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Department of Economics, Management and Humanities

Accumulation of electricity

Master Thesis

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Thesis advisor, CTU: Ing. Tomáš Králík

Thesis advisor, TPU: Doc. Igor A. Plotnikov, Ph. D.

Bc. Ondřej Grygar

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L.S.

České vysoké učení technické v Praze Fakulta elektrotechnická

Doc.Ing. Jaroslav Knápek, CSc.
vedoucí katedry

v.z.

Prof.Ing. Pavel Ripka, CSc.
děkan

V Praze dne 28.11.2013

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In Prague at ……………………… ……………………………..

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Abstract

This master thesis deals with issue of electricity accumulation. The aim of this thesis is technically and economically evaluate options of electricity accumulation and optimization of a power system with accumulation. In the first part of the thesis the most common accumulator types with their storage principle, construction, technical parameters, advantages and disadvantages were described. Then possibilities of using accumulation in power engineering were defined and described. The next part of the thesis was focused on accumulation in stand-alone system with renewable energy sources especially with photovoltaic panels. The stand-alone system was the subject of the thesis case study. The goal of the case study was to evaluate construction of stand-alone system in Tomsk region of Russian Federation. The stand-alone system was designed, described and optimized for better economics results, which were reflected in a lower cost of electricity for consumers.

Abstrakt

Tato diplomová práce se zabývá problematikou akumulace elektrické energie. Cílem práce je technické a ekonomické zhodnocení možností akumulace elektrické energie a optimalizace energetického systému s akumulací. V první části této práce jsou popsány nejrozšířenější typy akumulace elektrické energie. U každého typu akumulace je uveden princip uchování energie, konstrukce, technické parametry spolu s výhodami a nevýhodami této technologie. Dále jsou v práci popsány možné případy užití akumulace v energetických systémech. Další část práce je zaměřená na použití akumulace ve spojení s obnovitelnými zdroji energie, konkrétně s fotovoltaickými panely, v ostrovních systémech. Cílem případová studie této práce je zhodnotit výstavbu ostrovního systému v Tomské oblasti Ruské Federace a následnou její optimalizaci s cílem minimalizace ceny elektrické energie pro uživatele ostrovního systému.

List of abbreviations

AGM	Absorbed Glass Mat
AFC	Alkaline Fuel Cells
A	Ampere
Ah	Ampere-hour
CAES	Compressed Air Energy Storages
dm	decimeter
DOD	Depth Of Discharge
DG	Diesel Generator
ESOI	Energy Stored On Investment
kg	kilogram
Li-Ion	Lithium-Ion
MCFC	Molten Carbonate Fuel Cells
NPV	Nett Present Value
NiCd	Nickel–Cadmium
PAFC	Phosphoric Acid Fuel Cells
PVC	Polyvinyl chloride
PEM	Proton Excange Membrane
RF	Russian Federation
SOFC	Solid Oxide Fuel Cells
UPS	Uninterruptible Power Supply (Source)
VRB	Vanadium Redox Battery
V	Volt
W	Watt
Wh	Watt-hour
YSZ	Yttria-Stabilized Zircona

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Introduction

In the beginning of the 19th century Alessandro Volta discovered the first electric cell and the power of direct current at the same time. After almost 90 years from discovering of direct current, Nikola Tesla invented alternating current and laid the foundation for today´s power industry. The last century the mankind started to generating and consuming electricity in large scale. Electric power helps people in all areas of their activity. Due to large extension of usage electric power people started to be dependent on its supply.

Electricity is generated in power plants from primary sources. The most widespread type of power plant is thermal power station using coal or gas as a primary source of energy. More than 60 % of energy generated in the world is from this type of power plants, but coal reserves on earth are not endless and their combustion leads to air pollution.

In the first half of the 20th century scientists tried to find a new source of cheap energy and after long years they invented how to get large amount of energy from fission of uranium. The first nuclear power plant was built in Obninsk near to Moscow in 1954. Since that time nuclear power plants were built worldwide. One of many advantages of nuclear power plants is no air pollution, but big disadvantage is nuclear waste of burned out fuel. The waste products volume of nuclear power plants compared to the amount of produced electricity is much better than at heat power plants. Prosperity of nuclear power plants was slowed by Chernobyl disaster in 1986.

People started to think about more safe sources of energy with no air pollutions and potentially endless reserves. These sources are called renewable resources and include energy of sun, wind, water, biofuel, geothermal energy and energy of biomass. In the last decade renewable resources began to take a greater share of the energy mix. In 2011 there was an accident on nuclear power plant Fukushima Daiichi. After the Fukushima disaster all around the world tightened up operation and security systems of all nuclear power plants. In some countries all nuclear power plants were shut down and new aim of power industry was development of renewable power sources.

Advantage of renewable resources is that they produce clean energy without pollution. The main disadvantage of renewable resources is their unpredictability and therefore it is difficult to control them. Their decentralized character can be an advantage or a disadvantage.

One way how to improve system containing renewable resources of energy is accumulators enabling accumulation of energy from period of generation to period of consumption. By using of accumulators the energy power systems can become independent and allow operation as stand-alone system.

The topic of energy accumulation was chosen for several reasons. First reason was an interest to problems of accumulation, new types of storage elements and cases of their using. Second and the main reason was that in the future storage technology will be used on a larger scale than today. Trends in the energy industry focus on energy efficiency, increasing the security of electricity supply and generation of electricity from renewable sources. In all these areas can be used accumulation of energy like a tool to achieve the goals.

For example accumulators can locally act as a backup power sources for individual buildings or entire areas. They will serve as a bridging source until a backup power like diesel generators will start up or classic power source is restored. They can also provide energy storage from period of production for later consumption. These properties can be used in conjunction with renewable resources such as wind power or solar, which have variable production and can be heavily regulated.

Using accumulators in a large scale can increase the efficiency of electricity production in power plants. Power plants will be able to work in their economic points and surpluses will be stored in accumulators. Energy from these accumulators can balance energy in the grid or compensate frequency. Accumulators have fast response and they are the best elements for this purpose.

The aim of this work is to analyze the use of energy storage elements in power engineering. Describe the various possible situations in which it is appropriate to use accumulators and more focus on storage systems in conjunction with photovoltaic power plants. Outcome of this work will be the technical and economic evaluation of the stand alone system project with photovoltaic panels and accumulation of energy. System has to secure electricity supply for several residential buildings. As a part of the work also will be the optimization of the dynamic model of accumulation.

1 Accumulators

Electrical energy is used in almost all areas of human activity. Humanity has become dependent on its supply. To cover the consumption the electrical energy is mass-produced in power plants and then transported to individual consumers. Electrical energy has one great disadvantage. It is not possible to store electricity in its form in large scale. Because of it, power plants have to generate the exact amount of electric energy, which will be consumed at every moment. With this issue, it must be estimated the prediction of consumption based on a statistical analysis. But there is a way to accumulate energy.

Currently, the only possibility of storing electrical energy is transformation into another form as for example chemical, thermal or mechanical energy. In these forms it is possible to preserve energy for longer periods of time. Unfortunately with any storage or energy transformation are connected with energy losses. It is therefore the primary aim to regulate the production of the power stations and then to use the stored energy. Nevertheless, with appropriately combination of the production of electric power and its accumulation, it can be achieved a higher efficiency of production and distribution of electricity.

Accumulators are technical devices, which allow us to store energy. Stored energy can be subsequently used and accumulator works like an energy source. Most of the storage elements allow to repeat charging and discharging and therefore it works in cycles. All energy storage devices are possible to divide into groups according to the principle of energy conservation. Each type of accumulators has another characteristics, advantages, disadvantages and functions of use. Accumulators of energy have a large scale of use, from providing of energy to supply of watches or mobile phones to balancing frequency and electricity amount in the power grid.

1.1 Quantitative storage

Quantitative storage includes stocks of solid, liquid or gaseous fuels. (1) It is the accumulation of fuels for its subsequent transformation into electrical, thermal, mechanical or chemical energy. This accumulation is not explicitly considered like accumulators which can temporarily receive and store energy for later use. Quantitative storage elements are simple reservoirs of fuel, which will be used in the time of need.

1.2 Thermal accumulation

Thermal accumulators are sets of different technologies which store thermal energy into a particular mediums. These mediums are usually water or molten salts. (2) Accumulated thermal energy can be stored for hours, days, months or for the period between the seasons. A typical short-term storage is to preserve the heat energy, for example obtained from solar panels, from the day to the night when will be used. The storage tanks may have different sizes depending on locality, which they provide the thermal energy for. Accumulator tanks can be from small ones, providing thermal energy only for one house, to huge massive tanks or rock caverns which collecting thermal energy for whole region. (3)

The main goal of thermal accumulators is conservation of heat energy with minimal losses therefore the tanks with a heat transfer medium must be perfectly insulated. Typically the heat from the accumulators is used directly, or via the heat exchanger. There are also technologies in which are huge accumulators used in conjunction with power plants to achieve better efficiency (see in appendix A for diagram example). During off-peak periods excess steam from turbine heats the storage medium in tanks. Then accumulated heat in peak periods helps to pre-heat feed water instead of tapped turbine steam. Thanks to this, steam goes through the entire turbine and producing more electricity.

1.3 Chemical accumulators

1.3.1 Lead-acid batteries

Lead-acid batteries are the oldest and one of most widely used rechargeable batteries.

Construction

Lead-acid batteries consist of plates (electrodes), separators and electrolyte. In the charged state a negative electrode material consists of spongy lead (Pb) with antimony, because of better mechanical characteristic. (4) The positive electrode is made from lead oxide (PbO_2). Plates are in the form of rectangular grids. The space between the grid is filled with electrolyte which consist of 33-35% dilute sulphuric acid. Between positive and negative plates are separators preventing a short-circuit between physical contact. Separators prevent the movement of ions and increase the resistance of cells and they are usually made from wood, rubber, glass, cellulose, PVC or polyethylene plastic. For more details see Figure 1 with construction scheme.

Types

There is a few types of lead-acid batteries according to their usage.

First type is designed for cars. In this type of batteries there are a lot of thin plates to maximize the surface area and therefore the output current. Disadvantage of this type of batteries is susceptibility to deep discharge, which results in rapid decrease of battery capacity. It is also necessary that for these batteries were regularly charged to prevent of sulphation.

The second type of lead-acid batteries is designed for deep discharge. It differs from the previous type only by the larger thickness of plates. The battery can transfer less peak current, but they can be more frequently discharged. This type of batteries is used in photovoltaic hybrid system or in UPS.

Sulphation is an effect during which the electrodes are covered by crystalline lead sulphate, which causes a decrease in battery capacity. The capacity can be restored using desulphation. Desulphation is charging by short pulses of higher current that converts crystalline sulphate back on active electrode materials.

Lead-acid batteries can be recharged quickly or slowly. When a battery is charged quickly, it can't be charged to full capacity. In that case only electrolyte between the electrodes is being charged, but not the whole active material as it is in slowly charging. This relationship is known as Peukert's law (5):

$$It = C\left(\frac{C}{IH}\right)^{k-1} \qquad \textbf{1.1}$$

Where: H is the rated discharge time [h], C is the rated capacity at that discharge rate [Ah], I is actual discharge current [A], k is Peukert constant and t is the actual discharging time [h]

(see appendix B for graphs of lead-acid batteries charging and discharging characteristics)

Specification of lead-acid battery	
Energy density	50 - 80 [Wh/dm^3]
Specific energy	30 - 50 [Wh/kg]
Specific power	180 [W/kg]
Charge/discharge efficiency	50-90 [%]
Self discharge rate	3-20 [%/month]
Lifetime	500 - 1000 [cycles]
Nominal cell voltage	2,1 [V]
Cost per installed kWh	90 - 220 [€]

Table 1 - Technical and economic parameters of Lead-acid batteries

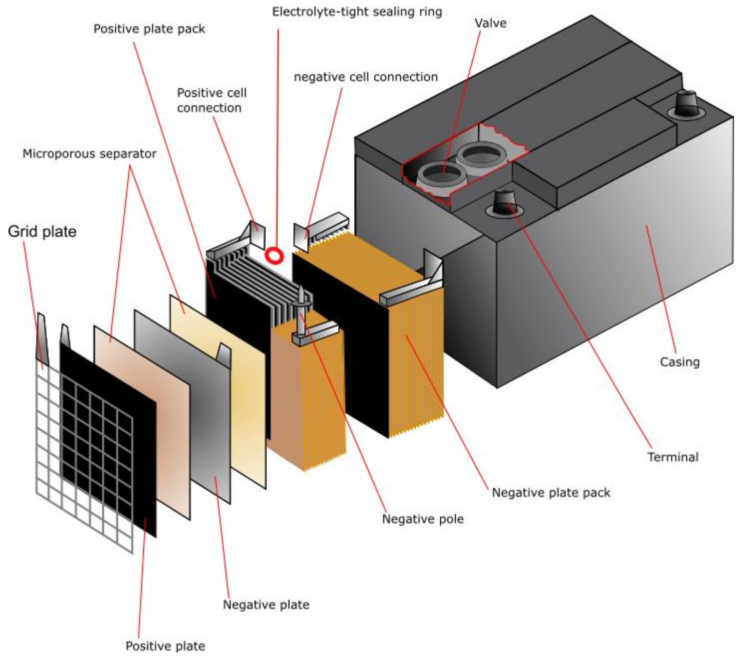


Figure 1 - Construction of Lead-acid battery (6)

Chemical reactions of lead-acid batteries on electrodes during the cycles:

Charging

Negative plate reaction: $PbSO_4(s) + H^+(aq) + 2^-_e \rightarrow Pb(s) + HSO^-_4(aq)$
Positive plate reaction: $PbSO_4(s) + 2H_2O(l) \rightarrow PbO_2(s) + HSO^-_4(aq) + 3H^+(aq) + 2^-_e$

Discharging

Negative electrode reaction: $Pb(s) + HSO^-_4(aq) \rightarrow PbSO_4(s) + H^+(aq) + 2^-_e$
Positive electrode reaction: $PbO_2(s) + HSO^-_4(aq) + 3H^+(aq) + 2^-_e \rightarrow PbSO_4(s) + 2H_2O(l)$

Advantages

- low price
- ease of manufacturing
- high power

Disadvantages

- low specific energy and energy density
- self discharging
- impact on the environment

Application

Lead-acid batteries are mainly used in automobiles and in applications where there is not problem with small specific energy and energy density of battery. For example like backup power (UPS). Also lead-acid batteries are used like traction batteries used in battery electric vehicles or in submarines like part of diesel-electric system. (7)

1.3.2 NiCd batteries

Construction

Nickel-cadmium batteries are type of galvanic cell. NiCd batteries use nickel oxide hydroxide and metallic cadmium as electrodes. The positive plate is made from nickel oxide hydroxide NiO(OH) and negative plate is made from cadmium. Like electrolyte is used potassium hydroxide. NiCd battery structure is assembled from the electrode plates with separators between them. NiCd batteries are produced in two types. First shape has submerged electrodes with liquid electrolyte and the second shape are sealed batteries. NiCd batteries are closely similar to NiMH batteries. For more details about construction see Figure 2.

Specification of NiCd battery	
Energy density	45 - 150 [Wh/dm^3]
Specific energy	40 - 80 [Wh/kg]
Specific power	150 [W/kg]
Charge/discharge efficiency	70 - 90 [%]
Self discharge rate	10 [%/month]
Lifetime	800 - 2000 [cycles]
Nominal cell voltage	1,2 [V]
Cost per installed kWh	220 - 360 [€]

Table 2 - Technical and economic parameters of NiCd batteries

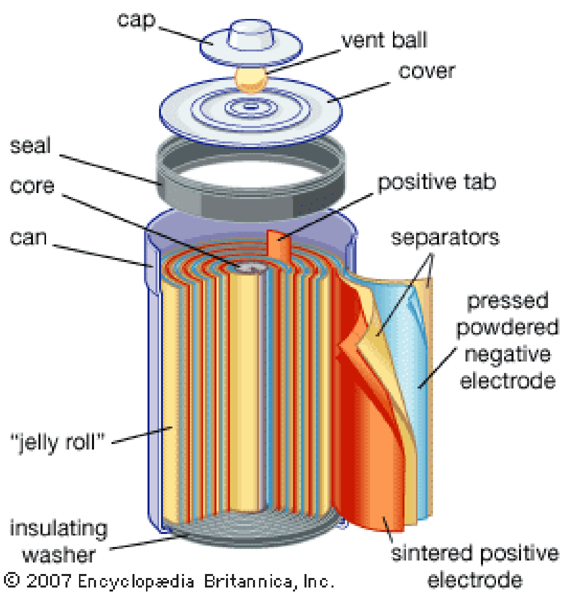


Figure 2 - Construction of NiCd batteries (8)

Charging

Charging of NiCd batteries is possible in a few ways with differing charging ratios. Batteries are charged by constant current and regardless of the charging speed it is necessary to supply more energy than actual capacity of batteries because of the losses during the charging. For example charging with rate C for one hour will charge battery at 80%. It is also possible to charge the batteries by rates C/10 for 14-16 hours or 4-6C for about 15 minutes. NiCd batteries may suffer by memory effect. Memory effect is the memory of battery of state of charge. If the NiCd battery is charged or discharged to same state of charge hundred times then on these points may occur sudden drops in voltage.

Discharging

Negative electrode reaction: $2NiO(OH) + 2H_2O + 2^{-}_{e} \rightarrow 2Ni(OH)_2 + 2OH^{-}$

Positive electrode reaction: $2NiO(OH) + Cd + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$

(see appendix C for graphs of charging and discharging characteristics)

Advantages

- deep discharging without negative effect
- long life
- possibility of charging by higher current
- functionality at low temperatures

Disadvantages

- high price
- big difference between the highest charging and lowest discharging voltage
- toxicity of cadmium

Application

The sealed type of NiCd batteries is used in small portable electronics like cameras, radios, calculators, instruments or television sets. The larger type of batteries with liquid electrolyte is used mainly like standby power or like aircraft starting batteries.

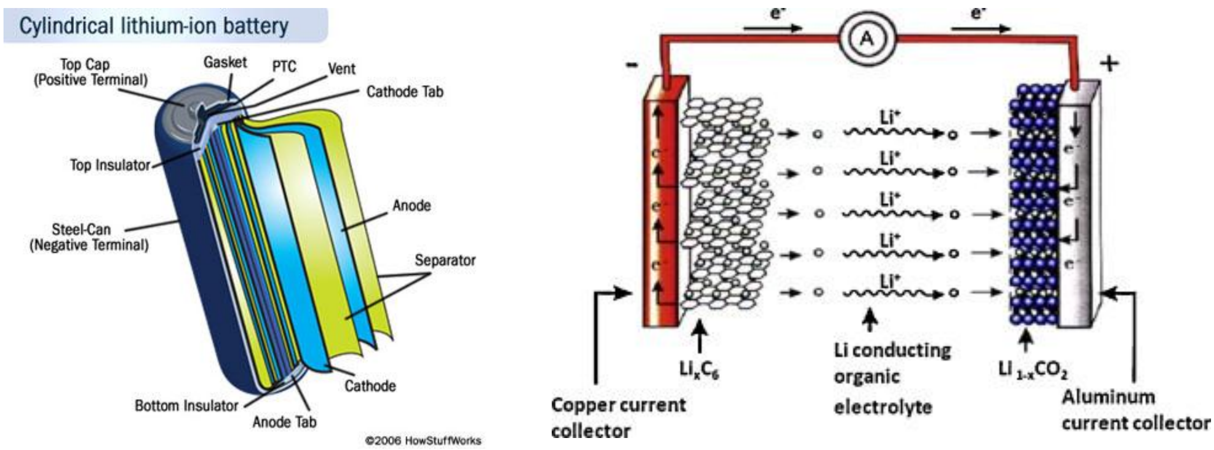
1.3.3 Li-Ion batteries

Construction

Lithium-ion batteries are rechargeable batteries. The material of positive electrode can be lithium cobalt oxide, lithium iron phosphate or manganese oxide. The negative electrode is made from carbon. (9) It can be made in two forms. First form of negative electrode is carbon coke and the second is typical carbon. These two constructions have different discharge characteristic. Electrolyte is made of organic solvent propylene or ethyl carbon. Li-Ion batteries have a liquid electrolyte and thus the increased requirements for protective packaging. The voltage of Li-Ion battery cells is depended on material used for positive and negative electrodes. See Figure 3 for detail of Li-Ion principle and construction.

Specification of Li-Ion battery	
Energy density	250 - 730 [Wh/dm^3]
Specific energy	100 - 265 [Wh/kg]
Specific power	250 - 340 [W/kg]
Charge/discharge efficiency	80 - 95 [%]
Self discharge rate	5 [%/month]
Lifetime	400 - 2000 [cycles]
Nominal cell voltage	3,2; 3,6/3,7 [V]
Cost per installed kWh	220 - 500 [€]

Table 3 - Technical and economic parameters of Li-Ion batteries



(a) *(b)*

Figure 3 - (a) Construction of Li-Ion batteries (10) (b) principle of Li-Ion batteries (11)

Charging

When Li-Ion batteries are charged the external source has higher voltage and the same polarity like the battery. The time of charging is depended on battery capacity and charging power. (12)

Negative electrode reaction: $C_n + xLi^+ + xe^- \rightarrow C_nLi_x$

Positive electrode reaction: $LiCo_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$

Overall reaction: $LiCoO_2 + C_n \rightarrow Li_{1-x}CoO_2 + C_nLi_x$

Discharging

Current is carried by lithium ions which during discharge goes from negative to positive electrode through electrolyte and separator.

Negative electrode reaction: $C_nLi_x \rightarrow C_n + xLi^+ + xe^-$

Positive electrode reaction: $Li_{1-x}CoO_2 + xLi^+ + xe^- \rightarrow LiCo_2$

Overall reaction: $Li_{1-x}CoO_2 + C_nLi_x \rightarrow LiCoO_2 + C_n$

(see appendix D for charging and discharging characteristics of Li-Ion batteries)

Advantages

- high specific energy and energy density
- no memory effect
- number of charge cycles
- can be made in different shapes

Disadvantages

- high price
- ignition hazard
- reduction of capacity with age
- damage when fully discharged

Application

Li-ion batteries are most commonly used as a power source for consumer portable devices. Recently, more and more applied in military equipment, electric vehicles and aerospace industries. (13)

1.3.4 Fuel cells

Construction

Fuel cell is an device which converts chemical energy of fuel and oxidant directly to electrical energy. Fuel cells are galvanic cells which consist of two electrodes separated by membrane or electrolyte. To the negative electrode a fuel is supplied and the oxidant to the positive electrode. Electrodes of fuel cells are catalytically and reactively stable. Material of electrodes is usually metals or carbon nanotubes. (14) Electrodes can be coated with catalyst to higher efficiency. Electrolyte in fuel cells can be made from acids, alkalis or compressed gas. The type of fuel cell is determined according to used electrolyte, fuel, or electrode catalysts. The most common fuel cells are hydrogen with potassium hydroxide (KOH) as electrolyte. (15)

The fuel in fuel cells is divided to a positively charged ions and negative charged electrons during the reaction. Only positive ions can pass through the and negative electrons are passing through output terminals to the load in form of electrical current. Fuel cells produce direct current continuously until the fuel or oxidizer is disconnected from the cell. For detail of fuel cell scheme see Figure 4.

Specification of Fuel cells	
Energy density	205 - 400 [Wh/ dm^3]
Specific density	300 - 400 [Wh/kg]
Power to area of cell	0,5 [W/cm^2]
Efficiency	55 - 80 [%]
Operating temperature	-20 - 1000 [°C]
Nominal cell voltage	0,5 - 1,23 [V]
Lifetime	2000 - 60 000 [h]

Table 4 - Technical and economic parameters of Fuel cells

(see appendix E for charging and discharging characteristics of fuel cells)

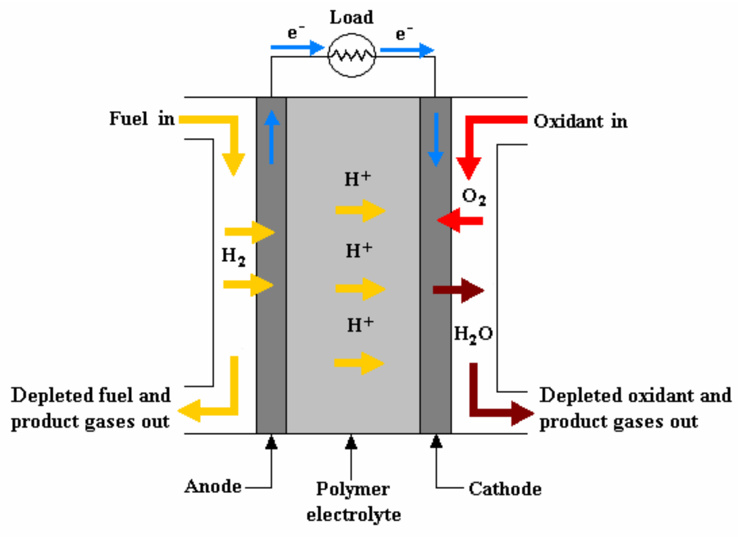


Figure 4 - Scheme of Fuel cell (16)

The most common types of fuel cells (17)

Alkaline Fuel Cells - AFS

These type of fuel cells were developed as one of the first. They used alkaline electrolyte. Specifically an aqueous solution of KOH is in the asbestos matrix of cells. Fuel of these cells is hydrogen and oxidant can be pure oxygen or air without CO_2. The operate temperature of the AFCs is depended on concentration of electrolyte. The temperature can be in range from 23°C to 250°C.

Chemical reactions in AFS:

Cathode reaction: $H_2O + O_2 + 4e^- \rightarrow 4OH^-$

Anode reaction: $2OH^- + H_2 \rightarrow 2H_2O + 2e^-$

Phosphoric Acid Fuel Cells - PAFC

PAFC is regarded as the first generation of modern fuel cells. In PAFC is used 100% phosphoric acid like electrolyte.(18) Acid is fixed in asbestos or teflon-bonded silicon carbide matrix. Platinum is used as catalyst. Operate temperature of PAFCs is in range from 150°C to 220°C. Usually the PAFC works as stationary power generations and offers a possibility to be used in cogeneration units. Typical efficiency of these cells is about 35 %.

Chemical reactions in PAFC:

Cathode reaction: $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O$

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Molten Carbonate Fuel Cells - MCFC

Electrolyte in MCFC is molten mixture of alkalines like Li, Na and K. Electrolyte in cell is in ceramic lithium aluminum oxide (LiAlO2) matrix. Fuel for MCFCs can be gas from steam reforming of fossil fuels or biogas. Oxidant is air. The operate temperature is from 600° C to 700 ° C. The molten salts provides high conductance of CO3-II group. Efficiency of cell is usually around 50 %, but if cell is connected to turbine efficiency can be around 65 %. The MCFCs are usually used in cogeneration units or in power plants.

Chemical reactions in MCFC:

Cathode reaction: $CO_2 + ½O_2 + 2e^- \rightarrow CO_3^{2-}$

Anode reaction: $CO_3^{2-} + H_2 \rightarrow H_2O + CO_2 + 2e^-$

Solid Oxide Fuel Cells - SOFC

The electrolyte in SOFC is yttria-stabilized zirconia (YSZ). It is solid ceramic membrane based on ZrO2 stabilized by Y2O3. Advantage of these cells is that it is not necessary to use catalysts. Operate temperature is around 800-1000 °C. Normal efficiency of the SOFCs is around 50-60 %, but due to thermal reaction product which can be used in expanse turbine the efficiency can be higher up to 85 %. As fuel for these cells is used biogas, fuel gas or gas from the steam reforming of fossil fuel and air works as an oxidant.

Chemical reactions in SOFC:

Cathode reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$

Anode reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Advantages

- environmentally friendly
- extremely reliable
- high efficiency
- reactions in fuel cells are not degraded over time
- continuously electricity supply

Disadvantages

- start-up times of certain types of fuel cells
- the need for hydrogen infrastructure
- energy intensity of production

Application

Fuel cells have a large range of applications. They can be used like stationary or portable energy sources. Stationary fuel cells are very often used like a commercial primary and backup power in industries or in other sectors. Fuel cells are also used in space program and in military technologies. Also the fuel cells are used in all types of transportation (cars, buses, motorcycles, airplanes, boats and submarines). (19) (20) (21)

1.3.5 Flow batteries

Construction

Flow batteries are rechargeable fuel cells with external tanks for electrolytes. There are two types of electrolyte: positive charged and negative charged. Electrolyte is pumped from tanks into reaction cell. In the cell there is membrane separating electrolytes. Electrical energy is stored in electrochemical potential of different oxidation states of salts dissolved in the electrolyte. Ions between electrolytes are exchanged through membrane and free electrons in electrolyte are caught in collector generating electrical current. Thus cells transform chemical energy of electrolytes directly to the electricity, so flow batteries have high efficiency. (22)

Number of cycles is theoretically limitless, because electrolytes in tanks are separated and at any it is possible to refill electrolyte at any time. In technical documentations of flow batteries there is usually written lifetime of thousands of cycles in dependence on type of flow batteries. For example lifetime of Vanadium redox batteries is more than 12 000 cycles. Big advantages of flow batteries are fast response about 1ms and possibility of discharging to 100% depth without impact on electrolytes and lifetime of batteries. (23)

There are many types of flow batteries: reduction-oxidation (redox), hybrid, organic or membraneless. One of the most common type of flow cells is vanadium redox batteries.

Vanadium redox batteries

Vanadium redox batteries (VRB) contains the active vanadium salt in different oxidation states of redox pairs (positive pairs: V(IV)/V(V), negative: V(II)/V(III)) and concentrated sulphuric acid. VBR cells have ion exchange membrane (PEM) with thickness about 0,25 mm, where on one side proceeds oxidation of electrolyte and on the other side of membrane proceeds electrochemical reduction of electrolyte ions. Voltage of VBR cell is in range of 1,2 - 1,6 V and cells in accumulator are connected in series. During charging and discharging decisive chemical reactions take place on the carbon electrodes where vanadium oxidation is changed. Scheme of VRB is shown on Figure 5.

Chemical reactions in VRB (24)

Negative electrode: $V^{3+} + e^{-} \leftrightarrow V^{2+}$

Positive electrode: $VO^{2+} + H_2O \leftrightarrow VO^{2+} + 2H^{+} + e^{-}$

Overall: $V^{2+} + VO^{2+} + 2H^{+} \leftrightarrow V^{3+} + VO^{2+} + H_2O$

Specification of Flow batteries	
Energy density	10 - 33 [Wh/dm^3]
Specific density	10 - 85 [Wh/kg]
Power to area of cell	0,8 - 1,4 [W/cm^2]
Efficiency	65 - 75 [%]
Nominal cell voltage	1,15 - 1,55 [V]
Lifetime	2000 - 12 000 [cycles]
Cost per installed kWh	150 - 350 [€]

Table 5 - Technical and economic parameters of Flow batteries

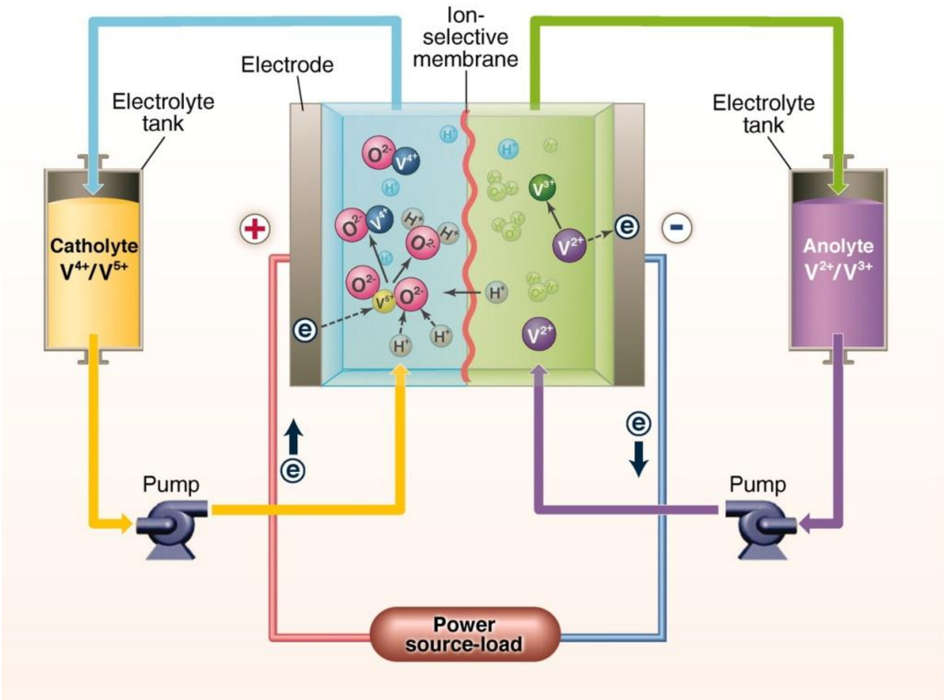


Figure 5 - Scheme of VRB Flow cell (25)

Advantages

- fast response in 1 ms
- reliability
- high efficiency
- long lifetime without self-discharge
- high number of cycles
- without harmful emissions.

Disadvantages

- pumping losses
- chemical reaction losses

Application

Flow batteries can work as energy storage in range from small UPS system to large accumulation of electrical energy connected to power grid. In power grid flow batteries can help with load balancing, peak shaving. Also is possible to connect flow batteries to renewable resources to store unused electric power or use it in stand-alone systems.

1.4 Mechanical accumulators

1.4.1 Using kinetic energy - Flywheels

Construction

The flywheel is a device, which allows to store energy in motion of rotation. In flywheel is accelerated massive cylinder called rotor by electric motor. Electric power is transformed to kinetic power of spinning rotor. The first rotors of flywheels were made of steel and energy was mainly stored in weight of rotor´s cylinder. But strength of steel was limiting during the faster rotation. There was a danger of disintegration of the material of the rotor and thus the destruction of the entire flywheel. Modern flywheel´s rotors are made of carbon-fibres. This material is much stronger than steel and allow accelerate rotor to higher rotation. Adverse effects reducing efficiency of flywheel are aerodynamic drag and frictions.

To minimize aerodynamic drag the rotor is rotating in vacuum. Vacuum, which is provided by vacuum pump system. In classic bearings there are big frictions. In modern flywheels the magnetic bearings are used in order to improve efficiency and elimination of frictions. With all these improvements the rotor of the modern flywheels is able to spin up to 50 000 rounds per minute. In this speed in case of accident arises a risk of danger and due to this danger flywheels are installed under the ground. (26)

In time of need the flywheel is slowed down and motor working as generator to supply electricity into a power grid. Stored energy depends on mass of rotor, rotation speed square and radius. Flywheels can provide short-term power backup and bridge the time needed for start of long-term power backup systems with larger capacity because of fast response. Next usage of flywheels can be balancing of frequency in the power grid. For this way of use is typical more cycles of charging and discharging. The flywheels are suitable for these purposes because of excellent cycle and load following characteristic. (27) Technology of modern flywheels allows more than ten of thousands deep cycles with minimal maintenance.Usually life time of flywheels is around 20 years. For detailed scheme of flywheel see Figure 6.

Specification of Flywheels	
Energy density	20 - 210 [Wh/dm^3]
Specific energy	5 - 200 [Wh/kg]
Specific power	5000 [W/kg]
Efficiency of cycle	80 - 97 [%]
Rotational frequency	10 000 - 100 000 [rpm]
Lifetime	100 000 - 1 000 000 [cycles]
Cost per installed kWh	1000 - 3500 [€]

Table 6 - Technical and economic parameters of Flywheels

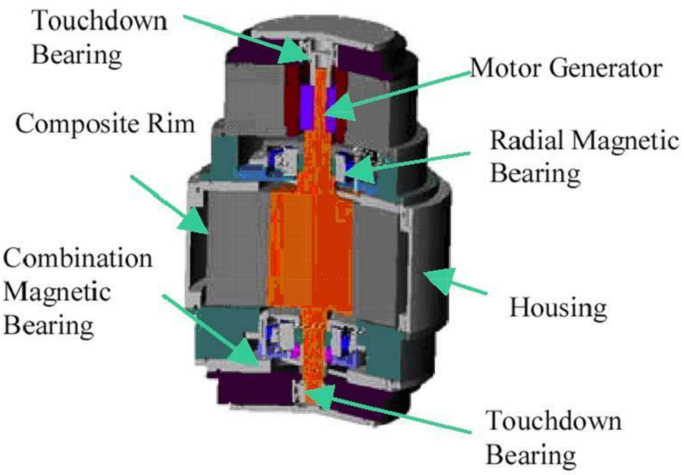


Figure 6 - Scheme of Flywheel (28)

Stored energy of flywheel E is given:

$$E = \frac{1}{4}\, m \,. r^2 . w^2 \qquad \textbf{1.2}$$

Where m is proportional to mass of cylynder , r^2 is square of cylinder radius and w^2squere of the speed at which flywheel spins. (29)

Advantages

- environmentally friendly
- extremely reliable
- high efficiency
- fast response
- long life

Disadvantages

- possibility of an accident at high rotation speed

Application

The flywheel storage is used in power engineering as uninterruptible power supply, peak buffer or with renewable resources to store excess electricity. Also the flywheels have application in other fields as in automotive industry in hybrid/electric cars. (30) (31)

1.4.2 Using potential energy - Hydro pumped storage power stations

Construction

Hydroelectric pumped storage power plants accumulate energy in potential energy of water. Power plant has two water reservoirs. One of them is located on the lower place and the second on the higher place. The height difference between the reservoirs is one of the parameters determining the amount of stored energy. The reservoirs are connected with gravity pipe of large diameter.

Principle of hydroelectric pumped storage power plants is that in time of off-peak period or in time when is in the grid more electricity, which unbalancing the flows in the grid, the water is pumped from lower reservoir to the higher reservoir. The power plant consumes electricity from the grid and transforms in into potential energy of water in the higher reservoir. In the higher reservoir water can be accumulated for a long period of time. In peak time or when is necessary provide electricity to the grid, the water is pumped down into the turbine to generate electric energy.

Building of hydroelectric pumped storage power plants is quite difficult. At first it is necessary to have a suitable and enough large location, which would meet the requirements for the construction of reservoirs. During the construction can be used of relief of nature for build reservoirs near watercourses, lakes or the sea shore. It is possible to build artificial dams. (32) The process of construction is really expensive, but hydroelectric pumped storage power plants has really long lifetime. Usually a lifetime of this type of power plants is supposed to be approximately 100 years.

Importance of hydroelectric pumped storage power plants was increased with expansion of nuclear power plants. Nuclear power plants are hard to regulate, but they are one of the cheapest producers of electricity so far. Due to this fact the goal is to keep continuing operation of nuclear power plants in the economic point. This operation affect the off-peak periods, where is in grid more electricity. Hydroelectric pumped storage can compensate for this excess electricity and accumulate energy for peak periods. (33)

Hydroelectric pumped storage power plant is the only accumulator of energy where can be electricity stored in large scale and for a long time periods. Another advantage is the quick response and the ability to control. Efficiency of modern pumped storage power stations in small cycle is up to 75 %. Small cycle is counted without losses generated by transportation of electricity from producer to station and from station to consumer. Hydroelectric pumped storage units can compensate amount of electricity in power grid and balance drop of frequency. For scheme of hydroelectric pumped storage power plant see Figure 7.

Energy of stored water E in [Wh], is given:

$$E = \frac{\rho . g . h . V . \eta}{3600} \tag{1.3}$$

Where η is efficiency of the cycle, ρ is density of the water [1000 kg/m^3], g is acceleration of gravity [9,81 m/s^2], h is altitude difference between the two reservoirs [m] and V is volume of the higher reservoir [m^3] (34)

Specification of hydroelectric pumped storage	
Efficiency of small cycle	65 - 85 [%]
Energy density	2,72 [Wh/cubic/m]
Lifetime	100 [years]
Cost per installed kWh	10 - 150 [€]

Table 7 - Technical and economic parameters of Hydroelectric pumped storage

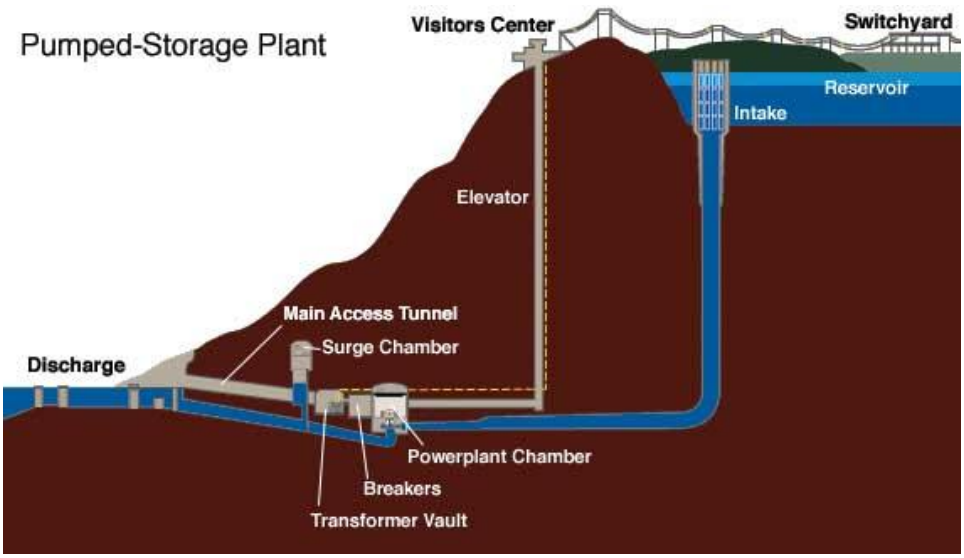


Figure 7 - Scheme of hydro pumped storage power station (35)

1.4.3 Using pressure energy - Compressed air

Construction

One of the most prospective methods of energy accumulation is using the compressed air. Compressed air energy storages (CAES) are able to store large amounts of energy for long periods. Principle of CAES is to use electricity in off-peak time to compress air into reservoir and in the peak time, when there is the deficiency of electricity in the grid, use pressure energy of the compressed air to generate electricity in turbine. This process is simple, but there are some complications with compressing. When air is compressed the temperature is increasing. The temperature of the stored air can reach more than 650 °C and it leads to heat losses during the storing. (36) Next problem is that during the expansion temperature drops. Heat during expansion is important because it is one of the parameters determining the amount of the stored energy. Therefore before expansion it is necessary to re-heat compressed air. It can be done by gas turbines. As reservoirs for the compressed air are usually used underground caverns or old mines. There are also in developing another ways how to store compressed air for example huge air bags placed on the bottom of the sea and using natural water pressure. (37) Lifetime of CAES is counted more than 30 years. Accumulation of energy in compressed air is environmentally friendly without pollutions. Disadvantages of CAES are small energy density, high investment and long construction time. There are three main types of CAES and in each type are used other physical principles: diabatic, adiabatic and isothermal CAES.

Diabatic CAES

In this type of CAES is heat from compression of the air lost. Usually is dissipated into the atmosphere as waste. It means that stored energy in CAES is decreased. In process of expansion lost heat is missing and it is necessary to add it. The heat is the most often generated by burning of natural gas in the turbine which generate electricity. Exhaust from gas burning re-heat compressed air travelling to the turbine where expands. By heat losses of the compressed air the efficiency of accumulation is degraded. Also burning of the natural gas leads to additional costs and pollution. For scheme of diabatic CAES see Figure 8.

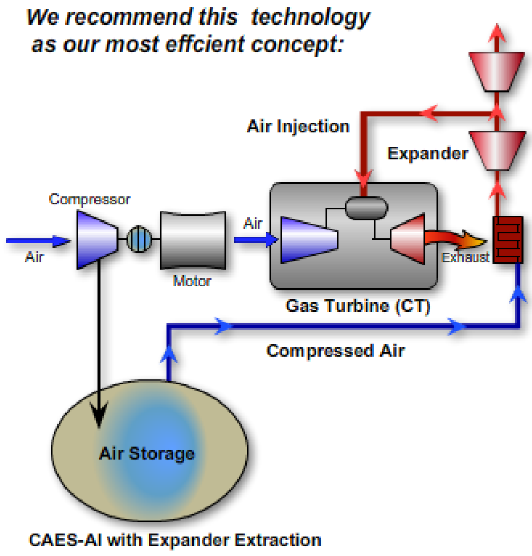


Figure 8 - Scheme of diabatic CAES with gas turbine (38)

Adiabatic CAES

Principle of the adiabatic CAES is that heat generated during compression is stored in thermal accumulator and again used during expansion of the air. There is no need of additional fuel to heat the air. Like the thermal storage element is usually used oil or molten salts. Oil can be heated up to 300 °C and molten salts up to 600 °C. Efficiency of this CAES type is in range from 70 to 75 %. . For scheme of adiabatic CAES see Figure 9.

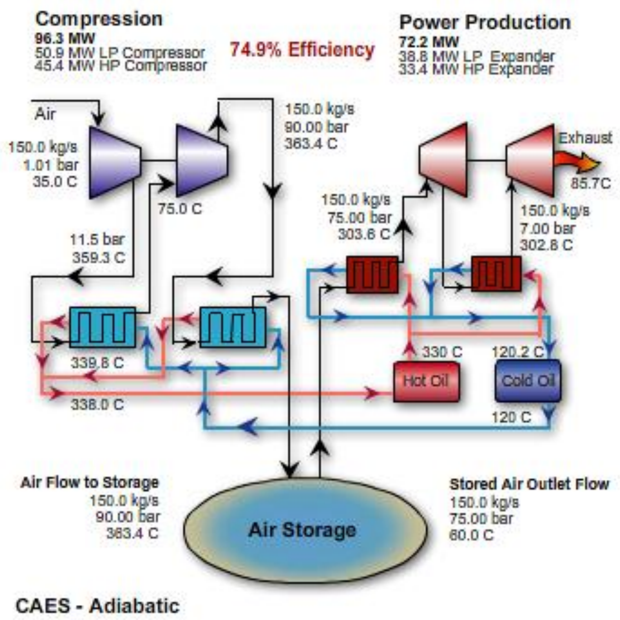


Figure 9 - Scheme of adiabatic CAES with oil thermal accumulation (38)

Isothermal CAES

Isothermal CAES uses isothermal processes during compression and expansion without changes of temperature and high thermal losses. (39) To minimize losses during the storage, the compressed air has temperature approaching ambient temperature. In time of need, during the peak periods, compressed air generates electricity using isothermal expansion in turbine. Theoretically this system can reach 100% efficiency, but in real there are no ideal isothermal processes which leads to losses. (40)

Specification of CAES	
Energy density	2 - 6 [Wh/dm^3]
Specific energy	30 - 60 [Wh/kg]
Efficiency	75 - 90 [%]
Lifetime	5 000 - 20 000 [cycles] 30 [years]
Cost per installed kWh	10 - 120 [€]

Table 8 - Technical and economic parameters of CAES

1.5 Electromagnetic accumulators

1.5.1 Supercapacitors

Construction

Supercapacitors are special electrolytic capacitors with large capacity. Principle of storing electricity is something between classical capacitors and batteries. In supercapacitors the electric charge is stored by electrostatic force on the surface of electrodes. Electrodes are made from porous materials, which have large surface area for example carbon which has up to 2000 m2/g. The new nanomaterials with extreme large active surface can also help to increase the capacity of supercapacitors. Between electrodes is electrolyte which can be aqueous-based or consist of anhydrous organic solvent. Usually electrolyte is liquid or like a gel. Electrodes are separated by dielectric of thickness of tenths of nanometers. Thanks to small thickness of dielectric is also small breakdown voltage. Voltage range of supercapacitors with aqueous-based electrolyte is from 1 to 1,2 V and with anhydrous organic solvent electrolyte is from 2,3 to 3 V. (41) In order to achieve a higher voltage , the supercapacitors are serially connected, but the total capacity is reduced. The strings with more than three capacitors require voltage balancing as prevention from over-voltage. Supercapacitors can be charged and discharged in a few seconds. Due to small internal resistance the supercapacitors can be discharged with current in order of kA. (42) Lifetime of supercapacitors is in the hundreds of thousands of cycles. Sometimes is quoted to one million cycles. Disadvantage of supercapacitors is self-discharge. Supercapacitors are suited to short term cover of peak currents.

There are two principles how supercapacitors store electricity. The first principle is called "double-layer capacitance". It is electrostatic process where a separated charge is stored on Helmholtz double layer. The second one is pseudocapacitance. Pseudocapacitacne is electrochemical storage achieved by faradic reduction-oxidation reactions with charge transfer.

Double-layer capacitance

Double layer is effect which arises between surface of supercapacitors electrodes and electrolyte when voltage is applied. This effect is a margin composed of two layers of ions. The first layer is in the surface of lattice structure of electrodes material. The second layer is made of ions from electrolyte and has opposite polarity. Between these two layers is only monolayer of solvent molecules. The monolayer of solvent is called the inner Helmholtz plane and creates a molecular dielectric between oppositely polarized ions. This layer is adheres by physical forces. Chemical bonds in molecules are polarized. The outer Helmholtz plane consists of counter-charges and indicates the amount of stored charge.

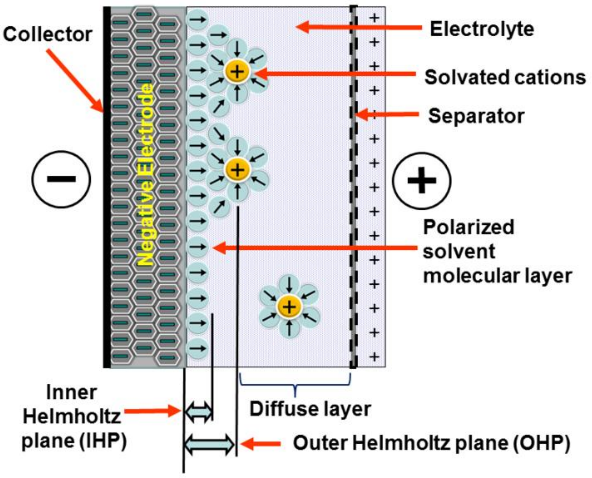


Figure 10 - View of double-layer capacitance (43)

Pseudocapacitance

Pseudocapacitance arises when absorbed cations from electrolyte penetrate into double-layer. Stored energy is achieved by reversible faradic reduction-oxidation reactions on the surface of electrodes. Typically, pseudocapacitance occurs with charge transfer between electrolyte and electrode.

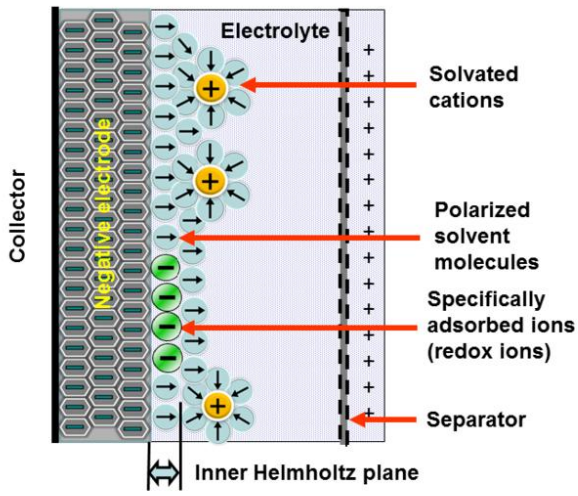


Figure 11 - View of pseudocapacitance (43)

Specification of Supercapacitors	
Energy density	5 - 60 [Wh/dm^3]
Specific energy	5 - 30 [Wh/kg]
Power density	100 - 10 000 [W/kg]
Efficiency	90 - 99 [%]
Nominal cell voltage	1- 2,8 [V]
Lifetime	up to 1 000 000 [cycles] 5 - 20 [years]
Cost per installed kWh	1 700 - 7 000 [€]

Table 9 - Technical and economic parameters of Supercapacitors

Advantages

The biggest advantage is supercapacitors high power density. Supercapacitors is possible fully charge and discharge in a few seconds. During the charge and discharge the temperature is kept low. Supercapacitors are safe and have theoretically unlimited cycle life. Due to low resistance supercapacitors have high specific power.

Disadvantages

High cost per watt and high self-discharge are main disadvantages of supercapacitors. Also low cell voltage and low specific energy are insufficient.

Application

Supercapacitors are using in electrotechnic devices to stabilize fluctuating power supply, like source of uninterruptible power source or where it is necessary to use a rapid energy. Properties of supercapacitors are used in automotive industry to recovery energy in hybrid or electric cars or in other vehicles. In power engineering is their use in systems containing renewable sources of energy, where is necessary to stabilize output power.

2 Comparison of accumulators

Main parameters of accumulators are specific energy [Wh/kg], specific power [W/kg], efficiency, self discharge, lifetime and price. As next parameters influencing use cases are energy density [Wh/dm^3], voltage, safety or impact to environment. All accumulators have different parameters, advantages and disadvantages. Because of it each type of accumulators is suitable for different purposes. In following graphs accumulators are compared according to some parameters to better clarity.

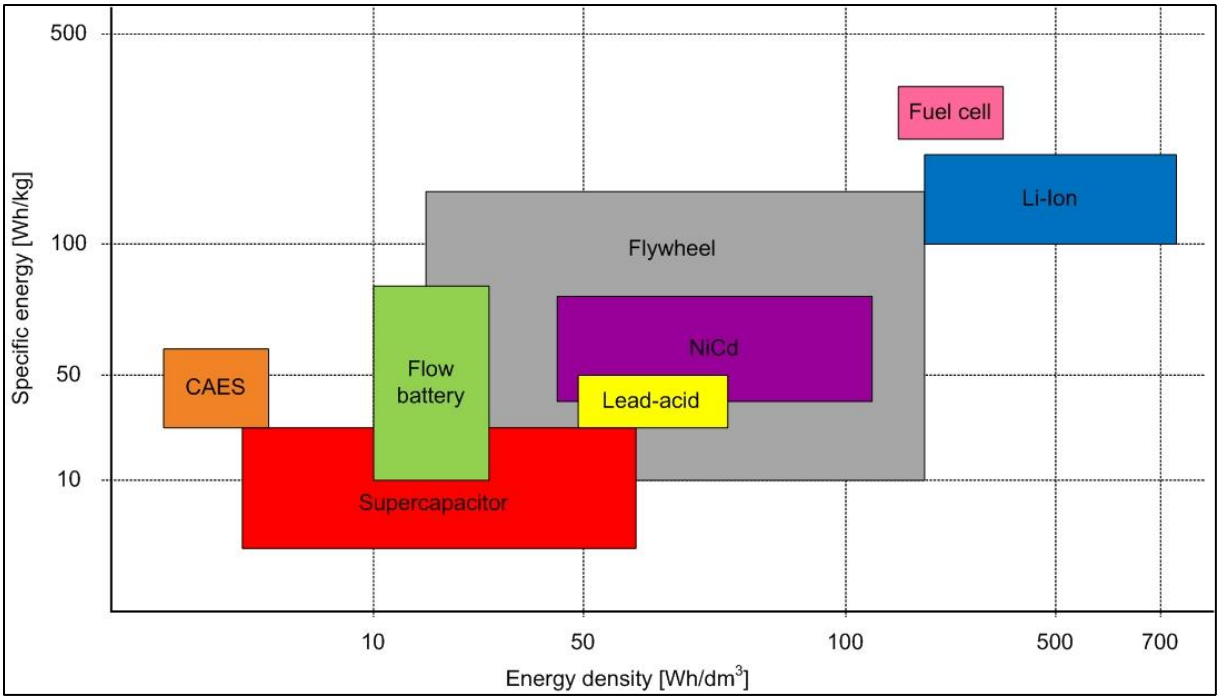


Figure 12 - Comparsion of accumulators by specific energy and power density

Higher energy density allows build smaller size of accumulators with equivalent capacity. Size of storage elements is important for example in automotive industry or in electrotechnics where it is necessary to minimize size (largeness) of energy sources. In portable electrotechnic devices is better to use Li-Ion batteries because of their extreme high energy density. If accumulators are compared by specific energy then apply the higher specific energy the lesser weight of accumulators. There are many areas where the emphasis is on the weight of energy source. As example the aircraft industry requires low weight of all components. Using of the fuel cells seems to be suitable alternative instead of heavy acid based batteries. (44)

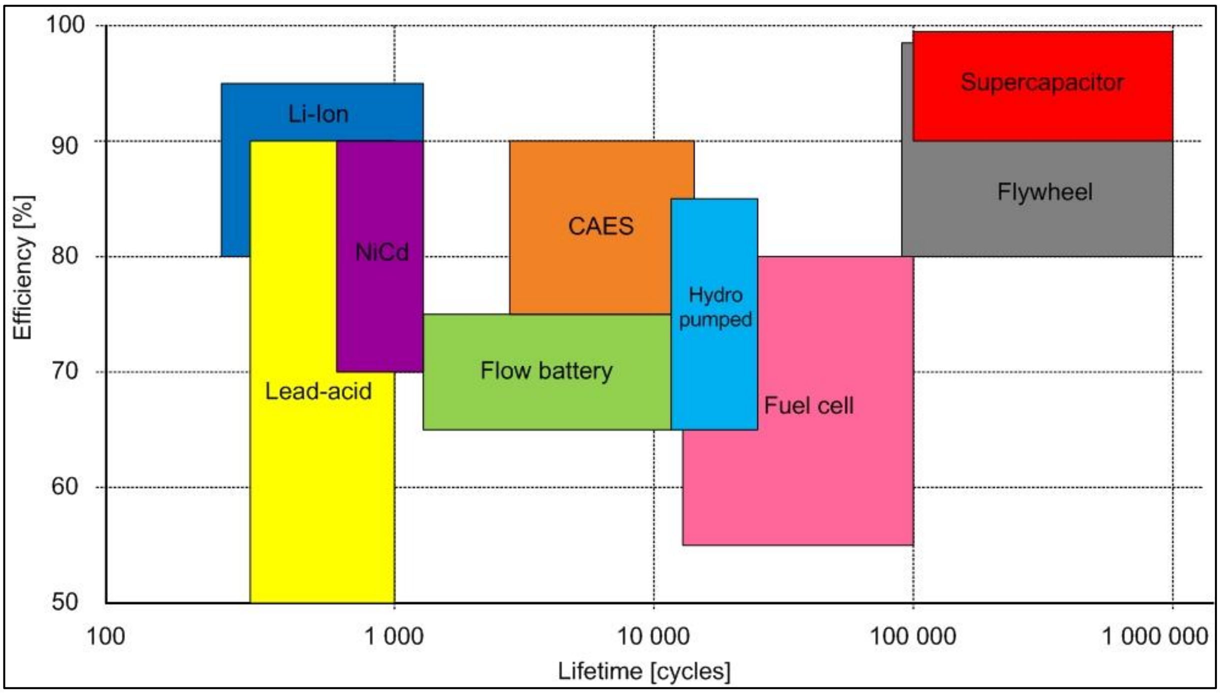


Figure 13 - Comparison of accumulators by efficiency and lifetime in cycles

Next comparison is by lifetime and efficiency. The main objective is to maximize efficiency. It means to charge and discharge accumulator with minimal losses. The highest efficiency of a cycle is in supercapacitors, but it is only in short time horizon, because supercapacitors have relatively large self-discharge losses. As next devices with high efficiency are flywheels, suitable for large scale accumulation, and Li-Ion batteries are useful mainly for small portable devices. In case of CAES high efficiency is reached only if is also stored heat from air compression.

From the perspective of accumulator's life the best results have supercapacitors and flywheels. In power industry the flywheels are used for fast response accumulation of energy in relatively large scale. Supercapacitors fill only support tasks as balancing on power or frequency in smaller areas because of their enormously high price. As the most important accumulators in power industry are CAES and hydro pumped storage. Their lifetime is high in tens of thousands cycles and it is only lifetime of some components, which are possible to be replaced. Dams and caverns, where the medium is stored, have longer lifetime. These accumulators have one more advantage compared with the rest of accumulators. It is the price per Wh. The important parameters of described accumulation technologies are in Table 10.

	Energy density [Wh/dm^3]	Specific energy [Wh/kg]	Efficiency [%]	Lifetime [cycles]	Investment cost [€/kWh]
Lead acid	50-80	30-50	50-90	500-1000	90-220
NiCd	45-150	40-80	70-90	800-2000	220-360
Li-Ion	250-730	100-265	80-95	400-2000	220-500
Fuel cells	205-400	300-400	55-80	-	-
Flow batteries	10-33	10-85	65-75	2000-12000	150-350
Flywheels	20-210	5-200	80-97	10^5-10^6	1000-3500
Hydro pumped	0,1-1,5	-	65-85	-	10-150
CAES	2-6	30-60	75-90	5000-20000	10-120
Supercapacitors	5-60	5-30	90-99	10^5-10^6	1700-7000

Table 10 - Comparison of accumulators

The price has the key role for deciding, which type of accumulation should be chosen. Important indicators are costs per installed power and capacity. In table 10 there are approximate values of costs per kWh. The highest costs have supercapacitors and flywheels. Supercapacitors and flywheels have the highest costs. The high price is balanced by high efficiency, fast response and lifetime of these accumulators. Real efficient use of these accumulators depends on specific conditions of each accumulation project but usually they provide fast small-scale energy storage as support services. The cheapest accumulation is provided by hydro pumped and compressed air energy storages. In power industry those technologies ensure large-scale energy accumulation from off-peak time to peak periods.

Prices of all technologies changes over time. The new technologies from beginning are expensive and then with enlargement of technology price goes down. The high price of supercapacitors is an example of it. It is a new technology which starts to extend.

Next point of view on accumulation technologies is ratio of consumed energy for their construction and energy which stored by their lifetime. Charles J. Barnhart and Sally M. Benson conducted a comparison study of accumulation technologies where used ESOI (energy stored on investment) index. The best technologies according this index are hydro pumped storages and CAES with ESOI over two hundred. These technologies during their lifetime can store two hundred times more energy than is required for their construction. The rest of technologies have much poorer this ratio. Usual lead-acid batteries have ESOI equal to two. As the best batteries are Li-Ion with ESOI equal to ten. This index is more relevant from global point of view than for economical decision making.

3 Energy storage in power grid

Energetics, like other area of industry is not stable but still evolving. In recent years, there are noticeable changes in the composition of production. Earlier coal and nuclear power plants were the main producers of electricity supporting by hydro and hydro pumped power plants. During the last decade the renewable sources such as photovoltaic and wind power plants have started to take their places on the field of electricity production. These power plants achieve cleaner production of electricity without emitting greenhouse gases, pollution and conserve limited primary energy sources such as coal, gas and oil. Disadvantages of these power sources consider to be randomness and instability of production. The most hopeful solution to these problems is the use of accumulation which can stabilize production or store electricity from time of production to time of demand.

Accumulators may not only solve the problems associated with renewable resources but can solve a large variety of cases. Using the accumulators can help power plants to work with higher efficiency, allow systems to work in stand-alone mode, to increase reliability of power grid and many others. Accumulators are one of the main elements of modern concept Smart Grid. This is simply a list of several examples of using accumulators, because their real use is much wider.

Nowadays there is a large scale of accumulation technologies. Each of these technologies has their specific parameters, advantages and disadvantages. Therefore the each type of accumulator is appropriate for other purposes.

3.1 Voltage regulation

The one of parameters of quality of electricity is voltage. In power transmission and distribution networks are voltage levels which must be followed. Voltage on these levels has to be kept within specified limits. Usually acceptable voltage deviation is up to ± 5 % of voltage level. To keep voltage deviations in limits there are a few methods. The first method is regulation by tap-changing of transformers. The second one is using reactive elements as capacitors. In case of voltage drop in power lines there are accumulators connected to the nodes, they have capacitive character which improves voltage. In case of overvoltage inductive compensators are connected. (45) (46)

3.2 Frequency regulation

The frequency is also important quality parameter of electricity. In power grid have to be filled equation between electricity generation and consumption. If this condition is not observed the frequency deviates from the desired value. In Europe the frequency value is 50 Hz. Any larger deviation can lead to losses and damage of connected equipment. To maintain the frequency balanced, regulation on the generator side or consumer side must be added. One way how to regulate balance is usage of accumulators. In period when generation is bigger than consumption the frequency is higher. Accumulators can absorb energy from the grid to decrease frequency to desired value and return the required balance. In period when generation is lower the accumulators provide missing energy to stabilize the frequency.

3.3 Supply time-shift

Consumption of electricity is changing every moment and the difference between consumption in the day and at night is huge. Generating of electricity in power plants must react on this fact and adapt production. Regulation of production is usually done by changing of output power in base power plants or by turning on and off other production units. Consumption of electricity is covered by nuclear and coal power plants for their lowest production costs. Additional power units as gas turbines have higher production costs and they are used in peak periods when demand is highest. In night when consumption is low the peak power plants are switched off and output power of remaining power plants is reduced to keep balance between generation and consumption. It leads to increasing of production costs because of power plants don´t work in their economic points with the lowest costs.

This problem can be solved by using accumulators. Accumulation elements in off peak periods as nights can absorb energy from the grid and store it for the peak periods when provide energy back to the grid. Accumulation allows base power plants to work with the lowest production costs which increase their effectiveness. The suitable accumulators for this purpose can have lower response and cycle lifetime, but higher capacity.

3.4 Accumulation with renewable sources

Renewable sources of energy (RES) as wind and sun radiation have their own advantages and disadvantages. The biggest advantage is that generation of electricity from these sources is environmentally friendly without pollutions. Also they save the primary sources as gas, oil and coal. The disadvantages, which affecting power grid, are randomness and changeability of electricity generation.

Systems of renewable sources of energy with accumulation element can provide stable output power without deviations. Accumulators can absorb deviations in generation to stabilize output power or absorb surpluses in peak periods and in off peak periods providing electricity.

3.5 Stand-alone systems

Special cases of power supply are stand-alone power systems (SAPS). These systems do not depend on external power and they are built in remote locations where the connection with distribution network is not possible. As energy source usually serves RES with diesel generators. In stand-alone systems it is necessary to use accumulators which store surpluses of energy production to the time of demand. The next application of accumulators is to maintain the quality of the supplied electricity such as voltage and current stabilization.

3.6 End-User bill optimization

By accumulation is possible manage bills of end users. Users pay for connected point and consumed energy. Payment for connected point is given by maximum power of demand. In this case usage of accumulators with required capacity can help to shave peaks in consumption and allow to install circuit breakers with lower nominal current and thereby reduce the payment. Consumers with two-part tariffs can use accumulators to store electricity during low tariff and during high tariff consume it. By this end-users can reduce their payment for electricity and also increase their supply security.

The next option is use accumulators for commercial purposes and store low price electrical energy within low tariff period and provide this energy to the grid in time of high tariff period.

3.7 Smart grid

Smart Grid is concept of energy networks consist of power lines and communication technology system to monitor and optimize energy flow in the lines. Goal of Smart Grids is to improve efficiency of electricity generation, transmission and consumption. The Smart Grid concept is based on collection data from metering in nodes of power grid. Based on this information the electricity generation is managed. The higher efficiency can be achieved by generation of electrical energy in near locations from their consumption. This process minimizes the transmission losses.

One part of these systems are accumulators storing surpluses to time of demand, improving security of supply, balancing voltage and frequency and improving economy. Rather than large scale accumulators will be supported smaller local energy storage devices working and supporting adjacent areas. In Smart Grid concept are also considered electric cars which would serve as accumulators to provide balancing of the grid.

4 Stand-alone systems with photovoltaic panels

The stand-alone systems are very problematic from viewpoint of power supply. These systems cannot rely on external power supply and have to be totally independent. Because of it stand-alone systems have to have large enough source of energy to cover all demand throughout the year. As main source usually work RES. The most widely used RES are solar and wind power plants. To provide permanent supply of electrical energy the systems have to contain storage elements. As storage elements are used batteries, fuel-cells, flow batteries and for special purposes supercapacitors.

The next part of this work is especially aimed on problems of stand-alone systems with photovoltaic panels. Photovoltaic plants don´t have mechanical parts, which mitigate fluctuations of output power due to their inertia, as wind power plants do. Therefore generation of electricity from photovoltaic power plants is extreme variable compared to other RES and strongly needs accumulation for balancing of power supply.

For better understanding of electricity generation from photovoltaic power plants, a brief description of solar energy with calculations of incident sun radiation, principle and types of photovoltaic panels and schemes of solar panels connections in stand-alone energy systems is given below. This information can help to better calculate and optimize energy storage in these systems.

4.1 Solar energy

Solar energy is energy of radiated light and heat from the Sun. Inside the Sun there are nuclear transformations which cause radiation. The fossil fuel energy, wind energy, energy of biomass, water energy and heat are manifestations of solar radiation on the Earth. Solar power plants convert solar energy directly from incident solar radiation. Solar devices which transform solar energy to electric power can be divided into two groups according their type of transformation (Photovoltaic, Concentrated/Thermal)

Sun radiation consists of ultraviolet (wavelength less than 400 nm), visible light (wavelength from 400 to 750 nm) and infrared (wavelength over 750 nm). Share of visible light under the normal conditions is approximately 45 %. Ultraviolet radiation is mostly absorbed by ozone layer. Sun radiation is different in space and in each point on Earth's surface. Volume of radiation depends on season, time of the day, weather, latitude and longitude of observed place.

4.1.1 Calculation of falling sun radiation

In method book of D. V. Samoilov "Расчёт величины поступления теплоты от солхечной радиации на поверхность земли" calculation of falling sun radiation is given by following procedure. (47)

Total radiation falling on inclined area is given:

$$Q_{inc} = S_{inc} + D_{inc} + R_{inc} \qquad \textbf{4.1}$$

where S_{inc} is direct radiation falling on inclined area [W/m^2], D_{inc} is diffused radiation falling on inclined area [W/m^2] and R_{inc} is radiation reflected from the Earth´s surface [W/m^2].

$$S_{inc} = S_{per} + \cos\theta \qquad \textbf{4.2}$$

where S_{per} is direct radiation falling on perpendicular area [W/m^2] and $\cos\theta$ angle of direct radiation [rad]

$$S_{per} = \frac{S_0 \sin\alpha}{\sin\alpha + c} \qquad \textbf{4.3}$$

where S_0 is permanent radiation [W/m^2], c is coefficient of permeability of the atmosphere
Angle of direct radiation $\cos\theta$ is given:

$$\begin{aligned}\cos\theta = {} & \sin\delta.\sin\varphi - \sin\delta.\cos\varphi.\sin s.\cos\gamma \\ & + cos\ \delta.\cos\varphi.\cos s.\cos\omega \\ & + \cos\delta.\sin\varphi.\sin s.\cos\omega + \cos\delta.\sin s.\sin\gamma.\sin\omega\end{aligned} \qquad \textbf{4.4}$$

where φ is geographical latitude [rad], δ is declination of the Sun [rad], s is angle of area to horizon [rad] and γ is azimuth angle.

Declination angle of the Sun:

$$\delta = 0.41\, sin\left(360.\frac{284+N}{365}\right) \qquad \textbf{4.5}$$

where N is ordinal number of the day in the year

Sin angle α:

$$\sin\alpha = \sin\delta.\sin\varphi - \cos\delta.\cos\varphi.\cos\omega \qquad \textbf{4.6}$$

Calculation of diffused radiation D_{inc} is according to:

$$D_{inc} = D_{hor}[0{,}55 + 0{,}434.\cos\theta + 0{,}313(\cos\theta)^2] \qquad \textbf{4.7}$$

where D_{hor} diffused radiation falling on horizontal area [W/m^2]:

$$D_{hor} = \frac{1}{3}\left(S_0 - S_{per}\right)\sin\alpha \qquad \textbf{4.8}$$

4.1.2 Shockley–Queisser limit

Energy of Sun radiation falling on Earth's surface is in average 1000 W per m^2. This energy is transformed to electricity by photovoltaic panels. Transformation is restricted and calculated by Shockley–Queisser limit. This limit indicates maximum efficiency of transformation with solar cell which use single p-n junction. Efficiency is based on band gap of used semiconductor and radiation spectrum. For single p-n junction maximum efficiency of cells is 33,7 %. This efficiency is possible increase by using more p-n junctions. For double p-n junction efficiency is up to 42 % and for triple up to 49 %. (48)

4.2 Photovoltaic (PV)

Solar (photovoltaic) panels consist of solar cells. Solar cells are semiconductor devices which convert sun light energy to electric energy. The transformation uses the photoelectric effect, in which the electrons are emitted from the material due to absorption of the photons. For detailed view on solar cell see Figure 14.

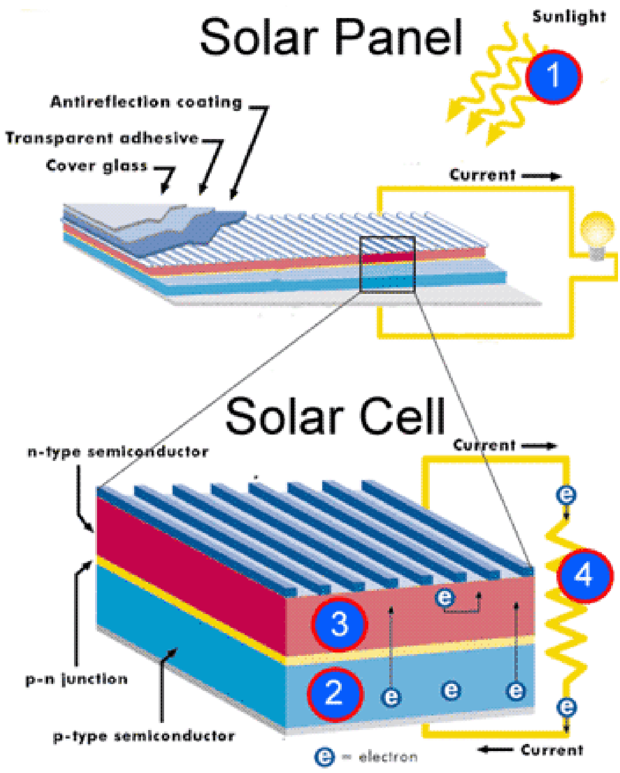


Figure 14 - Solar cell (49)

4.2.1 Solar (photovoltaic) cell

Solar cell is semiconductor device. In semiconductors electrons are normally tightly bounded in crystalline lattice of semiconductor and material is non-conductive. But by adding an element with the greater number of valence electrons we get N type conductivity. Conversely by adding an element with lesser amount of electrons we get P type conductivity. Solar cell consists of two desks. One desk is N-type which is negative charged because there are predominating negative electrons. The second desk is P-type where predominate places "holes" which can accept the free electrons. Space between these plates is place called P-N junction. It is place where electrons and holes makes pairs and create electric field which prevents to other electrons to move from N-layer to P-layer. (50)

Sunlight is the electromagnetic radiation consisting of oscillating photons. If photons, incident on the solar cell, have enough energy the semiconductors absorb these photons. During the absorption the photons emit electrons from semiconductor and make electron-hole pair. These emitted electrons are removed by electrodes causing direct current. Volt-ampere characteristics of solar panel are shown on Figure 15.

4.2.2 Solar cells types

Cristalline silicon cells

Cristalline silicon solar cells consist of semiconductor slices thinner than 1 mm. Under the slices is surface positive electrode. On the upper surface of semiconductor slices is negative electrode which collects free electrons. The surface of solar cell is protected by glass plate. Also titanium oxide can be added to the glass providing antireflective layer. Crystalline silicon solar cells can be divided into two main groups according the silicon crystallinity. These groups are monocrystal and polycrystal silicon solar cells.

The monocrystal solar cells are usually made by using Czochralski procces. During this process the silicon is melted at 1500 °C. Then into the melted silicon is immersed rod with seed crystal. Then rod starts slowly rotate and move upwards and silicon wrapped around the seed crystal begins to cool. By this process can be formed really big monocrystalline silicon ingots. Solar cells wafers are cut from these cylindrical ingots. But to cover square shaped solar panels it is necessary to cut round wafers to the correct shape. Due this step there is a lot of waste and price of monocrystal cells is higher . Efficiency of monocrystale silicon cells is around 25 %. (51)

Polycrystalline silicon cells are made from cast square silicon ingots. These ingots consist of many small silicon grains. During the process of forming polycrystalline ingots is used seed crystal and then melted silicone is carefully cooled. Polycrystalline silicon cells are cheaper than monocrystalline but they have lower efficiency. Efficiency of polycrystalline silicon cells is around 20 %.

Thin film

Thin film solar cells are the third generation of solar cells and they are made by different technology process, then classical crystaline silicon solar cells. Technology of creating thin film solar cells allows reduce the amount of active material of solar cell. The material is deposited in thin layers usually thick from a few nanometers to tens micrometers. These layers are made by similar process like printing of the ink printer. Thin film solar cells are more effective than normal crystaline silicon solar cells and lots of variants of these panels exist varying in price and efficiency. Thin film solar cells can be divided into two groups: rigid and flexible.

Rigid thin film cells are sandwiched between two glass panels because of protection of cells and antireflective function. This type of cells is two times heavier than normal silicon cells because of glass panels. Main technologies of this group of cells are CdTe, CIGS and Amorphous silicon (a-Si). The cadmium telluride (CdTe) thin film solar cells are most competitive because of low price.

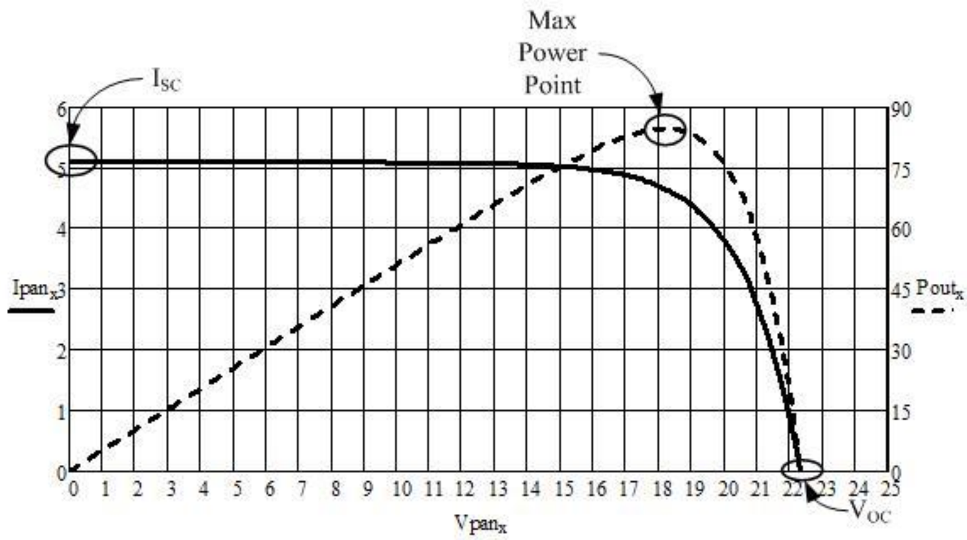
Flexible thin film cells are created by depositing the photoactive layer on a flexible substrate which can be insulator or conductor. If the substrate is an insulating material then monolithic integration is used. The most effective solar cells are gallium arsenide multijunction photovoltaic cells with efficiency up to 44 %. (52) Commercially available flexible thin film solar cells are modules using amorphous silicon triple junction.

Organic solar cells

These solar cells are possible to create because of new technologies and knowledge of genetic engineering and nanotechnology. Organic solar cells are made by using proteins and photosynthesis to generation of electric power. Organic solar cells should be cheaper and in the future more effective than classical crystaline silicon solar cells.

Surface of solar panel to produce 1kW	
Solar panel type	**Surface in m^2**
Monocrystaline High-performance	6 - 9
Polycrystaline silicon	7,5 - 10
Copper-Indium-Diselenide	9 - 11
Cadmium Telluride	12 - 17
Amorphous Silicon	14 - 20

Table 11 - Comparison of solar panels



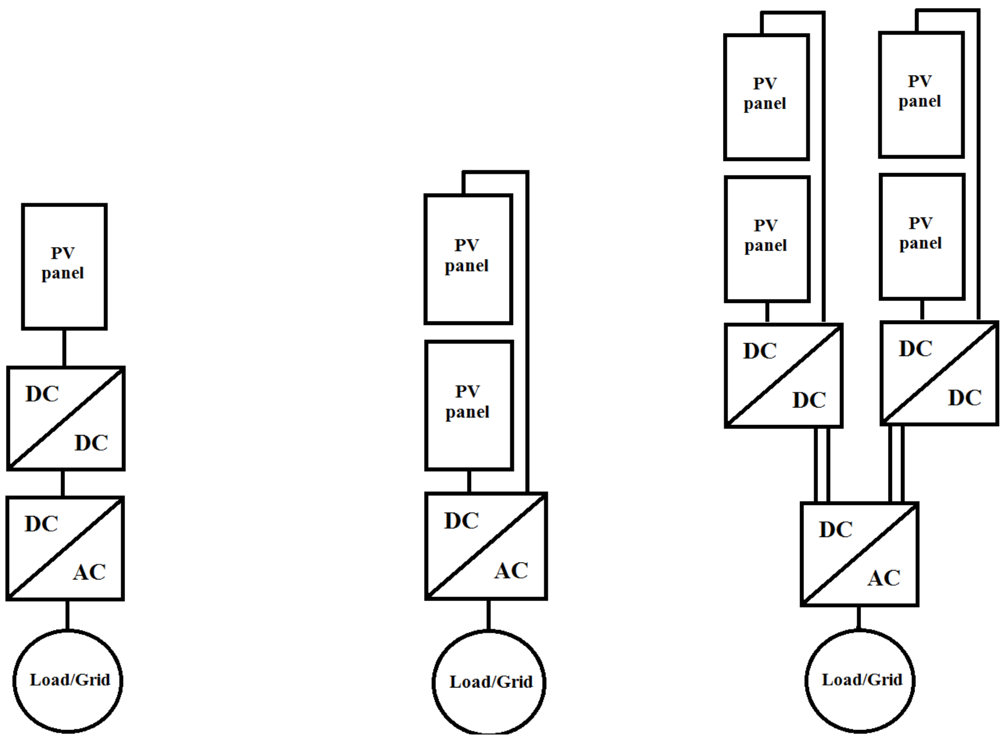
Graph 1 - Volt-ampere and power-voltage characteristics of solar panel where: Isc - short-circuit current, Voc - open-circuit voltage (53)

4.2.3 PV systems

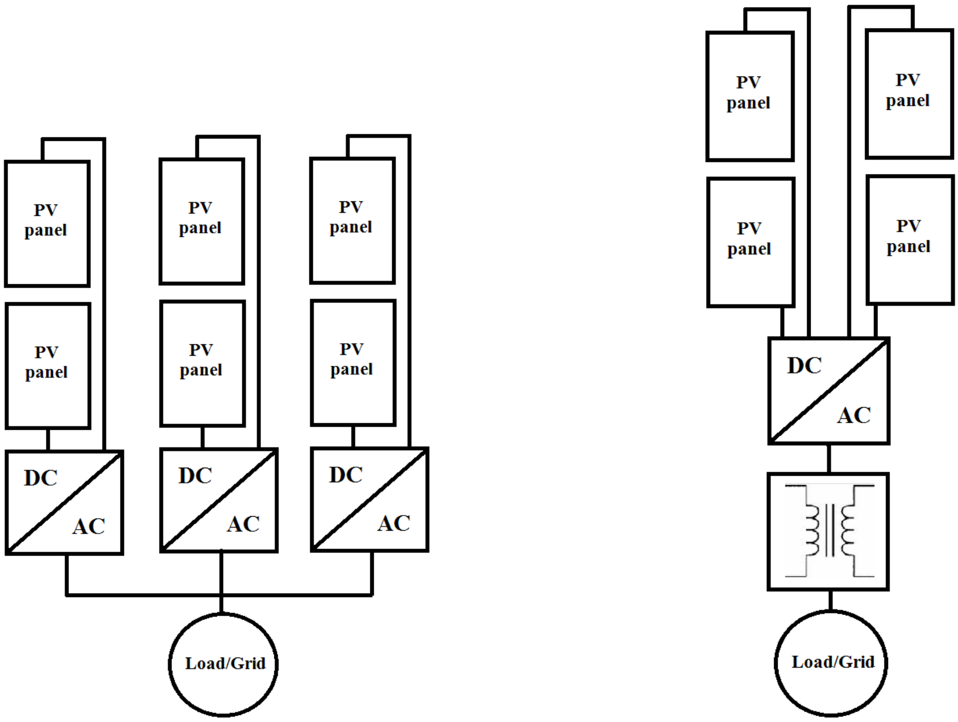
Solar panels produce direct current with output voltage in the order of units of volts. The solar panels are necessary to connect into larger systems, because of low voltage output of one panel. To increase the voltage the solar panels are serially interconnected. The connection of systems depends on installed power of solar panel or solar power plant. Also scheme of connection will depends on the purpose and philosophy of use.

The simplest connection is if the solar panels directly feed the appliance as an isolated system without accumulation. Another option connection is adding storage element for unused surpluses of electric energy. The system of solar panels can also be connected to the distribution network for the sale of produced or excess electricity.

4.2.4 Schemes of connection of solar panels without accumulation



(a) *(b)* *(c)*



(d) *(e)*

Figure 15 - Connection schemes (a) Module Integrated, (b) String, (c) Multi-String, (d) Mini-Central, (e) Central

Parameters of connection		
Type of connection	Power	Semiconductor voltage class
Module Integrated	300 W	150 - 600 V
String	1 - tens of kW	600 - 1200 V
Mini-Central		
Multi-String	tens of kW	
Central	hundred of kW - MW	1200 V

Table 12 - Comparison of solar panel connection types

Each type of solar panels connection has its own field of use. Usually it depends on total power of solar panels or in which point of transmission network they are connected. All types of connections have advantages and disadvantages. (54)

Module integrated

Module integrated scheme is used for low power solar power plants. All solar panels are connected to converters. In the first step of conversion, the direct voltage is charged to desired value and in second step of conversion the direct current to altering current. Disadvantage of this scheme is lesser reliability in case of fault of any element in this scheme.

String

String scheme is designed for connection of more solar panels. It allows build power plants with higher power than in case of Module integrated scheme. In this scheme there is only one converter converting direct current from solar panels to alternate current. This scheme has higher reliability in case of fail of one solar panel part because supply in this case will not be interrupted. The weakest point of this scheme is converter because in case of fail of converter all supply will be interrupted.

Multi-String

Multi-String scheme is consist of branches of String scheme connected to DC/AC convertor. In each branch are solar panels connected to DC/DC convertor changing voltage to designated value. Also this step is to stabilize the supply. In this scheme is also the weakest point the DC/AC converter. In case of its fault the supply will be interrupted.

Mini-Central

Mini-Central scheme solves a problem with weak point in reliability of previous variants. In this scheme the String schemes branches are parallel connected to the load. Advantage of this scheme is higher reliability due to independent parallel lines but disadvantage is higher price as a consequence of many converters.

Central

Central scheme of connection of solar panels is designed for solar power plants with big installed power. Solar panels are connected to the converter where the direct current is converted on alternate current and in the next step transformed on high voltage via the transformer. Output of this system is high voltage of electricity prepared for connection to the distribution or transmission network.

4.2.5 Schemes of connection of solar panels with accumulation

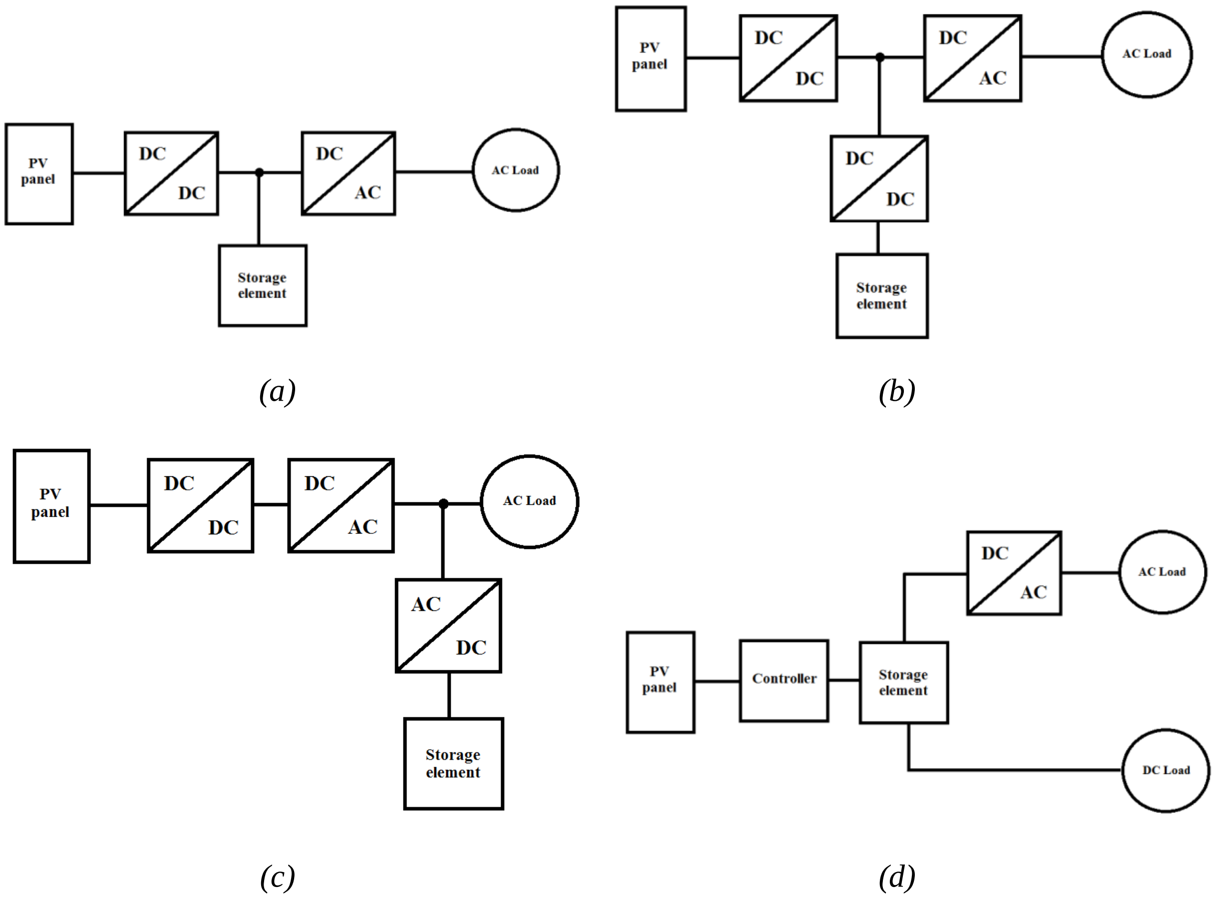


Figure 16 - Schemes of system connections

There are several ways how to connect solar panels with accumulation to the energy supply system. Each system is suitable for specific purposes. The power of converters and capacity of accumulation is depended on power of solar panels and specific demand of each system.

In the scheme *(a)* from Figure 17, there is generated direct voltage from photovoltaic panels transformed by DC/DC converter to required voltage level, which is suitable for storage element. This electricity is in the next step transformed by DC/AC converter and connected to the load.

The schemes *(b)* and *(c)* from Figure 17 are intermediate steps, created by DC/DC and DC/AC convertors between generation and load. It is because of voltage levels of components. The accumulation in the scheme *(b)* is connected to the DC part of system and provided by the DC/DC converter which is necessary for transformation of voltage level. In the scheme *(c)* there is energy storage connected to the AC node via AC/DC converter, because accumulation works in DC mode.

In the scheme *(d)* from Figure 17 there is charging of accumulators driven by controller. Electricity from accumulators is supplied to DC load and via DC/AC converter to the AC load.

5 Case study

Objective of the case study is to evaluate construction of stand-alone system with renewable source of electricity. Stand-alone system is situated into the Tomsk region in Siberian Federal District of Russian federation. The electricity network is focused around administration centre the city of Tomsk, along the river Tom and in larger towns or villages as Asino, Kedrovyj, Kollashevo or Byelij Yar. Except these locations in the region there are many small villages and communities in remote areas where is absence of electricity transmission lines. In these areas there is the stand-alone system the only option how to secure electricity supply to the rural houses.

Solar panels were chosen as a primary source of energy. Wind power turbines were also considered from the beginning, but this option was in the end rejected because of low average speed of wind in the area of Tomsk region. The average speed is in range from 1,2 to 3 m/s in the 10 meters above the ground. (55) These values are insufficient for economic electricity production from wind power plants.

Construction of some RES types in given location is complicated by bad subsoil or remote locations. In the Tomsk region there are huge swamps which prevent construction of geothermal power plants. Distance and remoteness complicated construction of complex structures. Based on these facts the solar power plants were published as the optimal option.

Figure 17 - Map with location of Tomsk region (56)

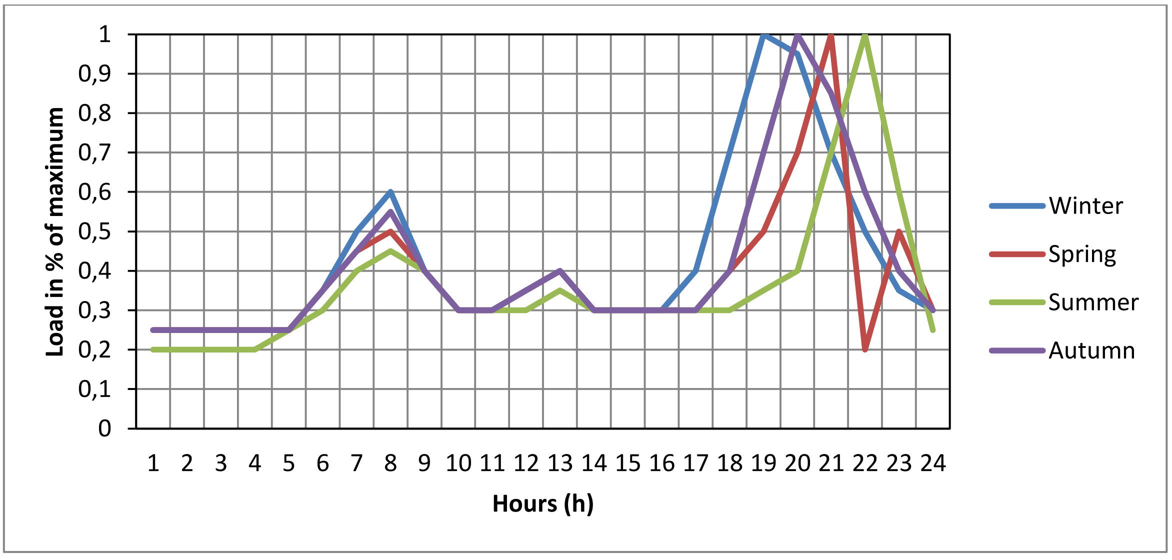
5.1 Project description

Project of stand-alone power system is located near the city of Tomsk. The specified place is without possibility of connection to the transmission network. The stand-alone system will provide a full supply for several rural buildings. As sources of electrical energy will be photovoltaic panels with diesel generator. Diesel generator will take a role of secondary source and backup. To the power system will be connected accumulators to store surpluses, of generation from photovoltaic panels, to time of demand. Considered lifetime of project is 20 years.

5.2 Input data

5.2.1 Consumer load

Consumers of the stand-alone system are rural buildings. System will provide electricity for electrical appliances, domestic hot water and for heating. The buildings have approximately 43,5 kW peak consumption power. For calculation of total consumption per year was used typical daily load diagrams of Russian rural buildings and methodology from document "Электроснабжение сельского хозяйства" of authors И. А. Будзко, Т. Б. Лещинская, Б. И. Сукманов. (57) Daily load diagram is dependence of consumed power on time in 24 hours period. For each season of the year was used one typical daily load diagram because in each season the load varies.



Graph 2 - Typical daily load diagrams of Russian rural building

For dimensioning of electricity sources it is necessary to calculate consumption of all days in each season of the year and total amount of electricity per year, which is 150 MWh. More detailed report of consumption is in Table 13.

Season	Days	Consumption/day [kWh]	Total consumption [kWh]
winter	90	445,88	40129
spring	92	395,85	36418
summer	92	376,28	34617
autumn	91	426,30	38793
Total per year	**365**		**149957**

Table 13 - Electricity consumption of Russian rural buildings

5.2.2 Insolation

In general under the good weather conditions the energy of incident solar radiation is $1kW/m^2$, but real amount of incident solar radiation which can be transformed to the electricity by solar panels depends on many factors. These factors are for example: latitude, longitude and altitude of the location, season of the year, angle of solar panels, clearness and so on.

As the underlying data for calculation of incident solar radiation were obtained from meteorological server Gaisma. (58) The first input was graph with marked sunrise, sunset times in each month of year for calculation of sun hours per day of all month. The next important data were average values of insolation per day in each month of the year. Insolation is incident energy of solar radiation in kWh/m^2. All the obtained data were specially for Tomsk region see Table 14.

Month	Days	Dawn	Sunrise	Sunset	Dusk	Insolation [kWh/m^2/day]	Clearness
January	31	8:55	9:46	17:05	17:53	0,61	0,41
February	28	7:59	8:44	18:35	19:18	1,42	0,48
Mart	31	6:56	7:33	19:25	20:03	2,73	0,51
April	30	5:33	6:14	20:28	21:09	4,16	0,52
May	31	4:14	5:05	21:29	22:21	5,35	0,52
June	30	3:25	4:30	22:12	23:16	5,74	0,51
July	31	3:58	4:52	21:59	22:54	5,69	0,52
August	31	5:02	5:48	20:58	21:43	4,46	0,5
September	30	6:11	6:49	19:41	20:19	2,78	0,44
October	31	7:14	7:51	18:03	18:43	1,6	0,42
November	30	8:09	8:57	17:01	17:46	0,81	0,42
December	31	8:59	9:51	16:47	17:37	0,42	0,37

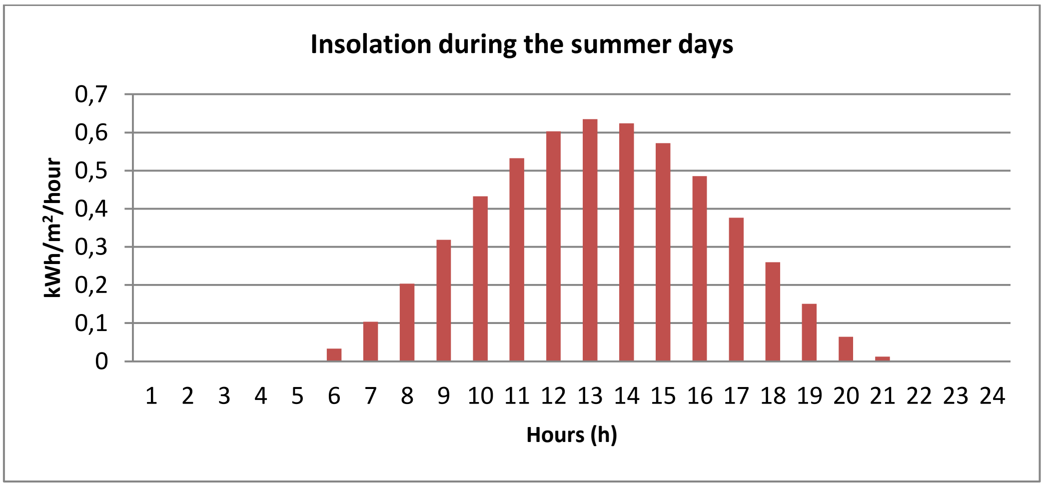
Table 14 - Input data for calculation of photovoltaic generation

The obtained day values of insolation are not sufficient for calculations, because in real world sun radiation is not constant for whole 24 hour period and using average insolation per hour is also unsuitable. Because of it, the next step was creation a sun radiation model more dynamic during the day. This was achieved by approximation by sine function, which is similar to real process of solar radiation intensity changing during the day under the good weather conditions.

Calculation of sine shape insolation was done by following formula:

$$E_x = E_{\text{avg}} + \sin\left(\frac{2x\pi}{n}\right). E_{\text{avg}} \tag{5.1}$$

where E_x is insolation of x-th sunny hour in [kWh/m^2/hour], E_{avg} is average insolation of day in [kWh/m^2/hour], x is ordinal of sunny hour and n is number of sunny hours in day.



Graph 3 - Example of recalculated sine form of insolation

5.2.3 Sources of electricity

Photovoltaic panels

As primary source of electricity were chosen photovoltaic panels. There are many types of photovoltaic panels with different parameters. The most important parameters are efficiency, panel's area and price. Higher efficiency of panels increases the amount of produced energy but the price of these panels is higher. To avoid improper selection of panels, in this case study there will be compared three different types of photovoltaic panels described in following table.

	Avancis PowerMax 125	Samsung S-energy SM-245 PC8	Yingli Solar 260C-30b Panda
Power [W]	125	245	260
Efficiency [%]	11,6	14,72	15,9
Length [m]	1,595	1,665	1,65
Width [m]	0,672	0,999	0,99
Area [m^2]	1,07	1,66	1,6335
Power/m^2 [W/m^2]	116,62	147,29	159,167
Price [€]	162	302	290
Price/W [€]	1,296	1,233	1,1154

Table 15 - Parameters description of intended panels

Photovoltaic panels will be connected serial-parallely to achieve required output voltage for converter.

Diesel generator

The role of diesel generator is backup energy source. In case when photovoltaic panels will not generate electricity and batteries will be discharged the diesel generator will produce electricity to cover the supply. Diesel generator has to be able to cover whole power demand in case of accident of the remaining power system. Advantages of diesel generators are fast response and possibility be switched on at any time. Fuel for diesel generator will be stored in external tanks with sufficient capacity.

For the specified stand-alone system it will be sufficient to use any diesel generator with power about 45 - 50 kW. Nominal fuel consumption is usually up to 210 g per generated kWh. It means, with density of diesel 840 g/dm^3, that consumption is 0,25 l/kWh.

5.2.4 Fuel price trends

The fuel price is not constant during the whole life of the project. The price of oil is depended on global market, supply and demand. The prediction of the future oil price is difficult and uncertain. There are several long term studies of oil price prediction, but some of them are contradictory. In one prediction the price decreases and in another one rapidly increases. (59) (60) If we consider the scenario of declining prices is optimistic and scenario of increasing prices pessimistic, the realistic scenario will be compromise between optimistic and pessimistic. In this case study was calculated with 6% annual growth of fuel price because this amount of the annual change in the fuel price was found to be the most probable.

5.2.5 Accumulation

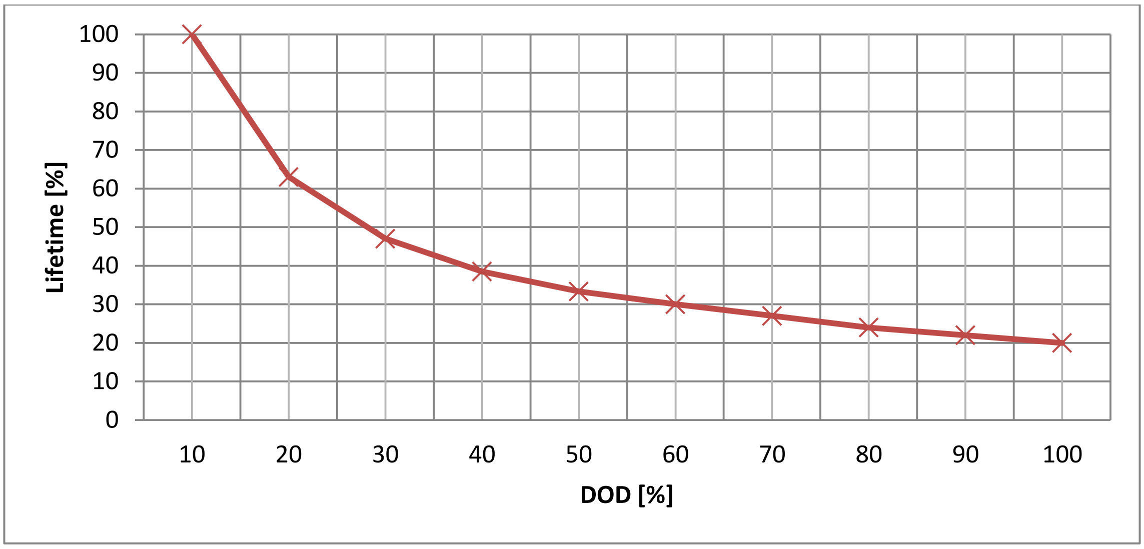
For continuous supply of electricity, even in time when solar panels do not generate electrical energy, accumulator batteries are used. In this project the AGM (Absorbed Glass Mat) and Gel lead-acid batteries are considered. The nominal voltage of one battery cell is 12V. Batteries will be connected serio-parallely to achieve the desired parameters for the system. The primary goal of accumulation in the system will be storing of electricity surpluses from photovoltaic panels and providing electricity in time of demand. Next goal of accumulators is to improve security of electricity supply in case of blackout. Accumulators also compensate power flow in the system and improve quality of provided electricity.

Great attention will be paid to the charging and discharging because under the bad conditions of these processes can be rapidly reduced lifetime of batteries. Charging of lead-acid batteries is limited by charging voltage and current which is usually around ten percent of their nominal capacity.

Charging of AGM and Gel batteries runs in two steps. First step is application constant current for period till cells voltage reach 14,1 V for Gel and 14,4 V for AGM cells. Then charging is to be switched to mode with constant voltage. This voltage is in range 14,1 - 14,4 for Gel batteries and 14,4 - 14,6 for AGM cells. If batteries are charged with voltage higher than maximum value from these ranges their lifetime is dramatically reduced.

For example if voltage exceeds about 0,7 V the lifetime is reduced up to 60 %. Charging period of batteries take time in hours. Usually batteries are fully charged in 10 - 13 hours. Also it is possible to rapidly charge batteries with higher current around 0,5 times of their nominal capacity from 1 to 2 hours, but every time the battery is charged this way, their lifetime is reduced. Another adverse phenomenon is self-discharge, which is about 5 % per month on selected batteries.

Lifetime of batteries is related to their depth of discharging (DOD). Dependence of life of batteries on the DOD is illustrated in the following chart:



Graph 4 - Dependence of battery lifetime on DOD

In the project will be selected from the three types of photovoltaic panels. Characteristic of each type are shown in following table:

Parameters	Varta Deep cycle AGM	BL 121000	BL 12440
Voltage [V]	12	12	12
Capacity [Ah]	150	100	44
Capacity [Wh]	1800	1200	528
Length [mm]	484	331	197
Width [mm]	171	173	166
Height [mm]	241	233	171
Volume [dm^3]	19,946	13,342	5,592
Weight [kg]	46	32	13,8
Price [€]	275	186	98
Price/Wh [€/Wh]	0,153	0,155	0,186
Density [Wh/dm^3]	90,243	89,940	94,420
Lifetime [cycles]	2400	1000	1000

Table 16 - Parameters of considered batteries

5.3 Technical calculations

5.3.1 Solar generation

Amount of generated electricity is depended on incident solar radiation, weather conditions and efficiency of solar panels. Calculation of generated electrical energy was done by following formula from book " Возобновляемая энергетика в децентралном электроснабжении" of authors Б. В. Лукутин, О. А. Суржикова and Е. Б. Шандарова. (61)

$$W_m = \frac{\mathrm{k.P_m.E}}{1000} \qquad \mathbf{5.2}$$

where W_m is amount of generated electricity in [kWh], P_m is nominal power of photovoltaic panel [W], E is insolation during the observed time period [kWh/m^2], k is correcting coefficient which takes into account losses of power due to heating of panels and the movement of the sun throughout the day. This coefficient is 0,5 for summer season and 0,7 for the winter. The number 1000 in the denominator represents insolation in [kWh/m^2] under the ideal conditions.

The expression can be modified:

$$W_m = \mathrm{k.\eta.E} \qquad \mathbf{5.3}$$

where η is efficiency of the photovoltaic panels in [%].

5.3.2 Accumulation

Charging and discharging of accumulators is accompanied with losses. Cycle efficiency of considered lead-acid batteries is assumed around 80 %. In model was calculated separately with charging and discharging efficiency 90 %. It is because of better dimensioning of accumulators capacity.

As first generated electricity from photovoltaic panels is provided for consumption. If surpluses are in production then electricity is stored into batteries. When electricity production from photovoltaic panels is lower than demand, batteries start to provide electricity. In case that photovoltaic panels do not generate electricity and batteries are discharged to their minimum then diesel generator provide the rest of electrical energy. Charging and discharging of batteries is driven by controller so that at the beginning of each cycle (day) and at its end is always the same amount of charge.

5.3.3 Connection scheme

Elements in stand-alone system will be connected according the following scheme:

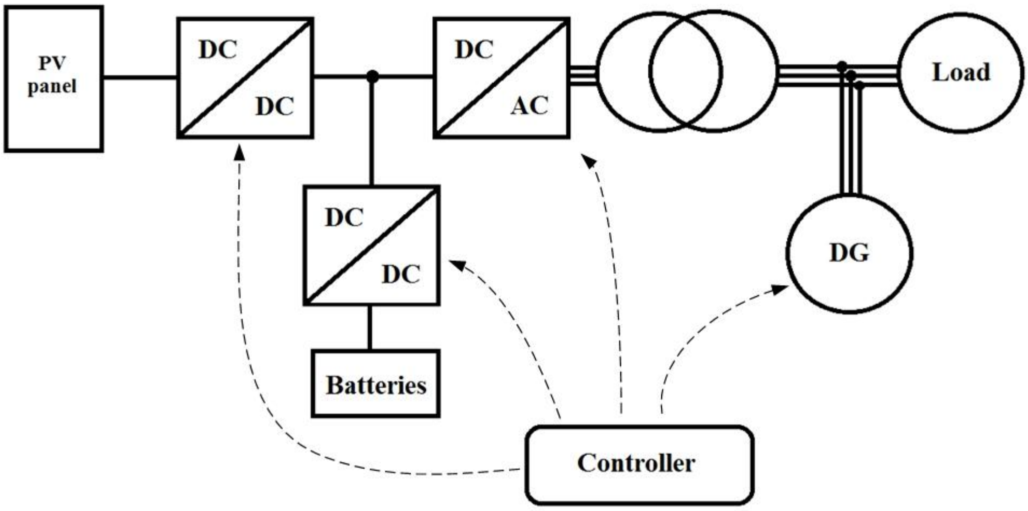


Figure 18 - Proposed block scheme of stand-alone system

The scheme shows that photovoltaic panels are connected to the buck/boost DC/DC converter, which adjusts voltage on required level. As photovoltaic panels accumulation is connected to the system through buck/boost DC/DC converter. Direct current part of the stand-alone system is connected to load by DC/AC converter with 3-phase transformer. Diesel generator is connected directly with the 3-phase load. Energy flow in the system is managed by automatic controller.

5.4 Economic model

Acceptance or rejection of projects is mostly based on economic evaluation. The economic analysis should consider what kind of inputs will enter into a project and what else may affect the value of the project.

The NPV (Net Present Value) was used because this indicator includes time value of money and cash flows in each year of life of the project.

Formula for calculation NPV:

$$NPV(i,T) = \sum_{t=0}^{T} \frac{CF_t}{(1+i)^t} \qquad \textbf{5.4}$$

where: i is the discount rate (opportunity cost of capital), T is lifetime of project, t is t-th year of the project, CF_t is cash flow in t-th year of project.

The inflation was also used in calculations. Values of inflation were found in long term prediction of inflation in Russia Federation.(62) The project used a inflation value 5 %, which is average value of inflation during the project lifetime. Real inflation may not be strictly the same as in the prediction because inflation depends on the economic and political situation, which may change.

In this project there are not incomes during its lifetime because generated electricity is consumed by owners of the system. Thanks to this in project there are no revenues only investment cost in the beginning and operating cost in the following years. The NPV indicator shows all costs for the life of the project implied to the beginning. From NPV value is subsequently easy to count theoretical price per kWh given from stand-alone system. Constant price of electricity without taking into account escalations was calculated from NPV via discounted production. If escalations of electricity price are taken into account the fictive revenues from electricity sales are added. Minimal price of electricity is then calculated under condition when NPV of the project is equal zero.

All prices in case study are given in EUR (€) but fully reflected prices in Tomsk region. Used convert ratio of rubles to the euro was 1 € = 49 rubles. For calculations was used 7% discount rate.

5.4.1 Investment

Investment includes all costs connected with the project in the zeroth year, before putting the system into operation. These costs are project documentation, purchase prices of equipment, transportation of equipment and construction works. All investment costs are shown in following table:

Costs	Price
Project documentation	7 000,00 €
Photovoltaic panels	1 115,00 €/kW
Electric and control system	60 000,00 €
Convertors	44 656,30 €
Accumulators	153,00 €/kWh
Diesel generator	12 000,00 €
Construction and transport	30 000,00 €

Table 17 - Investment costs of stand-alone system project

The final price of photovoltaic panels and accumulators depends on variant. Prices shown in table are for the installed unit power of panels and unit capacity of accumulators.

5.4.2 Operating costs

Operating costs are related to using of system. These costs have to be taken in account every year, since the system start up. The used escalation of operating costs was in size of inflation. Operating costs which were calculated in the case study:

Repairs and service

All equipment from time to time stop working. It can be by wrong operation, construction flaw or material fatigue. Reparation of broken devices cost money and time. These disturbances are random and it is difficult to predict them. For cases when some device breaks down was created a account, where the money are saved for repairs. With smooth operation of the devices is also connected service of supplying companies. Price of support services of supplying companies depends on range of services. In this case study total amount of money intended for repairs and services was 5 000 € in zeroth year.

Operating

Operating costs consist of payment to trained person who will take care about the power system. Trained person will be someone local who will be able to repair small defects, refuel or check the system. Operating cost were calculated for 2000 € per year. Other activities and repairs are within the service costs.

Insurance

In project it was also calculated with insurance of the power system for cases of its damage. In this case study was insurance calculated from value of investment. Insurance costs are 1 % of investment per year.

Fuel costs and transport

Fuel costs depends on variant of stand-alone system. In variants where there is huge electricity generation from photovoltaic panels the fuel consumption and fuel costs are lesser. Price of fuel evolves through the years and as the most probable evolution was used 6% year over year ratio.

Transport of fuel will be realized by tanks with volume 10 000 litres. The frequency of supply depends on variant of stand-alone system. Cost of fuel transport was calculated for 700 € per one supply. The amount of costs also depends on exact location of stand-alone system and on various options of transport.

5.4.3 Recovery of old equipment

All devices in power system has their lifetime or number of operating hours. Because of it, some devices have to be replaced during the lifetime of project.

Batteries

The batteries have the shortest life. Their lifetime depends on DOD and on their type. The average lifetime of batteries is around 1000 cycles. Each cycle of batteries in stand-alone system take place in one day. Because of this, the batteries are necessary to replace every two or three years.

Diesel generator

The next device which should be replaced during the lifetime of project is diesel generator. Typical lifetime of diesel generators is in range from 20 to 30 years. If diesel generator is frequently used the life is up to 25 000 operating hours. Life of diesel generator in this project depends on variant, but after each 25 000 hours of work should be replaced by the new one.

Converters

The last devices whose lifetime is shorter than life of project are converters. The producers specified that life of converters can be up to 15 years. In this study was used lower margin of lifetime which is 10 years of operating.

Photovoltaic panels

Photovoltaic panels have 25 - 30 years of life, but in the end of this period the panel´s characteristics are much worse. As more realistic was considered use of 20 years. Under the good maintenance photovoltaic panels can achieve good results in generation during whole period.

5.5 Optimization of economic model

The goal of the optimization is to improve NPV and reduce price per kWh while maintaining the purpose of the project in its range.

5.5.1 Choosing the equipment

First step of optimization is choosing of photovoltaic panels and battery type. Characteristics of appropriate panels and batteries are described in chapter 5.2. Within this step NPV were calculated with all combinations of panels and accumulators. The calculation model was configured for the "winter" way of stand-alone system operating. It means that electricity generation from photovoltaic panels is sufficient in all days even in winter, when the solar radiation is lesser. In this variant system covers electricity demand only with photovoltaic panels and accumulators without diesel generator. The results are shown in table given below:

	Varta Deep cycle (430 pieces)	**BL 12100 (646 pieces)**	**BL 12440 (1466 pieces)**
Avancis PowerMax 125 (8591 panels)	NPV: -2 568 906 € €/kWh: 1,477	NPV: -3 317 610 € €/kWh: 1,908	NPV: -3 593 904 € €/kWh: 2,067
Samsung S-energy SM-245 PC8 (4363 panels)	NPV: -2 483 142 € €/kWh: 1,428	NPV: -3 231 845 € €/kWh: 1,859	NPV: -3 508 139 € €/kWh: 2,018
Yingli Solar 260C-30b Panda (4113 panels)	**NPV: -2 338 662 €** **€/kWh: 1,345**	NPV: -3 087 366 € €/kWh: 1,776	NPV: -3 363 659 € €/kWh: 1,935

Table 18 - NPV values and prices per kWh of all equipment combination

The result shows that for secure supply is needed different number of pieces, which are written in parentheses, in different types of panels and batteries. The best combination with the highest NPV is using deep discharge AGM batteries Varta and Yingli photovoltaic panels. The constant price without escalations per kWh from this system was 1,345 €.

If the system is set to "summer" operation, the photovoltaic panels are set to cover summer demand. For other seasons diesel generator is used and optimal equipment selection would be the same.

5.5.2 Choosing the operational variant

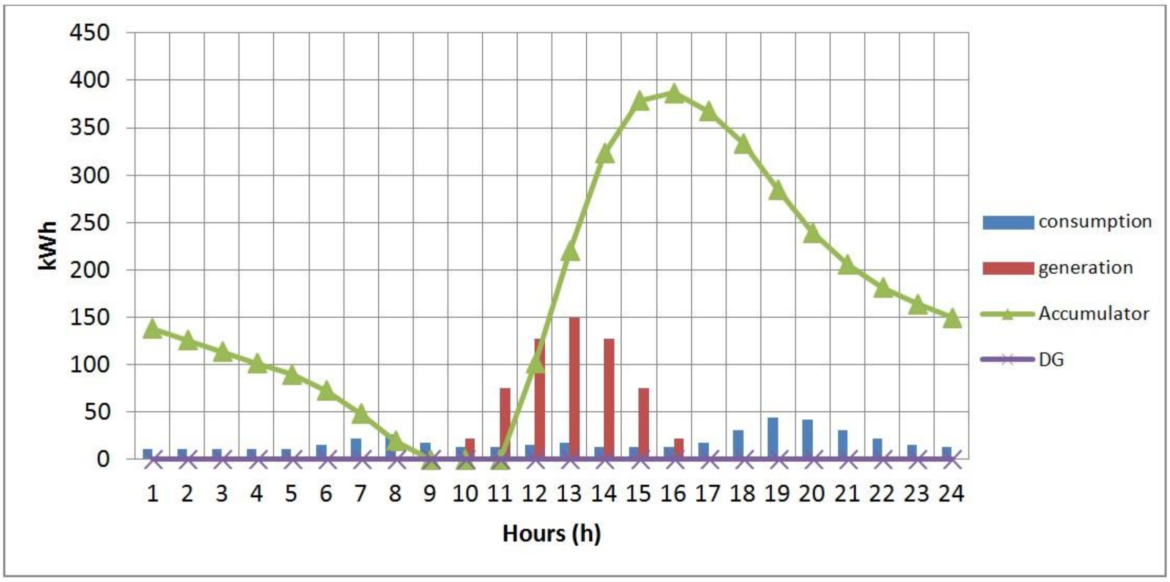
Economic results depend not only equipment but also on its operating mode. In previous chapter 5.5.1 was mentioned "winter" variant of stand-alone system. This variant requires the highest number of photovoltaic panels and batteries, because electricity is provided only from panels even during the winter days and batteries have to store the amount of electricity necessary for supplying in dull time.

The winter variant have some disadvantages. The first one is high investment price of panels and batteries. The second one is high losses of unused energy in spring, summer and autumn, when electricity production is higher than consumption. If the number of panels and batteries is reduced on the one hand the investment costs decreases but on the other hand increases fuel cost for diesel generator. The dependency of project NPV values on different number panels and batteries was calculated.

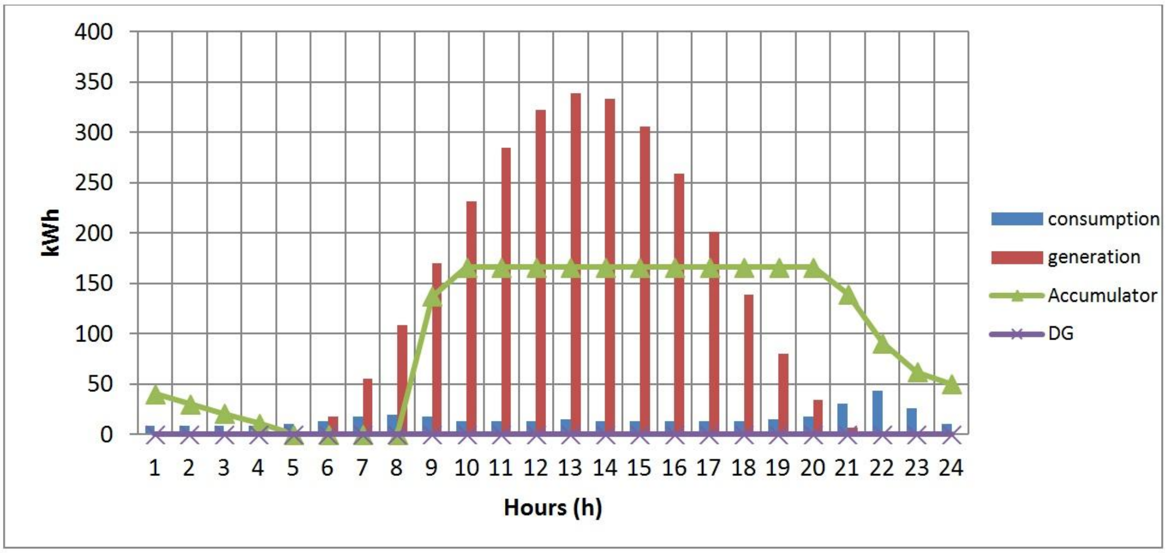
(see appendix F for tables with result)

Winter variant

In the table in appendix F there are highlighted three important variants. The variant highlighted by red colour is optimization in winter way. In this variant was used 4113 pieces of photovoltaic panels of installed power 1069 kW. The accumulation consists of 430 deep cycle batteries with total capacity 386,7 kWh. Diesel generator was not used.



Graph 5 - Cycle process during winter days - "winter" variant



Graph 6 - Cycle process during summer days - "winter" variant

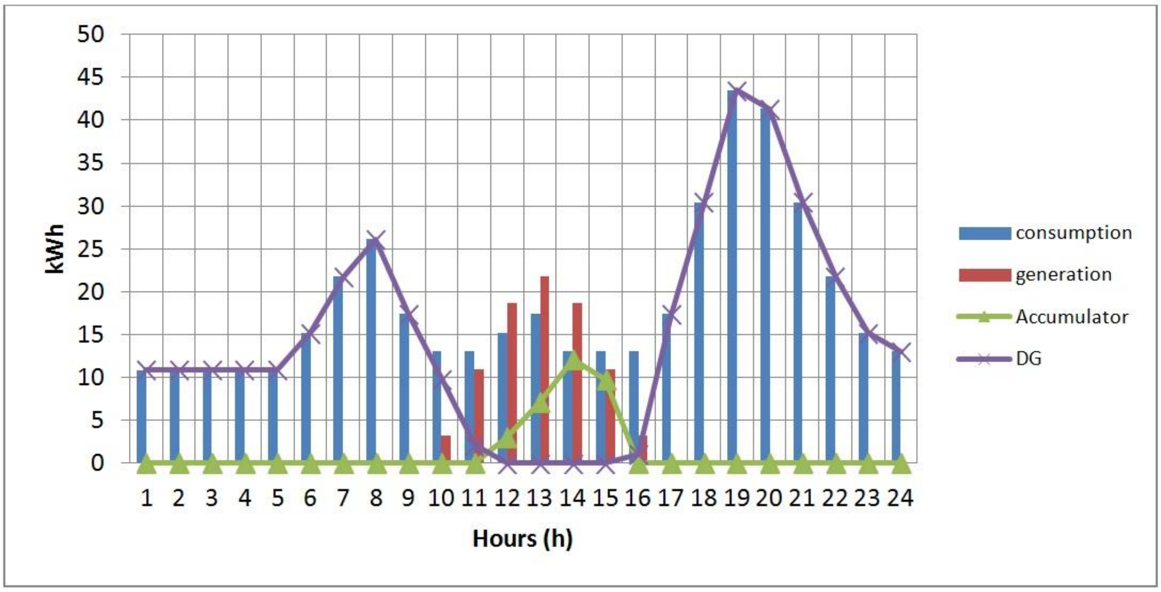
(see appendix G for other cycle processes of winter variant)

The Graph 6 shows that electricity generation from photovoltaic panels in summer is much higher than consumption and battery capacity. Due to this panels have to be disconnected and excess of electricity will be lost.

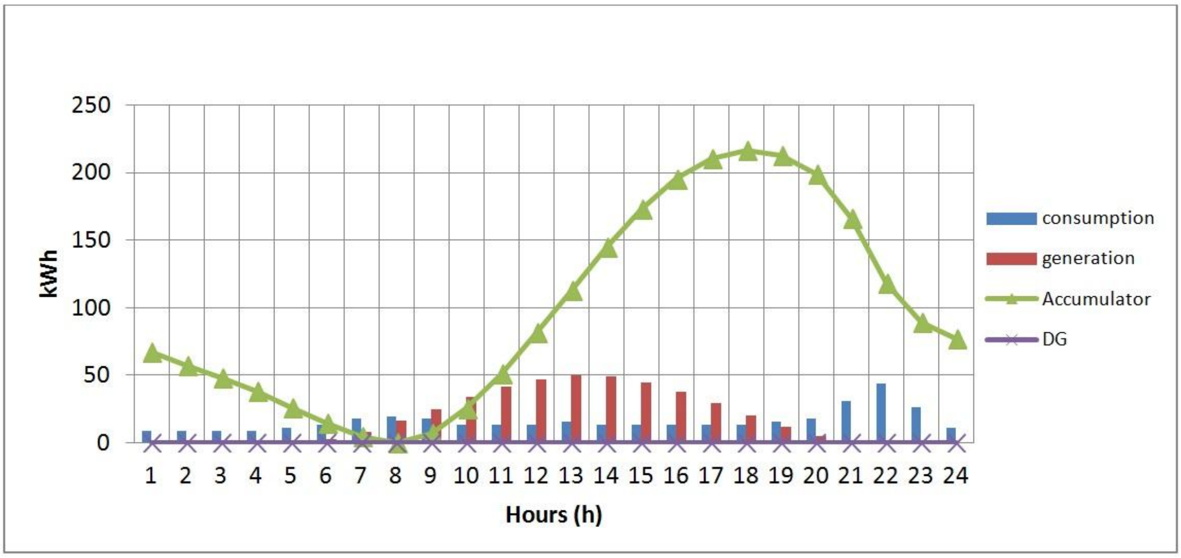
The winter variant have the lowest NPV which is - 2 338 662 €. The price of electricity in this variant is 1,345 €/kWh without escalation. If we take into account 5% escalation of electricity price the minimal price per kWh is 0,891€. The electricity from winter optimized variant is the most expensive in comparison with other variants.

Summer variant

The second variant is highlighted by blue colour and represents system optimised in summer way. The system consist of 601 photovoltaic panels with installed power 156 kW and 242 batteries with 216,5 kWh capacity. Photovoltaic panels are set to cover whole summer demand only in combination with batteries. In other seasons whole amount of electricity provided by panels is consumed and in periods, when generation from photovoltaic panels is lower than demand, the diesel generator helps with supply. In this variant diesel generator provides around 62,25 MWh per year.



Graph 7 - Cycle process during winter days - "summer" variant



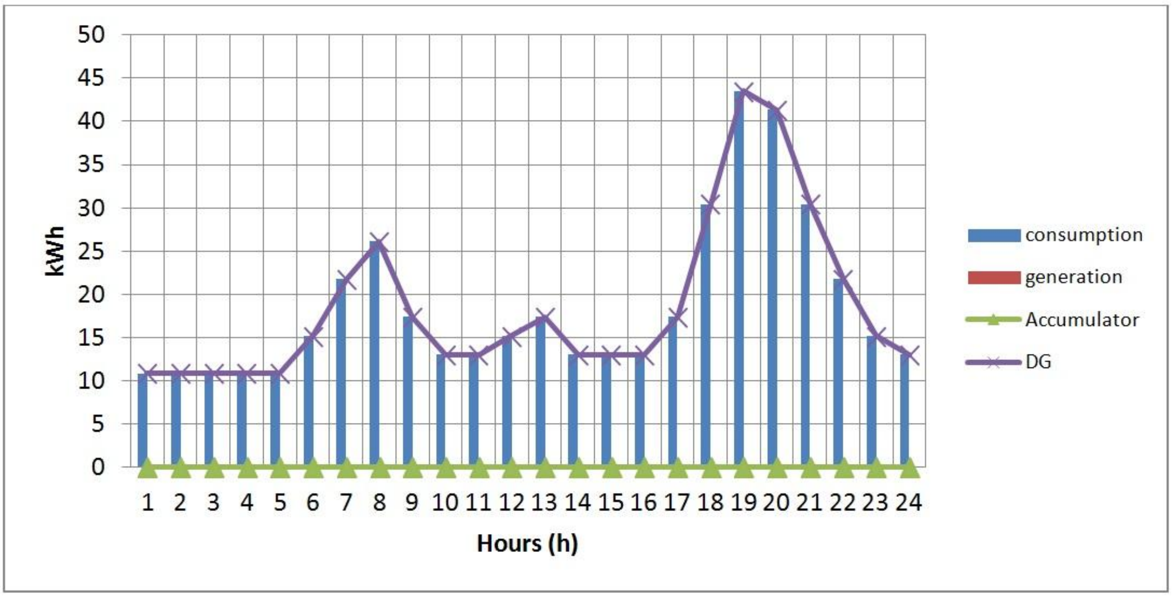
Graph 8 - Cycle process during summer days - "summer" variant

(see appendix H for other cycle processes of summer variant)

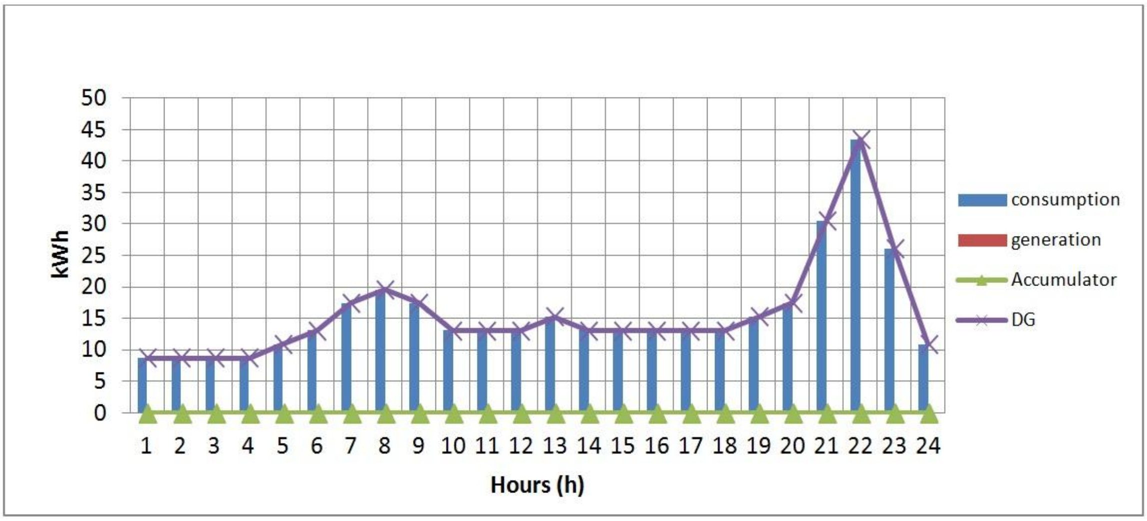
In comparison with the previous variant the investment costs are lesser due to reduced number of panels and batteries. The NPV of this variant is - 1 133 495 €. Constant price of electricity from this variant of stand-alone system is 0,652 €/kWh. Minimal electricity price with 5 % escalation is 0,432 €/kWh. This price is two times lower than from winter variant.

Diesel generator variant

The last important variant is project with the highest NPV value. In this case study a system with the lowest electricity price is system only with diesel generator. There are neither photovoltaic panels nor batteries in this system. Diesel generator cover whole 150MWh demand per year. This variant is characterized by low investment costs but higher operating costs (fuel costs).



Graph 9 - Cycle process during winter days - "DG" variant



Graph 10 - Cycle process during summer days - "DG" variant

(see appendix I for other cycle processes of "diesel generator" variant)

NPV value in this project is - 712 638 €. Discounted sum of fuel costs over lifetime of project is 530 606 € which is more than 78 % of project NPV value. Constant price of electricity is 0,409 €/kWh. Minimal price per kWh with taking into account 5% escalation is 0,271 €.

Generally the results shown that the best variant is the variant with diesel generator as a source of electricity. Diesel generator does not need accumulation because it is able to generate electricity in each time of need. Combination of diesel generator with accumulators leads on the one hand to higher price of the system but on the other hand to higher reliability of supply. Batteries can provide stored electricity even when diesel generator is broken or under maintenance.

Variants that use panels and batteries are expensive not only because of their prices but due to the complex structure of the entire system that needs expensive equipment such as converters. The efficient number of photovoltaic panels is up to 601. Higher number of installed panels leads to higher investment costs and generated electricity will be unnecessarily large. It can be seen especially in summer period when production will be higher than consumption, panels will be disconnected and electricity will be lost.

	Winter	Summer	Only DG
NPV	-2 338 662 €	-1 133 495 €	- 712 638 €
Number of PV panels	4113	601	0
Installed power of panels	1 069 kW	156 kW	0 kW
Number of batteries	430	242	0
Installed capacity of batteries	386,7 kWh	216,5 kWh	0 kWh
DG production/year	0 MWh	62,24 MWh	149,56 MWh
Min. price/kWh (without escalation)	1,345 €	0,652 €	0,409 €
Min. price/kWh (5% escalation)	0,891 €	0,432 €	0,271 €

Table 19 - Information about important variants of optimized system

Further in this work will be mentioned only electricity prices, escalated by 5 % per year. This price escalation is the most likely.

5.5.3 Choosing the depth of discharge

The last step in optimization is choosing the depth of discharge. This parameter regulates number of used accumulators in the system and frequency of their replacement. If batteries are deeply discharged their life is reduced. In the project it means that number of installed batteries will be lower but their replacement will be more often. On the one hand investment costs decrease but on the other hand sum of costs connected with their replacement in following years increases. Optimization was carried out in previously described three variants. Results of optimization are in following table:

	Winter	**Summer**	**DG**
DOD [%]	NPV [€]	NPV [€]	NPV [€]
10	-3 109 854	-1 567 514	-712 638
20	-2 605 317	-1 283 565	-712 638
30	-2 479 760	-1 212 903	-712 638
40	-2 376 979	-1 155 059	-712 638
50	-2 338 662	-1 133 495	-712 638
60	-2 293 744	-1 108 215	-712 638
70	-2 243 946	-1 080 189	-712 638
80	-2 218 758	-1 066 014	-712 638
90	-2 196 522	-1 053 499	-712 638
100	-2 197 354	-1 053 968	-712 638

Table 20 - Results of DOD optimization

The results show that it is better discharge batteries deeper regardless reducing of their lifetime. Deeper cycle discharging of batteries leads to higher value of NPV in all variants where batteries were used. It is clear that variant only with diesel generator remains the same. Explanation for other variants is that at the beginning of project the price of money was higher. From this point of view it is better have lower investment in the zeroth year and have more often expenditures for the recovery of batteries in following years.

After optimization remains the best variant only with diesel generator as a source of energy. In this variant the best price of electricity is 0,271 €/kWh. The variant with summer operation reach the better price 0,401 €/kWh by DOD 90 - 100 %. The worst is winter operation variant with price of electricity 0,837 €/kWh when DOD is in range 90 - 100 %.

5.5.4 Comparison of prices per kWh

The price of electricity in Tomsk region for rural houses is 1,82 rubles per kWh. (63) It is single part tariff price of electricity for year 2013/2014. After converting it reached 0,037 €/kWh.

The most appropriate variants of stand-alone power systems for implementation are the summer optimized variant and variant with diesel generator without photovoltaic panels. It is because of their low price per kWh. The variant with winter optimization is inefficient and realization of this project would not be worthwhile.

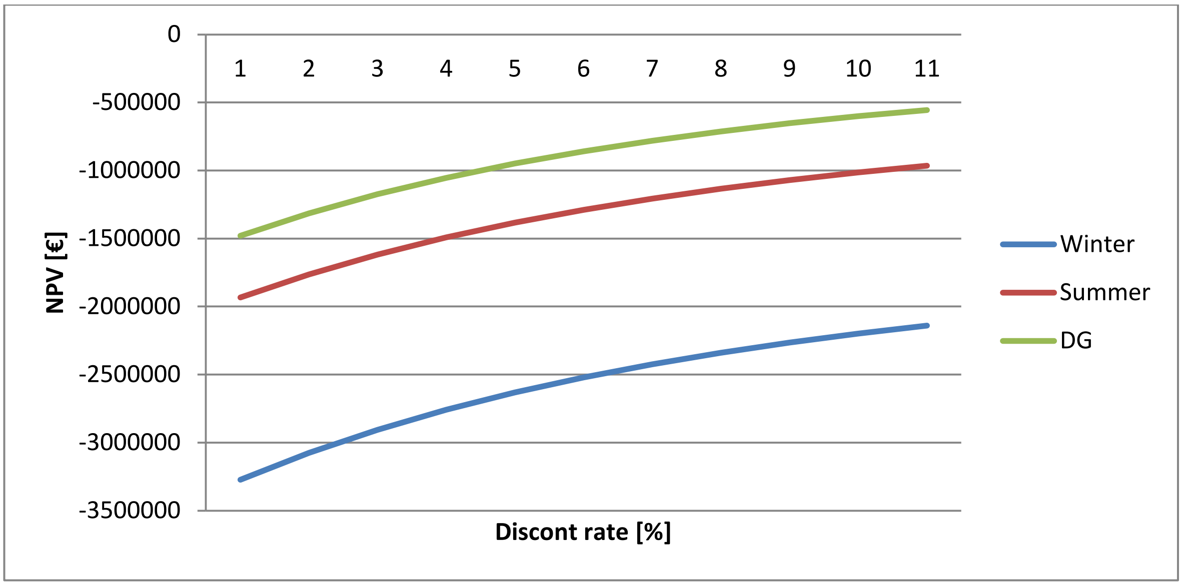
After comparison of electricity prices from stand-alone system with common prices in Tomsk region is clear that prices from stand-alone system are much higher. In case of summer variant the difference against common price is 3,64 €/kWh. It is more than 10 times higher price. In diesel generator variant it is better, the difference against common price is only 0,234 €/kWh but anyway it is still more than 7 times more expensive. These differences can be reduced by grants on electricity generated from renewable sources but in any case these grants do not cover whole differences in electricity price.

5.6 Sensitivity analyses

The sensitivity analyses were made to find out the dependency of the project value on different inputs. These analyses show the character of the project value when the inputs are changed in the most likely range. The appropriate variant can be caused by changes of inputs.

Discount

As first examination of the input is discount. Discount changes the value of future cash flows and it is for each entity different. Discount rate from range from 0 to 10 percent was used for the analysis. Result of analysis is shown in a graph bellow:

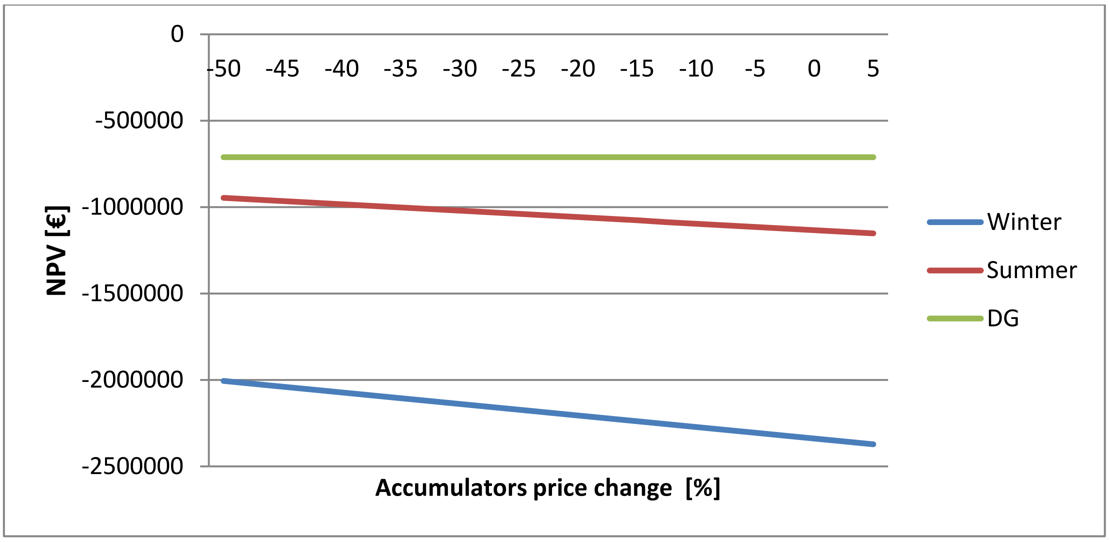


Graph 11 - Discount rate analysis

With the higher discount rate the NPV increases. In observed range the order of variants remains at all values of the discount rate.

Equipment price

Next input which influences on value of the project is investment. The prices of all used devices in the system can be changed. A few years ago the photovoltaic panels passed developmental revolution. It was time when renewable sources of electricity start to be supported by governments. The production price of photovoltaic panels sharply dropped. This fact allowed to implement previously unfeasible projects. Nowadays the attention is focusing to the accumulation technologies. In many countries the development of accumulation technologies is in plans for the near future. Smart grid concept of transmission lines also relies on using of energy storage elements. Therefore the drop of accumulators price is the most possible. It would have consequences for value of the whole project of stand-alone system. Dependence of NPV on price of accumulators is shown in following graph:



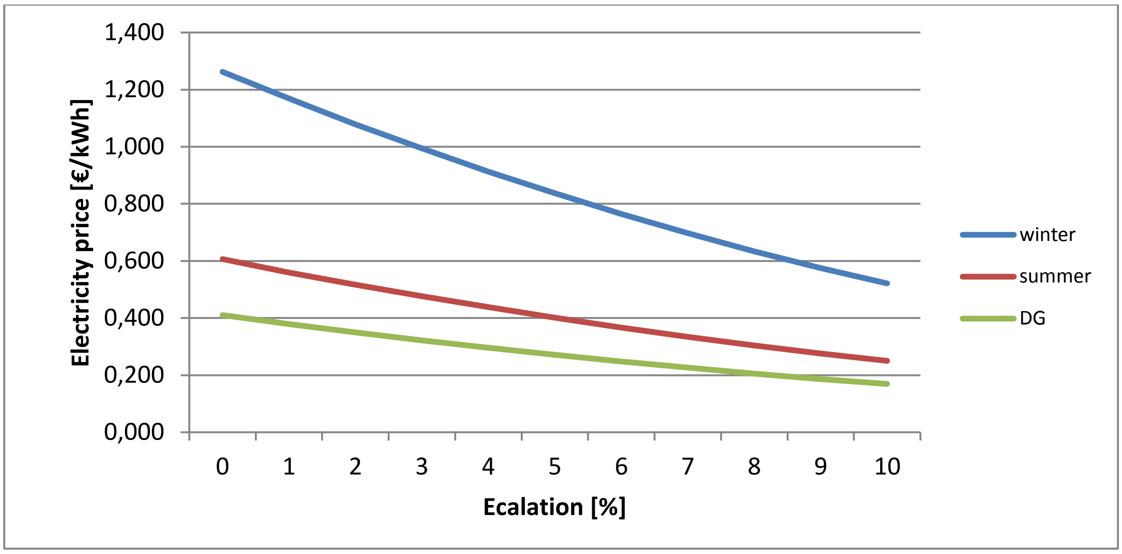
Graph 12 - Accumulators price analysis

The most affected variant by changing of accumulator price variant is the system optimized on winter operation, because there is the highest number of accumulators in this variant. Order of variants of stand-alone systems remains without changes even if the reduction of price of accumulators is 50%. The price of batteries affects only output price of electricity but not the preferences of variants.

Electricity price

To evaluate minimal electricity price per kWh from the system it is necessary to add fictive revenues because in the project there are no sales of electricity. These revenues are discounted and the minimal price depends on expected price escalation. The dependence of minimal electricity price on electricity price escalation and its results are shown in Graph 13.

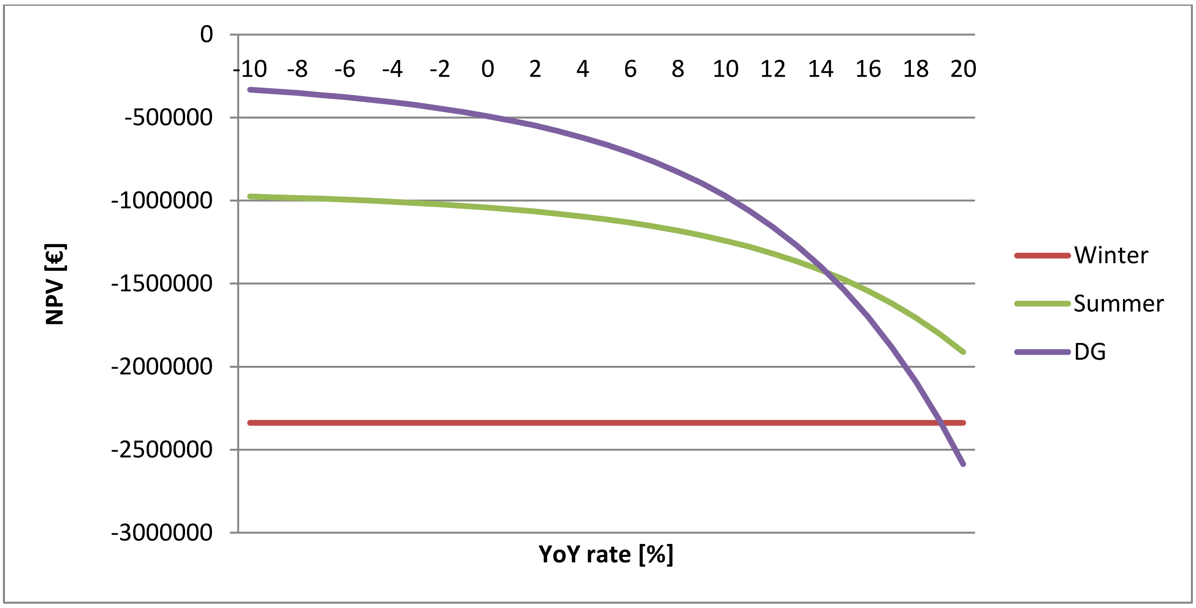
All the variants behave the same way in percentage changes of the price. If we look at the results in terms of absolute differences, the largest difference in prices is in winter variant and the lowest in one will be in variant with diesel generator.



Graph 13 - Electricity price escalation analysis

Fuel price

Price of fuel for diesel generator can have a great influence on variants of stand-alone system. In each variant diesel generator produces different amount of electricity in orders of MWh per year. The year over year (YOY) ratio of fuel prices is hard to predict for a longer period. The fuel price depends on many factors such as political or economical situation. To represent a correlation between escalation of fuel price and NPV of the project was analysed YOY in range from -10 % to +20 %.

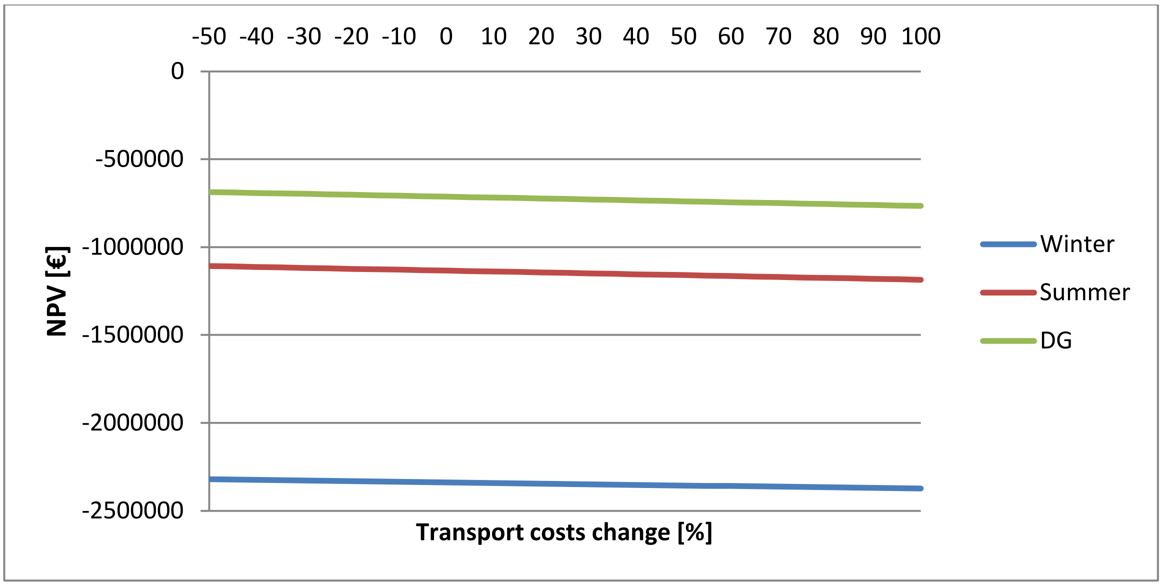


Graph 14 - Result of fuel price analysis

The impact of fuel price is bigger than in other inputs in previous analyses. The highest YOY values of fuel price escalation result higher deviations in NPV. The important point is 14 % of YOY rate when order of variants is changed. The variant with summer operating optimization becomes more preferable against the variant with diesel generator. If YOY rate reaches 19 % the variant with diesel generator becomes the worst one. This variant is strongly depends on fuel because the whole amount electricity is generated from it.

Transport costs

The last input which can affect the value of project are transport costs. For each location in Tomsk region these costs are different. It depends on availability of location and possibilities of different types of transport to reach the location. If the fuel tanks are transported by train it will be cheaper than by truck. The distance between a location and the city of Tomsk also influence on costs. Results of analysis is represented in following graph:



Graph 15 - Results of transport costs analysis

The transport costs do not have a big impact on NPV of the project. The order of all variants is without changing. Summer and winter variants have higher transportation costs in zeroth year because of higher amount of photovoltaic panels and accumulators. In variant with diesel generator there was low transportation in zeroth year but higher fuel transportation costs during following years.

5.7 Case study results

This case study evaluate project of stand-alone system in Tomsk region. All inputs for the calculation and optimization were defined and taken into account. The consumer load and solar generation models were carried out according to the given methods. A base variant of stand-alone system was the winter operation variant. The optimization was performed in several steps. In the first step the equipment was chosen, then operational mode and in the end the depth of battery discharge. In process of optimization there appeared two more important variants of stand-alone system: optimized for summer operating and only with diesel generator.

The variant with diesel generator is the cheapest one with final price of electricity 0,271 €/kWh. Electricity supply from this variant of the system is not secured in case of diesel generator fault. The electricity from summer optimized variant costs 0,401 €/kWh. The electricity price is higher than in previous variant but supply is more secure. This security is provided by two electricity sources and batteries, which can serve in case of system fault as a backup.

The effective number of photovoltaic panels and batteries in the system is up to number in summer variant. Higher installation of panels and batteries is redundant. Optimal portfolio of variants is between diesel generator variant and summer optimization. The price of kWh will be in range 0,271 - 0,401 €/kWh but the higher price will provide higher security of supply and share of clear energy generated from renewable resources. The most important thing in making a choice between variants is requirement of supply security. Ecology impact can be also decisive for the selection of variant.

Conclusion

Nowadays the energetics is an area that ensures activity of the whole civilization as we know it. Mankind becomes completely dependent on electricity supply. Energetics is still developing new technologies, which allow more efficient production of electric energy at power plants and by that save primary energy sources. The last decade renewable sources of electricity as solar, wind, geothermal, biofuel power plants are strongly supported. These technologies are more often represented in energy mixes of states all around the world.

On the one hand renewable sources of electricity as photovoltaic panel and wind turbines use almost free and inexhaustible sources for electricity production but on the other hand this production is random and unpredictable. This can affect transmission and energy quality. If renewable sources provide larger amount of electricity in time of low demand there will be more electricity in transmission lines which leads to increasing of electricity frequency and voltage. Voltage and frequency are important parameters of electrical energy quality. Electricity parameters are strictly monitored to prevent their deviation from the predetermined values because in that case electrical equipment can be seriously damaged.

For regulation of energy amount in transmission lines the storage elements are used. Electricity is not storable in its form. The only way how to storage electrical energy is transformation into another form of energy as mechanical, chemical or thermal. Losses are the main disadvantage of these transformations. Because of losses the usable amount of electricity is reduced sometimes up to 50 %. There are many storage elements as hydro pumped storage plants, compressed air energy storages, flywheels, batteries, flow batteries, fuel cells or supercapacitors. Each type of accumulation has its own efficiency, advantages, disadvantages and field of use.

For long term energy storage are suitable hydro pumped storage plants and CAES. These accumulators have low losses in "charged" state and can store a large amount of energy. These two types together with flywheels can serve as centralized regulators of energy in transmission. Flywheels have advantage of fast response against hydro pumped storage plants and CAES.

For decentralized accumulation with lower capacity are suitable all chemical accumulators and small flywheels. There are a lot of types of chemical accumulators as lead-acid, Li-Ion, NiCd, fuel cells and flow batteries. Li-Ion batteries are used in small portable devices, but for purposes of high voltage power are inappropriate. The most widely used batteries are lead-acid batteries which are used in automotive industry as well in energetics. Maintenance-free gel and AGM lead-acid batteries are suitable for accumulation connected to renewable resources with low and medium installed power. These batteries are produced in many variants as long life or allowing deep discharge. Disadvantage of all chemical batteries is self-discharge.

Another technology is used in flow batteries. These accumulators have tanks with electrolyte and electricity is generated in reactor cell. Because of separate tanks the flow batteries do not self-discharge and their capacity depends only on volume of electrolyte tanks. This type of accumulator is one of the most perspective. Nowadays already exist workable systems with vanadium redox flow batteries but this technology is still under development.

For special purposes supercapacitors are used. This type of accumulation store electricity in its form but has huge self-discharge losses. The supercapacitors have extremely fast response and can be charged and discharged by large currents therefore the supercapacitors can work as energy buffers storing high energy peaks. This technology is really expensive in comparison to other accumulators and using of supercapacitors is limited by this.

Accumulators can be used in power system for several purposes. The most common is storage electricity from time when surpluses are in generation to time of demand. The next purpose of accumulators is compensation of voltage and frequency for improving the quality of electrical energy in the power systems. Accumulators can serve as backup sources of electricity to secure electricity supply in case of power failure.

The special type of power systems are stand-alone systems. These autonomous power systems are built in remote locations or in places where is no possibility of connection to the transmission grid. As the most suitable sources of electricity for stand-alone systems are renewable resources as photovoltaic panels and wind turbines. Due to irregularities in the production from RES the accumulators are required for security of supply in each time of demand. Often a diesel generator is used as an additional source of electricity.

The Tomsk region is a large location with area 316 900 km². Its population is around one million. The highest population density is in the city of Tomsk, adjacent areas and in bigger cities and villages. In these areas is also concentrated electrification and transmission network. In the Tomsk region there are many small villages or remote dwellings where is not possibility of electrical supply. If the inhabitants of these places want to have electricity the stand-alone system will be the only choice.

The case studied in this work was focused especially on stand-alone system providing electricity for buildings in remote area of the Tomsk region. The goal was to evaluate the project of power system construction providing the electricity supply to people living there. With regard to the local conditions the photovoltaic panels were chosen as a main source of electricity. Lead-acid batteries were used for accumulation. The diesel generator was considered as an additional source. The evaluation from a technical and economic point of view was made after designing the system.

In economic model the system was optimized to achieve lower electricity price. Firstly the equipment was chosen, secondly operating mode and as the last step the battery deepness of discharge. In each of these steps the price of electricity from stand alone system was successfully reduced. In the end of optimization two viable variants remained. It was the system with photovoltaic panels optimized for summer operating and the system only with diesel generator. The variant with diesel generator was found as the best one with the lowest price per kWh. NPV value of diesel generator variant was -712 638 € and price of electricity was 0,271 €/kWh. The NPV of the summer optimized variant was -1 053 968 € with price of electricity 0,401 €/kWh.

The choice of variants depends on point of view. If the price of electricity is the only condition the variant with diesel generator is the most suitable. The price of electricity is not the only condition because the security of supply is also important. If diesel generator breaks down electricity supply will be stopped. Therefore, when taking into account security of electricity supply and quality of electricity the summer variant is better. The next point is an influence of electricity generation on environment. Photovoltaic panels in summer variant of the system generate clear energy that is another advantage of this system against the variant with diesel generator which pollutes the environment.

The real values of project depend on many factors such price of equipment, transport, fuel, discount or price escalation. According to the result of sensitivity analyses only the price of fuel has larger influence on total value of the project and order of project variants. The variant with diesel generator is the mostly affected by this parameter because it completely depends on fuel. Change in order of variants occurs only when the annual changes in fuel prices are larger than 14 %, which can occur only in exceptional cases.

The common price of electricity in Tomsk region is 0,037 €/kWh. This price is several times lower than cost of electricity provided from optimized stand-alone system variants. The difference between prices can be reduced by government grants on electricity generation from renewable resources. The next improvements of project value can be done by drop of used equipment prices or by using of another technology in the system. Changing of accumulation technology during the project lifetime can be one of the way to achieve better results. The new perspective vanadium redox flow batteries can substitute the common lead-acid batteries and improve economics of the project.

The next ways how to expand case study of stand-alone system can be consideration of another accumulation types in calculation, prediction of price changes of each accumulation type and created according to these results optimization of accumulation deployment. To achieve better economics results types of accumulation may be changed during the lifetime of stand-alone system.

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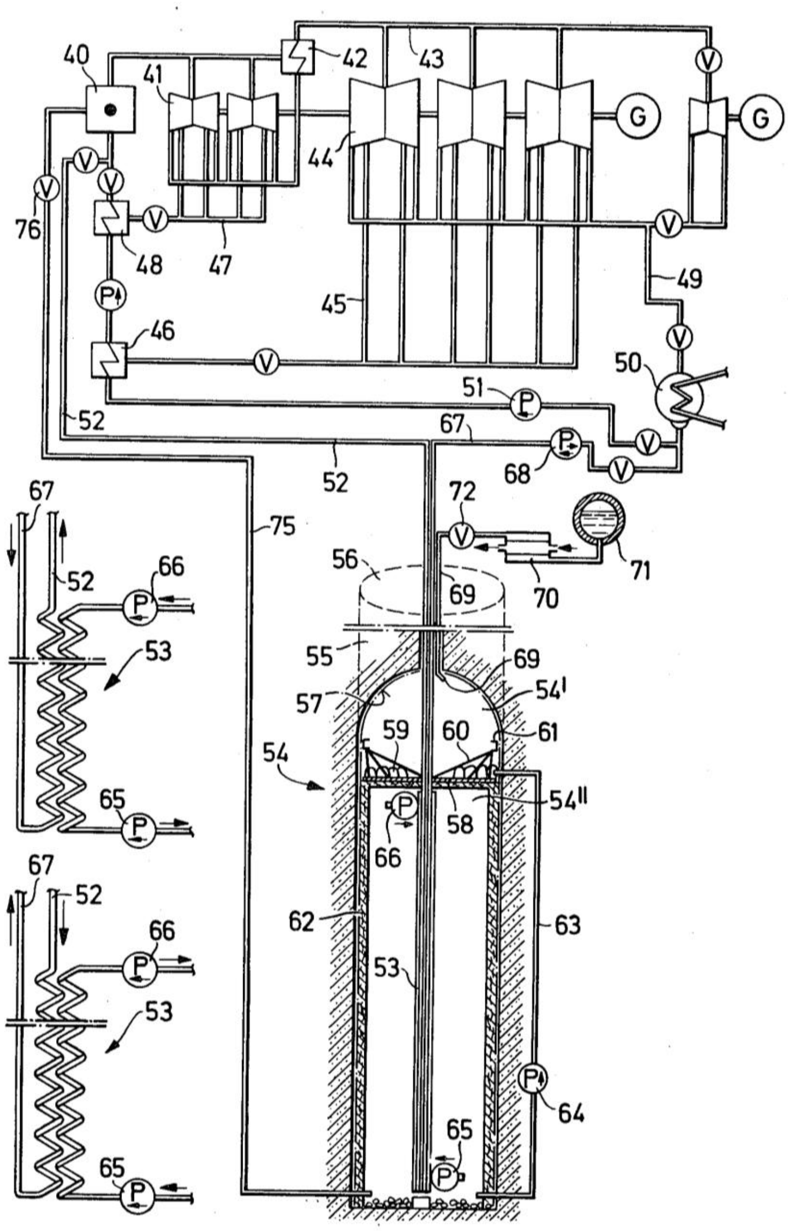
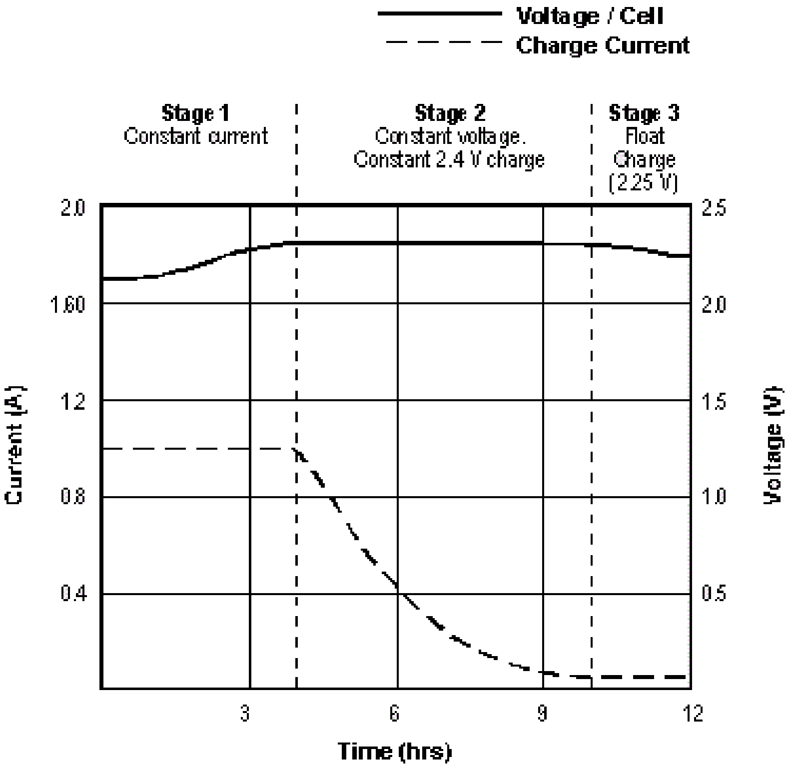
Appendices

A Thermal accumulation

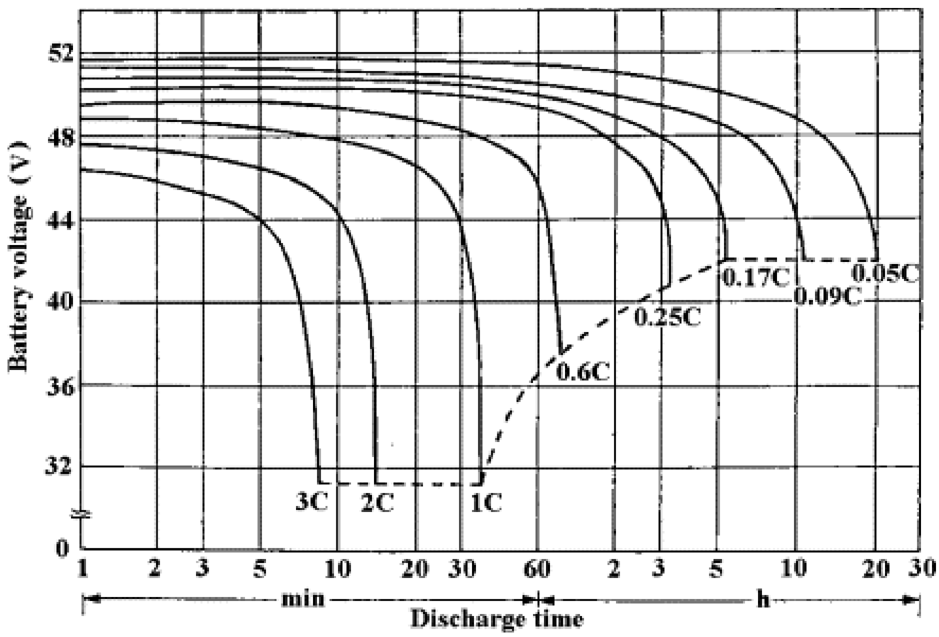


System of thermal energy accumulator in connection with nuclear power plant to store surpluses of thermal energy in off-peak periods (64)

B Lead-acid battery characteristics

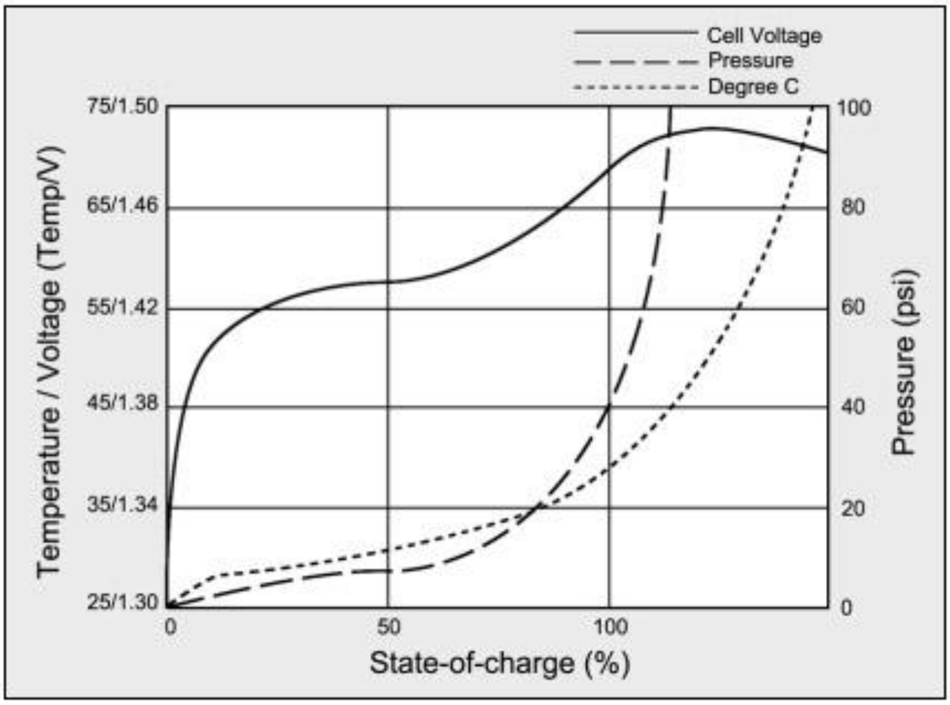


Charging characteristic of Lead-acid batteries (65)

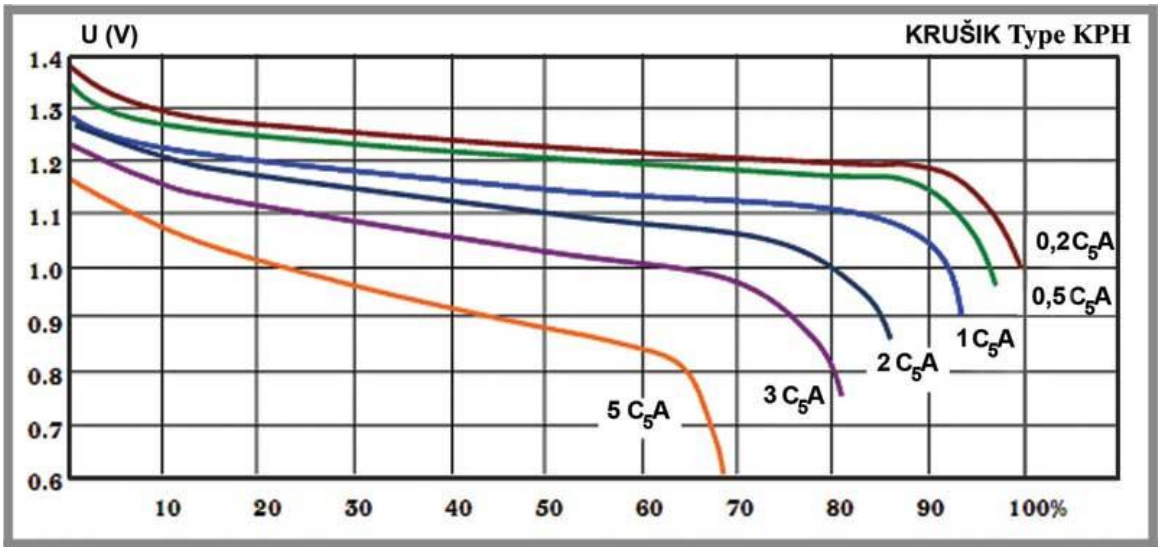


Discharging characteristic of Lead-acid batteries (66)

C NiCd battery characteristics

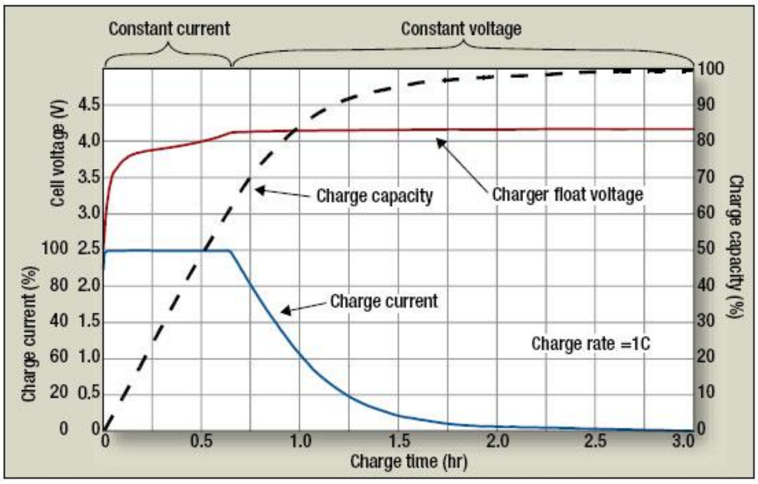


Charging characteristic of NiCd battery (67)

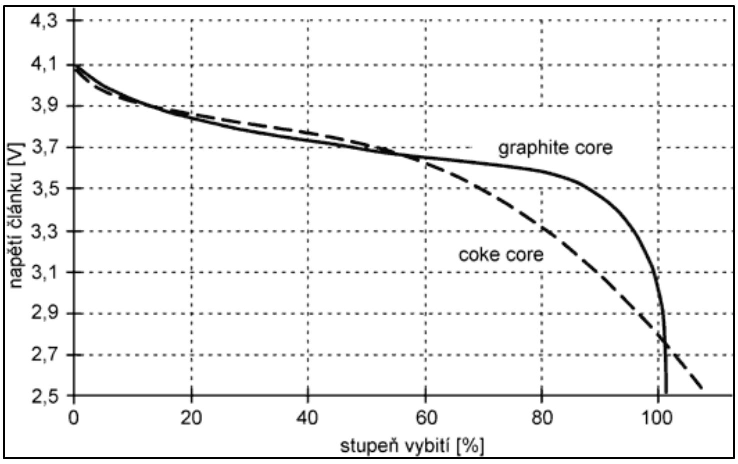


Discharging characteristic of NiCd battery (68)

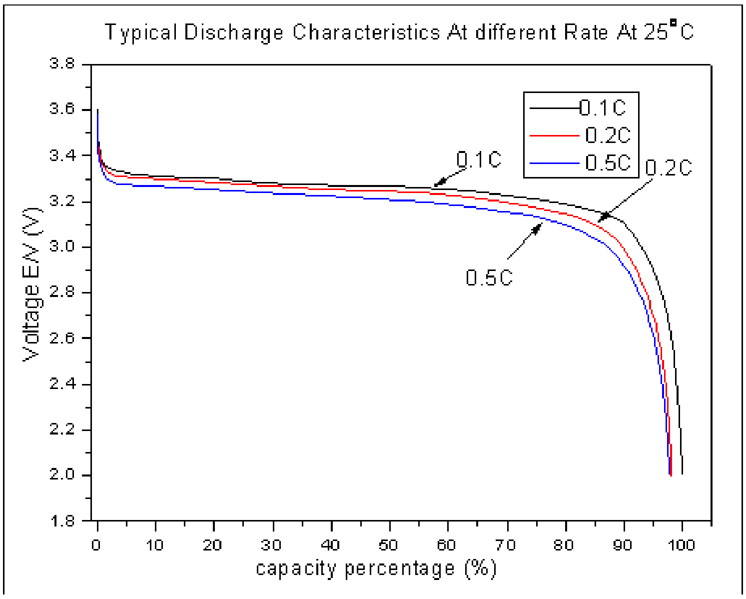
D Li-Ion battery characteristics



Charging characteristic of Li-Ion battery (69)

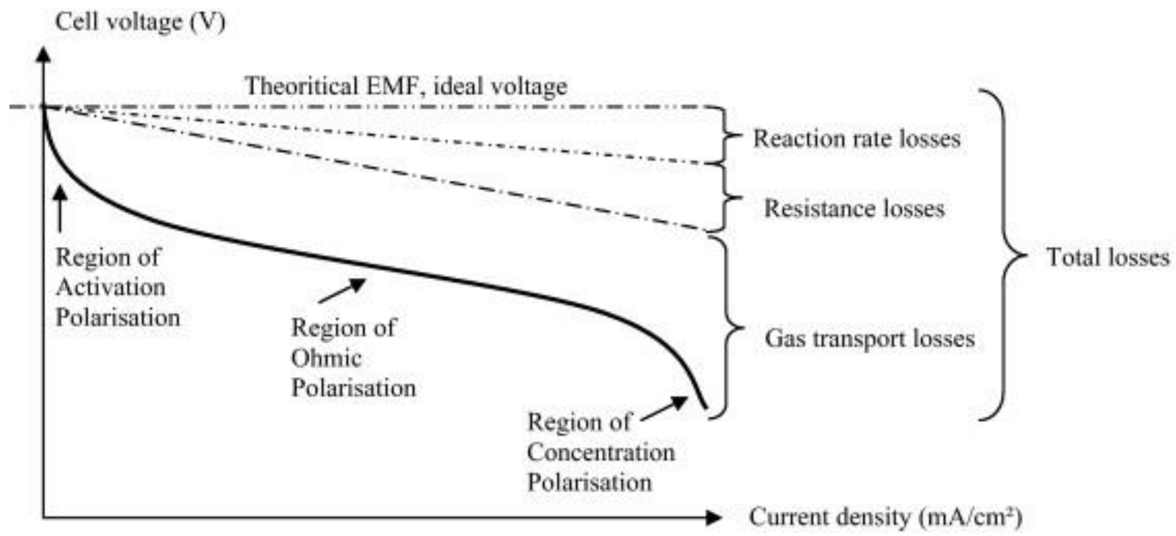


Discharge characteristic of Li-Ion battery (70)



Changing of discharge characteristic by using different current rate (71)

E Fuel cells characteristic



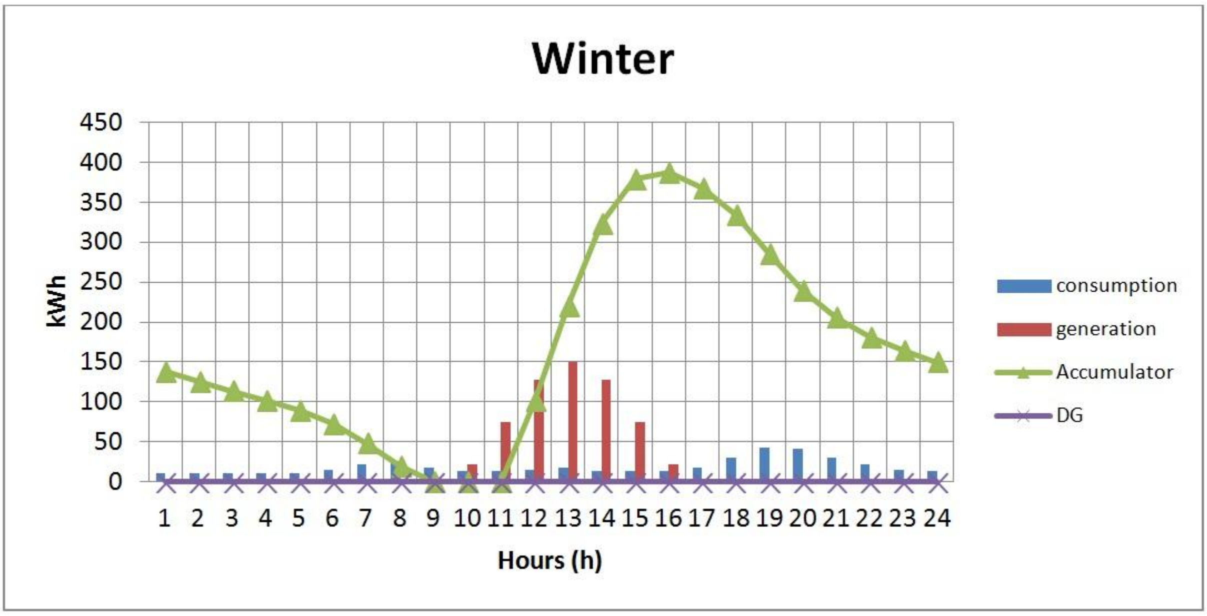
Characteristic of Fuel cell (72)

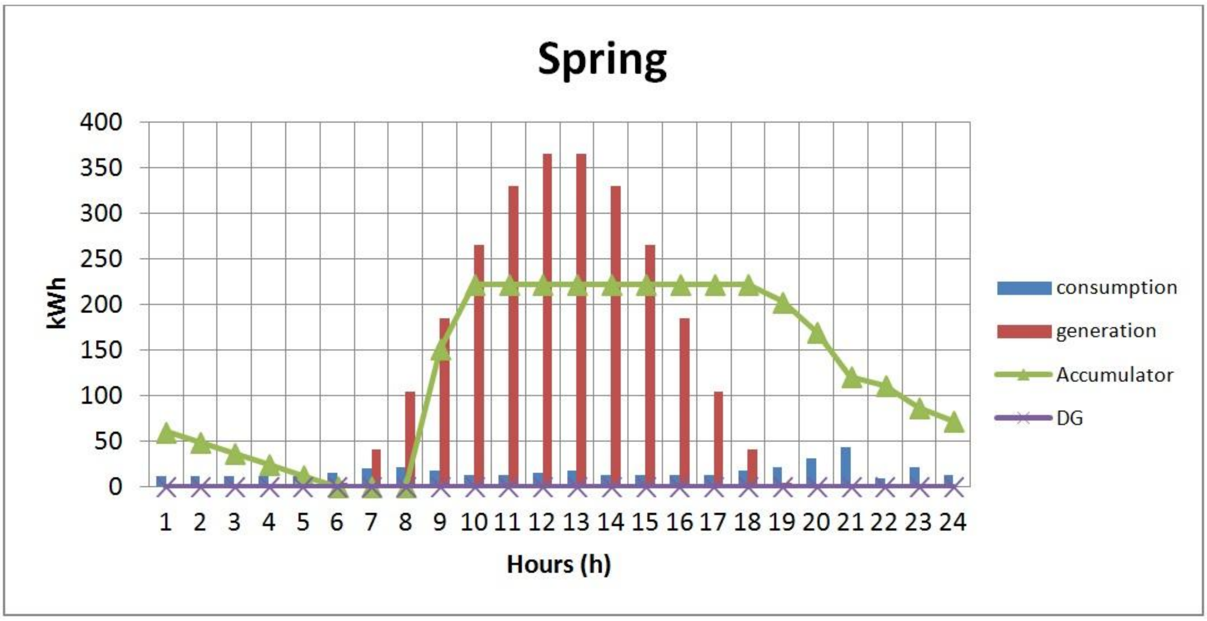
F Results of operating mode optimization

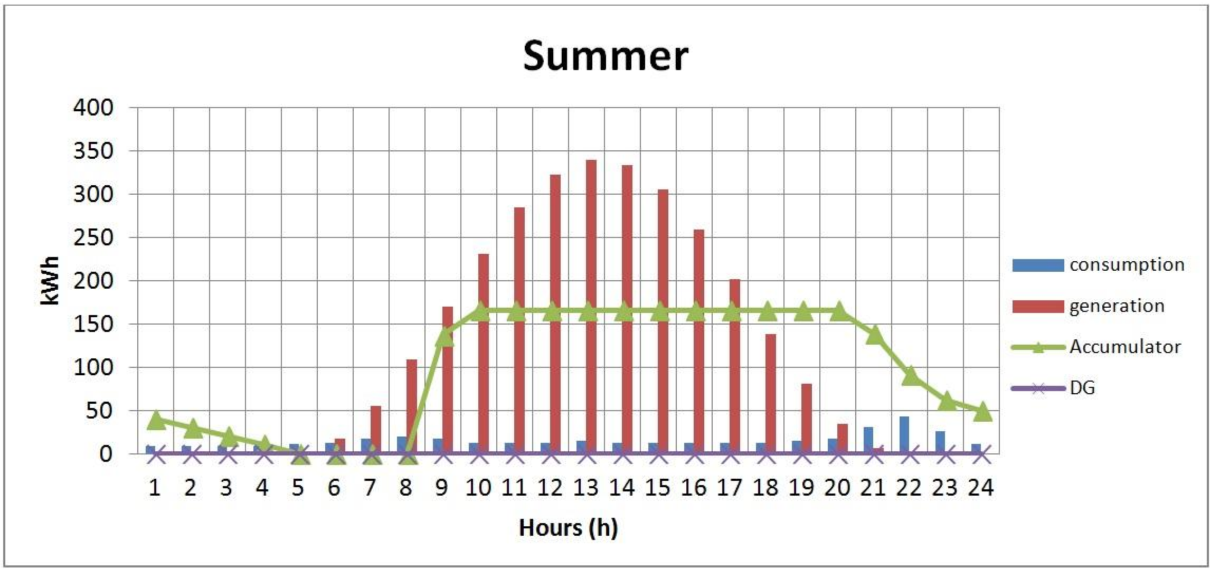
	NPV [€]	Installed capacity of accumulation [kWh]										
		0	**30**	**50**	**100**	**150**	**200**	**216,5**	**250**	**300**	**350**	**386,7**
Installed power of PV [kW]	**0**	**-712 638**	**-765 083**	**-799 017**	**-885 397**	**-971 777**	**-1 058 156**	**-1 085 921**	**-1 141 451**	**-1 227 830**	**-1 314 210**	**-1 375 910**
	65	**-867 507**	**-897 010**	**-930 945**	-1 017 324	-1 103 704	-1 190 083	-1 217 848	-1 273 378	-1 359 757	-1 446 137	-1 507 837
	130	-903 048	-921 171	-940 726	**-994 871**	**-1 050 219**	-1 129 226	-1 156 991	-1 212 521	-1 298 901	-1 385 280	-1 446 980
	156	-924 726	-944 531	-958 931	-1 011 058	-1 061 518	**-1 114 582**	**-1 133 495**	**-1 189 024**	**-1 275 404**	**-1 361 783**	**-1 423 483**
	195	-964 491	-979 329	-994 170	-1 031 865	-1 085 782	-1 135 045	-1 155 898	-1 200 127	-1 283 791	-1 370 171	-1 431 870
	260	-1 039 851	-1 053 534	-1 058 070	-1 096 339	-1 133 585	-1 184 246	-1 206 552	-1 251 009	-1 337 389	-1 423 768	-1 485 468
	325	-1 116 661	-1 130 344	-1 134 881	-1 165 052	-1 198 872	-1 239 015	-1 258 235	-1 301 983	-1 388 363	-1 474 742	-1 536 442
	390	-1 193 964	-1 203 961	-1 212 842	-1 235 699	-1 267 924	-1 310 103	-1 324 004	-1 361 662	-1 441 590	-1 527 969	-1 589 669
	455	-1 272 990	-1 282 987	-1 291 868	-1 314 724	-1 338 854	-1 382 297	-1 395 825	-1 435 772	-1 505 680	-1 582 784	-1 644 483
	520	-1 352 493	-1 362 795	-1 371 410	-1 394 532	-1 412 451	-1 451 773	-1 468 453	-1 509 576	-1 579 540	-1 657 453	-1 719 153
	585	-1 433 924	-1 444 177	-1 453 057	-1 476 180	-1 494 099	-1 525 715	-1 542 768	-1 583 805	-1 653 821	-1 729 216	-1 790 915
	650	-1 511 784	-1 526 381	-1 535 261	-1 558 384	-1 575 580	-1 602 946	-1 617 011	-1 658 057	-1 725 270	-1 804 208	-1 865 908
	715	-1 594 719	-1 609 316	-1 618 197	-1 641 319	-1 658 515	-1 686 416	-1 698 395	-1 732 788	-1 800 451	-1 879 616	-1 941 316
	780	-1 677 656	-1 692 254	-1 701 135	-1 724 258	-1 741 453	-1 769 887	-1 781 867	-1 809 409	-1 875 653	-1 955 045	-2 016 745
	845	-1 760 954	-1 775 179	-1 784 060	-1 806 451	-1 824 751	-1 853 357	-1 865 337	-1 893 077	-1 950 856	-2 030 474	-2 092 174
	910	-1 844 270	-1 858 495	-1 867 376	-1 889 768	-1 908 067	-1 936 827	-1 948 502	-1 976 745	-2 032 064	-2 105 882	-2 167 581
	975	-1 927 587	-1 941 812	-1 950 693	-1 973 085	-1 991 135	-2 020 299	-2 031 973	-2 060 413	-2 115 732	-2 181 310	-2 243 010
	1040	-2 010 904	-2 025 130	-2 034 010	-2 056 402	-2 074 453	-2 103 769	-2 115 444	-2 144 081	-2 199 400	-2 264 254	-2 318 439
	1069	-2 048 563	-2 062 787	-2 071 669	-2 094 061	-2 112 111	-2 141 497	-2 153 173	-2 181 899	-2 237 218	-2 302 175	-2 338 662

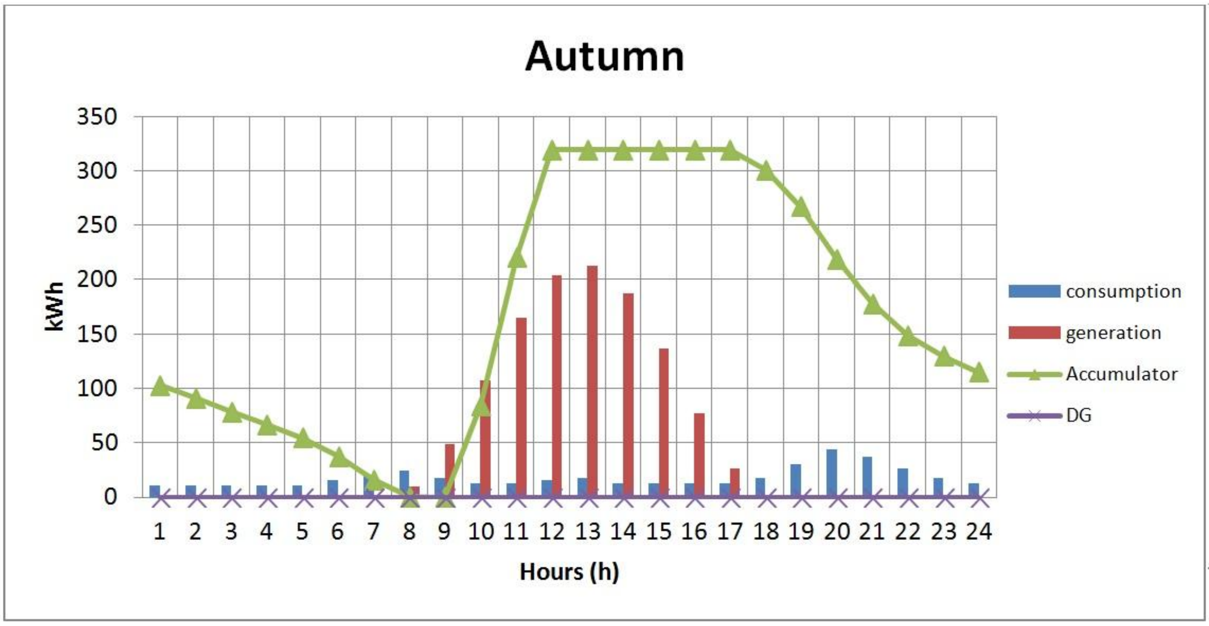
	DG generation [kWh]	Installed capacity of accumulation [kWh]										
		0	**30**	**50**	**100**	**150**	**200**	**216,5**	**250**	**300**	**350**	**386,7**
Installed power of PV [kW]	**0**	**149 958**	149 958	149 958	149 958	149 958	149 958	149 958	149 958	149 958	149 958	149 958
	65	115 458	110 633	110 633	110 633	110 633	110 633	110 633	110 633	110 633	110 633	110 633
	130	104 260	96 576	92 890	84 610	76 609	75 816	75 816	75 816	75 816	75 816	75 816
	156	102 307	93 899	88 949	80 104	71 824	63 609	**62 244**	62 244	62 244	62 244	62 244
	195	99 688	90 165	85 215	73 587	65 307	57 027	55 289	52 515	51 868	51 868	51 868
	260	97 536	87 681	81 111	68 564	56 189	48 193	46 827	44 153	44 153	44 153	44 153
	325	95 678	85 823	79 253	64 583	52 208	40 794	38 610	36 438	36 438	36 438	36 438
	390	94 122	84 267	77 697	61 272	48 524	37 492	34 775	30 363	28 751	28 751	28 751
	455	92 845	82 990	76 420	59 995	45 124	34 424	31 707	27 797	23 702	21 396	21 396
	520	91 774	81 919	75 349	58 924	42 499	31 561	28 843	25 231	21 136	19 033	19 033
	585	91 184	81 329	74 759	58 334	41 909	29 049	26 331	22 771	18 676	16 665	16 665
	650	90 741	80 886	74 316	57 891	41 466	27 393	23 886	20 377	16 282	14 330	14 330
	715	90 489	80 634	74 064	57 639	41 214	27 281	23 227	18 092	13 997	12 105	12 105
	780	90 238	80 383	73 813	57 388	40 963	27 170	23 116	16 997	11 717	9 885	9 885
	845	90 082	80 227	73 657	57 232	40 807	27 059	23 005	16 938	9 438	7 665	7 665
	910	89 930	80 075	73 505	57 080	40 655	26 948	22 894	16 878	8 733	5 439	5 439
	975	89 779	79 924	73 354	56 929	40 504	26 836	22 782	16 819	8 674	3 219	3 219
	1040	89 627	79 772	73 202	56 777	40 352	26 725	22 671	16 760	8 615	2 970	999
	1069	89 559	79 704	73 134	56 709	40 284	26 675	22 621	16 733	8 588	2 970	**0**

G Winter variant cycles

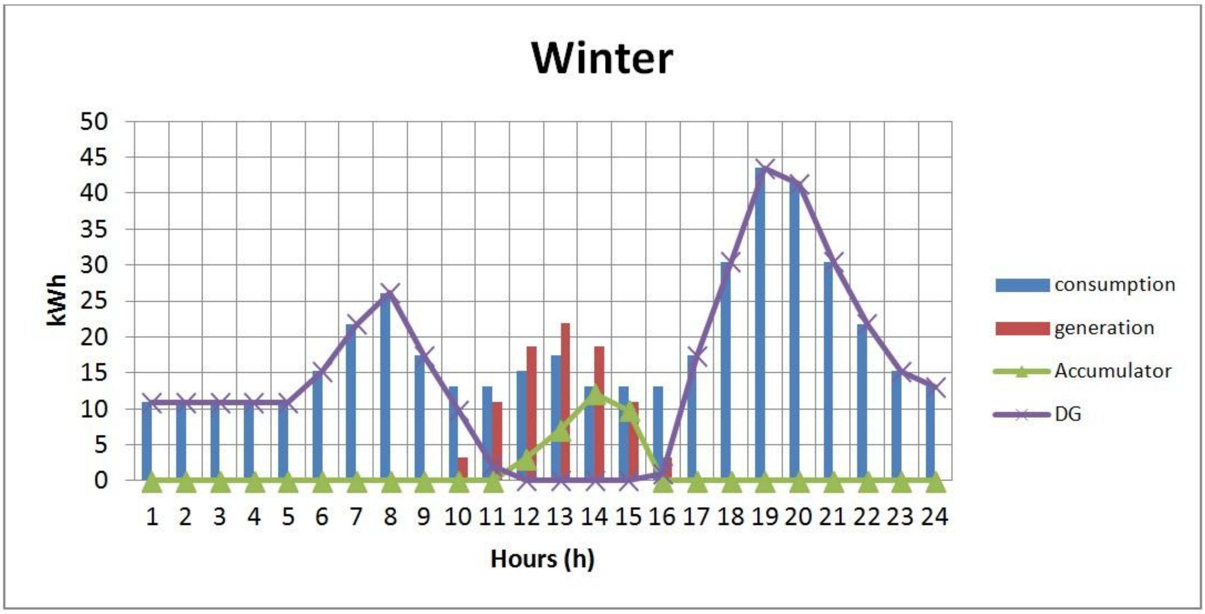


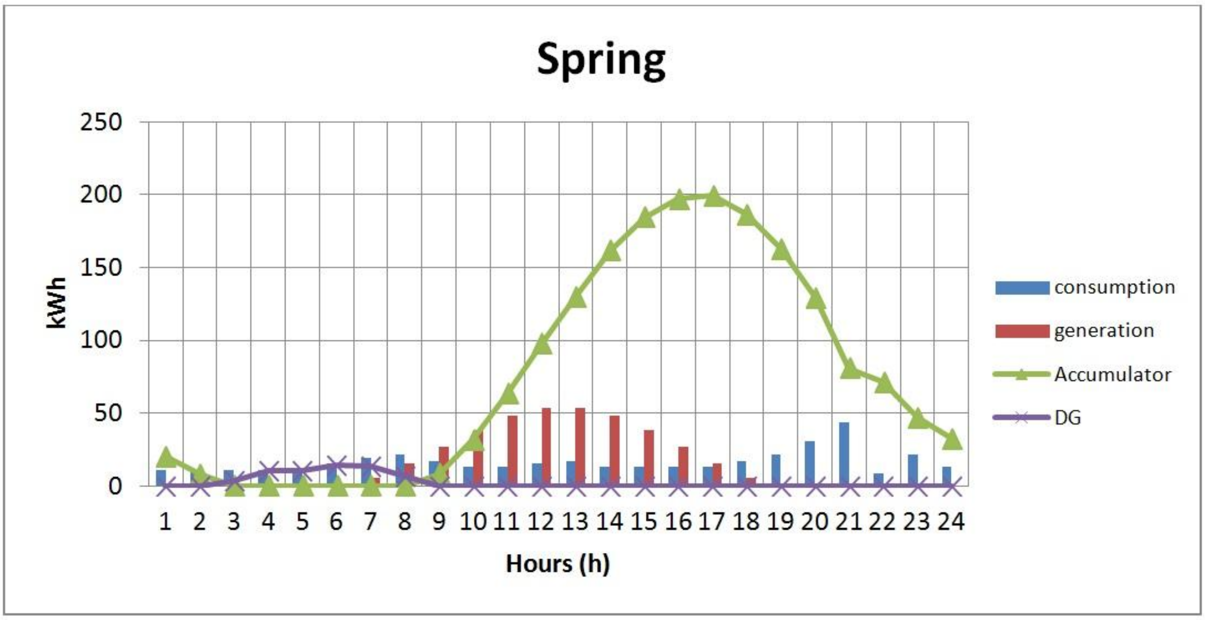


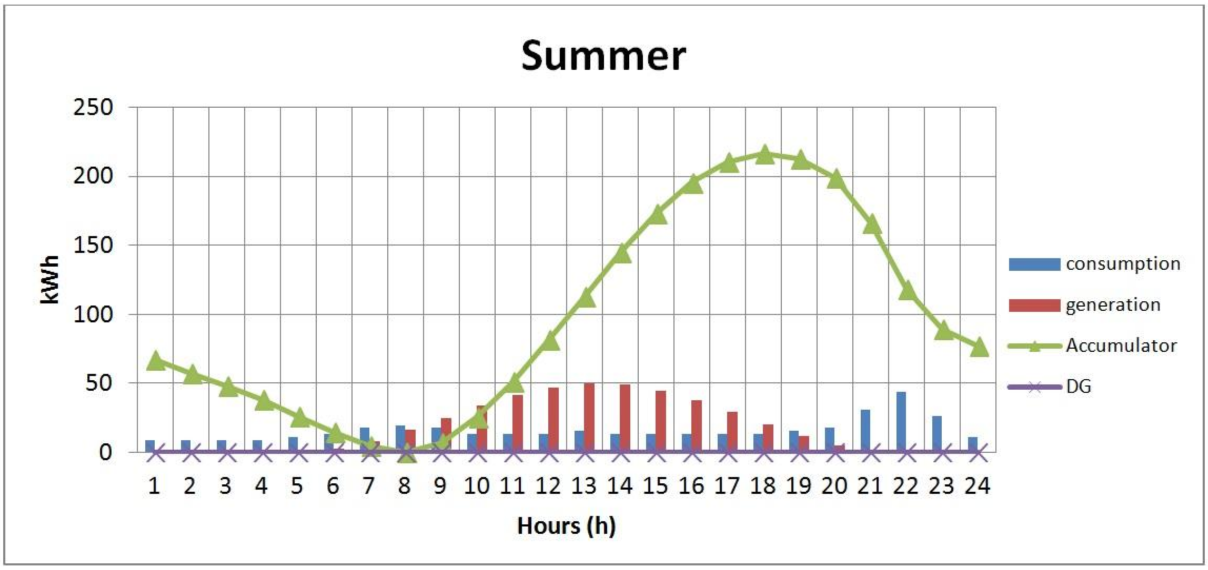

Summer
400
350
300
250
200
150
100
50
0
kWh
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours (h)
consumption
generation
Accumulator
DG


Autumn
350
300
250
200
150
100
50
0
kWh
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours (h)
consumption
generation
Accumulator
DG

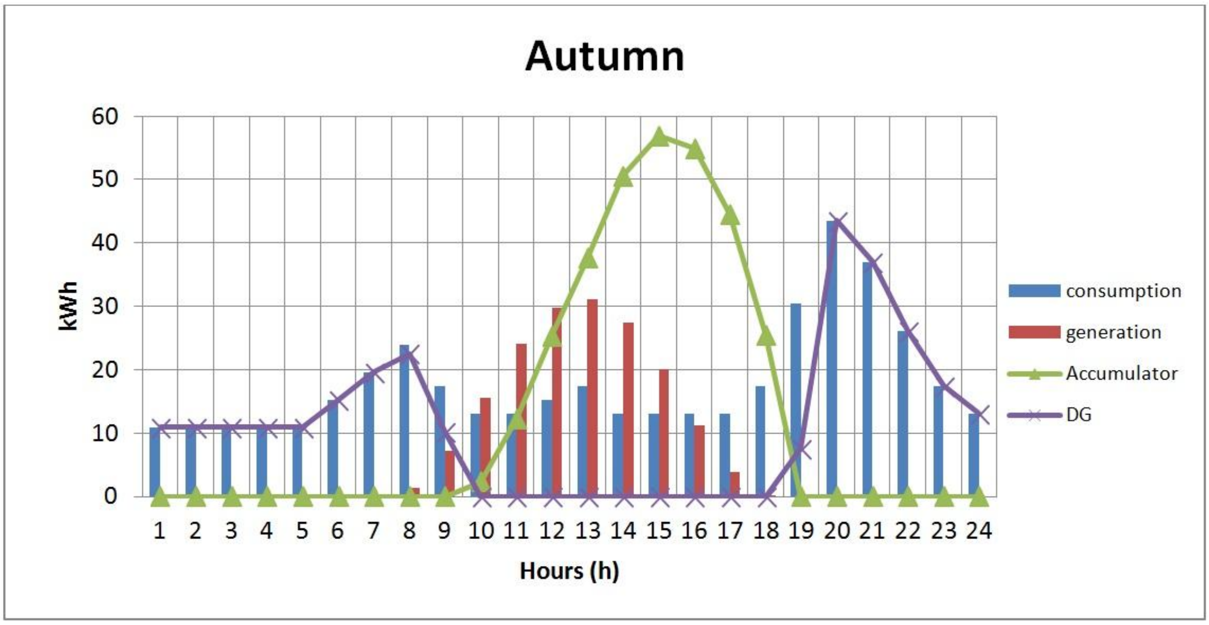
H Summer variant cycles





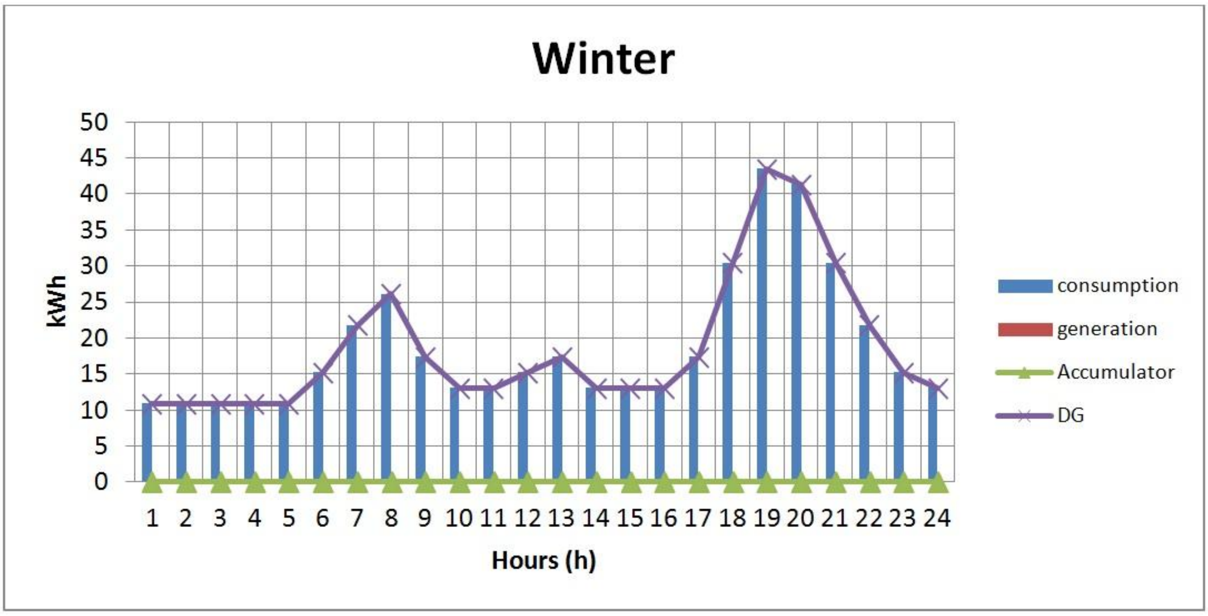


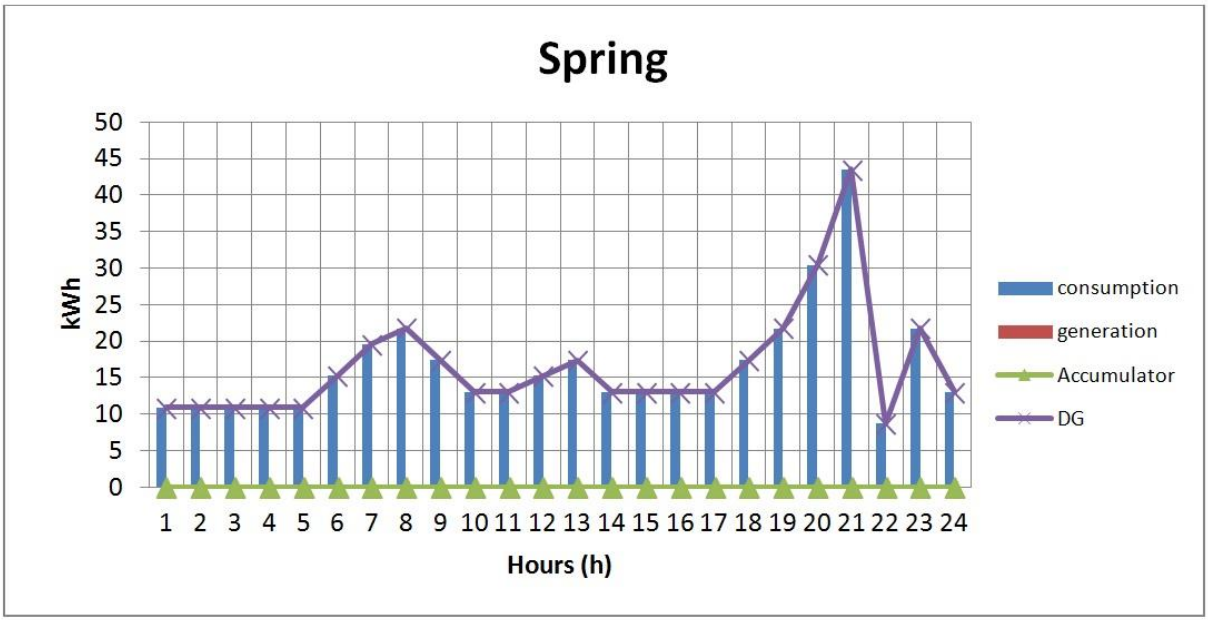
Summer
250
200
150
100
50
0
kWh
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours (h)
consumption
generation
Accumulator
DG

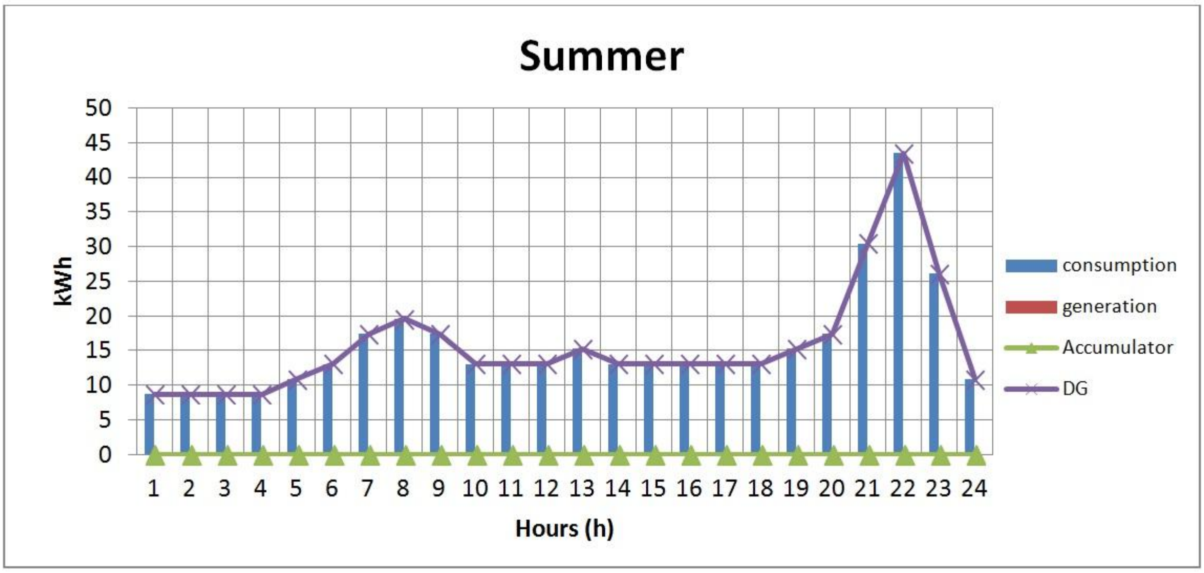


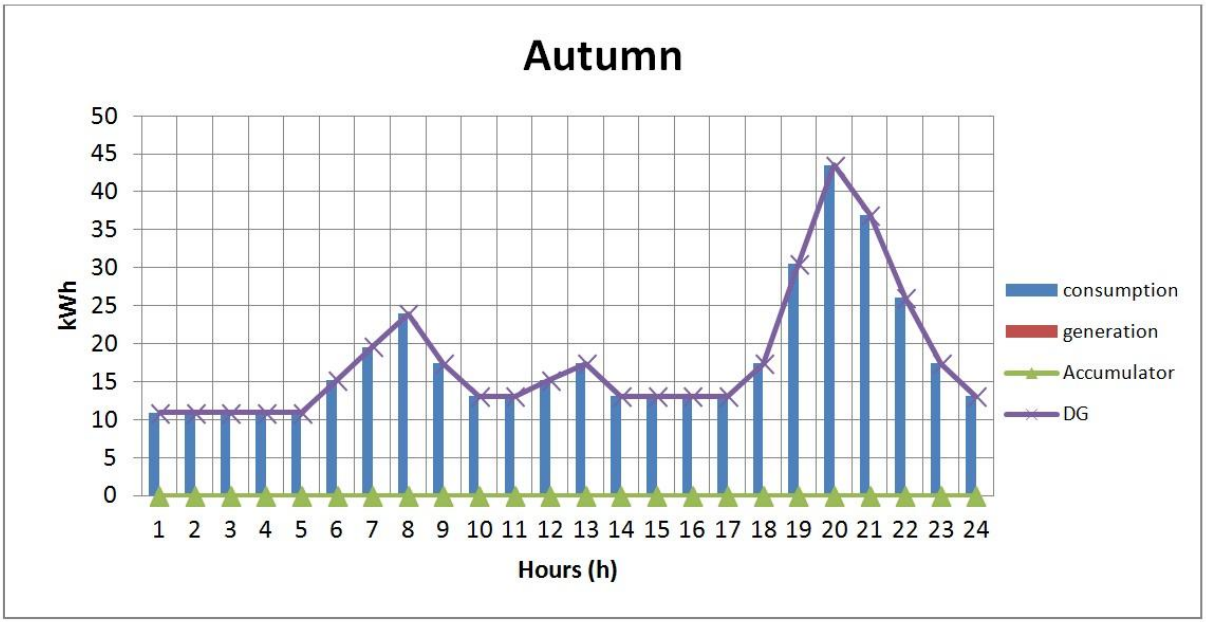
Autumn
60
50
40
30
20
10
0
kWh
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours (h)
consumption
generation
Accumulator
DG

I DG variant cycles






Summer
kWh
Hours (h)
consumption
generation
Accumulator
DG
0
5
10
15
20
25
30
35
40
45
50
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24


Autumn
kWh
Hours (h)
consumption
generation
Accumulator
DG
0
5
10
15
20
25
30
35
40
45
50
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

J Example of system model calculations in Excel

Technical calculation of accumulation

					Accumulator state				
Hours	**Consumption**	**Total gen.**	**Undersupply/hour**	**Oversupply/hour**	**0,000**	**DG power/hour**	**DG in work**	**Cumul. undersupply**	**For fixed capacity**
12	15,225	18,65549446	0	3,430494457	3,087445011	0	0	413,30	216,5
13	17,4	21,85627128	0	4,45627128	7,098089164	0	0	413,30	216,5
14	13,05	18,65549446	0	5,605494457	12,14303418	0	0	413,30	216,5
15	13,05	10,92813564	2,12186436	0	9,785407109	0	0	411,00	216,5
16	13,05	3,200776823	9,849223177	0	0	1,042356779	1	400,00	216,5
17	17,4	0	17,4	0	0	17,4	1	380,70	216,5
18	30,45	0	30,45	0	0	30,45	1	346,90	216,5
19	43,5	0	43,5	0	0	43,5	1	298,50	216,5
20	41,325	0	41,325	0	0	41,325	1	252,60	216,5
21	30,45	0	30,45	0	0	30,45	1	218,80	216,5
22	21,75	0	21,75	0	0	21,75	1	194,60	194,6
23	15,225	0	15,225	0	0	15,225	1	177,70	177,7
24	13,05	0	13,05	0	0	13,05	1	163,20	163,2
1	10,875	0	10,875	0	0	10,875	1	151,10	151,1
2	10,875	0	10,875	0	0	10,875	1	139,00	139
3	10,875	0	10,875	0	0	10,875	1	126,90	126,9
4	10,875	0	10,875	0	0	10,875	1	114,90	114,9
5	10,875	0	10,875	0	0	10,875	1	102,80	102,8
6	15,225	0	15,225	0	0	15,225	1	85,90	85,9
7	21,75	0	21,75	0	0	21,75	1	61,70	61,7
8	26,1	0	26,1	0	0	26,1	1	32,70	32,7
9	17,4	0	17,4	0	0	17,4	1	13,40	13,4
10	13,05	3,200776823	9,849223177	0	0	9,849223177	1	2,40	2,4
11	13,05	10,92813564	2,12186436	0	0	2,12186436	1	0,00	0
	445,875	**87,42508512**		0		**361,0134443**	**20**		
				Max	**12,14303418**	**43,5**	kW		
					Losses	**2,563529437**	kWh		

Economic calculation of NPV

Years	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Year of project	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Production	149 957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55	149957,55
Discounted production	149 957,55	140 147,24	130 978,73	122 410,03	114 401,90	106 917,66	99 923,05	93 386,03	87 276,66	81 566,97	76 230,81	71 243,75	66 582,95	62 227,05	58 156,12	54 351,52	50 795,81	47 472,72	44 367,03	41 464,51	38 751,88
Revenues	25 379,89	27917,8751	30709,6626	33780,6288	37158,6917	40874,5609	44962,017	49458,2187	54404,0406	59844,4446	65828,8891	72411,778	79652,9558	87618,2514	96380,0765	106018,084	116619,893	128281,882	141110,07	155221,077	170743,185
Investment																					
Project documentation	-7 000,00																				
Photovoltaic panels	-174 290,00																				
Electric and control syst	-60 000,00																				
Converters	-44 656,30																				
Accumulators	-36 972,22																				
Diesel generator	-12 000,00																				
Construction and transp	-30 000,00																				
Operating costs																					
Fuel costs		-12 863,42	-13 635,23	-14 453,34	-15 320,54	-16 239,77	-17 214,16	-18 247,01	-19 341,83	-20 502,34	-21 732,48	-23 036,43	-24 418,62	-25 883,73	-27 436,76	-29 082,96	-30 827,94	-32 677,62	-34 638,27	-36 716,57	-38 919,56
Repairs and service		-5000	-5250	-5512,5	-5788,125	-6077,5313	-6381,4078	-6700,4782	-7035,5021	-7387,2772	-7756,6411	-8144,4731	-8551,6968	-8979,2816	-9428,2457	-9899,658	-10394,641	-10914,373	-11460,092	-12033,096	-12634,751
Operation		-2 000,00	-2 100,00	-2 205,00	-2 315,25	-2 431,01	-2 552,56	-2 680,19	-2 814,20	-2 954,91	-3 102,66	-3 257,79	-3 420,68	-3 591,71	-3 771,30	-3 959,86	-4 157,86	-4 365,75	-4 584,04	-4 813,24	-5 053,90
Insurance		-3649,1852	-3831,6445	-4023,2267	-4224,388	-4435,6074	-4657,3878	-4890,2572	-5134,7701	-5391,5086	-5661,084	-5944,1382	-6241,3451	-6553,4124	-6881,083	-7225,1371	-7586,394	-7965,7137	-8363,9994	-8782,1993	-9221,3093
Transport of fuel		-1 089,27	-1 143,73	-1 200,92	-1 260,97	-1 324,01	-1 390,22	-1 459,73	-1 532,71	-1 609,35	-1 689,82	-1 774,31	-1 863,02	-1 956,17	-2 053,98	-2 156,68	-2 264,51	-2 377,74	-2 496,63	-2 621,46	-2 752,53
Recovery																					
Accumulators		0,00	-36 972,22	-36 972,22	0,00	-36 972,22	-36 972,22	0,00	-36 972,22	-36 972,22	0,00	-36 972,22	-36 972,22	0,00	-36 972,22	-36 972,22	-36 972,22	0,00	-36 972,22	-36 972,22	0,00
Diesel generator		0,00	0,00	0,00	0,00	0,00	0,00	-12 000,00	0,00	0,00	0,00	0,00	0,00	0,00	-12 000,00	0,00	0,00	0,00	0,00	0,00	0,00
Convertor		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-44 656,30	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
CF with revenues	-339 538,64	3 316,00	-32 223,17	-30 586,58	8 249,42	-26 605,60	-24 205,94	3 480,56	-18 427,20	-14 973,16	25 886,21	-51 373,88	-1 814,62	40 653,94	-2 163,51	16 721,56	24 416,32	69 980,69	42 594,82	53 282,29	102 161,13
CF only costs	-364 918,52	-24 601,88	-62 932,83	-64 367,21	-28 909,27	-67 480,16	-69 167,96	-45 977,66	-72 831,24	-74 817,61	-39 942,68	-123 785,66	-81 467,58	-46 964,31	-98 543,59	-89 296,52	-92 203,57	-58 301,19	-98 515,25	-101 938,78	-68 582,06
DCF	-364 918,52	-22 992,41	-54 967,97	-52 542,82	-22 054,74	-48 112,42	-46 089,53	-28 632,58	-42 388,44	-40 695,82	-20 304,83	-58 809,68	-36 172,58	-19 488,52	-38 216,90	-32 365,17	-31 232,54	-18 456,66	-29 147,11	-28 186,92	-17 722,91
NPV only costs	-1 053 499,08	€																			
NPV with revenues	-340 861,30	€																			

Contents of enclosed CD

- Diploma thesis - Accumulation of electricity.doc - contain the main text of the thesis
- Diploma thesis - Accumulation of electricity.pdf - contain the main text of the thesis
- Diploma thesis - System model.xlsx - contain tables, graphs and all calculations