Lappeenranta University of Technology

Faculty of Energy Technology

Master Degree Program in Industrial Electronics

Master’s Thesis

Solovev Sergei

Optimization of PV and battery capacity for domestic purposes

Examiners: Prof. Jarmo Partanen

D.Sc. (Tech.) Tero Kaipia

ABSTRACT

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The usage of PV batteries nowadays became more and more widely spread. Due to the fact that the efficiency of modern PV is rising every year the prevalence of this source of energy is increasing. As the source of the energy is sunlight, these batteries need to be complimented by storage capacitors which will store energy for future use. Nevertheless the less the calculation of demanded amount of energy according the load and capacity of a storage battery that will keep the end consumer in work during certain time still is not overviewed. In this thesis the overall system will be considered and there will be made economic calculations for configurations of such system that will depend from the load. Also the behavior of the system in different geographical and climate conditions that influence of the amount of energy produced will be overviewed.

Acknowledgements

When I was included in the double-degree program I was just thinking about the opportunity to increase my level of English-speaking. But when the real study started I realized how much I don’t know I electronics, energetics and electrical drive. The study was really hard to me as I studied in Russia in parallel. Still I went through all the studies and gained a lot of important knowledge which are helping me to progress in researches. I want to thank all the lecturers in LUT, especially professor Juha Pyrhonen. In my opinion he is the best lecturer and he made nearly impossible thing – make me understand electrical drives during couple of months. All the studies in LUT made me more collected, responsible and what I think is more important made me really interested in electrics.

Also I want to thank Katja Hynynen for her patience in managing our education and special treatment to every one of us, especially to those who came to study from abroad. And of course I want to say thanks to my supervisor professor Jarmo Partanen for his tranquility in work with me, as I delayed my thesis for so much time that if it was someone else, I were already dismissed, for his wise instructions that pointed me on most sensitive points in my thesis.

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Contents

List of tables

List of figures

17. a) energy (higher), b) demanded energy (lower)

18. The part of the imitation model that represents the battery logic.

19. Level of charge on the battery during one year.

20. a) Sent back to grid energy (upper), taken from the grid energy (lower).

21. Theoretical gradient of charge level on the battery.

22. The representation of the case when the system is fully autonomous.

23. Theoretical gradient of charge level on the battery.

24. The representation of the case when the system is fully autonomous.

List of Symbols and Abbreviations

Abbreviations

DC	Direct Current
AC	Alternative Current
PV	Photo Voltaic
NiMH	Nickel-metal hybrid
NiCd	Nickel Cadmium
LSD	Low Self Discharge
VAC	Volts Alternative Current

Symbols

E_{load}	Energy (load)
E_{PV}	Energy (PV)
E_{grid}	Energy (taken from the grid)
E_b	Energy (taken from the charged storage battery)
$E_{ch.b}$	Energy (for the storage battery charge)
$E_{payback}$	Energy (sent back to grid)
λ	Latitude of the place where the length of the day need to be calculated
α	angle of the earth to the perpendicular to radius of earth movement
β	latitude of tropics, the belt of the Earth
δ_{av}	optimal position angle
δ_{max}	maximal angle of the sun to the panel during year
δ_{min}	minimal angle of the sun to the panel during the year
n	the day from the beginning of the year
P_{pv}	*nominal power of the each solar panel*
N	number of solar panels
D_{season}	*number of days in one season*
η	reducing coefficient reflecting weather circumstances during one season
$T_{payback}$	payback time
P_{system}	cost of the system per one year of work
P_{earned}	amount of money gained by the system without payback
$P_{payback}$	amount of money that can be received if the system is able to produce extra energy
AM	atmospheric mass

θ	angle from vertical (zenith angle)
LSTM	local standard time meridian
EoT	equation of time
TC	temporary correction factor
LT	local time
LST	local standard time
HRA	hemispherical reflective antenna
Elevation	elevation of the sun to earth during the day
R_{solar}	solar constant
η_{pv}	efficiency of the PV battery
S	square of the each PV battery
R	irradiation of the sun near the surface of Earth
C_b	capacity of storage battery
P_d	power of daily load
U_b	nominal voltage of storage battery
η_p	lowest safe level of the charge of batter

1. Introduction

1.2 Modern status of energy systems

Modern conditions dictate further more consumptions of electrical energy day by day. From the experiments of Ampere and Faraday till present state electricity placed the most important position in our society. We can't imagine our lives without electricity light, domestic devices and electrical machines in every transport we are using. Electricity is an index of standard of living in every country and of course. The higher it is the better life in separate country. The 90% of rural territory of Africa have no proper access to electricity as there economy is low and cant effort to build large scale grid or there is constant danger for its remove by local people. Same problem still presents in Southeast Asia in countries like Cambodia and Myanmar where the percentage of electrification is between 13 and 24%. [9,15,22]

All our demands in electricity are satisfying by energy systems and it is important to make the supplement uninterruptable. Outages in energy systems may cause serious problems in many aspects of live e.g. industrial facilities were large scale and power machines are operating and without supply they can damage not only working place but also hurt working personal or hospitals were the energy support of different devices is a question of live saving. Even simple houses not desirable for disable. This issue touches not only standard 3-phase grids but also those that include DC elements.[12,13]

This thesis mostly dedicated to domestic consumption of energy in standalone houses. Buildings like this mostly situated far from big cities and even towns away from main grids and owners want to have their own energy generation so they can control it. In addition some houses such as farms can be situated in such places where there are no grids at all and there is no possibility to connect to anywhere.[20] The only option in such case is only making own isolated system. In this thesis will be considered such system.

1.2 Problem description

Most of the countries have fixed taxed on the energy consumption from the main grid. The value of tax can be high or low depends on the country and its possibility to produce energy from different sources. Dependence here is proportional to the difficulty of its production. For example in countries like USA orientation on self-consumption of gained resources so they can have pretty cheap energy compare to countries that are deprived from such luxury like Japan, Germany, Norway etc. If they need to buy energy resources the price on them will be higher because of the additional price for transportation and some benefit for country of origin.[11]

Such countries trying to avoid cost overrun and change standard and most widely spread energy supplies by those methods they can allow on their territory. The most universal way to compensate this problem is to use renewable sources of electricity. This branch of energetics is the quickest in development all over the world. The reason is obvious – such technology can be used nearly far and wide. In the era when fossil fuels constantly rising in prize this decision more than reasonable. In this thesis only solar panels (photovoltaic sources) will be considered.[17]

The reason of choosing PV technology is that because in this thesis overviewed only domestic purposes. This sector develops very fast and efficiency of panels rising dramatically both in industrial and in private sector, because the power generated by solar station theoretically depends only from the number of panels in a system in common. So only a few panels need to be placed for the enclosed system supplying one separate house.

In practice solar panels generate energy from the sunlight, so it can't be predicted exact amount of energy produced during the day. As the weather can be predicted only for the week ahead, there is need to be reserve for system not to turn off and make a discomfort or even risk for housemates. In this case there is needed to be an alternative supply for at least the most frequently using conveniences. There are many variants for reserve supply like from diesel-generator set to supply from the main grid if there is one nearby.

Either with or without any outer reserve such system can be called microgrid. In common such system includes source of energy, power electronic devices for conversion, often it is called the nexus, end loads and storage device like battery for the reserve. Microgrind assumed to be fully isolated so it can be created everywhere despite from environment around.[15,16]

So the main idea is to find out how microgrid behave in different conditions and producing universal model from the system to be made anywhere around the world. The main principle can be described by following expression:

$$E_{load}= E_{PV}+E_{grid}+E_{b}-E_{ch.b.}-E_{payback}, \quad (1.1)$$

Where E_{load} – amount of energy that will receive consumer, E_{PV} – energy produced by solar panels, E_{grid} – energy that received from the reserve grid if it is connected to one, E_{b} - energy gained from the battery, $E_{ch.b.}$ – energy needed to cover energy discharge from battery, $E_{payback}$ – possible amount of energy that will go to the grid for profit of the micro grid owner.

In different situations some of the components of equation can be absent. If amount of energy from the PV is enough for the consumer there is no need in wasting storage energy, battery is full and appears some free amount, in another words $E_{load} < E_{PV}$, then the difference can be set back to the grid if system connected to one. In this case the equation will look like that:

$$E_{load}= E_{PV}-E_{payback} \tag{1.2}$$

In addition every value is constantly changing as the necessity in power changing during the day cycle and generation from PV is also changing depends on weather and time of a day, the state of battery and amount of taken and sent energy to the grid changing too. Consequently the expression needs to be written in continuous form as a function of time:

$$E_{load}(t) = E_{PV}(t) +E_{grid}(t)+E_{b}(t)-E_{ch.b.}(t)-E_{payback}(t), \tag{1.3}$$

Summarize this, there need to be made a system that could supply entire house without interruptions, control the level of charge in battery, and sent back to the grid extra energy, generated from PV. [5]

1.3 Economical profit and payback

Every system has certain amount of components, which have their own prices for elements itself and maintenance. For making these systems more attractive for installing in house the price need to be as low as it possible. Reaching this target splits on two components. One common period of payback will be the measure for the economical basics of the system.

First of all, all the components in the system need to be chosen so they will cover all the demands from the system. This means that energy system needs to be reliable, because maintenance can cost much but what is more important outages cause discomfort for the owner. Also the correlation between functionality and the cost need to be adequate. This implies in fact that as low the price is the faster pure benefit will start.[10]

Second is ability of the system to send extra generated energy back to the grid. Here everything is more complicated – not all the countries provide private owners sell energy for the profit of any kind. Moreover this is restricted on the government level. The reason of this in most cases is because of the standards on energy quality and private sources can't provide it on worth level so the period of payback grows.

Another factor that has an influence is a place where the system is situated. As it was said before according to the place the weather and daylight activity is changing. These effects not only on the amount of produced energy but also on the cost of the facility. Dependence of the situation and amount of energy will be considered in further topics. What it can be said here is that the closer it to the north the more issues in applying uninterruptable supply will appear. Obviously in northern territories the climate is colder and there need to be heating systems that takes much part of gained energy.[18]

To summarize it – one of the main targets of the thesis is crating universal model that will include all the factors that are mentioned above for making forecast of how much time it will need for payback. Will it be profitable to use such system on every territory or there will be issues and this will be not profitable compare to more widely spread generation from fuel? This includes prices on the electricity from the grid, possibilities for selling energy back, reliability of a system etc.

1.4 Conclusion

All the elements such as PV, loads and protections of any kind in this thesis are only the instrument of obtaining data for the core thing that is making possible to operate wise and effective whole system. Questions of efficiency of generation or problems with safety are also important for the progress in developing well-working frame but not the purpose in the thesis. Only generated or taken from the grid amount of energy count. So the system needs to analyze the state of the main element or elements for sustainable functioning.

In every modern technologically developed system nowadays there is a management device so ultimate target of this thesis is in making control system for the battery as it the most important part of the system that is not depended from random parameter like sunlight rather than PV and takes the role of stabilizer in supplying the house. It can be assumed that for such control no need to know much about the amount of energy produced or sent, only the state of change of the battery. For example if the battery is not full than the energy from PV is not enough for now to cover all consumptions for the domestic purposes and if it keeps discharging but not empty or on the level when it can damage battery itself than the reserve energy is spending along with generating from PV. In this case the state of a battery is a key thing in optimization of such process.

There need to be a forecast for such system to predict how it will behave in different environment and will the system gain full payback during its lifetime. In thesis will be presented to cases – the absence of outer grid that can supply system if it will be need and without it. Existence of the grid is without any doubts advantage compare to stand alone islanded microgrid because of the availability of operation of extra energy generated by this microgrid and additional reserve for the system. In the end of the thesis there will be made a comparison between this two variants of microgrids.

Also the economic analysis of such system will be made and gained the degree of profitability of an ability to sell generated energy to the grid. How much this will lower the price on the whole system and maintenance and the size of a battery and consequently price on it for self-sufficient microgrid in different geographical conditions.

2. Description of the elements of the system

2.1 System functionality

The systems with renewable sources of electricity are very profitable because of fact that we don’t need to buy fuel to work. But renewable sources of energy are unstable as they need alternative supply from nature. As we speak about solar panels – here is the problem with cloudy weather. So in the system there need to be battery to make an additional supply when there is not enough sunlight.

In this section there will be made an overview on the elements that make up this system. In common this system includes energy source that as was mentioned is one or group of PV panels depends of how much energy it will be needed for full supply of the end consumer. Second is the transmission line with reserve and conversion devices by necessity. And there need to be said about consumer of electricity, its demands and features.

The construction of this system is not revolutionary and is well studied. More or less system is using in most of the grids and microgrids with renewable energy sources. PV panels are in use since 1954 and for domestic purposes they are using from 80’s. Still the observation of efficiency of constantly developing technologies in this area is needed. There is big variety of conditions in which it can be applied, so there is need to be the calculations to finding out the advisability under them.

In further topics there will be a description of all of these components. Also when we speak about the elements, there need to be made an analysis for choosing the most appropriate parameters for each of them. And finally the main concept of the system will be shown.[16]

2.2 Solar panels for domestic purposes

Originally solar panels were used for satellites. As in space there is no obstacles for sun ray, panels can generate energy constantly. In addition there is no air so there are no losses in transmission of energy between sun and PV elements, because of the reflection of rays from molecules of oxygen, carbon, etc. There a lot of issues with gaining energy from the sun. As we live on the planet with different coordinate positions on the surface of the planet and consequently climate zones potential of gaining energy from the sun is vary dramatically. Depending of the climate, the weather activity is different, e.g. the annual production of the energy changes. In this topic there will be description of the factors that have influence on the overall annual production of energy via solar panels.

Production of the energy characterized by the radiation of the sunlight rays that are coming from the space. As the planet turns around there is a moments of absence of the energy at all, called night. Depending of the latitude of sun observation's place, the night and day length changes. The reason of that is the position of sun to earth. It is not always perpendicular to the same latitude of the earth and changes during the year. The further the position of the observation place from equator the more daylight time changes across the year. The axis around which the earth is turning is under the 23^{O} to the line which is perpendicular to radius, by which earth is turning across the year. This value is constant and the only thing that changes is the angle of rotation around the axis of earth.

As this value is not changing while earth is moving over the sun there different areas on the earth and taking sunlight. In one half of the year there more sun light to upper part of the earth, closer to the Arctic pole, while during the second part on the year sun is lighting mostly part closer to Antarctic pole. As the area on which sunrays are falling is changing, the gap when sun is in line of sight from the point on earth is changing to. If the area is bigger than this gap is wider, so while the earth is turning around there is more time to sunrays to fall on this point. This time when there is more sunlight than night time is called summer. So there is a summer in different position of earth in space for north and south poles. While in North Pole winter goes, in South Pole there is summer and vice versa. By this the time of the daylight activity can be calculated in every coordinate of the earth, nevertheless the formulas will be shown in next topic.

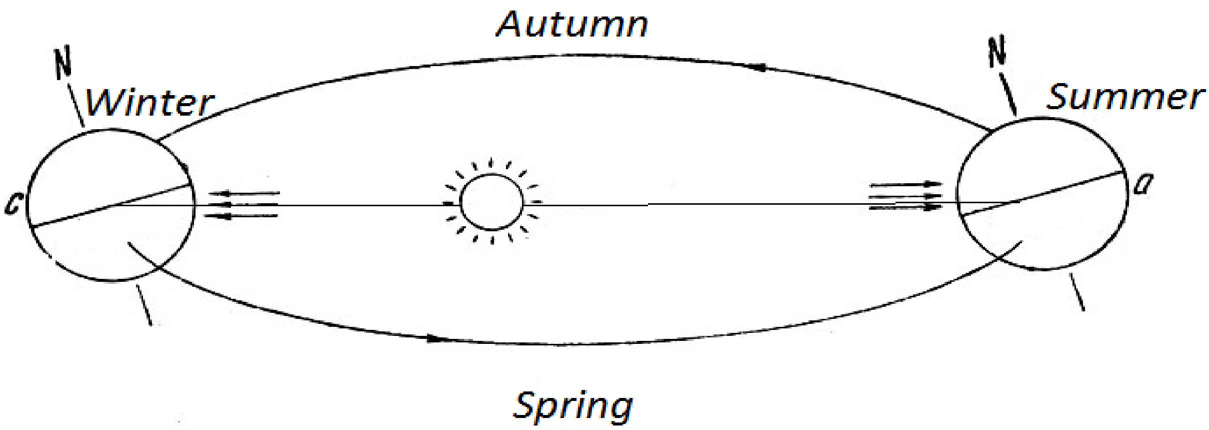

Figure 2.1: Position of the Earth to sun across the year (to North Pole)

Another factor of generation of energy amount is how much radiation of sun is falling on the PV. This value depends on several factors. The first is the distance between earth and sun during the year. This value is changing as the position of the sun is not marching the radius by which our planet is moving. The biggest distance $152*10^6$ km and the closest is $146*10^6$ km, so during the North Pole winter sun radiation is more intensive than during summer. The amount of the radiation that is going to the Earth's atmosphere is called solar constant as there is no obstacle to the rays in space. Also there is an important factor – the angle by which rays are falling to the PV. The most effective is when the panel is perpendicular to the source of rays. Because of that many solar panels have turning device to constantly face the Sun. If this angle is not 90^O then some part of rays and consequently ration which is generating electrical energy by PV is reflecting from the surface of panel.

Still particular amount of energy reflecting from earth to the PV and compensate some amount of energy lost by the reflections. For gaining best effect from PV there need to be chosen a best position for the device to consume sunrays. Because of the fact that electrical drive for turning device is consuming generated energy which makes them less effective and makes the price on solar panels higher, many customers picking the still ones. So there need to be calculated the optimal position for the panel to gain best effect. This value across the year not changing and can varies only if observation period is less than whole year. In common optimal angle can be calculated by following formula:

$$\text{Cos}(\delta_{av}) = \frac{\text{Cos}(\delta_{max}) - Cos(\delta_{min})}{2}, \quad (2.1)$$

where δ_{av} – optimal position angle, δ_{max} –maximal angle of the sun to the panel during year, δ_{min} – minimal angle of the sun to the panel during the year.

In addition solar panel need to be turned to the south as the pick height of it is there.

The last factor that has influence on the amount of produced energy by solar panels is weather and atmosphere. Our planet surrounded by layers of air, which are particles of different aerosol mixes – oxygen, nitrogen, carbon, carbon dioxide, helium etc. While rays are falling from the space to earth there is some losses appear as part of the rays are refract and reflect back to space. This amount is not big as there is more free space than molecular itself in many times. But in cloudy weather the concentration of water mixed with air can be high, so the sunrays are reaching earth much less than the there is no clouds. If by 100% it will be taken absolutely clear sky than with cloudy weather efficiency of solar panel falls approximately by 25%. If the weather is very cloudy (e.g. before the storm) this value can rise to 45%.[11]

Also the rain and slow that are nearly constantly falls in curtain places on the earth in autumn and winter or sand or dirt cause efficiency drop of panels too. The dirt, rain drops, snow can fall down of the panels. Depending on the degree of covered panel the efficiency also drops proportionally. If the rain or slow problem can be removed by choosing angle on which this will just drop down, the problem with dirt, for example in desert can cause unstable work of solar panels. So they need to have appropriate care.

2.3 Consumer

In this thesis there is a system for domestic purposes, so the end consumer of produced energy will be the modern convenience of the house. Every house we will have nearly the same set of devices. All of them can be splinted on two groups – those that are using to support live inside and the rest. To the first group it can be added the heating in cold time of year and ventilation. This part of devices and systems has the priority and need to be constantly supplied to prevent danger to the residents of the house. [4]

In this topic there will be no certain value for the consumption of all the devices in total not in separate as the end task of the thesis is in making universal model for most of the houses and need to fit every condition.

Another part of consumers is large verity of devices in the house starting from fridge and ends with boilers for the bathroom and different special devices that may not be in every house. To simplify model of consumption all the electrical devices can be splinted on several group inside of which there will be no principal difference, e.g. toaster and blender on the kitchen.

To reflect the demands of the house in electricity and to plan the system that will supply it the need to be made a graph of energy consumption during the day.

In addition if house is situated in cold climate, there need to be taken into account that during the winter energy consumption is higher and different usage of light, as on the most part of the planet night and day time is changing during the year. Still lighting is one of the smallest parts of consumption and can be neglected, but the heating is not, as heating is massive energy consumer, especially in private houses.[22]

For the purpose of modeling the amount of energy that is usually consumed by citizens, there can be offed such graph to reflect the 24-hour energy load in the house. For the purpose of modeling there is no certain value, as it varies from one house to another:

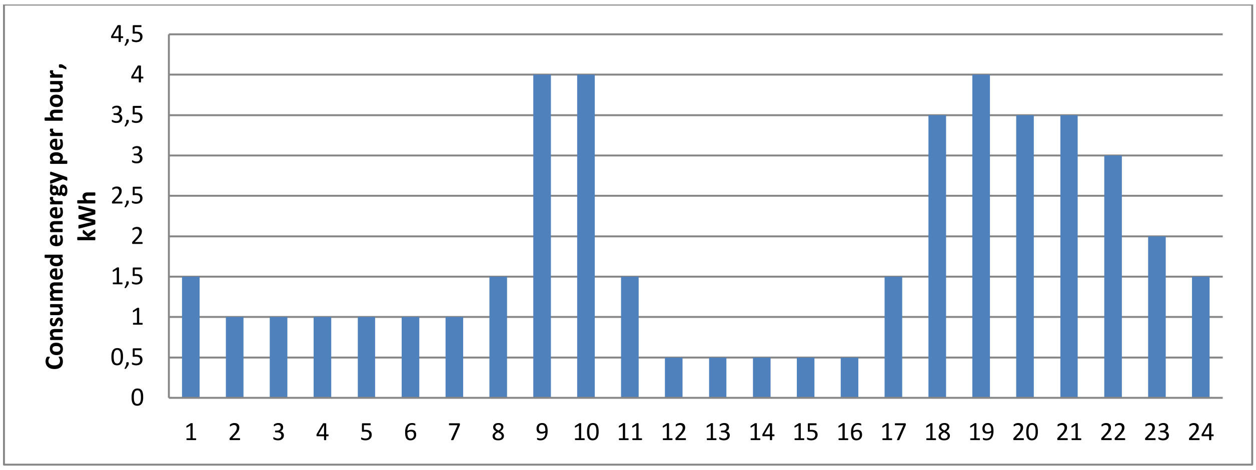

Figure 2.2: Daylong loads of the electrical devices in typical house

Here 1-25 is hour during the day. It is assumed that in this house lives normal family with adult that are working on 5/2 work. So they wake up at 8 and goes to the work closer to 10. In the morning it is need to be prepared meal and taken shower, so the consumption is rising during this period. If there are children in a family they goes to school or university. Next 7 hours no one in the house, after that all the family gathering and again consumption rises. In addition during the night the boiler for hot water is working, so the consumption compare to day is higher. This graph is only the example but can helps to predict picks in power consumption. As the controller that is controlling battery charge is monitoring the activity in the house every few minutes and can be prepare by graph like that and starts charging the battery in advance.[22]

During the colder months graph is nearly the same, but overall loads are higher by one notch more.

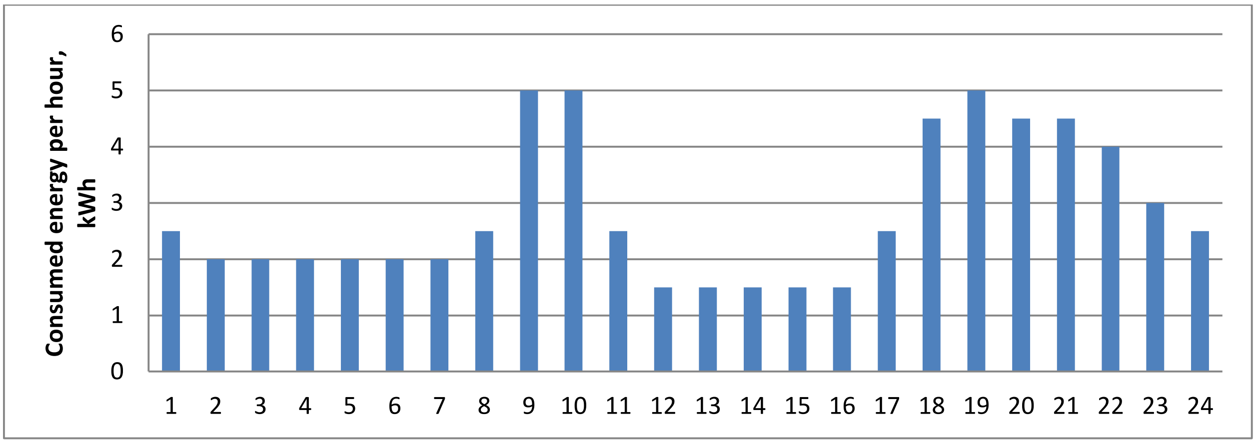

Figure 2.3: Daylong loads of the electrical devices in typical house during cold months

In addition it can be taken into account that different devices consume different levels of power from tenths of kilowatt to tens of kilowatt like boiler.

The customer is a private house and the standard voltage in such case will be 230 VAC. Still the PV batteries and the storage battery are working with DC, in most cases – 12 V, which means that the inverter will be used to convert DC to AC. The form of sine can be not very straight so for the purposes of cost saving 6-pulse inverter can be applied. Nowadays the efficiency of the inverters is reaching 98%. [21] Still for the purposes of the thesis the load will include also the inverter as in focus only DC part of a system.

Mostly the devices in the common house are modern conveniences such as washing machine, vacuum cleaner, different king of blenders etc. and heating devices like cooker and heaters so mostly the load is represented by active and induction resistance. Any problems in such cases are not included in this diploma thesis like high harmonics issues or electromagnetic compatibility of devices to the network of the house also figures 2.2 and 2.3 are representing the load already with possible efficiency issues and peak values in certain moment of time.

2.4 Battery

There a large choice of the batteries nowadays. The difference between them is reduced mostly to the material from which they made. The task of this topic is to choose the material from which the battery will be made and best fits to the demands of the system.

The most common batteries are alkaline (zinc and manganese dioxide), lithium-ion, lithium-polymeric, ammonium-chloride, acid and nickel-cadmium batteries. To solve which one is fits it is need to be known what the end task of the battery is.

In this case, for private house usage the main characteristics need to be the following: As the battery is in usage not all the day, but every day for some time as there is always some time when sunlight is insufficient to generate proper amount of energy the battery constantly charging and discharging and need to be resistant to such impact.

Also some batteries are very sensitive to the level of change on which they prefer to keep energy. Some of them are capable not to lose their maximum charge level when they are fully charged, and vice versa – some are preferred to be discharged or resistant to any level of charge at current time. In our case – constantly changing level of battery while the solar panels not always are capable to charge it dictates that it is need to be battery unpretentious to the charge level of the battery.

One of the main parameter if we speak about private usage of the system is the price. Customers want to have their system as at low cost as it possible, even with small disadvantages compare to more expensive variants. The specific cost here is the most valuable meaning.

Last one parameter for the battery is it’s durability – how much cycles this battery can provide and how fast battery can charge and discharge before it comes in unsuitability. These values have direct influence on the cost of the maintenance.

Next here will be listed advantages and disadvantages for most widely spread types of batteries. First – acid batteries – one of the oldest types of batteries. Mostly used in cars and sources of uninterruptable supply. They can produce big current, have large range of operating temperature, relatively low capacity loss on low temperatures and long durability which correct usage. Nevertheless they have relatively large size, can self-discharge during long storage. What is most important – is that in deep discharges, they losing capacity and can even brake down.

Nickel-cadmium batteries: they are well knows as components for portative electronics. They have very low internal impedance, so they can charge fast and handle large currents, also they have long durability (tens of years). Still they are preferred to keep discharged and have relatively high price. Nowadays they are losing popularity to NiMH – Nickel –metal hydride batteries.

NiMH – compare to nickel-cadmium has larger capacity, approximately by one third but has shorter durability (around 300-500 cycles) and two times more self-discharge. Optimal working level of current is near 0,5 of capacity, so that means if there is a capacity of 20000 mAh, the nominal current need to be kept around 10 amperes. Like a NiCd preferred to be kept discharged. In addition they are sensitive to low temperatures and can loss to 30% of capacity. Finally the price of NiMH is higher than of NiCd.

Another type of batteries is LSD – Low Self Discharge. Traditional NiMH capacitor losing 20% per month. LSD – keeps 75% for 3 year. It is able to provide current 2 times more than capacity and have 2-3 times longer durability, recommended to supply large current but not durable consumers, still is able to work with devices that have long period consume on low voltages. But the price is higher compare to NiMH and NiCd.

Next group of batteries are nowadays are very famous and widely spread – Lithium ion batteries. They have overall usage in portable devices – mobile phones, cameras, etc. This popularity is obtained by Li-ion batteries because of their specific weight. They can provide current to 2 times more than capacity, but for long term usage not recommended to cross level of one capacity. Also they preferred to keep level of 40% from capacity and age even without use. Normally are using only for 5 years. On a low temperature they can lose capacity. More important that in overcharge susceptible to spontaneous combustion or can even explodes. In deep discharge can break down. To advantages can be added – low self-discharge, large capacity and long durability (more than 1000 cycles)

It must be kept in mind that there is a control device that can be set up to keep level of the charge not lower that some point. From all this variety of batteries the most suitable is one that is has longer durability. Temperature resistance is not so important, since battery can be placed inside the house. Also problem with discharge is not important, because battery can nearly always be charged to maximum from solar panels. One of the parameters that are definitely play important role is range of output current, because at peaks of consumption it can be high. So the best battery from listed – is LSD NiMH batteries, they have durability and large variety of current to supply. Certainly the price on them is high, but since durability and reliability higher than competitors have can be good choice.[14]

2.5 Overview of the system

The purpose of the system is to provide uninterruptable supply for the private house with the solar panels. It is very important to predict the behavior of the weather and sun activity during the year to build system without outages: either will be enough sun for consumption and for reserve battery charge or there is no possibility, for example during the winter, to fulfill the demands. In this case the reverse for the PV need to be construct.

So there are two solutions. First one is to make reserve supply for connected system to the grid. So when outage can appear the reserve grid stats to transfer energy replacing the main one. This solution can be realized when we already have such reserve grid e.g. There is a separate grid for mining complex and factory and we can take part of energy from it to another consumer. In another case building one more grid only for safety net in common will be too expensive. So this solution can be used in towns or for large scale manufacturing or nearby.[8]

Another way to solve a problem is to make so-called “islanded” grid. The island grid is an enclosed system with its own energy generation nevertheless what it is kind of. In such solution there are a lot of obvious advantages. This grid can be made separately from main grid so this widens the variety of territories where it can be build. Lots of countries, especially northern, have a lot of far distant villages or even lonely farms and houses that are also in need of electricity. The main problem here is the further they are from main grid the more problematic will became there electrification and the more expensive for owner it will be.

The control of the battery level in islanded grid also will control the inverter that will transfer the solar panels that produce DC voltage to the system of the house that consume 220 VAC as a standard voltage nowadays. It there is an option with reserve grid this control device will manage the supply to the end consumer. Since the battery systems can either provide DC and AC with in-build inverter, the battery can be placed before the inverter of solar panels or after it. For the reserve from another grid there need to be transformer to standard 220 VAC. In the thesis it is assumed that reserve grid is already on this level of voltage.[3,17]

2.6 Conclusion

Such system presents as a fully enclosed system and the purpose of the thesis is to calculate the benefits of using it instead of normal supply from the main grid. As the customer pays only for the system and there are no taxes on the consumed energy this system can cover its cost by some time. The key device in the system is the control of the battery its cost is needed to be cover during the lifetime of it.

In the next topic there will be made a universal model that will include all the elements of the system from economical point of view.

3. The description of economic model

3.1 Introduction

Every invention, every system that is assumed to be effective needs to have its own positive efficiency factor. That means that it is assumed to produce some work or reduce the consumption of resources nevertheless what they are. So each device or the system brings certain benefits to our life. And this can be calculated only by counting the economic gain that can be from the system. The main value here is how fast the system can pay for itself. The faster it will be the more efficient from the economical point of view it will be.

It this particular system it was used solar panels and the battery for stable work. As the energy that produced by the sun for our purpose is free of charge it is compared with the amount of money that could be spent on the supply of the house with classical connection to the grid. There are a lot of parameters that have influence on the production or payback time of the system. Also each consumer is unique in its amount of taken energy and there are some values that very for one consumer to another like a presence of different electronic devices in the house or geographical position of consumer with sources of energy from which depends not only amount of produced energy but also how much energy will be spent on the heating and light.

In this chapter there will be made a description of the economic model for the system with solar panels as a main source of electricity. It should show how fast this system can return the funds that were made in it, how much energy it can produce in money worth and if it is possible and there is some extra energy produced how much profit the owner can have. For more realistic model also was taken into account such parameters as a life time of the components of the system and its efficiency.

3.2 Geographical position and production of energy

The key parameter for the system is the ability to cover the consumption of the energy. So it is needed to be compared amount of produced energy and amount of spent energy. About the consumption there will be overviewed in a separate topic. Consequently the amount of produced by the solar panels energy need to be more or equal to the consumed energy or in other case it is need to be covered by the remote source. In this topic it is not necessary to include the battery as an additional source of energy as the time is counted in seasons and the battery will charge and discharge many times. Alternatively additional source of energy such as grid can be counted during long term as a reserve supply. The battery in the economic model is figuring only as a guarantee of stable supply. Without an interruptible supply there will appear a discomfort or even danger to users of supplied devices.

As it was described in a previous chapter the position of the sun to the Earth is not constant and is changing both in distance and in angle as a planet turning over its axis. The goal is to make dependence between the behavior of the planet to the sun during the year and the producing amount of energy to the consumer. As it is well-known the production of the energy from the sun can be gained only during the day well the sunrays a falling to the solar panels under enough angle. So the formula is the following:

$$D = 24 - \frac{24}{\pi}\arccos(\tan\lambda \tan(\arcsin(sin\alpha\ sin\delta))) \ , \qquad (3.1)$$

Where D is a number of sunlight hours during the day. λ – latitude of the place where the length of the day need to be calculated, α – the angle of the earth to the perpendicular to radius of earth movement, β – latitude of tropics, the belt of the Earth, δ- terrestrial latitude. All the angles in the formula are in radians.

Respectively to describe the behavior of the Earth position it is needed to be calculated how earth is turning around its perpendicular of orbital surface during the year. As the trajectory of the axis is a circle than the angle of position can be described by sinusoidal faction. Also need to be described the matching of such days of the year like the autumnal and vernal equinox, summer sunshine state, etc.

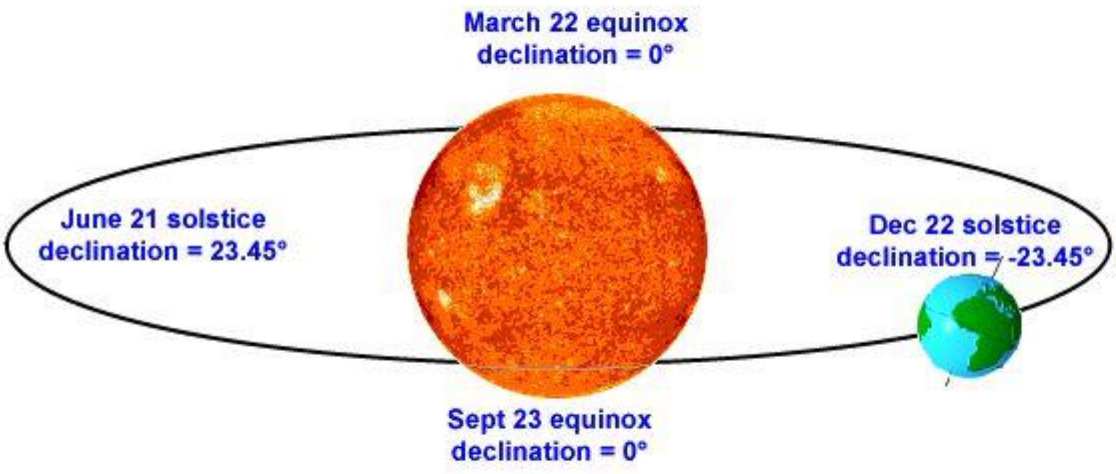

Figure 3.1 Representation of annual declination of the sun

The value of the declination of the Sun, which is denoted as δ, undergoes seasonal changes. This is due to the fact that the earth moves in an elliptical orbit around the sun, as well as the inclination of its own axis of rotation. If Earth's axis is not tilted, the decline was constantly equal to 0 °. Whatever it was, she tilted 23.45 ° and the angle of declination is from 23.45 ° to -23.45 °. The angle of declination becomes zero twice a year during the spring and autumn equinox.

So the formula to the angle is the following:

$$\alpha = 23{,}45 \cdot \mathrm{Sin}(0{,}9863 \cdot (n-81) \cdot \frac{180}{\pi}), \quad (3.2)$$

where n – the day from the beginning of the year.

Declination of the Sun - is the angle between the equator and the imaginary line connecting the centers of the Earth and the sun. Despite the fact that in reality the earth revolves around the sun, it is more convenient to consider the opposite: that the sun revolves around a stationary earth. For the settlement must go to another system of coordinates in which the Sun rotates around the Earth.

The graph of the movement of the Earth across the year shows the meaning of the formula more clear:

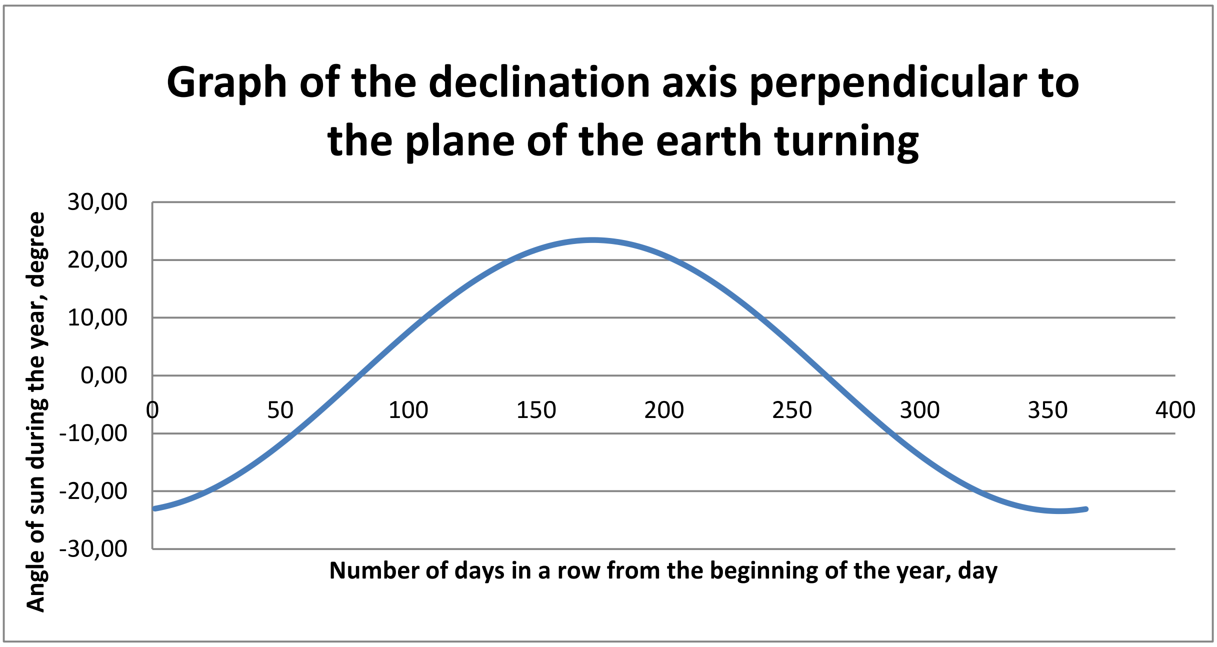

Figure 3.2: Graph of the declination axis perpendicular to the plane of the earth turning around the sun.

Consequently as the formula (3.1) contains (3.2) than the length of the day during the year will change in the same manner. The main limitation in formula (3.1) is that the length of the day is 24 hours and on the tropics latitude there is no change of the daylight duration which is reflected in the components of the formula.

The output from (3.1) is a graph that reflects the average day length on any latitude on the Earth to make model more universal. So, as the latitude is closer to zero (to the belt of the Earth) the less amplitude of the sinusoid will be. Near the tropics the amplitude will not change and will be 12 hours that can be show in the model.

For the annual accounting of the profit from the system with the sum of all the produced energy needed. So the annual production of energy by solar panels will be the power of all the panels multiplied on the length of there was which is equal to amount of sunny hours across the year.

But as it was described in previous chapter there is a big range of weather climates and different weather might appear during the year. For better accounting of weather change, the whole year have been splinted on the seasons. It was made because mainly the weather changes between the seasons. For every season the reducing coefficient have been made. Each coefficient reflects how many days during one season are not sunny or couple of days has cloudy or rainy weather.

These coefficients can be calculated only statistically and individual for every place where the system will be used. For example during the winter there 90 days in total and 40 days in this period were cloudy and 30 were snowy in average during 10 years of observation. So the efficiency in that case will be:

$\eta = (40*0.5+30*0.2)/90 \approx 0.29$ % - efficiency of sunrays during the season. This coefficient multiplied on the ideal circumstances which are clear sky.

After that all the annual energy production can be calculated:

$$E_{pv} = P_{pv} \cdot N \cdot \sum(D_{season} \cdot \eta) \quad (3.3)$$

where $P_{pv} - nominal\ power\ of\ the\ each\ solar\ panel,$ N – number of solar panels, $D_{season} - number\ of\ days\ in\ one\ season,$ η - reducing coefficient reflecting weather circumstances during one season.

3.3 Consumer

The common characteristics of the consumer were given in previous chapter. Here will be reflected how the value of the consumed energy is calculated for the model. To simplify the calculations accounting of the load was taken across the whole day and night. It was assumed that the house in which the system is situated have boiler for producing hot water. This boiler is working all the night so it is 10 hours average.

To make realistic values of the load across the day the table of average use different electric devices were used. In the model taken sum of chosen devices, but for every individual case this value can be changes according to following table:

Device name	Average work per day	Consumed amount of energy during the day, kWh
electric range	Cooking meal for 4 people	2.5
iron	2 hours	1
microwave	Cooking of two pieces of meat	1
vacuum cleaner	1.5-2 hours	1
steamer	8 hours	1
exhaust hood	24 hours	2
exhaust fan	24 hours	1
hair dryer	2 hours	1
dishwasher	One load	2
Electric shaver	Shaving 1800 times	1
Washing machine	Full load workout on 2.5 hours	2.5
Drum drying of washing machine	One load	2.5
Freezer	24 hours	1
Stereo system	8 hours	1
TV-set	6 hours	1

Electric kettle	40 cups boiling	1
Coffee machine	75 cups of coffee	1
Drum mower	3 hours	1
Lightbulb of 100 W power	10 hours	1
Toaster	70 toasts	1
Lightbulb fluorescent 40W power	20 hours	1
Home theatre	10 hours	2
Notebook	12 hours	0.24
Personal computer	12 hours	0.7
Electric boiler	50-80 liters of water	1

Table 3.1: List of most widely spread electric devices and there average consumption during the day.

This is only core devices which are used in nearly every house and not depends of the circumstances like season of year. Still it half of the world there is a time when the heating is needed. This is also included is the calculations with its own parameters and the period of year when it is needed. Since the calculations made to the whole year it is not important when the heating season is, the only important thing is its length.

3.4 Output from the model

As the system can be of variability and for example number of solar panels can be not enough to fully cover the demands of the load the additional supply from the grid is needed. As an output the production and the consuming of energy is comparing. If the production is lower than the potential of solar panels in generation of energy than additional supply is needed. Such electricity from the grid has it is own tariff for every kWh of energy taken.

In vice versa case when there is an extra energy during the year it can be sold to the grid by remuneration. Not all the countries let private owners to give power to the grid. Mostly there need to be an official paper that is conforming that the owner is guaranteeing an appropriate quality of the sent electricity. Of course the price of produced energy by owner is mostly lower that if it was received from the grid.

All these parameters have equivalent in money as the profit can be clearly seen only as such. Also it is important to include the price of the elements of the system. The energy produced by it is free of charge so the producing energy from year to year paying back its cost. It was picked out to element that are the most valuable to the system – the generation of energy complex which is consist of set of solar panels and the battery that provides stable workout. There cost need to be covered by produced energy from panels and equivalent to those amount of energy that should be taken from the grid instead. As the accounting is carried out annually, the cost of the components can be splinted on their guaranteed lifetime and subtract every year from the difference between earned by producing energy from renewable source of energy and spent amount of money. In addition the annual price of maintenance considered in the model because such system from time to time needs to be checked out. In the end the amount of earned money will be received.[19]

To calculate the payback period the following formula can be written:

$$T_{payback} = \frac{P_{system}}{P_{earned} + P_{payback}} \quad (3.4)$$

Where P_{system} – Cost of the system per one year of work, euros; P_{earned} – amount of money gained by the system without payback, euros; $P_{payback}$ – amount of money that can be received if the system is able to produce extra energy and it can be sold to the grid. The proper choice of the battery can dramatically change the payback from the system, because battery is one on the biggest price in the system cost. As it mostly depends from the capacity, the calculations need to be made. In further topics this will be made.[9]

3.5 Conclusion

By counting several models in different circumstances like different abilities to produce energy, different fund in a system and geographic position by reviewed model it was received bug range of payback period. But the price on the solar panels nowadays is not very big as same as on the batteries for private houses which is reflecting the fact that even in bad conditions payback time not crossing notch of 10 years which is good result compare for example to the wind turbines which payback period can starts only from 10-15 years.

In the model were not taken in account not realistic circumstances like North and South Pole, because of the polar night which is not letting solar panels work during half of the year. Also were not taken into account very big loads that can fits only to the whole apartment house.

As a perspective this model can be extended to reflect more detailed behavior of the weather for more accurate calculations of produced energy. Also can be created full 24-hour load graph with points of minimum and maximum for better calculation of the everyday accounting of the load. Still the parameters in this models are enough to judge is the system efficient or not from economic point of view.

4. Imitation model of the solar panel system with storage battery

4.1 Introduction

After the economic analysis that proved the efficiency of the system with solar panels it is be to be discussed the continuous operation of the system. This includes the non-interrupting process of production and consuming the energy gained sun. The cases that have influences on the amount of energy that can be produced constantly changes as it was described in previous chapters. In this chapter this parameters will be included in the imitation model that will predict the behavior of the system during one year, including geographic and natural and other factors.

The complex of the factors that are lowering the level of production of energy can create the situation when energy from panels is not enough to cover the demands of single house which is the end consumer in our case. In this case here will be also described how the system behaves. This creates the following question: is it possible to make a system with the solar panels fully offline without any support from grid or not?

The imitation model have been made in Simulink toolkit of Mathlab program as this is one of the most flexible tool to create any kind of systems by using mathematical approach. So, all the components in the represented model are based on the mathematical formulas and logical consequences. Also in this chapter the output of the diploma thesis will be made.[2]

To fully reflect the demands to the system, the straight requirement to the system should be met. These are:

- The sources of energy should cover the load demands by means of PV batteries and/or storage battery at least during most favorable time of year
- The system should have diagnostics of level of storage battery charge and fulfill it by the energy from PV and/or grid if it is included to the system
- The capacity of the battery should be calculated so that if there is no other sources of energy at least 24 hours of smooth supply will be provided
- The standard level of voltage should be used
- Free energy should be given to the grid

4.2 Model and behavior of producing energy by solar panels

4.2.1 Common information

To understand how the imitation model for the energy generation part of the system will look like there need to be made a theoretical explanation. In the description part of present diploma thesis already made quick preview of the basics of the earth to sun movement. In this part it will be reviewed closer as any parameter for the model is very important, especially in such complicated object.[1]

In details: light of the Earth surface depends from:

- Atmospheric phenomenon as a absorption and dissipation
- Local changes in atmosphere such as clouds, dirt and others
- Latitude of the place
- Time of the year and day

These factors have influence on the common energy flow, its spectral structure and angel on which the sunlight is falling. The main sequence of atmosphere availability is that the sun irradiation is different depending from its location. These changes due to local effects (clouds, season changes) as well as other effects like longevity of day on different latitudes. In a desert sun irradiation more stable as a there is no clouds, in equatorial region – due to less season changes of location to sun.

The irradiation on the surface of Earth is different from which is falling on the atmosphere. This is due to the presence of natural barriers in atmosphere as mentioned above.

Very important factors for photovoltaic effect are:

- Lowing of sun flow density as a consequence of absorption, dissipation and reflection in atmosphere
- Changing of spectral structure of sunlight as a consequence of absorption different length of the waves.
- Appearance of diffusion or non-direct component in sun irradiation
- Local changes of atmosphere which have additional influence of the power, specter and direction of falling irradiation. [7]

When photons are going through the atmosphere they are absorbing by gases, particles of dust and aerosols. Some gases like ozone (O_3), carbon dioxide (CO_2) and water steam (H_2O) are absorbing photons very well with the energy close to the energies of chemical chains of these gases. As a consequence of these absorptions on the curves of the specter the holes are appearing according to these energies. For example, significant part of further infrared irradiation, 2 micrometers, is absorbing by steam and carbon dioxide. Ozone is absorbing ultra-violet irradiation, less than 3 micrometers (but not all, part is still going through).

The absorption by atmospheric gases changes the spectral structure of ground light irradiation; meanwhile they practically have no influence on the common density of the flow. The consequence of the molecular absorption is not the separate deep minimums in specter, but the overall specter density lowering, depending from the length of the route of the sunlight going through the atmosphere.

In addition the light that goes through the atmosphere also suffers dissipation. One of the mechanisms of dissipation in atmosphere is Rayleigh dissipation. It is significant to the short-length waves because it has vise-versa dependence from its length. Also there is dissipation due to aerosols and particles of dust.

The dissipation is not coming in one direction and that is why it is seems like the light comes from entire sky. Such light is call diffused or dissipated. As mostly blue specter is valuable to dissipation the sky seems to be blue to us. In clear day dissipation is up to 10%.

The last factor that has influence on amount of falling sun irradiation is presence of local inhomogeneity in atmosphere. Spectral density is slightly changes depending from cloud cover.

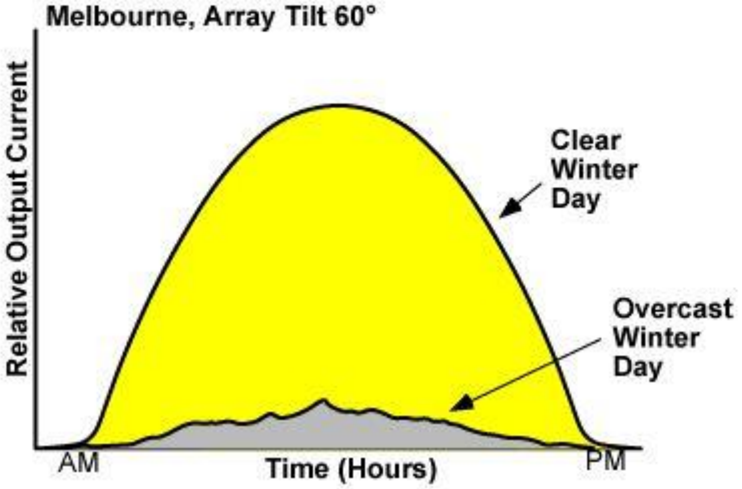

Figure 4.1: Output current from PV battery in sunny and dull days during the winter in Melbourn.

4.2.2 Atmospheric mass

Atmospheric mass – is a length of the route, which is done through the atmosphere referred to the shortest possible path (when the sun is at its zenith). Atmospheric mass shows how much decreased spectral irradiance after passing through the atmosphere and absorption of air and dust. [7] The atmospheric mass is defined as:

$$AM = \frac{1}{Cos(\theta)}, \qquad (4.1)$$

Where θ – is an angle from vertical (zenith angle).

When the Sun is right above, θ = 90 degrees and atmospheric mass equal to one.

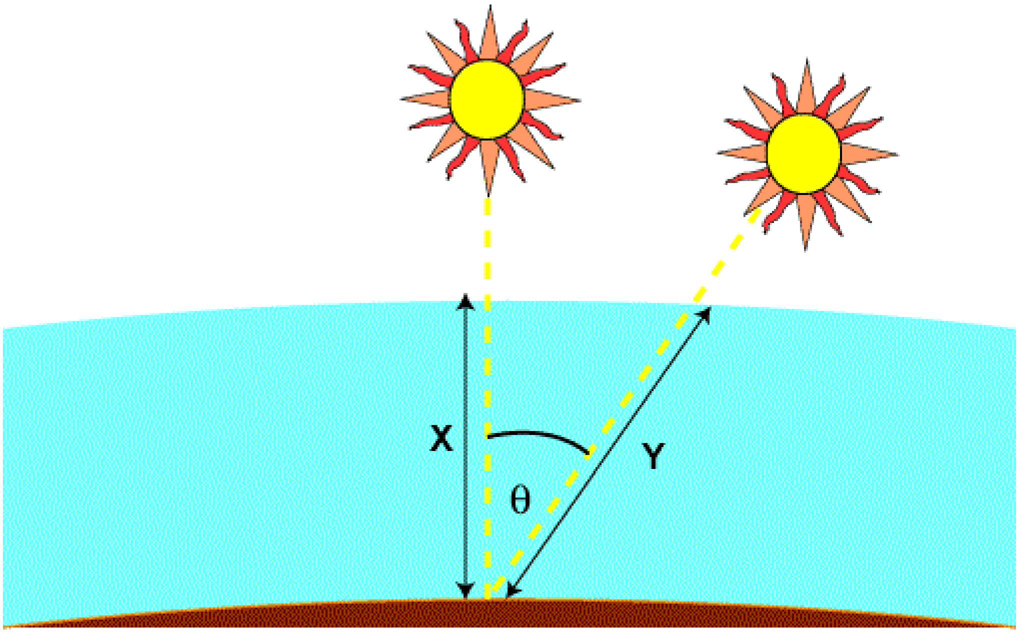

Figure 4.2 Graphical explanation of the formula (4.1).

It is assumed that the atmosphere - it is flat horizontal slice. But in fact it is not. The curvature of the atmosphere leads to the fact that when the sun is near the horizon, atmospheric mass different from the length of the atmospheric path. At sunrise, the sun angle, measured from vertical is 90 and the atmospheric mass must be equal to infinity, then it is obvious that the length of the atmospheric path is finite. The following equation takes into account the curvature of the sphericity of the Earth:

$$AM = \frac{1}{Cos(\theta) + 0{,}50572 \cdot (96{,}07995 - \theta)^{-1{,}6364}} \qquad (4.2)$$

4.2.3 Sun movement across the sky

The movement of the sun across the sky, which we see every day, is due to the Earth's rotation around its axis. As a result, changing the angle at which the direct component of the light falls on the ground. For a stationary observer on the Earth it seems that the sun moves across the sky. The position of the Sun in the sky depends on the observer's location, time of day and year. [7] The movement of the sun below

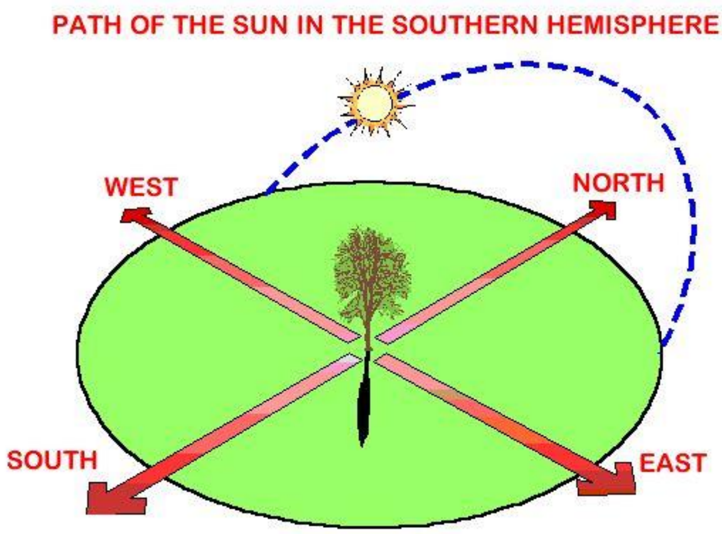

Figure 4.3: Movement of the sun in western hemisphere.

The movement of the sun across the sky greatly affects the amount of energy produced by the solar cell. The illumination of the surface and the flux density of the incident irradiation are equal, if the irradiation falls at a right angle. When the angle between the sun and absorbed by the surface illuminated surface decreases. When the sun's rays fall parallel to the module and the angle to the normal of 90, illumination drops to zero. For other values of the angle of incidence is equal to the relative intensity of the irradiation cos θ, where θ - the angle between the sun's rays and the normal to the module.

The angle between the sun and the specific location on the Earth depends on the position of this place (longitude), time of year and day. In addition, the location depends on the length of time of sunrise and sunset. Therefore, to calculate the angle of sunlight, you need to know the latitude, longitude, day of the year and time of day. This will be described in following parts.

4.2.4 Sunlight time

Local solar time and local time

12:00 local solar time (LST) - the time when the sun is at its zenith (highest in the sky). Local time (LT) is usually different from the local solar time due to the existence of the tilt of Earth's orbit, people use time zones and artificial time offsets introduced to save energy.[7]

LST Meridian (LSTM)

LST Meridian - Meridian is used to refer to a specific time zone and for the establishment of Greenwich Mean Time. LSTM is shown below

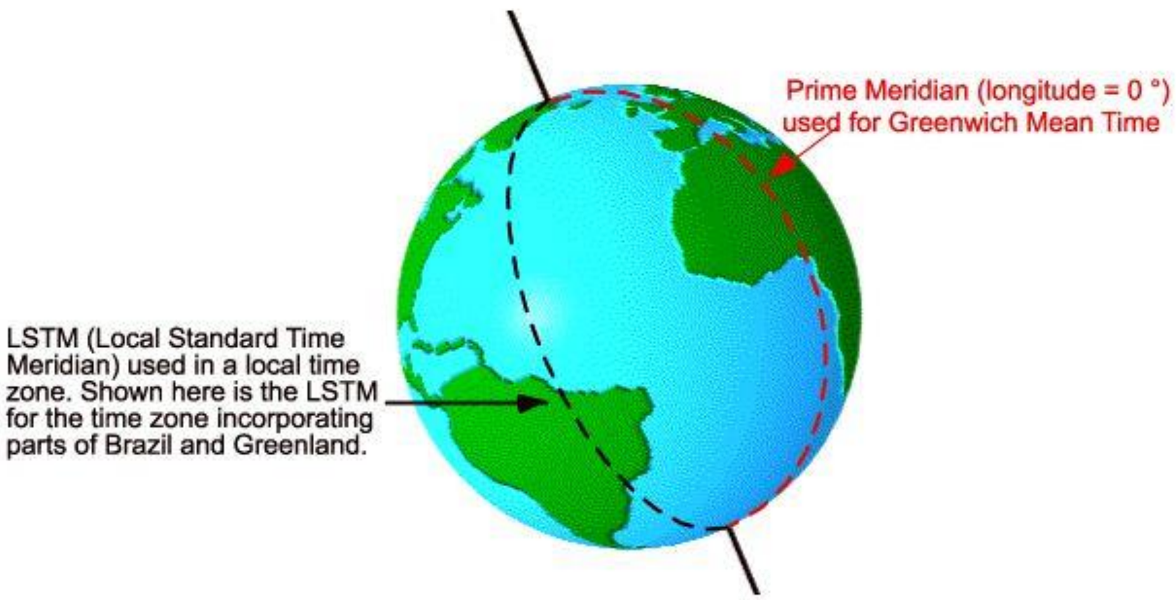

Figure 4.4: The example of LSTM on the world map.

LSTM is calculated using the formula:

$$LSTM = 15^{O} \cdot \Delta T_{GMT}, \qquad (4.3)$$

Where ΔT_{GMT} – difference between local time and average time on Greenwich, hour.

Next the equation of time is described. The equation of time in minutes - it is an empirical equation that takes into account an amendment to the eccentricity of Earth's orbit and the tilt of Earth's axis.

$$EoT = 9{,}87 \cdot Sin(2B) - 7{,}53 \cdot Cos\,(B) - 1{,}5 \cdot Sin\,(B), \qquad (4.4)$$

$$\text{Where } B = \frac{360}{365}(n - 81) \qquad (4.5)$$

in degrees and n – is a number of days from the beginning of the year. The amendment, which is determined by the equation of time, is shown in the chart below:

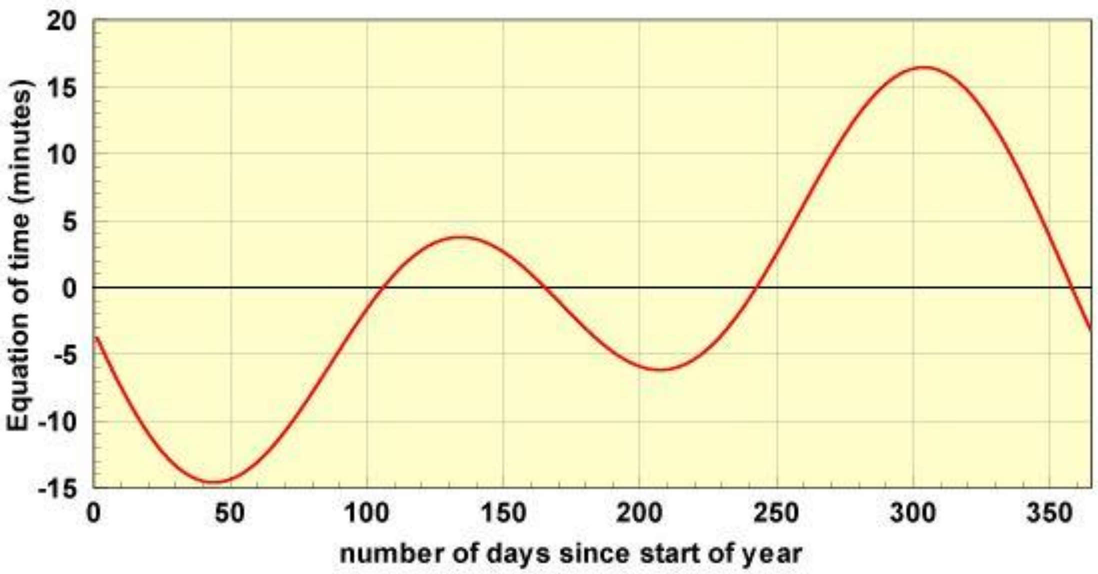

Figure 4.5: The curve of the EoT characteristics.

For the accounting of changes in local solar time at the one time zone change longitude within this zone, the Temporary correction factor is calculating (in minutes).

$$TC = 4 \cdot (LSTM - logitude) + EoT) \qquad (4.6)$$

Accounting these two local solar time corrections can be obtained from the local time using the following formula:

$$LST = LT + \frac{TC}{60} \quad (4.7)$$

The final goal in calculations is to have the transition to the placement of the sun to earth in every minute, so next there need to be introduced the hour angle. It converts local solar time in the number of degrees which the sun passes through the sky. By definition, the hour angle is zero at noon. Since the Earth rotates 150 per hour, for every hour of the afternoon sun passes 150. In the morning the sun angle is negative, in the evening - a positive.

$$HRA = 15^{o}(LST - 12) \quad (4.8)$$

Also in model need to be accounted the declination of the sun, which was described in previous chapter in details.

4.2.5 Elevation of sun

The final goal of the part of the model which is describing the production of energy is to make a description of sun movement across the sky mathematically. So, particularly, this needs to me a sinusoidal movement with the respect to the time. And the amplitude of this sinusoid will change during the year, It is need to depended from all the cases mentioned above. In this case the elevation copcept is use.[7]

Elevation (elevation angle) - the height of the sun in the sky as measured in degrees from the horizontal. The words "height" and "elevation" is also often used to describe the height in meters above sea level, which makes a bit confusing. At sunrise, the elevation angle is 0 ° and 90 ° - when the sun is highest in the sky (just above the head, which can be observed, for example, at the equator at the vernal and autumnal equinoxes). Zenith angle elevation is similar except that it is not measured by the horizontal axis and the vertical. Zenith angle = 90 ° - elevation.

Elevation changes throughout the day. It also depends on the latitude of the location and time of year. When designing the PV system, it is important to know the maximum elevation for the area, which is the maximum height of the Sun in the sky at a particular time of the year. The sun reaches its maximum height at noon solar time, and this height depends on the angle of declination and latitude, as shown in the image below:

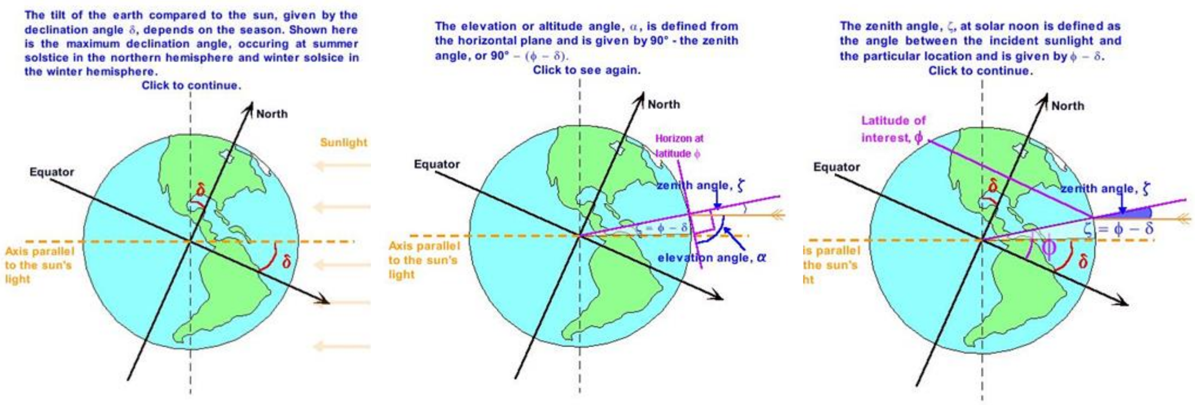

Figure 4.6: The dependence of The maximum angle of elevation on a sunny afternoon (a) depends on the latitude and the declination angle (δ).

The figure can be obtained elevation angle on a sunny afternoon in the northern hemisphere:

$$\alpha = 90 - \varphi + \sigma \tag{4.9}$$

and for the southern hemisphere:

$$\alpha = 90 + \varphi - \sigma \tag{4.10}$$

where φ - is latitude locations. In the equation for the northern hemisphere the latitude is positive at locations in the northern hemisphere and negative in the southern hemisphere. In the equation for the latitude of the southern hemisphere is positive for locations in the southern hemisphere and negative in the north. φ - the angle of declination, depending on the time of year.

In the area of the northern troFigures autumnal solstice the sun is directly overhead and the elevation angle is 90 °. In the summer at latitudes between the equator and the TroFigure of Cancer in the solar elevation at noon more than 90 °, given that the sun moves more to the north than the south, as in much of the northern hemisphere. Similarly, at latitudes between the equator and the southern troFigure at certain periods of the year the sunlight comes from the south rather than north.[7]

The elevation thus can be calculated by such formula:

$$Elevation = Sin^{-1}[sin\ \sigma \cdot sin\varphi + cos\delta \cdot \cos(HRA)] \qquad (4.11)$$

This equation in continuous mode is reflecting the annual sun movement with the respect to the horizon. For producing energy purposes still only positive part of sinusoid is needed as only this part of sinusoid reflect the position above the horizon and sun is able to transport energy to PV batteries.

4.2.6 Irradiation calculation

To find out how much energy can be produced by the system with solar panels it is need to be known how much irradiation can be collected by panels. To find this out we need to see what the unit of measurement of solar irradiation is. When the sun is transporting its irradiation to the Earth in the space there is no obstacle for the photons and the amount and radiation is constant. It is called solar constant and is equal to roughly 1.362 kW/m^2.

Solar irradiance is measured by satellite above Earth's atmosphere, and is then adjusted using the inverse square law to infer the magnitude of solar irradiance at one Astronomical Unit (AU) to evaluate the solar constant. The approximate average value cited, 1.3608 ± 0.0005 kW/m^2, which is 81.65 kJ/m^2 per minute, is equivalent to approximately 1.951 calories per minute per square centimeter, or 1.951 langleys per minute.

Solar output is nearly, but not quite, constant. Variations in total solar irradiance (TSI) were small and difficult to detect accurately with technology available before the satellite era (+/- 2% in 1954). Total solar output is now measured as varying (over the last three 11-year sunspot cycles) by approximately 0.1%.

This solar constant going through the atmosphere and loosing part of the energy which depends from the factors mentioned above. In common the solar the elevation level shows the angle of the sun in every point of time during the year, so the irradiation is proportional this value. It is not very important if this calculation is straight, so to find out how much energy can be gained in clear day next formula can be written:

$$R = R_{solar} \cdot \frac{Elevation}{90}, \quad (4.12)$$

where R_{solar} – is a solar constant, kW/m².

Also the production of energy depends on the squire on which the irradiation is falling. This parameter depends only from the number of panels on which sunlight is falling and there square. By this we receiving the amount of energy that we gaining in a unit of time.

$$E = \eta_{pv} \cdot R \cdot N \cdot S, \quad (4.13)$$

where η_{pv} - efficiency of the PV battery, N – number of the PV battery in a system, S – square of the each PV battery.

Finally to make the model more realistic the reflection coefficient (1.1 from the normal radiation) and the weather coefficient is added, that reflects the reduction of ground irradiation by clouds, rain and snow which can settle on the PV batteries.

The weather coefficient is made by the opportunities of Simulink toolkit. The idea of this coefficient described in the chapter of economic model. The representation of this coefficient is following:

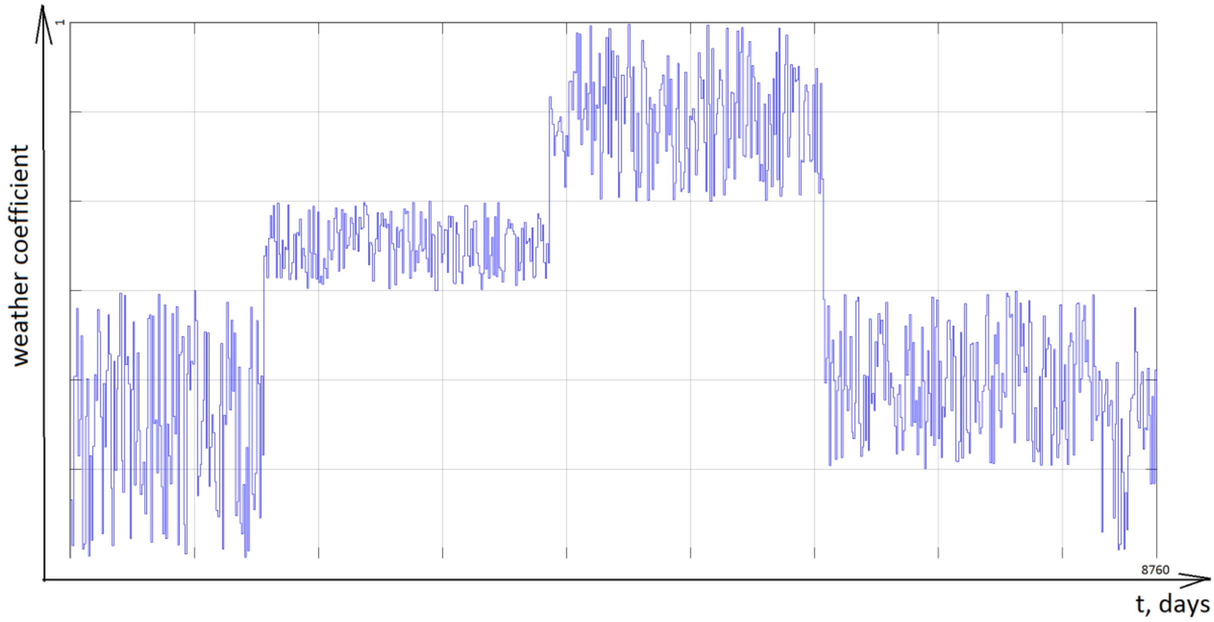

Figure 4.7: The weather coefficient changes every season.

The time in the model starts from the 22th of December, the day when the shortest day in the year, the discreteness of the weather conditions is 12 units of times which is equal 12 hours in real life. Every season is roughly splinted from each other, to highlight the difference of the weather during the year. Certainly this graph needs to be made individual to every territory.

4.3 Mathematical model

All the equations (4.2) – (4.13) are moved to Simulink toolkit. The time limit were chosen as 8760 – the number of hours in the single year. The overall characteristics of produced energy will look like this:

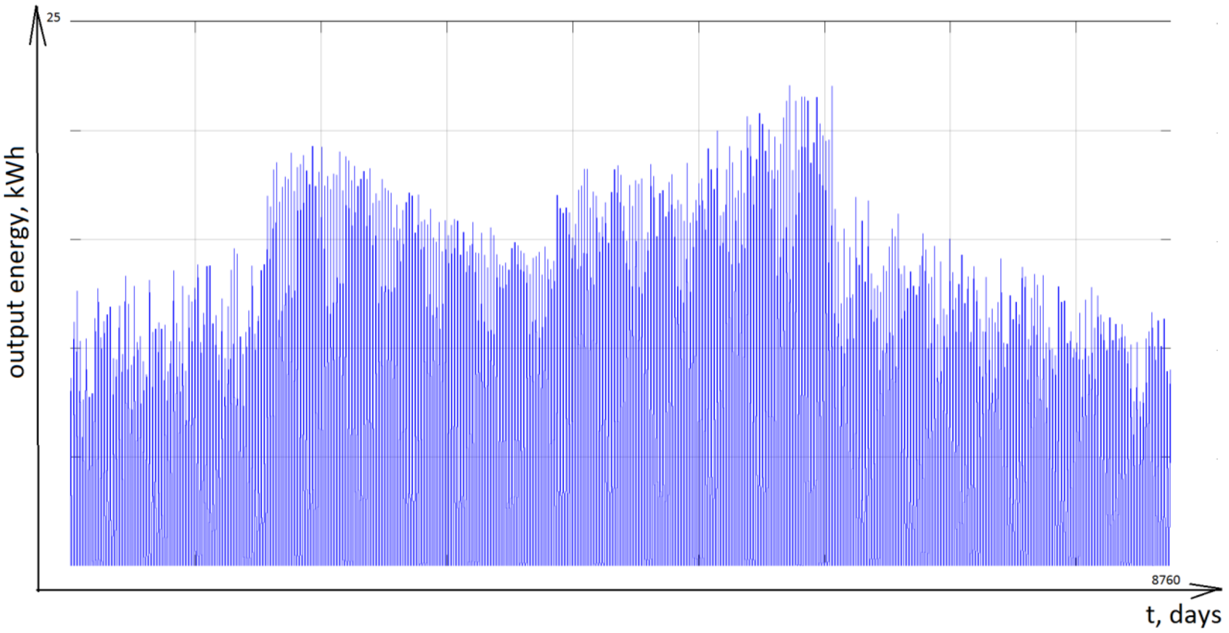

Figure 4.8: Output energy from the PV batteries set with 15 PV batteries, 6 m^2 each.

In closer look on the one iteration there can be understood how the model works:

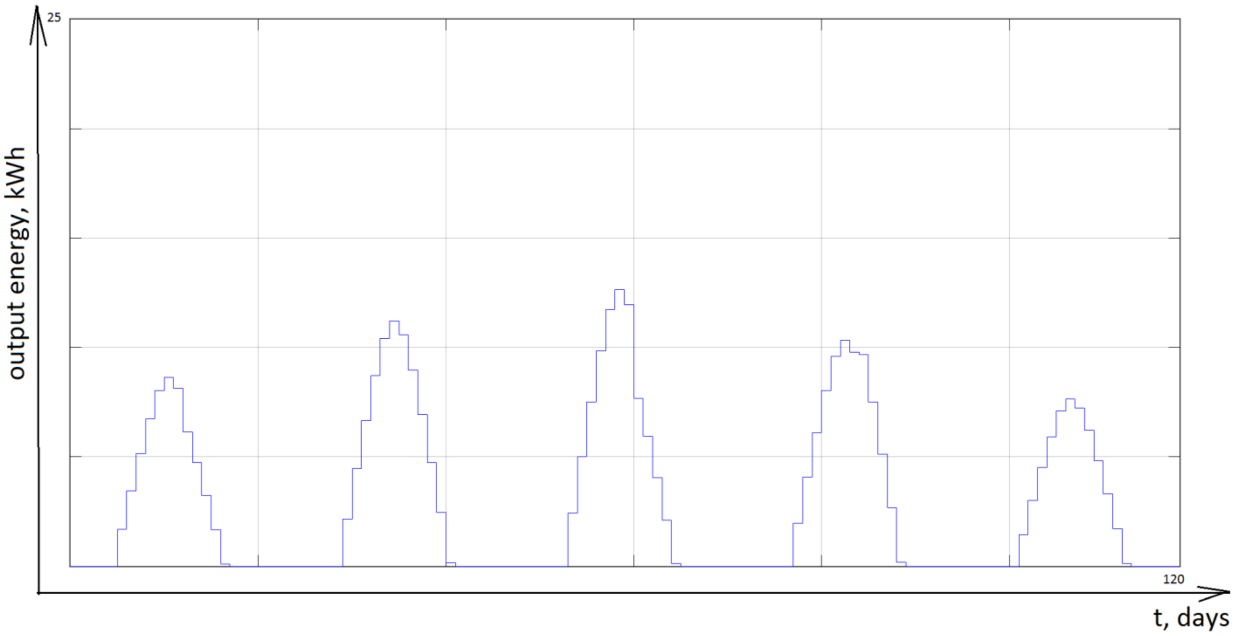

Figure 4.9: Every day production of energy.

The discreteness of the system is one hour as the equation from which this system consists is customized to such numeration. One half-sine on the graph is a level of produced energy in one day. The length of this sine represents how many hour during the day sun is above the horizon. On the North or South Pole this sine will never fall to zone during polar day:

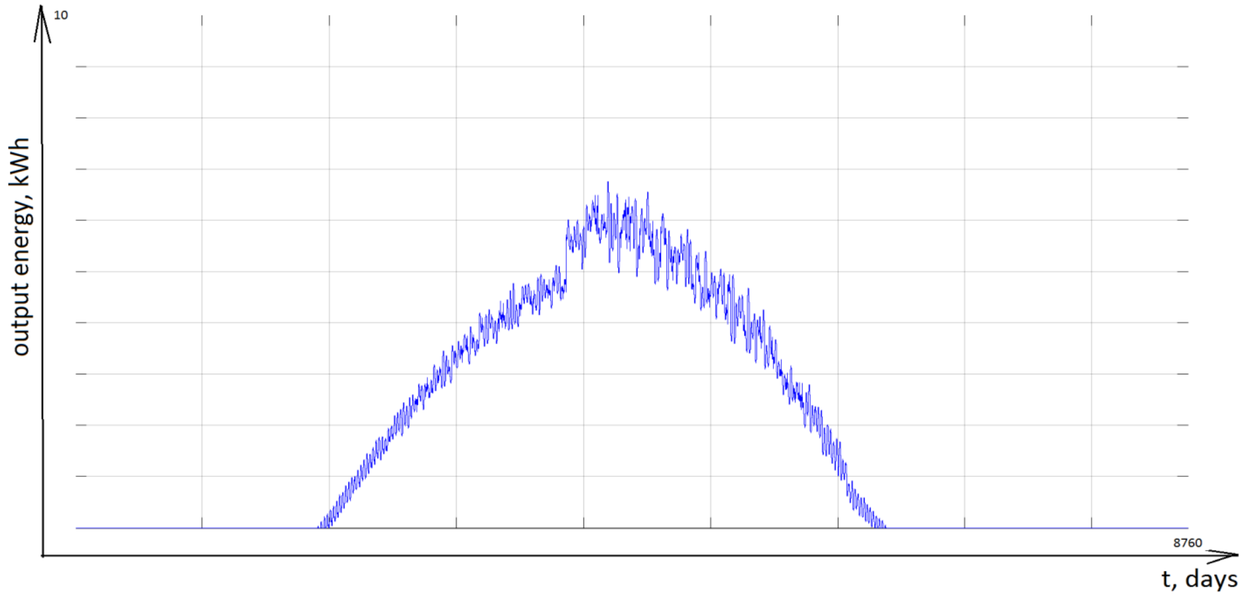

Figure 4.10: Annual production of energy on the 89 degree of northern attitude, North Pole.

4.4 The model of the system's load

In the table 3.1 the basic load in the house are represented. The load of the all house was taken randomly just to reflect some level of load in average house with a normal family with the peaks and holes in a load curve. In the curve also was taken in account the heating season. Certainly this is not necessary in the countries near the equator:

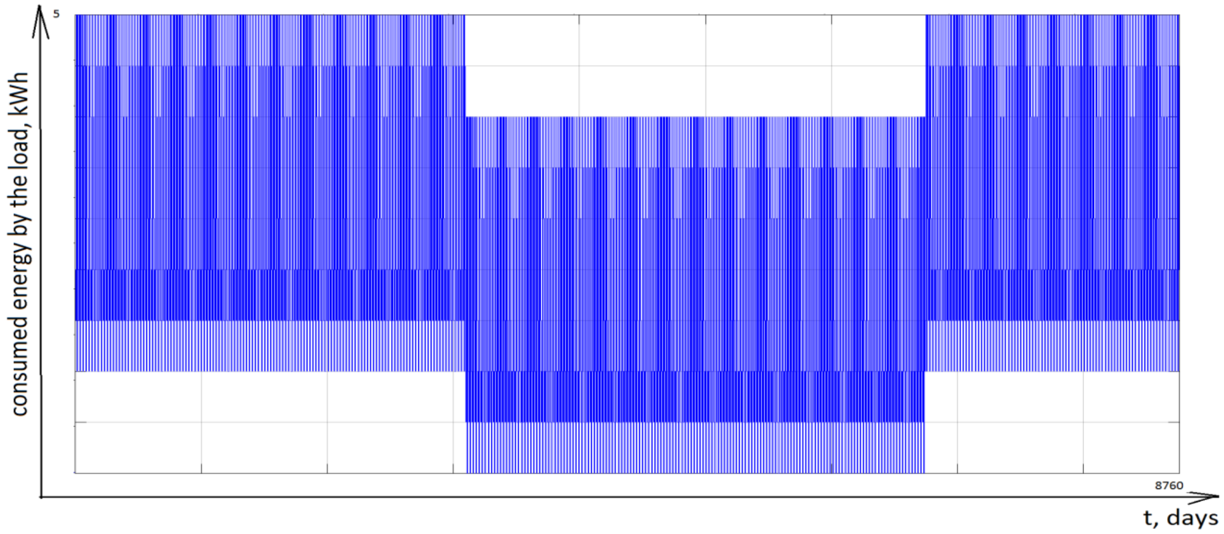

Figure 4.11: The curve of the annual load of the system.

The curve consists of repeating every day loads close to those that was shown on Figure 1.2 and 1.3. Only amplitude changes as the way of life in most common family is much the same. So statistically this is universal curve, except the heating season option.

Model of the system operation with the energy, the difference in consumed and gain energy always exists. Also part of the energy will go on the battery charge, or vice versa, when energy is not enough take the charge from the battery. More over the level of the charge need to be on the high level, close to the maximum as it is need to be a stock in times of accident blackouts and when produced energy less than consuming.[23]

As the energy goes through the battery first the level of free and necessary energy can be shown:

$$E_{free} = E_{pv} - E_{consumed} \tag{4.14}$$

So if this value is lower than zero, than this is an amount of energy than need to be filled by outer source, when more than zero – it is an energy that can go on the charge or to the grid. This how it looks this value in continuous mode:

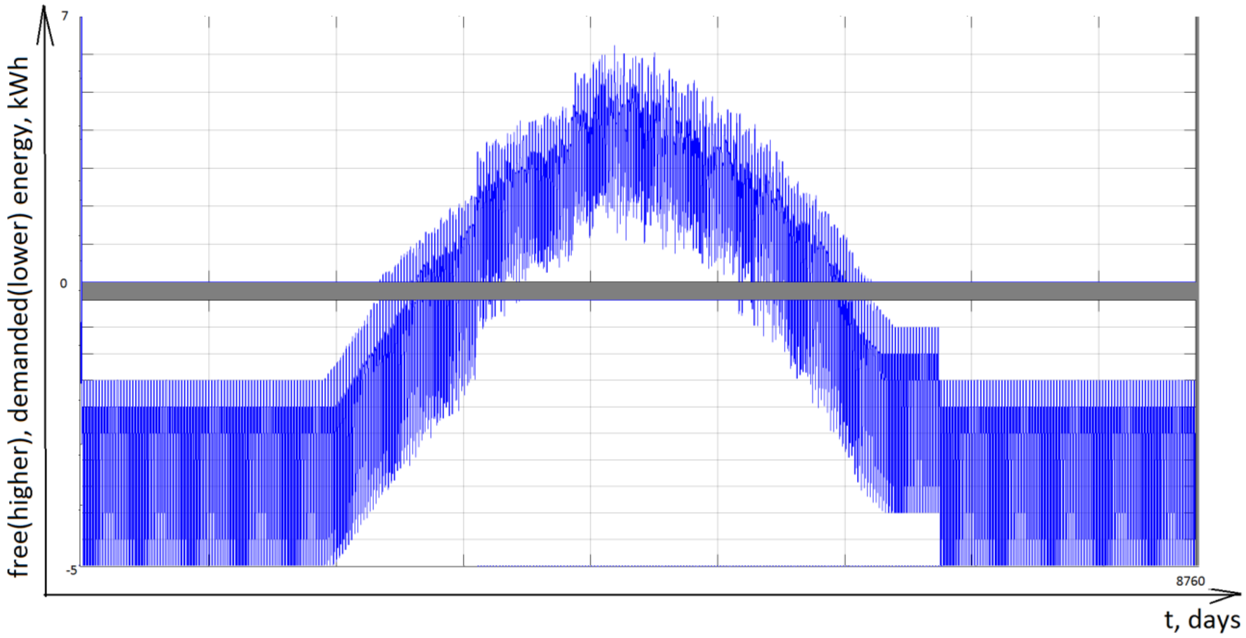

Figure 4.12: a) energy (higher), b) demanded energy (lower)

4.5 The battery capacity and model of its behavior

One of the purposes of the thesis is to optimize the capacity of the battery. This means that the capacity needs to be as small as possible because of its price that proportional to its capacity. But also the capacity needs to be large enough to handle the blackouts for enough time, at least a day.

In common there is a method to calculate optimal parameters to the battery.

The formula for this is following:

$$C_b = \frac{P_d}{U_b \times \eta_p}, \quad (4.15)$$

where P_d – power of daily load, U_b – voltage of the battery in this case this value 12 V, η_p – lowest safe level of the charge of batter, %.

As the load power is constant and voltage and level of the battery are defined. The level easily can be calculated.[21]

By the present load curve and η_p=50% – this value is around 70 kWh, so C_b ≈12 Ah. P_d=70 kWh is a sum of energy consumed by the load every hour.

The charge of the battery is a continuous process, the function of time so the process of battery charge can be represented as an integral of energy. The presented model contains this process – time integral of energy and the barriers which are represents the lower level of battery and upper battery limit, 12 kAh and 6 kAh respectively.[3,8]

The model itself is shown below:

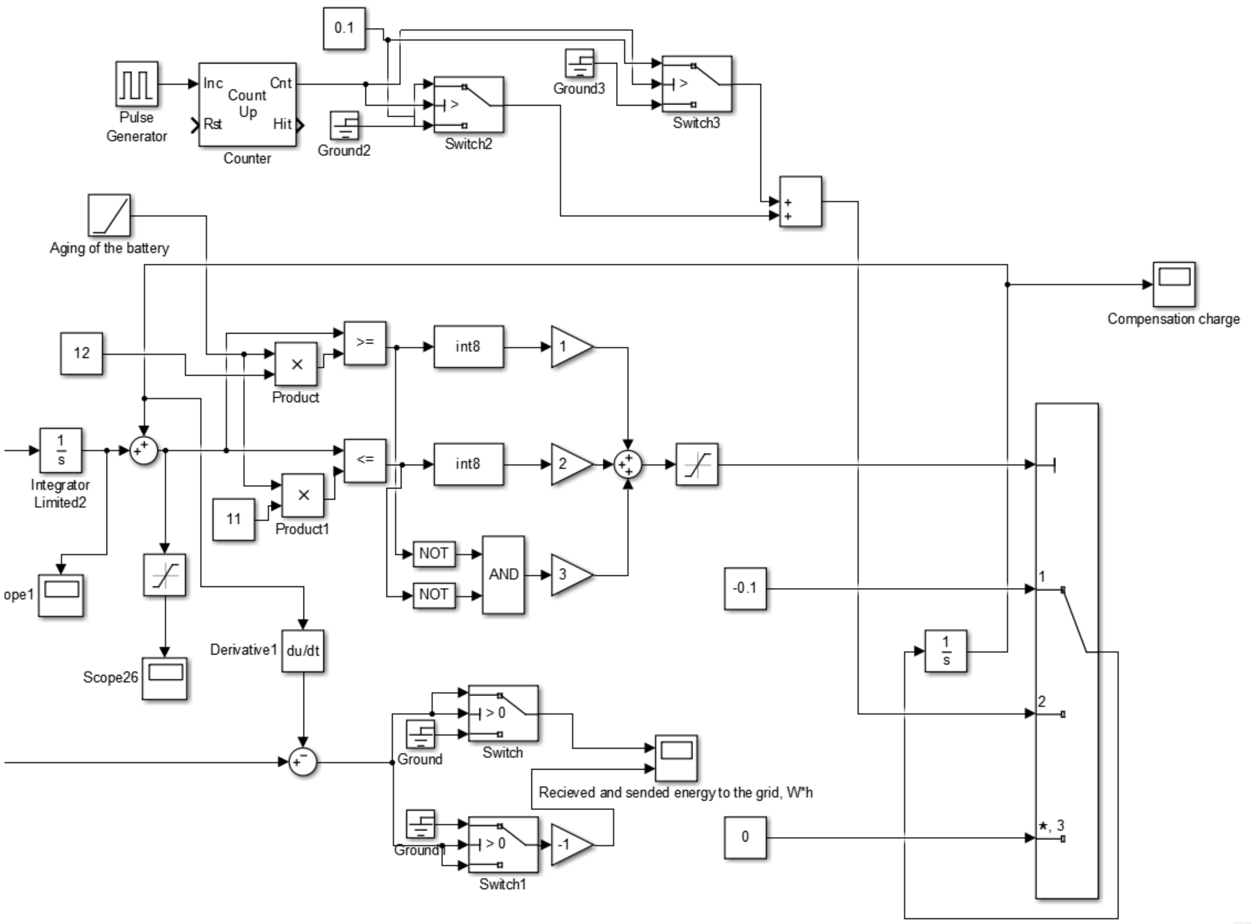

Figure 4.13: The part of the imitation model that represents the battery logic.

The grid assumed to be 100 A in both directions. This value is limited only by the square of cut of a cable. Typically is value is around 50 mm^2 with three phase inside. As here uning kA, the values in the model are 0,1 respectively.

From left side before the integral the E_{free} comes to the battery, after it goes through the integral it become the level to charging or discharging of the battery. The level of charge on the battery is always starts on not less than 50% level because manufacturer must guarantee the battery unharmed before start of usage.

After that the system makes the identification of the present level of charge in the battery – if it is lower than maximum, than the energy goes to fill it, if it is on the maximum or close to this value, the energy goes to the grid. If the E_{free} is negative, the gradient will be descending and to keep battery on the proper level additional energy need. In other cases system is waiting of changes. As the state of charge is in integral form the discreteness of the system equals to the discreteness of the Simulink toolkit, which is less than 10^{-8} of one unit of time, so almost constantly monitoring of the system state. With such low power, the grid presented in a model as a source of current equal to 1 A. In practice this enough to cover load with the help of PV batteries and reserved energy.

On the figure 4.13 can be seen the level of charge during one year with the account of aging battery level. In this model it was taken as 1% per year because it is assumed that the battery was used properly:

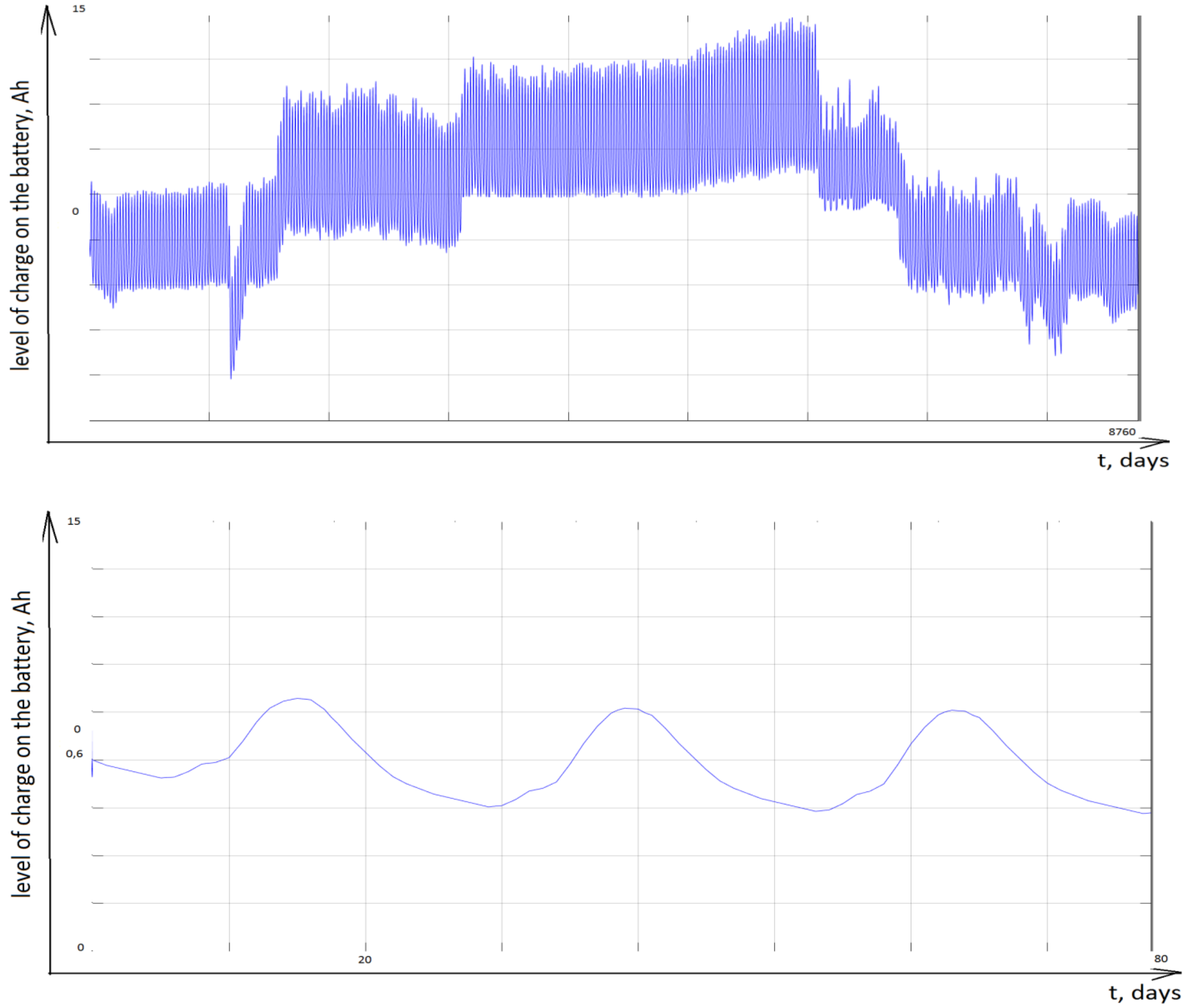

Figure 4.14: Level of charge on the battery during one year and during one day respectively.

In this model artificially made a blackout which last 24 hours. AS it can be seen from the figure, level of the battery straightly falls to the level of 6 Ah, which is a minimal level of the charge. On the curve also can be seen the moments when produced energy more than consumed.

The control of the energy is applied by the algebraic positive feedback, which is a fulfillment of the faults of the system. The difference of the primary energy flow before the integration and derivation of the feedback leads to the amount of gained and sent energy to the grid:

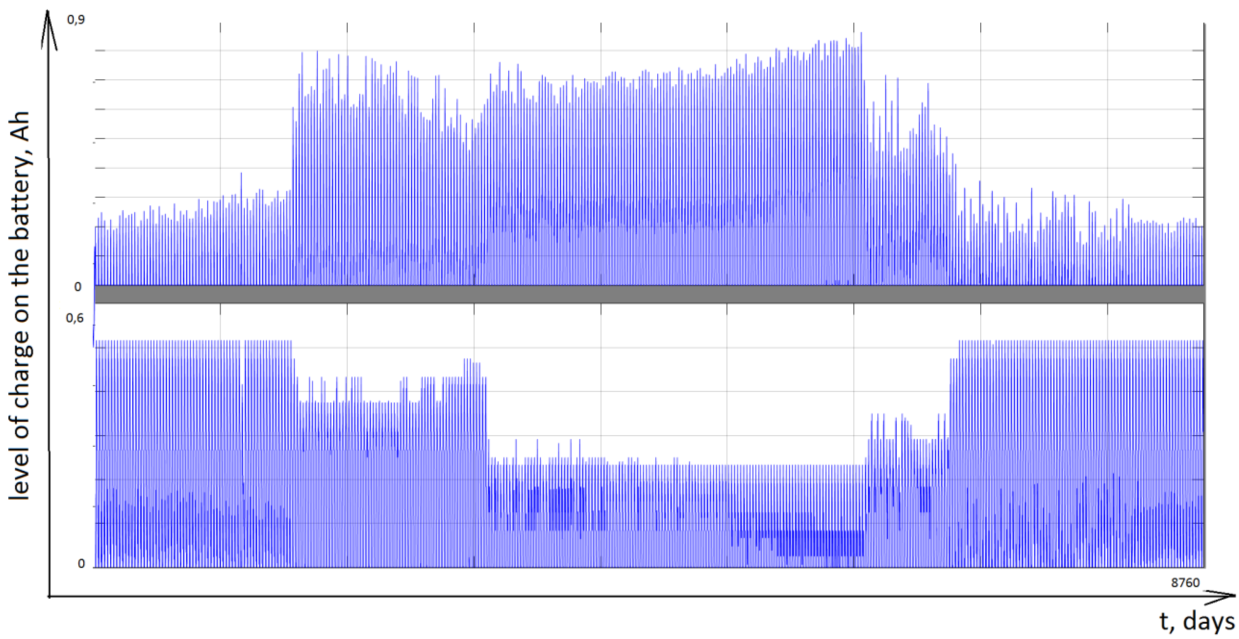

Figure 4.15: a) Sent back to grid energy (upper), taken from the grid energy (lower).

If there were no control on the storage battery and the level of charge were endless and theoretically can be negative, the gradient of charge will look like this:

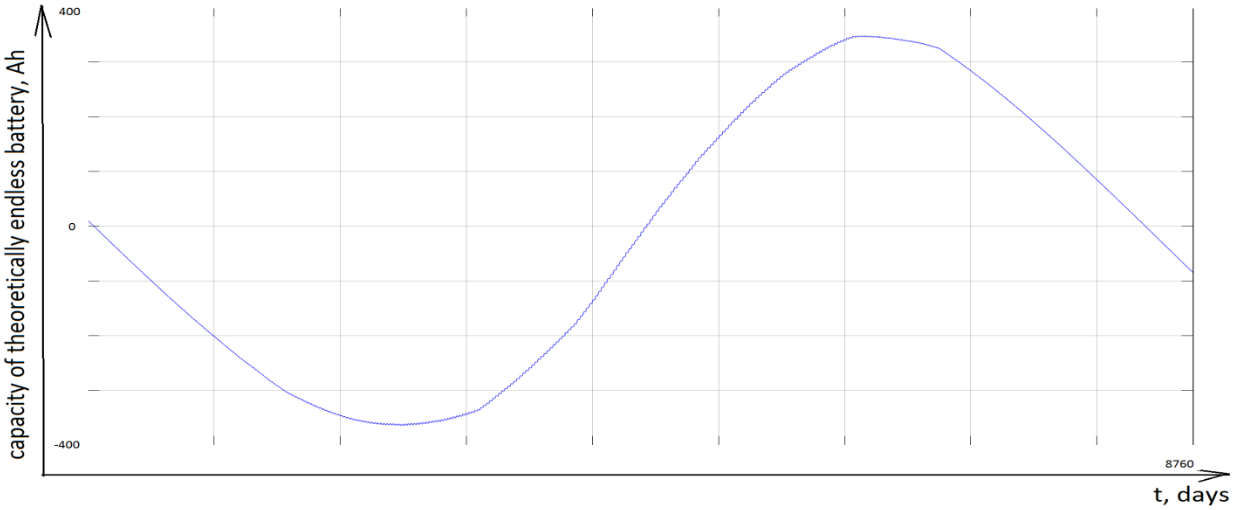

Figure 4.16: Theoretical gradient of charge level on the battery.

So particularly, the control of the battery is works on the correction of level of energy in battery, as the negative values without support will leads to full inability to supply the load, and all the energy that is higher than maximal level of charge will just dissipate.

4.6 Output of thesis

The purpose of the thesis was to make an optimization of the PV batteries and storage batteries. The engineering process includes not only the optimization of parameters from the efficiency of the system point of view. But also is very important, and in this thesis was made accent on it, the economic efficiency. This includes the finding out the optimal ratio between the price on the parts of the system and its workability.

In the first two chapters the overview of the system was made and the frames and appropriate devices were chosen. As we speaks about the PV batteries there is a big difference in efficiency, but optimal and most widely spread battery are with the efficiency 18% (monocrystals of silicon) because of their relatively low price. Certainly the efficiency becomes more important on the bigger latitudes, as there is more lack of sun there especially during the winter time, but this is compensation but longer days during the summer time and the payback from selling energy to the grid compensate bigger spending during winter.

The storage battery is optimal not only by parameters of efficiency, but also need to meet the requirements of proper work. In this thesis LSD NiMH type of batteries were chosen because of their features. The optimal capacity of the battery depends of the load and can be calculated to universal formula that was tested on the imitation model. With such optimization the payback period can be decreased on 10-15%, depending on circumstances such as weather and geographical position of a system. Together with applying straight amount of energy to specific cases so that the production of energy will be optimal during the year the benefits can raise twice more. By the definition optimal it means the more than half of the year production of energy will be more than shortage of energy and necessarily of using grid energy.

It is possible to have the conditions so that there is no need in additional supply, but this is only possible closer to the Greenwich and if nearly all the year the weather is sunny, also there need to be enough PV batteries to cover the load demands.

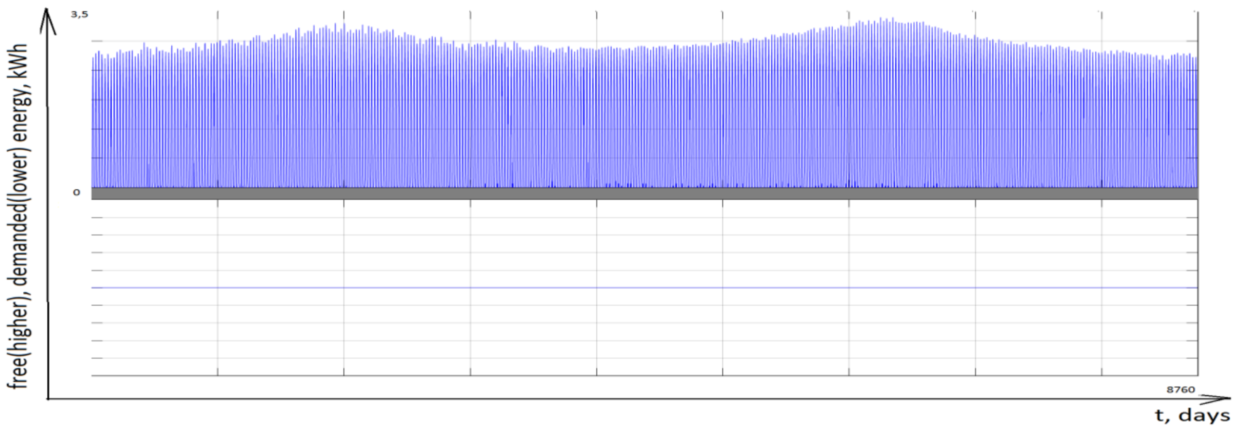

Figure 4.17: The representation of the case when the system is fully autonomous.

As it can be seen on the figure lower graph like on figure 4.14 is an amount of energy that is taken from the grid. The production of energy and the loads are the same, but the latitude and weather conditions change to the real ones in the area of North Africa or South Europe. In this case the payback of the system can be seriously accelerated. By the calculations the payback lowers nearly twice.

Still the main objectives of the thesis were not reached as few examples of the possible solutions were made and this is insufficient to relay on this data for creating the universal system of optimization of PV and storage battery capacity that will be optimal to any circumstances.

Further work on the optimization of parameters of PV and storage batteries can be so to make automatic selection of parameters right in the mathematical or imitation model. This parameters need to be independent from the outer conditions that are described here in details. Also there in this thesis the electrical parameters, such as voltage drop or the current-voltage characteristic of storage battery taken into account. This will lead to more careful calculations both of energetic and economic parameters of the system.

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