CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

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POWER SUPPLY OF DECENTRALIZED HOUSEHOLD IN KAZAKHSTAN VIA PHOTOVOLTAIC SYSTEM

MASTER'S THESIS

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Declaration

I hereby declare that I have done this thesis entitled “POWER SUPPLY OF DECENTRALIZED HOUSEHOLD IN KAZAKHSTAN VIA PHOTOVOLTAIC SYSTEM” independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague 06.08.2021.

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Abstract

The practical part of the present research was focused on the design proposal of an off-grid photovoltaic system for the power supply of a decentralized household located in the South of Kazakhstan. To make a design of such kind of technical solution, a methodology was presented.

Firstly, the current situation related to solar energy in Kazakhstan was reviewed. It was found that climatic conditions, as well as the level of solar irradiation, are favourable for the implementation of the technology for the power supply of both: urban and rural areas. This fact promotes the rapid development of energy generated by photovoltaics on large-scale and small-scale levels.

The proposed power supply system was designed taking into account such inputs as electrical loads, energy demand through the year, level of solar irradiation. Due to the location of the model household remotely from the electrical grid, an off-grid photovoltaic system with battery bank and diesel generator were proposed. It was found that in conditions of Kazakhstan for autonomous power supply in rural areas, hybrid photovoltaic systems are effective from both technical and economical points of view. It is confirmed by the conducted economic analysis using such investment criteria as net present value, internal rate of return, payback period and profitability index. In addition, comparative analysis for an alternative scenario and sensitivity analysis were conducted.

The scientific contribution of the work is in the proposed universal methodology for the design of such kinds of projects. The universality of the methodology lies in the fact that it is applicable not only to the local conditions of Kazakhstan, but also to other countries, which can contribute to the sustainable energy development.

Key words: renewable energy, solar energy, photovoltaic modules, PV system, off-grid, hybrid system

Contents

List of Tables

List of Figures

List of the abbreviations and symbols

SDG – sustainable development goals

UN – United Nations

PV – photovoltaic

RES – renewable energy sources

TPP – thermal power plants

PVOUT – photovoltaic power output

GHI – global horizontal irradiance

AC – alternating current

DC – direct current

A – ampere

V – volt

W – watt

kWh – kilowatt-hour

kWp – kilowatt-peak

MW – megawatt

W/m^2 – watt per square metre

PVC – polyvinyl chloride

UV – ultraviolet

°C – degree Celsius

m – meter

m^2 – square meter

EU – European Union

UNECE – United Nations Economic Commission for Europe

Ah – ampere hour

CAPM – Capital Asset Pricing Model

L – litre

MU – monetary units

Ω – Ohm

1. Introduction

In 2015 United Nations (UN) General Assembly presented 17 sustainable development goals (SDG) [1]. This list includes goal "SDG7" on energy, which invokes for "ensure access to affordable, reliable, sustainable and modern energy for all" [2]. Energy is a driving force for global development and therefore implementation of this goal will create a huge number of possibilities for people around the world. New job places, schools, hospitals, industry, and in the end economic growth will arise with the help of energy sources.

According to the UN [2] 17% of total consumed energy was generated by renewable sources in 2017. The amount of energy generated by green technologies is rising year by year. Kazakhstan is not an exception and due to the vastness of its territory and diversity of climatic conditions from severe North to warm South, different types of renewable energy sources are implemented. The installed capacity of solar power plants in 2020 was 891.6 MW which is the largest amount among all types of renewable energy sources (RES) in Kazakhstan [3].

The technology of extracting energy from the Sun is quite simple. All that is required for successful implementation of the technology are special equipment and a favorable number of solar days. Due to the direct dependence of solar power plants on the energy of the Sun, the technology will not have the same efficiency in all parts of the world [4]. Solar energy is inexhaustible and safe and represents a great solution for both urban and rural areas [5]. The main disadvantages of modern PV technology are in relatively low efficiency which is in range from 15 to 22% [6] and storability of accumulator batteries for power supply during the periods of low insolation [5].

This Master's Thesis aims to design a power supply system based on PV technology for households in a selected area of Kazakhstan. In addition, part of the goal is to evaluate the project from a financial point of view to present its profitability.

2. Literature review

2.1. Solar energy sector of Kazakhstan

Electricity production in Kazakhstan is carried out by 179 power plants of various forms of ownership. As of 01.01.2021, the total installed capacity of power plants in Kazakhstan is 23,621.6 MW, and the available capacity is 20,078.6 MW [7].

The major part of Kazakhstan’s electricity generation is covered by using coal, thanks to rich reserves of this fuel on the territory of the Republic. For the first 9 months of the year 2020, about 80% of the total electricity generation was realized by thermal power plants (TPP). However, a substantial part of the existing TPP was built in soviet times and already reached 40 years of maintenance [8]. That leads to the low efficiency which today is 27% for average coal power plant [9]. This fact in line with the ambitions of the first president of the Republic pushed him to issue a Concept for the transition of the Republic of Kazakhstan to a "green economy" in 2013 [10] and Concept for the development of the fuel and energy complex of the Republic of Kazakhstan until 2030 in 2014 [11].

The aforementioned programs set standards and plans for the development of the whole energy system of the country, including RES. According to the plan [10], by 2020 share of renewables in the total electricity generation should be 3%, which is already achieved [8], and by 2030 it should be 30%. This number looks perkily because even European Union (EU) has a plan of 32% share of RES by 2030 [12]. Therefore, in 2018 during United Nations Economic Commission for Europe (UNECE) Renewable Energy Hard Talks [13], plan was changed to 10% of RES by 2030.

Table 1 shows the distribution of renewable energy generation by its type. As we can see, the largest part of generated "green" energy is solar energy. Moreover, with the support of the state due to tax incentives and the inclusion of RES in the list of priority investment projects, this number will be only increased [14]. Speaking about small-scale private photovoltaic (PV) systems, direct subsidies as a support are provided to stand-alone renewable plants. The mechanism covers up to 50% of the investment costs, provided if the equipment was manufactured in Kazakhstan. However, today the local equipment manufacturing industry is in its infancy, and the purchase of local equipment may be unprofitable due to the high cost [15].

Table 1. Renewable electric-power production in Kazakhstan [3]

Indicators	**Units**	**For 9 months of 2020**
Installed capacity including:	MW	**1,528.5**
Wind turbines	MW	404.40
Small-scale hydro power plants	MW	224.69
Solar power plants	MW	891.61
Biofuel power plants	MW	7.82
Electric-power production including:	mln. kWh	**2,377.9**
Wind turbines	mln. kWh	742.16
Small-scale hydro power plants	mln. kWh	586.24
Solar power plants	mln. kWh	1,045.05
Biofuel power plants	mln. kWh	4.5
Share of generated electricity by RES in the total volume of electric-power production	%	3.05
The increase in electricity generation by renewable energy facilities for 9 months of 2020 compared to the same period in 2019 is - 69%		

2.2. Solar energy potential of Kazakhstan

Solar energy potential is the criteria for sizing the PV system [16]. The sun emits solar radiation to the Earth. Diffused radiation is scattered by particles in the atmosphere. Direct radiation in turn to diffused is the one that comes directly from the sun without any barriers. Reflected radiation comes to the surface and then gets reflected by it. Irradiance (with units $W/m^{2)}$ is the intensity of solar radiation per unit of time on a unit of surface area. Insolation (with units $Wh/m^2/day$) is the total energy received from the sun in a day on a unit of surface area [17].

The potential of solar energy in Kazakhstan is about 2.5 billion kWh per year, and the number of hours of sunshine per year is estimated at 2,200-3,000 out of 8,760 [10]. Figure 1 represents the specific yield or how much energy in kWh can be generated by a 1 kWp capacity PV system. Photovoltaic power potential (PVOUT) is a practical potential output considering all important factors, namely: the theoretical potential represented by global horizontal irradiance (GHI), the ambient temperature, the system configuration type, shading and soiling, and topography of the area [18].

According to presented data, the major part of the country allows achieving a high level of output, especially in Southern regions as Kyzylorda, Turkistan, Zhambyl, and Almaty. However Central and Northern regions are also effective for PV technology implementation. Thus in 2020 in the Northern Akmola region, the 100 MW solar PV power plant was built which is one of the biggest within the Commonwealth of Independent States [19].

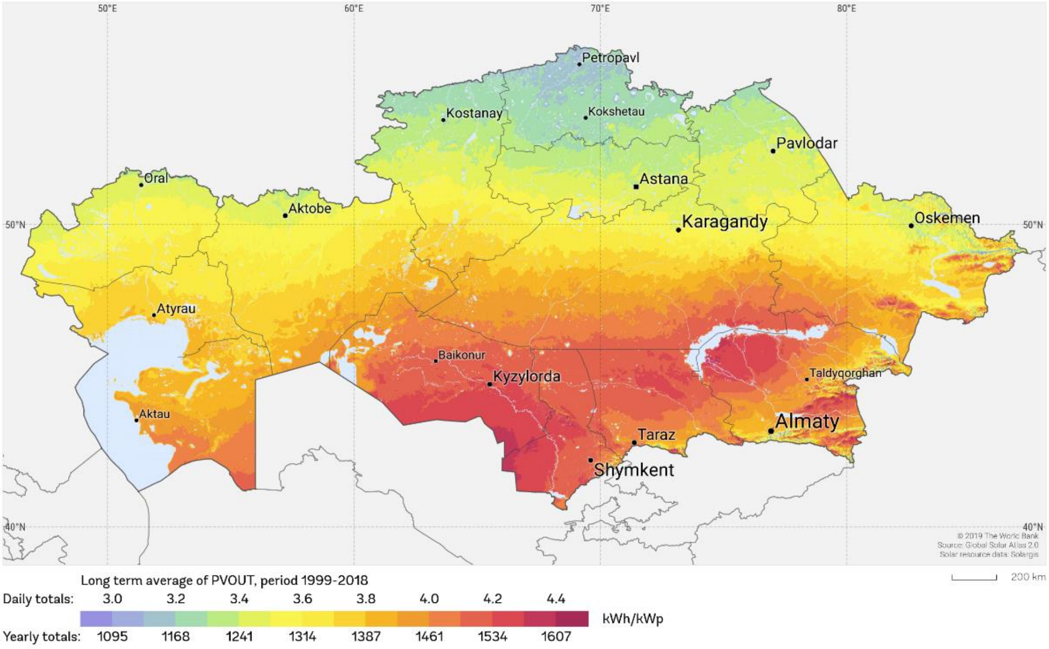


Figure 1. Photovoltaic power potential map of Kazakhstan [18]

However, not all territory is suitable for PV systems installation due to constraints as forests, rugged terrains, urban or industrial areas, nature conservation, etc. According to Global solar atlas factsheet about Kazakhstan [20], around 43.3% of unoccupied territory is suitable for PV systems. Following Table 2 shows the daily distribution of PVOUT in this suitable area. In accordance with Table 2, the highest share of the suitable territory allows obtaining output in a range from 3.6 to 3.4 kWh/kWp/day.

Table 2. Distribution of PVOUT within the suitable area of Kazakhstan [20]

PVOUT [kWh/kWp/day]	Suitable area [43.3% of total area]
over 4.2	1.7%
4.2 – 4.0	6.8%
4.0 – 3.8	8.9%
3.8 – 3.6	9.7%
3.6 – 3.4	12.6%
3.4 – 3.2	3.4%
below 3.2	0.2%

2.3. Solar PV system and its components

In this chapter, a description of the PV system for power supply of decentralized area is presented.

2.3.1. Solar PV system

A solar photovoltaic system is a combination of equipment for converting light energy of the sun into electrical energy and its transmission to the consumer. Such systems could be as small-scale rooftop mounted structures with a capacity of few kilowatts, as large power stations of hundreds of megawatts [21]. Besides PV systems could be classified depending on the end-use application, namely: grid-connected and off-grid systems. The main difference between them is in the presence or absence of connection to the power grid [22]. In accordance with the topic of this work, an off-grid system is used for the design proposal and is described in more detail in the following subchapter.

2.3.1.1. Off-grid hybrid solar PV system

Off-grid (or stand-alone) solar PV systems are commonly used for power supply in cases, when the central power grid is far away, like in rural areas. In contradistinction to grid-connected systems, such a system requires accumulator batteries for power supply during periods of low solar activity, for example during the night [21]. Moreover, if an uninterrupted power supply is required, an additional source of electricity, like a fuel-powered generator is used and such a configuration is called a hybrid PV system [22]. Following Figure 2 shows how typical off-grid hybrid PV system looks like:

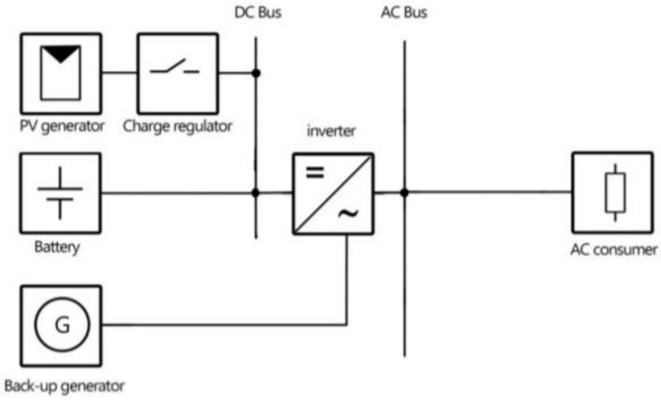


Figure 2. Layout of an off-grid hybrid PV system [22]

2.3.2. Solar PV modules

The basic element of the solar module is a solar cell [4]. A solar cell is a semiconductor device that converts solar light energy into direct current (DC) electricity by photovoltaic effect [4]. In order to increase their utility, cells are connected into the structure which is called the PV module. Then again, in order to obtain the desired level of current and voltage modules are connected into strings and arrays [23]. This is more clearly demonstrated in the following Figure 3:

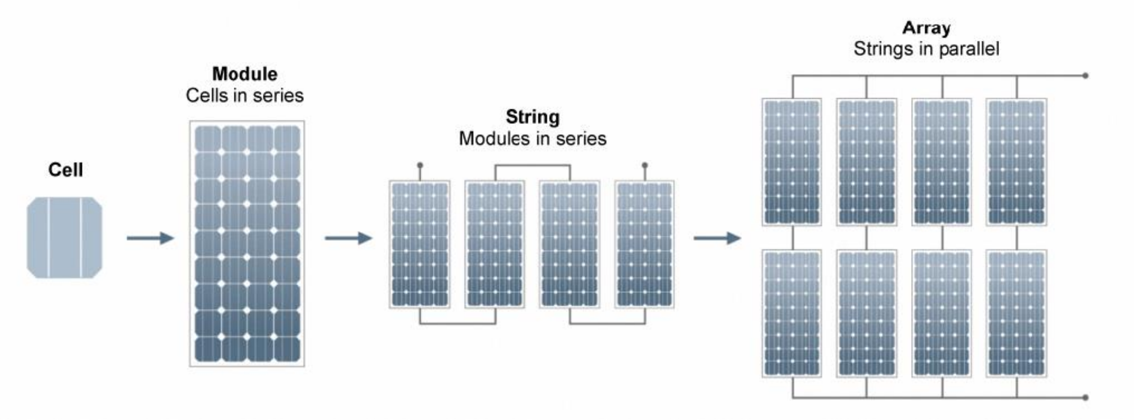


Figure 3. Solar cell, module, string, and array [23]

At the moment there are many types of solar modules on the market. They vary in their efficiency, appearance, and purpose. There are three types of modules that are dominant on the market: monocrystalline, polycrystalline, and thin-film [24]. Figure 4 demonstrates the share of different types of PV modules technology.

Each type of solar module has its advantages and disadvantages and the decision of which type to use depends on the project goal. In case when there is no area constraint, it is possible to install polycrystalline modules with lower efficiency. If the area is limited and the maximum output is required, it is better to use more expensive monocrystalline modules with higher efficiency. In case when modules to be installed on the roof that cannot withstand additional weight, light thin-film modules are a solution [25].

However, there is not much sense to use thin-film modules for residential needs because of their low efficiency [25]. Therefore for this Thesis’s design proposal mono and polycristalline types are considered. In the following subchapters, they are described in more details.

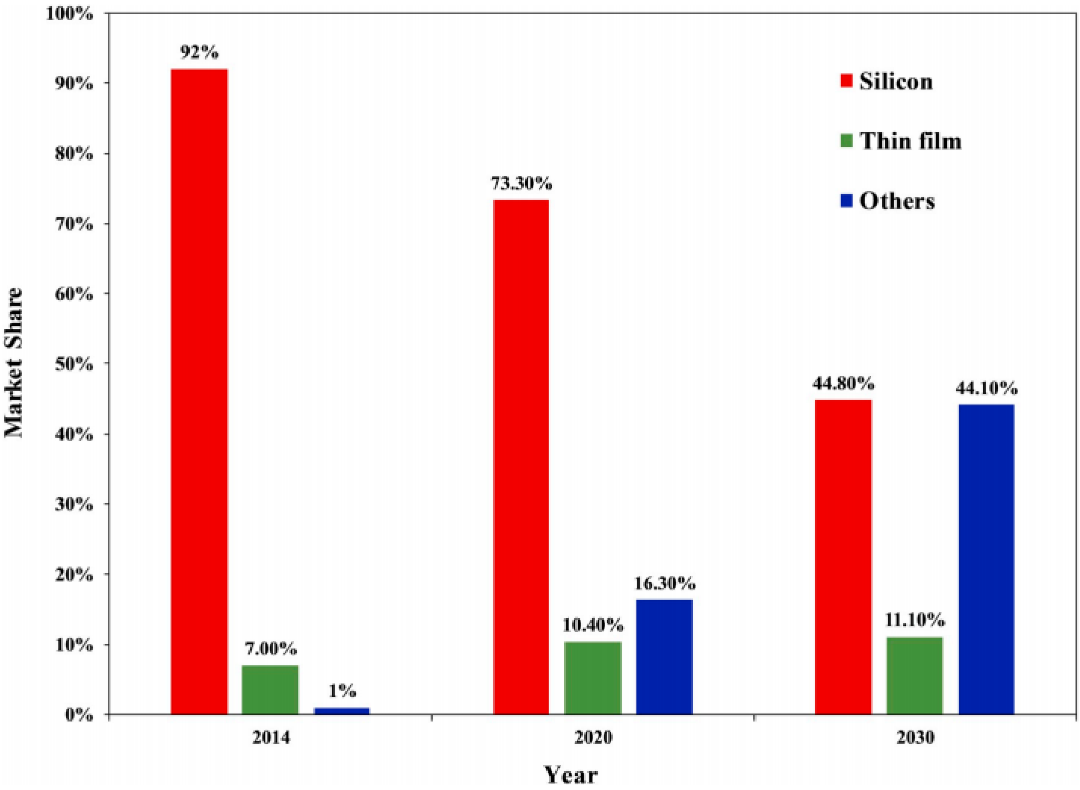


Figure 4. Market share of PV modules by technology type [24]

2.3.2.1. Monocrystalline PV modules

According to Barbose and Naïm [26] monocrystalline type of PV modules is most commonly used for residential solar installations.

This type of modules performs with the highest efficiency among commercially used up to 22.6% [27]. Such efficiency caused by the purest structure due to the manufacturing method called the Czochralski process. This method implies the growth of a single solid silicon crystal. Because the monocrystalline solar cell is made of a single crystal of silicon, the flow of electrons through the cell is better and therefore efficiency is higher [28]. Higher efficiency means that it is required a smaller number of solar modules and therefore less space to provide desirable output [26].

Another feature of this type of modules is its color and shape which is shown in the following Figure 5:

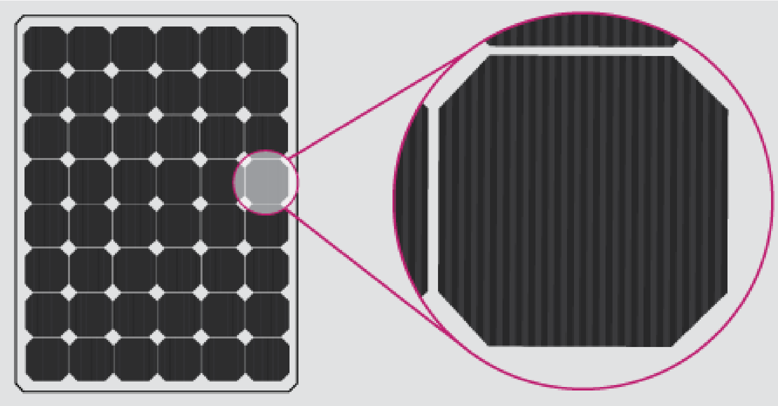


Figure 5. Monocrystalline solar cell [25]

2.3.2.2. Polycrystalline PV modules

A characteristic feature of polycrystalline PV modules is their bluish color (see Figure 6). It is due to the reflection of the sun from silicon fragments which are not uniform as in monocrystalline type [25].

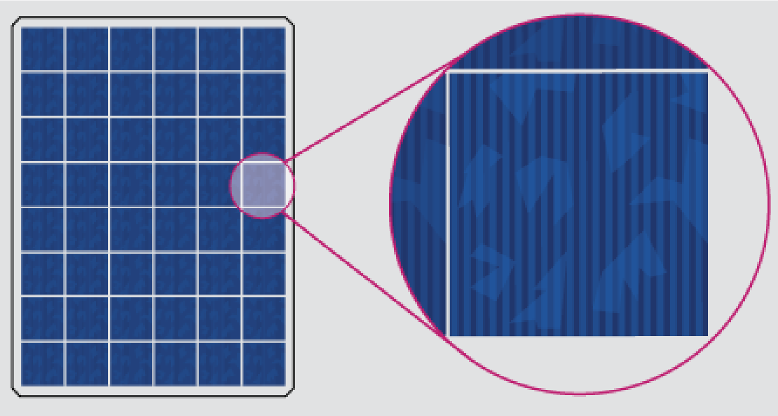


Figure 6. Polycrystalline solar cell [25]

The technological process of manufacturing PV modules from fragments of silicon is easier and that leads to the fact that polycrystalline PV modules tend to be cheaper than monocrystalline [29]. That is why such type of modules is widely used among small-scale PV systems for power supply of private households [25]. However, due to the recombination loss which occurs at the grain boundaries, the efficiency of such models is lower and is around 15-19.5% [29].

2.3.3. Mounting structures

PV mounting system or solar module racking system is a complex of actions and equipment used for installation and fixing of PV modules on the buildings, roofs, or on the ground. Choosing of relevant mounting structure for PV systems depends on several factors, such as features of the terrain and relief, required output and installed power, cost, lifespan, climatic conditions [30].

Roof mounting (see Figure 7) is the most common option for small-scale private PV systems [31]. The PV modules as an array are mounted in parallel with the surface of a roof with a several inches gap between them for cooling purposes. In case when the surface of the roof is flat, an additional structure for angle change is mounted in order to achieve optimal angle. The optimal angle is the tilt angle of PV modules perpendicular to fallen solar rays. It is necessary to take into consideration an additional weight laying on the roof caused by PV modules [31].

Figure 7. Roof PV mounting system [32]

Another option is the installation of PV modules on the ground. However, for small-scale systems, the fixed structures are usually implemented, while for large-scale projects tracking axis systems are preferable. Fixed structures do not allow to change orientation or tilt angle after installation. Such structures require lower investments but output, in turn, will not be optimum because of the different positions of the sun during the day. Solar tracking systems in turn are expensive but allow to obtain higher output. A tracking system allows the panels to follow the movement of the sun and therefore increases the time in direct sunlight which causes higher energy generation [33].

There are three main types of solar tracking systems: manual, passive and active. Manual trackers are needed to be manually adjusted in accordance with the sun location. Passive trackers contain liquid with a low boiling temperature which evaporates when affected by sunrays. This evaporation creates an imbalance that leads to the moving of PV modules towards the sun. Active trackers are driven by motors [33].

Another common classification of trackers is by the number of degrees of freedom, namely single-axis solar trackers and dual-axis solar tracker. Horizontal single-axis trackers (see Figure 8) keep the optimal tilt angle of the modules when the sun moves from east to west [34].

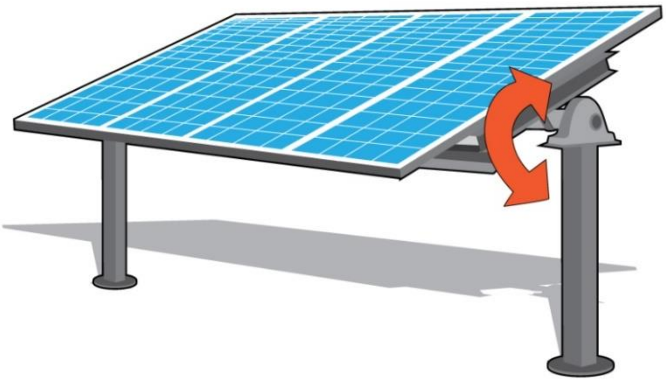


Figure 8. Horizontal single-axis solar tracker [34]

Dual-axis trackers (Figure 9) in turn able to follow the sun movement from East to West and from North to South. Thus, dual-axis trackers allow to obtain even higher boost of production, but on the other hand it makes the system more expensive with shorter lifespan due to the many moving parts [35].

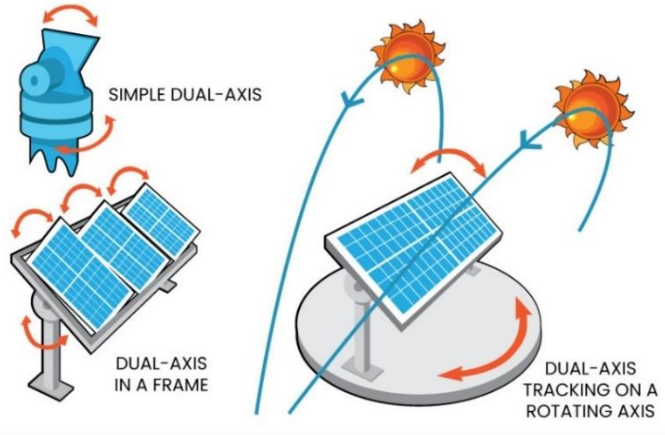


Figure 9. Dual-axis solar trackers [35]

Increase in energy generation for single-axis systems is in a range from 25% to 35% and for dual-axis systems it is 40% [33]. Following graph (Figure 10) represents increase in energy generation of tracking systems in comparison to fixed systems:

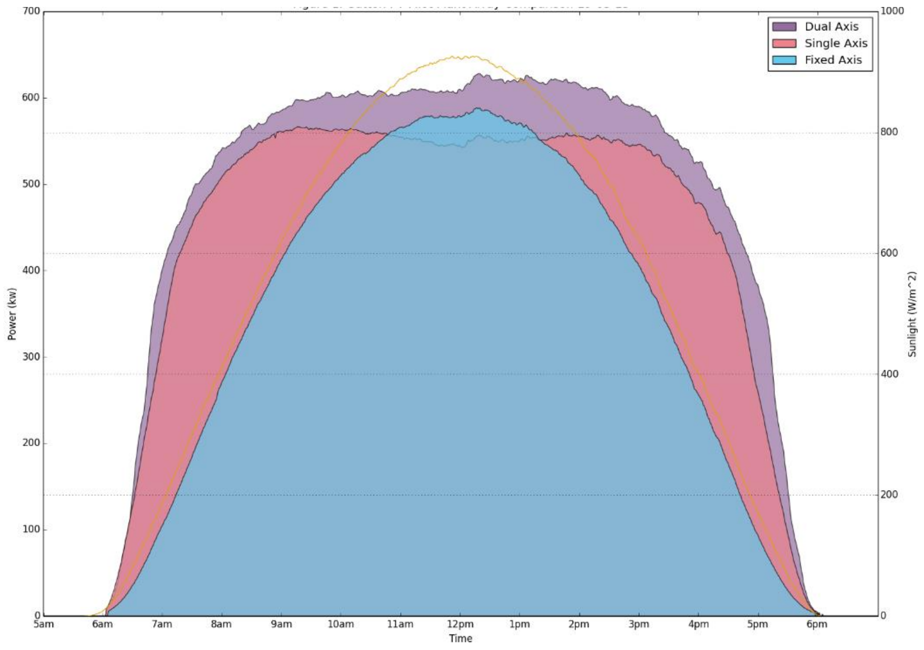


Figure 10. Daily power production using different mounting structures [36]

2.3.4. Solar charge controller

Off-grid PV system usually includes accumulator-batteries for power reserve. In order to provide charging of batteries, a solar charge controller is used. Its main function is to regulate voltage and current going from PV modules to the batteries in order to provide correct charging and prevent discharging and overcharging thereby increasing the batteries life span [37].

Solar charge controllers or solar regulators as they are also known, are rated in accordance with maximum charge current and maximum input voltage. These variables determine how many PV modules could be controlled [37].

There are two main types of controllers in accordance with applying technology: pulse-width modulation (PWM) and maximum power point tracking (MPPT). Although PWM type is much cheaper, MPPT is more advanced and performs with higher efficiency [38].

2.3.5. Inverters

Inverter is the device main function of which is to convert the DC voltage generated by PV panels into alternating current (AC) voltage. There is also special type of inverters called Bi-directional inverter which is a "bridge" between AC power generator and battery bank. Inverters are classified depending on configuration of PV system. For small-scale off-grid PV systems the most common types are [39]:

- Module integrated inverters, usually for 1 PV module (50-400 W)
- String inverters, usually for small roof-top systems of 1 string (0.4-2 kW)
- Multistring inverters, usually for medium roof-top systems (1.5-6 kW)

The structure of module integrated inverter and string inverter is illustrated below in the Figure 11.

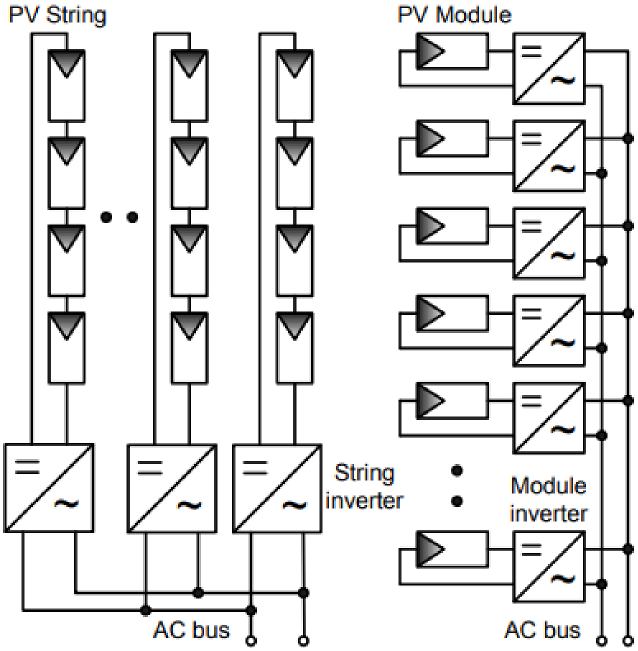


Figure 11. Structure of string inverter (left) and module integrated inverter (right) [40]

PV system could be divided into several parallel strings. Each string is connected to corresponding inverter which is called "string inverter". Such inverters usually contain controller and are capable to separate MPPT of each string what increases the energy yield. Inverters with higher values of input power are called "multistring" and they are capable to be connected to several strings of PV modules [40].

2.3.6. Battery bank

Accumulator batteries in PV system play role of a reserve source of power during periods of lack of energy generation by PV modules. Such periods are the nighttime or cloudy climatic conditions with low level of irradiance [41]. During the day batteries charged by PV modules and then used on demand. A complex of connected accumulator batteries is called battery bank [42]. There are two possible types of connecting batteries between each other: in parallel and in series. Connecting in parallel increase voltage level of the bank keeping capacity constant, while in series connecting increases total capacity at constant voltage level [43].

2.3.7. Auxiliary energy source

In hybrid off-grid PV system usually an additional auxiliary power source is implemented. It could be used as for direct power supply of appliances, as for charging of accumulator batteries. Usually, auxiliary device is fossil fuel generator sets fuelled by diesel, gasoline, bio-diesel, propane or natural gas and supplying AC power. In addition to backup function, sometimes such generators are used as complementary devices working continuously together with PV modules or as a primary energy source where PV modules serve for saving of fuel [43]. According to the standard [44] there are 4 main regimes of generators in PV system (see Table 3).

It is recommended not to fully charge battery bank via auxiliary generator but up to 85%-90% and the remaining part is better to be charged by PV modules. The reasons are and fuel and energy economy [45].

For remote areas the most common type of auxiliary generators is AC diesel generator because of the following characteristics and advantages [46]:

- Low capital costs
- Reliability
- Quick start and loading
- Efficiency
- Simple operation and maintenance
- High energy density of fuel
- Quick installation

Table 3. Generator’s operation regimes [44]

	Emergency standby power (ESP)	Limited time running power (LTP)	Prime running power (PRP)	Continuous operating power (COP)
Maximum usage	200 h/year	500 h/year (300 h continuous)	Continuous	Continuous
Average output power (24 h)	70% rated power	70% rated power	70% rated power	80 – 100% rated power
Overload availability	No	No	No	No
Ability to operate in parallel applications	No	No	Yes	Yes

2.3.8. DC and AC cables

Once all necessary equipment of PV system is known, connecting conductors (wires and cables) should be calculated. There are several types of circuits in PV system. They could differ in type of the current (AC or DC), voltage and current levels, length and environmental exposure. Circuits have special requirements for sizing their conductors and overcurrent protection [47]. Figure 12 shows wiring diagram of an off-grid PV system with diesel generator.

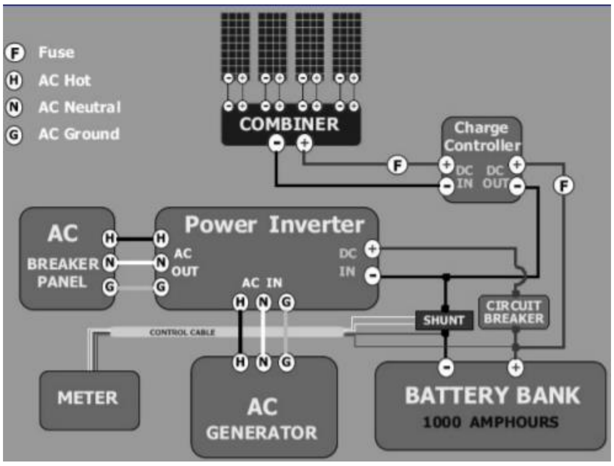


Figure 12. Off-grid PV system wiring diagram [48]

When current goes through the conductor, some amount of voltage is lost due to a conductor resistance. Loss of voltage means loss of power. Resistance increases with the length and therefore length of conductor should be minimized in order to decrease system loses and cost [48]. Resistance in turn decreases when the diameter of the cable increases. Value of current is in direct ratio to the voltage drop, thus with decreasing current level the voltage drop also decreases. Wires and cables conductor’s materials are copper or aluminium. Acceptable voltage drop of cables on DC side which connect PV modules with accumulator batteries is 3%. As it was described voltage drop is determined by the following parameters [22]:

- Length of cable
- Current on cable
- Size (diameter) of cable
- Material of cable

Wires differs in number of conductors in them (solid or stranded) and in insulation type (bare or insulated). Indoor wires usually have polyvinyl chloride (PVC) insulation, while outdoor wires should have special sustainable to ultraviolet (UV) light wires with UV insulation [17].

3. Aims of the Thesis

3.1. Main objective

The main objective of the Thesis was to create a design proposal of a power supply system for the household located in rural area of Kazakhstan. Power supply was to be carried out via photovoltaic technology.

3.2. Specific objectives

Achieving of the main objective was supported and supplemented by specific objectives such as:

- assessment of the potential of using solar panels in different regions of Kazakhstan;
- description of the current situation in solar energy sector of Kazakhstan;
- evaluation of the design proposal from the economic point of view.

4. Methodology

4.1. Design of an off-grid PV power supply system

In this chapter the step-by-step solution for technological proposal of the off-grid PV system for power supply of model small crop farm with a small garden plots is presented. Exact location of the farm and other necessary inputs will be described in the following subchapters.

Main criteria for a design of PV system are as follows [49]:

- daily average load demand
- power demand
- system voltage
- availability of other power sources

Main parameters of PV system are as follows [49]:

- energy supply strategy (ways of energy supply)
- DC or AC type of loads
- number of days of autonomous work
- size of solar array
- size of battery bank
- ratings of system's components

4.1.1. Site identification

Initial step in design of PV system is identification of the site area. It is very important because at various spots on Earth we observe different level of solar irradiance, type of meteorology and landscape conditions and therefore obtain different output [50].

Chosen case object of power supply is a small-scale farm located in remote area of Zhambyl region, Kazakhstan (see Figure 13). Decision was made firstly, taking into account information presented in the Chapter 2.2., namely high level of solar irradiation and PVOUT. Secondly, in Zhambyl region was built the biggest in Central Asia PV solar power plant which was awarded by the European Bank for Reconstruction and Development as the best project in the category "Sustainable development" in 2016 [51].

Thirdly, Southern regions of Kazakhstan have favorable climatic conditions for farming activities.

Figure 13. Location of the farm [52]

In reality chosen area is a grassland with herbaceous cover and without any buildings (see Figure 14), but for realization of proposed design it is assumed that here is located small-scale farm with small garden plots. It has no connection with power grid and therefore is suitable for off-grid PV system.

Figure 14. Aerial view of the farm area [53]

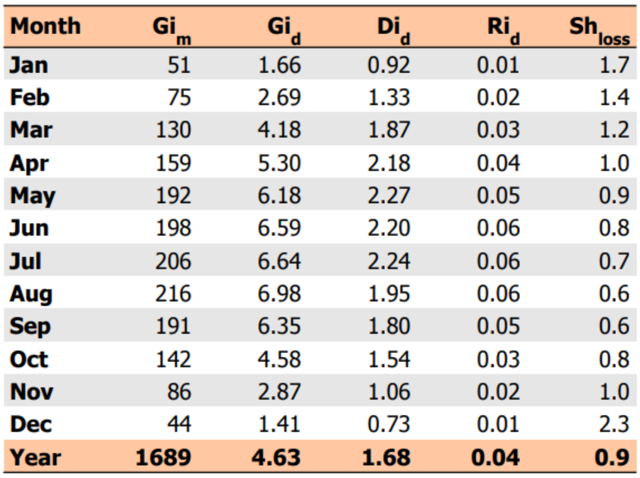
Following Table 4 describes parameters of chosen area:

Table 4. Parameters of the studied area [53]

Latitude and longitude	42° 53' 23", 72° 32' 30"
Altitude	830 m
Length (North-South)	40 m
Width (West-East)	40 m
Area	1,600 m^2

According to SOLARGIS report [54] surface of the area is uniform with insignificant slope of 4° to the North which allows to install land mounted structures. Average temperature in July is 23.7°C and in January is -5.4°C. Optimum inclination angle of PV modules is 31° with orientation on South. Following Table 5 shows several types of irradiation specific to the chosen area which affect PV system output with respect to the optimal inclination angle:

Table 5. Global in-plane irradiation [54]



Month	Gi_m	Gi_d	Di_d	Ri_d	Sh_{loss}
Jan	51	1.66	0.92	0.01	1.7
Feb	75	2.69	1.33	0.02	1.4
Mar	130	4.18	1.87	0.03	1.2
Apr	159	5.30	2.18	0.04	1.0
May	192	6.18	2.27	0.05	0.9
Jun	198	6.59	2.20	0.06	0.8
Jul	206	6.64	2.24	0.06	0.7
Aug	216	6.98	1.95	0.06	0.6
Sep	191	6.35	1.80	0.05	0.6
Oct	142	4.58	1.54	0.03	0.8
Nov	86	2.87	1.06	0.02	1.0
Dec	44	1.41	0.73	0.01	2.3
Year	**1689**	**4.63**	**1.68**	**0.04**	**0.9**

where

Gi_m – monthly sum of global irradiation [kWh/m^2];

Gi_d – daily sum of global irradiation [kWh/m^2];

Di_d – daily sum of diffuse irradiation [kWh/m^2];

Ri_d – daily sum of reflected irradiation [kWh/m^2];

Sh_{loss} – losses of global irradiation by terrain shading [%].

For further calculations the most important parameter is Gi_d.

4.1.2. Load and voltage level

In a design of the off-grid PV systems the energy demand data is not less important than data about solar resource availability. It is necessary to know power consumption in order to provide required power generation without an excess because off-grid systems cannot sell excess of energy into the grid [43]. In order to evaluate energy demand of a household the list of typical appliances and devices with their rated power and hours of use is created.

Studied farm model consists of two main parts: farmer house and small garden plots. All the appliances assumed to be AC type. Following Table 6 shows the total daily energy consumption of all farm's appliances:

Table 6. Loads of used appliances. Calculated based on [55]

Electrical appliance	Power (W)	Hours of use (h/day)	Energy demand (Wh/day)	Non-irrigation period energy demand (Wh/day)
Lighting	39	8	312	312
Laptop	100	4	400	400
Fridge	130	12	1,560	1,560
Air conditioner/heater	475	7	3,325	3,325
Oven	1,000	2	2,000	2,000
Pump	1,100	4	4,400	-
Total	**2,844**		**11,997**	**7,597**

PV system voltage level is determined in accordance with power demand [56] and following Table 7:

Table 7. Off-grid PV system voltage [57]

Power demand (W)	Energy demand (Wh)	Inverter and controller input voltage (V)
<1,500	<1,000	12
1,500-5,000	1,000-3,000	24 or 48
>5,000	>3,000	48 or 120

The more system's power is, the more system's voltage should be taken to reduce losses and cost of wires and cables [56]. For proposed design 48V voltage level is chosen. Then, the full load (P_{full}) of the system is found as follows:

$$P_{full} = \frac{\mathrm{W}}{U}, [Ah/day]$$

where

W – total daily energy demand [Wh/day];

U – system's voltage level [V].

For further design proposal two important assumptions are made:

1. Pump is used only during irrigation period from May to August.
2. Energy demand for non-irigating months is constant.

4.1.3. Battery bank sizing

In off-grid PV system generated energy could not always be fully used because demand does not always equal to supply. And vice versa, sometimes generation of PV modules reduced due to weather conditions and demand could not be covered. Therefore, energy should be stored in battery bank. Number of days of autonomy for proposed design is assumed to be equal to 2 due to generator's fail possibility.

Total capacity of a battery bank (C) is calculated as follows [56]:

$$C = \frac{P_{full} \cdot d}{k_d \cdot k_t}, [Ah]$$

where

P_{full} – full load of the system [Ah/day];

d – number of days of automomy;

k_d – depth of discharge of the battery;

k_t – temperature coefficient of the battery

After determination of total capacity of battery bank, number of batteries is to be calculated [56]. Taking into account information stated in the Chapter 2.3.6, number of batteries connected in parallel (N_{par}) is calculated as follows [56]:

$$N_{par} = \frac{\mathrm{C}}{C_{nom}}$$

where

C – total capacity of a battery bank [Ah];

C_{nom} – nominal capacity of chosen type of battery [Ah].

Number of batteries connected in series (N_{ser}) is calculated as follows [56]:

$$N_{ser} = \frac{\mathrm{U}}{U_{nom}}$$

where

U – system's voltage level [V];

U_{nom} – nominal voltage of chosen type of battery [V].

Total number of accumulator batteries (N_{bat}) is calculated as follows [56]:

$$N_{bat} = N_{par} \cdot N_{ser}$$

4.1.4. PV modules sizing

Required input for the calculation of number of panels is daily number of peak sun hours. Peak sun hours are the amount of solar insolation which would be received if the sun shining on its maximum level for a certain period. Value of peak sun hours for each month is equal to the daily sum of global irradiation [58] and is presented in the Table 5 and on the following chart (Figure 15):

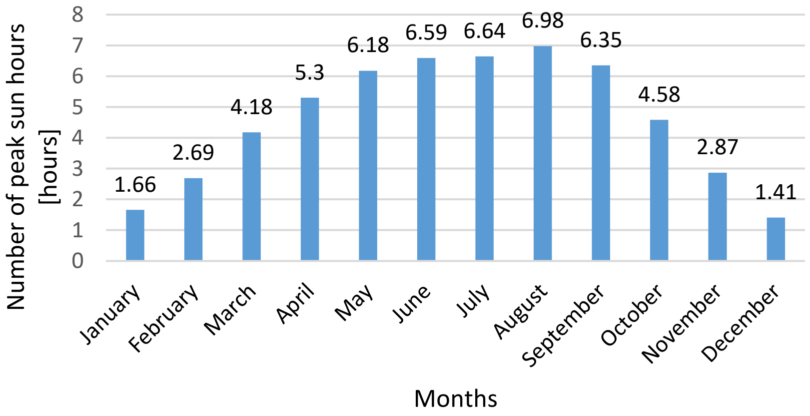


Figure 15. Number of peak sun hours [54]

In accordance with the power consumption data presented in the Table 5, and tacking into account the Assumption 1 (see subchapter 4.1.2.), that irrigating period lasts from May to August, number of modules is calculated for May as a month with the lowest number of peak sun hours.

Daily energy generation of PV system (W_{PV}) is calculated as follows [56]:

$$W_{PV} = G_{id} \cdot S_m \cdot N_m \cdot \eta_m \cdot k_{tm}\,, [Wh/day]$$

where

G_{id} – daily sum of global irradiation [kWh/m^2];

S_m – square area of PV module [m^2];

N_m – number of PV modules;

η_m – efficiency of PV module;

k_{tm} – temperature coefficient of PV module.

The temperature coefficient describes heat loss of the modules and assumed to be equal to 0.85 [56].

The following equation describes the number of PV modules (N_m). Obtained value should be rounded to the nearest higher integer value [56]:

$$N_m = \frac{P_{full} \cdot k_{cdb}}{G_{id} \cdot S_m \cdot \eta_m \cdot k_{tm}}$$

where

P_{full} – full load of the system [Ah/day];

k_{cdb} – charge-discharge coefficient of the batteries.

The charge-discharge coefficient describes losses on charge and discharge of the batteries and is equal to 1.2 [56].

After determining the total number of PV modules, it is necessary to calculate number of PV modules connected in parallel and in series [56]. According to the general rule of connection in parallel and in series, voltage of modules connected in series is equal to the sum of voltages of all modules while total current is equal to the current of one module. For connection in parallel conversely current of modules connected is equal to the sum of currents of all modules while total voltage is equal to the voltage of one module [59]. Following Figure 16 and Figure 17 represent an example of this concept:

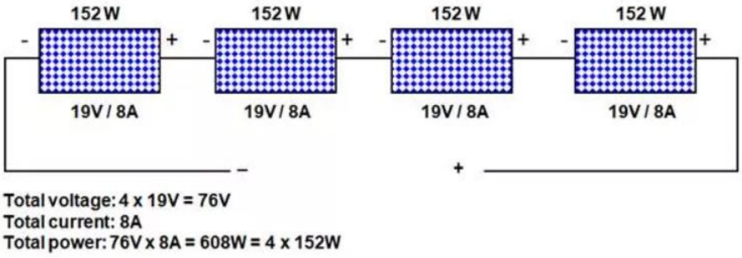


Figure 16. Example of in series connection of modules [59]

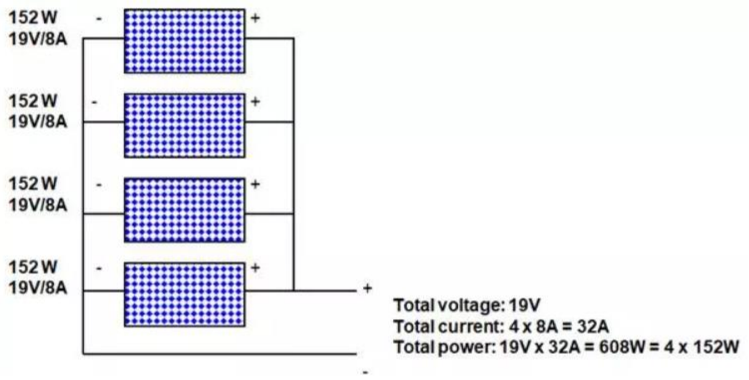


Figure 17. Example of in parallel connection of modules [59]

Number of modules connected in series (N_{mser}) for providing of required output voltage level is calculated as follows [56]:

$$N_{mser} = \frac{U}{U_{mnom}}$$

where

U – system’s voltage level [V];

U_{mnom} – nominal voltage of chosen PV module [V].

PV modules connected in series then should be connected in parallel and the number of parallel connections of PV modules (N_{mpar}) is calculated as follows [56]:

$$N_{mpar} = \frac{N_m}{N_{mser}}$$

where

N_m – number of PV modules;

N_{mser} – number of PV modules connected in series;

Overall current of PV system (I_{sys}) is then calculated as follows [56]:

$$I_{sys} = N_{mpar} \cdot I_{mnom}, [A]$$

where

N_{mpar} – number of PV modules connected in parallel;

I_{mnom} – nominal current of chosen PV module [A].

4.1.5. Charge controller sizing

Main criteria when selecting charge controller is its ability to withstand PV array current level [48]. Overall current of the system should be 75% of the controller current. Thus, current of the charge controller (I_{cc}) is calculated as follows [56]:

$$I_{cc} = \frac{I_{sys}}{k_{kon}}, [A]$$

where

I_{sys} – Overall current of PV system [A];

k_{kon} – controller coefficient of 75%.

Voltage of charge controller is the same as battery bank voltage and is equal to 48 V. Input voltage of charge controller should be more or equal to a voltage of PV modules string [48].

4.1.6. Inverter sizing

Inverter is selected in accordance with total power of all appliances. However, one more parameter called peak power should be taken into account. It could be found by multiplying the power of appliance with high surge current by 3 [48]. In presented model such an appliance with high surge current is pump. Also, to allow the system grow in the future, total power should be increased by 25% [48]. Therefore, peak power that inverter should withstand (P_{invp}) is calculated as follows:

$$P_{invp} = (\sum P_{app} + P_{hscapp} \cdot k_{sc}) \cdot k_{exp}, [W]$$

where

P_{app} – electrical appliance power [W];

P_{hscapp} – electrical appliance with high surge current power [W];

k_{sc} – surge current coefficient;

k_{exp} – coefficient of system expansion.

4.1.7. Generator sizing

Generators are normally sized in a way to cover batteries charging capacity plus to supply some of the loads at the same time [60]. There are several criteria for generator selection, such as: cost, power requirements, fuel availability and maintenance requirements [61]. Except output power, generators have following important technical characteristics: rotation speed, efficiency, fuel type, altitude effect, waveform harmonic content, frequency stability, amplitude stability, noise level, overload characteristics, power factor considerations [48]. Due to high maintenance cost of DC generators, it is common to use AC generators in PV systems [61].

Nominal power of diesel generator should be 25% higher than total energy demand obtained by the sum of all electrical appliances from the Table 6. Then the nominal power of diesel generator (P_{gen}) calculated as follows [55]:

$$P_{gen} = \sum P_{allapp} \cdot k_{gen}, [W]$$

where

P_{allapp} – power of all appliances [W];

k_{gen} – generator correction factor.

Fuel consumption of diesel generator (C_{gen})is calculated as follows [55]:

$$C_{gen} = E_{gen} \cdot C_{nom}, [g]$$

where

E_{gen} – energy generation [kWh];

C_{nom} – nominal fuel consumption of generator [g/kWh].

4.1.8. Wiring and cables sizing

Correctly sized wires and cables increase efficiency and reliability of the system. DC cables connecting PV modules, charge controller and battery bank must withstand maximum current of PV modules [48].

4.1.8.1. Cabling from PV modules to the charge controller

The cross section of the DC cable between PV modules and charge controller (A_{DC}) is calculated as follows [62]:

$$A_{DC} = \left(\frac{\rho_c \cdot l_c \cdot I_{cc}}{U_d}\right) \cdot c, [mm^2]$$

where

ρ_c – resistivity of the copper wire [Ω/m];

l_c – length of the cable [m];

I_{cc} – current of charge controller [A];

U_d – maximum voltage drop [V].

c – constant equal to 2.

The maximum current (I_{max}) is equal to the minimum current of the charge controller (I_{cc})[62]:

$$I_{max} = I_{cc}, [A]$$

The maximum voltage drop (U_d) should not exceed 3% [22] therefore it is calculated as follows [62]:

$$U_d = U \cdot k_{Ud}, [V]$$

where

U – PV system voltage [V];

k_{Ud} – voltage drop limit [%].

4.1.8.2. Cabling from battery bank to the inverter

DC cable through battery bank to inverter must withstand maximum inverter output current (I_{invout}). This current is calculated by dividing inverter power by multiplier of system voltage and inverter efficiency [48]:

$$I_{invout} = \frac{P_{invnom}}{U \cdot \eta_{inv}}, [A]$$

where

P_{invnom} – nominal inverter power [W];

U – PV system voltage [V];

η_{inv} – efficiency of inverter [%].

Then the cable cross section is calculated as follows [62]:

$$A_{DC} = \left(\frac{\rho_c \cdot l_c \cdot I_{invnom}}{U_d}\right) \cdot 2, [mm^2]$$

where

ρ_c – resistivity of the copper wire [Ω/m];

l_c – length of the cable [m];

I_{invnom} – maximum inverter output current [A];

U_d – maximum voltage drop [V].

4.1.8.3. Cabling from inverter to the load

AC cable between inverter and the load must withstand maximum inverter current at full load on the phase (I_{phase}). This current is calculated by dividing inverter power (P_{invnom}) by multiplier of output voltage of the load (U_l) and constant $\sqrt{3}$ [62]:

$$I_{phase} = \frac{P_{invnom}}{U_l \cdot \sqrt{3}}, [A]$$

where

P_{invnom} – nominal inverter power [W];

U_l – voltage of the load [V];

Voltage drop of output voltage (U_{dAC}) on a load of 220 V is 3% [62]:

$$U_{dAC} = 0.03 \cdot U_{AC}, [V]$$

where

U_{AC} – voltage on load [V].

Then the AC cable cross section (A_{AC}) is calculated as follows [62]:

$$A_{AC} = \left(\frac{\rho_c \cdot l_c \cdot I_{phase}}{U_{dAC}}\right) \cdot c, [mm^2]$$

where

ρ_c – resistivity of the copper wire [Ω/m];

l_c – length of the cable [m];

I_{phase} – maximum inverter current at full load on the phase [A];

U_{dAC} – voltage drop of output voltage [V];

c – constant equal to 2.

4.2. Economic evaluation of the proposed design

In this chapter the project will be evaluated from the economical point of view. Evaluation requires such inputs as investment costs, fuel costs and incomes. There are several main criteria for evaluation of investment efficiency, such as Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI) and Payback Period (PP) [63]. In addition, sensitivity analysis will be applied.

As it was mentioned there is a direct subsidy program for off-grid PV systems in Kazakhstan which covers 50% of investments if it was produced in Kazakhstan [15]. For further calculations this fact is applied with reduction of subsidy to 30% in order to compensate higher prices of domestic equipment.

4.2.1. Net Present Value

Net present value is the difference between the present value of cash inflows and outflows over a period of time. NPV is used in investment planning to analyze the profitability of a project. NPV is calculated as follows [63]:

$$NPV = -INV + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}, [monetary\ units\ (MU)]$$

where

INV – total initial investments [MU];

C_t – net cash inflow during the period t [MU];

r – discount rate [%];

t – period of time [years];

T – lifetime [years].

NPV rule states that investments with positive NPV should be accepted and investments with negative NPV should be rejected [64]. From two investment alternatives more preferrable the one with higher NPV [63].

Despite of the fact that NPV is considered as the most important criteria it has a drawback of not taking into account size of investment. That is why it is better to use not only NPV but also other criteria [63].

4.2.2. Internal Rate of Return

The internal rate of return is defined as the discount rate at which a project would have zero NPV [63]. From several alternative investments more preferable those with higher value of IRR. IRR is calculated as follows [63]:

$$-INV + \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} = 0$$

where

INV – total initial investments [MU];

C_t – net cash inflow during the period of time t [MU];

t – period of time [years];

T – lifetime [years].

4.2.3. Profitability Index

Profitability index is the value, which shows cost of the Net Present Value per one monetary unit of the initial investment [64]. PI is calculated as follows [63]:

$$PI = \frac{\sum_{t=1}^{T} DCF_t (1+r)^t}{INV}$$

where

DCF - discounted cash flow [MU];

INV - total initial investments [MU];

r - discount rate [%];

t - period of time [years];

T – lifetime [years].

Investment is efficient when the profitability index is higher than 1 as PI lower than 1 means that generated profit is lower than initial investment [64].

4.2.4. Payback Period

Payback period is a period when cumulative cash inflow is equal to initial investments (cash outflow). In other words, PP shows how much time is needed for investment to be paid off. PP is calculated as follows [63]:

$$PP = \sum_{t=1}^{T} (C_t - C_0) \geq C_0, [years]$$

where

C_t – cash inflow [MU];

C_0 – cash outflow [MU];

t - period of time [years];

T – lifetime [years].

4.2.5. Inflation rate

Inflation is concept describing losing of purchasing power by money or quantitative measure of the rate at which the average price level of a basket of selected goods and services in an economy increases over a period of time [65]. Inflation rate used in this Thesis is chosen according to Kazakhstan's National Bank and is equal to 7% [78].

4.2.6. Tax rate

A tax rate is the percentage at which an individual or corporation is taxed [66]. In this Thesis tax rate is equal to zero, due to the absence of direct incomes. As an income in this analysis was considered the savings of money spent on fuel.

4.2.7. Depreciation

Depreciation is an accounting method of allocating the cost of a tangible or physical asset over its useful life or life expectancy. In other words, depreciation is a method of allocating the cost of equipment over its lifetime [67].

There are two main types of depreciation [67]:

1. Straight-line (even distribution of cost during the years)
2. Accelerated (greater costs in yearly years and smaller costs in later years)

In this Thesis straight-line depreciation (D) was applied due to its simplicity and clarity and it is calculated according to the following formula [67]:

$$D = \frac{A_0}{T}$$

where

A_0 – cost of equipment [MU];

T – lifetime of the equipment [years].

4.2.8. Discount rate

Discount rate is an opportunity cost, as it is the return that can be received by investing in the project, rather than investing in financial markets [63]. For determination of a discount rate Capital Asset Pricing Model (CAPM) is used. CAPM describes risk and return relation and its equation is as follows [63]:

$$r = r_f + \beta_L \cdot MRP, [\%]$$

where

r – discount rate [%];

r_f – risk-free rate [%];

β_l – coefficient of sensitivity to market changes;

MRP – market risk premium [%].

Sensitivity to market changes explains how risky the investment is [63]. It is also differs depending on the sector of economy and for RES $\beta_l = 1.3$ [68].

MRP explains the relation between expected return on investment and risk free-rate [64]. For Kazakhstan MRP is equal to 2.13% [69].

Risk-free rate is a rate of return on governmental bonds. It is considered as the relatively safest investment and therefore has low return which is equal to 0.367% for Kazakhstan [70].

Thus, discount rate (r) used in this Thesis is as follows:

$$r = 0.00367 + 1.3 \cdot 0.0213 = 3.1\%$$

Following Table 8 represents summarization of all necessary inputs for economic analysis. Investment was reduced due to the subsidy and service life was taken from specification of the equipment. Income is considered as money saved on fuel after implementation of PV system. Costs are represented by the cost of fuel. Transportation costs, operation and maintenance costs were assumed to be 0.

Table 8. Inputs for economic analysis

70% of investments (after subsidies)	3,941 USD
PV modules service life	20 years
Battery bank service life	20 years
Inverter service life	10 years
Controller service life	10 years
Cables service life	10 years
Discount rate	3.1%
Inflation rate	7%
Tax rate	0%
Income	384.9 USD
Costs	85.6 USD

5. Results

5.1. Technical proposal results

5.1.1. Battery bank

Full load of the system:

$$P_{full} = \frac{11,997}{48} = 249.94\ [Ah/day]$$

Accumulator battery AES LiFePO4 (see Figure 18) satisfies to all system's requirements. Following Table 9 represents technical specification of chosen battery:

Table 9. AES LiFePO4 specification [71]

Model	AES LiFePO4
Electrolyte	Lithium iron phosphate
Depth of discharge	90%
Capacity	129 Ah
Current	130 A
Voltage	48 V
Efficiency	98%

Figure 18. AES LiFePO4 accumulator battery [71]

Total capacity of the battery bank:

$$C = \frac{249.94 \cdot 2}{0.9 \cdot 0.8} = 694.3\ [Ah]$$

Number of batteries connected in parallel:

$$N_{par} = \frac{694.3}{129} = 6$$

Number of batteries connected in series:

$$N_{ser} = \frac{48}{48} = 1$$

Total number of accumulator batteries:

$$N_{bat} = 6 \cdot 1 = 6$$

5.1.2. PV modules

According to solar energy-oriented web resource [72], one the most efficient type of solar modules for home use is manufactured by LG company. Selected module is illustrated in the Figure 19 below and the following Table 10 contains specification of the chosen module:

Table 10. Data sheet of chosen module type [73]

Model	NeON R Ace LG360Q1C-A5
Rated power	360 W
Nominal voltage	36.5 V
Nominal current	9.87 A
Open circuit voltage	42.7 V
Short circuit current	10.79 A
Efficiency	20.80%

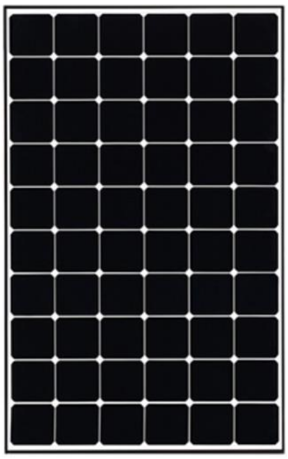


Figure 19. PV module NeON R Ace LG360Q1C-A5 [73]

Number of PV modules:

$$N_m = \frac{11{,}997 \cdot 1{,}2}{6{,}180 \cdot 1.73 \cdot 0.208 \cdot 0.85} \approx 8$$

Number of modules connected in series:

$$N_{mser} = \frac{48}{36.5} \approx 1$$

Number of parallel connections of PV modules:

$$N_{mpar} = \frac{8}{1} = 8$$

Overall current of PV system:

$$I_{sys} = 8 \cdot 9.87 = 78.96\ [A]$$

Daily energy generation of PV system:

$$W_{PV} = 6{,}180 \cdot 1{,}73 \cdot 8 \cdot 0.208 \cdot 0.85 = 15{,}122\ [Wh/day]$$

5.1.3. Charge controller

Current of the charge controller:

$$I_{cc} = \frac{78.96}{0.75} = 105.28\ [A]$$

Thus, charge controller Sunpal MPPT GSM220 is chosen (see Figure 20). Following Table 11 represents technical specification of the selected charge controller:

Table 11. Sunpal MPPT GSM220 specification [74]

Model	Sunpal MPPT GSM220
Voltage	220 V
Current	150 A
Efficiency	98%

Figure 20. Sunpal MPPT GSM220 charge controller [74]

5.1.4. Inverter

Power of inverter:

$$P_{invp} = (39 + 100 + 130 + 475 + 1{,}000 + 1{,}100 \cdot 3) \cdot 1.25 = 6{,}305\ [W]$$

Bi-directional inverter Kinergier Pro CK8.0S is chosen (see Figure 21). Following Table 12 represents technical specification of the selected inverter:

Table 12. Kinergier Pro CK8.0S specification [75]

Model	Kinergier Pro CK8.0S
Type	Bi-directional
Voltage	48 V
Power	6,500 W
Current	50 A
Efficiency	96%

Figure 21. Kinergier Pro CK8.0S inverter [75]

5.1.5. Generator

Nominal power of diesel generator:

$$P_{gen} = 2{,}844 \cdot 1{,}25 = 3{,}555\ [W]$$

AGi4P diesel generator is chosen (see Figure 22). Following Table 13 represents technical specification of the selected generator:

Table 13. AGi4P diesel generator specification [76]

Model	AGi4P
Fuel type	Diesel
Voltage	240 V
Power	4,000 W
Fuel tank volume	38 L
Fuel consumption nominal load	275 g/kWh

Figure 22. AGi4P diesel generator [76]

5.1.6. Fuel consumption

In presented Thesis diesel generator is an auxiliary power source during irrigation period and primal energy source during the rest of the year. Therefore, it is important to calculate fuel consumption throughout the year to estimate costs.

For further calculations an assumption is made that it generates 1,000 Wh per day during non-irrigating period.

Then, taking into account excluding of pump from the daily energy demand and energy generated by PV modules, amount of energy to be produced by diesel generator is found and presented in the following Table 14:

Table 14. Overview of energy generation during the year

Month	Non-irrigating energy demand [Wh/day]	Daily PV energy generation [Wh/day]	Daily diesel energy generation [Wh/day]
January	**7,597**	**3,586**	**4,011**
February	**7,597**	**5,810**	**1,787**
March	**7,597**	**9,029**	**-1,432**
April	**7,597**	**11,448**	**-3,851**
May	11,997	13,349	1,000
June	11,997	14,234	1,000
July	11,997	14,342	1,000
August	11,997	15,077	1,000
September	**7,597**	**13,716**	**-6,119**
October	**7,597**	**9,893**	**-2,296**
November	**7,597**	**6,199**	**1,398**
December	**7,597**	**3,046**	**4,551**

Table 13 shows that for March, April, September and October the energy generation of PV modules is sufficient for covering daily energy demand, therefore for these months' diesel generator is auxiliary energy source while PV modules are the primal source. Therefore, for this period the same assumption of 1,000 Wh of daily generation is applied.

Then using passport fuel consumption of generator from the Table 13 the fuel consumption for months with generator as primal source is found and presented in the Table 15.

Daily fuel consumption (FC) in January:

$$FC_{JAN} = 4{,}011 \cdot 0.275 = 1{,}103\ [g]$$

Table 15. Fuel consumption of diesel generator with PV system

Month	Daily diesel energy generation [Wh]	Daily fuel consumption [g]	Daily fuel consumption [L]	Monthly fuel consumption [L]
January	**4,011**	**1,103**	**1.35**	**40**
February	**1,787**	**491**	**0.60**	**18**
March	1,000	275	0.34	10
April	1,000	275	0.34	10
May	1,000	275	0.34	10
June	1,000	275	0.34	10
July	1,000	275	0.34	10
August	1,000	275	0.34	10
September	1,000	275	0.34	10
October	1,000	275	0.34	10
November	**1,398**	**384**	**0.47**	**14**
December	**4,551**	**1,252**	**1.53**	**46**
Total				**199**

According to the Bureau of National Statistics of Kazakhstan [77] and National Bank of Kazakhstan [78] the price per litre of diesel fuel is 0.43 USD.

Then, cost of fuel per year (C_{fuel}) is calculated as follows:

$$C_{fuel} = 199 \cdot 0.43 = 85.6\ [USD]$$

In order to calculate fuel economy after installation of PV system, cost of fuel when diesel generator is the only one source of energy should be found. Results summarized and presented in the Table 16.

Cost of fuel without PV system (C_{fuel1}) is multiplier of total fuel consumption (see Table 16) and price of fuel:

$$C_{fuel1} = 1{,}094 \cdot 0.43 = 470.4\ [USD]$$

Then, reduction of fuel costs is equal to:

$$\Delta C_{fuel} = C_{fuel1} - C_{fuel} = 470.4 - 85.6 = 384.9\ [USD]$$

Table 16. Fuel consumption of diesel generator without PV system

Month	Daily energy demand [Wh]	Daily fuel consumption [g]	Daily fuel consumption [L]	Monthly fuel consumption [L]
January	7,597	2,089	2.55	76
February	7,597	2,089	2.55	76
March	7,597	2,089	2.55	76
April	7,597	2,089	2.55	76
May	11,997	3,299	4.02	121
June	11,997	3,299	4.02	121
July	11,997	3,299	4.02	121
August	11,997	3,299	4.02	121
September	7,597	2,089	2.55	76
October	7,597	2,089	2.55	76
November	7,597	2,089	2.55	76
December	7,597	2 089	2.55	76
Total				**1,094**

5.1.7. Comparative scenario

This subchapter describes alternative scenario where PV system will be the primal energy source during the whole year.

By changing level of solar irradiation from May to December where it is the least during the year, the number of PV modules in the worst case is calculated:

$$N_{mdec} = \frac{11{,}997 \cdot 1{,}2}{1{,}410 \cdot 1.73 \cdot 0.208 \cdot 0.85} \approx 34$$

Then, cost of fuel is calculated:

$$C_{fueldec} = 120 \cdot 0.43 = 51.6\ [USD]$$

As we may see amount of PV modules in this case is more than 4 times bigger as well as costs which make this scenario ineffective. Even subsidy and fuel economy are not able to change it. More detailed calculations are in Appendix 1.

5.1.8. Summarization of the design proposal of PV system

An off-grid hybrid PV system for the farm located in remote area of the Southern region of Kazakhstan was designed. In accordance with electric appliances used on-farm, total electric loads were calculated. It was assumed that the electic device with highest energy demand (pump) is used only during irrigation period from May to August. The rest of the year farm is used for living as a house. Therefore PV system's primal goal is to generate enough energy for power supply during irrigation period. Secondary data about solar irradiation in the region was used. According to the month with the lowest amount of peak sun hours number of PV panels was calculated. Thus, the average daily energy generation of PV modules with respect to the global irradiation data from Table 5 and installed capacity is summarized in the Table 14. For backup purposes, a diesel generator was chosen. For the months with low level of solar irradiation, the energy generation of PV system is not enough to cover energy demand of the farm. Therefore diesel generator is used as the primal energy source during this period. Following Table 17 and Figure 23 describe proposed equipmnet and its price.

Table 17. Overview of proposed equipment and its price based on seller information

Equipment	Pieces	Price per piece [USD]	Price for all [USD]
PV modules	8	440	3,520
Batteries	6	85	510
Controller	1	300	300
Inverter	1	1,150	1,150
Cables	3	50	150
Total			**5,630**

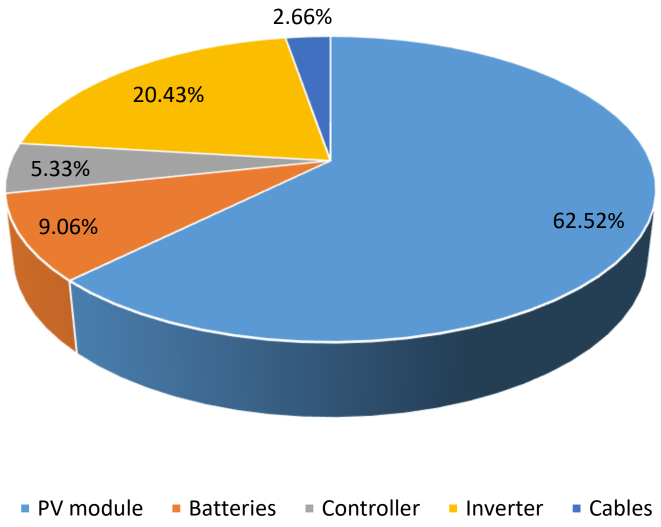


Figure 23. Share of equipment in total investments

5.2. Economic evaluation results

NPV

NPV was calculated for 20 years. Part of the equipment has shorter service life and therefore it should be purchased again which increase required investments. Calculations results showed that NPV with 30% reduction of investments due to the governmental subsidies is equal to 2,993 USD and therefore project is effective for investment. Moreover, NPV without subsidy is equal to 654 USD which also approve that proposed design is effective from the investment perspective.

IRR

Calculations showed that NPV is equal to zero when the discount rate is equal to 8.49% which is the value of IRR. Higher value of IRR than the discount rate indicates that investment is effective.

Profitability Index

Sum of all discounted cash flows divided by the total investments gives the ratio 1.76. As it is higher than 1 the proposed design is efficient.

$$PI = \frac{6{,}934}{3{,}941} = 1.76$$

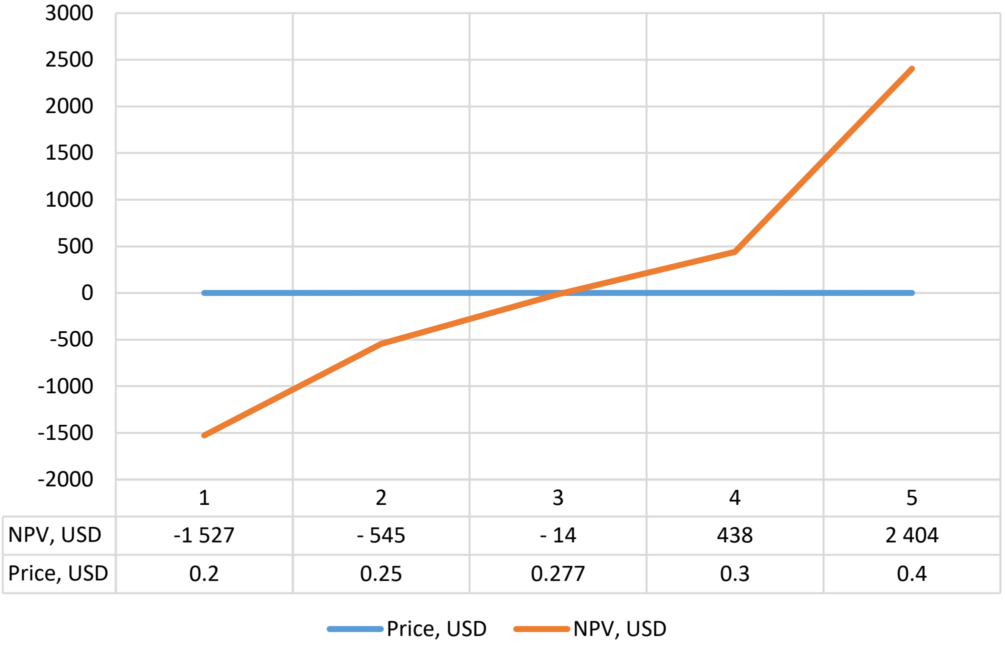
Payback Period

Necessary amount of time when total cash flow will increase initial investment costs is 15 years which is quite high. However, it is still less than service life of the PV system. That means proposed design is effective from economics perspective. In Appendix 2 calculation of these criteria is presented in more details.

5.2.1. Sensitivity analysis

Sensitivity analysis shows how changes of independent variables influence on dependent variable under given conditions [79]. In this Thesis NPV was adopted as a depended variable and fuel price as an independent variable.

In presented case, the fuel price is the most important component of economic analysis since it determines both: costs and incomes. Determined in previous chapters and applied in calculations, the fuel price was 0.43 USD per litre. Using Excel, the relation between fuel price and NPV was checked and results are presented on the following Figure 24:



	1	2	3	4	5
NPV, USD	-1 527	- 545	- 14	438	2 404
Price, USD	0.2	0.25	0.277	0.3	0.4

Figure 24. Relation between fuel price and NPV

Results indicate that with increasing of fuel price NPV also rises even if the costs become higher. This is because the income is based on difference between costs with and without PV system.

6. Discussion

According to the national energy program of Kazakhstan [10], the share of renewable energy sources should be increased year by year. The current situation in the energy sector is stable, however, the growth of population and urban areas require an increase in the installed capacity of the country. The development of solar energy fields is justified by building more and more new solar power plants for the power supply of urban areas. This progress in turn creates possibilities for sustainable development of rural areas. Implementation of subsidies policy and favourable climatic conditions create possibilities for the population of remote areas to build effective off-grid PV systems from both: technical and economical perspectives.

Assessment of the potential of PV technology on the territory of Kazakhstan was conducted using secondary data. SOLARGIS database provides information about the level of solar irradiation on the planet. According to the obtained data, the irradiation level is sufficient for using PV technology in all territories of the country. This is also confirmed by the fact of the rapid building of large-scale PV power plants in the Northern part of the country, where solar irradiation is lower in comparison to the Sothern regions. However, Southern regions are more developed from the point of view of agriculture due to the warm climate. That is why for a design proposal model Zhambyl region in the South was chosen. An alternative way to assess PV potential is to use PVsyst software which is presented in the work of Fedorov [80].

Due to the lower level of solar irradiation and less amount of peak sun hours during wintertime, it is necessary to have a much bigger installed capacity of PV modules in comparison to the summertime. This fact made a foundation in the proposed model in this Thesis. In the presented model, the major consumer of energy is a water pump which is used during the irrigation period. Therefore, the installed capacity of the PV system should be enough to cover this demand. However even though during the non-irrigation period energy consumption is lower, the energy generation could not cover this demand due to the lower power output potential during the winter. That means that much more installed capacity (number of PV modules) was required. In the case of the small-scale farms in the conditions of Kazakhstan, it is not effective from the economical point of view because it requires huge initial investments. Using the formula from Chapter 4.1.4

and by supplementing there the least level of solar radiation in December, the number of PV modules for power supply during the whole year was found in the amount of 34 pieces. This option requires more than 4 times higher initial investments. That is why an alternative compromise option of a hybrid PV system was chosen. Unlike this Thesis, for the economic evaluation of the PV system, Uwibambe [81] uses HOMER software which provides another economic methodology.

As it was described earlier hybrid systems require at least two different sources of energy. Weldemariam [82] for hybrid system uses wind turbine in addition to PV system due to favourable climatic conditions in researched area. In a presented model I used PV modules and diesel generator. Besides providing of power supply during wintertime the diesel generator serves as a backup source of energy within the irrigation period.

7. Conclusions

In the course of work on this Thesis, several findings were made. Renewable energy in general and solar energy in particular very rapidly are developing in Kazakhstan. Government builds large-scale PV power plants for the power supply of the cities and subsidizes small-scale private PV systems. Due to the vastness of the territory, there are a lot of remote rural areas which have no access to the electricity grid. Fortunately, the conditions of Kazakhstan are favourable for the implementation of PV systems for private use. This fact contributes to the sustainable development of not only rural areas but the country in general.

However, it was found that Southern regions with higher solar irradiation level are more preferable for small-scale PV systems. Moreover, in rural areas, it is not feasible to rely only on PV technology during the whole year.

Summing up it should be said that this Thesis could be used as a guide for small-scale PV systems design not only in Kazakhstan but in all countries. The described universal methodology could be adapted to any particular region with respect to local climatic conditions and suppliers of the equipment.

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Appendices

List of the Appendices:

- Appendix 1: Calculation of NPV for comparative scenario
- Appendix 2: Calculation of NPV

Appendix 1: Calculation of NPV for comparative scenario

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investm (subsidised).	-11 949										- 2 059										
Costs		- 52	- 55	- 59	- 63	- 68	- 72	- 77	- 83	- 89	- 95	- 102	- 109	- 116	- 124	- 133	- 142	- 152	- 163	- 174	- 187
Depr (PV+acc)		774	774	774	774	774	774	774	774	774	774	774	774	774	774	774	774	774	774	774	774
Depr (cont+inv+wires)		160	145	145	145	145	145	145	145	145	145	206	206	206	206	206	206	206	206	206	206
Income		419	448	480	513	549	587	629	673	720	770	824	882	943	1 009	1 080	1 156	1 236	1 323	1 416	1 515
EBT		- 566	- 526	- 498	- 469	- 437	- 403	- 367	- 329	- 288	- 243	- 257	- 206	- 152	- 94	- 33	34	105	181	262	349
TAX		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EAT		- 566	- 526	- 498	- 469	- 437	- 403	- 367	- 329	- 288	- 243	- 257	- 206	- 152	- 94	- 33	34	105	181	262	349
CF	-11 949	367	393	420	450	481	515	551	590	631	- 1 384	722	773	827	885	947	1 013	1 084	1 160	1 241	1 328
DCF	-11 949	356	370	384	398	413	429	445	462	479	- 1 020	516	536	556	577	599	622	645	670	695	721
NPV	- 3 096																				
NPV	- 3 096																				

Appendix 2: Calculation of NPV

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investm (subsidised).	- 3 941										- 2 059										
Costs		- 86	- 92	- 98	- 105	- 112	- 120	- 128	- 137	- 147	- 157	- 168	- 180	- 193	- 206	- 221	- 236	- 253	- 270	- 289	- 309
Depr (PV+acc)		202	202	202	202	202	202	202	202	202	202	202	202	202	202	202	202	202	202	202	202
Depr (cont+inv+wires)		160	145	145	145	145	145	145	145	145	145	206	206	206	206	206	206	206	206	206	206
Income		385	412	441	471	504	540	578	618	661	708	757	810	867	927	992	1 062	1 136	1 216	1 301	1 392
EBT		- 62	- 26	- 4	20	46	73	103	134	168	204	181	223	267	314	364	418	476	538	604	675
TAX		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EAT		- 62	- 26	- 4	20	46	73	103	134	168	204	181	223	267	314	364	418	476	538	604	675
CF	- 3 941	299	320	343	367	392	420	449	481	514	- 1 509	589	630	674	721	772	826	884	945	1 012	1 082
DCF	- 3 941	290	301	313	324	337	349	363	376	391	- 1 112	421	437	453	470	488	507	526	546	566	588
NPV	2 993																				
NPV	2 993																				