A technical review of existing off grid solutions with different scales in Finland

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ABSTRACT

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This bachelor's thesis discusses a hypothetical photovoltaic off-grid power generation system for a 49-square-meter summer house in a remote area outside Lappeenranta, Finland, which is only used for the summer months of June and July. Assuming that it is too far away from the transmission point and the cost of grid connection is high, off-grid power generation has become an option. The article discusses the types and background of each component in the system and the selection of some components. And it was finally determined that the battery capacity required when the average daily load is 3.94kWh, the number of autonomy days is 4 days, is 1207.13Ah, the photovoltaic module power is 1.44kW, and the inverter power is 5.12kW. Corresponding cost and economic benefits issues are also discussed.

SYMBOLS AND ABBREVIATIONS

Roman characters

p	Power	W
C	Battery capacity	Ah
I	Current	A
V	Voltage	V
E	Power	W
R	Radiation intensity	kWh/m²/day

Abbreviations

OSF	Official Statistics of Finland
PV	Photovoltaic
LCD	Liquid-crystal display
MPPT	Maximum power point tracker
DC	Direct current
AC	Alternating current
PERC	Passivated Emitter and Rear Contact
SLA	Sealed lead-acid
AGM	Absorbed Glass Mat
DF	Demand Factor
LVD	Low Voltage Disconnect
EOL	End of Life
DOD	Depth of discharge

Table of contents

Abstract

(Symbols and abbreviations)

1 Introduction 5
2 Method 6
  2.1 Set average summer house load model 6
    2.1.1 Summer case model (June and July) 7
  2.2 Review of existing off-grid solutions 9
    2.2.1 Overview of PV off-grid system 9
    2.2.2 Solutions for summer case model 15
3 Results 25
  3.1 The solution for a average summer house 25
  3.2 Cost-effectiveness considerations 26
4 Conclusions 28
References 29

1 Introduction

The main target of this Bachelor thesis is trying to find the most economic off-gird electricity solution for those summer house customers Finland which cannot have a proper access to electricity grid or wish to find a more economic solution instead of on-grid system. The location of summer house often stays far away from city grid system, which means they cost more than the urban area residents if they plan to be on grid. Especially in a country of lakes, the summer houses can be built everywhere near a lake, or on an island, which brings more difficulty to set a durable, safe, and economic plan to the electricity grid, therefore off-grid solution with solar power becomes an answer to many summer houses. But the problem is the solutions for different types of summer house is limited, so in this thesis there will be a technical comparation among popular off grid solutions for an average summer house model in Finland 2020 which is 49 m^2[1] (Source: OSF), and discuss its investment and operational cost to figure out the most economical solution in common. And the parameters and technical specifications of the various components of the off-grid solar system in this case are determined through calculation and simulation methodologies. It is used to provide specific calculation processes for users to carry out their own off-grid planning under different actual situations. Increase the breadth of user choice.

2 Method

Before the review of off-grid solutions, the load model should be built in chapter 2.1, with a single season model for summer house in Finland. In chapter 2.2 there will go through a concept of off-grid system or micro grid and then extend to prevalent off-grid solutions. The main methods used are calculation and simulation methodology.

2.1 Set average summer house load model

Before the discussion of off-grid systems, set a reasonable, realistic load model for is crucial, which make the selection boundary of off-grid solutions clean and Obvious. So chapter 2.1.1 and 2.1.2 will conduct daily electricity usage modelling. And the reasons of modelling decisions will be explained in next paragraph.

Because the special geographical factors of Nordic area, Finland shows a notably uneven distribution of sunshine duration in contrast to nations in lower latitudes. In addition, the location of summer cottages is usually more far away from urban area to settle in a place surrounded by fascinating natural views. Combining the above two factors, it is not a sensible choice to live in a summer house in a whole year for most of residents.

Figure 1 is the sun graph for Lappeenranta, Finland. it illustrates the sunshine hours distribution in a year. The x-axis shows the month, y-axis shows the 24 hours in a day. The light bule area is the sun hour in a day, dark area is the night of the day. We can directly see that the sunlight varies significantly throughout the year. And a huge amount of sunshine is concentrated on summer.

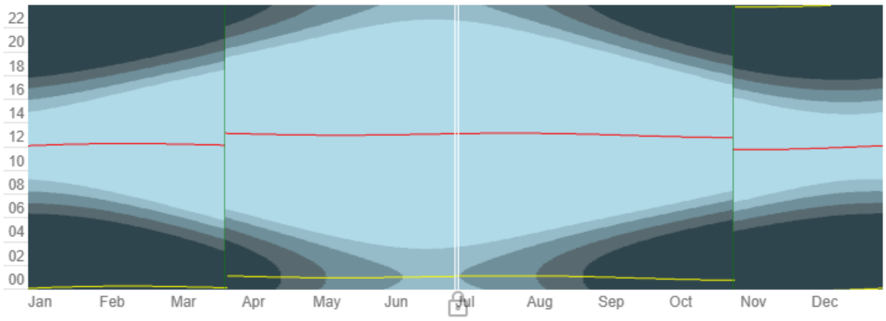


Figure 1. 2023 Sun Graph for Lappeenranta. (www.timeanddate.com)

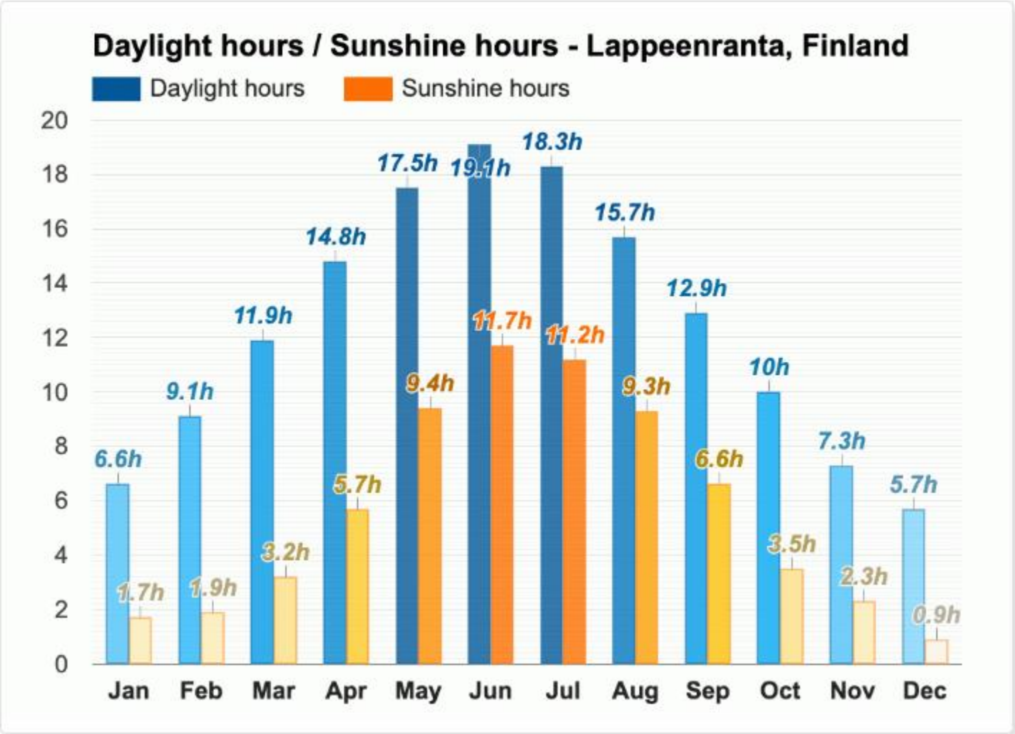


Figure 2. Average daylight/sunshine Lappeenranta, Finland. (www.weather-atlas.com)

Figure 2 is Average daylight/sunshine in Lappeenranta, different from daylight hours, sunshine hours have more impact on power generation of PV system, there would be different weather factors, especially in snow day, it's hard to maintain the PV system operate as usual. Therefore, to ensure that the surrounding environment is more comfortable and convenient, also the sunshine conditions are sufficient to fulfil the minimum electrical load, we set June and July, two highest intensities of sunshine months as sample.

The summer house discussed in this article has good thermal insulation performance and can insulate the house from around 10 degrees to 20 degrees, regardless of extreme weather conditions such as extreme exposure to the sun, heavy rain, and windstorms in summer.

According to the Finnish Meteorological Office[2], the average temperature in summer is between 15-25 degrees Celsius. The average temperatures in June and July from year 1991-2020 are 14.9 degrees Celsius and 17.7 degrees Celsius respectively.

2.1.1 Summer case model (June and July)

In this case, what we discussed is a relatively simple and basic electricity consumption situation, and additional large-scale electricity demand and luxury electricity consumption situations are not considered. Finally, a more basic power consumption is given. The difference in electrical power consumption caused by subjective factors is not considered, which may have a large error with the actual power consumption.

The first situation is the type where the electrical conditions inside the house are relatively simple. In summer conditions, people spend more time in outdoor activities. Various lakes, forests and outdoor recreational activities occupy a lot of people's time. In addition, Finland has sufficient sunshine hours in summer, and lighting power consumption also decreases. Overall daily electricity consumption will decrease. Here we only take a simple induction stove, refrigerator, lighting, sauna, LCD TV, and coffee machine.

In the lighting load, we select an intensity of 200lux to match a lower power consumption. We can use formula (1) from[3](page 39) to convert the light intensity into power. Substitute the light intensity, light area, and lighting efficiency into the formula to get the power.

$$P_{light} = \frac{E_v \cdot \mathrm{A}}{\eta} \tag{1}$$

Where

$Pwatts$	Input value in watts [W]
Ev	Lux [lx]
A	Area of illumination [m2]
η	Luminous efficacy [lm/W]

Except for lighting power consumption, the power of other electrical appliances takes a lower average value. To determine the daily electricity usage, we multiply the appliance's rated power by the duration of use to get the daily electricity usage (in kWh), and then multiply that by the total length of the usage period to get the total electricity usage. The electricity consumption of the sauna is calculated separately, because according to statistics, the per capita sauna usage frequency in Finland is at least once a week. To save electricity consumption, here we take once a week. Specific summer electricity consumption distribution shown as table 1

Table 1. Electricity consumption distribution for summer case model

Appliances	Level of use	Consumption [kWh/Day]	Total consumption [kWh/60days]
Induction stove	1 h/day	1.8	108
Fridge	24 h/day	0.5	30
Lighting	2 h/day	0.3	18
Sauna	1 h/week	4.5	36
LCD TV	2 h/day	0.2	12
Coffee machine	20 min/day	0.2	12
Solar water heater	1 h/day	0.3	18
Total		3.94	234

2.2 Review of existing off-grid solutions

Chapter 2.2 is divided into two parts. The three subsections will focus on small-scale solar power generation systems. Part 2.2.1 will introduce the basic structure of small-scale solar power generation off-grid systems and introduce each component. Next, 2.2.2 will discuss different possible solutions based on summer case model, and on this basis, look for possibilities to improve cost performance.

2.2.1 Overview of PV off-grid system

Stand-alone photovoltaic Systems as known as off-grid system are typically divided into 3 types depending on the battery storage and the hybrid power source. Direct PV system, is the simplest type, only consist of PV array, power conditioner and the load. The DC output is directly transferred to the load, in this case, the load can only be operated in sunlight.

Those designs are suitable for typical uses in ventilation system, and small circulation pumps in solar thermal water heating systems[4] (page 27). In this system, some power conditioners may be used between the array and the load, such as the maximum power point tracker (MPPT), which is a DC-DC converter that can be used to better utilize the maximum power of the array at any time. to optimize the output to the load. The connection figure is shown below.

Figure 3. Direct PV connection

The other two are very close and both have batteries as power storage for emergency backup or for use when sunlight conditions are not sufficient. These two systems with storage structures are more common and have a wide range of applications. The difference between them is whether there are multiple sources of power generation. Hybrid power generation uses other power generation sources including wind power generation, grid-connected power generation, and other power generation sources to drive the load. In this case, because there are more power sources, it has a more stable advantage than a system with only a single battery energy storage, but at the same time, because the system is too complex, for example, when other power sources are stored in batteries, a rectifier is needed to convert alternating current into direct current. Nowadays, there are more advanced power conditioners like periodic equalization, energy metering, temperature compensation, multi-power source management capability (such as PV-wind-diesel hybrid systems), and monitoring with remote access through modems[4](page 28). there are often more problems that need to be dealt with. The PV-hybrid connection figure is shown below.

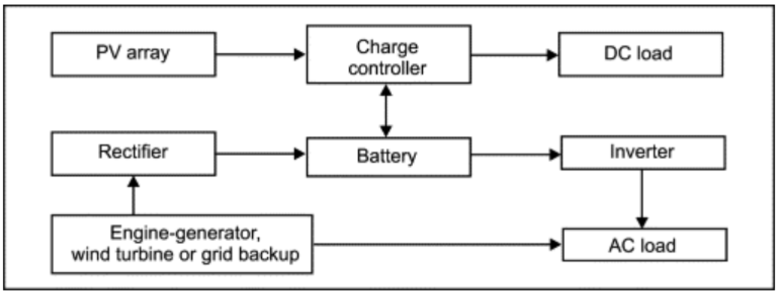


Figure 4. PV-hybrid connection [5]

The last system introduced, also is the only system discussed in this thesis, is PV-battery system. There is only one power source, and a battery as storage can be use during nighttime.

Compared with hybrid sources, this single-source independent power generation system has lower investment costs for households. At the same time, because the system is simple, there are fewer problems with later maintenance, and it is easier to handle. And due to Finland's unique geographical location, the temperature will not be too high. During the photovoltaic power generation process, the problem of photovoltaic cell unit power generation efficiency reduction caused by high temperature will not occur. This single photovoltaic power generation system is very suitable. Follow with PV-battery connection.

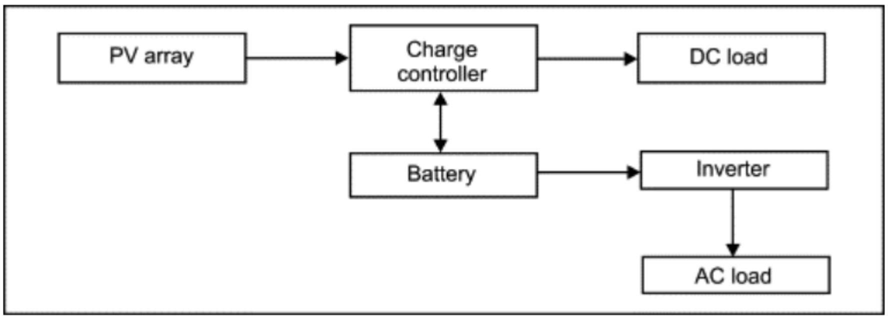


Figure 5. PV-battery connection [5]

Then go through components in the PV-battery system. First from photovoltaic panels, the main competitors in PV market are predominantly monocrystalline, polycrystalline, and amorphous silicon cells. While various other materials are under development, they have not reached the production scale achieved by silicon cells. Traditional monocrystalline cells have efficiencies of 13% to 16% and polycrystalline cells have efficiencies of about 12% to 14%, but by using new monocrystalline cells with embedded contacts and grooved surface areas, relatively high efficiency (about 18%). Amorphous silicon is the least efficient of the commercially available silicon-based products; although its efficiency is in the 8% to 10% range when brand new, the material's instability reduces efficiency to about 3% to about 6% stable efficiency after several months of exposure to sunlight[4](page28). At the same time, after recent years of development, the production process and equipment of single crystal panels have also been continuously improved and innovated. For example, the use of diamond wire cutting, black silicon technology, PERC cells, etc. can improve the utilization rate of silicon materials and reduce the thickness of silicon wafers to improve the conversion efficiency of cells[6]. At the same time, the prices of raw materials for monocrystalline panels are also gradually declining, such as silicon materials, glass, aluminium frames, etc.

This is related to the expansion of China's production capacity and the changes in supply and demand in the international market, thus achieving high efficiency.

The cost of monocrystalline panels continues to decrease. From the latest comparison of the monocrystalline and polycrystalline panel markets, we can find that the prices of the two types of panels will be almost the same in China in 2023. The silicon branch of the CNMIA reports that prices for monocrystalline silicon currently range from CNY 148 ($21.50)/kg to CNY 182/kg, while polycrystalline silicon prices are between CNY 145/kg and CNY 177/kg[7]. Therefore, monocrystalline panels will be used in subsequent panel selections.

After completing the setting of the panel type, it is also necessary to determine the tilt angle of the photovoltaic array. In order to increase the light efficiency, the best incident angles in different dimensions and seasons are different. Therefore, the tilt angle of the array must be adjusted frequently. Commonly used adjustment methods include manual method, array tracking method, and condenser and reflector.

Among them, the manual method is the simplest and most direct, but it requires human manipulation. At the same time, it is necessary to determine the accuracy of the tilt angle by stable and accurate means to avoid excessive errors. The array tracking method uses mechanical equipment and sensors to continuously monitor and track the direction of the sun, and automatically adjusts the array tilt angle through mechanical control[4](page 28). However, since the moving parts of the mechanical device require maintenance, repair and replacement, the cost of use is increased in disguise. Finally, there are the concentrator and the reflector. The concentrator achieves the effect of amplifying sunlight by placing lenses on the photovoltaic panel. The reflector places mirror-like reflectors around the photovoltaic panel to allow the panel to absorb additional sunlight. Concentrators are difficult to use at home due to their high cost and complex systems and cooling. Reflectors are not suitable for home use due to their large footprint and unsightly appearance. Therefore, in order to improve the utilization efficiency of sunlight, the most cost-effective household method at present is to manually adjust the tilt angle of the panel bracket according to the seasons to match the optimal tilt angle.

There are three common batteries, lead-acid batteries, lithium batteries, and nickel-chromium batteries, as shown in Figure 6. Nickel-chromium batteries and lead-acid batteries have been developed for a long time and are relatively mature. Lithium-ion batteries have developed rapidly in recent years and have gradually become a new choice. In the following paragraphs, the advantages and disadvantages of the three types of batteries will be discussed, and the final decision will be made to use them in the model.

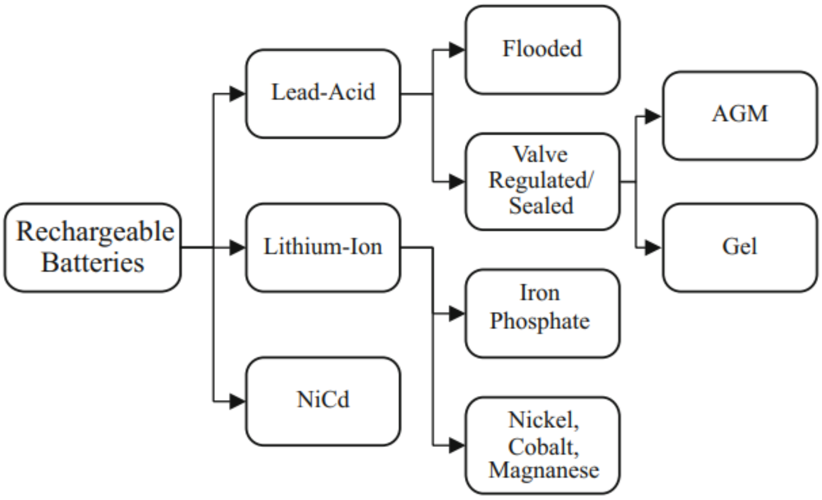


Figure 6. battery types[8](page 214)

Let’s first discuss lead-acid batteries. In microgrids, lead-acid batteries are often widely used because of their low cost and mature technology. Lead-acid batteries have a history of more than 100 years. The two common lead-acid batteries are Flooded lead–acid batteries and Sealed Lead–Acid batteries. Among them, flooded lead-acid batteries are the most common and mature type of lead-acid batteries. The electrolyte of this type of battery is liquid, and the battery is not sealed and is removable. It is designed to add pure water to supplement the water lost due to the electrolyte reaction. And care must be taken to add water to the battery within a moderate amount and to prevent accidental spillage of harmful acidic electrolyte. Flooded lead-acid batteries can also leak. Their open circuit voltage in the charged state tends to be slightly lower than other lead-acid batteries.

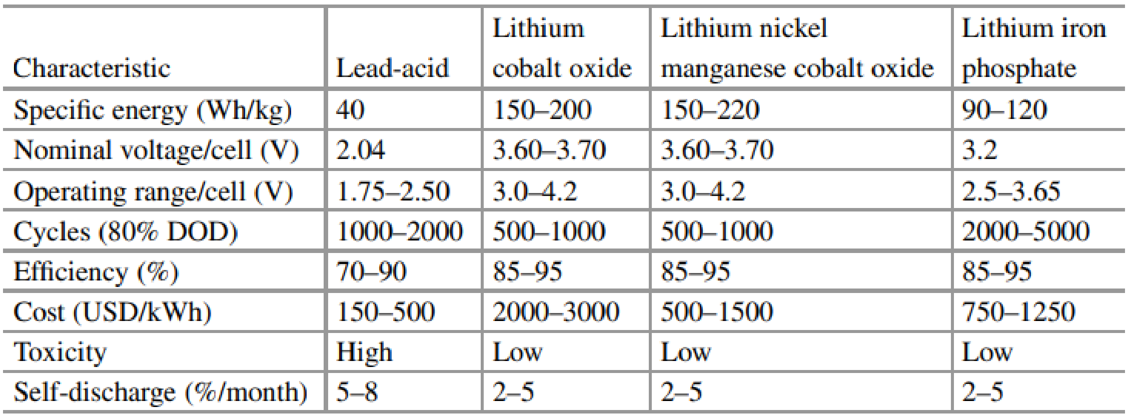
Then there are sealed lead-acid (SLA) batteries, which have the advantage that any gases produced can potentially recombine. Among them, hydrogen and oxygen are recombined into water, so there is no need to add water manually, thus avoiding maintenance. Sealed containers also prevent spills, so SLA cells are common in nonstationary applications, such as home solar systems. They are maintenance-free, leak-proof and suitable for a variety of moving scenarios. The downside is that SLA batteries tend to be more expensive than flooded batteries.[8](page 222-223)

There are two common subtypes of SLA batteries: gel batteries and absorbed glass mat batteries. Gel batteries are thickened by introducing silica so that the electrolyte does not move in large quantities. Absorbed Glass Mat (AGM) cells have a fiberglass structure built into them to absorb the electrolyte. Their respective relative advantages depend on the specific model and the price given by the manufacturer, and users need to compare them one by one.[8] (page 224)

Then there are nickel-chromium batteries. Nickel-chromium batteries also have a history of 100 years and are also highly popular. Its advantages are higher power and energy density than lead-acid batteries, about 500-75Wh/kg, high cycle times (about 3500 times) and the ability to work well at low temperatures (from − 20°C to − 40° C) and requires little maintenance[9].

However, the disadvantage is that chromium in nickel-chromium batteries is a toxic component, which poses environmental challenges, and the material cost is higher (about 1,000 US dollars/kWh)[9], which is almost ten times that of lead-acid batteries. Moreover, the self-discharge rate is high and the battery capacity decreases quickly, which requires huge costs in the later stages of use. Since the models in this article are all used in summer, the use of nickel-chromium batteries at low temperatures does not occur, and nickel-chromium batteries are excluded from the selection[10].

Finally, we discuss lithium batteries. Lithium batteries were put into large-scale application relatively late and became popular around the 1990s. Compared with lead-acid batteries, lithium batteries have many advantages, including faster charging speed and higher energy density than lead-acid batteries, less severe high discharge losses and slower automatic discharge. discharge rate. These characteristics give lithium batteries longer cycle life and better late-life performance, even up to 10,000 times without deep discharge or overcharging. And they have good thermal stability, making them less prone to thermal runaway and more tolerant of overcharging without requiring maintenance. The disadvantage is that lithium batteries themselves are prone to safety problems under high temperature and overcharge conditions, so compared with lead-acid batteries of the same capacity, the internal safety cost of the battery will be higher. The following is a comparison chart of three common lithium batteries and lead-acid batteries. After comprehensive consideration, the preferred battery is Lithium iron phosphate battery. It has the longest life and high efficiency when the price is not too high. It is the first choice for this model, followed by solid lead-acid battery with great price advantage[8](page 248-253).



Characteristic	Lead-acid	Lithium cobalt oxide	Lithium nickel manganese cobalt oxide	Lithium iron phosphate
Specific energy (Wh/kg)	40	150–200	150–220	90–120
Nominal voltage/cell (V)	2.04	3.60–3.70	3.60–3.70	3.2
Operating range/cell (V)	1.75–2.50	3.0–4.2	3.0–4.2	2.5–3.65
Cycles (80% DOD)	1000–2000	500–1000	500–1000	2000–5000
Efficiency (%)	70–90	85–95	85–95	85–95
Cost (USD/kWh)	150–500	2000–3000	500–1500	750–1250
Toxicity	High	Low	Low	Low
Self-discharge (%/month)	5–8	2–5	2–5	2–5

Figure 7. Comparison of batteries[8](page 253)

Finally, are regulators in the system. According to the DC-AC system we choose, the required regulators must include an inverter and the basic maximum power point tracker for battery charging. (MPPT) is commonly used in charge controllers and is used to optimize the output of the photovoltaic array, MPPT can achieve the maximum output of the photovoltaic array by changing the array input voltage (while maintaining the battery charging voltage).

It may also include other regulators to match the load power or to protect the battery. The specific situation needs to be known during the detailed calculation process. Other regulators that may appear will be discussed in the next section.

2.2.2 Solutions for summer case model

The modelling is carried out in the following order, from determining load characteristics, voltage selection, battery pack design, photovoltaic array design, Charge Controller Selection, to calculations and determinations one by one. Calculation steps are based on Louie, Henry. (2018)[8](page 396-412 pages).

Peak load can be the sum of the wattage of all appliances, but this means using all the appliances in the house at the same time, which is indeed a theoretically possible peak, which is often unrealistic because people usually don't or are very It is difficult to use all electrical appliances at the same time. We need to introduce a method to simulate peak power usage.

Among the load parameters, there is a parameter called demand factor (DF)[8](page 358), which is used to describe the peak load. It is the ratio of the maximum load at any time in the user's daily use environment to the sum of the load of all the user's electrical appliances. As shown in Equation 2. Where $P_{a,max}$ is the sum of the maximum power starting from the a=1 electrical appliance to a total of A electrical appliances. Under normal circumstances, DF will not exceed 1 and is expressed as a percentage. By multiplying the maximum load by DF is the actual peak load we can use, which can minimize the size of the inverter and thus reduce costs. Because we usually take the peak load to plan the inverter.

$$\mathrm{DF} = \frac{P_{peak}}{\sum_{a=1}^{A} P_{a,max}} \tag{2}$$

By observing the power of each electrical appliance, it was found that the maximum power appliance is the electric sauna furnace, with a power of 4.5kw, which is much higher than the sum of the power of other electrical appliances. Therefore, even if the specific power consumption is not known, it can be known that the peak load will inevitably occur. In the use scenario of electric sauna heater. Therefore, you only need to simulate the load situation when the electric sauna furnace is running to get the peak load. We assume that only refrigerator, lighting equipment and electric sauna heater are used at the same time, so the peak power is 4500w+150w+20w=4650w.

Next, determine the system voltage. In order to be compatible with the inverter and charge controller voltage, there are three commonly used voltages of 12, 24, and 48V to choose from. As a rule of thumb, use 12 V for systems with loads less than 1 kWh/day and 24 V for systems with loads between 1 kWh/day. 4 kWh/day, 48V when the load exceeds 4 kWh/day. The average daily consumption of the summer model load is 3.94kWh, so 24V is selected.

Then calculate the inverter parameters. First, you need to calculate the power of the inverter based on the peak load. In general, the rated power of the inverter should be at least as large as the peak load, and a design margin needs to be applied to mitigate the possibility that the peak value will be underestimated. situation, the calculation formula 3 is as follows.

$$\text{Inverter Power Requirement} = \text{Peak Load} \times (1 + \text{Design Margin}) \tag{3}$$

In general, the rated power of the inverter is related to the temperature. Most of the rated power is based on 25 degrees Celsius. If the ambient temperature will continue to be higher than the rated temperature, an inverter with a larger capacity will be required. The temperature in Finland is low in summer. If the inverter is placed appropriately, it is difficult to exceed 25 degrees Celsius, so 0.1 is selected as the design margin. The design margin refers to the proportion beyond the original rating designed to take into account unexpected situations. The situation in an inverter is usually 0 to 0.2. After calculation, it is found that The minimum required power is 4.65×(1+0.10) =5.12 kW.

Then calculate the maximum DC current, as shown in Equation 4.

$$\text{Max. Inverter DC Current} = \frac{\text{Required Inverter Power}}{\text{Nom.Battery Voltage} \times \text{Inverter Efficiency}} \tag{4}$$

In formula 4, the required inverter power is the calculated 5.12kw, and the battery voltage is consistent with the inverter voltage, which is 24V. Inverter efficiency varies depending on the specific model. Therefore, taking the typical inverter efficiency curve as an example (in Figure 8), the average efficiency of 85% is the inverter efficiency. In actual situations, the average efficiency can be changed according to the equipment model.

So $\text{Max. Inverter DC Current} = \frac{5115}{24 \times 0.85}$ = 250.74 A, rounded to 251A.

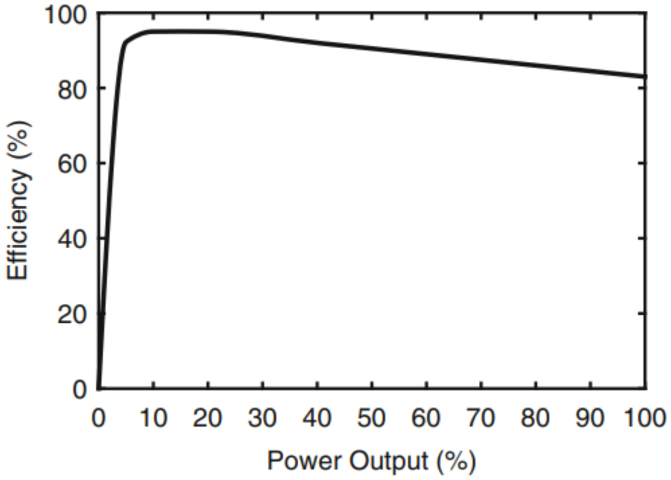


Figure 8. Typical inverter efficiency curve[8]

In addition, it is also necessary to consider whether the inverter is bidirectional. In this modelling, if DC power is needed, it will be obtained directly from the battery and DC bus, so that AC will not change to DC. Also to prevent permanent damage caused by deep discharge, the inverter must have a low voltage disconnect (LVD) function. Users can select some inverters based on estimated voltage, rated power, and maximum DC current.

Now we can design the various parameters of the battery, first calculate the average battery load, as shown in Equation 5.

$$\text{Avg. Battery Load} = \frac{\text{Avg.Daily Load}}{\text{Inverter Efficiency}\times\text{Nominal Battery Voltage}} \tag{5}$$

The average load is 3.94 kWh. Enter the value into equation 5 and calculate as follows

$$\text{Avg. Battery Load} = \frac{3940}{0.85\times 24} = 193.14\ \text{Ah}.$$

Next calculate the minimum rated capacity of the battery bank. The calculation formula is shown in equation 6. Days of Autonomy refers to the number of days that the battery bank can provide an average load before being depleted without charging. It is used to deal with extreme situations such as component damage and continuous rain for several days. The number of days of autonomy specified is usually between 2 and 12. We will choose four autonomous days to deal with the increased number of rainy days in Finland in June and July. It can be seen from Figure 9 that in June and July, the number of consecutive rainy days does not exceed 3 days, so 4 days are selected to prevent this situation. Since the entire life cycle of the battery is within the consideration of the minimum rated power, the capacity decline at the end of the battery should also be included. Most manufacturers define the maximum capacity at the end of the service life as 80% of the initial capacity. Here, the EOL (End of Life) rating is set to 0.8.

$$\text{Cx} = \frac{\text{Days of Autonomy}\times\text{Avg.Battery Load}}{\text{End of Life Rating}} \tag{6}$$

x is the current corresponding to the minimum capacity state. Since the battery discharge power changes with the current, it needs to correspond to the power under different currents, which corresponds to 251A here. Substituting the corresponding values into the following results:

$$C_{251} = \frac{4\times 193.14}{0.8} = 965.7\text{Ah}$$

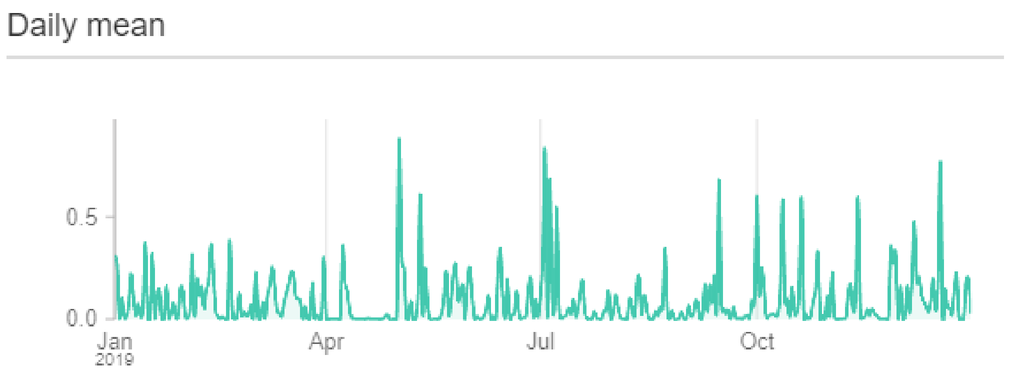


Figure 9. Precipitation days in Lappeenranta[11]

Since the battery capacity cannot be 0 after Days of Autonomy, the depth of discharge needs to be considered. According to most typical DOD values are 0.5 to 0.8, we choose 0.8 here to minimize the cost. So the final battery bank quota is as follows:

$$C'_{251} = \frac{C_{251}}{0.8} = 1207.13 \text{ Ah.}$$

Next we estimate the number of cycles in the battery bank by calculating daily DOD to select a battery type that balances both cost and performance. As shown in Equation 7. The calculated DoD_{daily} is 16%. We can obtain the number of cycles corresponding to the value based on the dod-cycle number curve of the battery. The corresponding curves of lead-acid batteries and lithium iron phosphate batteries are as follows.

$$\text{DoD}_{daily} = 100 \times \frac{\text{Avg.Battery Load}}{C'_x} \tag{7}$$

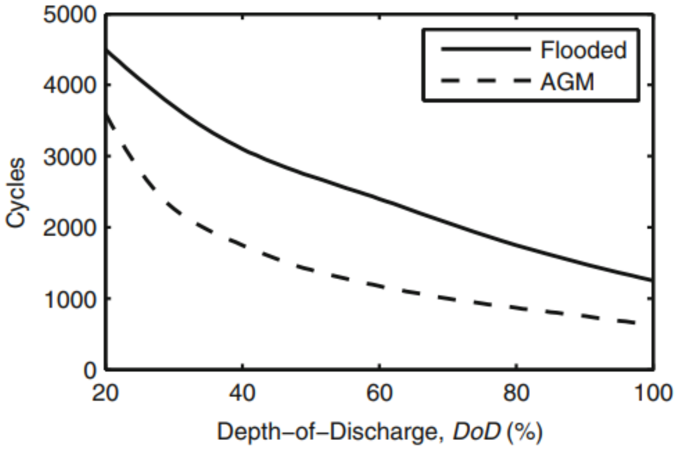


Figure 10. Cycle life of lead–acid batteries decreases with the depth-of-discharge[8](page 246)

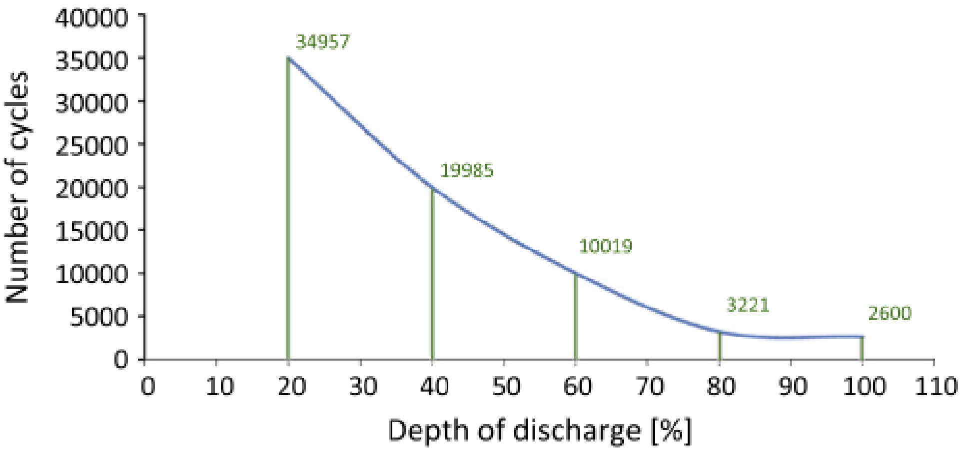


Figure 11. Cycle life of lithium iron phosphate batteries decreases with the depth-of-discharge[12]

Due to the long autonomy days and the use of high-power electrical appliances (sauna heaters), the estimated load is larger and the daily load is lower, which in turn leads to lower DOD. We take 20% as an approximate value, which can be read from the figure. If When using lead-acid batteries, the number of cycles is about 3,500. One cycle per day is equivalent to ten years of use, which is a very good life. When it comes to lithium phosphate batteries, the number of cycles is about 35,000, and the life becomes extremely long, almost 100 years, this is unrealistic. At the same time, lithium phosphate batteries seem to be unable to exert their advantages of high energy density at too low DOD, so we choose AGM lead-acid batteries, which are low-priced and have excellent and reasonable use. The service life can be updated along with other components in a longer cycle, reducing management costs.

After calculating the corresponding battery library characteristics, the number and arrangement of batteries can be determined. According to the knowledge of series and parallel connection, batteries in series can increase the voltage, and in parallel can increase the current. We calculate the corresponding number of batteries in series and parallel, Determine the total number of batteries. As shown in Equation 8 and Equation 9.

$$\text{Number of Series Batteries} = \frac{\text{Battery Bank Nominal Voltage}}{\text{Battery Nominal Voltage}} \tag{8}$$

$$\text{Number of Parallel Batteries} = \frac{\text{Required Battery Bank Capacity}}{\text{Battery Capacity}} \tag{9}$$

The total number of batteries is Number of Series Batteries multiplied by Number of Parallel Battery Strings. We assume that Number of Series Batteries is 8 and Number of Parallel

Battery Strings is 5, then the total number of batteries is 5×8=40, as shown in the figure below. In practical situation, users will encounter batteries with different prices and different capacities, which are related to the market the user is in, so we will not discuss them here. Users can bring in different battery voltage values and battery capacities to calculate by themselves.

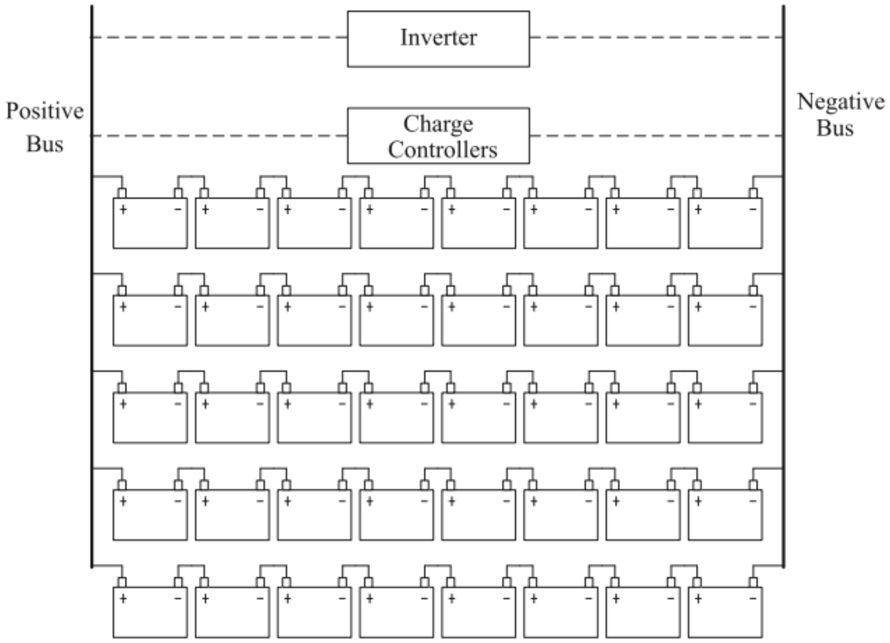


Figure 12. Number of batteries in the battery bank.[8]

Next is the planning of the PV array. First, we need to consider the calculation of the capacity factor. The capacity factor refers to the ratio of the estimated power generation over a period to the power generation generated continuously at rated power. As shown in Equation 10. where $\hat{E}$ is the estimated production, matching the period T, and P_{rated} is the rated power. A higher energy factor indicates a higher conversion rate and better utilization of the conversion technology. Typical values for PV panels are between 0.15 and 0.24.[8](page 369)

$$\text{Capacity Factor} = \frac{\hat{E}}{\mathrm{T} \times P_{rated}} \tag{10}$$

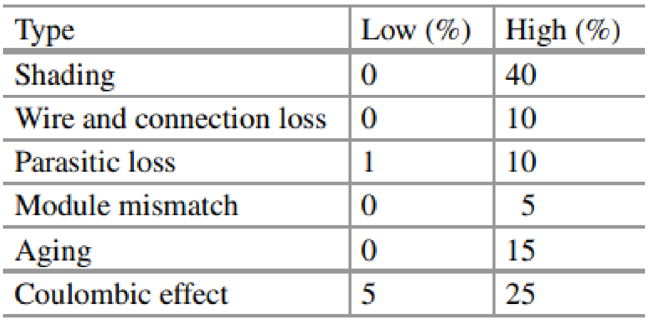
In the PV system, $\hat{E}$ and P_{rated} are replaced and simplified respectively, and the capacity factor expression with sunshine intensity as the variable can be obtained. The mathematical process will not be elaborated here. The simplified expression 11 is as follows, where $\bar{R}$ is radiation intensity.

$$\text{Capacity Factor} = \frac{\bar{R}}{24} \tag{11}$$

Obtain the solar intensity of Lappeenranta from the database, we know that the intensity in June and July are 5.53kWh/m²/day and 5.29kWh/m²/day respectively. Here we take the average value of 5.41kWh/m²/day and bring it into Equation 10 to calculate , the capacity factor is 0.23. Without considering other losses in the ideal case, we can calculate the rated power of the PV array as shown in Equation 12. Substituting the corresponding values, we get $P_{PV\ rated}$ = 0.92kW.

$$P_{PV\ rated} = \frac{\text{Avg.Daily Load}}{24\times\text{Capacity Factor}\times\text{Inverter Efficiency}} \tag{12}$$

Next, we consider the loss. There are many factors that affect the loss. There are situations where the array is blocked by trees or other objects, dust accumulation, resistance loss in the circuit, standby consumption of the controller monitor, and components. The efficiency decreases due to aging. These specific loss rates are difficult to calculate. Some typical ranges of losses are given below. We assume that the total loss is 20%. In actual situations, it can be adjusted based on experience and environment.



Type	Low (%)	High (%)
Shading	0	40
Wire and connection loss	0	10
Parasitic loss	1	10
Module mismatch	0	5
Aging	0	15
Coulombic effect	5	25

Figure 13. Typical generation and storage losses[8](page 408)

Then there is the influence of temperature. As shown in the figure below, the power output of photovoltaic modules will decrease as the temperature increases. The standard operating temperature of photovoltaic panels is 25 degrees Celsius. According to the climate database, the average temperature in June and July in Lappeenranta is lower than 25 degrees Celsius. Therefore, The temperature loss is almost 0 and can be ignored.

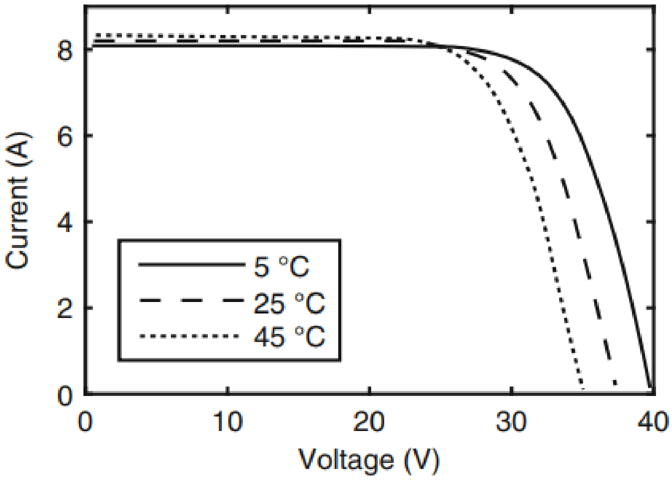


Figure 14. The effect of temperature on a PV I–V curve for a typical 285 W module[8](page 196)

Finally, there is the design margin. By additionally expanding the array capacity so that the power generation capacity slightly exceeds the capacity of the battery pack to supply the load every day, system stability can be improved. Photovoltaic array design margin KPV typically ranges from 0.1 to 0.2 (10 to 20%). Since there are continuous rains for several days in June and July, we choose a slightly higher value of 0.2. Finally, considering the impact of system loss, temperature loss and photovoltaic panel design margin, the final photovoltaic size can be calculated, P_{PV}=$P_{PV\ rated}$/0.8/1/0.8=1.44kW.

Next, plan the arrangement of the PV array and the selection of the charge controller. Since the photovoltaic array is directly related to the charge controller and battery, the voltage and current must be planned well and within the maximum current and voltage range of the charge controller. The voltage of the photovoltaic array should be less than the maximum voltage of the charge controller, which directly determines the maximum series length of the photovoltaic array, and the current of the photovoltaic array should be less than the maximum current of the charge controller, which directly determines the maximum number of parallel branches. The number of channels multiplied by the series length is the total number of photovoltaic panels required. We can use the number of photovoltaic panels multiplied by the rated power of the corresponding panel to check whether the total power meets the 1.44kW power required by the system. When it does not meet the requirement, We can change the selected current controller or select other specifications of photovoltaic panels until the maximum power is met. Or when the maximum current and voltage are met but the power is not met, we can also choose to split the photovoltaic array and connect it in parallel into several modules.

Finally, there are the constraints of the charge controller and the battery pack. It is necessary to ensure that the current provided by the charge controller is less than the maximum current recommended by the battery manufacturer to prevent damage to the battery. Different battery manufacturers have different current limits. We only need the total current of the battery pack to be greater than the charging The current provided by the controller is enough. That is to say, the total current of the photovoltaic array < current of the charge controller < maximum charging current of the battery pack.

3 Results

3.1 The solution for a average summer house

Now we summarize the results of the previous chapter. The previous chapter planned the specifications and selection criteria of important components in the system, including PV arrays, batteries, charge controllers, and inverters. The system is shown in the figure below. The problem of DC and AC bus access to the house is not considered, because the house also needs wiring under the grid-connected solution. This modelling only discusses the planning and cost of photovoltaic systems and necessary accessories.

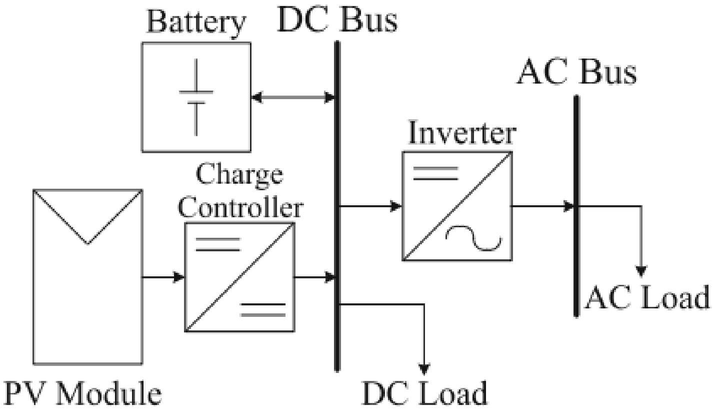


Figure 15. Final PV structure diagram[8](page 92)

First determine the power of the inverter according to the load, which is 5.12kW. And the maximum DC current of the inverter is 251A. The battery pack discharge current should be less than the maximum DC current of the inverter. The total capacity of the battery pack is calculated to be 1207.13Ah. The fastest discharge time under the maximum DC current is calculated to be 1207.13Ah/251A=4.81h. When users choose batteries, they can filter the battery pack capacity roughly within this range based on the sample of 251A, 4.81h. And based on the battery voltage, determine the number of batteries in series for each parallel branch, and determine the maximum current of each parallel branch based on the maximum DC current.

With these standards, we can calculate and select the most suitable type one by one from the battery specifications given by the dealer. The inverter can also be selected based on the set maximum continuous output power of 5.12kW, input voltage of 24V, and maximum DC current of 251A. After meeting the input voltage and output Finnish standard electricity consumption of 230V, 50Hz, the output of the inverter Sometimes there is a big gap between the power and the maximum DC current. We can choose to meet the output power while allowing the current to exceed the excess, which makes it easier to plan the battery pack.

Then there are the PV panels and charge controllers. Taking into account losses, temperature effects, and increased rainfall, the total required PV module power is finally calculated to be 1.44kW. Regarding the choice between the two, there are detailed instructions in Chapter 2.2.2 Calculating the total module power. If users find it difficult to make a choice, the most convenient way is to purchase a module controller and PV module combination provided by the manufacturer.

3.2 Cost-effectiveness considerations

After designing the system, there are still some considerations that can reduce consumption costs without excessively affecting system performance. For example, when setting up the inverter, we use the maximum discharge current to determine the capacity of the battery pack. This is a conservative estimate. If we have previous experience or similar system use cases and ensure sufficient capacity, we can use the average current to plan the battery pack, reduce the capacity of the battery pack but still meet the usage requirements, and save costs.

In addition, there is also a difference in the selection of battery packs between lithium batteries and AGM batteries. In this case, the average daily load is lower, and the peak load is higher, resulting in a lower DOD of the battery pack, so AGM lead-acid batteries are used. It also ensures a long service life. If the daily average load is high or close to the peak load during actual planning. There will be situations where lead-acid batteries have a shorter service life, in which case lithium batteries can be considered. When the DOD is 80%, the number of cycles is still more than 3,500. If you find a suitable sales channel to buy it, the cost within 10 years will be lower than that of lead-acid batteries (including replacement costs).

In addition, there is a need to consider the necessary accessories of the main components, such as the cost of photovoltaic mounting brackets. Choosing manually adjustable photovoltaic brackets can achieve maximum economic benefits. There is also a battery pack monitor for monitoring battery status. There are also different packaging, wires, switch costs, etc. that are different from grid-connected installations, which all need to be taken into consideration.

4 Conclusions

The previous chapters of this bachelor's thesis have discussed the stand-alone solar system background and technical design of domestic microgrids for remote villas in summer. Various possible technical solutions were discussed, and finally the battery bank capacity and PV module capacity of the microgrid system with an average daily load of 3.94kWh and a peak load of 4.65kw were determined through computational modelling, which are 1207.13Ah and 1.44 kW respectively. The possibility of improving user economic benefits and battery selection issues under higher load conditions are discussed. This time, through calculation and simulation methods, specific methods for battery type selection, inverter and PV panel capacity selection are given while being as close to the actual conditions as possible. However, there is a lack of specific data and no demonstration can be given on specific PV module and charge controller examples. However, the advantage of only calculating the selection criteria is that it increases the breadth of the user's selection range during actual design. The user can find corresponding components on the market under any parameters within the result range.

The problem that remains unresolved is that due to the variability of the market and the lack of data on market prices of components, it is impossible to determine the lowest-priced solution under this condition. In practice, since the specific data is often uncertain, there is almost no unique solution or "Best" design. Similarly, cost comparisons of off-grid and grid connections cannot be made due to the lack of data on long-distance grid connection costs in Finland.

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