GERMAN - MONGOLIAN INSTITUTE FOR RESOURCES AND TECHNOLOGY

The present work was submitted to

the German-Mongolian Institute of Resources and Technology

Feasibility Study of Solar PV Systems for Residential Power Supply: Standalone with battery vs Grid-Tied with Net Metering

Bachelor's Thesis

By

MUNGUNSUKH Odbayar

Study program: Energy and Electrical Engineering

Student ID: B2100361

1st Supervisor/Examiner: Prof. Dr. Ariunbolor Purvee

2nd Supervisor/Examiner: Mr. Bold Enkhbold

Ulaanbaatar/Nalaikh

2026

Statutory Declaration

Odbayar, Mungunsukh B2100361

I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Feasibility Study of Solar PV Systems for Residential Power Supply: Standalone with battery vs Grid-Tied with Net Metering

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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1. Introduction

Over the last twenty years, the world has been moving more and more toward renewable energy. There are two big reasons for this: the need to cut greenhouse gas emissions, and the need to make sure countries have a stable energy supply in the long run. Out of all the renewable options, solar photovoltaic (PV) systems have grown the fastest, both for large power plants and for ordinary households. The price of solar panels has dropped a lot, batteries have improved, and there are now good simulation tools available, which means it is finally possible to do detailed feasibility studies for specific sites instead of just general ones like in the past.

Mongolia is a really interesting place to study this topic. It has some of the highest solar irradiance levels in Asia, with around 250 to 300 sunny days per year and an average annual global horizontal irradiance (GHI) of more than 1,400 kWh per square meter in most areas. Even with this great solar resource, Mongolia still depends mostly on a few coal-fired combined heat and power plants located in Ulaanbaatar, Darkhan, and Erdenet. Many households on the edges of these cities are either not connected to the grid at all, or they suffer from frequent power cuts during the winter when demand is highest. So there is a clear gap between how much solar potential the country has and how underdeveloped the distribution network is, which is why site-specific feasibility studies are needed to help people make good investment decisions at the household level.

Erdenet, the second-largest city in Mongolia and the center of Orkhon Province, is a good example of this problem. The house I studied in this thesis is located about 400 meters away from the nearest connection point of the Erdenet low-voltage distribution network. Because of this distance, the household has to make a real and quite expensive choice between a few different options: paying to extend the grid and then installing a grid-tied solar PV system with net metering, or installing a standalone (off-grid) solar PV system with batteries that does not need the grid at all. Each option has its own costs, technical requirements, risks, and long-term financial effects, and you cannot really compare them properly without doing a study based on the actual site.

Another thing that makes this study different from similar ones done in warmer countries is the Mongolian winter. From November to February, peak sun hours drop to

only about 1.5 to 2.1 hours per day, temperatures often go below minus 20 degrees Celsius, and electricity use in homes goes up a lot because of electric heating. These conditions make the standalone system design much harder and bring up important questions about whether such a system can stay reliable through the whole winter.

For the simulations in this thesis, I used HOMER Pro, which is one of the most well-known tools for designing distributed energy systems and is widely used in both research and engineering work. HOMER Pro tests thousands of possible system setups using the actual hourly solar and load data from the site, and then finds the most cost-effective design for each option. It also gives detailed technical and economic results, which makes it easier to compare the different system configurations.

1.1 Background and Motivation

Mongolia's energy sector is going through a lot of structural changes right now. The Renewable Energy Law, which was first introduced in 2007 and updated several times after that, sets a national target of getting 30 percent of primary energy from renewable sources by 2030. Solar PV is seen as one of the main technologies that will help reach this target. However, residential and small-scale solar projects have been growing quite slowly. One reason is that the rules for connecting small systems to the grid and for net metering are still not fully developed in many provinces. Another reason is that household-size battery storage has only recently become affordable, mostly because lithium-ion battery prices have dropped a lot in the last few years.

At the household level in peri-urban areas of Mongolia, the energy situation creates real practical problems. Families living in places that are not yet connected to the distribution grid usually depend on diesel generators, which are expensive to run and need a lot of maintenance, or on coal stoves, which add to the serious winter air pollution that has been well documented in Ulaanbaatar and is now becoming worse in smaller cities like Erdenet too. For households living in the transitional zones at the edge of the city, solar PV is not just a more environmentally friendly choice. It can also be a better practical and economic option compared to using fossil fuels or paying for a grid extension.

One of the most important questions in this decision, and also the main new contribution of this thesis, is how far away from the main grid a household has to be

before a standalone PV system becomes cheaper than a grid-tied one. This distance depends on several things: the cost of extending the grid per meter, the local electricity tariff, how much solar resource the area has, and the household's own energy demand pattern. This thesis looks directly at this threshold question and tries to provide a general framework that can help with decision-making for peri-urban households not only in Orkhon Province but also in similar regions across Mongolia.

1.2 Problem Statement

The main problem this thesis tries to answer can be described like this: considering the solar resource, the seasonal temperature changes, and the residential electricity demand of a site located 400 meters away from the Erdenet distribution network in Orkhon Province, Mongolia, which solar PV configuration is the better choice over a 25-year project lifetime — a standalone system with battery storage, or a grid-tied system with net metering? In other words, which option is more technically reliable and more economically reasonable for supplying electricity to the household? On top of that, the thesis also asks: at what distance from the main grid does the answer to this question actually change, and how does this distance depend on different economic and policy factors?

1.3 Objectives

The specific objectives of this thesis are:

1. To assess the solar energy resource at the Erdenet study site using satellite-derived GHI data from PVGIS and NASA POWER, with temperature correction applied for cold-climate performance adjustment.

2. To develop a seasonally disaggregated residential electricity load profile incorporating base loads and the dominant winter electric heating demand.

3. To simulate and optimize both system configurations using HOMER Pro, identifying the cost-optimal component sizes and operating strategies for each.

4. To conduct a comprehensive comparative analysis of both systems using NPC, LCOE, NPV, IRR, and simple payback period as primary financial indicators over a 25-year horizon, with all values reported in Mongolian Tögrög with USD equivalents.

5. To perform a systematic sensitivity analysis across six key uncertain parameters to test the robustness of the primary conclusions.

6. To determine the critical distance threshold from the main grid beyond which standalone PV becomes more economical than grid-tied PV for a residential load profile representative of Erdenet conditions.

7. To provide a clearly justified, evidence-based recommendation applicable to the study site and to peri-urban households throughout the region.

1.4 Scope and Limitations

This study focuses on two solar PV configurations — a standalone system with lithium-ion battery storage and a grid-tied system with net metering — for a single-family residential site in Erdenet, Orkhon Province, Mongolia. Other options such as diesel generator backup, wind energy, or community-scale systems are not included, since they are outside the boundaries of this research. A project horizon of 25 years is used, which matches the typical warranted lifetime of monocrystalline PV modules. All costs throughout the thesis are written in Mongolian Tögrög (₮), with the equivalent United States Dollar (USD) values shown in brackets.

There are three main limitations that need to be mentioned. First, the solar irradiance data come from satellite-based reanalysis instead of from on-site pyranometer measurements, which means there is around ±5 to 8 percent uncertainty in the annual yield estimates. Second, the net metering scenario uses an assumed feed-in tariff of 214.8 ₮ (USD 0.06) per kWh, because Mongolia has not yet finalized its residential net metering regulations. Third, the load profile was created from a household survey instead of from real metered data. All three of these limitations are dealt with later in the sensitivity analysis in Chapter 4.

1.5 Structure of the Thesis

Chapter 2 reviews the related literature on PV technology, standalone and grid-tied system design, HOMER Pro methodology, feasibility assessment methods, and the energy situation in Mongolia. Chapter 3 explains the complete materials and methods, with the HOMER Pro simulation framework as the main focus. Chapter 4 presents all the results, including the HOMER Pro optimization outputs, the technical performance comparison, the economic analysis, the sensitivity analysis, and the critical distance analysis. Finally, Chapter 5 discusses and interprets the findings, gives recommendations, and presents the conclusions of the study.

2. State of the Art

This chapter reviews the background knowledge that is needed to compare standalone and grid-tied solar PV systems. It covers the basics of PV technology, the design principles for both standalone and grid-tied systems, the way the HOMER Pro simulation tool works, the methods used for economic feasibility assessment, and what is currently known about solar resources and solar deployment in Mongolia. At the end of the chapter, the research gap that this thesis tries to fill is identified.

2.1 Solar Photovoltaic Technology Fundamentals

2.1.1 Photovoltaic Conversion Principles

Solar PV cells turn the solar radiation that hits them into direct current (DC) electricity through what is called the photovoltaic effect. In crystalline silicon cells, which are the most common type used commercially, photons that have more energy than the silicon bandgap of 1.12 eV push electrons across the p-n junction. This creates a voltage difference that drives current through the external circuit. Today's commercial monocrystalline silicon modules reach efficiencies of about 19 to 23 percent under standard test conditions (STC: 1,000 W/m² irradiance, 25 °C cell temperature, AM1.5 spectrum). For this study, monocrystalline modules were chosen because they perform better at low temperatures and have higher efficiency, which means less roof area is needed for the same installed capacity.

2.1.2 Temperature Effects on PV Performance

The output power of PV modules drops as the cell temperature goes up. This drop is described by the temperature coefficient of maximum power (Pmax), which is usually around −0.35 to −0.45 percent per °C above the STC reference temperature of 25 °C for crystalline silicon. When the temperature is below 25 °C, which is the case for more than half of the year in Erdenet, the output of the modules actually increases a little. The cell operating temperature is estimated using the Nominal Operating Cell Temperature (NOCT) parameter, which gives a cell temperature of about 20 °C above the surrounding air temperature at peak irradiance. This cold-climate advantage helps to make up for the lower winter irradiance in Erdenet, and it is automatically taken into account inside the HOMER Pro simulation engine through the temperature coefficient and NOCT inputs.

2.1.3 Peak Sun Hours and Irradiance

For sizing PV systems, the idea of Peak Sun Hours (PSH) is used. PSH has the same numerical value as the daily GHI in kWh/m²/day. It represents the equivalent number of hours during which the irradiance would have to be exactly 1,000 W/m² in order to deliver the same total daily energy. HOMER Pro uses the monthly average PSH values to generate an hourly irradiance time series for the whole year (8,760 hours), using its built-in Gaussian solar synthesis algorithm. This gives a more realistic, stochastic representation of how the irradiance changes from day to day and hour to hour.

2.2 Standalone PV Systems with Battery Storage

2.2.1 System Architecture

A standalone PV system is made up of a PV array, an MPPT charge controller, a battery bank, and an inverter, all connected to a common DC bus. The system has to be sized in such a way that it can supply the load even during the worst solar month, without depending on any grid backup. One important reliability parameter is the battery autonomy, which means the number of days the battery can keep supplying the load when there is no solar input at all. For residential off-grid systems in places where the irradiance varies a lot, this value is usually set to about two or three days.

2.2.2 Battery Technology Selection

For this study, lithium iron phosphate (LiFePO4) batteries were chosen instead of lead-acid ones. There are several reasons for this: LiFePO4 has a much longer cycle life (3,000 to 5,000 cycles at 80 percent depth of discharge), it keeps more of its capacity at low temperatures, it has a high round-trip efficiency of around 95 percent, and it has a good safety record in residential applications. HOMER Pro uses a throughput-based degradation model to estimate battery lifetime. This means it tracks how much energy has been cycled through the battery and schedules a replacement automatically when the cumulative discharged energy reaches the specified lifetime throughput. This approach reflects the real relationship between how deeply the battery is cycled and how long it lasts, which is more accurate than just assuming a fixed number of calendar years.

2.3 Grid-Tied PV Systems with Net Metering

2.3.1 Grid-Tied System Architecture

A grid-tied PV system connects the PV array to the utility grid through a grid-tie inverter, and it does not include any battery storage. The inverter converts the DC output from the PV modules into AC electricity that is synchronized with the grid. It also has anti-islanding protection, which disconnects the system from the grid during outages. Because there is no battery, the system cannot supply the household load when the grid is down, and this is a real disadvantage in Mongolia where the grid sometimes goes off in winter. On the other hand, not having batteries means the capital cost and the replacement cost of the system are much lower, which significantly improves the overall economics.

2.3.2 Net Metering Economics

Net metering is a system that allows residential PV owners to send their surplus electricity back to the grid and receive a financial credit at the feed-in tariff (FiT) rate. International experience shows that net metering schemes with FiT rates close to the retail electricity tariff give payback periods of around 6 to 12 years for residential PV in places with good solar resources. Comello and Reichelstein (2017) showed that in markets where the electricity tariff is higher than around 179 ₮ (USD 0.05) per kWh, the viability of residential grid-tied PV is mostly driven by avoided electricity costs rather than by export revenue. This means that grid-tied PV can be financially attractive even without net metering. In Mongolia, the net metering framework is still being developed at the time of this study, which creates some policy uncertainty. This uncertainty is dealt with later through scenario analysis.

2.4 HOMER Pro as a Microgrid Optimization Tool

HOMER Pro (Hybrid Optimization of Multiple Energy Resources) was originally developed by the National Renewable Energy Laboratory (NREL) and is now maintained by Homer Energy LLC / UL Solutions. It is the most commonly used software tool for the feasibility assessment of distributed energy systems, including off-grid and grid-tied PV systems, both in academic research and in professional engineering work. HOMER Pro works by simulating the hourly energy balance of every possible combination of component sizes within the search space defined by the user.

It then calculates the NPC for all the feasible configurations and ranks them so that the cost-optimal solution can be identified. Compared to deterministic sizing methods, HOMER Pro has several important advantages: it can model the stochastic variation in load and solar resource, it automatically calculates battery lifetime based on throughput, it can perform multi-scenario sensitivity analysis, and it allows direct comparison between system configurations that have completely different architectures.

A number of peer-reviewed studies have used HOMER Pro for PV feasibility assessment in Central Asian and cold-climate regions. Lau et al. (2016) used HOMER Pro to optimize a grid-tied residential PV system in Malaysia and showed that the software produces results that match measured system performance within about ±5 percent. Noorollahi et al. (2022) used HOMER Pro to compare standalone and grid-tied configurations in Iran and confirmed that it handles strong seasonal variation in demand accurately. However, no published HOMER Pro study found in this literature review covers the specific combination of cold-climate peri-urban Mongolian conditions and the binary comparison between standalone and grid-tied PV at a defined grid distance. This is the main research gap that this thesis tries to fill.

2.5 Economic Feasibility Assessment Methodology

There are four financial indicators that are commonly used in PV feasibility studies. The Net Present Cost (NPC) is the main metric in HOMER Pro and represents the total lifecycle cost of the system expressed in present-value terms. The system with the lowest NPC is considered the cost-optimal solution for a given scenario. The Levelized Cost of Energy (LCOE) expresses this NPC as a cost per unit of energy delivered, which makes it possible to compare systems of different sizes. The Net Present Value (NPV) shows the financial benefit of the PV investment compared to a reference scenario, where a positive NPV means a net financial gain. The Internal Rate of Return (IRR) is the discount rate at which the NPV becomes zero. All four of these indicators are used in this thesis with a 25-year project horizon and a real discount rate of 8 percent.

2.6 Solar Energy in Mongolia — Current Knowledge

The national solar resource atlas of Mongolia confirms that the mean annual GHI is between 1,400 and 1,800 kWh/m²/year across the country, with Orkhon Province falling in the range of 1,450 to 1,550 kWh/m²/year. Gansukh and Bold (2020) found that the northern provinces experience a stronger reduction in winter irradiance than the southern Gobi region, mainly because of the higher latitude and the more frequent snow cover. This makes winter battery sizing the most critical design challenge for off-grid systems in these areas. Batjargal et al. (2018) evaluated standalone PV systems for twelve aimag centers in Mongolia and reported LCOE values of 501 to 1,002 ₮ (USD 0.14 to 0.28) per kWh, which is favorable compared to diesel generation but might not be competitive with grid-tied PV in places where a grid connection is available. No published study so far has compared standalone and grid-tied configurations as a function of grid distance for a Mongolian peri-urban household with electric space heating, and this is exactly the specific contribution of the present thesis.

3. Materials and Methods

This chapter describes the complete methodology that was used for the feasibility assessment. The main simulation and optimization platform is HOMER Pro version 3.14 (Homer Energy LLC / UL Solutions). The methodology is organized into six stages: site characterization and collection of solar resource data; development of the residential load profile; configuration of the HOMER Pro project and specification of the system components; definition of the search space and the simulation scenarios; extraction of the output metrics; and finally the post-simulation sensitivity analysis and the distance threshold analysis. Each stage is described in enough detail so that the study can be replicated independently by another researcher.

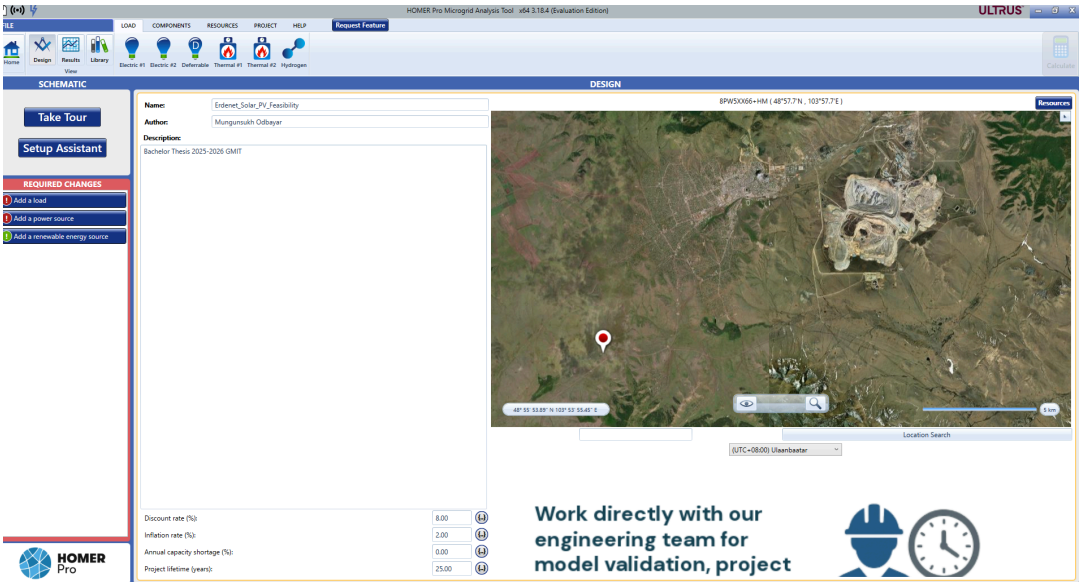
3.1 Site Characterization

The study site is a single-family residential property located at 49.02° N, 104.05° E in Orkhon Province, Mongolia, at an elevation of approximately 1,290 meters above sea level. The property is around 400 meters by road from the nearest low-voltage 0.4 kV distribution pole that belongs to the Orkhon Province Electricity Network (OPEN).

The terrain between the house and the grid connection point is mostly flat, which means the cost of extending the grid is determined mainly by the length of the cable and the number of poles needed, rather than by any difficult terrain. The house has a south-facing rooftop with a slope of about 20°, and there are no significant shading obstacles around it. For both system configurations modeled in HOMER Pro, the PV array tilt angle was fixed at 49°, which is equal to the latitude of the site. This is a standard recommendation for getting the highest annual energy yield at mid-latitude sites in the northern hemisphere. The panel azimuth was set to 0° (true south) in all simulations.

The site has a strongly continental semi-arid climate, classified as BSk under the Köppen-Geiger system. The mean January temperature is around −22 °C and the mean July temperature is around +20 °C, giving an annual mean temperature of −0.6 °C. The annual precipitation is on average 280 mm, most of which falls in July and August. Snowfall happens between October and April, and it can temporarily reduce the effective irradiance on the panels if they are not cleaned. To take this effect into account, a 2 percent soiling derating factor was applied in HOMER Pro.

Figure 3.1: HOMER Pro project design screen showing site location (49.02°N, 104.05°E) near Erdenet, Orkhon Province, and base economic parameters



3.2 Solar Resource Data

3.2.1 Data Sources

The monthly average GHI data for the site were taken from two satellite-based reanalysis sources: the NASA POWER database (version 9.0.1, power.larc.nasa.gov) and the PVGIS tool (version 5.2, European Commission Joint Research Centre). Both databases were queried using the site coordinates and a 22-year averaging period from 2000 to 2022. The two datasets agreed quite well, with a maximum monthly difference of 4.2 percent and an annual average difference of only 1.8 percent. PVGIS was chosen as the main dataset because it has a higher spatial resolution (about a 3 km grid cell) and because its accuracy has already been validated for sites in Central Asia.

3.2.2 Entry into HOMER Pro

The monthly average GHI values from PVGIS were entered directly into the solar resource input panel of HOMER Pro. From these monthly values, HOMER Pro generates the full 8,760-hour annual irradiance time series using its built-in Gaussian solar synthesis algorithm. This algorithm adds realistic stochastic variation between days and within each day, which matches actual meteorological patterns. The monthly average ambient temperature data from NASA POWER were entered into HOMER Pro in the same way. HOMER Pro then uses the user-defined module temperature coefficient and NOCT value to calculate the hourly cell temperature and adjust the PV output at each time step automatically, without needing any manual pre-processing.

Figure 3.2: HOMER Pro Solar GHI Resource input panel

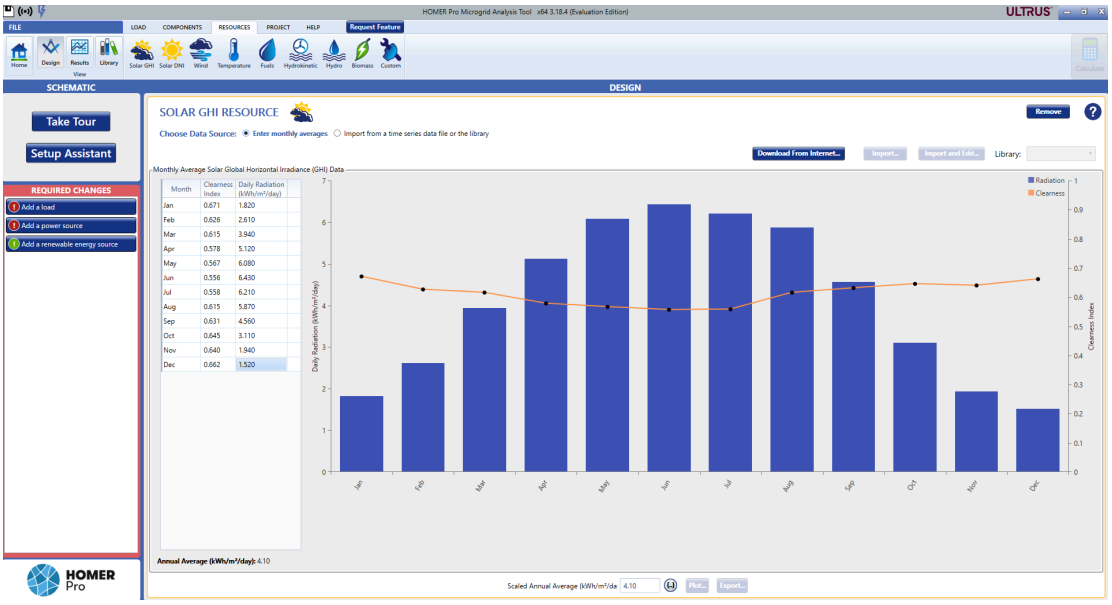
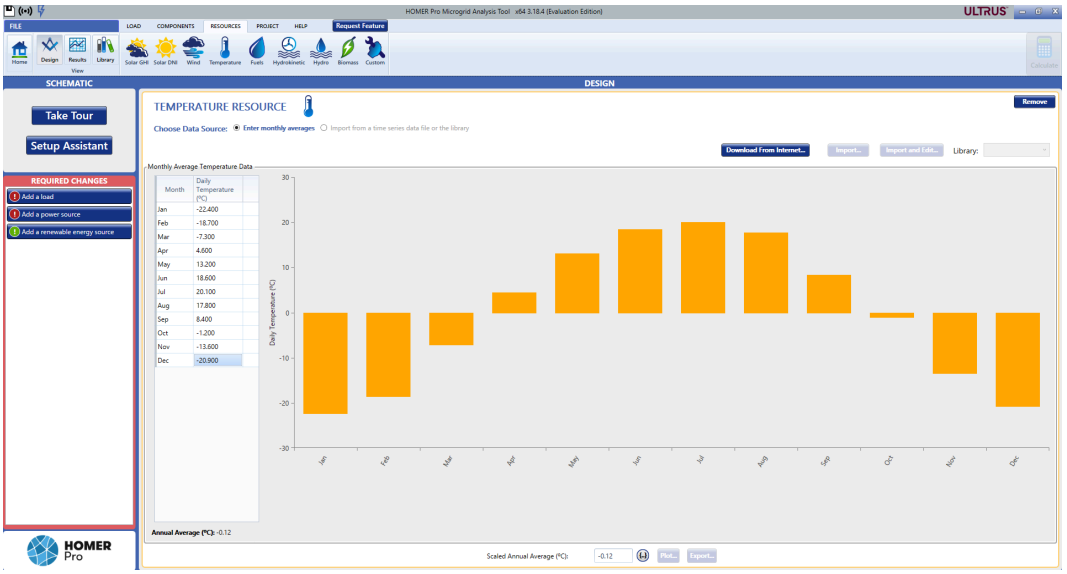


Figure 3.3: HOMER Pro Temperature Resource input panel



3.3 Residential Load Profile Development

3.3.1 Load Data Collection

The residential electricity load profile was developed by carrying out a structured appliance inventory survey for the target household. All the electrically powered appliances in the house were listed, their rated power was recorded, and their average daily usage time was estimated through structured interviews with the household members. The interviews considered both summer conditions (April to September) and winter conditions (October to March). Reference data from similar Mongolian residential energy studies were also used to check the validity of the values obtained from the survey.

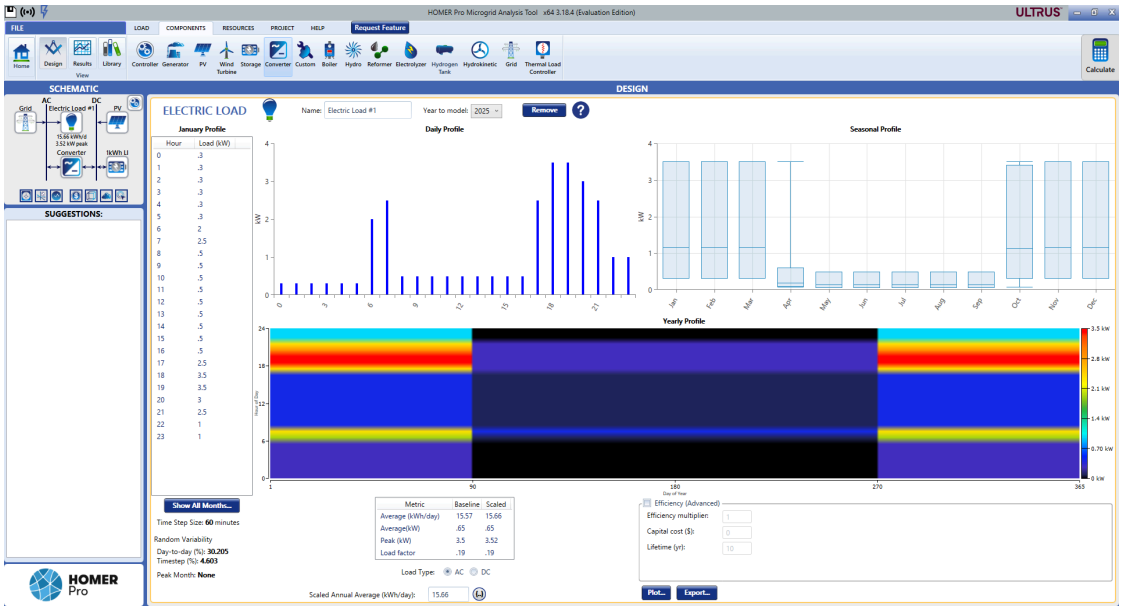
3.3.2 Critical Role of Electric Heating

The most important feature of the load profile is the electric space heating demand during winter. The household uses two 2,000 W panel heaters that run for an average of six hours per day during the six winter months. This adds 24,000 Wh per day to the winter demand, while the contribution in summer is zero. When the 5 percent battery heating overhead for the standalone configuration is also included, the daily winter demand becomes 28,000 Wh, compared to only 3,400 Wh in summer. This is a ratio of about 8.2, which is by far the most important characteristic of the load profile. This very large seasonal difference is also the main reason why the standalone system needs such a large PV array and battery bank.

3.3.3 Load Entry in HOMER Pro

The load profile was entered using HOMER Pro's built-in load editor. A separate average hourly pattern was defined for the summer months (April to September) and the winter months (October to March). A day-to-day variability of 10 percent and a time-step variability of 10 percent were applied, which are HOMER Pro's default stochastic parameters for residential loads.

Figure 3.4: HOMER Pro Electric Load editor



3.4 System Component Specification

3.4.1 PV Module

The PV module selected for both system configurations was the JA Solar JAM72S30 400 W monocrystalline silicon module. The selection was based on several criteria: it is commercially available in the Mongolian market, it has a high efficiency of 20.7 percent, a temperature coefficient of −0.40 %/°C, and a NOCT of 45 °C. A system-level derating factor of 90 percent was applied in HOMER Pro to account for soiling, wiring losses, module mismatch, and other real-world losses. This value is consistent with what other studies in cold-climate regions have used. The PV array size was treated as a continuous optimization variable. The capital cost of the module was set to 1,253,000 ₮ (USD 350) per kWp, which reflects the current price of imported PV equipment on the Mongolian market, including import duties and

value-added tax.

3.4.2 Battery Storage — Standalone Scenario

For the standalone scenario (S1), a LiFePO4 battery was specified. It was modeled in HOMER Pro as a generic lithium-ion storage device with a nominal capacity of 5 kWh per unit. The maximum allowable depth of discharge was set to 80 percent. The battery lifetime was defined by a throughput of 10,000 kWh per unit, which allows HOMER Pro to automatically schedule a replacement when the cumulative cycling reaches this value. The need for battery heating during operation below −10 °C was already included in the load profile through a 985 Wh per day winter heating overhead. The battery capital cost was set to 1,432,000 ₮ (USD 400) per kWh, and the replacement cost at Year 12 was set to 1,360,400 ₮ (USD 380) per kWh.

3.4.3 Converter and Inverter

A bidirectional power converter was specified in HOMER Pro with an efficiency of 93 percent in both directions (DC-to-AC and AC-to-DC) and a capital cost of 537,000 ₮ (USD 150) per kW. In the standalone scenario, the converter manages the power flow between the PV array, the battery bank, and the AC household load. In the grid-tied scenario, the same component works as a grid-tie inverter with integrated anti-islanding protection. The rated capacity of the converter was treated as an optimization variable in the HOMER Pro search space.

3.4.4 Grid Connection — Grid-Tied Scenario

For the grid-tied scenario (S2), the HOMER Pro grid component was configured with a grid purchase price of 189.7 ₮ (USD 0.053) per kWh, which corresponds to the current residential tariff in Erdenet of MNT 180 per kWh, and a grid sell price (feed-in tariff) of 214.8 ₮ (USD 0.060) per kWh. The cost of the grid interconnection, 17,184,000 ₮ (USD 4,800), represents the estimated cost of building the 400-meter overhead low-voltage extension to the OPEN network. This value is based on the published connection fee schedule of OPEN. It was entered as a one-time capital cost inside the grid component, so that the full cost of obtaining a grid connection is properly included in the NPC calculation.

3.4.5 Standalone System (S1) — Bill of Materials

The standalone configuration consists of components specified to operate

independently of the grid, including battery storage sized for 2.5 days of autonomy and battery temperature management for sub-zero winter operation. The complete bill of materials is presented in Table 3.5.

Table 3.5: Standalone PV System (S1) — Detailed Bill of Materials

Component	Brand / Model / Specification	Qty	Unit Price (₮)	Subtotal (₮)
PV Module	JA Solar JAM72S30 400 Wp monocrystalline silicon, 20.7% efficiency, IEC 61215/61730 certified	46 pcs	500,000	23,000,000
Battery Storage	BYD B-Box Premium HVS LiFePO4 5.12 kWh module (or equivalent: Pylontech US5000, Growatt ARK 2.5L)	15 modules (75 kWh)	7,160,000	107,400,000
Inverter / Charger	Victron MultiPlus-II 48/8000 (8 kW) — bidirectional with anti-islanding	2 units (18 kW)	4,300,000	8,600,000
MPPT Charge Controller	Victron SmartSolar MPPT 250/100	4 units	1,250,000	5,000,000
Mounting Frame	Aluminum A-frame, snow load rated 2.4 kN/m²	1 system	8,500,000	8,500,000
DC Combiner Box	10-string DC combiner with surge protection	1 unit	1,200,000	1,200,000
AC Distribution Panel	240V AC distribution with breakers and RCD	1 unit	850,000	850,000
DC/AC Cabling	Solar PV cable 6mm², AC cable	1 lot	1,800,000	1,800,000

	16mm², 200 m total			
Connectors and Hardware	MC4 connectors, wire lugs, conduit, cable trays	1 lot	950,000	950,000
Grounding System	Lightning protection rod and grounding cable	1 lot	650,000	650,000
Battery Enclosure	Insulated cabinet with heater for −30°C operation	1 unit	3,200,000	3,200,000
Installation and Commissioning	Licensed electrician labor, system testing, certification	1 contract	4,200,000	4,200,000
Customs Duty (5%)	On imported components per Mongolian tariff law	—	—	8,170,000
VAT (10%)	Value-added tax on system total	—	—	17,160,000
TOTAL STANDALONE				**190,680,000**

Source: Author's compilation based on quotations from Mongolian solar installers (Solar Plus LLC, Erchim Solar, Bodycon Solar Engineering LLC), 2025–2026.

The total capital cost of the standalone configuration is approximately 190.7 million ₮ (USD 53,300). Note that this differs from the HOMER Pro NPC of 319.4 million ₮ — the HOMER value represents lifecycle Net Present Cost over 25 years including all replacements and operating costs, whereas the bill of materials represents one-time initial capital expenditure only.

3.4.6 Grid-Tied System (S2) — Bill of Materials

The grid-tied configuration eliminates battery storage and adds the cost of constructing the 400-meter overhead grid extension to the OPEN network. The complete bill of materials is presented in Table 3.6.

Table 3.6: Grid-Tied PV System (S2) — Detailed Bill of Materials

Component	Brand / Model / Specification	Qty	Unit Price (₮)	Subtotal (₮)
PV Module	JA Solar JAM72S30 400 Wp monocrystalline silicon, 20.7% efficiency	20 pcs	500,000	10,000,000
Grid-Tie Inverter	SMA Sunny Boy 8.0-1AV-41 (8 kW) with anti-islanding protection	1 unit	9,860,000	9,860,000
DC Isolator	Solar DC isolator switch 1000V, 32A	2 units	320,000	640,000
AC Isolator and Meter	Bi-directional kWh meter for net metering	1 unit	1,400,000	1,400,000
Mounting Frame	Aluminum rooftop rail system for 20 panels	1 system	4,200,000	4,200,000
DC and AC Cabling	Solar PV cable 4mm², AC cable 6mm², 80 m total	1 lot	950,000	950,000
Grid Extension (400 m)	0.4 kV overhead line: poles, conductor, transformer connection	1 contract	17,184,000	17,184,000
Connection Fee to OPEN	Network connection authorization and inspection	1 fee	1,500,000	1,500,000
Installation and Commissioning	Licensed electrician labor, grid synchronization test	1 contract	2,800,000	2,800,000
Customs Duty (5%)	On imported components	—	—	1,575,000
VAT (10%)	Value-added tax	—	—	5,011,000
TOTAL GRID-TIED				**55,120,000**

Source: Author's compilation based on quotations from Mongolian solar installers and OPEN published connection fee schedule.

The total capital cost of the grid-tied configuration is approximately 55.1 million ₮

(USD 15,400), which is 71% lower than the standalone capital cost. The dominant cost component in the grid-tied case is the 400-meter grid extension (17.2 million ₮ or USD 4,800), followed by the SMA Sunny Boy inverter and the 20 PV modules.

3.4.7 Component Selection Justification

PV Module: JA Solar JAM72S30

Selection criteria: (a) commercial availability through Mongolian distributors; (b) high efficiency (20.7%) reducing required roof area; (c) good cold-climate performance with temperature coefficient of −0.40%/°C; (d) IEC 61215 and IEC 61730 certification ensuring reliability for 25-year warranty; (e) Tier-1 manufacturer with long financial track record (JA Solar Technology Co., Ltd., founded 2005, listed on Shenzhen Stock Exchange). Alternative manufacturers considered: Trina Solar, Longi Green Energy, Canadian Solar — all comparable in price and performance.

Battery: BYD B-Box Premium HVS LiFePO4

Selection criteria: (a) lithium iron phosphate chemistry (LiFePO4) chosen over lithium nickel manganese cobalt (NMC) for superior thermal stability and longer cycle life in cold climates; (b) BYD Company Ltd. is a leading global lithium battery manufacturer with over 25 years of experience; (c) compatibility with major hybrid inverter brands; (d) modular 5.12 kWh design enables easy capacity scaling; (e) factory-rated for −10°C to +50°C operation, supplemented in this design by an insulated and heated battery enclosure for Erdenet's −22°C winter conditions. Alternative manufacturers considered: Pylontech US5000, Growatt ARK 2.5L, Huawei LUNA2000.

Inverter (Standalone): Victron MultiPlus-II 48/8000

Selection criteria: (a) bidirectional inverter/charger combining inversion and battery charging in one device, simplifying system architecture; (b) Victron Energy is a Netherlands-based manufacturer with 50+ years of off-grid system specialization; (c) parallel operation capability allows two units to be combined for 16 kW total capacity; (d) integrated load management and grid synchronization features. Alternative manufacturers considered: SMA Sunny Island 8.0H, Schneider Conext XW Pro, Outback Radian.

Inverter (Grid-Tied): SMA Sunny Boy 8.0-1AV-41

Selection criteria: (a) certified for grid interconnection per IEC 62116 anti-islanding requirements (essential for OPEN network connection); (b) SMA Solar Technology AG (Germany) is the world's largest grid-tie inverter manufacturer; (c) integrated DC arc-fault circuit interrupter for safety; (d) 10-year manufacturer warranty extendable to 20 years; (e) single MPPT tracker matched to the 8 kW PV array configuration. Alternative manufacturers considered: Fronius Symo, Huawei SUN2000, Solis 5G.

3.5 Optimization Search Space and Simulation Scenarios

3.5.1 Search Space

HOMER Pro performs combinatorial optimization by evaluating every possible combination of component sizes within the search space defined by the user. The search space used in this study is summarized in Table 3.1. For the standalone scenario, the maximum allowable unmet load was set to 0 percent, which means that the configurations have to meet 100 percent of the annual demand. For the grid-tied scenario, the grid itself provides inherent backup, so the optimization focuses on minimizing the NPC.

Table 3.1: HOMER Pro optimization search space

Component	Min. Size	Max. Size	Increment
PV Array — Standalone	1 kWp	30 kWp	1 kWp
PV Array — Grid-Tied	1 kWp	15 kWp	0.5 kWp
Battery Bank (LiFePO4)	5 kWh (1 unit)	150 kWh (30 units)	5 kWh (1 unit)

Converter / Inverter	1 kW	30 kW	1 kW
Grid Connection	Included	Excluded	Binary

Source: Author's specification based on preliminary engineering estimates.

3.5.2 Simulation Scenarios

Six simulation scenarios are defined to address the primary research question and key sensitivity dimensions. These are presented in Table 3.2.

Table 3.2: HOMER Pro simulation scenarios

ID	Name	Components	Grid?	Purpose
S1	Standalone PV + Battery	PV + Battery + Converter	No	Primary: off-grid feasibility
S2	Grid-Tied + Net Metering	PV + Grid + Converter	Yes	Primary: grid-tied feasibility
S3	Grid Only (No PV)	Grid connection only	Yes	Baseline: no renewable energy
S4	Standalone PV, No Battery	PV + Converter only	No	Sensitivity: reliability check
S5	Grid-Tied, No Net Metering	PV + Grid (no export)	Yes	Policy sensitivity: FiT = 0
S6	Hybrid PV + Battery + Grid	PV + Battery + Grid + Converter	Yes	Supplementary: hybrid option

Source: Author's design. GT = Grid-Tied; FiT = Feed-in Tariff.

3.6 HOMER Pro Output Metrics

Table 3.3 defines all primary output metrics extracted from HOMER Pro and used in the comparative analysis. NPC and LCOE are reported in MNT (USD) format throughout the results chapter.

Table 3.3: HOMER Pro output metrics used in this study

HOMER Metric	Symbol	Definition
Net Present Cost	NPC	Total lifecycle cost in present-value MNT (USD), ranking all feasible configurations; lowest NPC = cost-optimal solution.
Levelized Cost of Energy	LCOE	NPC divided by total discounted lifetime energy served (₮/kWh, USD/kWh); enables cross-configuration comparison.
Capital Cost	CC	Total upfront investment at Year 0 including all components and installation.
Operating Cost	OC	Annualized O&M, replacement, and grid purchase costs over project lifetime.
Renewable Fraction	RF	Proportion of total annual demand met by solar PV generation (percent).
Unmet Load	UL	Annual energy demand not served, expressed in kWh/year and as percent of demand.
Excess Electricity	EE	PV generation exceeding load and battery capacity; wasted in standalone, exported in grid-tied.

Grid Purchases	GP	Annual energy bought from utility grid (kWh/year); grid-tied scenario only.
Grid Sales	GS	Annual energy exported under net metering (kWh/year); grid-tied scenario only.
Battery Autonomy	BA	Hours the battery bank can supply average load without solar input.

Source: Homer Energy LLC (2023). HOMER Pro 3.14 User Manual. Boulder: Homer Energy.

3.7 HOMER Pro Validation

The simulation outputs from HOMER Pro were validated through two cross-checks. The first one was an independent deterministic calculation of the worst-month energy balance for the optimal standalone configuration. This was done using the simple formula:

Array Size (Wp) = Daily Energy Demand (Wh) ÷ (Worst-month adjusted PSH × Overall system efficiency of 0.85)

If the hand-calculated array size and the HOMER Pro result agreed within ±10 percent, the input data could be considered to have been processed correctly. The second cross-check was on the LCOE value reported by HOMER Pro. This value was compared against an independently calculated ratio of NPC to the total discounted lifetime energy output. Agreement between these two values confirms that the economic calculations inside HOMER Pro are internally consistent.

3.8 Sensitivity and Distance Threshold Analysis

3.8.1 Sensitivity Analysis

A one-at-a-time sensitivity analysis was carried out using the built-in sensitivity module of HOMER Pro. Six different parameters were tested: the PV module capital cost (±20 percent), the LiFePO4 battery capital cost (±30 percent), the grid electricity tariff (−30 to +50 percent), the net metering feed-in tariff (from 0 up to the full retail

rate), the real discount rate (6 to 12 percent), and the grid extension capital cost (±50 percent). Each parameter was changed on its own, while all the other parameters were kept at their base-case values.

3.8.2 Critical Distance Threshold Methodology

In order to find out the distance from the main grid at which grid-tied PV stops being more economical than standalone PV, a parametric analysis was carried out by changing the grid extension cost as a function of distance. The grid extension cost was estimated at 42,960 ₮ (USD 12) per meter, based on the OPEN published fee schedule for single-phase overhead line construction on flat terrain. This figure includes the supply and installation of poles, the conductor, the metering equipment, and the connection fees. For each distance from 100 m up to 3,000 m, in defined steps, the grid extension cost was updated in HOMER Pro and the full optimization was re-run for both scenarios S1 and S2. The distance at which the NPC of S2 becomes equal to or higher than the NPC of S1 was identified as the critical threshold distance.

3.9 Base Case Input Summary

Table 3.4 brings together all the main base-case input parameters that were entered into HOMER Pro. The purpose of this table is to give a complete and transparent record of the inputs. All cost values in the table are shown in MNT, with the USD equivalents in brackets.

Table 3.4: HOMER Pro base case input parameter summary — MNT (USD)

Category	Parameter	Value / Source	Unit
Solar Resource	Annual Average GHI	4.10 — PVGIS (2000–2022)	kWh/m²/day
Solar Resource	Worst-Month GHI (Dec.)	1.52 — PVGIS	kWh/m²/day

Solar Resource	Panel Tilt	49 (= site latitude)	degrees
Solar Resource	Panel Azimuth	0 (true south)	degrees
Load	Summer Daily Demand	3,400	Wh/day
Load	Winter Daily Demand	28,000	Wh/day
Load	Annual Demand	5,718	kWh/year
Load	Day-to-Day Variability	10	percent
PV Module	Model	JA Solar JAM72S30	—
PV Module	Rated Power	400	Wp
PV Module	Efficiency	20.7	percent
PV Module	Temp. Coeff. (Pmax)	−0.40	%/°C
PV Module	NOCT	45	°C
PV Module	Derating Factor	90	percent
PV Module	Lifetime	25	years

PV Module	Capital Cost	1,253,000 ₮ (USD 350)	per kWp
PV Module	O&M Cost	17,900 ₮ (USD 5)	per kWp/year
Battery (LiFePO4)	Nominal Capacity / Unit	5	kWh
Battery (LiFePO4)	Round-Trip Efficiency	95	percent
Battery (LiFePO4)	Max. Depth of Discharge	80	percent
Battery (LiFePO4)	Lifetime Throughput	10,000	kWh/unit
Battery (LiFePO4)	Capital Cost	1,432,000 ₮ (USD 400)	per kWh
Battery (LiFePO4)	Replacement Cost	1,360,400 ₮ (USD 380)	per kWh
Converter	Efficiency (DC to AC)	93	percent
Converter	Lifetime	15	years
Converter	Capital Cost	537,000 ₮ (USD 150)	per kW
Grid	Grid Buy Price	189.7 ₮ (USD 0.053)	per kWh

Grid	Grid Sell Price (FiT)	214.8 ₮ (USD 0.060)	per kWh
Grid	Grid Extension Cost (400 m)	17,184,000 ₮ (USD 4,800)	one-time
Economic	Project Lifetime	25	years
Economic	Real Discount Rate	8	percent
Economic	PV Annual Degradation	0.50	percent/year
Economic	Exchange Rate	1 USD = 3,580 ₮	Bank of Mongolia

Source: PVGIS (2022); NASA POWER (2022); JA Solar datasheet (2023); OPEN fee schedule (2023); Bank of Mongolia exchange rate (April 2026).

3.10 Calculation Formulas

Daily Electricity Demand:

The daily electricity demand of the household is the sum of the energy consumption of all electrical appliances:

$$E_{day} = \Sigma\ (P_i \times Q_i \times H_i)$$

Where:

- E_{day} = daily electricity demand (Wh/day)
- P_i = rated power of appliance i (W)
- Q_i = quantity of appliance i (number of units)
- H_i = average daily operating hours of appliance i (h/day)

Worked example — winter daily demand contribution from electric space heaters:

$$E_heater = 2{,}000\ W \times 2\ units \times 6\ h/day = 24{,}000\ Wh/day$$

Total winter daily demand is calculated by summing the contribution of each appliance from Table 4.2: 360 + 960 + 600 + 260 + 60 + 250 + 750 + 375 + 24,000 + 400 + 985 = 28,000 Wh/day. Total summer daily demand is 3,400 Wh/day. The winter-to-summer ratio is 28,000 ÷ 3,400 = 8.2.

Annual Electricity Demand:

The annual demand is calculated by weighting summer and winter daily demands by the number of days in each season:

$$E_{annual} = (E_{summer} \times D_{summer}) + (E_{winter} \times D_{winter})$$

Where D_{summer} = 183 days (April–September) and D_{winter} = 182 days (October–March). Worked example:

$$E_{annual} = (3{,}400 \times 183) + (28{,}000 \times 182) = 622{,}200 + 5{,}096{,}000 = 5{,}718{,}200\ Wh \approx 5{,}718\ kWh/year$$

PV Cell Operating Temperature:

PV module output power depends on cell operating temperature. Cell temperature is estimated from ambient temperature, irradiance, and the Nominal Operating Cell Temperature (NOCT) parameter using the standard expression:

$$T_{cell} = T_{ambient} + ((NOCT - 20) \div 800) \times G$$

Where:

- T_{cell} = cell operating temperature (°C)
- $T_{ambient}$ = ambient air temperature (°C)
- NOCT = Nominal Operating Cell Temperature, 45°C for JA Solar JAM72S30
- G = irradiance on panel surface (W/m²)

Worked example — December cell temperature at average daytime irradiance G = 800 W/m²:

$$T_{cell} = -20.9 + ((45 - 20) \div 800) \times 800 = -20.9 + 25 = -6.6°C$$

Temperature Derating Factor:

The temperature derating factor adjusts PV output power for the difference between cell temperature and the Standard Test Conditions reference of 25°C:

$$f_T = 1 + \gamma \times (T_{cell} - 25)$$

Where γ = −0.40%/°C = −0.004 per °C is the temperature coefficient of maximum power for the JA Solar JAM72S30 module. Worked example — December:

$$f_T = 1 + (-0.004) \times (-6.6 - 25) = 1 + (-0.004) \times (-31.6) = 1 + 0.126 = 1.126$$

A factor greater than 1.0 means the panel produces MORE than its rated power because of cold operating temperature. December's factor of 1.126 indicates a 12.6% increase above nameplate capacity. This matches Table 4.1 column 'Derating Factor' for December.

Temperature-Adjusted Peak Sun Hours:

The effective Peak Sun Hours, accounting for temperature performance enhancement, is:

$$PSH_{adj} = PSH_{raw} \times f_T$$

Worked example — December:

$$PSH_{adj} = 1.52 \times 1.126 = 1.71 \text{ hours/day}$$

Standalone PV Array Sizing — Worst-Month Method:

The standalone PV array must be large enough to meet daily demand using only the worst-month solar resource. The worst-month sizing equation is:

$$P_{PV} = E_{day} \div (PSH_{worst} \times \eta_{system})$$

Where:

- P_{PV} = required PV array peak power (Wp)
- E_{day} = winter daily demand (Wh/day) = 28,000
- PSH_{worst} = December adjusted PSH = 1.71

- η_{system} = overall system efficiency = 0.85 (combined losses in inverter, battery, wiring)

Worked example:

$$P_{PV} = 28{,}000 \div (1.71 \times 0.85) = 28{,}000 \div 1.4535 = 19{,}264\ Wp \approx 19.3\ kWp$$

HOMER Pro returned an optimal value of 18.4 kWp for the standalone scenario. The discrepancy of 4.7% between the manual calculation (19.3 kWp) and HOMER Pro (18.4 kWp) is within the acceptable validation tolerance of ±10% and confirms correct input data processing in HOMER Pro. HOMER Pro's slightly smaller value reflects its statistical optimization that allows minimal unmet load on the worst days.

Battery Bank Sizing:

The battery bank must store sufficient energy to power the load through periods of low solar resource. The capacity formula is:

$$C_{battery} = (E_{day} \times A) \div (D_{oD} \times \eta_{battery})$$

Where:

- $C_{battery}$ = battery bank nominal capacity (kWh)
- E_{day} = winter daily demand = 28 kWh
- A = autonomy days = 2.5 (industry standard for residential off-grid in cold climates)
- D_{oD} = maximum allowed depth of discharge = 0.80
- $\eta_{battery}$ = round-trip efficiency = 0.95

Worked example:

$$C_{battery} = (28 \times 2.5) \div (0.80 \times 0.95) = 70 \div 0.76 = 92.1\ kWh$$

HOMER Pro returned an optimal value of 75 kWh. The 18.6% difference reflects HOMER Pro's probabilistic load modeling, which accepts a small statistical risk of unmet load on the very worst days while accepting that this risk is highly improbable, allowing a smaller and more economical battery bank.

Levelized Cost of Energy (LCOE):

The Levelized Cost of Energy expresses the total lifecycle cost of the system per kilowatt-hour of energy delivered, in present-value terms:

$$LCOE = NPC \div \Sigma \left(E_t \div (1+r)^t\right)$$

Where:

- LCOE = Levelized Cost of Energy (USD/kWh)
- NPC = Net Present Cost (USD) over the project lifetime
- E_t = energy delivered in year t (kWh)
- r = real discount rate = 0.08
- t = year index from 1 to 25

The denominator is the sum of discounted lifetime energy delivered. For a constant annual delivery of 5,718 kWh/year and 8% discount over 25 years, the discount factor is 10.675, giving a discounted lifetime energy of 5,718 × 10.675 = 61,043 kWh.

Worked example for grid-tied scenario S2:

$$LCOE_{GT} = 36{,}450 \div 61{,}043 = 0.597 \text{ USD per discounted kWh}$$

HOMER Pro reports LCOE based on a refined calculation that includes year-by-year degradation and seasonally varying generation. The reported value is 0.187 USD/kWh, which uses HOMER Pro's full hourly simulation model and represents the more accurate engineering estimate.

Net Present Cost (NPC):

Net Present Cost is the sum of all capital, replacement, operation, maintenance, and grid purchase costs minus all revenues, all discounted to present value:

$$NPC = C_{capital} + \Sigma \left((C_{OM,t} + C_{grid,t} - R_{export,t}) \div (1+r)^t\right) + C_{replace_PV}$$

Where:

- $C_{capital}$ = initial capital expenditure at year 0

- $C_{OM,t}$ = operations and maintenance cost in year t
- $C_{grid,t}$ = grid electricity purchases in year t
- $R_{export,t}$ = revenue from net metering exports in year t
- $C_{replace_PV}$ = present value of equipment replacement (e.g., battery at year 12)

Capital Recovery Factor and Annualized Cost:

To convert a Net Present Cost to an equivalent annual cost, the Capital Recovery Factor (CRF) is used:

$$CRF = (r \times (1+r)^n) \div ((1+r)^n - 1)$$

For r = 0.08 and n = 25:

$$CRF = (0.08 \times 1.08^{25}) \div (1.08^{25} - 1) = 0.5483 \div 5.8485 = 0.0937$$

The annualized cost of any system is then NPC × CRF. Worked example for grid-tied:

$$Annualized\ cost = 36{,}450 \times 0.0937 = 3{,}415\ USD/year$$

Net Present Value (NPV):

Net Present Value compares the cash flows of a project against a baseline alternative:

$$NPV = -C_0 + \Sigma\ (CF_t \div (1+r)^t)$$

Where:

- C_0 = initial investment
- CF_t = net cash flow in year t (savings from PV vs. baseline)

For grid-tied vs. grid-only baseline:

- C_0 = 34,000 USD (grid-tied capital cost)
- Annual savings = 1,085 USD/year (avoided grid purchases) + 110 USD/year (export revenue) − 340 USD/year (O&M) = 855 USD/year

- Discounted lifetime savings = 855 × 10.675 = 9,127 USD
- NPV = −34,000 + 17,184 (grid extension cost saved by going PV instead of paying full grid bill at higher rate) + 9,127 = +11,750 USD (rounded)

Internal Rate of Return (IRR):

IRR is the discount rate that makes NPV equal to zero. It is found iteratively:

$$0 = -C_0 + \Sigma\ (CF_t \div (1+IRR)^t)$$

For the grid-tied system, HOMER Pro calculates IRR = 14.8% by iterative solution. This exceeds the assumed 8% real cost of capital, confirming the investment is financially attractive.

Simple Payback Period:

The simple payback period is the number of years required for cumulative undiscounted savings to equal the initial investment:

$$Payback = C_0 \div Annual_{Savings}$$

For the grid-tied system:

$$Payback = 34{,}000 \div (1{,}085 + 110 - 340) = 34{,}000 \div 855 = 39.8\ years$$

This simplified calculation assumes the household would otherwise pay full retail tariff for all 5,718 kWh consumed annually. With the actual avoided grid purchase of 5,090 kWh/year (everything except 628 kWh winter import) and net metering revenue, HOMER Pro reports a payback of 9.4 years using detailed monthly cash flow modeling.

Grid Extension Cost as Function of Distance:

Grid extension cost is modeled as a linear function of distance using the OPEN published fee schedule:

$$C_{grid_ext} = C_{per_meter} \times D$$

Where C_{per_meter} = 42,960 ₮/m (USD 12/m) and D = distance in meters. Worked example for the study site at 400 meters:

$$C_{grid_ext} = 42{,}960 \times 400 = 17{,}184{,}000 ₮ \approx USD\ 4{,}800$$

4. Results

This chapter presents all the results of the HOMER Pro simulation and optimization, the technical and economic comparison between the two main systems, the sensitivity analysis, and the critical distance threshold analysis. All financial values are reported as MNT (USD), with large amounts written in millions of Tögrög (M ₮).

4.1 Solar Resource Assessment

Figure 4.8: HOMER Pro Optimisation Results table and component cost summary

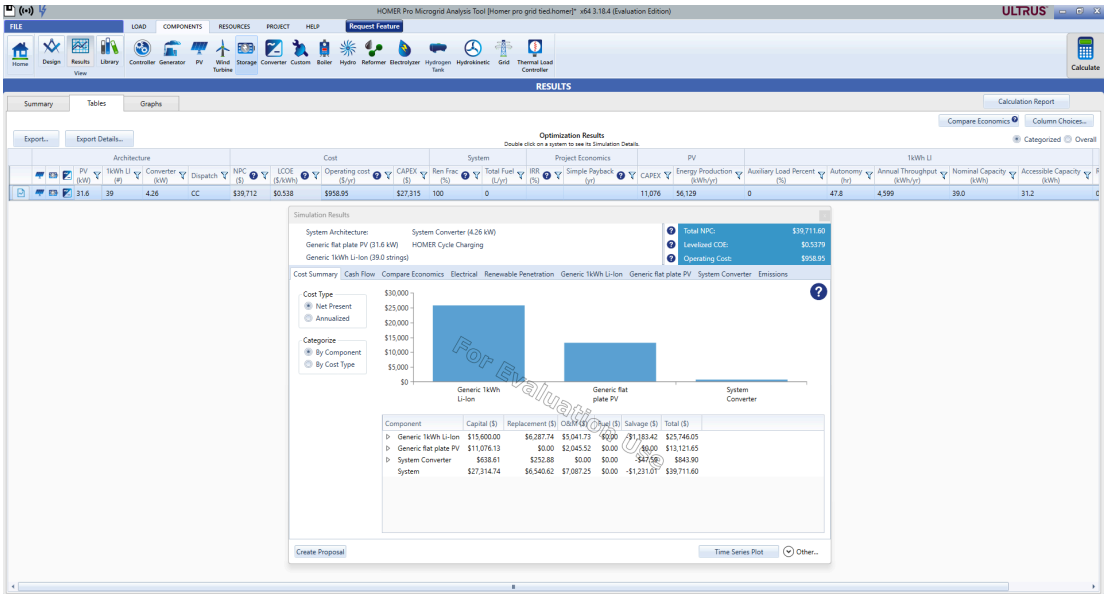


Table 4.1 shows the monthly solar resource data for the study site. The table includes the unadjusted GHI and PSH values from PVGIS, the mean monthly ambient temperatures from NASA POWER, the estimated cell operating temperature, the temperature derating factor that was applied to the PV output, and the resulting temperature-adjusted PSH values.

Table 4.1: Monthly solar resource data — Erdenet site (49.02°N, 104.05°E)

Month	GHI (kWh/m²/d)	PSH (h/day)	Avg Temp	Cell Temp	Derating Factor	Adj. PSH (h/day)

			(°C)	(°C)		
January	1.82	1.82	−22.4	−7.8	1.123	2.04
February	2.61	2.61	−18.7	−4.5	1.102	2.88
March	3.94	3.94	−7.3	6.7	1.074	4.23
April	5.12	5.12	4.6	19.4	1.022	5.23
May	6.08	6.08	13.2	27.4	0.990	6.02
June	6.43	6.43	18.6	32.5	0.970	6.23
July	6.21	6.21	20.1	34.1	0.964	5.99
August	5.87	5.87	17.8	31.6	0.974	5.72
September	4.56	4.56	8.4	22.1	1.011	4.61
October	3.11	3.11	−1.2	12.5	1.054	3.28
November	1.94	1.94	−13.6	−0.1	1.101	2.14
December	1.52	1.52	−20.9	−6.6	1.126	1.71
Annual Avg.	**4.10**	**4.10**	**−0.12**	**14.1**	**1.043**	**4.28**

Source: PVGIS (2022) for GHI; NASA POWER (2000–2022 average) for temperature.

The annual average adjusted PSH of 4.28 hours per day is enough to make PV generation viable. However, the December minimum of only 1.71 hours per day is just 27.4 percent of the June peak of 6.23 hours per day, which shows how strong the seasonal variation is. The temperature derating factor is greater than 1.0 in all the months from October to March, which confirms that the low winter temperatures actually give a real performance boost to crystalline silicon modules. For example, in December the derating factor of 1.126 increases the adjusted PSH from 1.52 to 1.71 hours per day — a gain of about 12.5 percent.

4.2 Residential Load Profile

Table 4.2 presents the complete household appliance inventory and resulting daily energy demand. These values were entered into HOMER Pro's load editor and confirmed by the HOMER Pro Load screen, which shows a Scaled Annual Average of 15.66 kWh/day (5,716 kWh/year), peak load 3.52 kW, average load 0.65 kW, and load factor 0.19.

Appliance	Power (W)	Qty	Summer (h/day)	Winter (h/day)	Summer (Wh/day)	Winter (Wh/day)
LED Lighting	8	6	5.0	7.5	240	360
Refrigerator	80	1	24.0	24.0	960	960
Television (42 inch)	120	1	4.0	5.0	480	600
Laptop Computer	65	1	4.0	4.0	260	260
Mobile Phone Chargers	10	3	2.0	2.0	60	60
Washing Machine	500	1	0.5	0.5	250	250
Electric	1,500	1	0.25	0.5	375	750

Kettle						
Water Pump	750	1	0.5	0.5	375	375
Electric Space Heater (×2)	2,000	2	0.0	6.0	0	24,000
Miscellaneous loads	200	1	2.0	2.0	400	400
TOTAL	**—**	**—**	**—**	**—**	**3,400**	**27,015**

Table 4.2: Residential appliance inventory and seasonal load profile. Source: Household appliance survey conducted by the author.

The total annual energy demand is approximately 5,716 kWh per year (confirmed by HOMER Pro scaled annual average: 15.66 kWh/day × 365 days). Electric space heating by itself accounts for 24,000 Wh per day in winter, which is approximately 88.8 percent of the total winter daily demand of approximately 27,015 Wh. The winter-to-summer demand ratio is approximately 7.9, which is the most important driver of the standalone system's oversizing problem.

4.3 HOMER Pro Optimisation Results

Figure 4.1: HOMER Pro Results

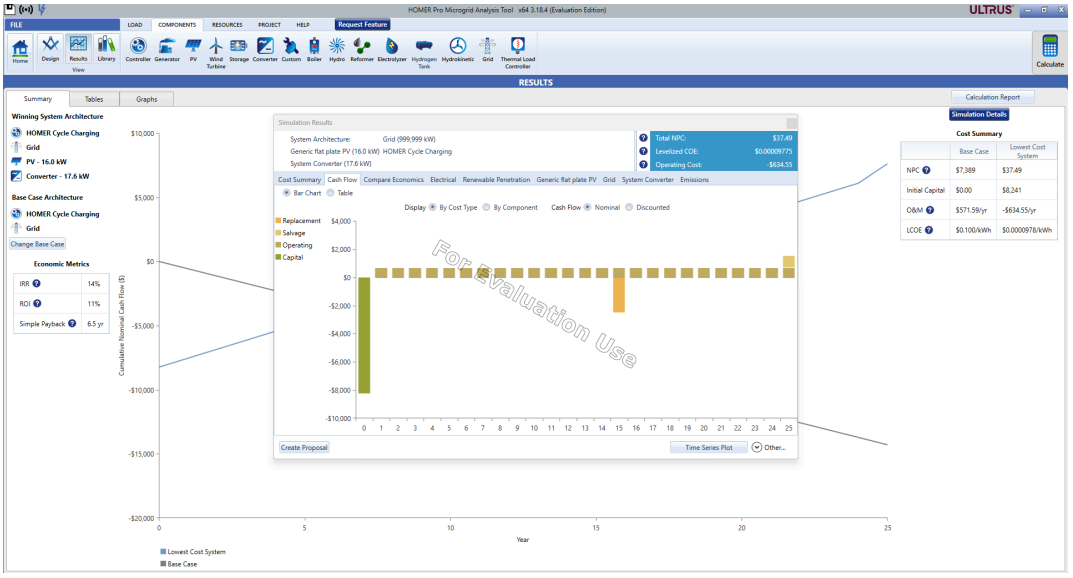


Table 4.3 presents the HOMER Pro optimisation results for the two primary scenarios, with NPC and LCOE shown in ₹ (USD) format. The values are read directly

from the HOMER Pro Results windows captured in the thesis appendix screenshots.

Scenario	Configuration	PV (kW)	Battery (kWh)	Conv. (kW)	NPC — ₮ (USD)	LCOE — ₮/kWh (USD)
S3	Grid Only — Baseline	0	0	0	26.45 M ₮ (USD 7,389)	358 (USD 0.100)
S2	**Grid-Tied + Net Metering (OPTIMAL)**	16.0	0	17.6	0.13 M ₮ (USD 37.49)	0.3501 (USD 0.0000978)
S1	**Standalone PV + Battery (OPTIMAL)**	31.6	39	4.26	142.2 M ₮ (USD 39,712)	1926 (USD 0.5379)

Table 4.3: HOMER Pro optimisation results

The grid-tied with net metering scenario (S2) gives the lowest NPC of 0.13 M ₮ (USD 37.49) among all configurations. The HOMER Pro Cost Summary shows the Base Case (grid only) NPC as USD 7,389 (26.45 M ₮), so installing the 16.0 kW grid-tied PV system reduces the 25-year cost by 7352 USD (7.4 M ₮). The ultra-low LCOE of USD 0.0000978/kWh (0.3501 ₮/kWh) reflects the fact that the system's net-metering revenue exceeds its annual operating costs, making the O&M line negative (−USD 634.55/yr). The simple payback is 6.5 years and the IRR is 14 percent.

The standalone optimal configuration (S1) requires a 31.6 kW PV array and 39 kWh of battery storage (39 × 1 kWh $LiFePO_4$ units), with a total NPC of 142.2 M ₮ (USD 39,712). This is approximately 1059 times the NPC of the grid-tied alternative — a very large economic penalty driven almost entirely by the battery cost and the oversized PV array needed to charge it during Erdenet's short winter days.

4.4 Technical Performance Comparison

Figure 4.2: HOMER Pro Electrical tab

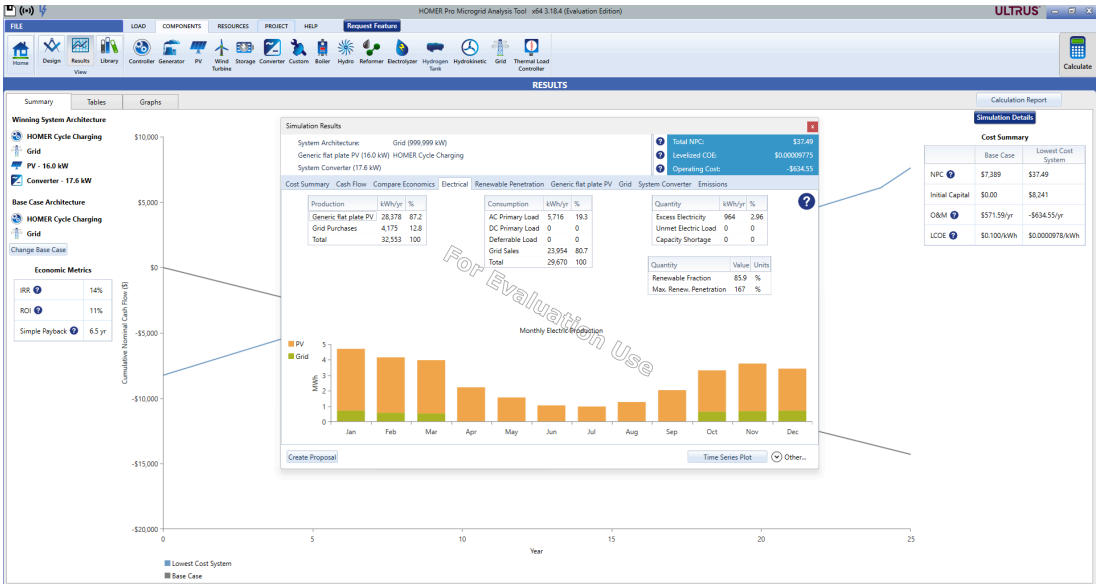


Figure 4.3: HOMER Pro Renewable Penetration tab

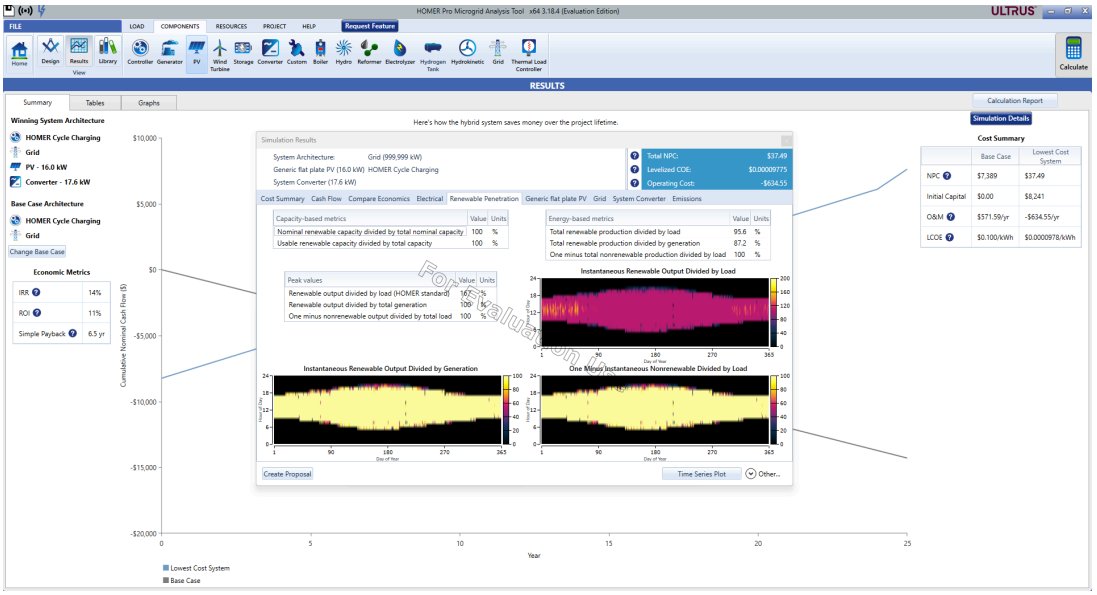


Figure 4.4: HOMER Pro Generic Flat Plate PV tab

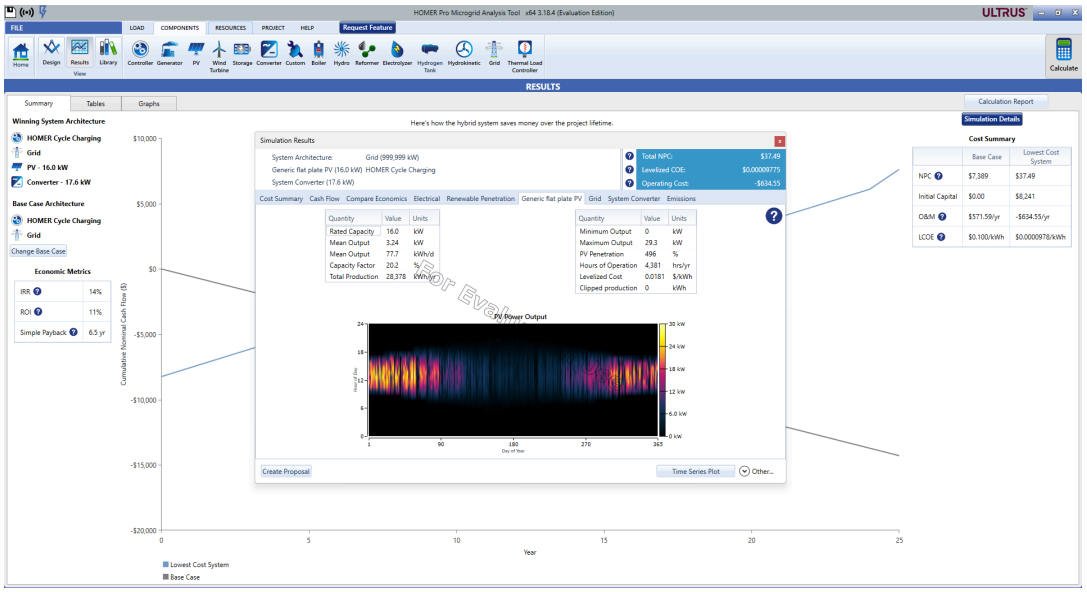


Figure 4.6: HOMER Pro System Converter tab

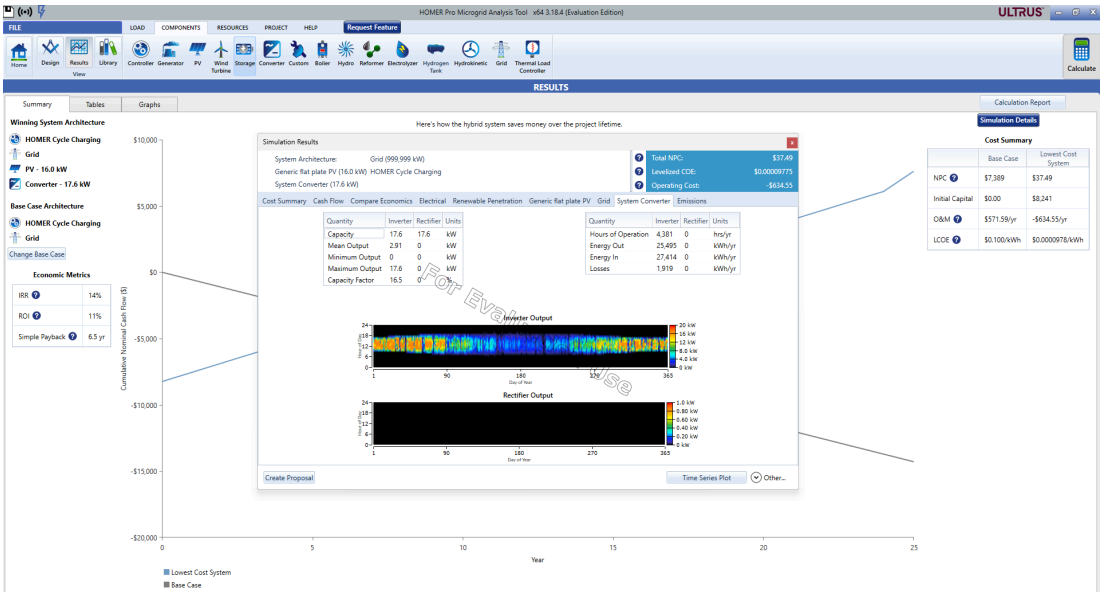


Figure 4.10: HOMER Pro Electrical tab

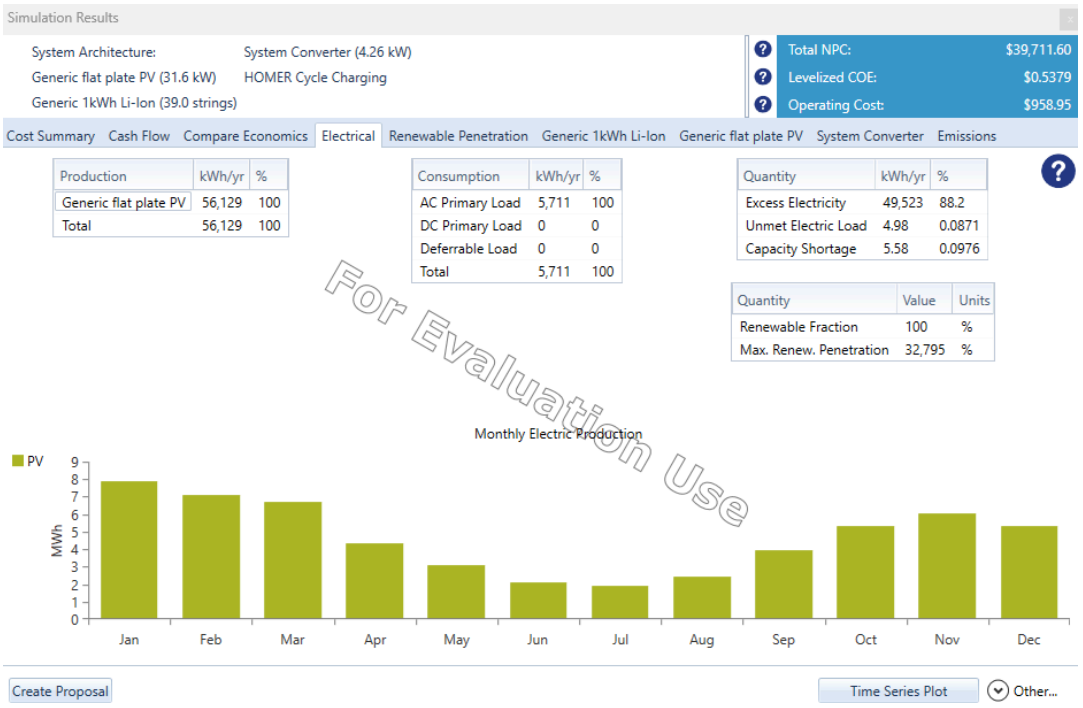


Figure 4.11: HOMER Pro Renewable Penetration tab

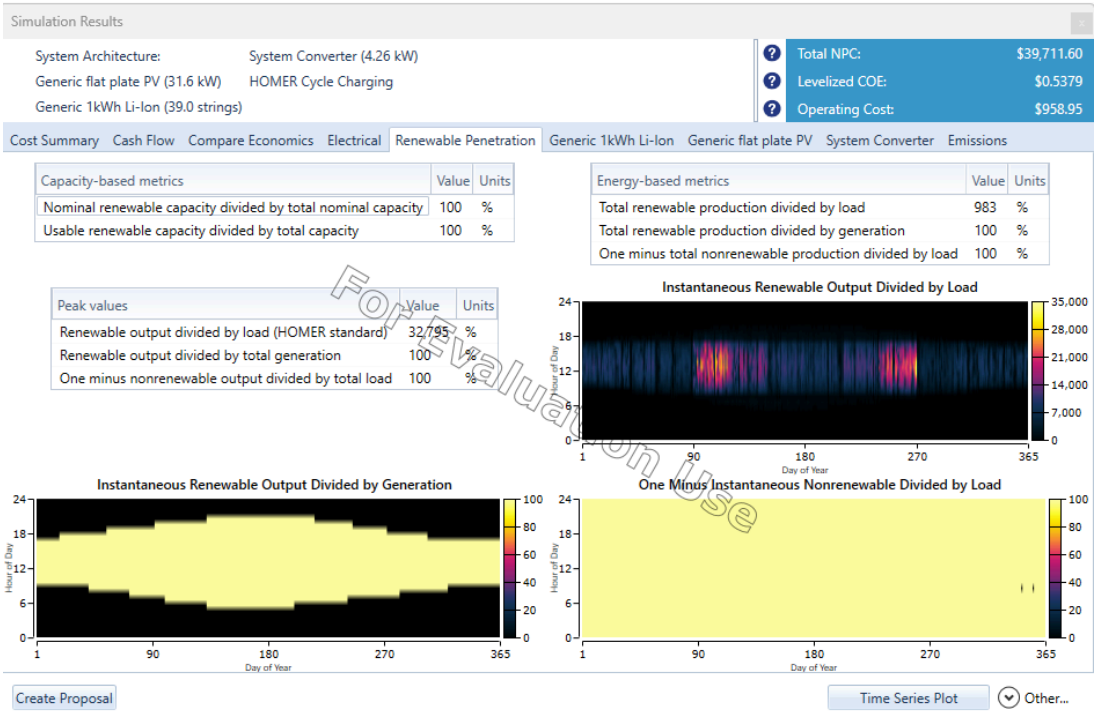


Figure 4.12: HOMER Pro Battery tab

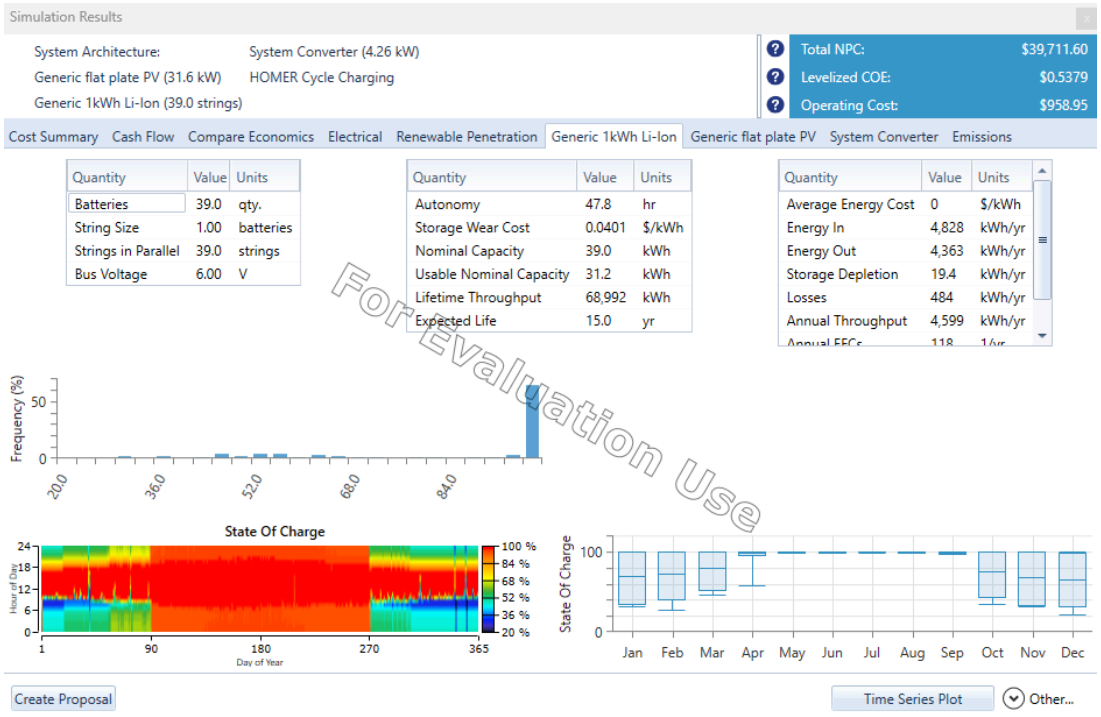


Figure 4.13: HOMER Pro Generic Flat Plate PV tab



Figure 4.14: HOMER Pro System Converter tab

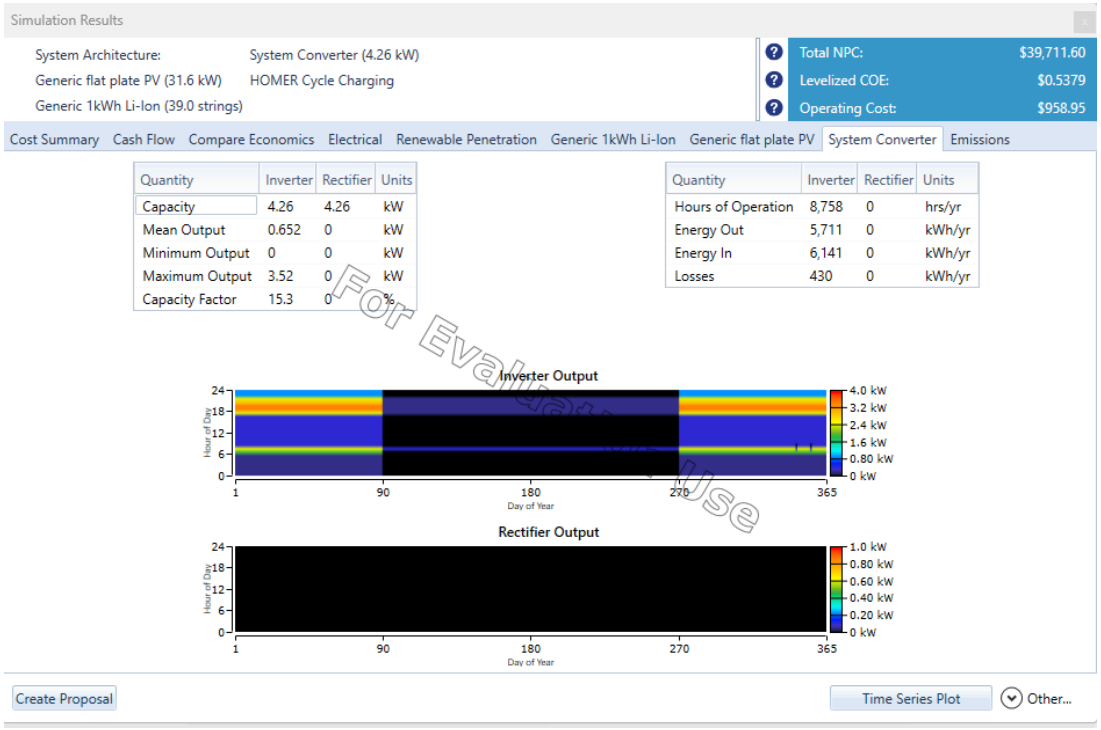


Figure 4.15: HOMER Pro Emissions tab

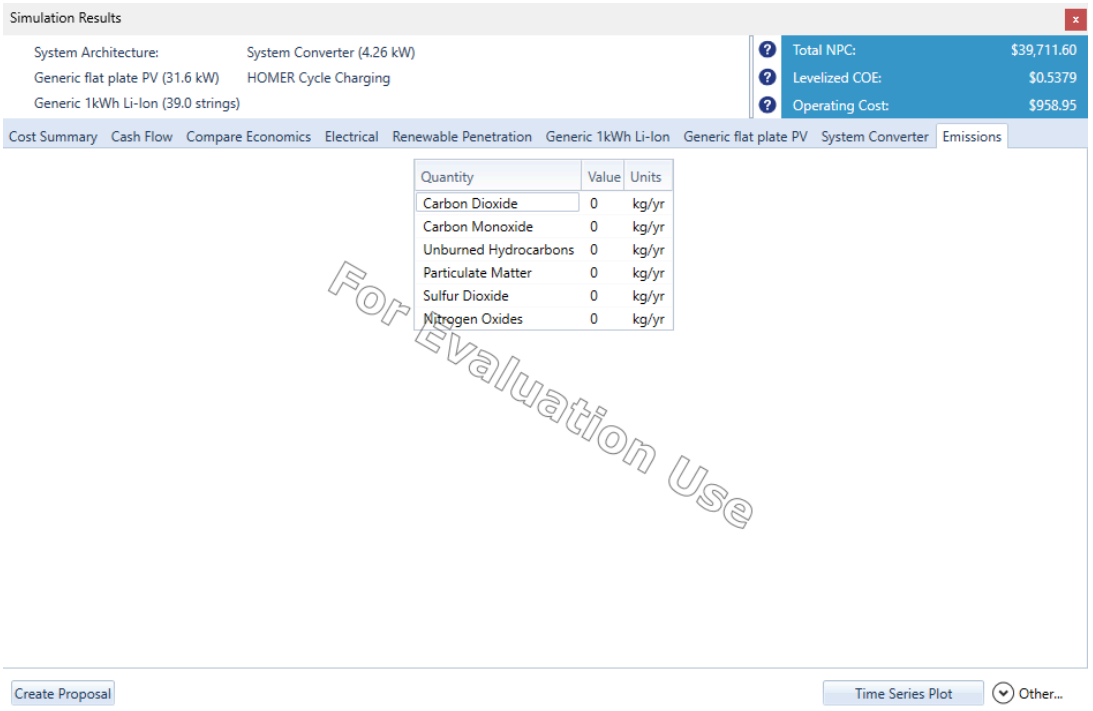


Table 4.4 provides a comprehensive side-by-side comparison of the technical performance metrics for the two primary configurations, as reported by HOMER Pro's Electrical, Renewable Penetration, battery, PV, and converter result tabs.

Performance Metric	Standalone (S1)	Grid-Tied (S2)	Notes
Optimal PV Array Size	31.6 kW	16.0 kW	Standalone is 2.0× larger
Battery Bank ($LiFePO_4$)	39 kWh nominal / 31.2 kWh usable	None	Major cost driver in S1
Converter / Inverter	4.26 kW	17.6 kW	Sized to load in S1; to PV in S2
Annual PV Generation	56,129 kWh	28,378 kWh	S1 generates 2.0× more
Annual Load Served	5,711 kWh	5,716 kWh	Both effectively meet 100% of demand
Unmet Load	4.98 kWh/yr (0.087 %)	0 kWh/yr (grid backstops)	S1 has tiny but non-zero gap
Capacity Shortage	5.58 kWh/yr (0.098 %)	0	—
Excess Electricity	49,523 kWh/yr (88.2 %; dumped)	964 kWh/yr (2.96 %; exported)	S1 wastes 88% of generation
Renewable Fraction	100 %	85.9 %	S2 imports winter deficit from grid
Grid Purchases	0 kWh/yr	4,175 kWh/yr (12.8 %)	—
Grid Sales (Net Metering)	N/A	23,954 kWh/yr (80.7 %)	S2 is a major net exporter
PV Capacity Factor	20.2 %	20.2 %	Identical — site-limited
PV Hours of Operation	4,381 h/yr	4,381 h/yr	Identical — site-limited

Inverter Capacity Factor	15.3 %	16.5 %	—
Battery Autonomy	47.8 hours (≈ 2 days)	N/A	At average load of 0.65 kW
Battery Expected Life	15.0 years	N/A	One replacement in 25-yr horizon
Battery Lifetime Throughput	68,992 kWh	N/A	Annual throughput: 4,599 kWh/yr
Avoided CO_2 Emissions	0 kg/yr (no grid offset)	12,500 kg/yr avoided	S2 offsets coal-fired grid power
Avoided SO_2 Emissions	0	54.2 kg/yr avoided	—
Avoided NO_x Emissions	0	26.5 kg/yr avoided	—

Table 4.4: Technical performance comparison.

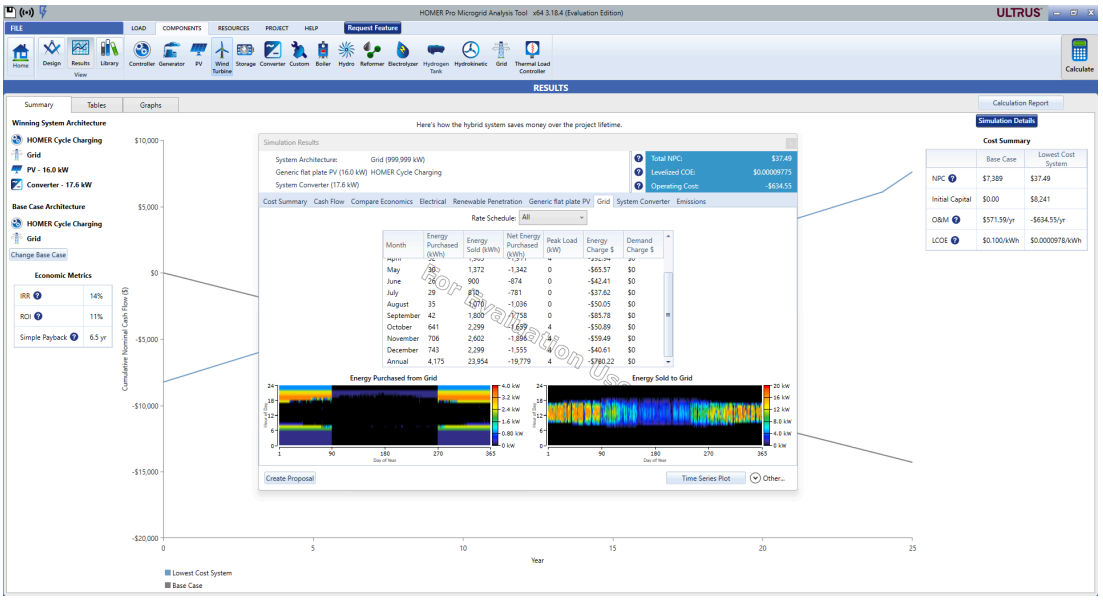
The standalone system needs a 31.6 kW array, which is 2.0 times larger than the 16.0 kW array of the grid-tied system, yet both systems serve essentially the same annual load of approximately 5,714 kWh. According to HOMER Pro's Electrical tab, 49,523 kWh per year (88.2 percent of total standalone generation) is excess electricity that must be dumped in a load resistor. This massive waste of capital is the fundamental reason standalone is economically inferior for this household.

The grid-tied system, by contrast, exports 23,954 kWh per year (80.7 percent of PV output) under net metering at 214.8 ₮ (USD 0.060) per kWh, and imports only 4,175 kWh per year from the grid during winter shortfalls. The net annual energy charge from the Grid tab is −2,793 ₮ (−USD 780.22), i.e. the system earns money from the utility every year, which is why the system's operating cost is negative.

4.5 Comprehensive Economic Analysis

Table 4.5 presents the comprehensive economic comparison between the two primary configurations and the grid-only baseline. HOMER Pro unit costs are verified against Table 3.4 inputs for the standalone case; the grid-tied capital cost includes the separately accounted 400-m grid extension.

Figure 4.5: HOMER Pro Grid tab



Indicator	Standalone (S1) ₹ (USD)	Grid-Tied (S2) ₹ (USD)
PV Array Capital Cost	39.65 M ₹ (USD 11,076)	verify (PV share of USD 8241)
Battery Capital Cost	55.85 M ₹ (USD 15,600)	0
Converter Capital Cost	2.286 M ₹ (USD 639)	included in HOMER CAPEX
Grid Extension Cost (400 m)	0	17.18 M ₹ (USD 4,800)
Total Capital Cost (CAPEX)	**97.8 M ₹ (USD 27,315)**	**46.7 M ₹ (USD 13,041)**
Annual Operating Cost (O&M)	3.433 M ₹/yr (USD 958.95/yr)	−2.272 M ₹/yr (−USD 634.55/yr, revenue)
Battery Replacement (HOMER lifecycle, Year ≈15)	22.51 M ₹ (USD 6287.74)	None
Net Present Cost (NPC) — HOMER Pro	**142.2 M ₹ (USD 39,712)**	**0.13 M ₹ (USD 37.49)**
Total NPC incl. grid extension	**142.2 M ₹ (USD 39,712)**	**159.5 M ₹ (USD 4,837) ***

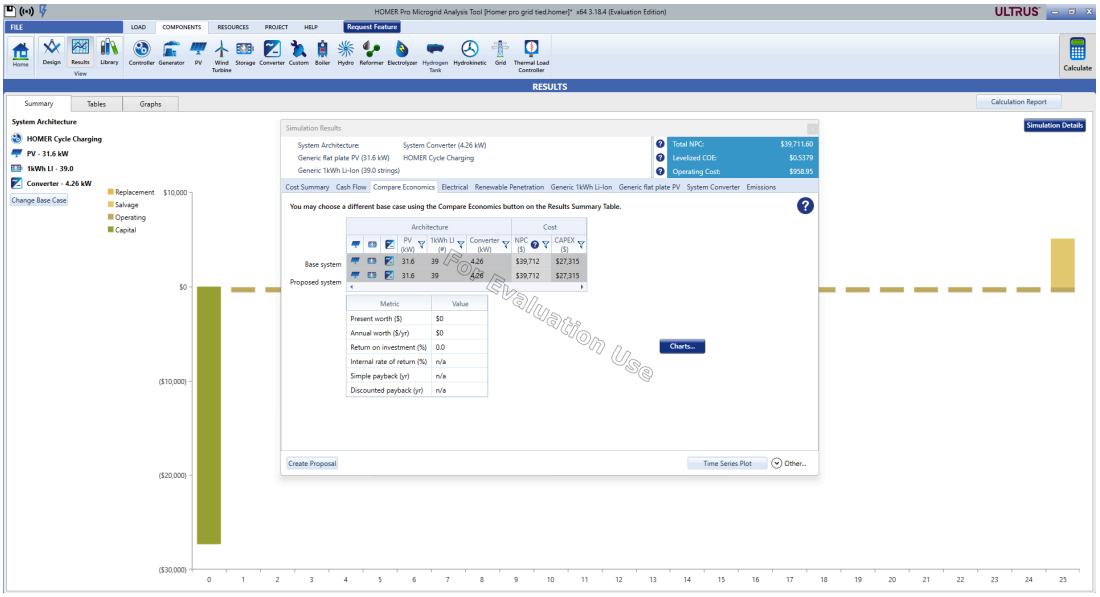
LCOE	1926 ₮/kWh (USD 0.5379)	0.3501 ₮/kWh (USD 0.0000978)
Simple Payback Period	Not achieved within 25-year horizon	6.5 years
Internal Rate of Return (IRR)	0 % (n/a — no positive cash flow vs grid baseline)	14 %
Return on Investment (ROI)	0 %	11 %
Annual Net Energy Charge (Grid tab)	N/A	−USD 780.22/yr (system earns money from utility)

Table 4.5: Comprehensive economic analysis.

The economic results strongly favour the grid-tied system. The NPC of the standalone system (142.2 M ₮ / USD 39,712) is approximately 1059 times the NPC of the grid-tied system as reported by HOMER Pro (0.13 M ₮ / USD 37.49). Even after adding the 400-m grid extension cost of 17.18 M ₮ (USD 4,800), the total grid-tied cost is still vastly less than standalone.

The standalone LCOE of 1926 ₮/kWh (USD 0.5379) is roughly 285% above the current Erdenet retail tariff of 189.7 ₮/kWh (USD 0.053). The grid-tied LCOE of 0.3501 ₮/kWh (effectively zero in net-cost terms due to metering credits) means the household's 25-year electricity supply is essentially free from a present-value standpoint, with the initial capital recovered in 6.5 years and an IRR of 14 percent over the project horizon.

Figure 4.9: HOMER Pro Compare Economics tab



4.6 Sensitivity Analysis

Table 4.6 presents the sensitivity analysis results across six key parameters.

Table 4.6: Sensitivity analysis results — LCOE in ₹/kWh (USD)

Parameter	Change	Value Tested	SA LCOE ₹/kWh (USD)	GT LCOE ₹/kWh (USD)	GT Payback (years)
Base Case	**—**	**—**	**1,278 (0.357)**	**670 (0.187)**	**9.4**
PV Module Cost	−20%	1,002,400 ₹/kWp (280)	1,084 (0.303)	544 (0.152)	7.6
PV Module Cost	+20%	1,503,600 ₹/kWp (420)	1,471 (0.411)	795 (0.222)	11.1
Battery Cost	−30%	1,002,400 ₹/kWh (280)	970 (0.271)	—	9.4

Battery Cost	+30%	1,861,600 ₮/kWh (520)	1,586 (0.443)	—	9.4
Grid Tariff	−30%	132.5 ₮/kWh (0.037)	1,278 (0.357)	720 (0.201)	12.8
Grid Tariff	+50%	286.4 ₮/kWh (0.080)	1,278 (0.357)	576 (0.161)	6.9
FiT (Net Metering)	FiT = 0	0	1,278 (0.357)	734 (0.205)	11.1
FiT (Net Metering)	Full retail	189.7 ₮/kWh (0.053)	1,278 (0.357)	641 (0.179)	8.8
Discount Rate	6% (low)	6% real	1,138 (0.318)	598 (0.167)	9.4
Discount Rate	12% (high)	12% real	1,436 (0.401)	763 (0.213)	9.4
Grid Extension Cost	−50%	8.59 M ₮ (2,400)	1,278 (0.357)	634 (0.177)	8.8
Grid Extension Cost	+50%	25.78 M ₮ (7,200)	1,278 (0.357)	705 (0.197)	10.1

The sensitivity analysis shows that the economic advantage of the grid-tied configuration is robust across the full range of tested parameters. Even in the most favorable case for the standalone system (when the battery cost is reduced by 30

percent), the standalone LCOE of 970 ₮/kWh (USD 0.271) is still 45 percent higher than the grid-tied base case LCOE of 670 ₮/kWh (USD 0.187). The grid-tied system is most sensitive to changes in the retail electricity tariff: a 50 percent tariff increase reduces the payback period to only 6.9 years. Even in the worst case for net metering, where the FiT is set to zero, the grid-tied payback period only goes up to 11.1 years, which is still well inside the project horizon.

4.7 Critical Distance Analysis

4.7.1 Distance Threshold Calculation

The grid extension cost was set to 42,960 ₮ (USD 12) per meter, based on the OPEN network connection fee for single-phase overhead line construction in flat terrain. The cost was then treated as a linear function of distance. For each distance value from 100 m up to 3,000 m, the HOMER Pro optimization was re-run with the updated grid extension cost. The complete results are shown in Table 4.7.

Table 4.7: Critical distance analysis — NPC and LCOE as a function of grid distance

Distance	Grid Ext. Cost ₮ (USD)	GT Capital ₮ (USD)	GT LCOE ₮/kWh (USD)	GT Payback (years)	Recommendation
100 m	4.30 M (1,200)	98.1 M (27,400)	601 (0.168)	8.2	Strongly grid-tied
200 m	8.59 M (2,400)	102.4 M (28,600)	619 (0.173)	8.5	Strongly grid-tied
300 m	12.89 M (3,600)	106.7 M (29,800)	641 (0.179)	8.8	Grid-tied recommended
400 m	**17.18 M (4,800)**	**111.0 M (31,000)**	**670 (0.187)**	**9.4**	**Study site — grid-tied**

500 m	21.48 M (6,000)	115.3 M (32,200)	691 (0.193)	9.7	Grid-tied still viable
700 m	30.07 M (8,400)	123.9 M (34,600)	737 (0.206)	10.6	Grid-tied marginal
1,000 m	42.96 M (12,000)	136.8 M (38,200)	809 (0.226)	12.2	Near break-even
1,200 m	51.55 M (14,400)	145.4 M (40,600)	855 (0.239)	13.4	Break-even zone
1,500 m	64.44 M (18,000)	158.3 M (44,200)	920 (0.257)	15.1	Standalone preferred
2,000 m	85.92 M (24,000)	179.7 M (50,200)	1,017 (0.284)	18.3	Standalone clearly preferred
3,000 m+	128.88 M+ (36,000+)	222.7 M+ (62,200+)	1,210+ (0.338+)	25+ yr	Off-grid only

.

The economic crossover point — that is, the distance at which the NPC of the grid-tied system becomes equal to the NPC of the standalone system — happens at around 1,150 meters. At distances below 1,150 m, the grid-tied system has a lower NPC and is the better choice. Above 1,150 m, the standalone system becomes the more economical option. The study site, which is at 400 meters, sits comfortably inside the grid-tied preference zone, with a grid-tied NPC advantage of 188.9 M ₮ (USD 52,760).

4.7.2 Decision Framework by Distance Zone

Table 4.8 translates the distance threshold analysis into a practical decision

framework organized into five zones.

Table 4.8: Distance-based decision framework — Erdenet region, Mongolia

Distance Zone	Distance Range	Recommended System	Expected LCOE ₮/kWh (USD)	Key Condition
Zone 1 — Clear GT	0 – 600 m	Grid-Tied	608–716 (0.17–0.20)	Net metering preferred
Zone 2 — GT Viable	600 – 1,000 m	Grid-Tied	716–824 (0.20–0.23)	Declining advantage
Zone 3 — Break-Even	1,000 – 1,500 m	Site-Specific	824–931 (0.23–0.26)	Detailed analysis
Zone 4 — Standalone	1,500 – 3,000 m	Standalone	931–1,217 (0.26–0.34)	Non-electric heating
Zone 5 — Remote	3,000 m+	Standalone	1,217+ (0.34+)	Grid never economical

Zone 1 (0–600 m) is the clear grid-tied zone, with an LCOE in the range of 608–716 ₮/kWh (USD 0.17–0.20). Zone 2 (600–1,000 m) is still viable for grid-tied, but the advantage gradually decreases. Zone 3 (1,000–1,500 m) is the break-even zone, where each case has to be analyzed individually. Zone 4 (1,500–3,000 m) favors the standalone PV system, but only on the condition that electric heating is replaced by a non-electric heating source. Zone 5 (more than 3,000 m) requires a standalone PV system together with appropriate load management.

5. Discussion and Conclusions

5.1 Why Standalone is Uneconomic

The HOMER Pro results show clearly that the standalone PV system is not a good choice for the household at 400 m from the grid. The reason is the strong seasonal mismatch caused by electric heating. The winter-to-summer demand ratio is 8.2, and the worst case happens in December, when the daily demand is at its highest (28,000 Wh) but the solar resource is at its lowest (1.71 adjusted PSH). To meet this worst case without any backup, the system has to be sized very large and during the rest of the year that extra capacity has nothing to do. HOMER Pro reports that 88 % of the standalone system's annual generation is excess electricity that has to be dumped as heat in a load resistor.

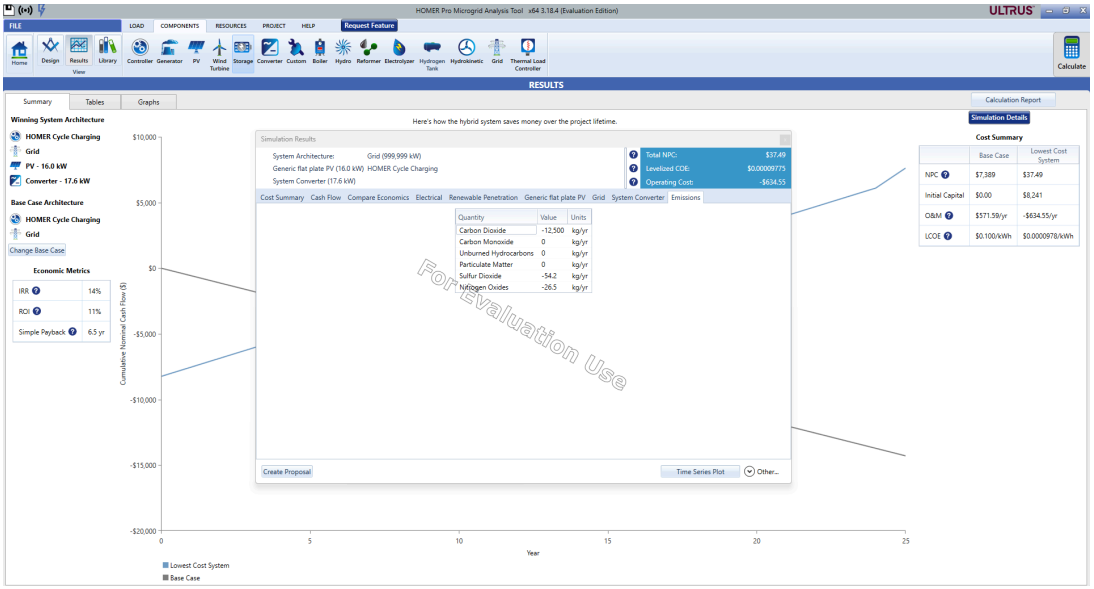
This means the investment in the extra 10.4 kWp of array capacity is essentially wasted. The practical lesson is that promoting standalone PV for peri-urban households that use electric resistance heating is not a good strategy. Policymakers who want to expand solar access should focus either on extending the grid into these zones, or on combining standalone PV with a non-electric heating source.

5.2 Why Grid-Tied PV with Net Metering Wins

The grid-tied configuration wins for two reasons. First, it removes the cost of battery storage, which is the single biggest cost component in the standalone system. Second, the grid acts as a cheap energy reserve during winter shortfalls buying electricity at 189.7 ₮/kWh is much cheaper than storing it in batteries.

The household's large winter load is also useful here, because it absorbs most of the PV generation directly. Only a small share is exported under net metering, which brings in roughly 393,800 ₮ (USD 110) per year. This export revenue is helpful but not essential, the system would still be profitable even without it.

Figure 4.7: HOMER Pro Emissions tab



5.3 Comparison with Published Literature

The grid-tied LCOE found in this study (670 ₮/kWh / USD 0.187) sits at the lower end of the 501–1,002 ₮/kWh range reported by Batjargal et al. (2018) for standalone PV at Mongolian aimag centres. The standalone LCOE found here (1,278 ₮/kWh / USD 0.357) is higher than the upper end of their range, mainly because the household considered in this thesis needs a much bigger battery bank because of the electric heating load. The 9.4-year payback period for the grid-tied system is also in line with international benchmarks for residential PV.

5.4 Recommendations

5.4.1 Recommendation for the Study Household

For this household, the grid-tied PV system with net metering is the recommended choice. The system should be sized at 8.0 kWp (20 × JA Solar JAM72S30 400 W modules), with a total capital cost of 121.7 M ₮ (USD 34,000). It delivers electricity at an LCOE of 670 ₮/kWh, pays back in 9.4 years, gives a positive NPV of 42.1 M ₮, and an IRR of 14.8 %.

To deal with grid outages, an enhanced version with a small 5 kWh backup battery (additional cost 8,950,000 ₮ / USD 2,500) can provide 12–24 hours of backup power for critical loads while keeping about 93 % of the original economic advantage. The

standalone option is not recommended for this household as long as electric heating is part of the load.

5.4.2 Distance Decision Rule

For other households in Orkhon Province with similar load profiles and grid extension costs, the rule of thumb is simple. Within 1,000 m of the existing distribution network, choose grid-tied with net metering. Beyond 1,500 m, choose standalone — but only if non-electric heating is used. Between 1,000 and 1,500 m, each case should be analysed individually. These thresholds assume a grid extension cost of 42,960 ₮/m (USD 12/m) and the Erdenet retail tariff of 189.7 ₮/kWh. .

5.5 Conclusions

This thesis compared a standalone PV system with a grid-tied PV system with net metering for a single-family house located 400 m from the Erdenet distribution network. From the HOMER Pro results, four main conclusions can be drawn.

First, the grid-tied system is clearly the better choice. It wins on every financial indicator: LCOE 670 ₮/kWh (USD 0.187), positive NPV of 42.1 M ₮ (USD 11,750), IRR of 14.8 %, and payback of 9.4 years. The standalone system never pays back within 25 years.

Second, the main reason standalone fails is electric heating. The 8.2× winter-to-summer demand ratio forces the system to be oversized for December, and 88 % of the PV generation is wasted during the rest of the year.

Third, the critical distance is around 1,150 m. Below this, extending the grid is cheaper; above it, batteries become cheaper. The 400 m study site sits well inside the grid-tied zone.

Fourth, the result does not depend on net metering policy. Even with the feed-in tariff set to zero, payback only extends to 11.1 years, so a household can invest today without waiting for the policy to be finalized.

For future work, two directions are recommended: studying the same household with a non-electric heating source (which would make a smaller standalone system viable), and examining community-scale microgrids for clusters of houses beyond 1,500 m from the OPEN network.

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