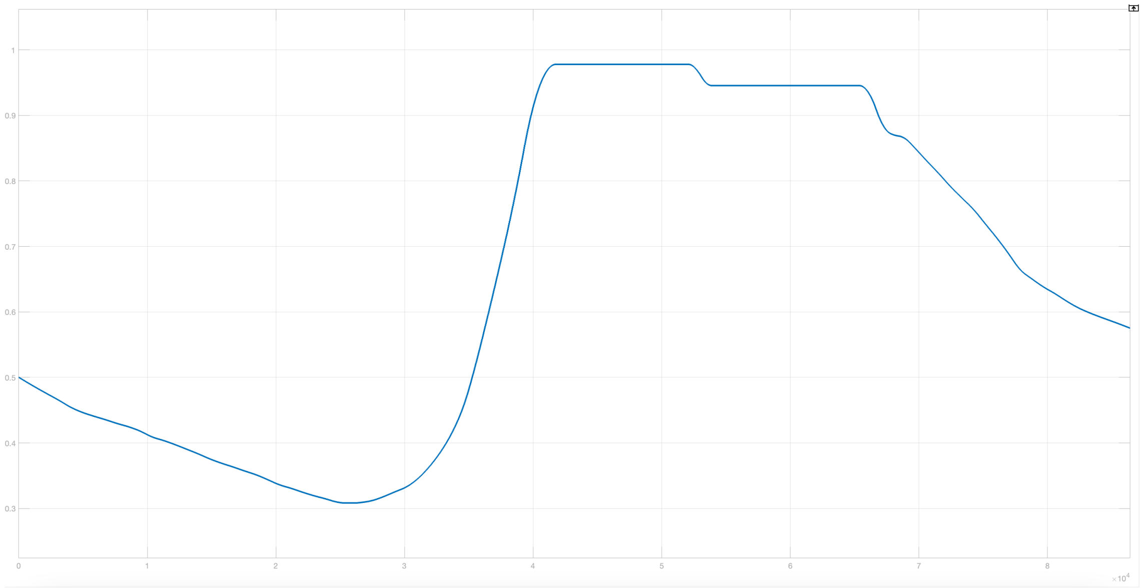

Figure 4.23: SOC(blue)

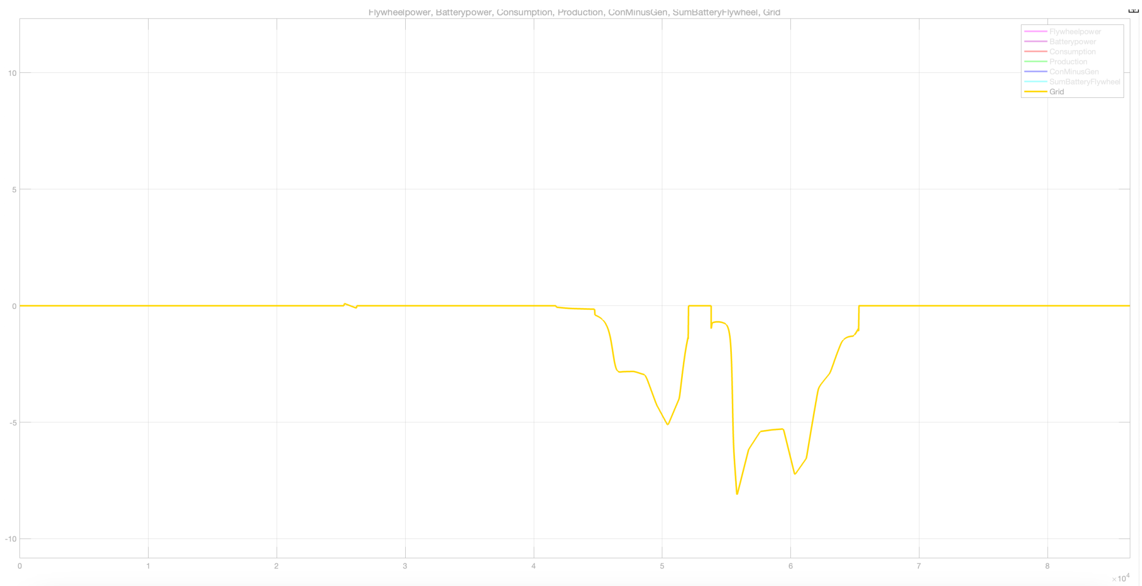

Figure 4.24: Energy exchanged with the grid(yellow)

4.4.3 Day 3

Generation-demand

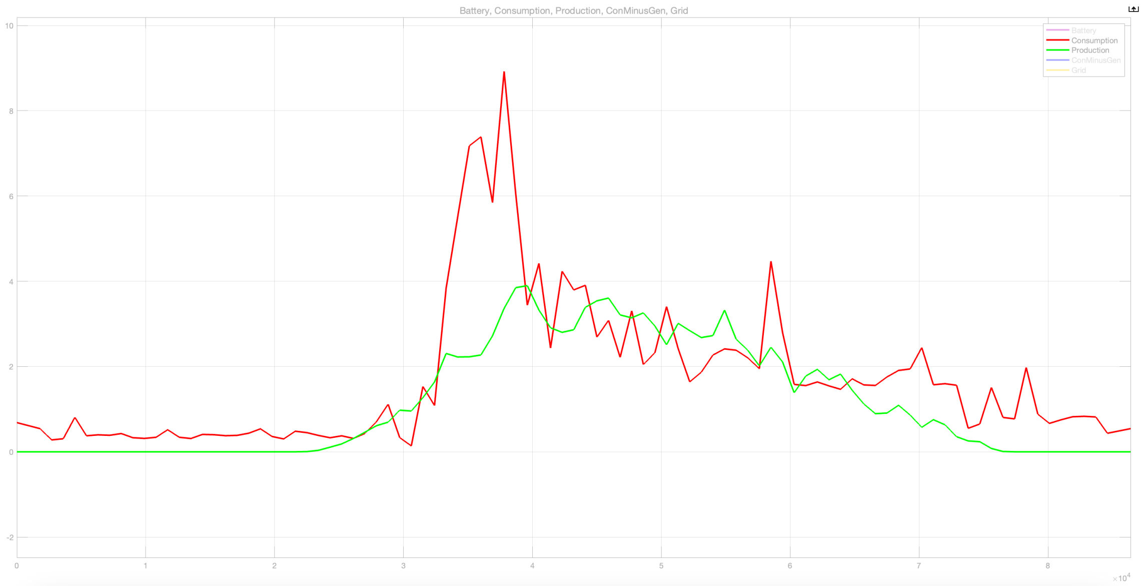

Figure 4.25: Generation(red)-Demand(green)

Battery model

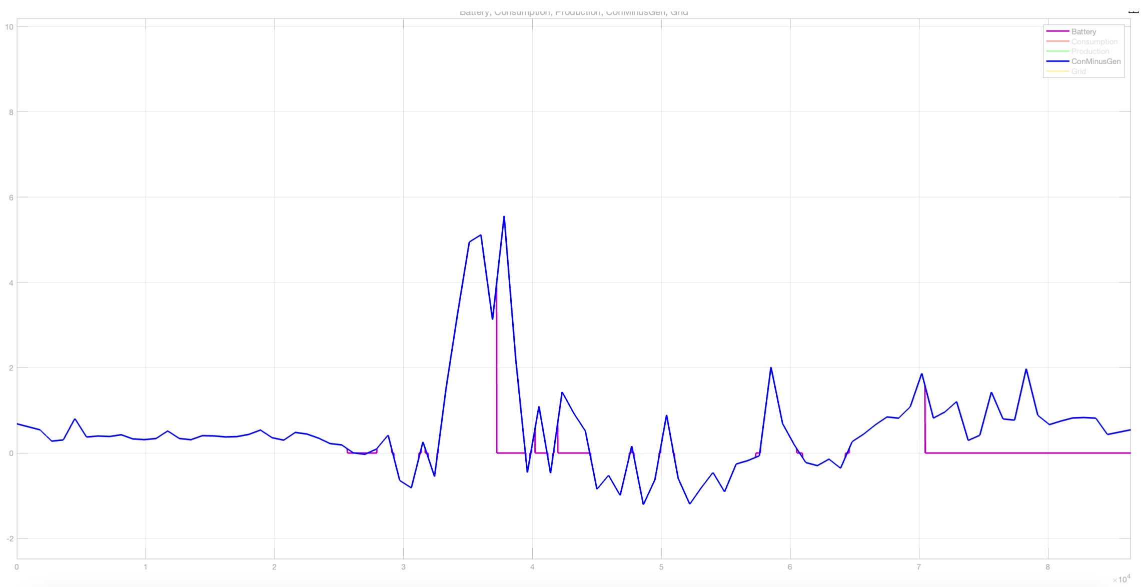

Figure 4.26: Battery power(purple)-Consumption minus generation(blue)

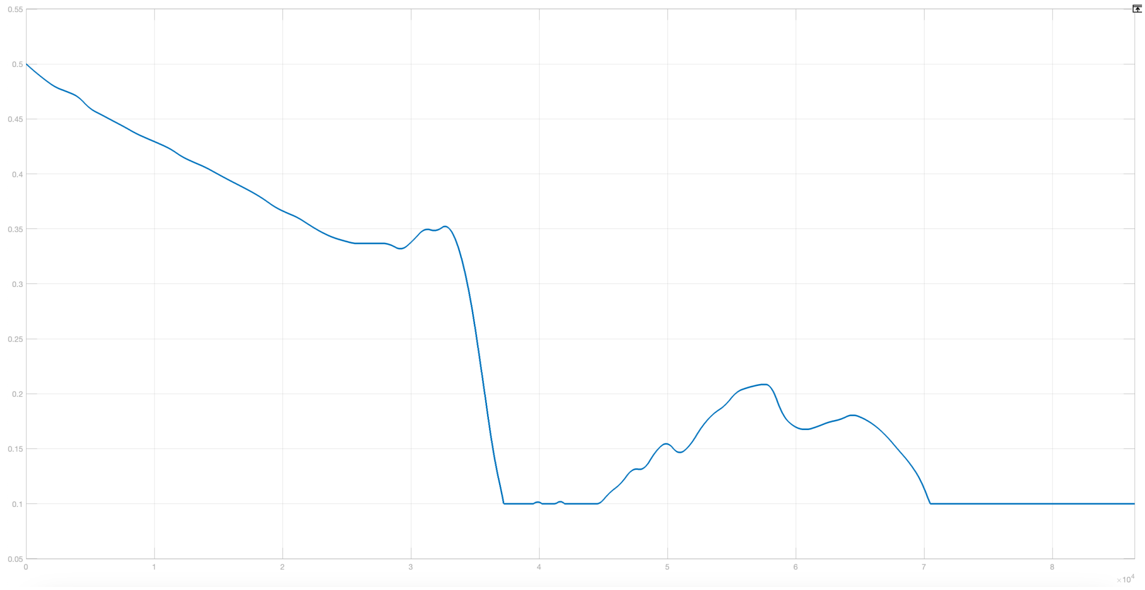

Figure 4.27: SOC(blue)

Figure 4.28: Energy exchanged with the grid(yellow)

Flywheel model

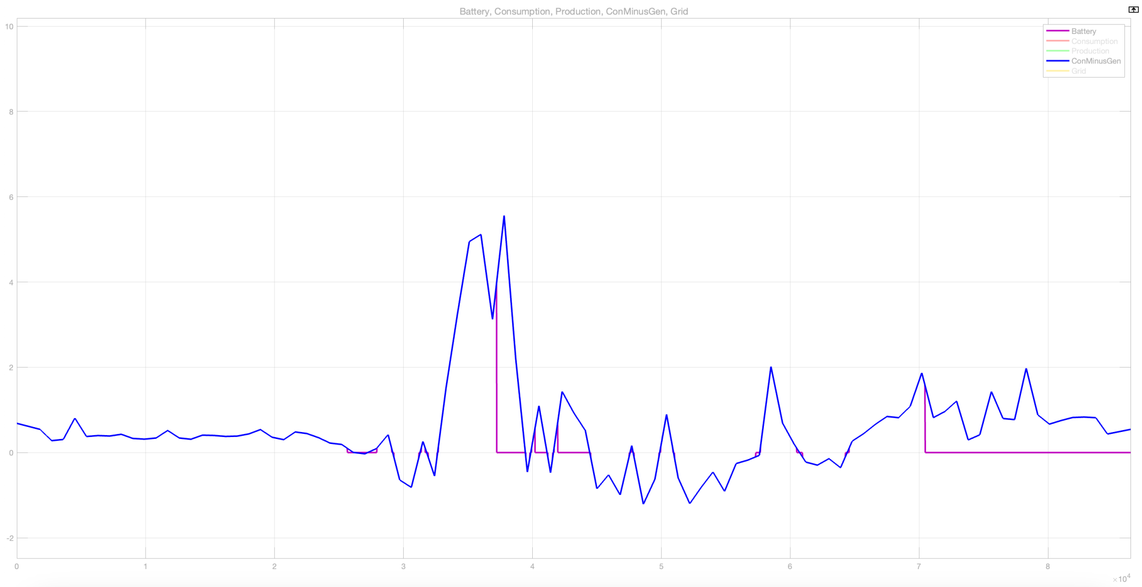

Figure 4.29: Flywheel power(purple)-Consumption minus generation(blue)

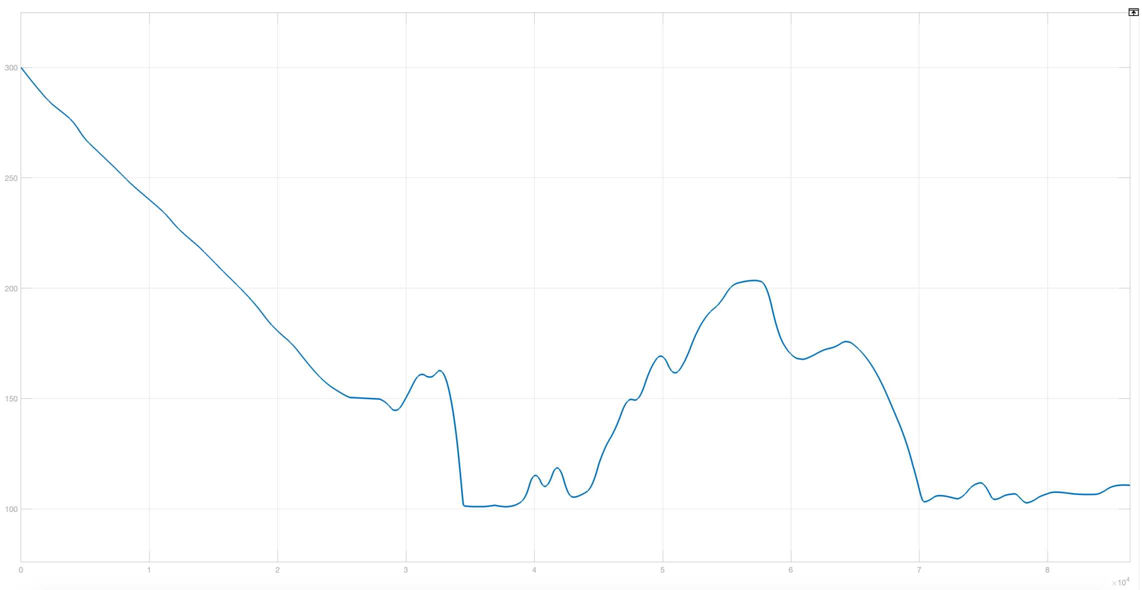

Figure 4.30: Speed(blue)

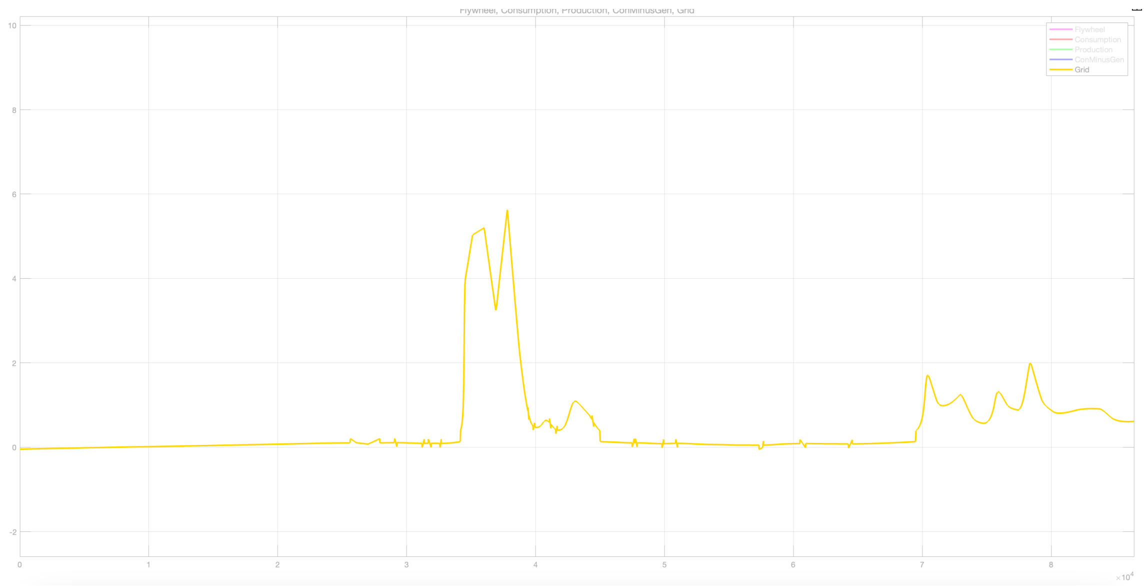

Figure 4.31: Energy exchanged with the grid(yellow)

Full model

Figure 4.32: Battery power plus flywheel power(cyan)-Consumption minus generation(blue)

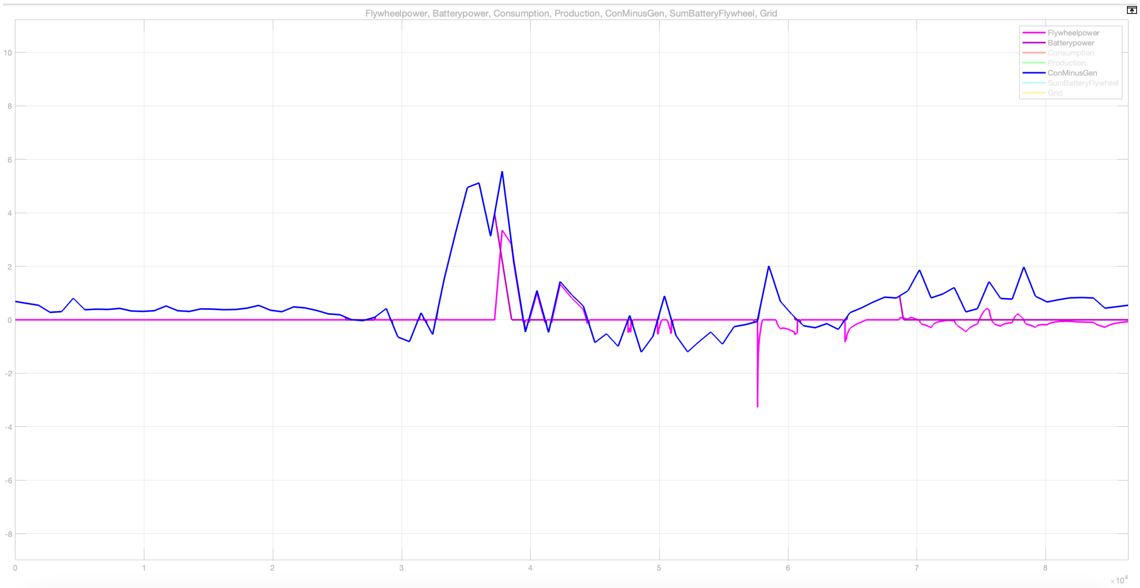

Figure 4.33: Battery power(purple)- Flywheel power(pink)-Consumption minus generation(blue)

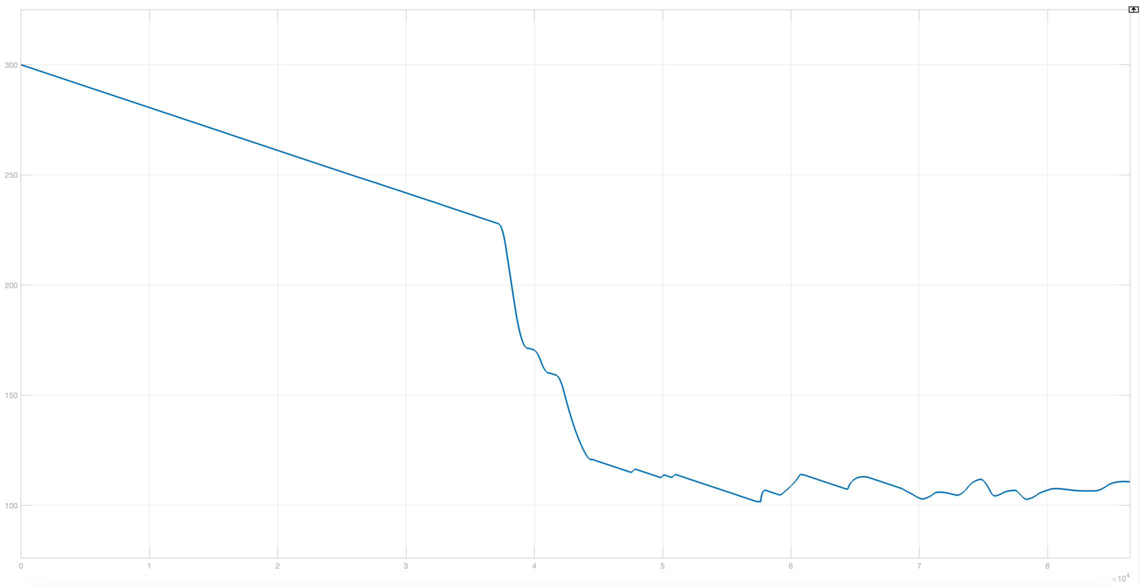

Figure 4.34: Speed(blue)

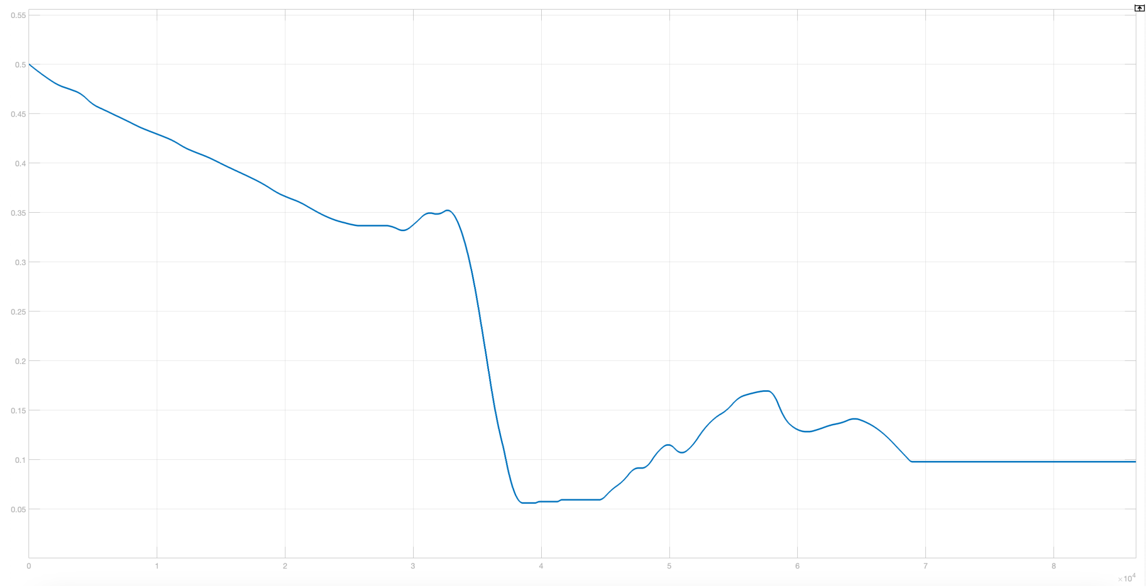

Figure 4.35: SOC(blue)

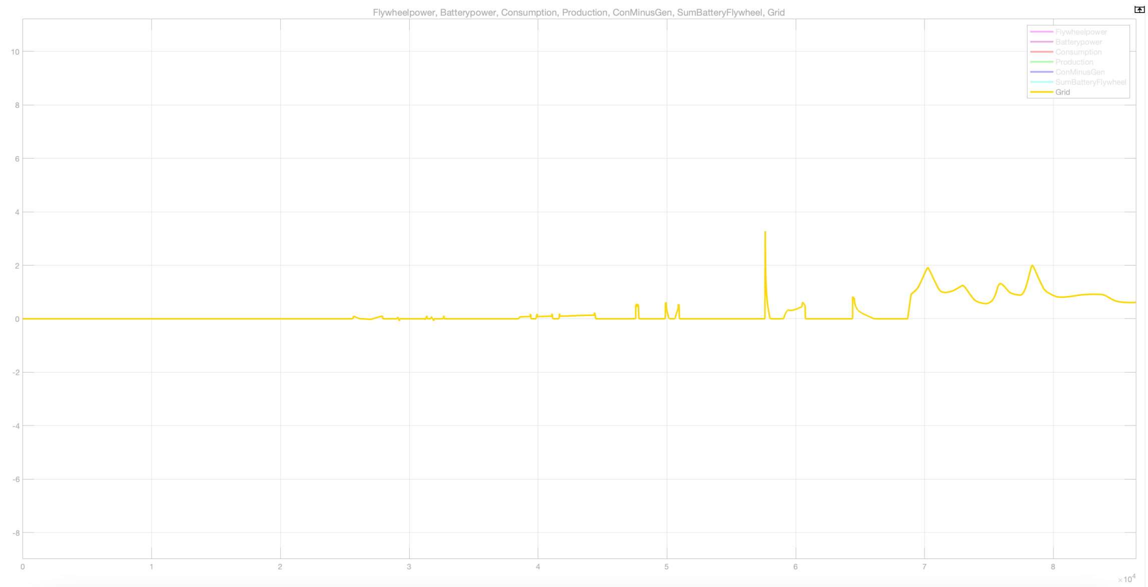

Figure 4.36: Energy exchanged with the grid(yellow)

Chapter 5

Conclusion

Today's society is facing a huge environmental problem. Many actors are a cause of the pollution caused by humans but one of the most important actors is the energy consumption in the form of electricity.
The electric power system is relying on many CO2 consuming technologies like gas, carbon, fuel etc. For this reason, nowadays, the use of energy is environmentally not sustainable and the aim is to change this in the coming years.
Europe is investing massively to become a carbon neutral continent and it starts with the electricity production.

To obtain a power system that is sustainable many new technologies have to be improved. One of them is the possibility of storing energy.
As storing energy is mostly done by lithium-ion batteries at the moment, everyone knows that this technology is not ideal for different reasons, bad recyclability, raw materials that are not unlimited and energy-consuming extraction methods. Mechanical energy storage looks to be an option in the future if the technology becomes more mature and efficient in the coming years. Flywheels are a high expectation technology in terms of mechanical energy storage.

In this thesis three different Matlab Simulink models have been developed to be able to compare them easely. The three models represent an energy storage system connected to a solar panel installation that has as aim to supply the energy demand of a household. The three different energy storage systems are the next one: A classic lithium-ion battery, a flywheel and a mix of both energy storage systems.
Different assumptions have been done to try to obtain real life result that could give us information about the feasibility of using a flywheel for home-appliance energy storage.

The possibility of using a flywheel to store energy for a household looks possible. The kinetics of the flywheel are matching the needs for a classic household. The capacity of storage can be enough even in responsible budget flywheels.
There is no doubt that the lithium-ion battery is performing better but as said before, the flywheel is winning and by far on the ethycal side thanks to it's long life expectancy and lack of expensive raw materials.

Using a battery at home became a financially attractive investment only a few years ago, and this is even not the case in all the countries. But as the technologies are maturing and the costs of electricity are going up it will certainly be everywhere in the future. With this work, that proves that a flywheel could be used in such an application, proves that the opportunity exists that flywheels become financially attractive for private use in the coming years.
This result is encouraging and the numbers of years to obtain this attractiveness will depend on many factors like, researches, politics, climate change etc.

It is hoped that in a few years many people could become self-sufficient in terms of energy thanks to a solar panel installation and a storage system that is mechanical, like a flywheel. This would be a great input to obtain big energy storage capacities in the power system, which is maybe not possible via large scale projects that are complicated and always slowed down due to politics, budget, environmental association etc.

Ending this thesis with a positive result gives me the hunger to continue extending my knowledge about this subject that passionates me incredibly. The market of the energy storage is a large and unexplored market where I would love to give my career for. Opportunities are unlimited in terms of research's or startup ideas in many different areas of these captivating subject and it's future has a promising taste.

Bibliography

[1] BBC. Greta thunberg quotes: 10 famous lines from teen activist. 2019. https://www.bbc.co.uk/newsround/49812183.

[2] Richard Black. A brief history of climate change. 2013. https://www.bbc.com/news/science-environment-15874560.

[3] Reseau de transport d'd'électricité. Rte. Up to date. https://www.rte-france.com/eco2mix/les-donnees-de-marche#.

[4] Solar energy industry association. Solar industry research data. 2018. https://www.seia.org/solar-industry-research-data.

[5] EPA. Electricity storage. 2021. https://www.epa.gov/energy/electricity-storage.

[6] EU. Energy storage – the role of electricity. 2017. https://energy.ec.europa.eu/system/files/2017-02/swd2017_61_document_travail_service_part1_v6_0.pdf.

[7] EU. Energy storage can help increase the eu's security of supply and decarbonisation. 2020. https://energy.ec.europa.eu/topics/research-and-technology/energy-storage_en.

[8] EU. Eu strategy on energy system integration. 2020. https://energy.ec.europa.eu/topics/energy-system-integration/eu-strategy-energy-system-integration_en.

[9] EU. United nations treaty collection. 2022. https://treaties.un.org.

[10] Johannes Friedrich. The history of carbon dioxide emissions. 2014. https://www.wri.org/insights/history-carbon-dioxide-emissions.

[11] Francisco Diaz Gonzàlez. Slides from the course given by francisco diaz gonzàlez in the course: "energy storage" at the upc. 2018. https://atenea.upc.edu/course/view.php?id=69996.

[12] LGChem. Site of lgchem. Up to date. https://www.lgessbattery.com/eu/home-battery/product-info.lg.

[13] LGChem. Site of punch power. Up to date. https://punchflybrid.com/punch-power-200/.

[14] Jiří J. Klemeš Panos Seferlis The Italian asociciation of chemical engineering Petar S. Varbanov, Timothy G. Walmsley. Long-discharge flywheel versus battery energy storage for microgrids: a techno-economic comparison. 2019. https://www.aidic.it/cet/19/76/159.pdf.

[15] Different poeple. The discovery of global warming. 2022. https://history.aip.org/climate/timeline.htm.

[16] Trinomics. Energy costs, taxes and the impact of government interventions on investments. 2020. http://trinomics.eu/wp-content/uploads/2020/11/Final-Report-Cost-of-Energy-LCOE.pdf.

[17] Unknown. Battery vs flywheel. 2017. https://nj.gov/bpu/pdf/publicnotice/stakeholder/Omnes%20Energy%20BATTERIES%20vs%20FLYWHEELS_March%2019%202019.pdf.

Chapter 6

Annexes

6.0.1 Codes Matlab function

EMF battery

```
function controlPointP  = control(PV, Con, SOC, PowerMaxBattery,
    PowerMinBattery, SOCMAX, SOCMIN)


% Calculates de the control setpoint i
% i positive discharging battery
% i negative charging battery
% i=0 Battery not connected

    controlPoint = 1
    i=1

    Power = Con - PV

    if (Power > PowerMaxBattery)
        Power = PowerMaxBattery

    elseif (Power < -PowerMaxBattery)
        Power = -PowerMaxBattery

    elseif (Power > -PowerMinBattery && Power < PowerMinBattery)
        Power = 0

    else
        Power = Power

    end

    if (Power > 0 && SOC < SOCMIN)
        Power = 0

    elseif (Power < 0 && SOC > SOCMAX)
        Power = 0
    end

    Power = Power   % kW

    controlPointP = Power %Watts
```

Storage device battery

```
function [SOC, Power, V] = batterySim(ControlPointP, SOC, C, V, eta
    , R, soc_ocv_lookuptable, ocv_ocv_lookuptable_cell)

P = ControlPointP * 1000        %Kw to watts
I = P/V                         %watts/volt = Amp res

% Update charge and voltage
SOC = SOC - eta * 1 * I/C; % p.u.

%%%%%%%%%%%%%% interpolate to have the new open circuit voltage

OCV = interp1(soc_ocv_lookuptable,ocv_ocv_lookuptable_cell,SOC)


%%%%%%%%%%%%%% to update the new voltage at the battery terminals

V = OCV + R * I

Power = P/1000;  % (kW)

end
```

EMF flywheel

```
function controlPointP  = control(PV, Con, Speed, SpeedMax,
    SpeedMin, PowerMaxFlywheel, PowerMinFlywheel, SpeedMinMargin,
    SpeedMaxMargin,Kmargin)


% Calculates de the control setpoint i
% i positive discharging battery
% i negative charging battery
% i=0 Battery not connected

    i=1
    Power = Con - PV

    if (Power > PowerMaxFlywheel)
        Power = PowerMaxFlywheel

    elseif (Power < -PowerMaxFlywheel)
        Power = -PowerMaxFlywheel

    elseif (Power > -PowerMinFlywheel && Power < PowerMinFlywheel)
        Power = 0

    else
        Power = Power

    end

    if Speed > SpeedMin && Speed < SpeedMin + SpeedMinMargin
        Power = Power - Kmargin/(Speed - SpeedMin)
    elseif Speed < SpeedMax && Speed > SpeedMax - SpeedMaxMargin
        Power = Power + Kmargin/(SpeedMax - Speed)

    elseif (Power > 0 && Speed < SpeedMin)
        Power = 0

```

```
    elseif (Power < 0 && Speed > SpeedMax)
        Power = 0
    end

    %Power = Power * 1000  %From kW to W

    controlPointP = Power
```

Storage device flywheel

```
function [SpeedDerivate, Power, V, I, k1] = batterySim(
    ControlPointP, Speed, k2, FrictionCst1, FrictionCst2,
    FrictionCst3,Inertia, EfficiencyFlywheel)

P = ControlPointP * 1000 % W
w = Speed
J = Inertia
Te = P/w                                    % Torque needed to
    supply the power demanded
T1 = FrictionCst3
V = Speed * k2
I = P/V
k1 = P/(Speed)

dw = -(Te + T1)/J


SpeedDerivate = dw


Power = P/1000  % (kW)

end
```

Fullmodel EMF battery

```
function controlPointP  = control(PV, Con, SOC, PowerMaxBattery,
    PowerMinBattery, SOCMAX, SOCMIN)


% Calculates de the control setpoint i
% i positive discharging battery
% i negative charging battery
% i=0 Battery not connected

    controlPoint = 1
    i=1

    Power = Con - PV

    if (Power > PowerMaxBattery)
        Power = PowerMaxBattery

    elseif (Power < -PowerMaxBattery)
        Power = -PowerMaxBattery

    elseif (Power > -PowerMinBattery && Power < PowerMinBattery)
        Power = 0
```

```
    else
        Power = Power

    end

    if (Power > 0 && SOC < SOCMIN)
        Power = 0

    elseif (Power < 0 && SOC > SOCMAX)
        Power = 0
    end

    Power = Power * 1000  %From kW to W


    controlPointP = Power/1000 %KiloWatts
```

Fullmodel EMF flywheel

```
function controlPointP  = control(PV, Con, Speed, SpeedMax,
    SpeedMin, PowerMaxFlywheel, PowerMinFlywheel, SpeedMinMargin,
    SpeedMaxMargin,Kmargin)


% Calculates de the control setpoint i
% i positive discharging battery
% i negative charging battery
% i=0 Battery not connected

    i=1
    Power = Con - PV

    if (Power > PowerMaxFlywheel)
        Power = PowerMaxFlywheel

    elseif (Power < -PowerMaxFlywheel)
        Power = -PowerMaxFlywheel

    elseif (Power > -PowerMinFlywheel && Power < PowerMinFlywheel)
        Power = 0

    else
        Power = Power

    end

    if Speed > SpeedMin && Speed < SpeedMin + SpeedMinMargin
        Power = Power - Kmargin/(Speed - SpeedMin)
    elseif Speed < SpeedMax && Speed > SpeedMax - SpeedMaxMargin
        Power = Power + Kmargin/(SpeedMax - Speed)

    elseif (Power > 0 && Speed < SpeedMin)
        Power = 0

    elseif (Power < 0 && Speed > SpeedMax)
        Power = 0
    end

```

```
    %Power = Power * 1000  %From kW to W


    controlPointP = Power
```

fullmodel power distribution management system

```
function [ControlpointBattery, ControlpointFlywheel]= fcn(
   ExControlpointBattery, ExControlpointFlywheel,ConMinusGen)

    if ConMinusGen > 0
        if ExControlpointBattery + ExControlpointFlywheel >
           ConMinusGen
            PowerFlywheel = ConMinusGen - ExControlpointBattery
            if PowerFlywheel > ExControlpointFlywheel
                PowerFlywheel = ExControlpointFlywheel
            else
            end
        else
            PowerFlywheel = ExControlpointFlywheel
        end

    elseif ConMinusGen < 0
        if ExControlpointBattery + ExControlpointFlywheel <
           ConMinusGen
            PowerFlywheel = ConMinusGen - ExControlpointBattery
            if PowerFlywheel < ExControlpointFlywheel
                PowerFlywheel = ExControlpointFlywheel
            else
            end
        else
            PowerFlywheel = ExControlpointFlywheel
        end



    else
    PowerFlywheel = ExControlpointFlywheel
    end



ControlpointBattery = ExControlpointBattery;
ControlpointFlywheel = PowerFlywheel;
```

fullmodel storage device battery

```
function [SOC, Power, V] = batterySim(ControlPointP, SOC, C, V, eta
   , R, soc_ocv_lookuptable, ocv_ocv_lookuptable_cell)

P = ControlPointP * 1000      %watts
I = P/V                     %watts/volt = Amp res

% Update charge and voltage
SOC = SOC - eta * 1 * I/C; % p.u.

```

```
%%%%%%%%%%%%%% interpolate to have the new open circuit voltage
    %%% this can be done with the function interp1. The syntaxis is
        : OCV = interp1(SOCcolumn,OCVcolumn,SOC)

OCV = interp1(soc_ocv_lookuptable,ocv_ocv_lookuptable_cell,SOC)


%%%%%%%%%%%%%% to update the new voltage at the battery terminals
    %%% this can be done by V = OCV + R * I

V = OCV + R * I

Power = P/1000;  % (kW)

end
```

fullmodel storage device flywheel

```
function [SpeedDerivate, Power, V, I] = batterySim(ControlPointP,
    Speed, k2, FrictionCst1, FrictionCst2, FrictionCst3, Inertia,
    EfficiencyFlywheel)

P = ControlPointP * 1000 %Watts
w = Speed
J = Inertia
Te = P/w                                    % Torque needed to
    supply the power demanded
T1 = FrictionCst3
V = Speed * k2
I = P/V

dw = -(Te + T1)/J

SpeedDerivate = dw


Power = P/1000  % (kW)

end
```