CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF ENERGY ENGINEERING

DESIGN OF AN ENERGY INDEPENDENT HOUSEHOLD

BACHELOR'S THESIS

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BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

Bachelor's thesis title in English:

Design of an energy independent household

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Guidelines:

1) Literature review on the possibilities of supplying households with electricity and heat with respect to off-grid installations
2) Calculation of heat loss of a single family house, calculation of heat and electricity requirements throughout the year, construction of power load duration diagram
3) Definition of scenarios of the heat and electricity sources installations following the energy demands of the house, respecting real equipment available on the market
4) Mass and energy balances of the specified scenarios, economic evaluation and sensitivity analysis towards selected criteria

Bibliography / sources:

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

4/5./2021
Date of assignment receipt

Student's signature

Declaration

I declare that I have written my bachelor’s thesis independently under the guidance of prof. Ing. Jan Hrdlička, Ph.D and have only used the documents listed in the reference list attached with this thesis.

In Prague, On ……………………. Signature…………………………

Title: Design of an Energy Independent Household

Author: Gaurav Singh

Supervisor: prof. Ing. Jan Hrdlička, Ph.D

Abstract:

The aim of this thesis is to design the off-grid heat and electrical systems of a house in the Central Bohemian Region, which is not connected to electrical or gas grid. The heating system is designed by calculating the heat loss and domestic hot water consumption of the house, and an annual heat load diagram is constructed. Three scenarios are described to provide heating, using biomass and gas boilers. The capacity of the electric system is designed using the monthly solar irradiation for the region. The cost and sensitivity analyses using net present value (NPV) were performed for all systems described.

Keywords: heat loss, off-grid, biomass, photovoltaics, domestic hot water, fuel, energy, NPV, sensitivity analysis

Acknowledgments

I would like to thank the supervisor of this bachelor’s thesis prof. Ing. Jan Hrlička, Ph.D. for his valuable inputs during our consultations. I would also like to thank my family, for their support during my bachelor’s program.

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Symbol	Description	Unit	Symbol	Description	Unit
t_{id}	Internal Design Temperature	°C	R	R Value or thermal insulance	$\frac{m^2K}{W}$
t_e	Mean External Temperature	°C	U	Overall Heat Transfer Coefficient or U Value	$\frac{W}{m^2K}$
t_{ed}	External Design Temperature	°C	ρ	Density	$\frac{kg}{m^2}$
$\dot{Q}_{DHW}$	Daily DHW Heat Load	kW	$q_{v,min}$	Volumetric Air Change Rate	$\frac{m^3}{s}$
Φ_d	Total Design Heat Load	W	n_{min}	Minimum Air Change Rate	$\frac{1}{h}$
$\dot{Q}_{SH,day}$	Daily Space Heating Load	W	Q_{DHW}	Annual DHW Consumption	$\frac{kWh}{year}$
$\dot{q}$	Heat Flux	$\frac{W}{m^2}$	Q_{SH}	Annual Consumption for Space Heating	$\frac{kWh}{year}$
λ	Thermal Conductivity	$\frac{W}{m\,K}$	Q_{total}	Total Annual Heat Loss of the Dwelling	$\frac{kWh}{year}$
b	Thickness of Heat Transfer Surface	m	$\Phi_{T,d}$	Design Transmission Heat Loss	W
$Q_{E,m}$	Monthly Electrical Energy Consumption	$\frac{kWh}{month}$	$\Phi_{V,d}$	Design Ventilation Heat Loss	W
$Q_{E,d}$	Daily Electrical Energy Consumption	$\frac{kWh}{day}$	I_D	Average Daily Solar Irradiation	$\frac{kWh}{m^2}$
$A_{PV}\ or\ A$	Area of PV Array	m^2	P_p	Peak Power of PV Array	kW_p
C_B	Capacity of the Battery Bank (Nominal)	kWh	c_p	Specific Heat Capacity	$\frac{J}{kg\,K}$

1. Introduction and Aim

Any modern household requires electricity for lighting and appliances, hot water for domestic consumption and in colder areas of the world, space heating is essential. In urban and metropolitan areas, these requirements are met by an electric grid and in some cases, supplemented by a gas connection. If a house is not connected to the electrical or gas grid; perhaps because it is in a remote area with no power lines or if the owner simply wishes to be self-reliant, then it must be equipped with systems that supply it with off-grid heat and electricity.

The aim of this thesis is to design and analyse the feasibility of an energy independent household located in the Central Bohemian Region. To design the pertinent heat and electricity systems of such a project, it is important to first understand its energy requirements. The requirements of households around the world are different and they can change drastically with variations in temperature, rainfall, and sunlight. For this thesis, all meteorological data used will be from the Czech Republic.

In the table below we can see the average energy division for a European household.

Space Heating	63.6%
Water Heating	14.8%
Lighting and Appliances	14.1%
Cooking	6.1%
Space Cooling	0.4%
Other	1.0%

Table 1: Division of Energy Consumption in EU Households (1).

To calculate the energy demand of the house, the demand will be divided into three parts

- Space heating – determined by the annual heat loss of the heated space
- Domestic hot water (DHW) – estimated using existing literature
- Electricity consumption – estimated from available literature and compared to total energy consumption.

2. Literature Review of Existing Off-Grid Studies

Many studies focus on achieving a completely renewable solutions to self-sufficiency, and often face similar challenges of fulfilling the seasonal heat demand and reducing energy storage costs.

A study done by Grosspietsch et al. (2) focuses on a stylized neighbourhood in Switzerland and assesses the cost of providing an autonomous electricity and heat supply. It identifies several configurations to achieve an off-grid renewable energy supply at the neighbourhood level. The first configuration consists of a PV system with a lithium battery storage and a heat pump to provide space heating ("PV-battery-HP"). The second configuration consists of the same system, with the addition of a hydrogen storage ("PV-battery-H_2-HP"). This system distributes between a lithium battery and a hydrogen storage tank, and hence requires additional devices such as an electrolyser to produce the hydrogen when there is excess power generated by the PV, and a fuel cell to use this hydrogen when the demand is higher. In both configurations the entire system is dependent on the electricity produced by the PV array, and hence the required capacity exceeds available rooftop area. This is due to the large gap between heat demand and average sunlight hours in the Swiss winter.

The study further discusses an alternate configuration which combines a natural gas-based ICE (Internal Combustion Engine) to supply both heat and energy. Since this configuration relies on the provision or the production of natural gas, the study considers it not to be a fully autarkic configuration and does not report its results.

The results of the study state that given the typical seasonal nature of the Swiss energy demand, both the configurations require large PV installations and large storage capacities. Which leads to a relatively high cost of the system; In the first configuration, the battery accounts for a third of the total cost. These costs can be reduced as the efficiency of PV modules rise, and passive constructions that reduce the heat demand of households. Overall, the study found that a decrease in technology costs by 21% for the PV-battery-HP scenario and a 51% for PV-battery-H_2-HP would make them economically competitive.

Another well-known off-grid project is the "The Self-Sufficient Solar House in Freiburg" (SSSH) (3) which was designed by The Fraunhofer Institute for Solar Energy Systems. All the energy demand for this house was met through energy radiated by the sun. The planning of the house started in 1988, and it began construction in June 1991. The design for the house itself, not only its energy systems, was done with energy savings in mind. One of the biggest challenges the house faced was to adequately heat the house during the winter, given the low levels of solar insolation during the European winter. At the time, it was decided that the possibility of using large seasonal storages was both expensive and inefficient. To solve this problem, the institute developed transparent insulation systems to utilize solar radiation for space heating. The focus on energy saving was also used in the electrical system, where special energy efficient appliances were purchased and hot water for a dishwasher and washing machine was provided by solar collectors. The house consisted of a solar collector system for domestic hot water, a photovoltaic system in conjunction with H_2/O_2 storage system.

The electrical and DHW systems were designed to work in tandem, where the solar collectors for the hot water provided a solar fraction of 90%. The rest of the energy required in the months of December, January and February was supplied by the hydrogen storage system connected to the PV array. The cooking stove was also operated using catalytic combustion of hydrogen with air.

The electrical system consisted of PV panels, a lead acid battery for short term storage of 3-4 days and a hydrogen storage system consisting of an electrolyser and a fuel cell. The fuel cell compensated for the loss in solar-generated electricity during the winter.

The cost of the construction of the SSSH was 1.6 million DM (€0.81 million) , of which 0.7 million DM (€0.35 million) was for all the technical components. Despite the high initial cost of the house, the study predicted that there could be a cost saving potential for a second generation SSSH.

A paper by Akinyele et al. (4) discusses the possibility of a hybrid electricity system in an off grid residential application in Wellington, New Zealand. The study differs from the two mentioned above because it focusses solely on electricity production for household electrical appliances excluding hot water, space heating and cooking. The house is located on a hill 210 meters above sea level and thus has access to undisturbed wind and solar resources. Three scenarios are investigated to cover the electricity demand of the house. The first scenario is named “Generator only” where a petroleum fired generator is used to cover the entire demand; this option serves as a control for the economic calculations. The second scenario, namely “Wind, PV and Battery” uses a combination of photovoltaics, wind turbine and a battery with 2 days of autonomy. The system is designed such that the wind system has a significantly higher annual yield compared to the PV. The third scenario “ Wind, PV and Battery with Generator” puts together the first two scenarios and uses the generator to manage the state of charge at a certain level and provide for the missing supply when the wind/PV systems have a lower output.

The life cycle cost analysis of the three scenarios revealed that scenario one was most expensive, due to high fuel costs and replacement of equipment, despite its low initial costs. The cost of energy per kWh was lowest for scenario 2, followed by scenario 3. The study also noted that the environmental impact of the first scenario was significantly higher than for the other two.

This study shows the feasibility of wind powered electrical systems in geographically favourable locations. The house in question was well above sea level and received plenty of wind energy throughout the year. For locations at sea level, which receive lower wind energy due disturbances by manmade structures, wind may not be a viable option.

Another study done by the University of Victoria (5) discusses the design of an off-grid passive house built with shipping containers. The house was built using passive standards, with all surfaces having a maximum U value of 0.15 W/m^2. There are considerations made for rainwater harvesting and water treatment, to further the goal of self-sufficiency. Space heating for the building relies completely on thermal gains from large windows that capture solar radiation. Hot water is provided by a solar water heater, along with a drain water heat recovery unit. The hot water system also contains a small air source heat pump as a backup. The PV system consists of a PV array that is designed for input solar radiation for the month of January. The main challenge stated in the paper was the insulation for the passive house; the entire container needed to be encapsulated in insulation to eliminate thermal bridging. The energy modelling for the project was created using a modelling software called HOT200 and was used to simulate the energy performance of the building.

The final cost analysis showed that insulating the outside or the inside of the container was equally expensive, and that the container house was significantly more expensive than traditional passive house designs. The paper concludes that the goal of increasing sustainability was achieved, and the house is self-sufficient in power, water, and sewage treatment. The materials used were long lasting, high quality and recycled materials to reduce waste.

3. Theoretical Basis and Equations

This section will deal with the basis for calculations performed regarding the types of heat loss for a dwelling and estimation of domestic hot water consumption. The household electricity consumption and parameters important for the design of an electrical system will also be described.

3.1 Heat Loss and Design Heat Load

Heat loss of the house is calculated using the degree-day method. The Degree-Day method uses the meteorological data from a given place, specifically the average temperature for every given day in the year. Once we obtain this data, we select an internal design temperature which is the ideal indoor temperature. Subtracting the mean external temperature on a given day from this base temperature, we can find a daily change in temperature. If this change is positive, we call it a Heating Degree Day (HDD). (6)

$$HDD = (t_{id} - t_e) \qquad (3.1 - 1)$$

This is calculated for every day that the mean external temperature falls below 13°C. The internal temperature used for the calculations of heat loss has been set to 21°C. The design heat load of the building is the heat loss of the building calculated when the external temperature is extremely low. For Prague this value is set to -12°C. (7)

$$t_{id} = 21°\mathrm{C} \qquad\qquad t_{ed} = -12°\mathrm{C}$$

The heat loss of any given day is given by the degree day formula (8)

$$\dot{Q}_{SH,day} = \Phi_d \times \frac{(t_{id} - t_e)}{(t_{id} - t_{ed})} \qquad (3.1 - 2)$$

To calculate the heat loss during the entire heating season, the daily heat loss is multiplied by 24 and then summed up for all days of the heating season.

The design heat loss of the building is the sum of the design heat losses through transmission and ventilation. (9)

$$\Phi_d = \Phi_{T,d} + \Phi_{V,d} \qquad (3.1 - 3)$$

3.2 Transmission Heat Loss:

The heat loss of through a conducting wall depends on two parameters, the thermal resistance of the wall and the temperature difference between the surface of the inner wall and the outer wall.

We can tackle the problem of finding the total thermal resistance of the wall in the following way

1. If we have the thermal conductivity for the materials used in the wall, we can apply Fourier's Law in one dimension. (10)

$$\dot{q} = -\lambda \frac{dT}{dx} \qquad (3.2 - 1)$$

$$\dot{q} = \frac{\lambda}{b}\Delta T = \frac{T_{w1} - T_{w2}}{\frac{b}{\lambda}} \qquad (3.2 - 2)$$

Where T_{w1} is the higher wall temperature and T_{w2} is the lower wall temperature. The parameter $\frac{b}{\lambda}\left[\frac{m^2K}{W}\right]$ is referred to as the R value or RSI.

2. These R values can be added like electrical resistances, as shown in the figure

3. Once we have calculated the total thermal resistance for the wall, we can use its reciprocal to define overall heat transfer coefficient U value

$$U = \frac{1}{R_T} = \frac{1}{R_1 + R_2 + R_3} \qquad (3.2 - 3)$$

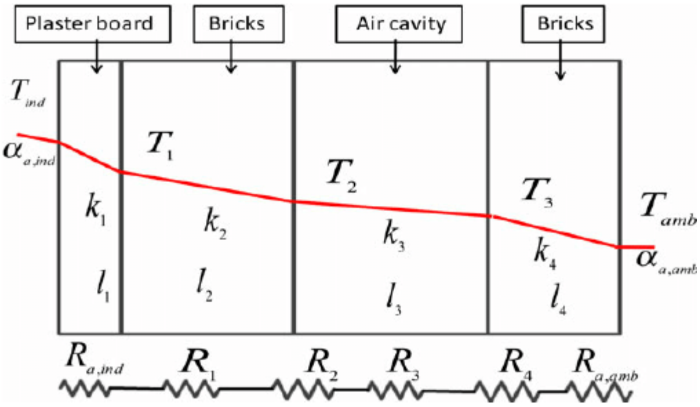


Figure 1: Heat Conduction (47)

Conductive or transmission heat loss for design conditions by this formula (when heat loss is directly to the exterior and thermal bridges are insulated) (9).

$$\Phi_{T,d}\,[W] = Area \times U\ value \times (t_{id} - t_{ed}) \qquad (3.2 - 4)$$

Thermal conductivities of materials used are below.

Material	Thermal Conductivity λ [W/m – K]
Softwoods	0.12
Mineral Wool	0.04
Brickwork, common	0.6 – 1.0
Hardwoods	0.16

Table 2: Thermal Conductivities of Materials (11).

3.3 Ventilation Heat Loss

This is the heat loss due to the heat stored in the volume of air in the room, and is given by the following formula (9).

$$\Phi_{V,d} = \rho \times c_p \times q_{v,min} \times (t_{id} - t_{ed}) \qquad (3.3 - 1)$$

$$q_{v,min}\left[\frac{m^3}{s}\right] = \frac{n_{min}}{3600} \times V_i \qquad (3.3 - 2)$$

Where V_i is the volume of the room. The values for minimal air change rate are given in the table below.

Room Type	n_{min} [h^{-1}]
Permanent dwelling areas	0.3 – 0.5
Kitchens, bathrooms (with windows)	0.5
Secondary rooms, internal rooms	0 – 0.3

Table 3: Minimal Air Change Rate. (7)

For this project, the value of 0.5 will be used.

3.4 Domestic Hot Water Requirement

To calculate the total heat requirement of the dwelling, it is important to estimate the domestic hot water requirement of the house. Domestic hot water (DHW) is the water used in any type of building, for domestic purposes, such as sanitation, food preparation, personal hygiene, and drinking (but not including space heating). The consumption of domestic hot water depends on various factors like the geographical location of the dwelling, the climate of the area and human behaviour. The average temperature demand for DHW systems is 50 – 65°C.

An Irish study done to estimate DHW demands starts by classifying dwellings based on occupancy and type:

Dwelling Type	Occupancy
Bungalow	3
Detached	≥ 4
Semi-detached	3
Flats	2

Table 4: Dwelling Type and Assumed Occupancy. (12)

The dwelling given to us is a detached house, and we can assume that 4 occupants inhabit it. The estimates for DHW demand, in liters/day and liters/day-resident are as follows:

Dwelling Type	L/day	L/day-resident
Bungalow	111.0	37.0
Detached	159.6	32.3
Semi-detached	111.0	37.0
Flats	86.0	43.0

Table 5: Average Daily DHW consumption. (12)

And finally, the study also calculates the average daily demand to heat the water for DHW purposes. The heat load is classified into that for new and existing dwellings. There is also a distinction made between the amount of energy required in February and July, as in winters, water is at lower temperatures and more energy is required to heat it up to the desired temperature.

Construction Periods	Dwelling Type	Average Heating Demand (kWh/L)	
		February	July
New	Bungalow	0.063	0.057
	Detached	0.062	0.056
	Semi-detached	0.062	0.057
	Flats	0.064	0.058
Existing	Bungalow	0.100	0.094
	Detached	0.088	0.081
	Semi-detached	0.102	0.095
	Flats	0.108	0.103 – 0.106

Table 6: Average Heating Demand. (12)

For our case, we choose the "new" construction period and a detached dwelling type, giving us the values highlighted above. As there is more energy needed to heat up the water in the colder months, for calculations made hereon, I will be using the higher value for months from October to March; and the lower value for April – September.

Assuming the house is inhabited by 4 residents, the average value of hot water consumed is 39.75 L/day – resident. This is in accordance with common values like 40 l/day-resident used in Central Europe.

3.5 Annual Electricity Consumption

While the heat loss of a building depends on its construction and size, the electricity consumption is more uniform across households. Once space heating and DHW production is provided for by direct heat sources, electricity is used for lighting, household appliances and cooking. The chart below shows energy use in EU households by end use.

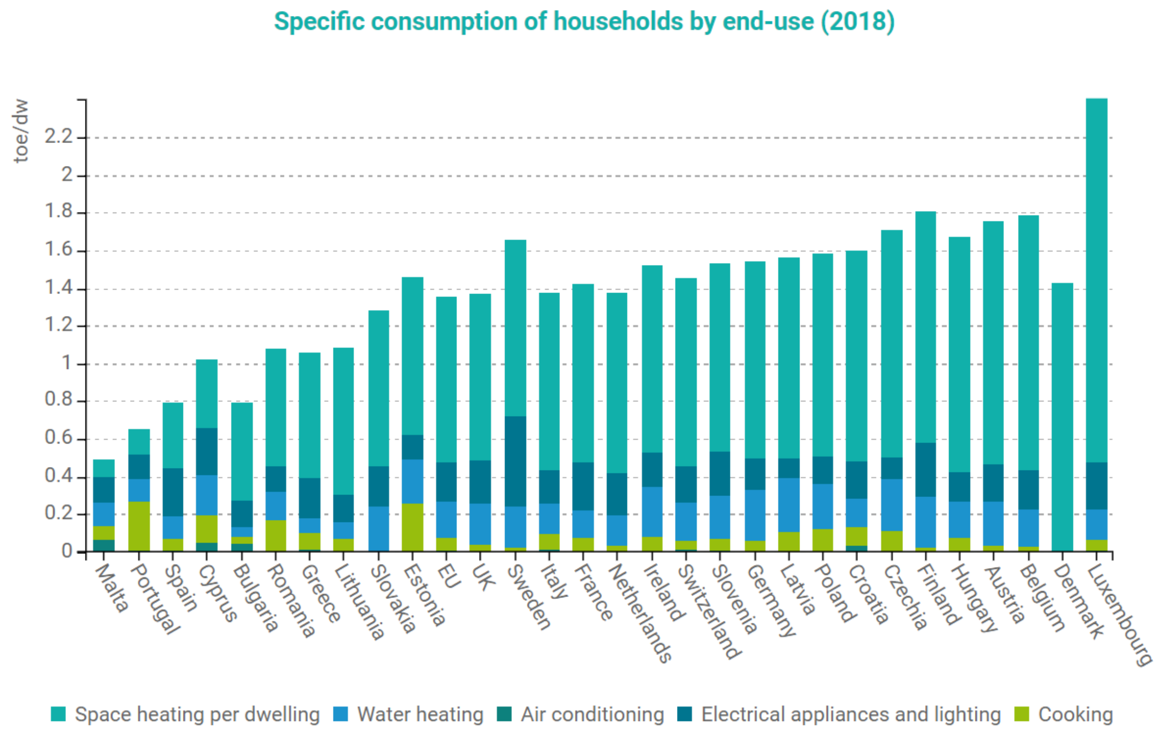


Figure 2: Specific consumption of households by end-use in 2018 (13)

Looking at the data for the Czech Republic in 2018, the following division of energy use is seen per dwelling. The data is given in tons of oil equivalent and must be converted to kWh.

Type of Consumption	Energy in TOE/dwelling	Conversion to kWh
Space Heating	1.21	14072.3
Electrical Appliances and Lighting	0.117	1360.71
Water Heating	0.272	3163.36
Cooking	0.111	1290.93
Air Conditioning	0.001	11.63

Table 7: Household Energy Consumption by end-use in Czech Republic (13).

The energy used for air conditioning will be neglected in this project, as most Czech homes do not have air conditioners installed, and the statistical consumption is very small. Summing up the numbers for “Electrical Appliances and Lighting” and “Cooking” the total electricity load for an average Czech household comes up to **2650 kWh/year**.

3.6 Electricity Source

As seen in the literature review most studies performed for off grid energy independence also use photovoltaics as a main source of energy, if not the only source.

PV cells use semiconductor materials that show the photovoltaic effect to convert incident solar radiation into electricity. It consists of a slab of semiconductor with one or more p-n junctions. Due to the internal electric field and the built in voltage difference across the junction, PV cells can generate electricity from incident photons that reach the p-n junction if the photon's energy is high enough to create an electron-hole pair. (14)

Figure 3: Photovoltaic Calls on the roof of a house (Pixabay Stock Image).

Commercial PV cells have efficiencies of 15%-20%, while research panels can reach efficiencies of a little over 20%. (15)

Peak power of a PV panel refers to its power output in laboratory conditions; when the panel is subjected to **1000 W/m²**, standard airmass is 1.5, and the temperature of 25°C. These conditions are specified in standards such as IEC 61215.

With time, PV panels lose their efficiency. This is important to consider when designing a PV system because the system designed at the current level of efficiency may fail to meet electricity needs in the future. A useful diagram is provided by the National Renewable Energy Laboratory shows

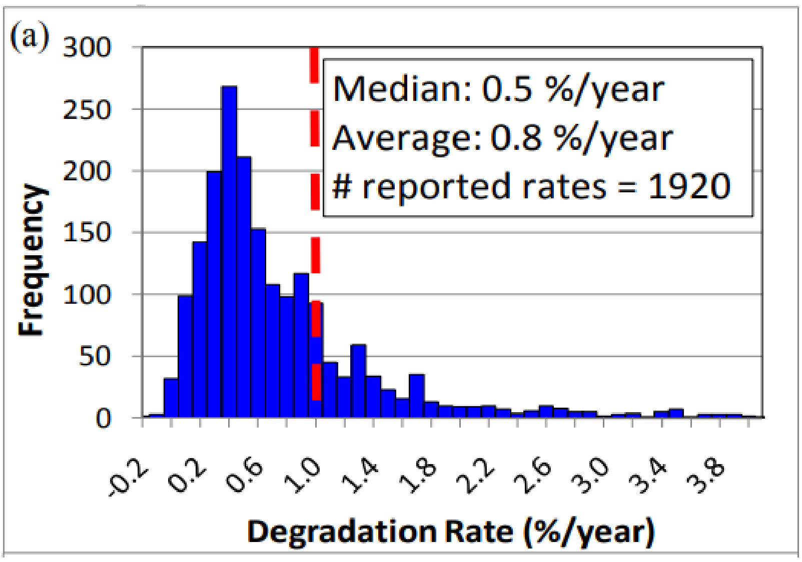


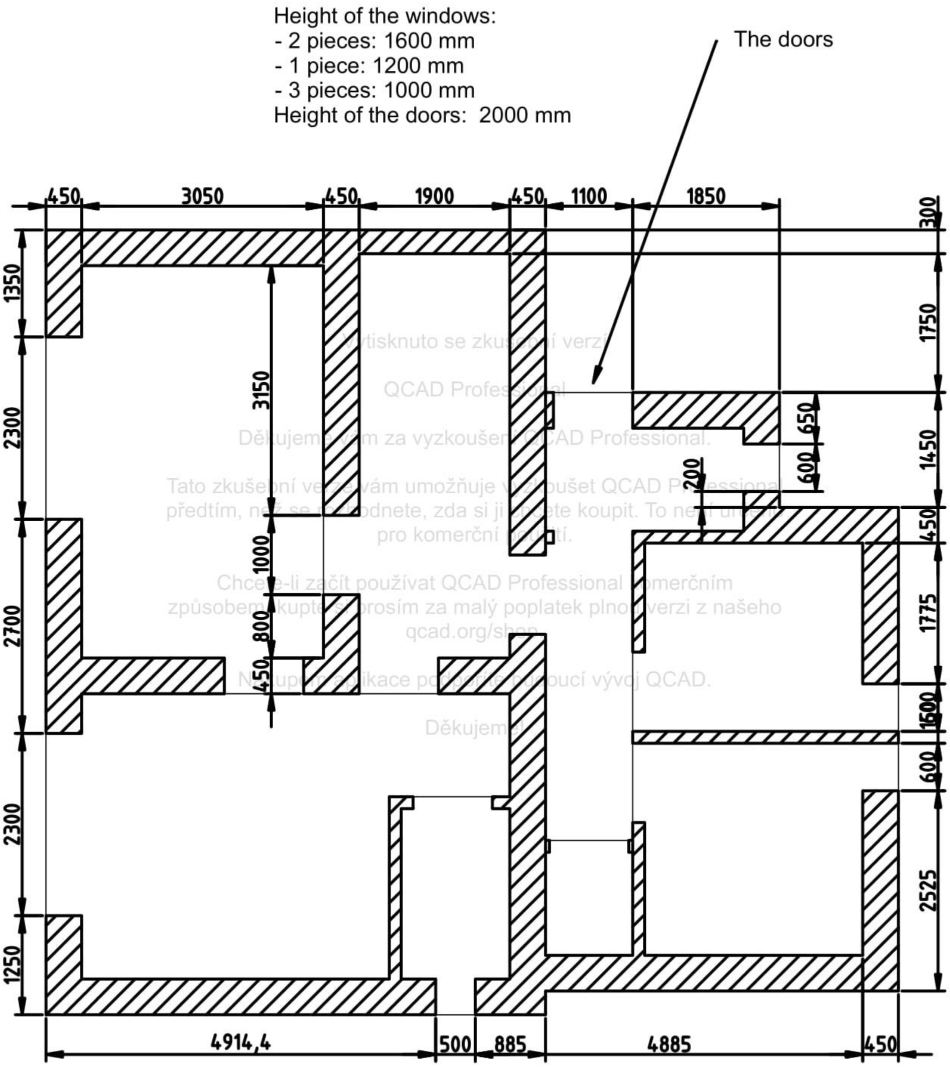
Figure 4: Panel Degradation Rates. (16)

The study further states that 78% of all the measured data lies behind the red line which shows a degradation rate of 1%. A degradation rate of 1% per year indicates that after 15 years, the panels will produce 85% of their original output.

4. Calculations and Initial Design

4.1 Surface Areas

Blueprint of the house:



Height of the windows:
- 2 pieces: 1600 mm
- 1 piece: 1200 mm
- 3 pieces: 1000 mm

Height of the doors: 2000 mm

The doors

Figure 5: Blueprint of the house.

To calculate heat loss, we must calculate the total are of the walls, ceiling, windows, and doors. This has been calculated using the geometry given in the blueprint and tabulated below.

Surface	**Area**
Ceiling	**97.32 m^2**

Windows – 3 types of windows - 3 windows x 2 floors = 3.6 m^2 - 2 windows x 2 floors = 14.72 m^2 - 1 window x 2 floors = 1.2 m^2	**19.52 m^2**
Door - 1 door	**2.2 m^2**
Wall Area - Wall perimeter x height of the building = 174.06 m^2 - Wall area under the windows = 17.74 m^2 - Wall area above the door = 0.99 m^2	**192.05 m^2**

Table 8: Relevant Surface Areas of the House.

Using these areas, we can calculate the heat loss through each surface.

The volume of air in the house can also be calculated as ceiling area times the height of the building. This has been calculated as **525.53 m^2**.

4.2 Overall Heat Transfer Coefficient of Surfaces (U-Value)

Using the values given for thermal conductivity in Table 1, the thermal conductivity of individual materials is calculated as

$$R = \frac{b}{\lambda} \qquad (4.2 - 1)$$

The R values of the individual materials are added up as the total R value R_T

$$R_T = R_1 + R_2 + R_3 \qquad (4.2 - 2)$$

And then U value is calculated as reciprocal of the total R value

$$U = \frac{1}{R_T} \qquad (4.2 - 3)$$

The values for all the surfaces were calculated and tabulated below.

Surface	Total R value	U value
Ceiling - 20 mm wood - 160 mm mineral wool	$R_{mineral\ wool} + R_{wood} = 4.143 \frac{Km^2}{W}$	$\mathbf{0.241\ \frac{W}{m^2K}}$
Wall - 450 mm of bricks - 100 mm of mineral wool	$R_{mineral\ wool} + R_{bricks} = 3.063\ \frac{Km^2}{W}$	$\mathbf{0.326\ \frac{W}{m^2K}}$
Windows - Double paned, low emissivity glass	$R_{window} = 0.48 \frac{Km^2}{W}$	$\mathbf{2.08\ \frac{W}{m^2K}}$
Door - 45 mm hardwood	$R_{door} = 0.28 \frac{Km^2}{W}$	$\mathbf{3.56\ \frac{W}{m^2K}}$

Table 9: Overall Heat Transfer Coefficient of All Relevant Surfaces

4.3 Heat loss of the House

Transmission Heat Loss

The total heat loss of the house through each surface can now be calculated using the equation for transmission heat losses described in section 3.2. The heat loss through each surface can be summed up to find the total transmission heat loss.

Using the values of area and U value calculated in the previous section, design transmission heat loss of the house can also be calculated by equation (3.2 -3)

$$\boldsymbol{\Phi_{T,d} = 4325\ W}$$

Ventilation Heat Loss

Similarly, using the equation for transmission heat loss listed in section 3.2 and using the minimal air change rate of 0.5/h ; the ventilation heat loss can be calculated.

Further design ventilation heat load (for design outdoor temperature -12 °C) and the air volume 525.53 m^3 can be calculated by equation (3.3 - 1)

$$\boldsymbol{\Phi_{V,d} = 2919\ W}$$

This has been calculated for each day in an excel sheet.

Domestic Hot Water (DHW) Requirement of the House

The house given to us is a detached dwelling, and we can assume an occupancy of 4 or more individuals and hence have the an average DHW requirement of 159.6 l/day. The daily demand for hot water is given as, using the values from Table 7

$$\dot{Q}_{DHW}\ [kW](winter\ months) = 159.6 \times \frac{0.062}{24} \qquad (4.3\text{ - }1)$$

$$\dot{Q}_{DHW}\ [kW](summer\ months) = 159.6 \times \frac{0.056}{24} \qquad (4.3\text{ - }2)$$

Dividing the year into 6 months of cold weather and 6 months of warm weather, we can estimate the total energy needed for the DHW system

$$Total\ DHW\ demand = 159.6 \times 30.5\ days\ \times 6\ months\ (0.056 + 0.062) \qquad (4.3\text{ - }3)$$

$$Q_{DHW} = \boldsymbol{3447\ kWh/year}$$

4.4 Annual Heat Load

The annual heat load of the house is calculated by adding the daily space heating load and the daily DHW consumption for every day of the year. The daily space heating load has been converted to kW for convenience.

$$Total\ Heat\ Load\ [kW] = \dot{Q}_{SH,day}[kW] + \dot{Q}_{DHW}\ [kW] \qquad (4.4\text{ - }1)$$

This value of total heat load is calculated for every day of the year, and then ranked in descending order to construct the annual heat load diagram. Day 0 of the diagram refers to the design heat load of the house. The start of the heating season is defined as the heat loss when the outdoor temperature is equal to the external design temperature of - 12°C. The end of the heating season is marked by the outdoor temperature being higher than 13°C. The meteorological data has been obtained from the Czech Hydrometeorological Institute for Prague in 2019. (17)

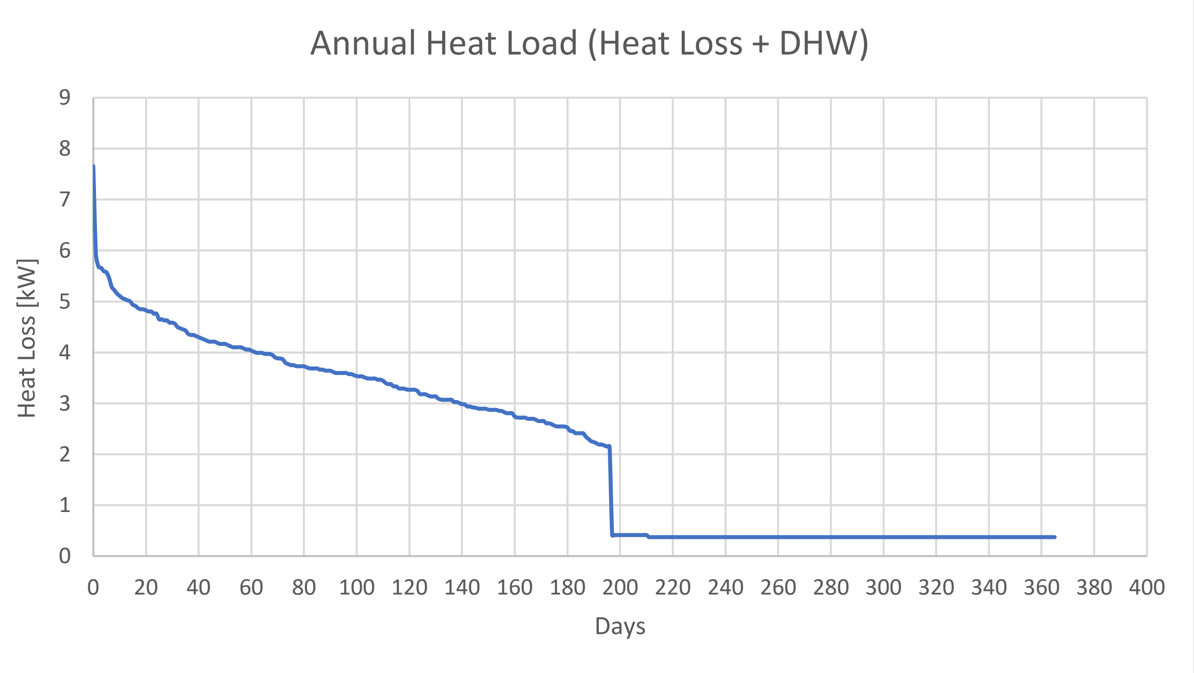


Figure 6: Annual Heat Load in kW.

From the chart above, it is seen that the heating season is about 200 days.

The area under the graph was calculated using the Reimann Sum Method in MS Excel. The area can then be multiplied by the number of hours in a day to annual heat loss Q $_{total}$ [kWh]

$$Area\ under\ the\ graph\ [kW \cdot day] \times 24\ [hr/day] = Q_{\ total}\ [kWh] \qquad (4.4 - 2)$$

$$\boldsymbol{Q_{\ total} = 18534\ kWh}$$

4.5 Choice of Heat Source

We can choose from several options to heat our building such as photovoltaic panels, a wind turbine, solar thermal collectors, biomass boilers and gas boilers. When heat is required on the output, it may be wiser to consider a source with heat as its output as well. This can save us the energy losses when converting electrical energy from a PV panel to heat energy in an electric boiler. This leaves us with the option of a boiler that burns wood pellets or a gas boiler.

In this project the following three prospects will be considered, and a brief description of each option is as follows:

4.5.1 Scenario 1 – Biomass Boiler

In this scenario, the entire annual heating demand is provided by a biomass pellet boiler. The boiler will run a complete cycle at regular intervals and will be connected to a buffer tank to allow smooth operation. The coverage of heat demand is as follows:

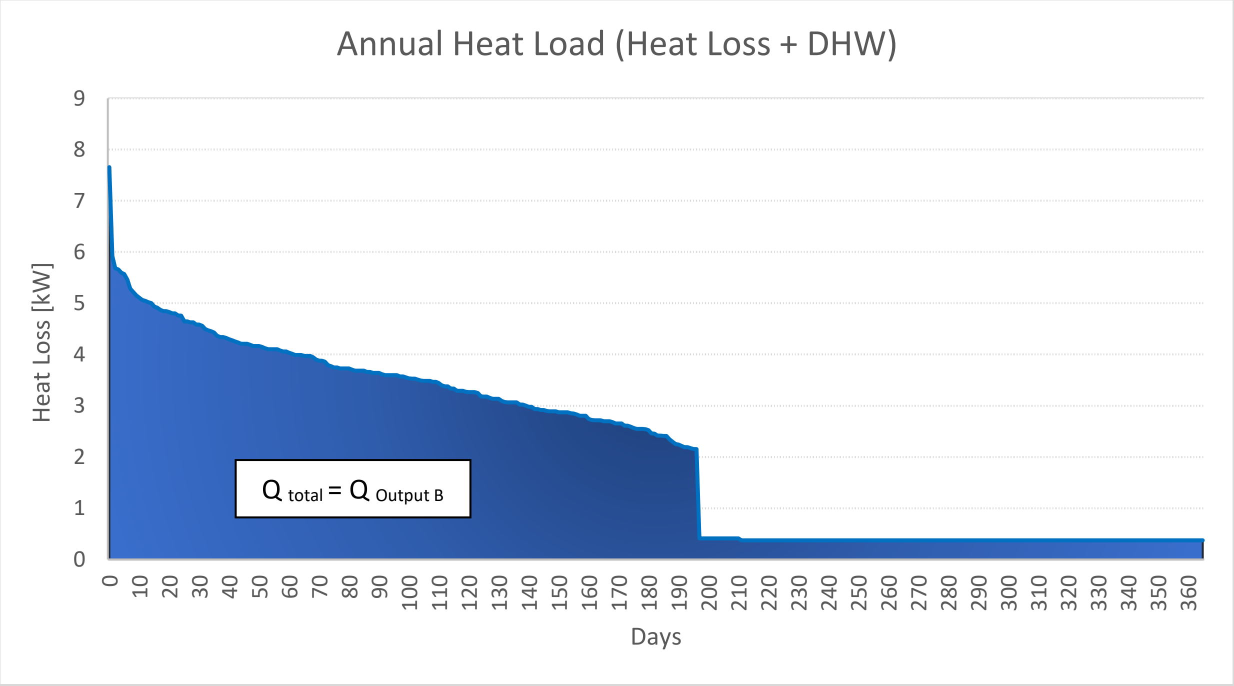


Figure 7: Annual Heat Load Using a Biomass Boiler.

In this case, all the heat requirement will be provided by the boiler, hence

$$Q_{\ total} = Q_{\ Output\ B} = 18534\ kWh$$

Where Q $_{Output\ B}$ is the output energy of the boiler.

4.5.2 Scenario 2 – LPG Boiler

In this scenario, the entire heat load will be supplied by a gas boiler running on LPG.

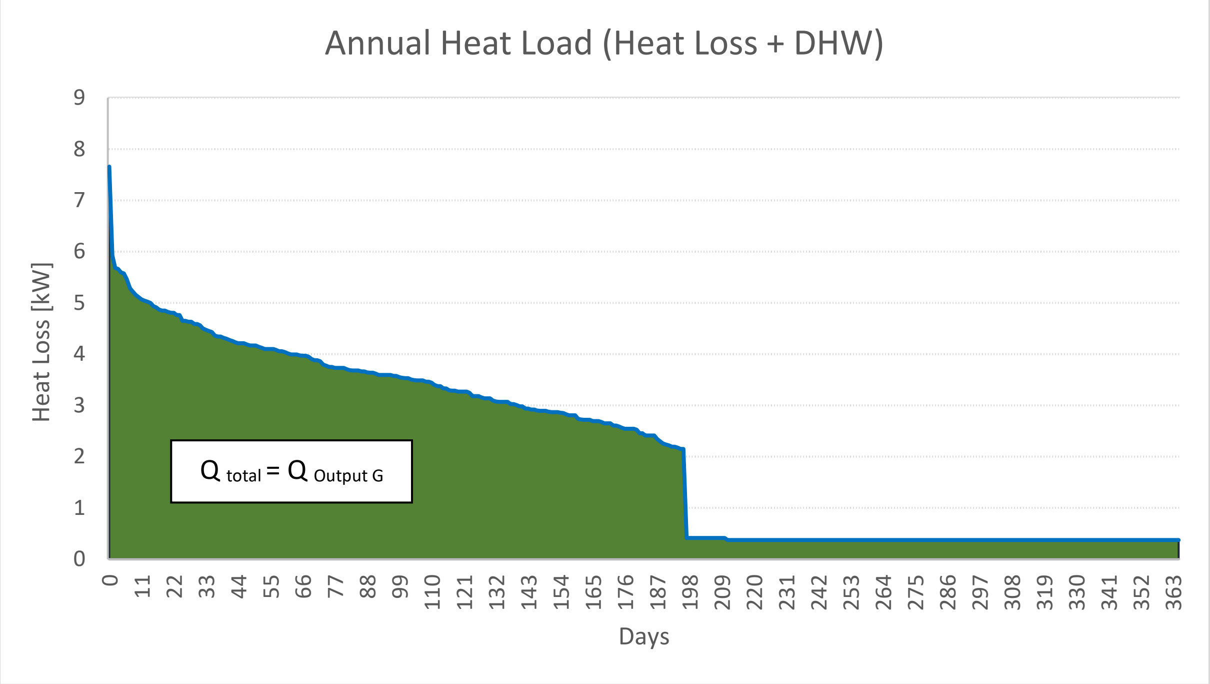


Figure 8: Annual Heat Load using an LPG boiler.

The annual heat requirement is calculated in much of the same way as it was in the previous case, except this time the entire heat requirement will be provided by the LPG boiler

$$Q_{\ total} = Q_{\ Output\ G}$$

Where $Q_{\text{Output G}}$ is the output of the LPG boiler.

4.5.3 Scenario 3 – Biomass Boiler for Space Heating and LPG Boiler for DHW

In this scenario, the two systems shown above will be combined. The gas boiler will run all year round to provide for the almost constant DHW supply while the biomass pellet boiler will be turned on only during the heating season (i.e. when the mean outdoor temperature drops below 13°C). The distribution of the load and a possible schematic can be seen below.

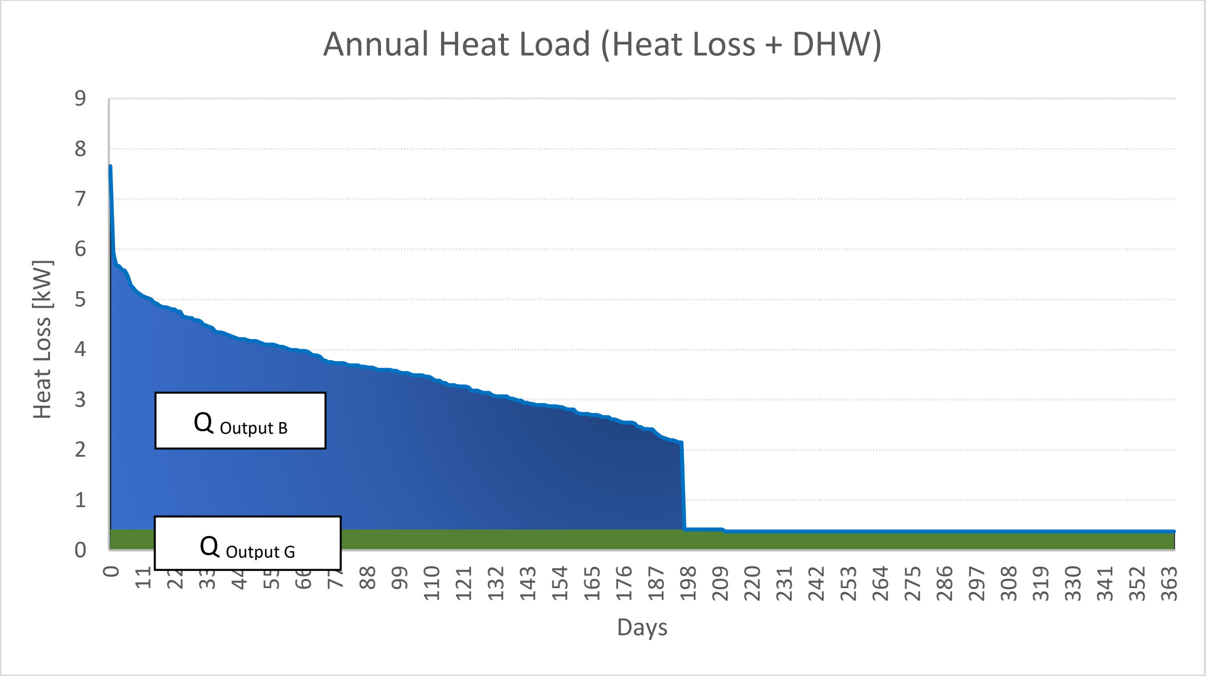


Figure 9: Annual Heat Load Using a Biomass Boiler for Space Heating and an LPG Boiler for DHW.

$$Q_{\mathit{Output}\ G} = Q_{DHW} = 3447\ kWh$$

$$Q_{\mathit{Output}\ B} = Q_{SH} = Q_{total} - Q_{\mathit{Output}\ G} = 15087\ kWh$$

This has the possibility of using the gas boiler as a backup for space heating if the pellet boiler fails.

5. Equipment and Mass/Energy Balance

5.1 Scenario 1 – Biomass Boiler

Calculation of Annual Fuel Consumption:

To calculate the mass of the pellets consumed by the boiler, we need to know the following:

1. The annual heat requirement in kWh
2. The average thermal efficiency of the boiler throughout the heating season
3. Calorific value of the wood pellets

The value of the annual heat requirement in kWh has been calculated as

$$\boldsymbol{Q_{total} = 18534\ kWh}$$

To know the average fuel efficiency of the boiler, we can choose a suitable boiler available on the market.

Klover ECOMPACT 250 (18)

The boiler is made by an Italian company called Klover. It is a wood pellet-based boiler with hot water as the output.

Parameters

Nominal Power Output: 23.4 KW

Consumption of Pellets: 5.25 kg/h

Tank Capacity: 75 kg

Weight: 380 kg

Efficiency: 92.8% (Under test conditions)

Figure 10: The Klover ECOMPACT 250.

The seasonal fuel efficiency for the boiler is given in its user data sheet to be **82.7%.** This value will be used for all further calculations.

$$\boldsymbol{\eta_{sb} = 82.7\%}$$

Although extensive literature on annual fuel efficiencies of small-scale pellet boilers is not readily available, in a study conducted in 2015 titled “Efficiency and operational behaviour of small-scale pellet boilers installed in residential buildings” in the journal of Applied Energy the annual efficiencies of 5 boilers installed in households in Austria was tested. In this study it was found that the fuel efficiency of a pellet boiler installed in a detached house with a nominal capacity of 26kW, fell from 92.9% (at nominal load) to 86% (in field conditions). (19) This boiler is the most relevant, as it is similar in efficiency and nominal capacity to the one used for this project. The results of the study are in line with the manufacturer’s value for this parameter.

Calorific Value of Wood Pellets:

For calculations of fuel consumption, we will be using the LHV (Lower Heating Value) of the wood pellets. It is standard practice to use the lower heating value in calculations of fuel consumption, as we cannot be sure if the latent heat of vaporization of water will be recovered during the operation of the boiler.

The typical moisture content for wood pellets ranges from about 7% - 10%. The typical value for LHV ranges from about 17 MJ/kg to 18.85 MJ/kg. (20) For this project, the lower of the two values 17 MJ/kg **(4.8 kWh/kg)** will be used.

Annual Mass of Pellets Required:

The seasonal efficiency of the boiler must be considered when calculating the energy required from the pellets

$$Input\ Energy\ = \frac{Q_{Output\ B}}{\eta_{sb}} = 22411\ kWh \qquad (5.1 - 1)$$

The input energy must be provided by the wood pellets, and hence their mass is calculated as follows:

$$Mass\ of\ Pellets = \frac{Input\ Energy\ [kWh]}{LHV\ of\ pellets\ \left[\frac{kWh}{kg}\right]} = \boldsymbol{4669\ kg} \qquad (5.1 - 2)$$

Pellet Hopper:

Considering that the consumption of pellets will be concentrated in the winter months, the boiler will need to be refilled very frequently. For example, on a cold week in January where the average heat loss is 120 kWh a day; the daily consumption of the pellets would be about 30 kg a day. During this week, the boiler may need to be topped up every second day. For smoother operation of the boiler, a hand fill hopper of 500 kg can be installed.

Running Time for Design Heat Load:

On the day the external temperature is -12°C, the total heat loss as seen from Graph 1 is 7.65 kW. To heat up the house for one day with design conditions, the pellet boiler will need to supply 183.6 kWh of heat. Dividing this by the nominal output of the boiler, minimum boiler running time on this day can be estimated as **8 hours**.

5.2 Scenario 2 – LPG Boiler

Calculation of Annual Fuel Consumption:

The calculation of annual LPG consumption is approached in much of the same way as the previous case. In this scenario, the following boiler has been chosen:

Vaillant EcoTEC plus 630 (21)

LPG based boiler made by Vaillant. Connected to a hot water cylinder on its output.

Parameters

Nominal Power Output: 30 kW

Weight: 38 kg

Maximum Water Temperature: 85°

Efficiency (ErP): 94%

Figue 11:The Vaillant EcoTEC Plus.

The seasonal (average during the heating period) efficiency of the boiler can be found in the data sheet to be **89.5%** (22)

$$\eta_{sg} = \mathbf{89.5\%}$$

Gas fired boilers are usually more efficient that solid fuel boilers due to the moisture content of the fuel (23), which can be seen in our analysis as well. There seasonal heating efficiency of a gas boiler is significantly higher than that of the biomass option.

Calorific Value of LPG:

Liquified petroleum gas or LPG is usually a mixture of propane and butane, containing more propane or more butane depending on the season and country of origin. (24)

The design of the system for be for a limiting case, so we can assume that the LPG obtained contains mostly butane – the component with a lower LHV.

The LHV of butane is 45.75 MJ/kg or **12.7 kWh/kg** (25)

Annual Mass of LPG Required:

The seasonal efficiency of the boiler must be considered when calculating the energy required from the fuel

$$Input\ Energy = \frac{Q_{Output\ G}}{\eta_{sg}} = 20732\ kWh \qquad (5.2 - 1)$$

We can note that the required input energy of the fuel is lower here than in the previous case due to the higher efficiency of the LPG boiler.

$$Mass\ of\ LPG\ = \frac{Input\ Energy\ [kWh]}{LHV\ of\ LPG\ \left[\frac{kWh}{kg}\right]} = 1632\ kg \qquad (5.2 - 2)$$

The density of liquid butane at 20°C is 578.6 kg/m^3 and liquid propane is 500.10 kg/m^3 (25)

The estimated annual requirement of LPG can be set to a **3000 l**.

LPG Tank Size:

The storage of LPG can be done on premises with the help of an above ground LPG tank. LPG are usually only 80 – 85% full. If we choose to fill the tank no more than 3 times a year (twice in the winter and once in the summer). Then the tank size can be estimated as follows

$$Tank\ Capacity \times 0.85 = \frac{3000}{3} \qquad (5.2 - 3)$$

$$Tank\ Capacity\ \approx 1200\ l$$

Running Time for Design Heat Load:

On the day the external temperature is -12°C, the total heat loss as seen from Graph 1 is 7.65 kW. To heat up the house for one day with design conditions, the LPG boiler will need to supply 183.6 kWh of heat. Dividing this by the nominal output of the boiler, minimum boiler running time on this day can be estimated as **6 hours**.

5.3 Scenario 3 – Biomass Boiler for Space Heating and LPG Boiler for DHW

In this scenario the LPG boiler would be used only for DHW production, as well as serve as a back-up for when wood pellets are in short supply. The LPG boiler may also provide us with higher efficiencies for only DHW production as it doesn’t have to deal with the ebbs and flows of a variable load. To increase the life of the biomass boiler by reducing its running time during the summer months, the biomass boiler is used exclusively for space heating.

The biomass boiler used in this case is the same as in the first scenario, while a smaller LPG boiler must be chosen.

A smaller LPG boiler of the same company can be used,

Vaillant EcoTEC plus 618 LPG (21)

Parameters (22)

Nominal Power Output: 18 kW

Maximum Water Temperature: 85°

Efficiency (ErP): 94%

The seasonal (average during the heating period) efficiency of the boiler can be found in the data sheet to be **89.6%**

$$\eta_{sg} = \mathbf{89.6}\%$$

Calculation of Fuel Consumption:

The calculation of fuel consumption is carried out in the same way as for the other setups. In this case, the calculation will include a calculation of wood pellets and LPG.

The seasonal efficiency of the boilers is considered when calculating the energy required from the fuel

$$Input\ Energy\ [LPG] = \frac{Q_{DHW}}{\eta_{sg}} = 3847\ kWh \qquad (5.3 - 1)$$

$$Input\ Energy\ [Biomass] = \frac{Q_{SH}}{\eta_{sb}} = 18242\ kWh \qquad (5.3 - 2)$$

Once the input energies of the fuels are known, the mass of each fuel can be calculated using the same calorific values as in the previous two cases.

$$Mass\ of\ LPG\ = \frac{Input\ Energy\ [LPG]}{LHV\ of\ LPG} = 304\ kg \qquad (5.3 - 3)$$

$$Mass\ of\ Pellets = \frac{Input\ Energy\ [Biomass]}{LHV\ of\ pellets} = 3800\ kg \qquad (5.2 - 4)$$

Tank Size for LPG:

Using the same approach as before, if we want the storage to be refilled/exchanged no more than 3 times a year

Like in the previous case, using the density of propane and butane,

$$Volume\ of\ LPG \approx 600\ l$$

$$Tank\ Capacity \times 0.85 = \frac{600}{3} \qquad (5.2 - 5)$$

$$Tank\ Capacity \approx 240\ l$$

For LPG storage this small, several gas bottles of a capacity of 40 – 50 kg could be considered.

Most of the energy is still provided by the wood pellets, so a similar hopper of 500kg as in scenario 1 can be used.

6. Electrical Source and System

Using the statistical data on electricity consumption shown in section 3.5 provided by Odysee-Mure the average electricity consumption for cooking, household appliances and lighting came up to about 2650 kWh for the Czech Republic. This translates to about 220 kWh each month and is not significantly seasonally influenced.

$$Q_{E,m} = 220\ kWh\ [per\ month]$$

$$Q_{E,d} = 7.21\ kWh\ [per\ day]$$

We could employ a variety of different approaches to produce the electricity required by our household, but the simplest approach would be to design a Photovoltaic (PV) system that converts solar radiation into electric current. As seen in the literature review most studies performed for off grid energy independence also use photovoltaics as a main source of energy, if not the only source.

An off-grid PV system consists of different equipment such as an inverter, battery, and charge controller. A possible schematic can be seen below.

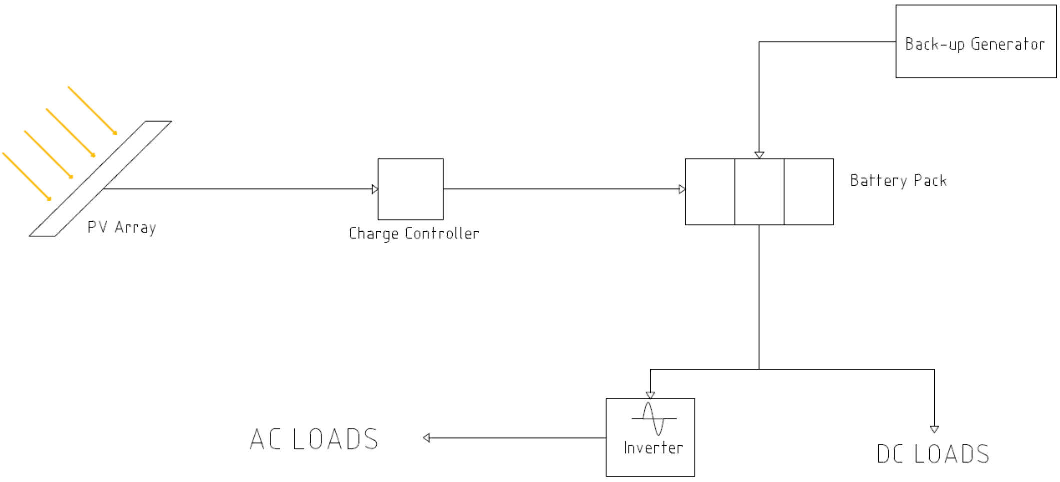


Figure 12: Configuration of Electrical System.

When designing the area of the PV array, we need to consider the following things

- The available roof area
- Average monthly irradiation
- Losses in PV systems
- Degradation of panels

Irradiation is the power per unit area that the sunlight delivers in a period, per square meter. It is measured in kWh/m^2

The data for average solar irradiation for Prague for each month of the year has been taken for a surface slope angle of 60° and a surface azimuth angle of 0° (south facing). The table below shows the average monthly irradiation for year.

Months	Solar Irradiation [kWh/m^2]
January	37.2
February	57.1
March	91.5
April	118.8
May	132.4
June	120.2
July	121.3
August	136.9
September	100.8
October	86.3
November	48.2
December	30.5

Table 10: Monthly Solar Irradiation. (26)

The lowest average daily solar irradiation will be used to size the PV system, so in this case it is for the month of December.

$$I_{D,Dec} \cong 1 \frac{kWh}{m^2} \qquad (6 - 1)$$

The size of the PV array can be estimated using the following equation (27)

$$A_{PVi} = \frac{Q_{E,d}}{I_{D,Dec} \times \eta_{PV} \times \eta_B \times \eta_I} \qquad (6 - 2)$$

Where is η_{PV} the efficiency of PV panels which will be considered as 15%, η_B is the efficiency of the battery (85%) and η_I is the efficiency of the inverter (90%) (27)

$$A_{PVi} = 62.7\, m^2$$

Considering that the panel will lose its efficiency over time, the highest value of which we can assume to be **1%** a year for crystalline silicon (from section 3.6). Designing the system for a period of 15 years, at the end of its life the system will produce 85% of its original value. Adjusting for this loss in efficiency, we have

$$A_{PVf} = \frac{62.7}{0.85} = 73.8\, m^2 \qquad (6 - 3)$$

Hence the PV array size can be further increased to 75 m^2.

$$A_{PV} = \mathbf{75\, m^2}$$

The peak power rating of the PV array is defined as the output of the array when it is exposed to 1000 W/m^2 of incident irradiance. Thus, it can be calculated using the following formula (27)

$$P_P = A_{PV} \times \eta_{PV} \times 1000 \frac{W}{m^2} \qquad (6 - 4)$$

$$P_P = \mathbf{11.25\ kW_p}$$

Battery Sizing

The battery is an integral component of the solar system, it will provide the house with electricity at night and on cloudy days. If the battery is sized to cover at least 3 days of consumption, we can say that the demanded capacity of the battery

$$C_{B,d} = 21.6\ kWh$$

For a lithium ion battery, the maximum depth of discharge, or the usable capacity is about 80%. The battery must be designed so that out required capacity is 80% of the total capacity.

$$\boldsymbol{C_{B,c} = 27\ kWh}$$

Sizing of back-up generator

In the event of many cloudy days in a row or some failure in the PV system, it is essential to have an auxiliary way to charge the battery. The goal of the back-up generator is to provide for the instantaneous power demand of the household. A good way to estimate the instantaneous demand is to look at high wattage household appliances. Here is a table detailing some appliances

Appliance	**Minimum Wattage**	**Maximum Wattage**
Dishwasher	1200 W	1500 W
Electric Stove	2000W	2000W
Laser Printer	600W	800W
Microwave	600W	1700W
Espresso Coffee Machine	1300W	1500W

Table 11: Wattage of Household Appliances. (28)

As we can see from the data above, if one or more of these devices are switched on at the same time, we will need the generator to cover an instantaneous demand of around 3 – 3.5kW.

6.1 Real Equipment

PV Array

The following panel can be chosen for the PV array

Amerisolar Polycrystalline Solar Panel 285Wp

Specifications:

Dimensions	1640 x 992 x 40 mm
Weight	18.5 kg
Maximum Power (Psp)	285 Wp
Efficiency	17.52 %
Operating Temperature	-40 ~ + 85°C
Warranty	30 years at 80.6% nominal power 12 years at 91.2% nominal power

Table 12: Specifications of Solar Panel. (29)

$$No.of\ Panels = \frac{P_P}{Psp} \cong \boldsymbol{40\ Panels} \qquad (6.1 - 1)$$

Using these panels, the solar array will consist of a total of 40 panels. The final power rating of the PV array will be

$$P = 40 \times Psp = \boldsymbol{11.4\ kWp} \qquad (6.1 - 2)$$

Final area occupied by the panels

$$\boldsymbol{A = 65\ m^2}$$

The final area occupied by the panels is lower than the initial area calculated because these panels operate at a higher efficiency than initially assumed.

Battery

To achieve the required battery size of 27 kWh, a useful approach is to create a battery stack with several individual battery units. The following system is considered

LG Chem RESU 10 Li-ion battery system

Specifications

Nominal Capacity	9.8 kWh
Usable Capacity	8.8 kWh
DC Round Trip Efficiency	95%
Capacity in Ah	189 Ah
Operating Temperature	-10 to 45°C
Warranty	10 years
Max Discharge Power	5.0 kW

Table 13: Specifications of LG RESU 10. (30)

Figure 13: LG Chem SESU 10 Li-ion battery system.

The battery pack will consist of 3 of the above units, providing a nominal battery capacity of 3 x 9.8.

$$\boldsymbol{C_B = 29.4\ kWh}$$

Backup Generator

As previously estimated, the generator chosen has a maximum power of 3.5kW and runs on petrol.

Kraft & Dele KD149

Specifications

Engine Type	Petrol, 4 stroke
Rated Power	3000 W
Maximum Power	3500 W
Fuel Tank Capacity	15 l
Engine Power	7 HP

Table 14 – Specifications of KD149 (31).

Figure 14: Kraft & Dele KD149.

Inverter:

The inverter will be sized to accommodate the AC loads at any given point in time. As seen from Table 7, the inverter can be sized similarly to the back-up generator.

Phoenix Inverter Smart 24V/ 3000VA

Output Voltage	210 – 245 V
Frequency	50 Hz or 60 Hz
Continuous Output Power	3000VA
Continuous Active Power	2400 W
Peak Active Power	6000 W
Warranty	5 years

Table 15: Specifications of Phoenix Smart Inverter. (32)

The warranty of the inverter is 5 years, and inverters usually last 5-10 years. (33) In the cost analysis of the PV, I have chosen to replace the inverter in the 8th year.

6.2 Summary of Electrical System

The dimensions of the electrical system can be summarized as follows:

Total Area of PV Array	65 m^2
Peak Capacity of PV Array	11.4 kW
Nominal Battery Bank Size	29.4 kWh
Generator Rated Capacity	3000 W
Continuous Inverter Output	3000 VA

Table 16: PV System.

7. Cost Analysis

The cost analysis will be conducted for all scenarios considered above; it will consist of the following parts.

- Calculation of Costs – Price of the equipment and the cost of the fuel will be evaluated using the previously chosen equipment.
- Cash Flow and NPV – A cash flow analysis will be carried out for a specific period and discount rate, and the Net Present Value of each scenario will be calculated.
- Sensitivity analysis – Using a MATLAB simulation, the parameter with the highest influence on the final cost will be identified and then it's impact on the cash flow will be illustrated.

7.1 Scenario 1 – Biomass Boiler + Electrical System

Equipment List:

Qty	Equipment	Price
1	Klover ECOMPACT 250 Pellet Boiler	138 975 CZK
1	0.5 Ton Hand-Fill Hopper	£660.83 ≈ 19 500 CZK
40	Amerisolar Solar Panel 285Wp	3130 CZK/panel
1	Phoenix Inverter Smart 24V/ 3000VA	26,186 CZK
2	LG Chem RESU 10 Li-ion battery system	139,900 CZK
1	Kraft & Dele KD149 Petrol Generator	5,600 CZK

Table 17: Scenario 1 Equipment List. (34) (35) (29) (32) (36) (31)

Installation and Labour Costs for PV:

Labour/installation costs for a PV system often account for 10% of the total cost of the system. (37) Using this percentage, the installation costs for the electrical system can be estimated at 48532 CZK. This value will be added to the initial cost in every scenario.

Price of Pellets:

In the Czech market, wood pellets can be found online at the prices between 4000 CZK to 7500 CZK per ton. The following pellets on the market have these parameters

Name	Enviton Dřevěné pellety – 1000 kg	MM Royal CZ - 1050 kg
Water Content	< 7.46 %	7%
Calorific Value	17.9 MJ/kg	> 17.5 MJ/kg
ENPlus A1 Certificate	No	Yes
Ash Content	<0.5%	0.3%
Price	4.19 CZK/kg	7.20CZK/kg

Table 18: Pellet Properties (38) (39).

$$Annual\ Cost\ of\ Pellets = Mass\ of\ Pellets\ \times Price \qquad (7.1 - 1)$$

The cost can vary from 19609.5 CZK to 33616 CZK annually, depending upon the brand of pellets. The average cost of pellets is **26612 CZK/year**

Cash Flow & NPV:

The Net Present Value is calculated by the following formula (40)

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i\ )^t} \qquad (7.1 - 2\ )$$

Where R_t is net cash flow during a single period t ; i is the discount rate; t is the number of time periods. Setting the discount rate to 8%, the following NPV has been calculated for a period of 15 years. For the year 0, the cash outflow is equal to the cost of the equipment, and for every year hence, to the cost of the fuel. In year 8, the cost of replacing the inverter is added.

Year	Cash Flow (CZK)	Discounted Cash Flow (CZK)
0	-643792	-643792
1	-26612	-24640.7
2	-26612	-22815.5
3	-26612	-21125.5
4	-26612	-19560.6
5	-26612	-18111.7
6	-26612	-16770.1
7	-26612	-15527.8
8	-52798	-28525.1
9	-26612	-13312.6
10	-26612	-12326.5
11	-26612	-11413.4
12	-26612	-10568.0
13	-26612	-9785.2
14	-26612	-9060.3
15	-26612	-8389.2

Table 19: Discounted Cash Flows for Scenario 1.

$$NPV_1 = -885724.3\ CZK$$

Sensitivity Analysis:

Sensitivity analysis was performed using a MATLAB model used to find the parameters which most affect the output cost. The simulation was set up using Simulink, where all the inputs including the heat load and the cost of the equipment was modelled. The total cost was calculated for 15 years, with the adjustment for discounted future cash flows included. Using the inbuilt sensitivity analyser, selected parameters were labelled as variables, and all others were regarded as constants. 100 values of each variable were randomly generated using a normal distribution, where the peak of the curve represented the current price of the component. Using these random values, the result of the simulation was evaluated and the dependence of the output on the variables was seen.

The parameters selected were

- Price of Pellets
- Price of the PV panels
- Price of battery systems
- Price of Biomass Boiler (Klover ECOMPACT 250)

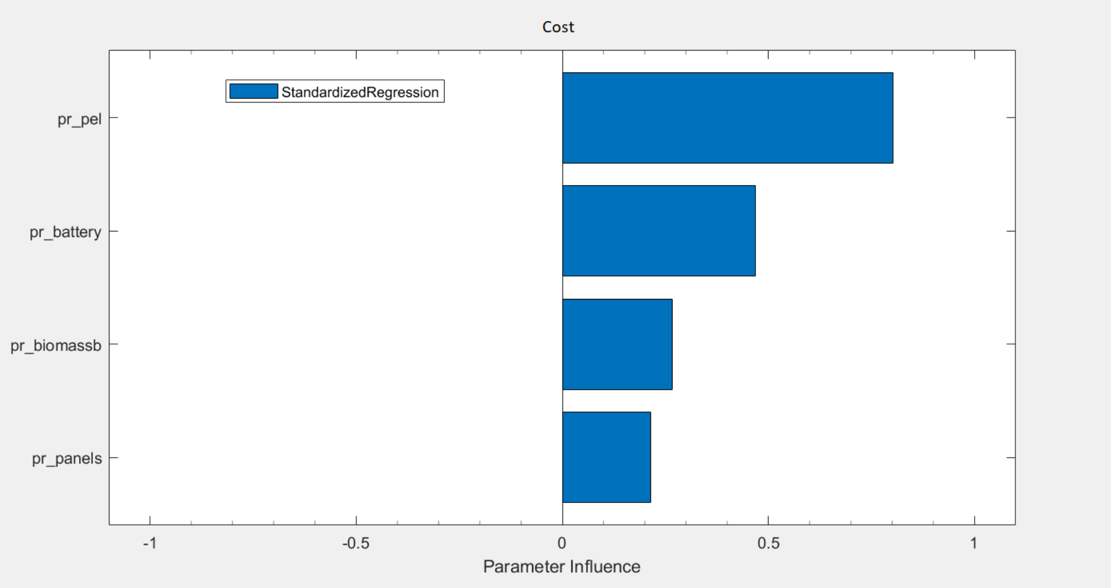


Figure 15: Parameter influence on Cost of Scenario 1.

As seen from the results of the simulation, the price of the pellets has the highest influence on the total cost, followed by the price of the battery and the price of the boiler. This can also be explained due to the large range of prices of the pellets; it is highly dependent on the brand of pellets the user is able to procure.

To further investigate the effect of the parameters, the following situations have been plotted on a graph. The curves represent cumulative discounted cash flows.

- 3% Annual Increase in pellet prices
- 20 % Increase in boiler price
- 15% Decrease in battery prices

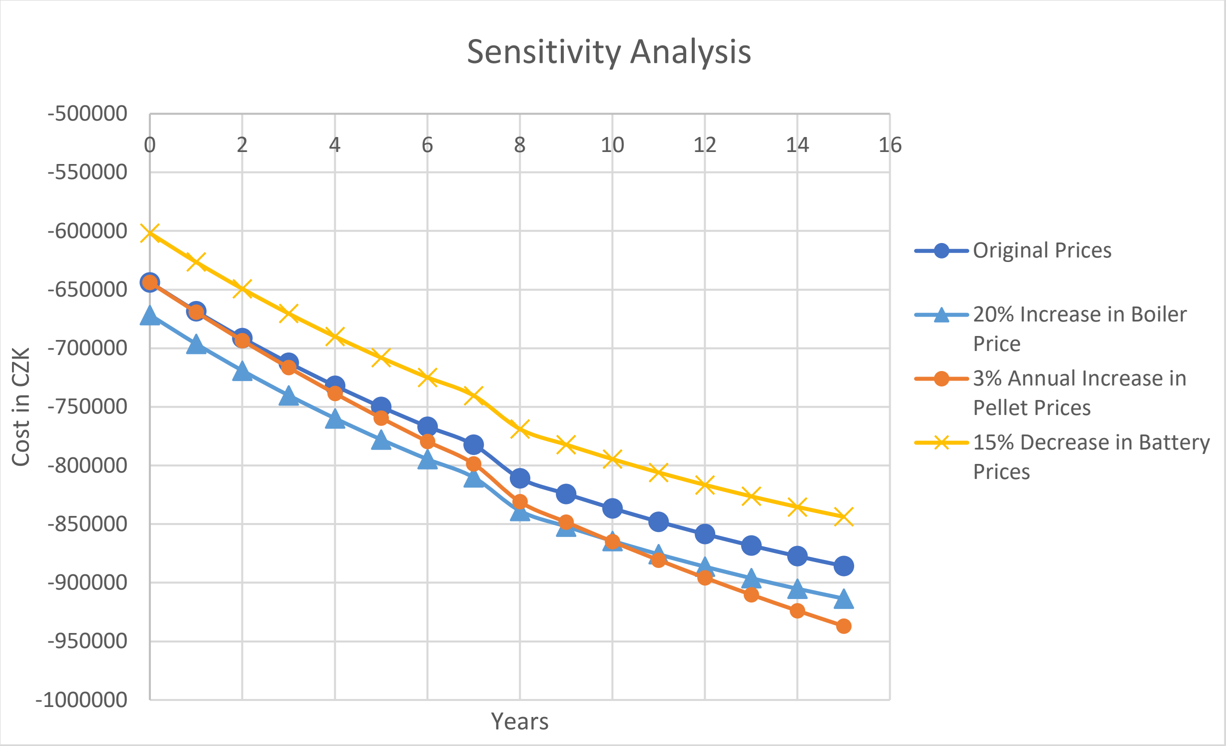


Figure 16: Sensitivity analysis Scenario 1.

7.2 Scenario 2 – LPG Boiler + Electrical System

Equipment List:

The electrical system equipment is identical as used in the previous case.

Qty	Equipment	Price
1	Vaillant ecoTEC Plus 630 LPG	£1331.63 ≈ 40,000 CZK
1	1200 litre LPG Storage Tank – Above Ground	£550 - £1,000 ≈ 25,000 CZK
40	Amerisolar Solar Panel 285 Wp	3130 CZK/panel
1	Phoenix Inverter Smart 24V/ 3000VA	26,186 CZK
2	LG Chem RESU 10 Li-ion battery system	139,900 CZK
1	Kraft & Dele KD149 Petrol Generator	5,600 CZK

Table 20: Equipment List for Scenario 2. (41) (42)

Price of LPG:

The price of LPG in the Czech Republic varies from about 12 – 14 CZK/litre. The most recent price as of February 2021 is 14.13 CZK/ litre. (43)

$$Annual\ Cost\ of\ LPG = Volume\ of\ LPG\ \times Price \quad (7.2.1)$$

$$Annual\ Cost\ of\ LPG = \mathbf{42390\ CZK}$$

The annual cost of LPG is significantly more than the cost of pellets calculated in the section above, but the price of the equipment is significantly lower. This can skew the sensitivity of the total price further towards the price of LPG, as we will see later in the sensitivity analysis.

Cash Flow & NPV:

The NPV has again been calculated for 15 years. For the year 0, the cash outflow is the cost of the equipment and for every subsequent year the cash outflows are the cost of the LPG. And like in the previous case, the inverter will be replaced in the 8th year

Year	Cash Flow (CZK)	Discounted Cash Flow (CZK)
0	-550318	-550317.7
1	-42390	-39250.0
2	-42390	-36342.6
3	-42390	-33650.5
4	-42390	-31157.9
5	-42390	-28849.9
6	-42390	-26712.9
7	-42390	-24734.2
8	-68576	-37049.5
9	-42390	-21205.6
10	-42390	-19634.8
11	-42390	-18180.3
12	-42390	-16833.7
13	-42390	-15586.7
14	-42390	-14432.1
15	-42390	-13363.1

Table 21: Discounted Cash Flows for Scenario 2.

$$\boldsymbol{NPV_2 = -927301.5\ CZK}$$

Sensitivity Analysis:

Sensitivity analysis was performed using a MATLAB model used to find the parameters which most affect the output cost. The procedure of the simulation is the same as was described in section 7.1.

The parameters selected were

- Price of LPG
- Price of the PV panels
- Price of battery bank
- Price of Gas Boiler (Vaillant ecoTEC Plus 630 LPG)

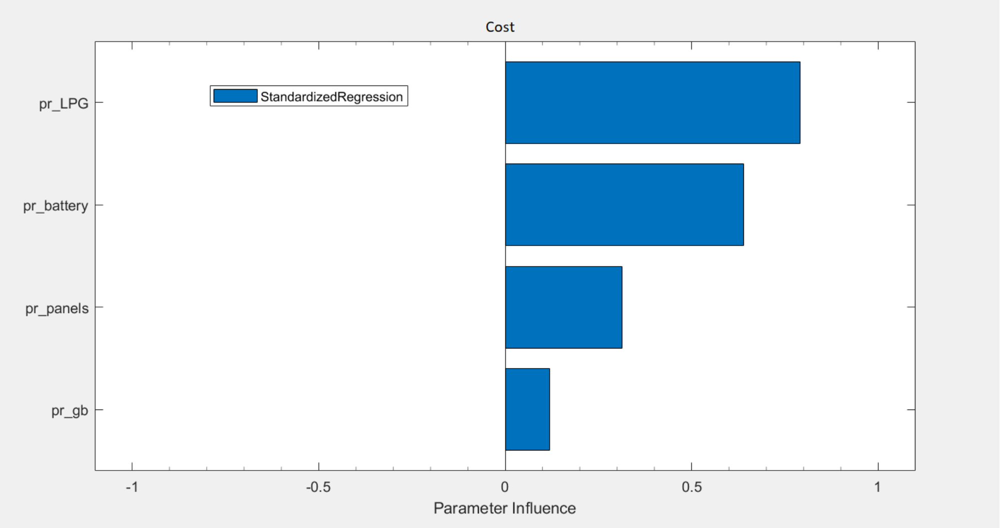


Figure 17: Parameter Influence on Cost of Scenario 2.

Similarly, as in the previous scenario, the price of the fuel is most influential over the total cost of the system. This is due to the low cost of the boiler when compared with the cost of the fuel.

We will attempt to plot the change in the cumulative discounted cash flows for changes in the parameters. The cases considered are

- 3 % Annual increase in LPG price
- 20 % Increase in boiler price
- 10 % Decrease in battery prices

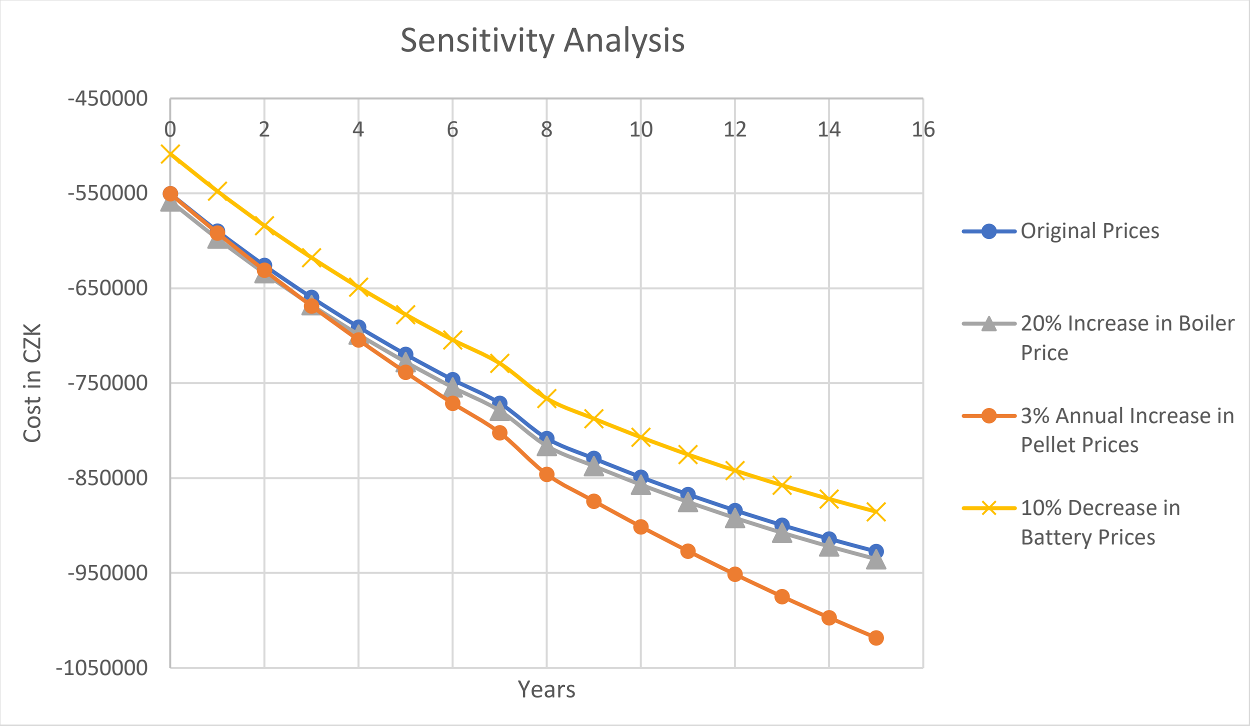


Figure 18: Sensitivity Analysis Scenario 2.

7.3 Scenario 3 – Biomass Boiler for Space Heating and LPG Boiler for DHW + Electrical System

Equipment List:

All equipment listed in this scenario with the exception of the LPG boiler is identical to those listed in the previous scenarios.

Qty	Equipment	Price
1	Vaillant ecoTEC Plus 618 LPG	£1,091 ≈ 32,257 CZK
1	Klover ECOMPACT 250 Pellet Boiler	138,975 CZK
1	0.5 Ton Hand-Fill Hopper	£660.83 ≈ 19,500 CZK
40	Amerisolar Solar Panel 285Wp	3130 CZK/panel
1	Phoenix Inverter Smart 24V/ 3000VA	26,186 CZK
2	LG Chem RESU 10 Li-ion battery system	139,900 CZK
1	Kraft & Dele KD149 Petrol Generator	5,600 CZK

Table 22: Equipment List for Scenario 3. (44)

Cost of Fuel:

Using the calculations made earlier regarding mass/volume requirements of fuel:

$$Annual\ Cost\ of\ LPG = Volume\ of\ LPG\ \times Price \quad (7.3.1)$$

$$Annual\ Cost\ of\ LPG = \mathbf{8478\ CZK}$$

$$Annual\ Cost\ of\ Pellets = Mass\ of\ Pellets\ \times Price \quad (7.3.2)$$

The cost of the pellets can vary from 15960 CZK to 27360 CZK, with an average cost of **21660 CZK**

Cash Flow & NPV:

The calculation of the NPV and cash flows is done in the same manner as in the previous cases, using the same assumptions.

For the year 0, the cash outflow is the cost of the equipment and for every subsequent year the cash outflows are the cost of the fuels. For this scenario, the initial cost of the equipment is the highest, but subsequent cash flows are comparable to the other scenarios.

Year	Cash Flow (CZK)	Discounted Cash Flow (CZK)
0	-676050	-676049.7
1	-30138	-27905.6
2	-30138	-25838.5
3	-30138	-23924.5
4	-30138	-22152.3
5	-30138	-20511.4
6	-30138	-18992.1
7	-30138	-17585.2
8	-30138	-16282.6
9	-30138	-15076.5
10	-30138	-13959.7
11	-30138	-12925.7
12	-30138	-11968.2
13	-30138	-11081.7
14	-30138	-10260.8
15	-30138	-9500.8

Table 23: Discounted Cash Flows for Scenario 3.

$$\boldsymbol{NPV_3 = -934015.3\ CZ}$$

Sensitivity Analysis:

Sensitivity analysis was performed using a MATLAB model as described in section 7.1. The parameters selected were

- Price of Pellets
- Price of LPG
- Price of Biomass Boiler (Klover ECOMPACT 250)
- Price of the PV panels
- Price of battery systems

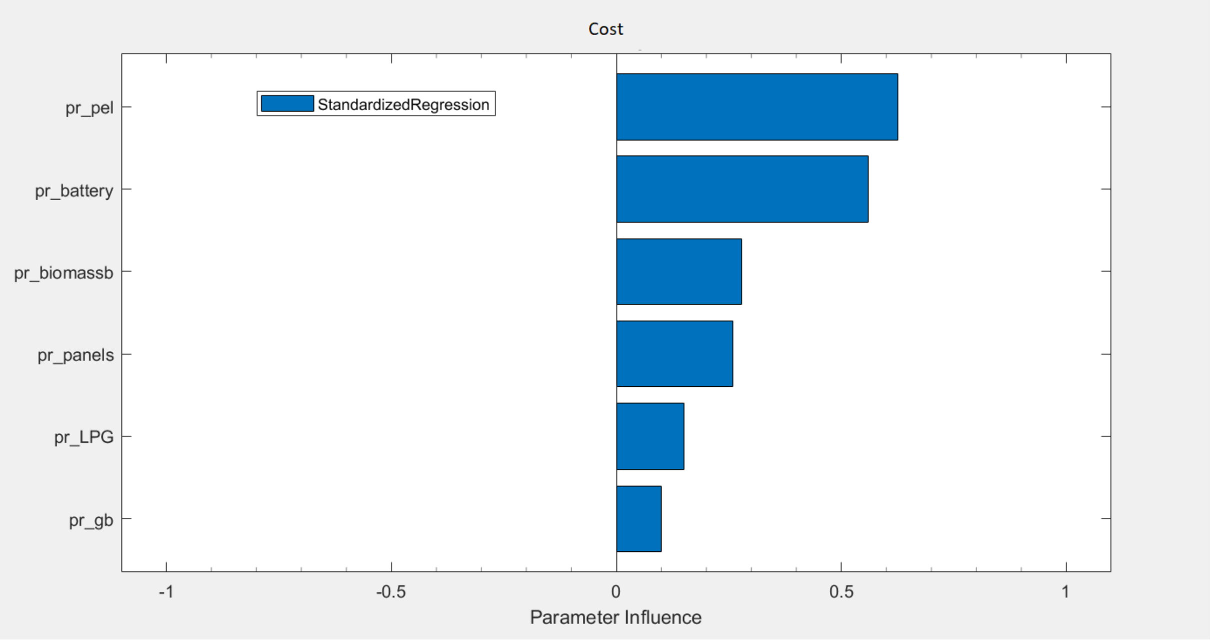


Figure 19: Parameter Influence on Cost of Scenario 3.

From the above graph, the price of the pellets has the highest influence on cost, but it is important to note that the price of the battery also has a significant effect on the total cost. Using the same approach as the previous two times, the effect of these parameters will be illustrated using a plot.

We will attempt to plot the change in the cumulative discounted cash flows for changes in the parameters. The cases considered are

- 3 % Annual increase in LPG price
- 3% Annual increase in pellet prices
- 15 % Decrease battery price

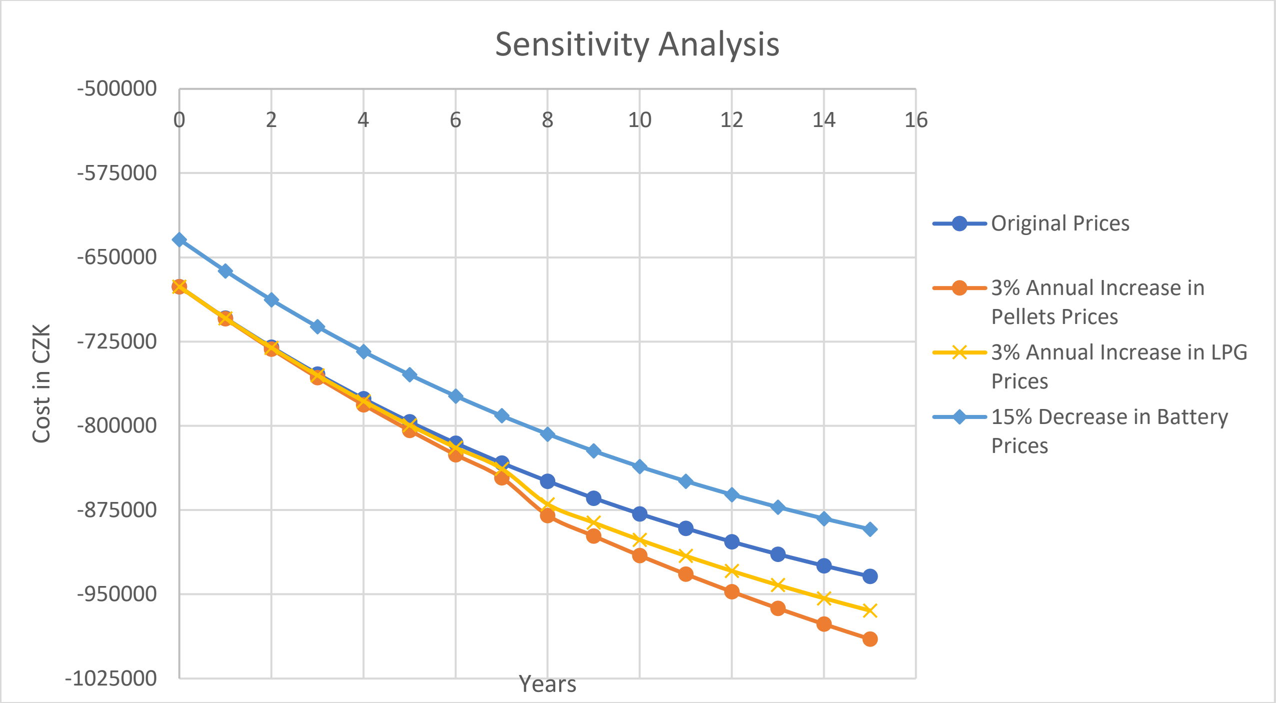


Figure 20: Sensitivity Analysis Scenario 3.

7.4 Discussion and Summary

The initial cost of the scenarios varied significantly, with scenario 2 and scenario 3 having the lowest and highest initial costs respectively. The most expensive component in every scenario was the battery bank for the PV system. The cost of Li-ion batteries has been decreasing steadily over the last decade (45), if the trend continues, it could have a large impact on the feasibility of standalone PV systems. Another development that could have an impact on the feasibility of the PV system is government subsidies. Many governments incentivize renewable energy production and offer to refund a portion of the cost incurred by the user. If such a scheme is available, then the cost of the standalone systems could go down further

The cost of all three scenarios discussed have a high dependence on the price of the fuel that the primary boiler uses. Even a 3% annual increment in the fuel prices has a greater impact on total cost when compared to a 20% increase in boiler prices. This can be seen in all three scenarios, but markedly in scenario 2 (Graph 6), where the cost of the system depends heavily on LPG prices. If LPG prices go up due to availability issues or due to taxes on carbon producing fuels, scenario 2 would lose favourability. As seen in Graph 8, the cost of fuel makes up the highest proportion in scenario 2, so this dependence on LPG prices is expected.

Apart from the price of the fuel, the price of the boilers and battery bank influences total cost. The cost analysis showed that scenario 1 was most economical with an NPV of -885,724.3 CZK, followed by scenario 2(-927,301.5 CZK) and scenario 3 (-934,015.3 CZK). Despite having very different initial investments, the NPV of scenarios 2 and 3 are comparable. In scenario 3, two boilers share the annual heat load, hence may be preferred over a single LPG boiler when equipment lifespan is of concern.

The breakup of the NPV can be seen for each scenario below, it shows us the portion of cost that comes from the initial investment (equipment) and the fuel.

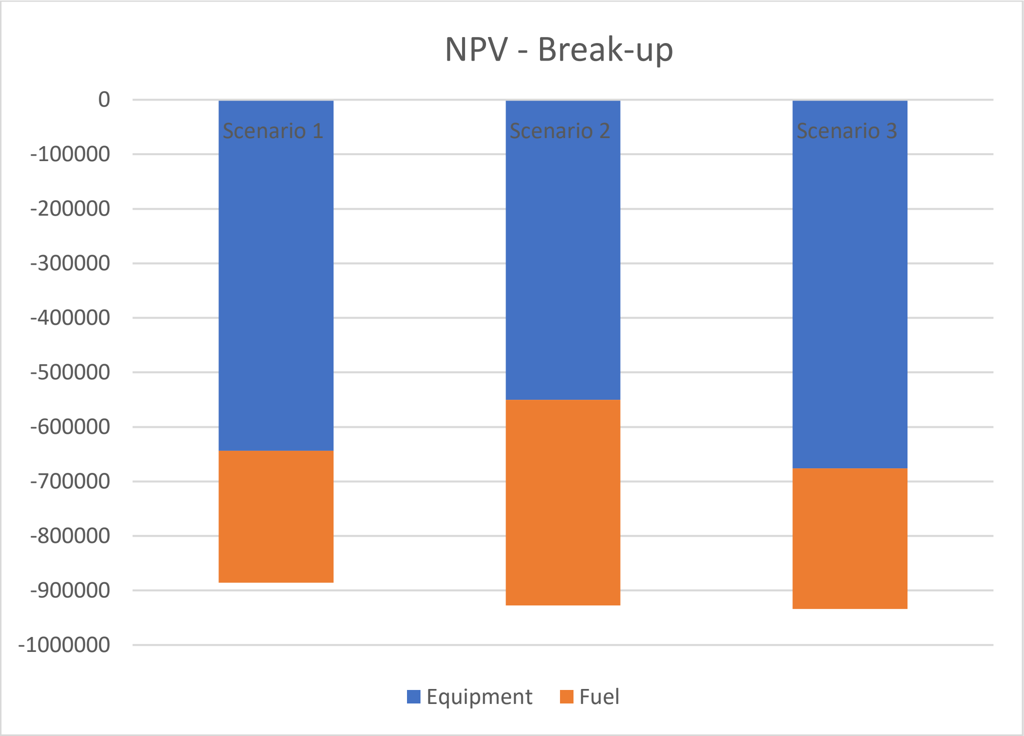


Figure 21: NPV Breakup.

8. Conclusion

A literature review of existing studies for off grid households was done to develop a perspective on the approach to the design. Existing off grid studies included various combinations of Solar PV, wind, passive heating design, and internal combustion engine and the costs thereof.

The design of an energy independent house located in the Bohemian region has been completed, along with the cost and sensitivity analysis of 3 possible scenarios. The energy demand of the house was divided into three parts i.e. space heating, domestic hot water (DHW) and electricity consumption. Electricity is used to power all appliances and for energy for cooking. Space heating is a major component of energy constituting approximately 65 % of annual household energy demand. Space heating requirement was determined by the annual heat loss of the heated space using detailed calculations based on design of the house. Domestic hot water (DHW) requirement was estimated using existing literature. Electricity consumption was estimated from available literature.

A solar PV array was chosen for the electricity source and a boiler that burns wood pellets or gas was considered for space heating and domestic hot water production. The PV system was dimensioned based on the solar irradiation in December (for a south facing array with an inclination of 60°). the system includes a battery bank with 3 days of back up supply. To improve reliability of the system, a backup petrol generator has been included. The peak power of the PV system is 11.4 kW with an array size of 65 m^2.

Three scenarios were considered for space heating and domestic hot water production, to work in tandem with the PV system. The heating scenarios consist of scenario 1 – biomass pellet boiler (nominal output 23.4 kW), scenario 2 – LPG boiler (nominal output 30kW) and scenario 3 – a combination of a pellet boiler (same as scenario 1) and an LPG boiler (nominal power 18kW) . In case of scenario 1 and 2, running time of each boiler to meet design heat load requirements have been calculated as 8 hours and 6 hours per day respectively. When considering renewability, scenario 1 is a completely renewable solution to the supply the load of the off-grid house, excluding the intermittent use of the back-up generator.

A cost and sensitivity analysis of the scenarios (including electricity) was performed, The NPV of each scenario was calculated for a period of 15 years and a discount rate of 8% per annum. It was found that scenario 1 was most economical, albeit with a high initial investment. Scenario 2 and 3 were found to have similar NPVs but differed substantially with respect to the initial investment required.

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