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Techno-economic Pre-feasibility Study of Wind and Solar Electricity Generating Systems for Households in Central Finland

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Abstract

The objective of this work is to investigate the viability of a wind, PV or hybrid wind-PV system supplemented with battery storage for electricity production to meet the electricity consumption of a typical household apartment in Central Finland. The assessment criteria for the analysis were cost of energy and total net present cost of each system configuration. We selected the Hybrid Optimization Model for Electric Renewables (HOMER) software, RETScreen, and PVsyst in our analysis and finally only HOMER was considered for performing system optimization analysis because of the creditability of its results. A PV-battery system is recognized as the most economically feasible option in our site with the lowest cost of energy as well as net present cost, however its application results in utilization of significant number of batteries which is not efficient. On the contrary, due to low wind speed in the site, the use of wind-battery power system comes out to be the most expensive option. The hybrid wind-PV-battery system is more preferable for its ability to diversify energy sources, and thus to increase reliability of the system and likely system performance, although it is more costly than the PV-battery system. For these reasons, the hybrid wind-PV battery system was recommended for supplying the electrical load requirement of our study.

Keywords

Wind energy system; PV system; Hybrid wind-PV energy system; RETScreen; HOMER; Cost

Preface

This work presented in this thesis is partial fulfilment of my Master's studies in Renewable Energy in the University of Jyväskylä. I would like to thank the Department of Physics as well as my supervisor Dr. Jussi Maunuksela for his support and patience during this work and the whole programme. I am deeply grateful to my siblings; Mahla Alavi, Zahrasadat Alavi and Sepideh Alavi as well as my dearest parents Soheila Keshavarzian and Ahmad Alavi for their positive guidance and valuable advice.

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1 Introduction

Provision of energy is an important element in our life. For having a modern sustainable society we need to have access to secure sources of energy, considering the globally increasing electricity demand. As renewable energy resources are widely available in many places around the world, the share of renewable energy applications for meeting energy demand is rising [1]. It has been suggested that the share of renewable energy could cover 50 % of the total energy demand by mid-century [2]. It is worth to mention that wind and solar energy resources for electricity production are much higher than current total electricity consumption, and with further R&D and technological learning the costs of production are expected to drop so that the costs of production will be more competitive with the conventional fossil-fuel-based energy production [3].

Electrification of households in new residential remote areas which are far from electric distribution grids requires extension of grid, that faces several difficulties. To name a few, cost of electricity grid is high in terms of installation, transmission, distribution, maintenance, infrastructure development, and upgrading. Hence, extending grid is not suitable for low electricity demand. The study conducted by the World Bank/UNDP in 2000 [4] shows that electrification of rural areas by extending grid only raised the total electricity generation costs and the electricity price may even rise to seven times the normal price in an urban area. Another problem is unreliability in frequency, blackouts, high electricity line losses and fluctuations of the grid voltage. Due to the fact that many countries have huge capacity of renewable energy resources of sun and wind, distributed renewable energy production systems could be an economic alternative to the extension of electricity grids. [5, 6]

It has been shown in some studies [7, 8] that for off-grid consumers of distant areas, the hybrid stand-alone electricity generation systems are more economically feasible. One of them is hybrid wind-PV system including battery storage. A wind-PV hybrid system is a combination of solar and wind energy to have an off-grid energy source. When they are combined together, they cope with the problem of fluctuations of power, and become more reliable energy sources. They collect energy from the wind and light by means of wind turbine along with solar panels. They also include charge controllers in order to regulate energy charging. An inverter from the battery bank changes DC to AC before the load. The cost of such system may, depending on the area of study, be comparatively low, and it can compete with power from the grid in remote areas since the total cost of lifecycle is significantly reduced. [6, 9]

The subject of this research is to deal with analysis of prefeasibility of stand-alone electricity generation systems, integrated to housing, for single family apartments in Central Finland by means of wind power and solar photovoltaic. As such, it evaluates the possibility of having distributed electricity production in the given built environment.

There are several earlier studies completed in other places around the world in this field of study. The literature discusses different ways of applying stand-alone systems. As an example, using sensitivity analysis, wind speed and generated power have main effects on the performance of the system. Further, it is cost effective to use wind-PV battery hybrid system than wind or PV alone for small communities. In case of Bangladesh, it has been proven [9] that for even distances between 8 and 12,4 km, considering uncertain payback period of the grid extension cost, a hybrid system is a viable option [10, 9]. In similar vein, in another study in Vietnam [6], it was shown that in rural areas PV and wind energy systems, which were implemented successfully, are economically feasible and are competitive with grid extension. In addition, Notton et al. [11] analyzed optimal available capacity of a standalone PV-wind system for a typical local consumer in five places with different wind speeds. They concluded that windy sites can produce more than 40 % of the total production by wind turbines, however for non-windy areas wind turbine portion would be 20 %, and configuration of the system is important for those sites. Additionally, they found that hybrid system is the best solution, and has higher performance than wind or PV alone. However, the optimal system in sites can have energy surplus of 75 % compared to energy consumption. Nema et al. [12] in a comprehensive study mentioned the other side of the coin that it is expensive to use solar PV and wind energy systems, and further R&D improvements are needed in order to see cost reduction in the future. It was mentioned by Khadem et al. [13] that the wind turbine cost is falling quickly, and also manufacturers are producing very efficient low power wind turbines. Moreover, market for small wind power systems is burgeoning and life time of such systems is being added [13]. From this discussion, it is clear that decent study about the identification of wind, solar and hybrid wind-PV electrification is of great importance both technically and economically for the electricity industry.

1.1 Objective

The objective of this study is to scrutinize the influence of resource parameters on the technical as well as financial feasibility of such system in electrification project through a case study in Central Finland. In this research, drawing upon meteorological data of wind speed and solar radiation, I have done a pre-feasibility study of stand-alone renewable energy systems for household applications using a method similar to the one used by Baniasad Askari et al. [14] in order to answer the following questions:

1. Can renewable energy systems, based on wind and solar resources, be a viable alternative to electricity supply from the grid in the area considered in the present study?
2. Which system configuration offers the most technically and economically viable solution to meet the required electricity demand?

The main thesis of the study is to shed light on possibility of taking advantage of each or both photovoltaic (PV) and wind turbine technology in order to satisfy the electricity demand of single family apartment in Central Finland throughout one-year period. Moreover, I set out to examine whether the site has potentiality for decentralized electricity generation from small-scale renewable energy technologies. Such energy infrastructure could be a good solution for the concern of sustainability and even may be technically more achievable in the near future.

For successful completion of the work, data from weather records, such as wind speed and solar radiation, were collected and then technical data were requested from the manufacturers in order to calculate relative power production. Also, RETScreen, PVsyst and HOMER provided us with software tools for calculating the possible power production. Therefore, by comparing calculated values with the energy consumption profile (data) we were able to find out whether it is possible to meet the demand with the help of one technology or maybe both.

1.2 Practical values

There are many practical values and benefits for implementation of the PV-wind hybrid system. As we know, power generation in many areas depends on fossil fuels which emit CO_2 and other pollutants in high amounts. Thus, a hybrid system would be an applicable and practical solution to reduce emissions and to improve environment. Such small-scale projects may not only contribute to reduced carbon emissions, but also can make a change in pattern of consumption and reach lower levels of demand via load shifting. [15]

Another benefit could be the flexibility of such projects in size, operation and expansion. They have flexible reaction to the change of electricity price and protect consumers against price fluctuation in many places [16]. Moreover, promotion of renewable energy applications is associated with creation of job opportunities. Energy security is one of the concerns of our world today that increases by reducing the reliance on importing of fossil fuels. Hence, supporting power generation from wind and PV can help in this matter and especially eliminate dependency to unreliable trading partners. [17]

During recent years we have seen inventions of new technologies as well as advancements supporting production with lower costs. If the same trend continues, the cost of off-grid systems will go further down to finally guarantee financial feasibility and be more appealing for investors. [18, 5]

By taking advantage of such systems we can have even net-zero energy building. This term is used about housings integrated with renewable energy production systems with the equal amount of energy production to the total household demand. [19] Moreover, implementation of renewable energy projects, including wind-PV hybrid, has the chance of getting different forms of financings, like taxes credits, green tags, capital subsidies, feed in tariffs, etc. in some countries [20].

1.3 Thesis outline

Chapter two sets out to sketch an overview of each wind power, PV and hybrid wind-PV technologies along with the basic theories as well as calculations. We then will mention some case studies and earlier projects in case of hybrid wind-PV systems around the world. In chapter three, the methodology used for data collection as well as component selection criteria will be described. Additionally, comparison between software tools (RETScreen, HOMER and PVsyst) will be made based on analyzing main results of the models. Then, after delineating upon our reasons, one of the tools will be chosen in order to be used in the study. Afterwards, the main results of system designs and discussion will be presented in chapter four. In the final chapter, we will enumerate the whole work and important results in brief and make our final conclusion as well as recommendation.

2 Technology

2.1 Solar photovoltaic technology

This technology has been used in autonomous systems for meeting electrical needs of applications such as refrigeration, lighting, water pumping or other low power loads. It includes PV modules, storage batteries, inverters and control components. [21] Photovoltaics are considered to be one of the most promising green technologies for attaining sustainable development [22, 23]. Using PV systems produces almost zero greenhouse gasses; thus, they are an environmentally friendly option for every area. They are stationary modules and work without any noise. Low maintenance cost, compared to wind turbines, is another advantage of PV systems. However, their relatively high initial cost is discouraging. It is interesting to know that the peak of power consumption usually happens at the summer time, i.e., when the peak of PV power generation takes place. This technology benefits especially areas with high solar and wind capacity. However, it should be noted that solar power generation is totally dependent on local weather conditions and large area which is required for per kW of power produced. [21]

2.1.1 Applications

In residential areas PV modules are often mounted on roof tops of residential buildings. For maximizing the utilization of solar resource and increasing the electrical output power, other facades of a building envelope should also be used. This kind of PV system is called building-integrated photovoltaic (BIPV). Therefore, with the help of such system, the power generated per unit area of the building will increase. One development is using semi-transparent PV module with which you could utilize the facade areas reserved for windows for electricity generation. [24]

Another development in PV systems is the hybrid photovoltaic thermal (HPVT) system. The conversion efficiency of solar to electricity is typically between 9 and 18 %, which means that more than 80 % of the incident solar radiation is either reflected or dissipated as heat. A hybrid photovoltaic thermal system can use a thermoelectric cooling module to decrease solar cell temperature and to produce hot water with the waste heat, thus providing both electrical and thermal energy. [22, 25] It should be kept in mind that diesel generators are still one of the most reliable solutions for electrification of remote areas, and solar energy is often combined with this conventional source in such places [26].

Performance of a photovoltaic system depends on the meteorological conditions of its location. In general, the system efficiency and output of a PV system vary during the day and different seasons of the year because of changing local meteorological conditions. Information on the daily and seasonal patterns enables energy planners to have a better understanding of the performance of a PV system. The meteorological data can be collected via online monitoring of PV systems in the site. [27, 28]

Stand-alone PV systems have played their roles as a helpful technology in electrification of rural areas around the world. The design of an off-grid stand-alone PV system depends on the required load. That type of system is called a solar home system (SHS), and includes PV modules, a charge controller, a battery and the load. [29]

2.1.2 General calculations

In this section and also in section 2.2.1 we give main equations that are relevant for calculating power production from PV panels and wind turbines, respectively. The formulas, which are described in this section and section 2.2.1, give background information to reader and support theories regarding energy production evaluation of the modeling tools that we have worked with.

The total solar radiation incident on a surface depends on the position of sun in the sky, which differs from month to month. The total solar radiation [12] incident on the array as the input of a solar cell is

$$I_T = I_b R_b + I_d R_d + (I_d + I_b) R_r \,, \tag{1}$$

where I_b and I_d are direct and diffuse solar radiations, respectively. Variables R_b, R_d and R_r are beam, diffuse and reflected tilt factors of solar radiation, respectively.

The voltage current equation in an ideal solar cell, with a current source in parallel with a diode, is provided by [12]:

$$I_{pv} = I_{ph} - I\left(e^{\frac{qV_{pv}}{kT}} - 1\right), \tag{2}$$

where I_{ph} is the photo current (A), I the diode reverse saturation current (A), q the charge of electron 1.6×10^{-19} C, k the Boltzman constant 1.38×10^{-23} J/K and T the cell temperature (K).

The output power of a cell [12] is given by:

$$P_{PV} = V_{PV} I_{PV} \,, \tag{3}$$

where I_{PV} is the output current of solar cell (A), V_{PV} is the operating voltage (V) and P_{PV} is the output power of solar cell (W).

The efficiency of a PV system [12] is

$$\eta = \eta_m \eta_{pc} P_f \,, \tag{4}$$

and η_m the modular efficiency [12] is given by:

$$\eta_m = \eta_r [1 - \beta(T_c - T_r)] \,, \tag{5}$$

where η_{pc} is the power conditioning efficiency, η_r is the module reference efficiency, P_f is the packing factor (the fraction of absorber plate area covered by the solar cells), β is the array efficiency temperature coefficient, T_r is the reference temperature for the cell efficiency, and T_c is the monthly average cell temperature. From [12], hourly power output of PV system with an area A_{PV} (m^2) on an average day of *j*th month, with incident total solar radiation of I_{T} (kWh/m^2) on PV surface is given by:

$$P_{sj} = I_{T_j} \eta A_{PV}. \tag{6}$$

2.2 Wind energy technology

Wind turbines capture the kinetic energy of the wind by means of a multiple bladed rotor coupled with an electrical generator on a tall tower. The taller the tower, the higher the wind speed hitting rotor blades can become [21].

A stand-alone wind energy conversion system is a complete off-grid system composed of the wind turbine, the turbine tower, the battery bank and an inverter. It is assumed that our wind energy system is considered for a household consumer of an apartment, which has small amount of consumption, and for such small-scale applications, small wind turbine can operate even if the amount of wind speed is not high. The power output curve of a selected wind turbine, distribution of the wind speed in the site and hub height of the wind turbine are three most important factors affecting the power output of a wind power system [30].

Selection of a wind turbine is difficult and a wrong choice may have negative consequences. Moreover, picking the right alternative has advantage above the lowest price. It is worth economically to wait little longer to find a quality system than having one which imposes extra costs to the projects. Mature selection requires recognition and consideration of countless dynamic factors. But, in pre-feasibility study we are concentrating on technical and economic aspects of making such decision. There are many manufacturers providing wind turbines with variable sizes, performance, costs, reliability and appearance. The size of the wind turbine should result in best possible return of the project. Larger wind turbines have taller towers and have added expenses in maintenance and are less efficient. Overall, the selection should provide us with an option with the best possible economic return. [31]

Wind energy as a mature and environmental-friendly technology is competitive with other technologies as having economic benefits. Globally many wind power programs have been done to promote it in order to play more important role in the clean energy market. [21]

2.2.1 General calculations

The following expression gives the power output of a wind turbine [32]:

$$P = \frac{1}{2} C_p A \rho U^3 \, , \tag{7}$$

where C_p is the power coefficient of the rotor and A is the swept area perpendicular to the direction of wind in square meter. Also, ρ is the air density (around 1,225 kg/m^3) and U is the wind speed (m/s). The relatively smaller density of air compared to water leads to utilization of larger size of wind turbine rotor than water turbine. The equation (7) shows that the wind power increases with the cube of wind velocity. Also, when the diameter doubles, the power increases consequently with a factor of four.

According to the Betz limit, the maximum possible conversion factor of kinetic energy for an ideal wind turbine is 59,3 %. It means that a wind turbine cannot extract more than 16/27 or 59.3 % of the power in the wind. In practice, due to mechanical imperfections, blade roughness and wake effects, etc. a typical value falls to a range of 10 to 35 % for applicable small wind turbines. Likewise, existence of an unsteady wind regime in a site can further reduce the capability of energy conversion. [32]

Typically available wind speed measurement has been done at a certain elevation and thus we need to estimate the wind speed at the elevation of interest. The wind speed at the hub height of a wind turbine is calculated on the basis of surface roughness and topographic features of the chosen area [33]. If we go higher above the ground, the effect of obstacles decreases and wind speeds grow consequently. For variation of the wind speeds with the height, we have two mathematical models: the logarithmic profile and the power law profile. In our study, we have considered logarithmic profile that takes into account the regional characteristics more realistically. This profile assumes that the wind speed is proportional to the logarithm of the hub height of the wind turbine. [33, 34] Thus, the wind speeds at any height [33] can be estimated from:

$$U(z) = \frac{U_*}{\kappa} \ln\left(\frac{z - z_d}{z_0}\right), \tag{8}$$

where κ is von Karman's constant, z is hub height, z_0 is the roughness length and z_d is the displacement height. The friction velocity (U_*) depends on the shearing stress and shows the wind speed near the Earth's surface.

By gathering wind speed data and processing them, we are able to specify a distribution of wind speeds that shows us the period of time for having a specific wind speed as a percentage of total time. This is reflected in wind speed probability distribution functions and would be helpful for predicting the frequency of wind speeds if we do not have wind data for a full year. Two most commonly used functions are Weibull and Rayleigh functions from which Weibull is used in HOMER. [32, 35] The probability density function of the Weibull distribution [32] is given as:

$$f(U) = \left(\frac{k}{C}\right)\left(\frac{U}{C}\right)^{k-1} \exp\left[-\left(\frac{U}{C}\right)^{k}\right], \tag{9}$$

where $f(U)$ is the probability of observed wind speed of U, k is the dimensionless shape factor and C is the scale parameter.

2.2.2 Wind power system performance factors

Site suitability and project terrain

We should consider operating characteristics of wind turbine against wind resource of the site. Geographical distribution of wind speed, probability function of the wind, and measurement of local wind flow are necessary components of wind resource assessment for a real wind turbine project, which ensures that a small wind turbine is truly viable for a given location.

Capacity factor

Capacity factor of wind turbine is an important parameter to be considered while choosing a particular type of wind turbine for the selected site. Capacity factor is related to providing enough power for a wind turbine in a specific area. For wind energy producers low predictability of wind production results in imbalance costs and negatively affects revenue and return of the investment. [36] Capacity factor is defined as the ratio of average power output to the rated power output, and is an indicator of the wind turbine performance. In other words, it is defined as full load hours of annual production divided by the rated capacity [37].

For computing the right value of capacity factor, long periods of observation are considered in order to be entirely unrelated to intermittency phenomenon. The capacity factor value is at any level from 0 % to 100 %, but in practice it is usually between 20 % and 40 %. The selection of the proper generator and the rotor size is an important issue in defining its value precisely. [38] While considering this parameter for turbines with different wind speeds characteristics from several producers, we should take into consideration the fact that the wind turbine with the highest capacity factor is the best option to the site in order to reach the maximum energy capturing [37].

Site’s wind distribution

The selection of wind turbine should be based on the wind resources of the site, and should account for the seasonal variations of wind speeds in the selected site for having a specified energy production level. Since the wind does not blow with the same strength, maximum production will not be equal to the installed nominal capacity. If we consider diurnal pattern of wind power production in winter time in Northern Europe, there is more production than in the summer time and we know that in Northern Europe load is strongly correlated to the outside temperature. Accordingly, the correlation between amount of wind power production and outside temperature in Northern Europe has a direct effect on the adequacy of power production. If we want to consider those areas, the machine should be able to withstand cold climatic condition to facilitate taking advantage of better resources in the winter. [39]

2.2.3 Building mounted wind turbines

Roof mounted small wind turbines can benefit from the building height. Especially, in a low wind speed, location placement is an important factor for accomplishing maximum performance of small wind turbines. Also, mounting small wind turbines to the corners of the building sides can take advantage of the accelerated air flow between buildings in urban areas. Meanwhile, noise and vibration reduction should be incorporated into perfect design of buildings mounted wind turbines. [40] Figure 1 shows a possible installing configuration of small wind turbines to buildings.

Figure 1: Placement of small building-mounted wind turbines [40]

2.3 Hybrid renewable energy systems

Many experts maintain that it is not possible for a single renewable energy source to replace all conventional energy sources (fossil fuels), whereas with a combination of different clean energy sources this becomes more viable. Such a system is called hybrid energy system [41]. Hybrid systems are usually a combination of renewable electricity generation units, such as wind, PV, hydro, biomass integrated with conventional ones, such as gas turbines, diesel generators and fuel cells. As conventional power plants need continuous supply of fuels, which is expensive to transport to isolated places, use of a hybrid renewable energy system can be a good solution for overcoming this economic limitation. The main benefit of a hybrid system is that the weakness of one source is rectified by the other source. Solar radiation and wind energy both are not available continuously and thus, by using both wind and solar technologies the periodical gap between demand and supply of each technology can be filled and the disadvantage of each one can be minimized. However, the design, control, and optimization of the hybrid energy systems are usually very complex tasks. It is recommended that accurate meteorological data should be available in order to avoid designing of an inappropriate system and to minimize operation and maintenance costs, especially in large scale projects. Hybrid energy systems could be considered as auxiliary power supply, in connection with main grids for compensating peak hour power demand, or utilized as autonomous energy producing units in mini grids. For instance, they can support areas with small agricultural loads, with special needs like telecommunication facilities, hospitals or everywhere that the exploitation of hybrid systems is efficient. Hybrid renewable energy systems usually have storage units in order to operate in duration of low power production. [21]

A schematic diagram of a typical hybrid wind-PV energy system is given in Figure 2. When the energy sources (solar and wind energy) are abundant, the generated power, after satisfying the load demand, will be supplied to feed the battery until it is fully charged. On the other hand, when energy sources are poor, the battery will release energy to assist the PV array and wind turbine to cover the load requirements until the storage is depleted. The required battery size usually depends on the load capacity and required backup period. As seen in Figure 2, the electricity produced via PV array and wind turbine is controlled by control components and the excess electricity produced by the hybrid system is stored by the battery bank to be used for later use. Here, the amount of the electricity produced via the wind and the solar energy systems depends on the total solar radiation on array surface and the wind speed in general. [42]

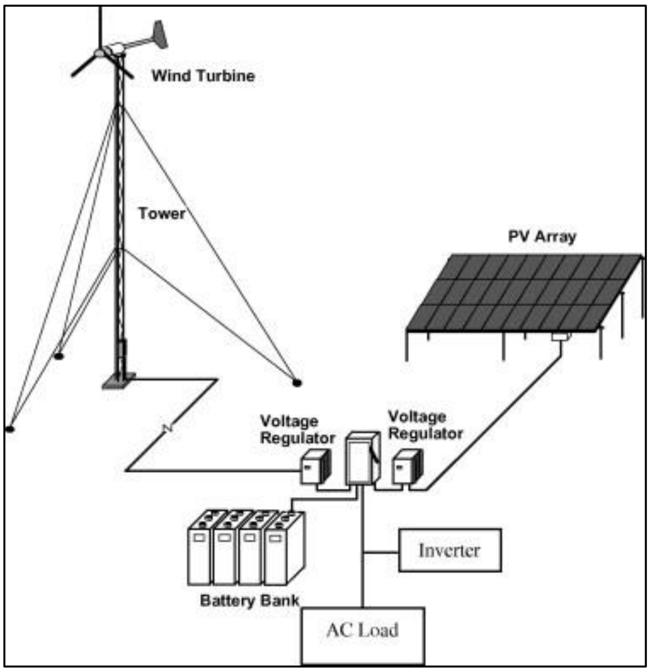


Figure 2: Schematic diagram of a typical hybrid wind-PV energy system [42]

An optimal combination of a wind/PV system depends on the sizes of the PV array and wind turbine, which should provide high availability with low cost. Having 100 % availability means that it is always possible to cover load demand. However, high-availability system means high initial cost and, thus, is not economically feasible. [43]

2.3.1 Examples of residential hybrid wind-PV projects

Here are some applications of hybrid power systems that have been introduced around the world during the last 13 years [26]:

- AC home appliances with total load of 1825 kWh/year in Vadodara, India; 2 kW PV system, 1 kW wind turbine and Vision 6FM 200D battery
- Refrigerator, air conditioner, TV set, lighting and electrical oven with total load of 181.04 MWh/year in Juara village, Tioman island, Malaysia; 200 kW PV system, 40 kW wind turbine and 540 pieces of Surrette 6CS25P battery.
- 500 houses with average load of 8760 kWh/year in Nice, France; 9.9 kW PV system, 4.8 kW wind turbine and 108 kWh battery bank.
- Typical community load of DC lights, fans and TV with total load of 61,685 kWh/year in Sitakunda, Bangladesh; 27 kW PV system, 39 kW wind turbine and 370 pieces of 6-V and 225-Ah battery.
- A hospital, institutions, school, shops, staff quarters and the village with 180 residents with total load of 360.985 MWh/year in Nabouwalu Vanua Levu Island, Fiji; 200 kW PV system, 64.8 kW wind turbine and 500 Hoppecke 12 OpzS 1500 battery.
- A typical village load of 15,768 kWh/year in Sukhalai, Hoshangabad, Madhya Pradesh, India; 8 kW PV system, 7 kW wind turbine and 44.29 kWh battery.
- A typical residential home with load of 1095 kWh/year in Ajaccio, France; 1200 W PV system and 400 W wind turbine.
- A typical rural load of around 58.4 MWh/year in Patenga, Chittagong, Bangladesh; 25 kW PV system, 42 kW wind turbine and 384.75 kWh battery.
- A typical household load in Samothrace, a Greek Island; 3 kW PV system, 2.5 kW wind turbine and 41.85 kWh battery bank.
- A household load of around 4.015 MWh/year in Urumqi, China; 5-kW PV system, 2.5 kW wind turbine and 8 pieces of 6-V and 1156-Ah battery.

Another example of hybrid wind-PV system, which we can consider here as a novel design, is an innovative design of a big scale system on the top of high rise buildings in Petaling Jaya, Malaysia [44]. This system provides clean energy for local use of the buildings.

Moreover, it has the capability to collect the rain water by means of built-in water collection system for free water supply. It takes advantage of Malaysian weather which has high solar radiation and high rainfalls. The advantage of using this system on the top of high rise building is that in low wind speed area the wind speed is increased due to escalated free-stream wind in all directions. It has also a system called power-augmentation-guide-vane (PAGV) that is used for increasing wind speed before entering wind turbine and, thus, the wind turbine size can be decreased for a given power capacity. The smaller wind turbine size provides optimum surface area for installation of other components such as solar panels and battery storage system. There are some advantages of such systems which enable the system to work in low wind speed, safety, etc. Moreover, the existence of the wind turbine is not noticeable.

The solar system of the hybrid wind-PV system in the example in Malaysia includes a PV array, charge controller and inverter. The solar cell is made of monocrystalline silicon with efficiency of 16,4 % using for solar radiation of 108 MWh/year. Furthermore, the wind energy system consists of an H-rotor vertical access wind turbine with no yawing mechanism, 17 m diameter and 9 m height on the top of 220 m building. The wind speed would be approximately 1,8 times bigger than the wind speed in the range of 1,5 to 2 m/s at reference height of 46,2 m. It is estimated that the wind system on the top of a 220 m height building is capable of generating annually 86,2 MWh. [44]

The mentioned project is a good example of on-site renewable energy generation in populated urban areas. Sectional as well as perspective views of such system together with illustrative view of its application are provided in Figure 3 and 4.

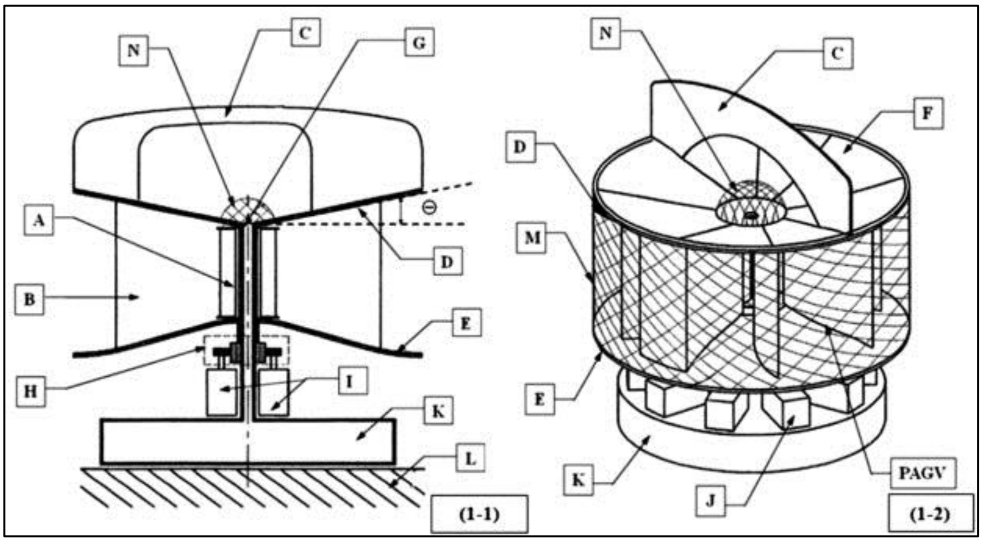


Figure 3: A wind-solar hybrid system with rain water collection [44]

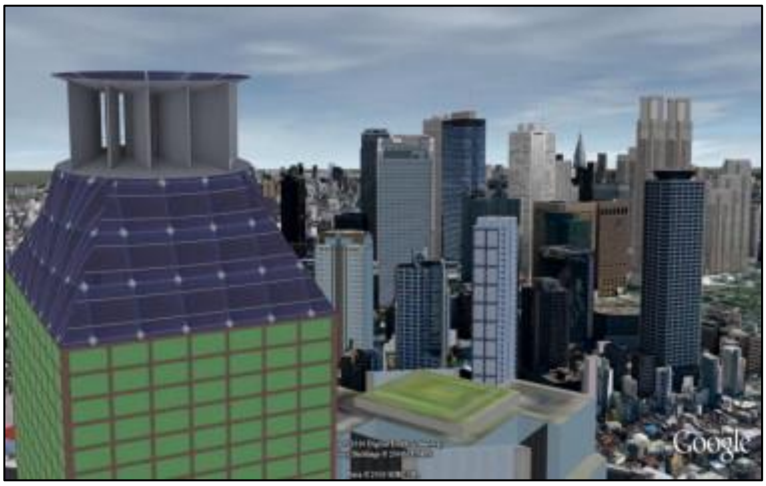


Figure 4: An illustration of a hybrid wind-PV system integrated on a high-rise building [44]

2.4 General considerations of permits and planning in Finland

The planning of wind power projects in Finland follows the rules of “Land Use and Building Act” [45]. The planning system includes national land use guidelines, the regional land use plan, the local master plan and the local detailed plan.

Depending on the location and size of the project, considerations such as building permit, flight security considerations for heights more than 30 meters, permission of the Electricity Market Act for cables higher than 110 kV and compulsory permissions for the land for new electricity transmission lines are required. Consequently, construction approval has to be cleared by respective authorities before the start of construction. The approval of surrounding neighbors is mandatory; they must be informed about possible sound emissions. Further, a statement from the Finnish Defense Force in a very early stage of the project is needed about possible disturbance problems for their radar equipment. For performing an analysis about disturbance level, the developer should contact the Federation of Energy Industries in order to buy a license from VTT, which costs EUR 171,71 per turbine. [46]

3 Methods and materials

In this study unlike other studies that analyze long-term local weather data to find the best possible option for utilizing local solar and wind energy resources, we have examined the possibility of using wind and solar power in a specified area for electricity production to cover the load demand of a hypothetical household apartment. In the simulation of stand-alone renewable energy systems in our study, there are few main parameters in sizing: the capacity of PV system, the rated power of wind power system, the capacity of the battery bank, the tilt angle of PV modules and the hub heights of wind turbines tower.

The main objective of this study was to find, compare and differentiate the optimum size of different wind, PV and hybrid wind-PV systems with battery storage, that are capable of fulfilling the energy requirements of a typical household apartment in Jyväskylä region.

We aimed to simulate wind and PV power systems in RETScreen and HOMER, including battery bank in the model as a backup. Load consumption data, wind and solar data in the site as well as wind turbine power curves of manufacturers first were considered as inputs of the systems and then system simulations were performed based on those inputs. Our strategy was to first compare the results given by the software tools for each wind power and photovoltaic system, and then to consider based on the results validity one of these tools for our final analysis. We also drew upon PVsyst model to find the capacity of PV arrays to be used as a RETScreen input. Moreover, per kilo watt price of PV system in both RETScreen and HOMER inputs was taken from PVsyst results. After comparing the results, validating the outputs and describing our reasons, we decided to select one software model for including its results in data analysis and discussion. Afterwards, we moved to the next step which was simulation of a hybrid wind/PV system with the same inputs in the HOMER tool. Therefore, in this way we were able to verify the technical and financial strength of the hybrid model and then compared the three system designs with each other in order to find out which one is better option for technical and economical fulfillment of the energy requirements of the given load and applicability of each system design. A total of 253010 system configurations were simulated for all cases in HOMER. Total simulation time was 2 h 51 min on a P4 930 Dual-core, 3.0 GHz, 512 MB RAM Intel computer. In this optimization process, warnings were generated indicating insufficiency in search space for wind turbine, converter, battery bank and solar panel. Subsequently, increases in number of components were considered. To this end, several runs were made before determining the optimum sizes of components required to achieve the best results. After seeing no changes in the outcomes, no further attempts were made to modify the search space. Finally, considering our technical and economic output data, we decided on the best system configuration among three different technologies and explained specifications of each power system design.

3.1 Location of the study and considerations

It is essential to describe the location as accurately as possible with respect to site installation and environment. This way, the production level can be adjusted accordingly. However, in this study our location was considered as a region and we only needed the variables in the software tools, such as wind speed data and solar radiation data. In this study we are considering Jyväskylä region in Central Finland. Thus, during working with software tools, relevant meteorological information was selected for this area. The database of RETScreen was used for importing meteorological data (average wind speeds and solar radiations) of Jyväskylä.

3.2 Energy consumption profile for a single family house

Accurate household load data is required for planning optimal production capacity of a small scale renewable power system. The data of domestic electricity consumptions is usually a sum of power of numerous households without detailed information about the events in each individual. An ideal case is the one with known consumption pattern and with details of household appliances. Yet another way is to consider statistical averages and sample data. Analyzing domestic consumption data, we could identify the basic characteristics of load curves of households which changes on a periodical basis. When methods described in [47] were used, mean data converged by increasing number of households. After removing the seasonal cyclic behavior from the data, the daily mean energy distribution was obtained. A model for generating household electricity load profiles was used then, based on bottom-up approach in which loads include appliance groups. The consumption data of 10000 households for one year was considered without heating electric heating loads. The simulated load was obtained by using “observation and hypothesis on the behavior of household electricity consumption data” as goal values. The simulated daily energy consumption throughout the whole year is presented in Figure 5.

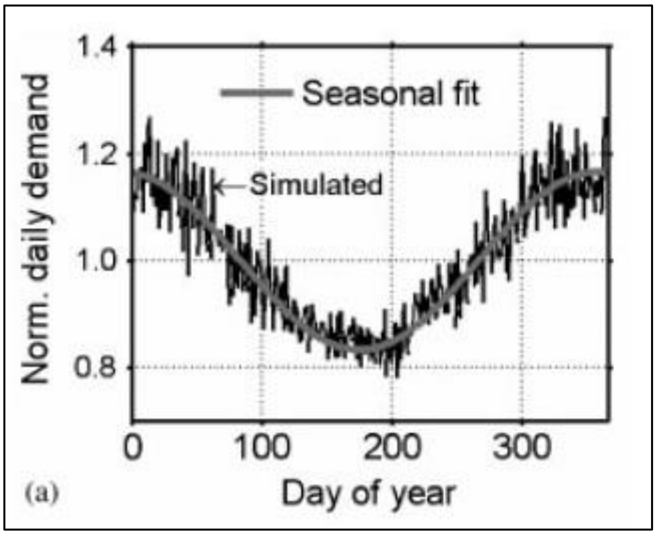


Figure 5: Daily electricity consumption for generated data set [47]

Using the curve in Figure 5, the mean energy per day per household for the generated data was calculated at 5,16 kWh per day [47]. This value is the one that was used as input for average daily consumption of each household in our models.

According to the data from [48], an average winter day in the third and fourth weeks of January is considered for estimating the peak load of two different types of detached house and apartment in winter time in Finland. Figure 6 shows us the average hourly consumption and share of each appliance.

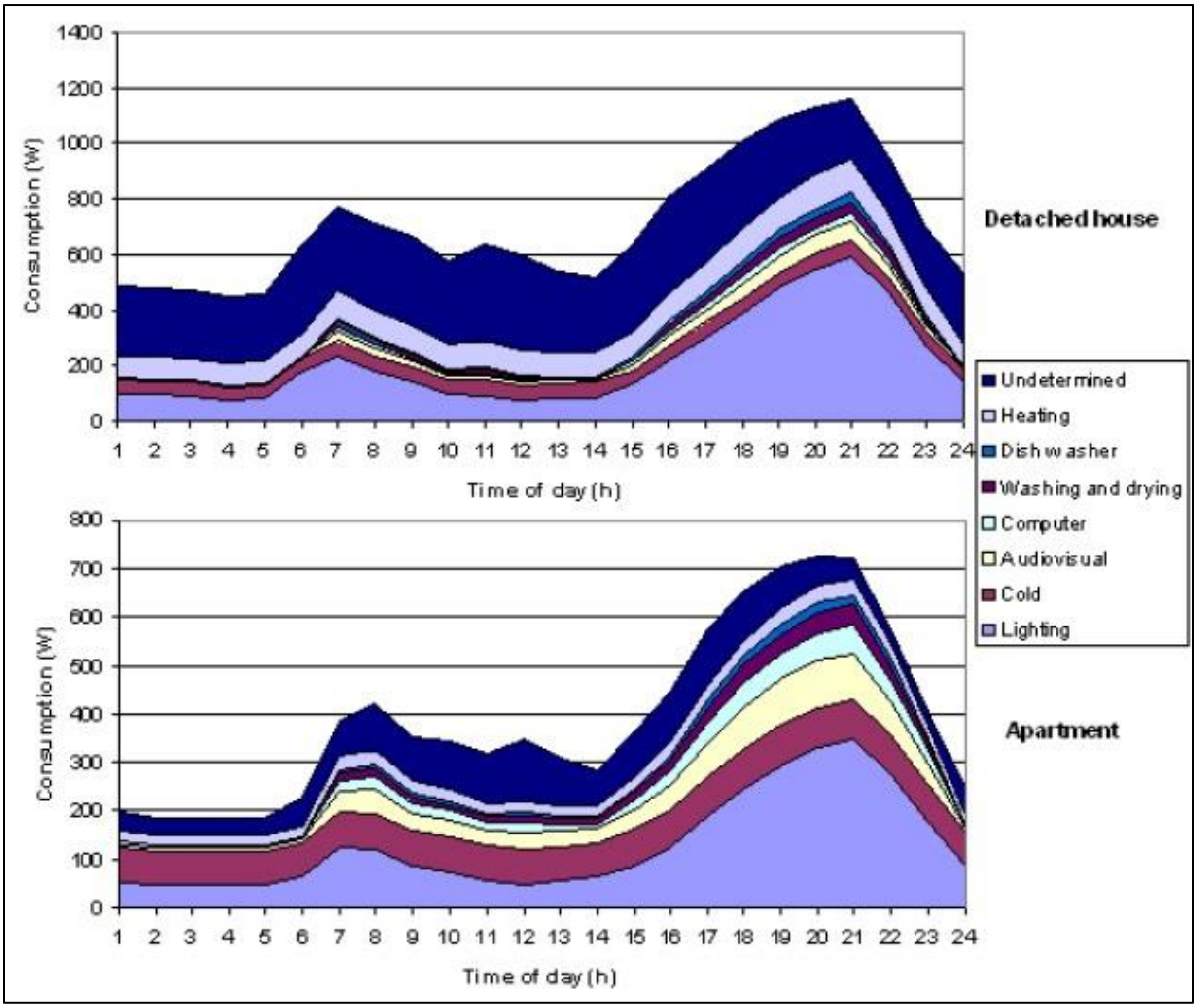


Figure 6: Average daily consumption and share of each appliance in an average winter day for two types of residential consumers [48]

As we can see from the curves in Figure 6, the peak load can be considered to be around 730 W and 1200 W for apartment and detached house, respectively. Since our input data is for a normal household apartment use, the relevant amount of 730 W of an apartment was taken as the peak load in our models.

3.3 Technical data from the manufacturers

In order to choose a turbine for our wind turbine model, small turbines below 15 kW in RETScreen as well as HOMER databases were classified into working wind speeds of 3 and 2 m/s. Due to lack of data about various small wind turbine properties and absence of low cut-in wind turbines, especially in HOMER, we searched in order to find wind turbine manufacturers whose products can perform in the site conditions. Thus, we opted for wind turbines with low cut-in wind speeds, smaller than the average wind speed in Jyväskylä. This way we can be sure that we can take advantage of the wind resource in the site. Information was collected from 5 manufacturers, and it included power output, costs etc. Based on the power curves and energy yield at low wind speeds, the WINDSPOT 1.5 and STEP V2GL showed best capability of energy production in low wind speeds of the site. Nevertheless, due to the modular application of smaller capacity of 1.5-kW wind turbine, we can use a set of them with higher reliability and smaller fluctuations in the energy output. It means that by having a number of small wind turbines, instead of a big one, we can have power generation in case of failure in some of the wind turbines. Consequently, we do not lose the whole capacity. Considering the power curves of these turbines, WINDSPOT 1.5 has slightly better performance than STEP V2GL in low wind speeds. Thus, ten 1.5-kW WINDSPOT 1.5 turbines have higher power production than one 15-kW STEP V2GL turbine in the low wind speeds of the site. Moreover, the sizing with 1.5-kW wind turbines would have smaller overestimation as well as underestimation of the size of the optimized system. Thus, our estimation about needed capacity would be precise enough.

For the reasons mentioned above, the WINDSPOT 1.5 turbine was selected to be used in this study. The equipment details, including technical data sheet, power curve and certifications, can be found in Appendix A. In this stage we did not consider the costs and the only important factor was the technical specifications of the wind turbines.

3.4 System simulation tools

3.4.1 RETScreen

RETScreen International can model different renewable electricity generating technologies such as wind energy, photovoltaics, small hydro and combined heat and power technology. It contains a wide range of built-in climate databases for ground-station locations in addition to access to NASA satellite weather database. RETScreen Software uses the NASA Surface Meteorology and Solar Energy (SSE) Data Set as a useful alternative for ground-based data or detailed resource maps for the project location. RETScreen makes a comparison between a “base case power system”, which is typically a conventional energy generating technology, and a “proposed case power system” that is built around a clean energy technology. Normally, the proposed case has higher initial costs than the base case. In the financial analysis of RETScreen total cost of the proposed case power system is compared with the total electricity cost of the base case power system. In the cumulative cash flows graph the model calculates how many years it takes to make the same accumulative savings from not paying for the electricity from the base case power system in order to compensate for the total cost of the proposed case power system.

Technical assessment in the RETScreen is obtained by calculating the amount of the load, which can be covered with the energy produced with the proposed power system. Thus, according to the daily electricity consumption and the power production by the proposed system, the RETScreen model calculates the percentage of the electricity delivered to load. [49]

3.4.2 Wind turbine system design in RETScreen

Considering the instruction and data from help of [50], we specified the important input data and their selection criteria that we needed to consider in order to run the model. The base case power system is the electricity from the grid. Also, all input descriptions and definition of important tabs of all three models are provided in Appendix B

Basic assumptions:

In our study we only considered “Off-grid” as the size of our project is small and we only sought to examine the possibility of using the power generated by a stand-alone wind or photovoltaic system.

We selected a relevant type of analysis, which needs fewer inputs and thus it is suitable for performing a pre-feasibility study. The method requires only resource data of the site and some cost estimates as well as simple calculations to finally make a judgment based on rules of thumb. For unit, “Metric units” was selected as a standard unit.

“Jyvaskyla (Mil/Civ)” was selected as the location we seek to consider its meteorological data as our input data. It should be mentioned that the average daily solar radiations as well as wind speed levels for each month in Jyväskylä were procured from ground-based monitoring station.

“Grid electricity” was selected for the base case power system technology, since the model compares its results with the proposed case power system. Meantime, the price of the grid electricity in our study was considered for the fuel rate. According to the EUROPE’S ENERGY PORTAL website [51], end-user electricity prices for households in different European countries were listed in a table on May 2013, in which the value for Finland was rated at 0.15718 Euro/kWh. We assumed zero for the annual operation and maintenance cost of the base case power system, since we do not consider any extra cost other than the grid electricity bill. Also, The value of the electricity rate for the base case power system was the sum of fuel rate and annual O&M cost which equals to 0.157 Euro/kWh.

The amount of daily DC electricity consumption was entered zero, as we assumed that we only have AC load.

We considered the amount of consumption for a single family house from section 3.2 plus 10 % of additional losses because of wiring. So, the amount of daily AC electricity consumption was calculated to be 5,676 kWh.

In case of the wind turbine system, we assumed that the load is partly covered by battery and partly by the wind power system. Thus, we chose the respective option “Zero” for the intermittent resource-load correlation in the model.

For our model we assumed that we always have load consumption during all months. Thus, we did not check the box for “Percent of month used” and the model assumes that all months are rated at 100 %.

The “Incremental initial costs” for a typical case is defined as the actual project costs that are variable with respect to project factors and that is usually related to the cost of infrastructure as well as installations. Since the consumer does not pay directly for the grid installation, we considered “Incremental initial costs” as zero. Furthermore, according to section 3.2, the maximum power consumption or annual peak load for an off-grid system, which is an apartment, was considered 730 W.

Inverter

Normally the capacity of inverter is similar to or higher than the annual AC peak load. Thus, we considered higher value which is inverter capacity of 2 kW from the manufacturer database. The efficiency range mentioned by the manufacturer is from 90 to 95 % and we considered it 90 % in our system.

Battery

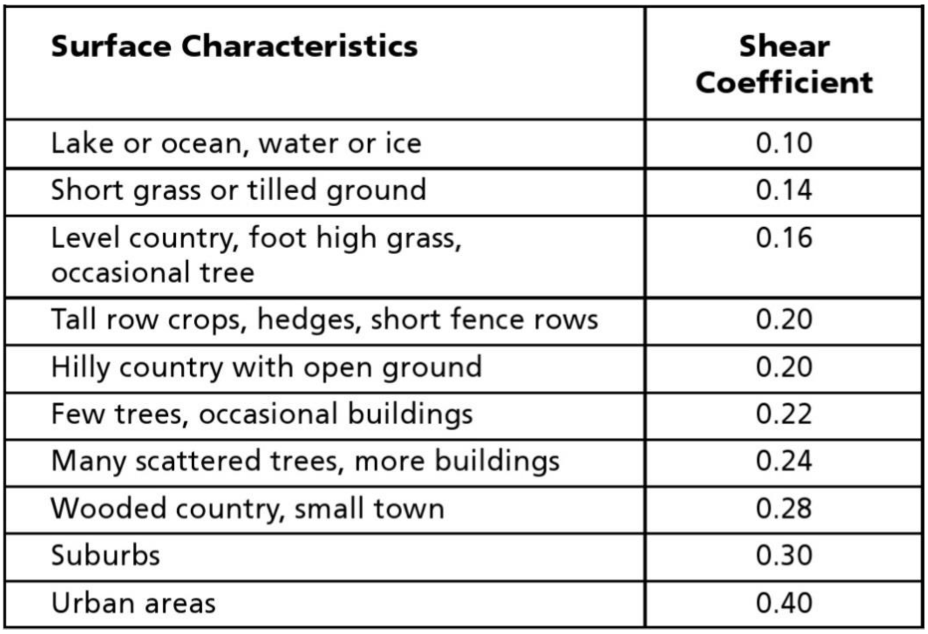
For the wind power system, we assumed that batteries, starting from full state of charge, can meet the load for 3 days solely. This means that the maximum duration of insufficient wind power production in the site was assumed to be 3 days. Meanwhile, in order to find a suitable value for days of autonomy for a PV system, we utilized the consecutive days of no-sun (No-Sun Days) maps provided by the NASA Langley Research Center which is reflected in help section of [50]. From the map for Finland we recognized that the approximate value is 5 to 6 days for the summer and around 15 to 20 days for the winter. According to these values, an average “days of autonomy” was considered 10 days for the PV system in our PV models. The battery bank voltage was selected 48 volts, which is similar to what is considered for a 3.6-kW off-grid PV case study in RETScreen. The efficiency of battery is usually specified at 25°C, and from the information of the battery supplier the efficiency is 90 %. According to the Trojan’s battery sizing guidelines [52], the typical value for the maximum depth of discharge is 50 %. This low value was selected to ensure that the batteries can reach higher lifetime. In addition, the value for charge controller efficiency was defined by the wind turbine manufacturer as 95 %.

According to the capacity we obtained in Ah by the model, we searched for products with prices on the web. Then we came up with a battery supplier with batteries suitable for wind and solar applications which included a useful battery sizing tool [53]. A typical optional gel battery type MK 8G24UT-DEKA 12V 74 Ah Gel Battery was selected. According to the data we used to get the calculated Ah value of a typical gel battery, the price was calculated as EUR 8268. The only aim of using the sizing tool is to select a set of battery with a specified price in order to include in our studies. The tool does not have any complicated method for sizing, other than what we clarified above. Moreover, we did not make any distinction between the battery type used for PV system and wind energy system.

Resource data

The optional height of 10 meter, in which the average wind speeds are measured, was selected. For adjusting the value of wind shear exponent, we considered our terrain as rough, with different size of trees as well as obstacles in a hilly terrain. Accordingly, taking into consideration the values of Table 1, an approximate value of 0,25 was selected.

Table 1: Wind shear exponents for different types of surface [54]



Surface Characteristics	Shear Coefficient
Lake or ocean, water or ice	0.10
Short grass or tilled ground	0.14
Level country, foot high grass, occasional tree	0.16
Tall row crops, hedges, short fence rows	0.20
Hilly country with open ground	0.20
Few trees, occasional buildings	0.22
Many scattered trees, more buildings	0.24
Wooded country, small town	0.28
Suburbs	0.30
Urban areas	0.40

Wind turbine data

As we described before, in section 3.3, we chose a 1.5-kW WINDSPOT wind turbine.

A value for number of turbines was used in order to calculate the whole energy production of all turbines. A set of smaller turbines has the advantage of smaller fluctuations in the energy output, while the cost of larger machines could be normally lower on the basis of per kW. In our case we considered 2 turbines by means of a rough approximation; because of low wind speed regime in our site, the rated wind speed of the wind turbine, which is 11 m/s, cannot be achieved to reach the full capacity of 1.5 kW to meet the peak load. Thus, we compensate the shortage of power production by adding another wind turbine.

According to the manufacturer datasheet and limits of 30 meters that was mentioned in section 2.4, a tower with **hub height** of 18 meters was selected. The **swept area** for the selected wind turbine is taken from the datasheet of the manufacturer as 13 m^2. By choosing a relative tab in the model, the **energy curve data** was calculated based on a Weibull wind speed distribution, which is suitable for long-term distribution of mean wind speed.

For the value of **“Incremental initial costs”** of the wind turbine, the total cost of the wind turbine was requested from the manufacturer as EUR 16.700 for each turbine. This price consists of costs of wind turbine system, tower, installation, control unit, safety switches and a 2-kW inverter.

The value for **array losses** was considered as 0 %, because we assumed that the wind turbines are small and located with enough space from each other so that they are not affected by negative consequence of wakes. Also, **airfoil losses** was considered zero as we assumed that our area is free of dust and the effect of ice is negligible. The effect of **miscellaneous losses** was considered negligible, thus we entered the minimum value which is 2 %.

In order to define a value for **availability**, we assumed that the system does not need a lot of maintenance as well as failures and stops during its lifetime. But, due to the installation in cold climate we considered this value as small as 93 % which is the smallest value that is defined by the software.

Financial parameters

According to the methods used by Eurostat [55], the annual **inflation rate** in Finland is set around the level of 1,5 percent. For defining **project life**, we only considered the life cycle of the system devices which was estimated 20 years. Moreover, since in this study we did not use any debts, **debt ratio** was entered as 0 %.

3.4.3 HOMER software

HOMER is software for designing hybrid energy systems, which simplifies the task of micro-power system design and analyzes combinations of renewable energy technologies like generators, wind turbines, photovoltaic systems, batteries, fuel cells, hydropower, combined heat and power, biomass and other systems. It is mainly for analyzing distributed generation (DG) systems, both grid-tied and off-grid systems, and can provide optimally system design for wind and solar resources. HOMER simulates different energy systems, compares the results with each other and gives economically and technically best option for renewable energy systems. It also assists in understanding the effects of uncertainties or changes in the inputs. [56]

This optimization model can appraise a range of design components over changing constraints and perform a sensitivity analysis to find out best options among proposed renewable energy systems. HOMER considers a system to be feasible if it can adequately serve the load demand and satisfy any other constraints imposed by the user. This is very useful for us in order to make an early decision about equipment options in our pre-feasibility study. Also, we are able to track the most suitable size of the system which is more cost effective and can adequately serve the electric demand. It even suggests a set of diesel generators, as a cheaper option than increasing the size of the battery bank. [57]

HOMER makes energy balance calculations for each 8.760 hours during the year. It compares the electric load with the available energy supply from renewable sources in each hour. Meanwhile, HOMER decides to charge or discharge the batteries, depending on the availability of resources. For the systems which are suitable for covering the load demand for the whole year, HOMER gives annual cost data and other performance summaries of all components and the whole system. [58] The software runs a fast hourly simulation of thousands of possible system configurations. After running the simulation, it tabulates feasible options, from the alternative sizes that user defined as the inputs, in ascending order of total net present cost. This includes initial, fuel, operation and maintenance costs. Thus, the one with the least cost is identified as the optimum point of the system simulation on the basis of user-defined parameters. [59]

Mathematical modeling in HOMER

For modeling wind power projects, wind resource data in a year should be provided as measured hourly wind speeds. If not available, HOMER synthesizes hourly data from monthly average wind speeds using Weibull shape factor, autocorrelation factor (reflecting how strongly the wind speed in one time step depends on the wind speeds in previous time steps), diurnal pattern strength (reflecting how strongly the wind speed tends to depend on the time of day) and the hour of peak wind speed. [58]

For modeling a PV system in HOMER, solar resource data can be provided as hourly average global radiation on the horizontal surface, monthly average global solar radiation on the horizontal surface, or monthly average clearness index. But, by entering monthly solar radiation data, the model generates synthetic hourly global solar radiation data using an algorithm created by Graham and Hollands [60]. Moreover, HOMER uses HDKR model, explained in Section 2.16 of [61], for calculating the global solar radiation incident on the PV panel for every hour of the year. The HDKR model considers the value of the solar resource for a specific time of a day, the time of year, the orientation and slope of the PV array as well as the location of the study [58].

3.4.4 Wind energy system design with HOMER

Using HOMER is an iterative process. We started with rough estimates for inputs and then the results were checked, estimates refined and the process was repeated to find acceptable values for the inputs. First, we defined our wind energy system and its components. The data provided in the help section of [62] supports our input selections and, thus we selected Primary Load, PV, Converter and Battery as “Equipment to consider”.

For load inputs hourly load quantities in kW were considered in order to have data about average daily load demand, which was calculated by the model and used as input data of daily profile. Thus, an average load of 0,237 kW/d was entered as hourly load. In this way, the model considered the same value of 5,69 kWh as total daily consumption. Actually, in the model the only important load inputs for the final system design are average daily consumption and peak load. According to Figure 6, the peak load happens between hour 20 and 21 during January. Thus, we entered 730 W in that time of the day in the software. This way, we can consider the effect of peak load in the system design. This change lead to a small increase of about 8 % in the amount of daily consumption which is not an important determining factor in our study. Including the value of peak load in the load inputs is important because it affects the converter size. Moreover, the system can meet the demand at its peak value. The other setting was the selection of “Load type” as AC, as we assumed that household devices work with AC electricity. We entered data without considering differences between months and days, as in our pre-feasibility study we assumed that all the months and days have the same load profile and the load profile applies to every day of the year. We did not change other default values in this part, as they do not affect the main results. The load profile which we used in HOMER model is shown in Figure 7.

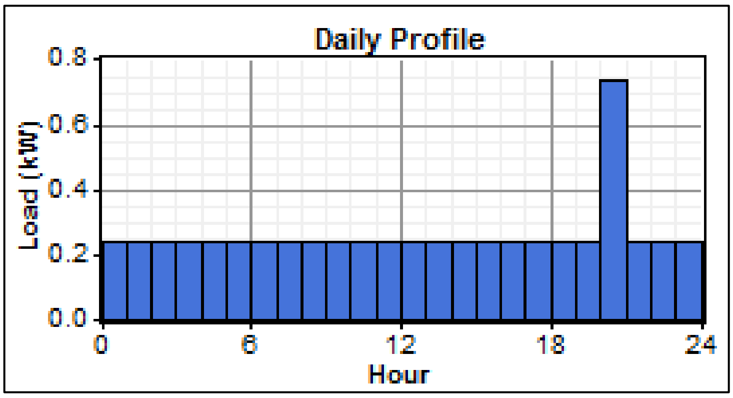


Figure 7: Daily load profile of a hypothetical household

The technical data and the power curve of the wind turbine were transferred to the software according to the data we got from the manufacturer. After that we defined cost, which is the same as in RETScreen model i.e. EUR 16700 for each turbine. Replacement cost was not important to be considered, as we do not need any replacement during the project lifetime. “Lifetime” and “Hub height” are the same as values for RETScreen model. The power curve of the wind turbine which was used by the model is shown in Figure 8.

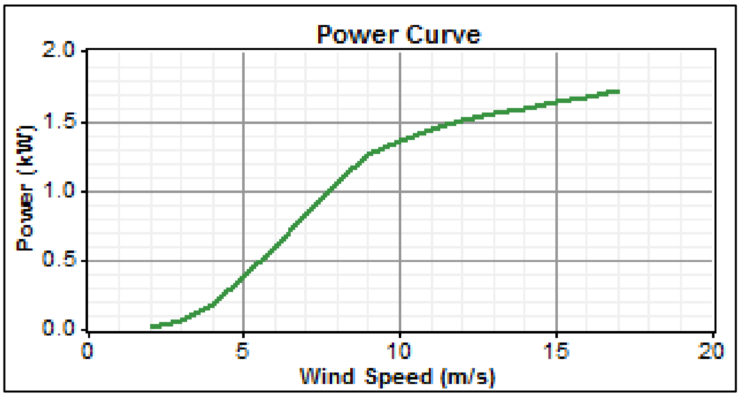


Figure 8: Power curve of the wind turbine

For **Converter, Lifetime** and **Efficiency** of the wind turbine model the same sizes and values were considered according to what we got from the manufacturer and used in our RETScreen model. For **Battery** in the wind turbine system, we used the values and calculated amounts, on the basis of days of autonomy, maximum depth of discharge, load demand and other parameters which we used in RETScreen model. We selected the same type of MK 8G24UT-DEKA 12V 74 Ah Gel Battery that we used in RETScreen model, from database of the battery sizing tool [53]. We sized a new battery bank in the battery sizing tool with nominal voltage of 48 V, round trip efficiency of 90 % (battery efficiency in RETScreen), minimum state of charge of 50 % (maximum depth of discharge in RETScreen) and nominal capacity of 953 Ah, which was calculated in RETScreen battery sizing section. Also, a lifetime of 20 years was considered, which means that the battery is supposed to last for the lifetime of the project. After defining the required battery with the nominal capacity of 953 Ah, we entered in the model the calculated cost of the battery type from the battery sizing tool [53] in Euro and the other required details. Also, different battery sizes were entered up to the number of required batteries that was gained from the battery sizing tool before, considering the days of autonomy. In this way the model is able to find the optimum point for the best set of batteries. For **Wind Resource Inputs** we used the same values that we had in the RETScreen model, which is from ground-based meteorological data base. Also, we used 2,2 for the value of "Weibull k" which is similar to shape factor value in the RETScreen model. **Variation with Height** of the wind speed profile was chosen as **Logarithmic** in the model, because that has mostly been used for extrapolating mean wind speed in the lower hub heights [63]. Also, surface roughness length was set to 0,25 which is the same value as used for the wind shear exponent in the RETScreen model. The wind speed profile that HOMER used and schematic diagram of the type of wind turbine system that HOMER can simulate are shown in Figures 9 and 10, respectively.

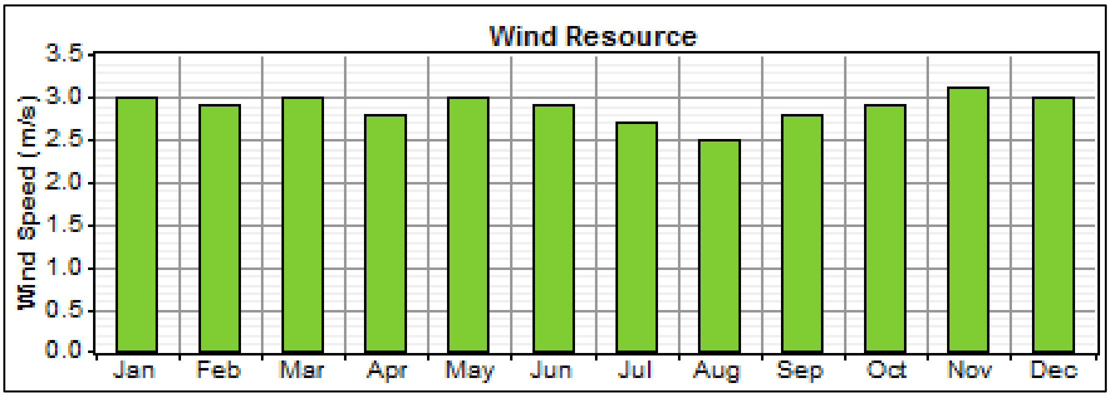


Figure 9: Average monthly wind speeds for the site

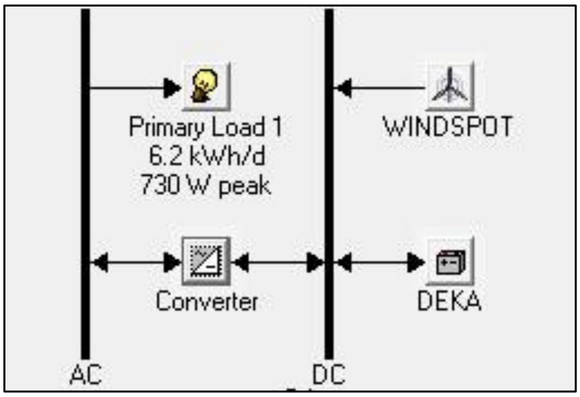


Figure 10: Schematic diagram of the proposed wind turbine system

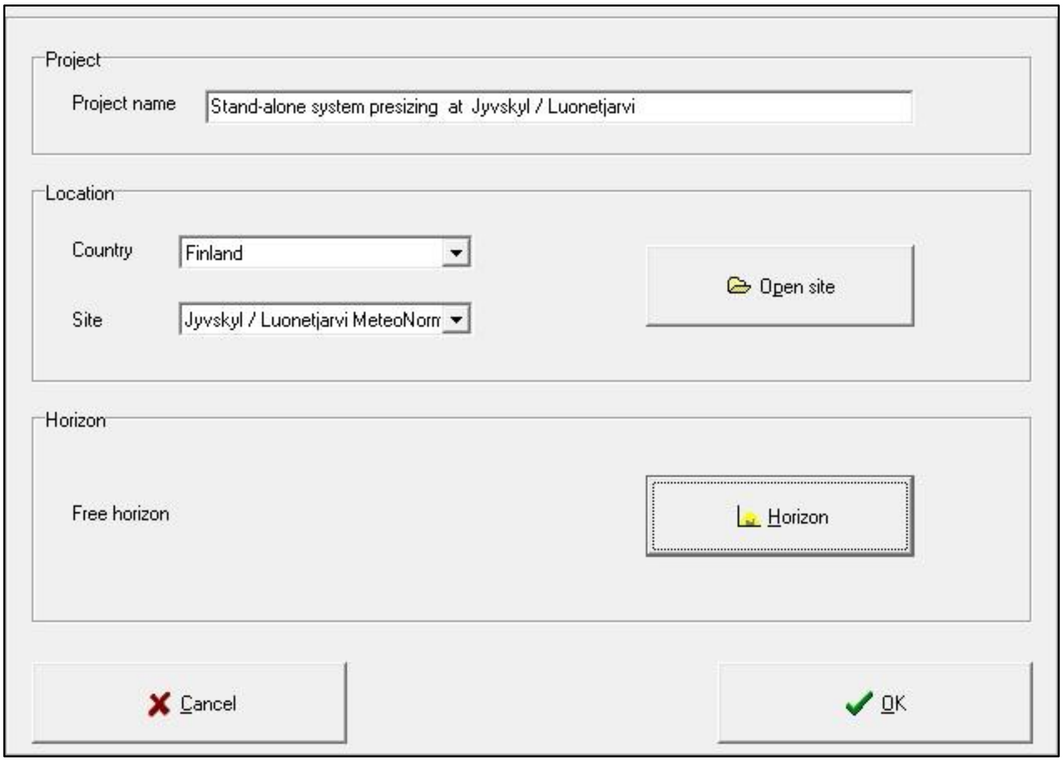
The project lifetime was set to 20 years and **Annual real interest rate** was considered zero, assuming that money is not borrowed for investments. Meanwhile, the system fixed O&M cost was reported by the manufacturer as EUR 500 per year for purposes like greasing wind turbine machine.

The maximum allowable value of the annual capacity shortage is desired to be zero and thus the model was run with this value. This means that HOMER sized the system to meet even a very high peak load for a very short time and also that the system met all loads for all times. The minimum renewable energy fraction was not restricted.

3.4.5 PVsyst software

PVsyst V6.11 is a tool for sizing and analyzing grid-connected, stand-alone, pumping and DC PV systems with the help of component databases. It has a database of irradiance values for 1500 stations. These values are average measured values for years between 1960 and 1990. The program has three different stages for modeling a project: preliminary design, project design and measured data analysis. Preliminary design is about pre-sizing a project so that we can evaluate the energy yield of the system by means of only few characteristic parameters of the system. Also, we are able to specify an approximate cost for the system. The preliminary design section enables us to play with the main parameters and find their effect on the performance of the system in order to optimize the design characteristics for project with a more precise simulation. Performing a detailed design of a PV system is done by defining the plane orientation, shading effects, number of PV arrays and other system components. The results have many variable values. In project design, precise results are obtained with hourly simulation. This step has a detailed economic evaluation that can be performed with the help of components prices. The monthly average irradiation levels are calculated on the basis of the instantaneous data for one day of each month and then the software generates data for 365 days. The accuracy of this method is between 10 and 20 %. [64]

As our study is about pre-feasibility, we only used "Preliminary design" section of this software since it gives us a rough estimation of energy yield of the system as well as user's satisfaction level with few variables. Moreover, the optimal size of the PV array along with capacity of battery bank, required to cover the load demand, were defined. By entering monthly recorded data provided by the "Sites" database as well as horizon data and adjusting collector plane orientation, the solar energy was calculated in monthly values. For determining the battery capacity we need favorable days of autonomy, which is one of the two basic user factors along with the required loss of load. This section analyzes three systems: Grid-connected, stand alone and pumping. All definitions given in this section are provided by help material of [64]. After selecting our system as "Stand alone" we defined the "Location" of the project in order to import meteorological details for the location. Thus, we selected "Finland" and then "Jyvskyl/Luonetjarvi MeteoNorm 6.1" in the model in order to import the irradiation data of our project. Figures 11, 12 and 13 show the adjustment of location in the model.



Project

Project name: Stand-alone system presizing at Jyvskyl / Luonetjarvi

Location

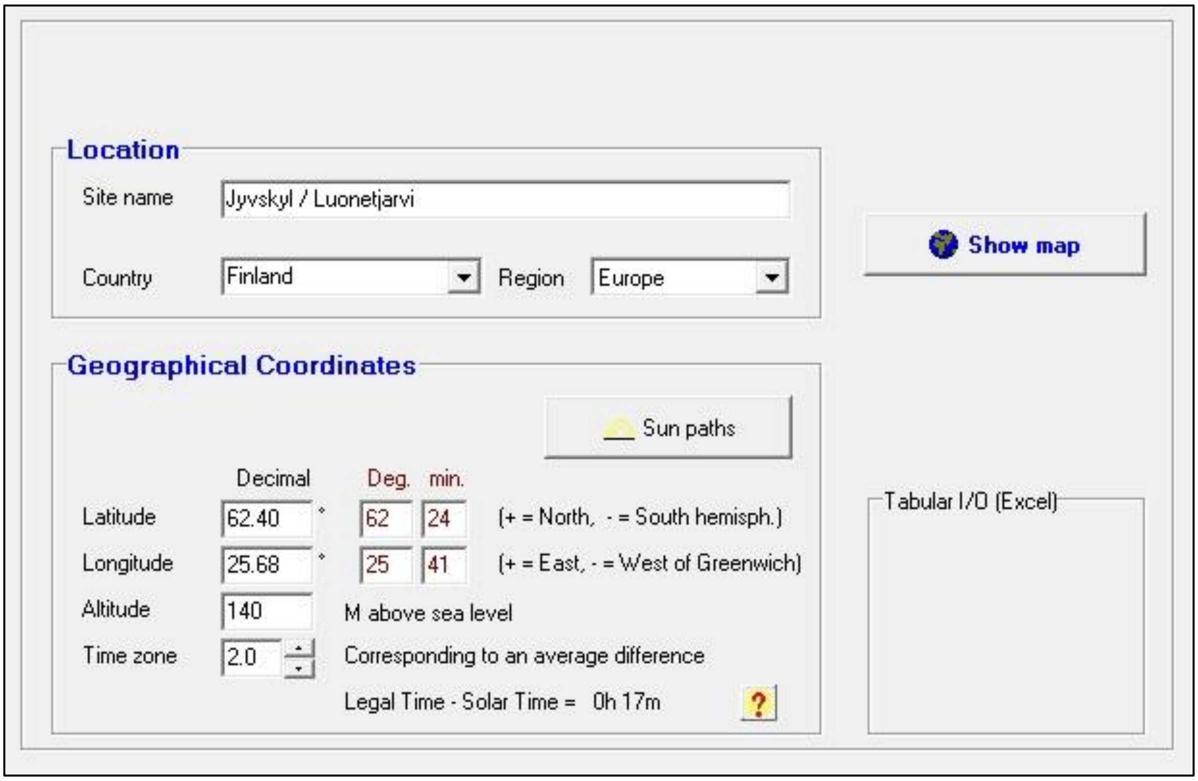
Country: Finland

Site: Jyvskyl / Luonetjarvi MeteoNorr

Horizon

Free horizon

Figure 11: Selection of the project location in PVsyst



Location

Site name: Jyvskyl / Luonetjarvi

Country: Finland

Region: Europe

Geographical Coordinates

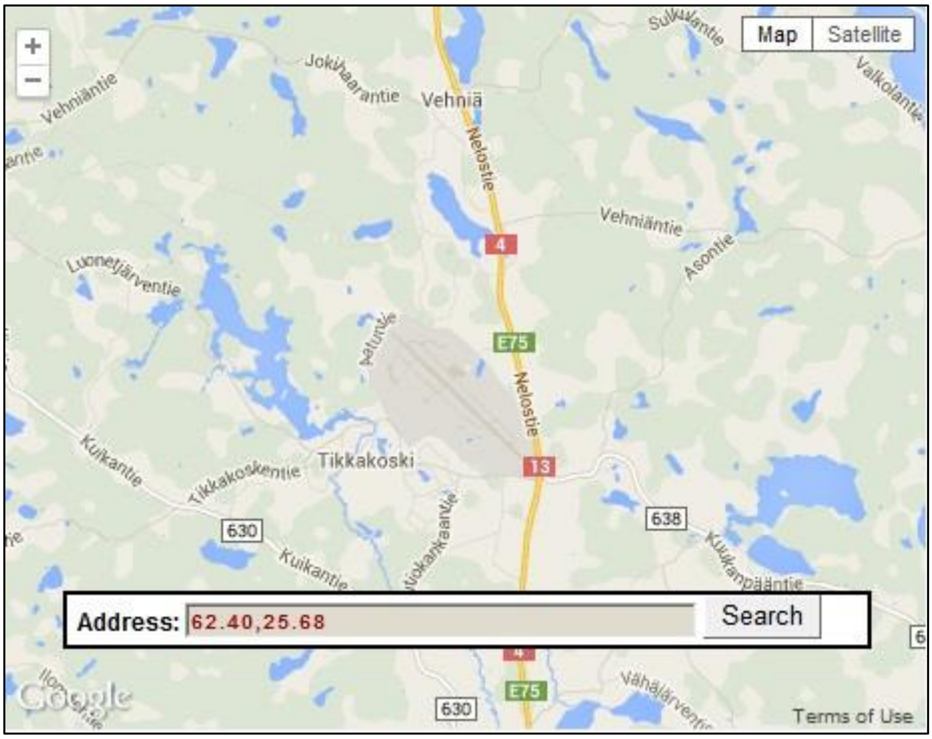
	Decimal		Deg.	min.	
Latitude	62.40	°	62	24	(+ = North, - = South hemisph.)
Longitude	25.68	°	25	41	(+ = East, - = West of Greenwich)

Altitude: 140 M above sea level

Time zone: 2.0 Corresponding to an average difference

Legal Time - Solar Time = 0h 17m

Figure 12: Geographical parameters of the site in PVsyst

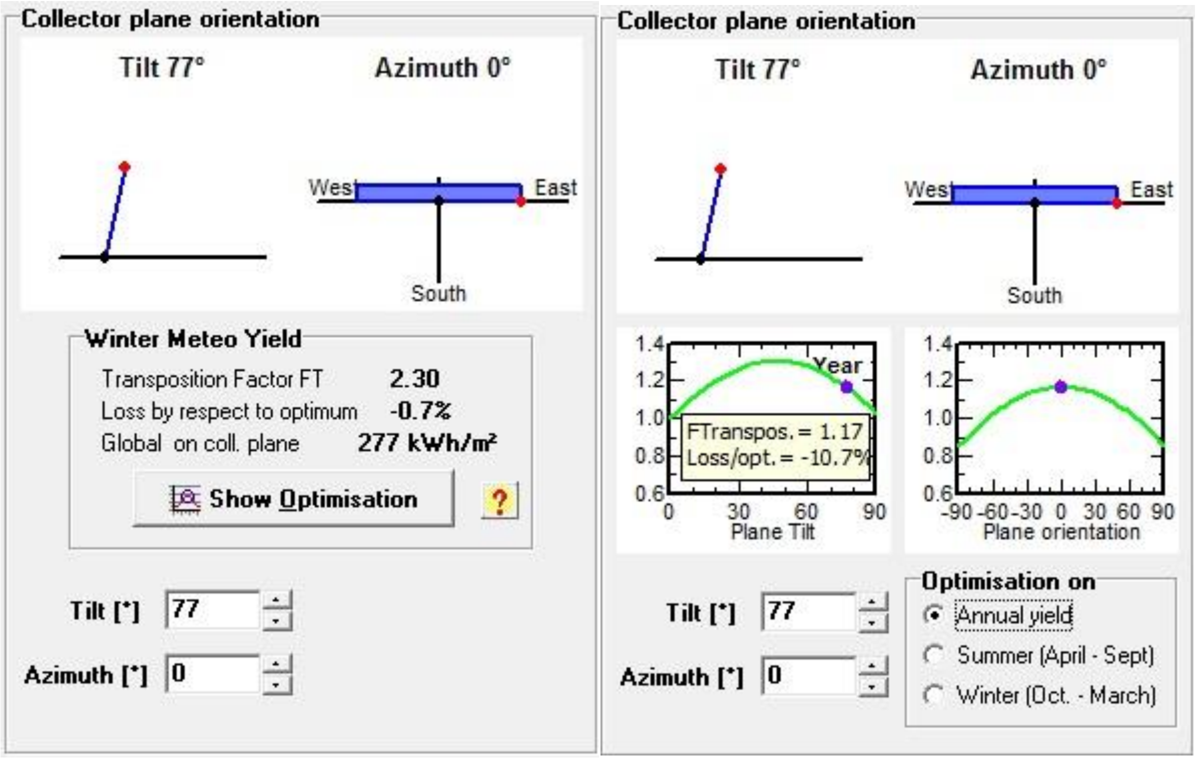


Address: 62.40,25.68

Figure 13: Location of the project provided in PVsyst

We also specified the system parameters tilt and azimuth angles. These parameters can be optimized on the basis of annual yield, summer (April-September) and winter (October-March). In cold climates, where our site is located, we need to minimize the effect of snow accumulation and also to maximize the solar radiation on the surface of the PV array during the winter. So, the tilt angle was considered as latitude of the site plus 15° [65]. Thus, in our site with the latitude of 62,4˚ the tilt would be 62,4˚ plus 15˚ and we adjusted it in the model as 77,4˚. For defining azimuth angle of PV array, it is preferred to face the equator and we assumed that the orientation of the roof of the building is also due south. So, for our location in Northern Hemisphere the azimuth angle was set to zero. [66]

For stand-alone systems, the plane orientation should usually be optimized according to the worst weather conditions, like for winter irradiance. But, due to the fact that in our location the difference between irradiation in winter and summer is very high, optimization according to annual yield was chosen in order to maximize the solar radiation on the PV array. The settings about collector orientation in the model can be seen in Figure 14.



Collector plane orientation

Tilt 77° Azimuth 0°

Winter Meteo Yield
Transposition Factor FT 2.30
Loss by respect to optimum -0.7%
Global on coll. plane 277 kWh/m²

Tilt [°] 77
Azimuth [°] 0

Collector plane orientation

Tilt 77° Azimuth 0°

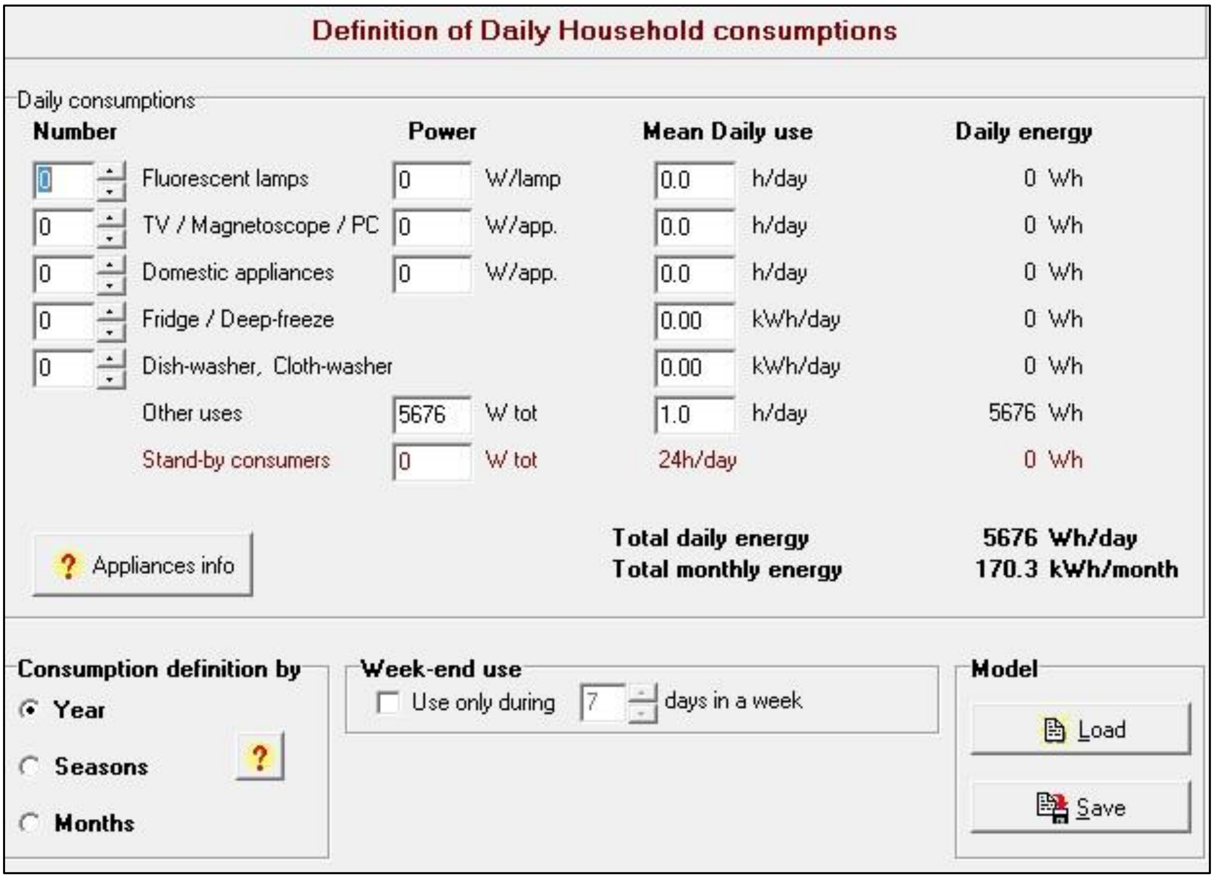
FTranspos. = 1.17
Loss/opt. = -10.7%

Tilt [°] 77
Azimuth [°] 0

Optimisation on
● Annual yield
○ Summer (April - Sept)
○ Winter (Oct. - March)

Figure 14: Optimized orientation of the PV plane in PVsyst

For defining household consumption, we specified that 7 days in a week we want to use the appliances. It was important to consider a 10 % additional consumption for the inverter system, as the software recommends. According to the data we have for the load, the daily consumption is 5,16 kWh/day. Thus, in the data input we entered the value of 5676 watts, which is 5160 plus 10 % due to assumed inverter losses. Total monthly energy consumption was calculated 170,3 kWh/month in the model. These settings in the model can be seen in Figure 15.



Definition of Daily Household consumptions

Daily consumptions

Number		Power		Mean Daily use		Daily energy
0	Fluorescent lamps	0	W/lamp	0.0	h/day	0 Wh
0	TV / Magnetoscope / PC	0	W/app.	0.0	h/day	0 Wh
0	Domestic appliances	0	W/app.	0.0	h/day	0 Wh
0	Fridge / Deep-freeze			0.00	kWh/day	0 Wh
0	Dish-washer, Cloth-washer			0.00	kWh/day	0 Wh
	Other uses	5676	W tot	1.0	h/day	5676 Wh
	Stand-by consumers	0	W tot	24h/day		0 Wh

Total daily energy **5676 Wh/day**
Total monthly energy **170.3 kWh/month**

Consumption definition by
● **Year**
○ **Seasons**
○ **Months**

Week-end use
☐ Use only during 7 days in a week

Figure 15: Total daily and monthly household use of energy in PVsyst

Parameters such as ”Required autonomy”, “Required LOL” and “Battery/system voltage” can be changed according to our needs. For the “Required autonomy” we entered 10 because we do not have any other back-up generator and because of having enough reliability [67].

For assigning the “Battery/system voltage” from the help section of [64], the voltage level of 24 volt is considered suitable for medium-sized systems up to 1000 watts of power or with load current of around 42 A. Thus, according to our load data in section 3.2 which is maximum 730 W, the system voltage of 24 volt was selected for our model.

Also, we entered “Duration” as 20 years; the same as that of wind turbine model. In this preliminary stage the costs are rough estimates and may vary from time to time and country to country. And since we are still modeling our project for Finland, the “Currency” was selected as EURO.

3.4.6 Evaluation of PV system using RETScreen software

After sizing the PVsyst, we decided to get also the results of the PV model from RETScreen software, by means of cost results of the PVsyst. The technology was set to “Photovoltaic”, but other project information and meteorological data were selected exactly similar to that of the wind power system we modeled in section 3.4.2.

For the load characteristics, we made sure that the daily AC electricity consumption value is set to 5,68 kWh/day. Also, the “Intermittent resource-load correlation” was set to negative. It is due to our assumption that the load demand and solar radiation most probably do not occur simultaneously and that the load needs to be supplied from the battery.

For the proposed case power system, we set the information about the Photovoltaic system. About battery system, the changes in component data were “Days of autonomy” of 10, voltage of 24 V and capacity of 2782 Ah as we got before from the battery sizing tool [53] and PVsyst model. Other inputs of the battery as well as inverter remained the same and have the same selection strategy as in the wind turbine model in section 3.4.2. The PVsyst software did not provide us with the separate prices for each component. Thus, we only used the total price from PVsyst results once in the “Photovoltaic” section in RETScreen.

The “Solar tracking mode” was considered as fixed, because the solar collector was assumed to be mounted on roof, which is a fixed structure. The slope was considered the same as the tilt angle of 77°, which was identified in the collector plane orientation section in the PVsyst model. Azimuth angle was set to zero.

The type of Photovoltaic panel was considered as monocrystalline silicon, due to the fact that monocrystalline silicon cell type has the highest efficiency among the options, which is 13 % from the help section of [50]. Also, capacity of needed PV panel was taken from results of PVsyst model, which is 10,187 kW. This value is reflected as a calculated parameter in Figure 21 in section 4.2.

The control method was selected as “Maximum power point tracker”, which is using a device for adjusting the operating voltage of the PV array at a rate that maximizes system output. From [50], the “Miscellaneous losses” was set to 20 %, which is the highest array losses that is predictable due to snow accumulation, cabling losses, etc. The “Incremental initial costs” was set to EUR 46720, which comes from the calculated total investment cost in the economic results of PVsyst software.

3.4.7 PV system design in HOMER

We defined our PV system in HOMER and selected Primary Load, PV, Converter and Battery as equipment to be considered. The load inputs are the same as in the wind turbine model in section 3.4.4. For the size and capital cost of our PV system, from the results of PVsyst software that is reflected in section 4.2, we got an average price of 850 Euro/kW for PV module. Also, from [68] the price for PV installation was given by around 2500 Euro/kW. Therefore, by adding these two values, the average price of a PV system was calculated as 3350 Euro/kW and used as capital cost in HOMER. We assumed that all of the components do not require replacement in their lifetime, so it was not required to consider the replacement costs. For PV panel sizes, we put some different sizes for optimizing the best option. For defining derating factor, we assumed that snow is being removed in the winter time frequently and thus, the default value of 80 % was considered by the software. For ground reflectance, the default value of the software for areas covered with snow is 70 %, which was our choice due to long period of snow in our location. Also, we assumed that we do not use any tracking system for directing the PV panels towards the sun. The other values were the same as we considered in section 3.4.5.

For size and capital cost of the converter, we used “Hidden cost” section of [64]. There is mentioned that the maximum price for “inverter specific cost” is 300 Euro/kW. Thus, we assumed a size of 10 kW with cost of EUR 3000 for the PV system in HOMER. Then for converter sizes, we entered different values in small steps to let the system choose the converter with a suitable size. Lifetime and efficiency values were considered equal to the same values used in the RETScreen model. We did not change the default values of other inputs.

For defining battery inputs in the PV system, we used the values and calculated amounts that we had in section 3.4.6. We used the same new battery that we got from the battery sizing tool [53]. So, we sized a new battery bank with nominal capacity of 2782 Ah and days of autonomy of 10. Thus, with this nominal capacity the tool calculated the number of required batteries for satisfying the days of autonomy of 10, which is around 150. This value then was our maximum point in battery sizes and we started from 0 up to 150. In this way we are able to define the optimum point for the needed number of batteries. Also, a life time of 20 years means that the battery supposed to last for the lifetime of the project. Other values were left unchanged. The schematic diagram of PV model in HOMER can be seen in Figure 16.

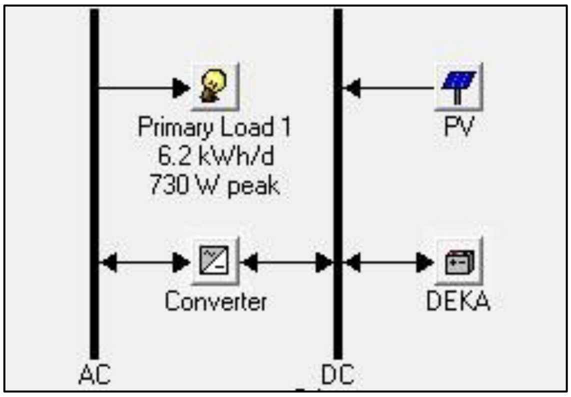


Figure 16: Schematic diagram of the proposed PV system in HOMER

Solar Resource: The solar radiation data, on the monthly average basis, are the same as in RETScreen model. The annual average solar radiation for this area is 2,49 kWh/m^2/d. Also, Eastern Europe was selected as the time zone of our location. Meanwhile, the clearness index for each month was calculated by HOMER and can be seen in Figure 17.

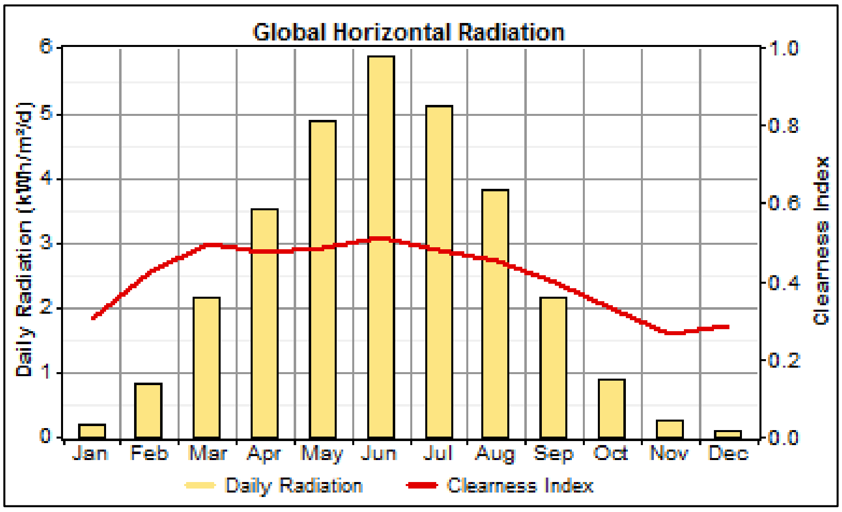


Figure 17: Daily solar radiation profile in HOMER

The system fixed capital cost was entered zero. Also, the project lifetime was considered as 20 years. Other parameters were not important to be changed. Finally in the constraint section, we assumed that the load should be met completely all the times, thus a desirable capacity shortage was set to zero.

Why hybrid model?

After all, we also examined the hybrid model, if we could see a better system design with better technical and financial specifications. Literature review reveals that during the last decade, hybrid renewable energy systems have been increasing their popularity and their potential was proven to be competitive with other technologies for remote places. It is foreseen that in the future they become competitive with grid electricity. [12] In general, wind and solar resources tend to have complementary characteristics in power generation which enables them, to some extent, to compensate each other when one of them is not enough. The hybrid system is often called as a reliable energy source because it uses both wind and solar energy and when they are used together, they provide improved quality of power with more constant energy flow than one stand-alone wind or PV. [69]

Furthermore, there are some disadvantages of single energy sources:

About PV Energy Generation System Alone:

- Having a constant power generation during a year is not possible due to variations of solar radiation over time.
- Batteries are not able to be charged during dark time in the site when we do not have enough solar radiation for power supply.

About Wind Energy Generation System Alone:

- A consistent power generation is not possible for wind power because wind does not have regular nature.
- The average wind velocity is around 3 m/s in our site which is not good for a standalone system.

For those reasons mentioned above, we decided to model hybrid wind-PV-battery system in our study. The only available design tool capable of carrying out the design of hybrid wind-PV-battery system is HOMER.

3.4.8 Hybrid PV and wind turbine design in HOMER

For modeling the hybrid system in HOMER, we chose PV model, then added wind turbine and tried modifying system inputs. For the load inputs we assumed the same inputs as we considered in section 3.4.7.

Then both PV and WINDSPOT wind turbine were added with the same input details that we had in the sections 3.4.7 and 3.4.4. The model automatically considered the same wind resource inputs and solar resource inputs that we had in our previous models. The only change we made in our PV and wind turbine inputs was adding more values of different sizes. In this way we let the model have alternative options for choosing the best combination of different sizes. So, for the PV system we added several values in small steps. The smaller we select the steps, the better the chances we have in order to get the best optimized results. For wind turbine we only could enter the values that are multiples of the 1.5-kW wind turbines. So, we did not have the possibility like we had in the PV system for considering different optional module sizes.

For converter of the hybrid system, we considered again the price of EUR 300 per kW. For converter sizes we also entered inputs up to maximum value of 15 kW in order to let the model consider better choice for the optimal system. The efficiency of the converter was considered 95 %. Other parameters remained unchanged.

For battery inputs we defined a new battery bank by taking advantage of the battery sizing tool [53]. We entered our inputs in the tool, which are our energy daily usage, days of autonomy, battery discharge rate and system voltage, with values similar to those of PV system. Also, we selected the same product as we used before in the wind energy model. Thus, the type MK 8G24UT-DEKA 12V 74 Ah Gel Battery was selected from database of the tool, with cost of EUR 159 for each battery. For days of autonomy, 10 days was considered in the tool, which is the highest value we used before. In this way, we could find out the maximum capacity and numbers of required batteries. So, the calculated number of batteries in the tool, which is around 150, was entered as the maximum limit in the sizes to consider. The other values were sorted in a descending order down to zero with small steps in order to provide the model with different sizes for optimization. The schematic diagram of the hybrid wind-PV system in HOMER is shown in Figure 18.

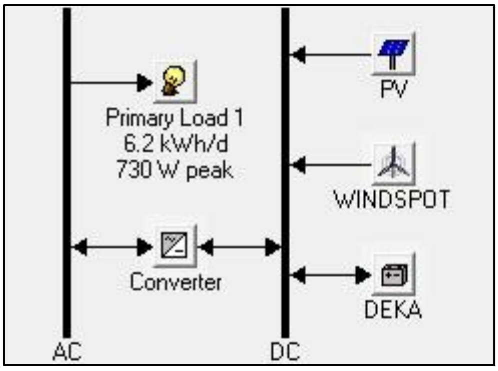


Figure 18: Schematic diagram of the proposed hybrid wind-PV system in HOMER

As we have the same PV system as well as wind turbines in the hybrid model, we considered system fixed capital cost of zero, system fixed O&M cost of EUR 500 per year and the same project lifetime. In the constraint section we only entered zero for maximum annual capacity shortage, as the shortage is not desirable, and other values remained the same.

For sizes to consider in the all sections mentioned before, we made sure that our sizes were enough by examining the results of every modeling. If a result showed with the size near to the final limit in the range of the relevant “sizes to consider”, we would add then more sizes to consider and again calculate. But, finally all sizes in the “Sizes to consider” were in enough range and we did not need to enter any extra sizes.

4 Results and discussion

4.1 RETScreen

4.1.1 Wind turbine

Base case power system

Total electricity cost: The total electricity cost based on the annual electricity use was calculated EUR 325.

Electricity-annual-AC: The calculated amount of annual AC electricity consumption is 2,072 MWh

Proposed case power system

Average battery temperature derating: The calculated value by the model is 10,2 %.

Capacity: The annual rated capacity of the battery bank was calculated by the model as 953 Ah. Also, the battery size in kWh was calculated, on the basis of capacity and voltage, by the model as 46 kWh.

Shape factor: In this case and due to selection of energy curve data based on the Weibull wind speed distribution, the model calculated this parameter and put as 2,2.

Summary

Gross energy production: The total annual energy production from wind energy system, without considering losses, was calculated 1 MWh by the model.

Losses coefficient: This value was calculated as 0,91 by the model.

Specific yield: This value was calculated as 55 kWh/m^2 by the model.

Capacity factor: This was calculated by the model as 3,7 %, which is very low.

Electricity delivered to load: This is an important result and shows how much of the load is covered by the wind energy system. The value was calculated 1 MWh, which can cover 46,9 % of the total energy demand.

Financial results

Initial costs

This section is about the total initial investment for the proposed case power system in order to produce energy, before it starts to make income. This was used as input in the calculation of the simple payback and equity payback.

Power system: This power price was calculated by the model as EUR 41668 and it is the same as “Total initial cost”.

Incentives and grants: As of 1st of January 2007, electricity generated from wind power is eligible for subsidies, which is EUR 0,69 per kilowatt hour [70]. Thus, the model multiplied the amount of annual “Electricity delivered to load” by kWh by 0,69 and calculated the value for “Incentives and grants”. Finally this calculated value was EUR 669,3. The calculated percentage shows that this grant only covers 1,6 % of the total costs, which is very small.

Annual costs and debt payment

This section includes the sum of operation & maintenance costs, fuel costs for the proposed case, debt payments and other costs.

Fuel cost-proposed case: This was calculated zero.

Total annual costs: The calculated value is zero.

Annual savings and income

This section represents the yearly savings or/and income obtained from the implementation of the proposed case power system. As an example, it includes the savings from not paying for the grid electricity.

Fuel cost-base case: This value was considered the same as total electricity cost from the grid, which is EUR 325.

Total annual savings and income: The value was calculated EUR 325 by the model, which is the same as fuel cost in base case.

Financial viability

This section provides financial indicators for the proposed case in order to evaluate economic aspects of the project.

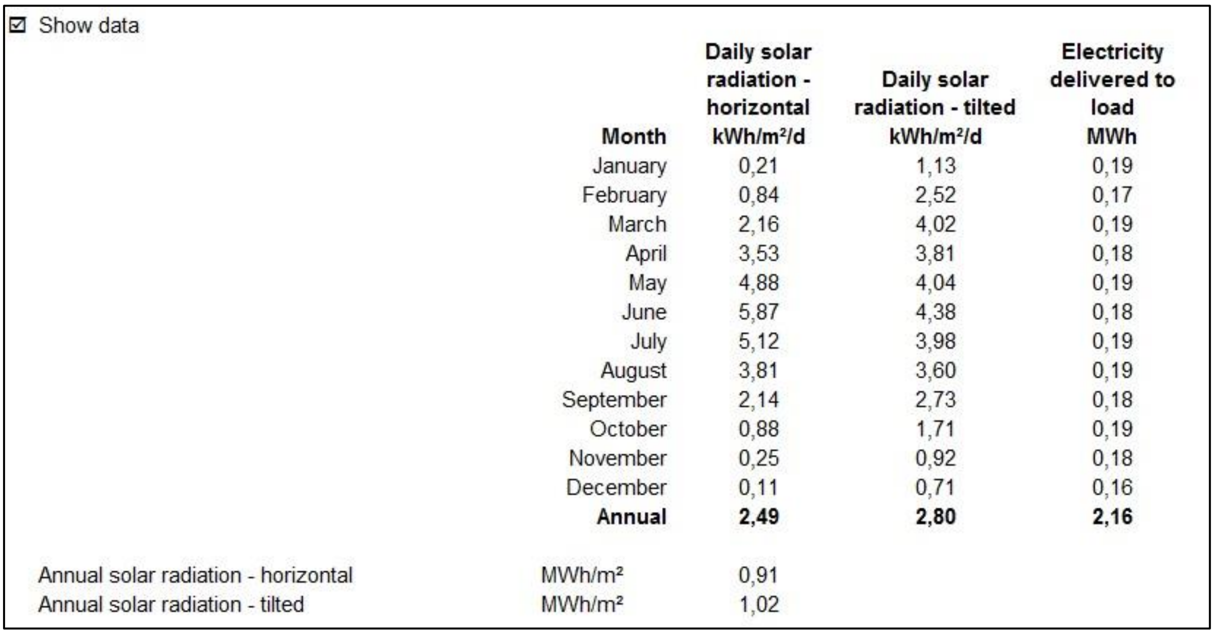
Pre-tax IRR-assets: The calculated value for the wind system is -12,1 %.

Simple payback: It was calculated 126 years which means that 126 years needed for the investor to refund their money from the electricity bill saved.

Equity payback: In our study, it shows that the number of years calculated in the simple payback is higher than the project life.

4.1.2 PV system

Figure 19 shows electricity delivered to load in MWh. We can see that the annual tilted solar radiation (1,02 MWh/m^2) is higher than the annual horizontal solar radiation (0,91 MWh/m^2), showing the effect of optimizing the tilted angle. In the same figure we can see that the amounts of electricity delivered to load for different months are quite similar to each other. As an example, the value for June, which is the sunniest month, is even slightly lower than the value for January, one of the darkest months. This is doubtful, since the electricity production of a PV system in the darker months must be lower than in the other months.

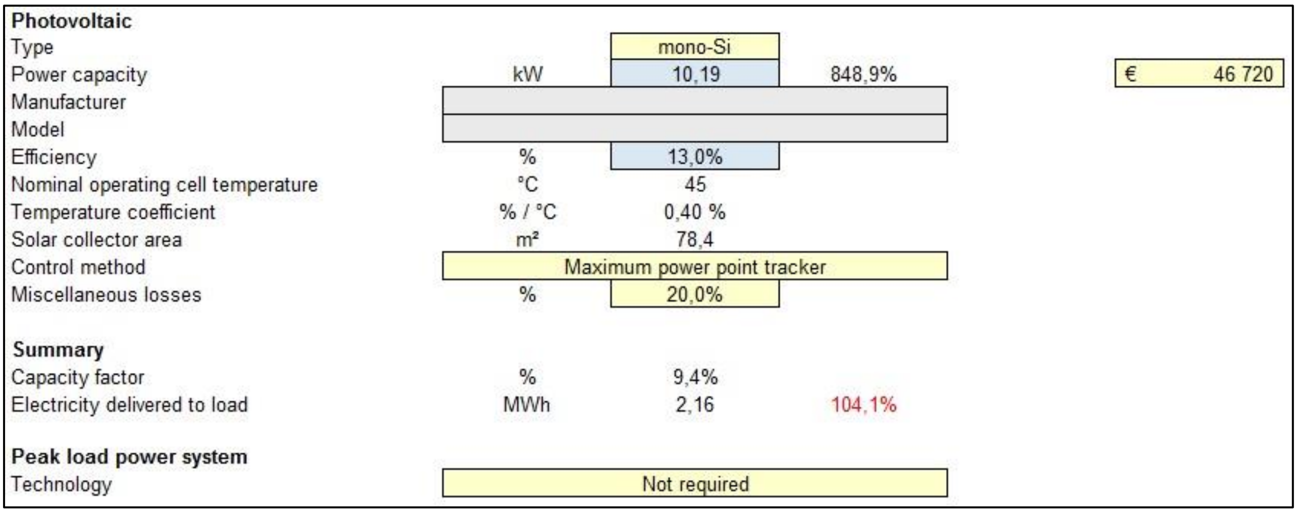


☑ Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity delivered to load MWh
January	0,21	1,13	0,19
February	0,84	2,52	0,17
March	2,16	4,02	0,19
April	3,53	3,81	0,18
May	4,88	4,04	0,19
June	5,87	4,38	0,18
July	5,12	3,98	0,19
August	3,81	3,60	0,19
September	2,14	2,73	0,18
October	0,88	1,71	0,19
November	0,25	0,92	0,18
December	0,11	0,71	0,16
Annual	**2,49**	**2,80**	**2,16**

Annual solar radiation - horizontal	MWh/m²	0,91
Annual solar radiation - tilted	MWh/m²	1,02

Figure 19: The results of tilted solar radiation and solar electricity generation in RETScreen



Photovoltaic				
Type		mono-Si		
Power capacity	kW	10,19	848,9%	€ 46 720
Manufacturer				
Model				
Efficiency	%	13,0%		
Nominal operating cell temperature	°C	45		
Temperature coefficient	% / °C	0,40 %		
Solar collector area	m²	78,4		
Control method		Maximum power point tracker		
Miscellaneous losses	%	20,0%		
Summary				
Capacity factor	%	9,4%		
Electricity delivered to load	MWh	2,16	104,1%	
Peak load power system				
Technology		Not required		

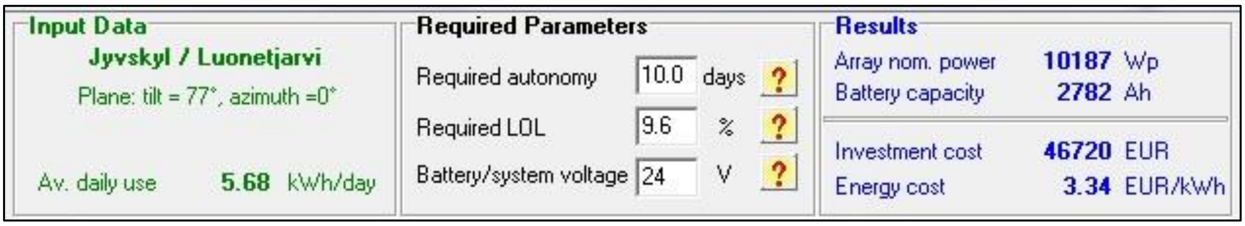
Figure 20: Settings and calculated values of photovoltaic system in RETScreen

One result from the Photovoltaic section that can be seen in Figure 20 is the percentage in red color. This percentage, 104,1 %, implies that the annual electricity production is 4,1 % higher than the annual electricity consumption. Solar collector area is the calculated area needed for installation of the PV array. The calculated value is 78,4 m^2, which could be suitable area on the roofs. But, generally the availability of space depends on the number of households using the roof space for such purpose.

Another value calculated here is the “Capacity factor” which has the same description as defined in the wind turbine model, but the typical values for a photovoltaic system is from 5 to 20 %. This value was calculated 9,4 %.

4.2 PVsyst

In “Sizing and Results” in Figure 21 we can see some results, including array nominal power, battery capacity, investment cost and energy cost, on the basis of the input data and default values of the software. The value of the “Required LOL” was calculated by the model and remained 9,6 %. Other main results on monthly basis are provided in Table 2.



Input Data

Jyvskyl / Luonetjarvi

Plane: tilt = 77°, azimuth =0°

Av. daily use 5.68 kWh/day

Required Parameters

Required autonomy 10.0 days

Required LOL 9.6 %

Battery/system voltage 24 V

Results

Array nom. power 10187 Wp

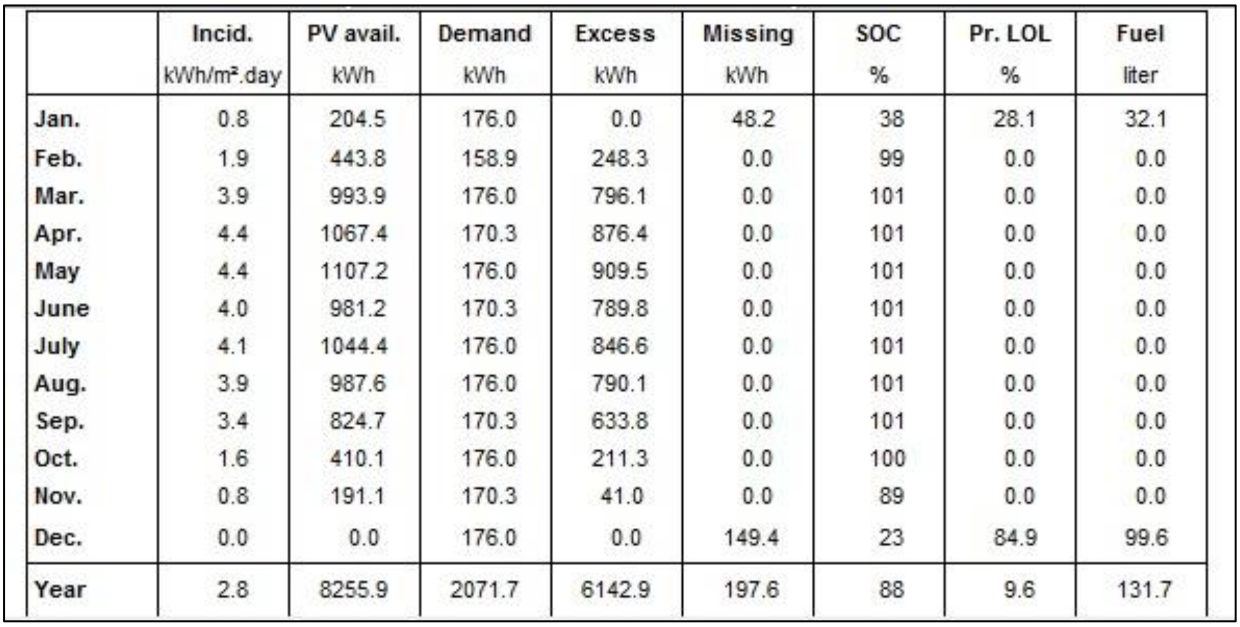
Battery capacity 2782 Ah

Investment cost 46720 EUR

Energy cost 3.34 EUR/kWh

Figure 21: General system sizing results in PVsyst

Table 2: Main results of the PV system in PVsyst



	Incid. kWh/m².day	PV avail. kWh	Demand kWh	Excess kWh	Missing kWh	SOC %	Pr. LOL %	Fuel liter
Jan.	0.8	204.5	176.0	0.0	48.2	38	28.1	32.1
Feb.	1.9	443.8	158.9	248.3	0.0	99	0.0	0.0
Mar.	3.9	993.9	176.0	796.1	0.0	101	0.0	0.0
Apr.	4.4	1067.4	170.3	876.4	0.0	101	0.0	0.0
May	4.4	1107.2	176.0	909.5	0.0	101	0.0	0.0
June	4.0	981.2	170.3	789.8	0.0	101	0.0	0.0
July	4.1	1044.4	176.0	846.6	0.0	101	0.0	0.0
Aug.	3.9	987.6	176.0	790.1	0.0	101	0.0	0.0
Sep.	3.4	824.7	170.3	633.8	0.0	101	0.0	0.0
Oct.	1.6	410.1	176.0	211.3	0.0	100	0.0	0.0
Nov.	0.8	191.1	170.3	41.0	0.0	89	0.0	0.0
Dec.	0.0	0.0	176.0	0.0	149.4	23	84.9	99.6
Year	2.8	8255.9	2071.7	6142.9	197.6	88	9.6	131.7

From Table 2 we can see that the total yearly power production is 8255,9 kWh. Thus, with the panel size of 10,187 kW, the PV system generates 8255,9 kWh electricity. By means of a simple calculation we see that each kW of the system capacity is able to generate 810,43 kWh/year. The last results are seen in “Costs” section in Figure 22, where we see economic gross evaluation like, calculated values of total investment, total yearly cost and energy cost per kWh.

Economic gross evaluation

Module cost	8659	EUR
Battery cost	10016	EUR
Regulator cost	3299	EUR
Transport/Fitting	24745	EUR
Total investment	**46720**	**EUR**
Annuities	3749	EUR/yr
Maintenance costs	2504	EUR/yr
Total Yearly cost	**6253**	**EUR/yr**
Energy cost	**3.34**	**EUR/kWh**

These values should only be considered as an order of magnitude. More precise evaluations will be available with detailed simulation.

Currency

Europa - EURO EUR

Loan

Duration 20 years

Rate 5.0 %

Ann. factor : 0.080

Figure 22: Screen capture of the economic results and costs in PVsyst

From Figure 22 it can be seen that the total module cost is EUR 8659. Therefore, considering the size of 10,187 kW of PV panel, the price of PV module was calculated at 850 Euro/kW. This value was used in section 3.4.7 in order to calculate the average price of PV system in HOMER.

4.3 Simulation tool for the final analysis

4.3.1 Comparison between RETScreen and HOMER wind turbine models

As shown in Figure 23, the amounts of monthly electricity production calculated by HOMER and RETScreen have huge differences. In this case, the number and type of turbines considered in RETScreen and HOMER are the same and we can compare them easily.

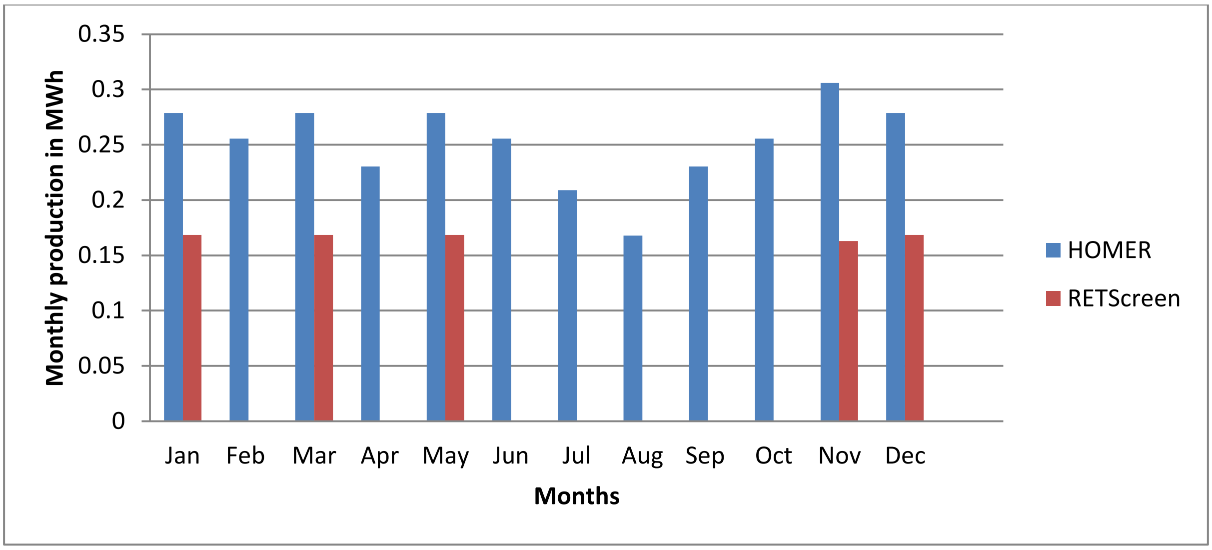


Figure 23: Comparison between the electricity generation in HOMER and RETScreen for wind model

As we can see in Figure 23, the main results of monthly electricity production are very different and even in seven months (February, April, June, July, August, September and October), when the average wind speeds were below 3 m/s, we did not have energy production in RETScreen wind energy model. This happened in spite of having similar inputs in RETScreen and HOMER. Furthermore, due to low amount of calculated power production in RETScreen, the need for battery storage in RETScreen increased and the model sized battery bank bigger with much higher price than that of HOMER (EUR 8268 in RETScreen compared to EUR 1908 in HOMER).

4.3.2 Comparison between RETScreen, PVsyst and HOMER photovoltaic models

As it is illustrated in Figure 24, the monthly average energy production levels in RETScreen and PVsyst are very different. The amount of electricity generation in PVsyst model is changing from month to month, while the monthly values in RETScreen model remain almost steady.

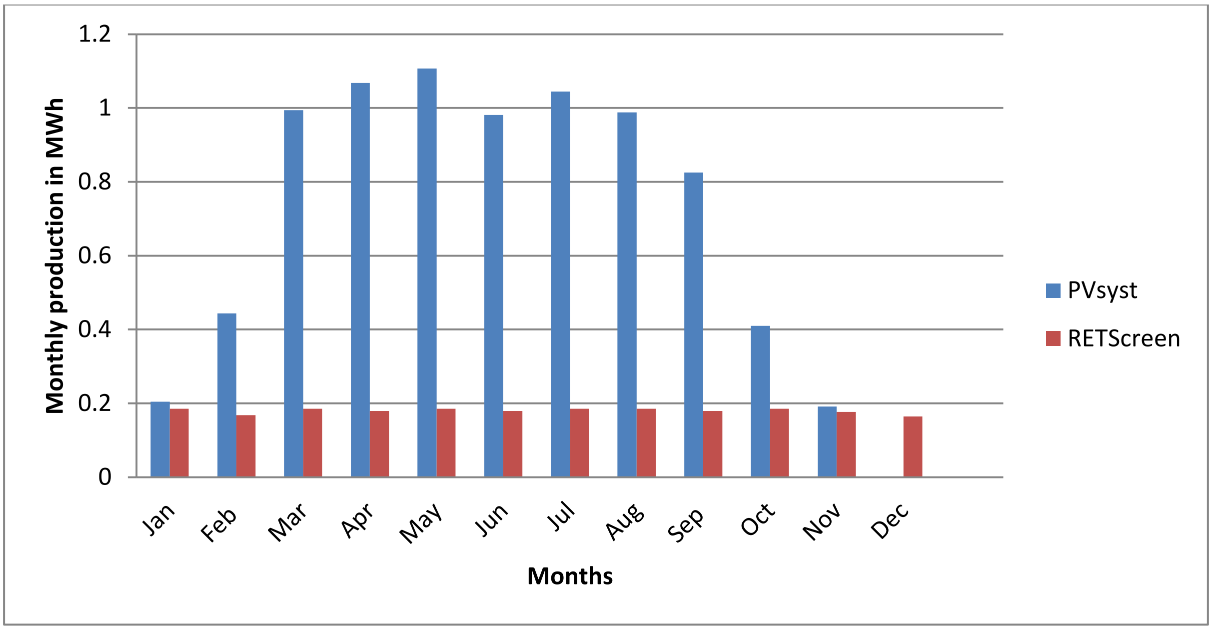


Figure 24: Comparison between the photovoltaic electricity generation calculated with PVsyst and RETScreen

This means that, even with the same inputs in both RETScreen and PVsyst, the results have huge differences and one of them, because of insufficiency of software in simulating small off-grid projects, must be excluded from our analysis. The results of HOMER and RETScreen for PV model are contrasted in Figure 25.

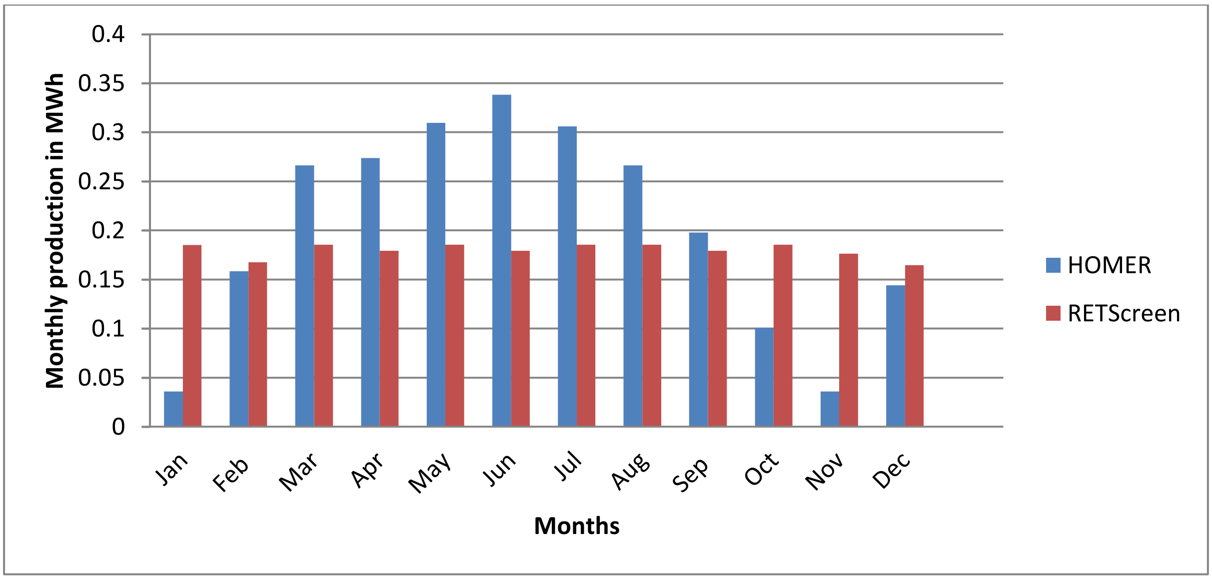


Figure 25: Comparison between the photovoltaic electricity generation calculated with HOMER and RETScreen

Comparing the monthly power production in HOMER and RETScreen from Figure 25, we can see that the monthly values are closer to each other than those of PVsyst and RETScreen. However, this is misleading, because the sizes of PV panels that were sized in RETScreen and HOMER are not equal. Actually, with a smaller size of PV module in HOMER, which is 2.5 kW, compared to 10,187 kW in RETScreen model, we have slightly more electricity production than the PV model in RETScreen. This means that the estimations of electricity generation per kW of PV module in HOMER and RETScreen have huge disagreement. The disagreement between the results of HOMER and RETScreen does not seem to be accredited and valid. These differences are not normal and contradict the claim of similarity between the results of RETScreen and HOMER claimed in [71]. Afterwards, we calculated yearly power generation from PVsyst and HOMER. The results are 810,43 kWh/year for 1 kW of PV module in PVsyst model as well as 948 kWh/year for 1 kW of PV module in HOMER. We can see, in contrast to the case of RETScreen and HOMER, that the estimation of electricity generation per kW of PV module in HOMER and PVsyst are similar to each other. However, PVsyst sized a bigger PV panel.

Finally, it seems that the results of RETScreen are far different from results of HOMER and PVsyst. Due to unexpected results in RETScreen, we made some enquiries with RETScreen International, Customer Support, and our results were described. The reply admitted that the problem is because of doing off-grid project and for some unknown reason the energy generated is not accounted the way we expected.

4.3.3 Summary

Our reasons for using results from HOMER instead of RETScreen in our data analysis are: First, HOMER provides us with the possibility to first consider our energy needs and then, considering a variety of options for sizes of each component, the best options obtained from simulations. This is useful and applicable method in our study. In contrast, studying only a proposed power system in RETScreen may not satisfy electricity demand and the results can be completely inappropriate and misleading. This method may lead us to disregard system sizes with better technical and financial feasibility. Since our goal is to investigate potentiality of our site for wind and solar electricity production, it is better to take advantage of approximate sizing by the model in advance to get a rough approximation of system sizes and their prices. So, it is preferable to rely on the sizing method in HOMER software, which seems more accredited than the method used for RETScreen. Second, unexpected results of RETScreen as well as unsatisfying replies from RETScreen International, Customer Support, admit that problems exist for simulating small-sized off-grid models with RETScreen. Therefore, we decided to only consider results from HOMER for our purposes.

4.4 HOMER

HOMER mixes and matches system configurations and accomplishes the energy balance calculations for each system configuration. It decides whether a configuration is feasible in order to meet the electricity demand under the specified conditions in the site. HOMER also estimates the installing and operating expenses of the system over lifetime of the project. HOMER displays all the possible system configurations, sorted by increasing net present costs (NPC). The optimized result of each technology with the least cost was selected and then the results were compared to each other on the basis of their energy production and net present costs. A system is feasible in HOMER when its energy production matches with the load. Table 3 displays configurations of optimized systems.

Table 3: System components of optimized systems

System types	PV (kW)	WINDSPOT	Battery DEKA	Converter (kW)
Wind system	-	2	12	1
PV system	2.5	-	70	1
Hybrid system	1	1	25	1

It is seen that all optimized systems have the same 1-kW converter. Among them, the PV system has the maximum use of batteries, with 70 numbers, while the wind system has the lowest number of batteries, with 12.

4.4.1 Energy production by technology

The optimization results of all three system designs are provided in Figures 26, 27 and 28, respectively.

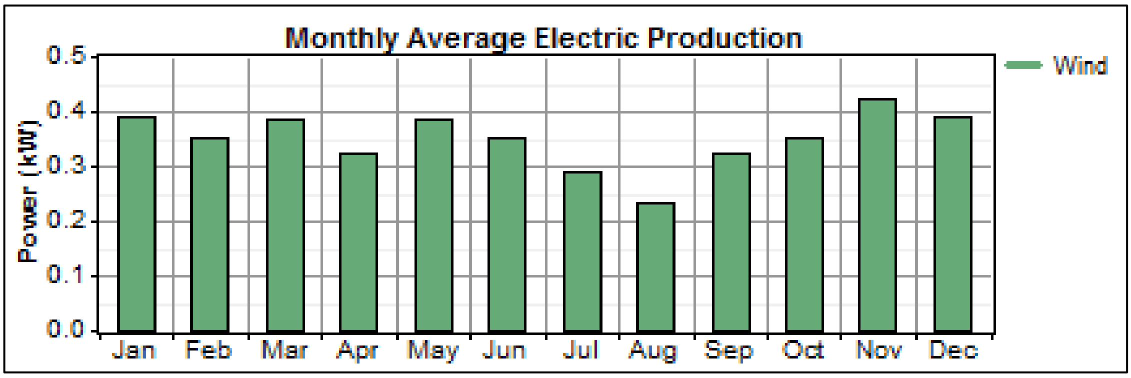


Figure 26: Monthly average electricity production from the optimized wind-battery system

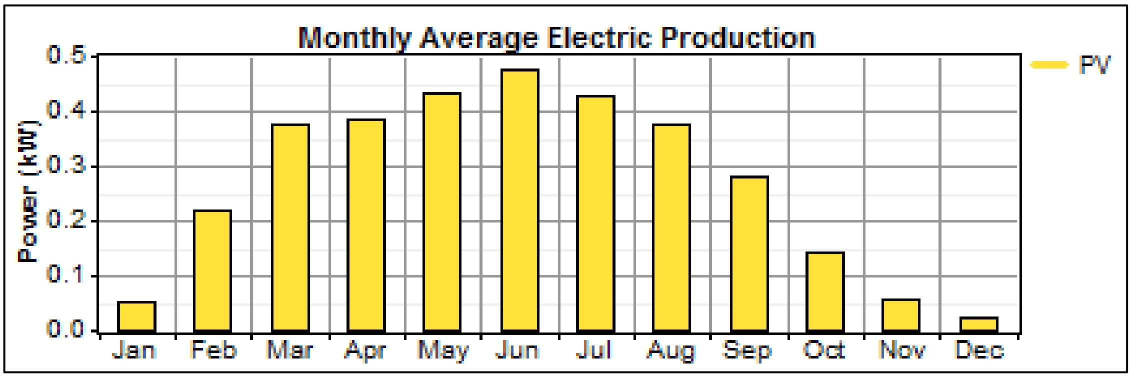


Figure 27: Monthly average electricity production from the optimized PV-battery system

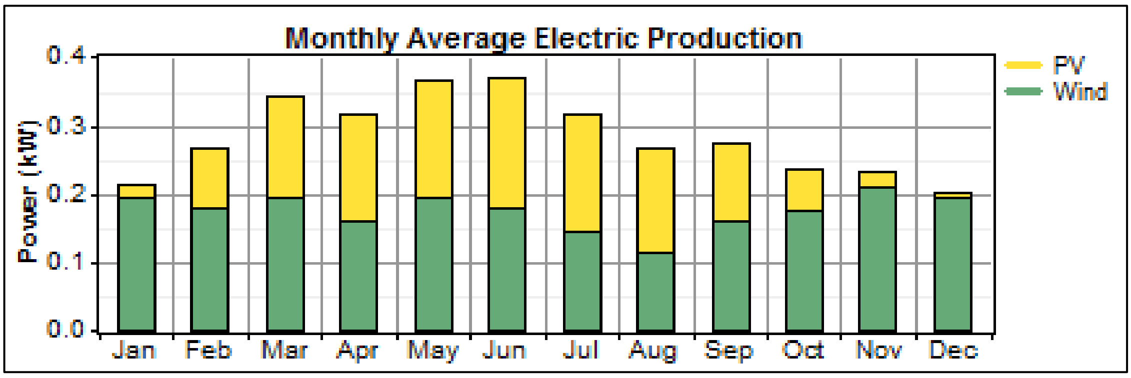


Figure 28: Monthly average electricity production from the optimized Hybrid wind-PV-battery system

Figure 27 depicts that highest solar electricity generation levels occur between March and August, while wind power system in Figure 26 demonstrates a decreasing power production trend from May to August. Figure 28 shows the contribution to the total electricity generated by individual system components in the hybrid model. In that figure it can be observed that wind energy has a dominant contribution in the hybrid energy model in January, February, March, September, October, November and December and totally contributed 62 % of the total energy production. On the other hand, the PV array contributed relatively lower value of 38 % of the total energy production with a capacity factor of 11,7 %.

Table 4: The comparison of annual electricity production among optimized different systems

System types	Annual electricity production (kWh/yr)	Excess electricity (kWh/yr)
Wind system	3069	443 (14,4 %)
PV system	2370	330 (13,9 %)
Hybrid system	2482	156 (6,28 %)

The shares of wind energy and solar energy delivery in the hybrid system are 1534 kWh and 948 kWh, respectively. The minimum amount of excess electricity occurs in the hybrid system.

4.4.2 Cost of system designs

Net present cost of energy (NPC) means the present value of the cost of investment and operation of a model design over its lifetime. It is used as the main financial indicator for comparing energy systems. The cost of energy (COE) is the average cost per capital of useful electricity produced by the proposed system and the values are included in the results. [72] Figures 29, 30 and 31 show the summary of component costs for different system designs. In these figures AIR and DEKA symbolize wind turbine and battery, respectively.

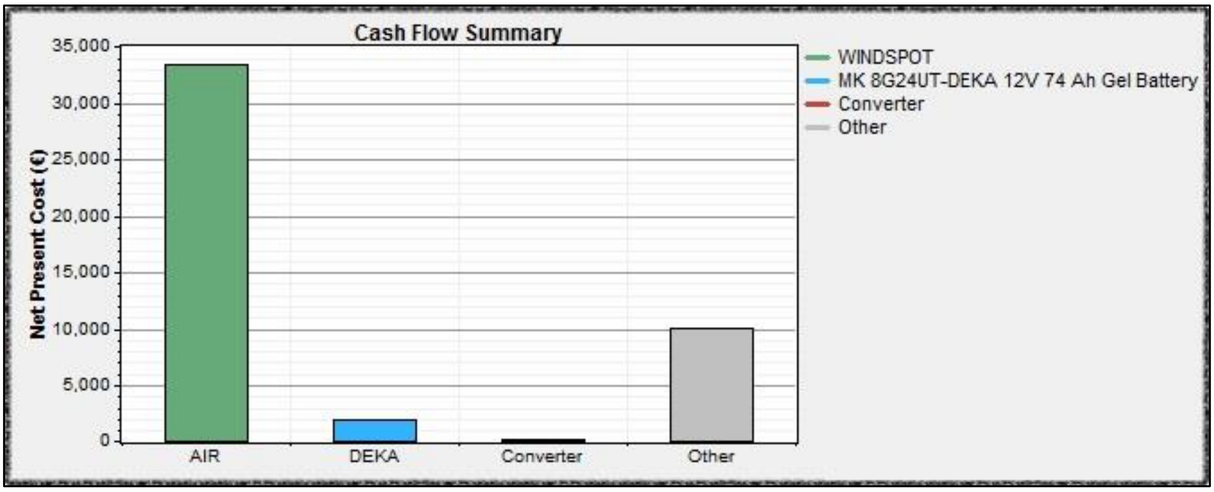


Figure 29: Cost summary of the wind energy system

As shown in Figure 29 the most expensive part of the wind energy system are the wind turbines, including two 1.5-kW WINDSPOT machines, while “Other” which represents O&M costs forms less than a quarter of the total cost. However, battery and converter costs are insignificant, with EUR 1908 and EUR 300 respectively, when comparing against wind turbine cost. It is because of using small number of batteries in the wind energy system.

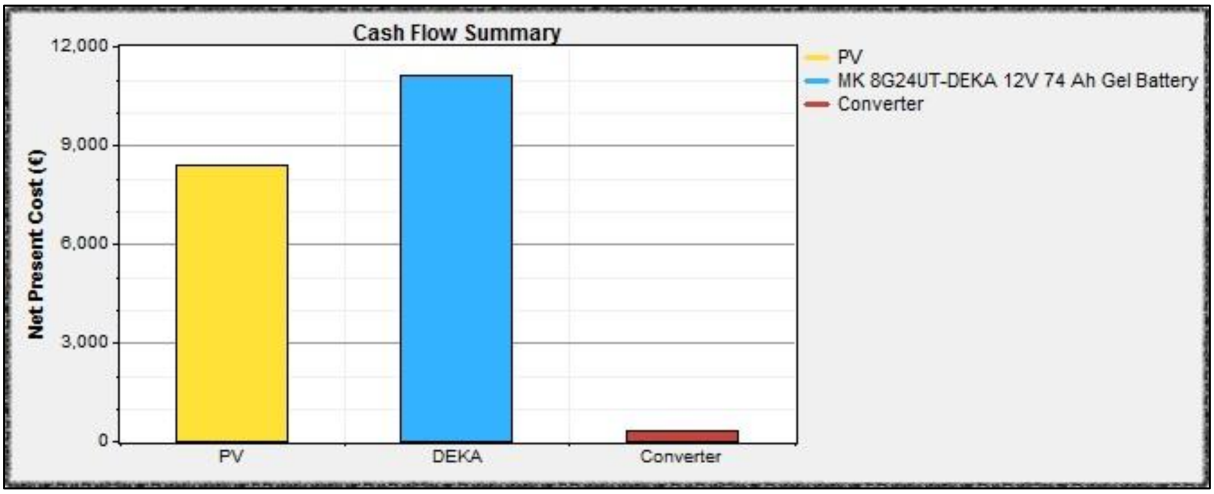


Figure 30: Cost summary of the PV energy system

Figure 30 reveals that the least expensive part of the PV system is the converter and battery storage is the most expensive part. In contrast to the wind power system, batteries in the PV system attribute to a higher cost and account for more than half of the total cost. The reason for this higher price is high number of batteries, 70, for satisfying the need for electricity consumption during lack of sunlight or night times. Moreover, the PV panel, as the main part of our solar power system, is only a quarter of the price of main part of the wind power system, the wind turbines.

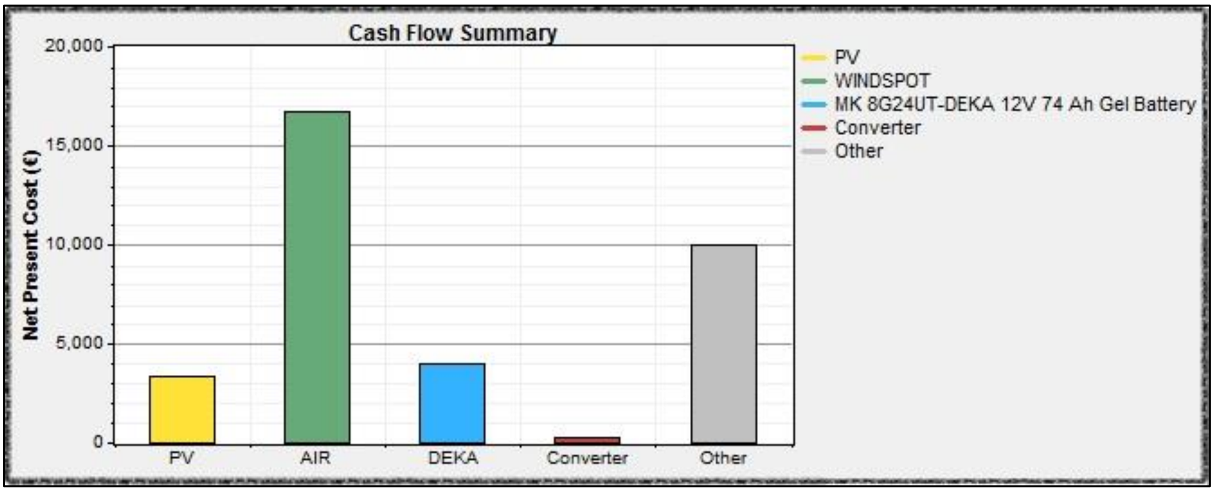


Figure 31: Cost summary of the hybrid wind-PV energy system

As seen in Figure 31, the most money in the hybrid wind-PV system goes to wind turbine, with EUR 16700. This means that utilization of wind turbine is a determining factor in the total cost of the hybrid system. In this system using smaller number of batteries, 64 % less than that of the PV system, resulted in EUR 7155 less investment in the battery system. Furthermore, smaller size of PV panel in the hybrid system caused EUR 5025, or 60 %, decrease in the cost of PV panel.

The cost comparison of optimized hybrid wind-PV system with wind system and PV system is given in Table 5. Excess electricity is defined by HOMER as a surplus of electric energy produced that cannot be used by the system for serving a load or even charging batteries. As indicated in the table, the optimized PV-battery system reduces the NPC about 56 % and 42 % compared with wind-battery and hybrid wind-PV-battery, respectively. Also, it is seen that the converter is the least expensive part of each system.

Table 5: The cost comparison among optimized different systems

System types	Initial cost (EUR)	NPC (EUR)	COE (Euro/kWh)
Wind system	35,308	45,408	1.007
PV system	19,805	19,805	0.439
Hybrid system	24,325	34,325	0.761

By evaluating the results of the economic analysis it is clear that the PV system is a better economic solution than the others since the cost is reduced due to not using the expensive wind turbine. By observing the cost analysis of the PV system, it can be seen that battery bank represents over 56 % of the overall systems' cost.

From the optimized systems it is clear that the PV-battery configuration has the lowest Cost of Energy, with 0.439 Euro/kWh. The second most cost effective system is the hybrid wind-PV-battery system, with 0.761 Euro/kWh. Finally, the wind-battery system is the most expensive option, costing 78 % more than the PV system. This is due to the lack of good wind resource in Jyväskylä region as well as the higher cost per kW of wind turbines compared to the PV panels. According to Table 5, the most economically feasible configuration is made up of 2.5-kW PV panels and a 1-kW converter with 70 batteries. The results revealed that the cost of energy depends closely on the availability of the renewable energy resources. However, the most reliable configuration which diversifies the energy sources and uses combination of wind and solar energy is the hybrid system.

5 Conclusion

Two energy models for stand-alone wind, PV and hybrid wind-PV systems were considered in this pre-feasibility analysis. The wind and PV systems were the main power generation devices with the battery operating as a storage device for surplus power. A hypothetical site in Jyväskylä, Finland was considered as the location of the study. Three modeling tools of RETScreen, HOMER and PVsyst were initially considered and their results were compared. None of the wind and photovoltaic models in RETScreen provided valid and reliable results and, thus, using RETScreen seemed to be inappropriate in this study. HOMER was used as our main simulating program in identifying feasible configurations and their applicability.

The simulation results revealed that the cost of energy for the proposed technologies is higher than for the conventional electricity from the grid, comparing 0.439, 0.761 and 1.007 Euro/kWh with 0.157 Euro/kWh from the grid. However, the demand for cleaner power and improvements in alternative energy technologies bear good potential for prevalent use of such systems. At present, a PV-battery system is recognized as the most cost-effective solution for stand-alone use. Cost of energy for such a small system in Jyväskylä (delivering ~ 6.18 kW h/d, peak ~ 0.730 kW), was estimated around 0.439 Euro/kWh.

It was found that wind resources in Jyväskylä do not have good potentiality for electricity generation compared to solar energy, especially during summer, and utilization of wind energy alone might not be cost effective. One of the key factors for having a high cost of wind power in this project is the lack of high wind speed in the Jyväskylä region. That factor resulted in utilization of only small fraction of the wind speed range around 3 m/s, raised the cost of energy for wind energy system and limited our choices for selecting a suitable wind turbine. The availability of wind turbine in the market which is compatible with low wind speeds and thus suitable for this area with weak wind resource is essential for the maximum exploitation of wind power. Having better technology for low-wind speed wind turbines in the future can reduce the cost of electricity production in such wind power projects. Significant advancement in small low-wind speed wind turbine technology is required before a wind–battery system becomes economically feasible option.

Hybrid energy systems are usually more reliable and less costly than the systems that use a single source of energy. However, in our study we have seen that the cost of PV system is less than the cost of our hybrid wind-PV system. That was partly due to manufacturing design for having bigger rotor blade as a solution to energy exploitation, and partly because of low possibility of power production from wind speeds in the site. These factors forced the model to consider higher rated capacity of wind turbines.

Solar power and wind power alone showed fluctuation in power production in different months. But, when using hybrid system to combine these two technologies, it balanced out the variations and made a more even flow of energy. If there is a scarcity of sufficient wind speed for power generation then PV panel can provide the power or vice versa.

The number of batteries in the systems is preferred to be as small as possible primarily due to negative environmental impacts of the batteries and also due to the needed space as well as periodic cost. However, they may need to be replaced sooner than their lifetime. The combined exploitation of the available wind and solar potential reduced considerably the energy storage capacity requirements of stand-alone PV system, from 70 to 25 numbers of batteries.

In general, hybrid wind-PV energy system enhances utilization of renewable sources and sustainability of such systems. Also, due to their ability to diversify the energy sources, hybrid systems are generally considered to be a better option for stand-alone applications. Reliability of the hybrid energy system is much higher than the other systems, and our preference to use it in our present study is little affected by higher price. This is because of the fact that the increase of the price in hybrid system does not seem to be significant.

Finally, although the hybrid wind-PV-battery system has a higher COE than the PV-battery system, it utilizes the available solar and wind resources in an optimal way and with the lowest amount of excess energy. The stand-alone PV-battery system is recognized as an economically feasible option, whereas the hybrid wind-PV-battery system gives a technically better solution. Because of reasons mentioned above, it is recommended to utilize the hybrid wind-PV battery system for electricity generation in Jyväskylä region based on solar and wind resources rather than wind power or photovoltaic system alone.

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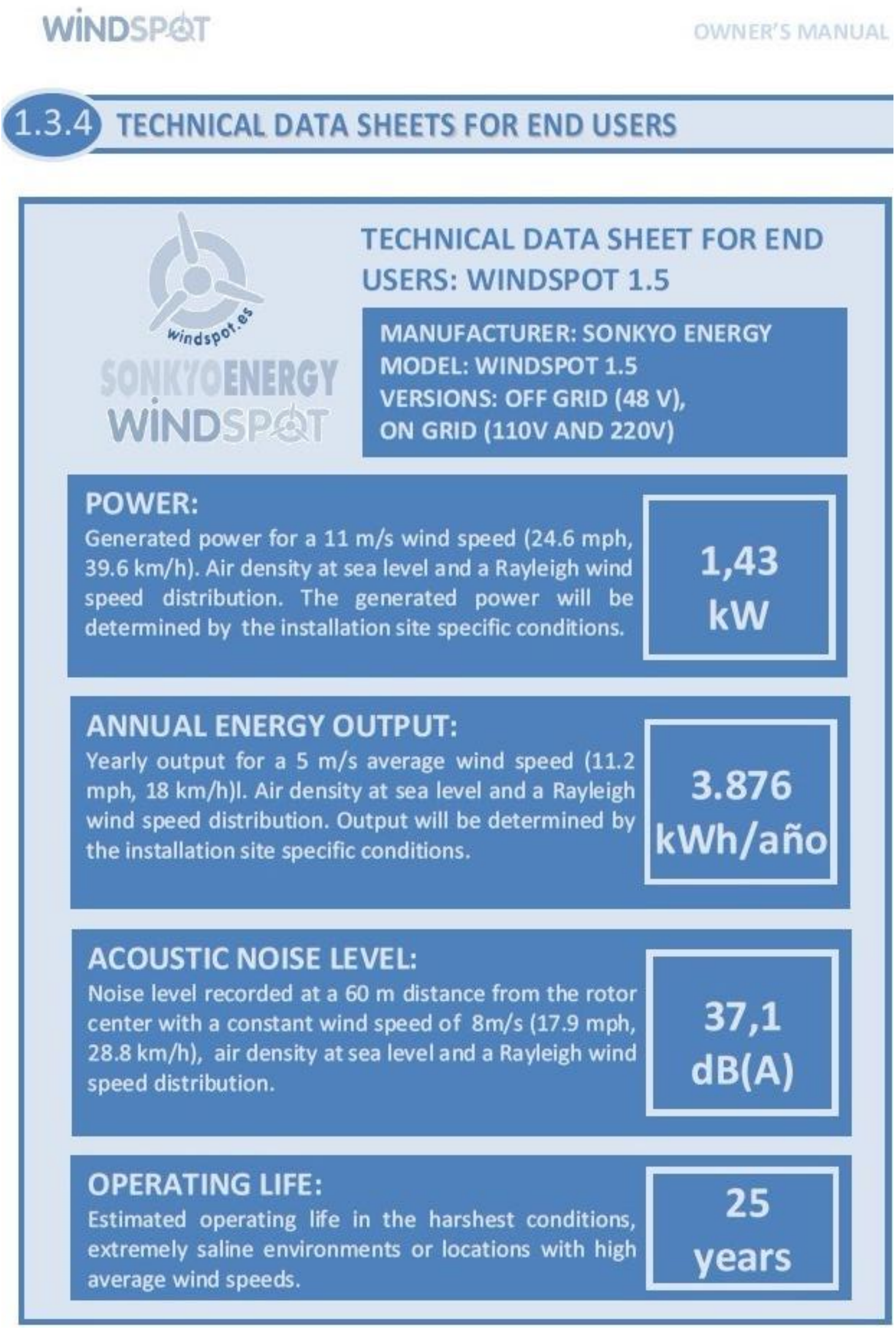
Appendix

A Wind turbine data sheet and certifications



WINDSPOT OWNER'S MANUAL

1.3.4 TECHNICAL DATA SHEETS FOR END USERS

TECHNICAL DATA SHEET FOR END USERS: WINDSPOT 1.5

MANUFACTURER: SONKYO ENERGY
MODEL: WINDSPOT 1.5
VERSIONS: OFF GRID (48 V),
ON GRID (110V AND 220V)

POWER:
Generated power for a 11 m/s wind speed (24.6 mph, 39.6 km/h). Air density at sea level and a Rayleigh wind speed distribution. The generated power will be determined by the installation site specific conditions.

1,43 kW

ANNUAL ENERGY OUTPUT:
Yearly output for a 5 m/s average wind speed (11.2 mph, 18 km/h)l. Air density at sea level and a Rayleigh wind speed distribution. Output will be determined by the installation site specific conditions.

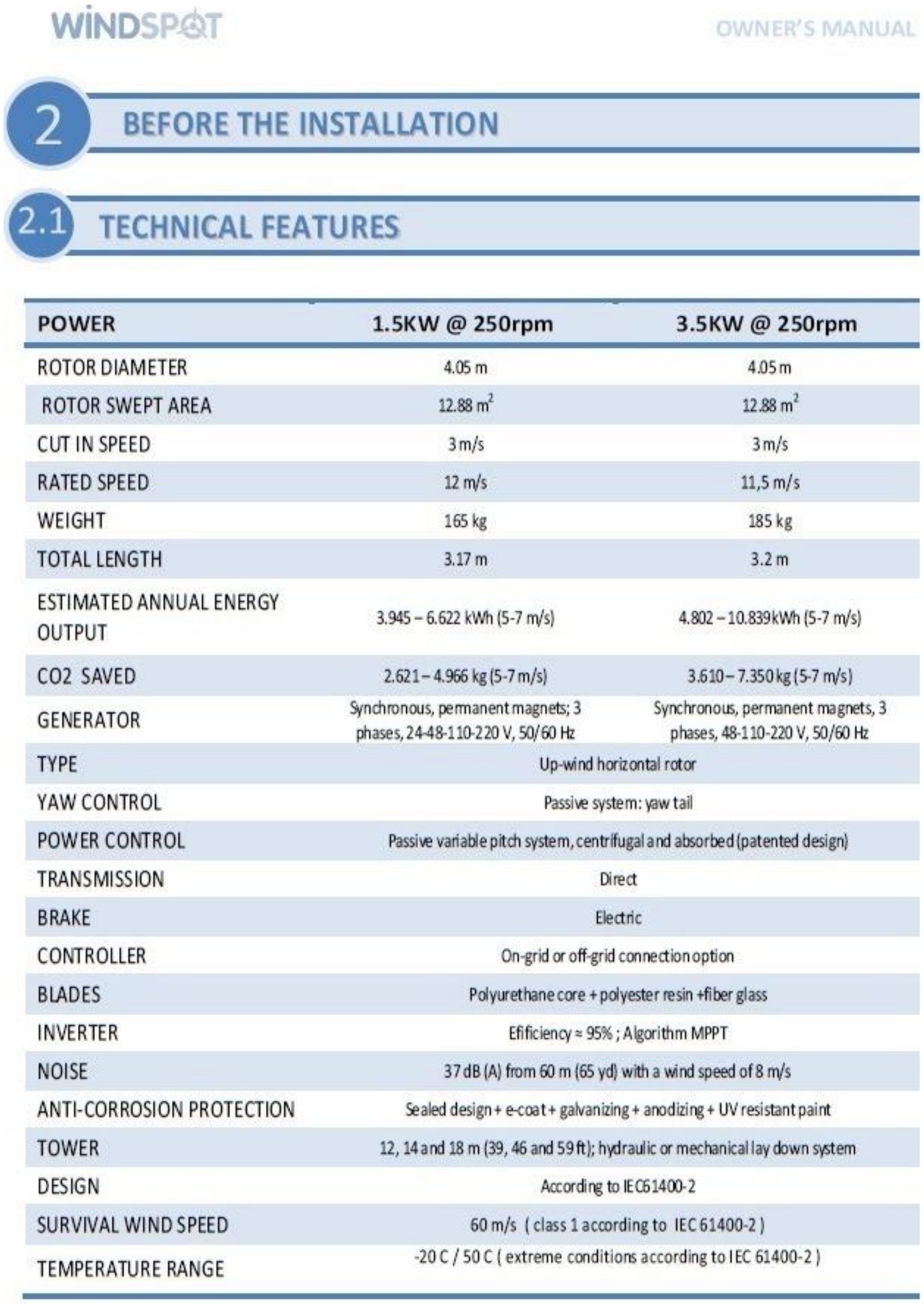
3.876 kWh/año

ACOUSTIC NOISE LEVEL:
Noise level recorded at a 60 m distance from the rotor center with a constant wind speed of 8m/s (17.9 mph, 28.8 km/h), air density at sea level and a Rayleigh wind speed distribution.

37,1 dB(A)

OPERATING LIFE:
Estimated operating life in the harshest conditions, extremely saline environments or locations with high average wind speeds.

25 years



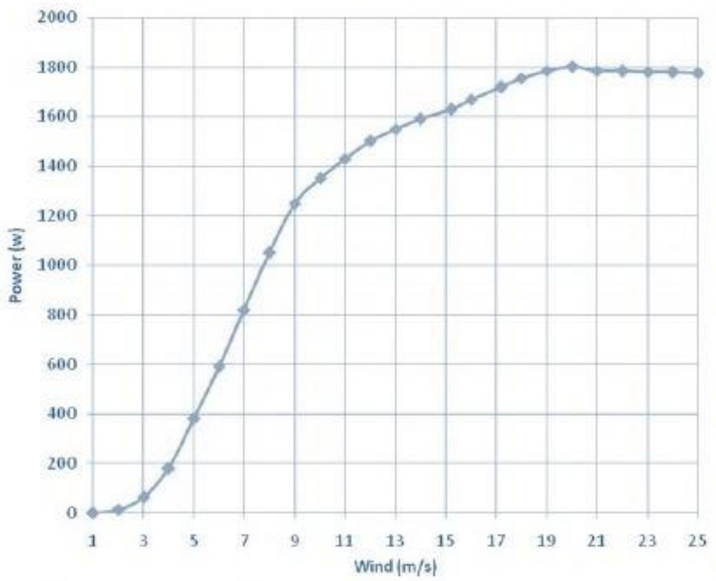
2 BEFORE THE INSTALLATION

2.1 TECHNICAL FEATURES

POWER	1.5KW @ 250rpm	3.5KW @ 250rpm
ROTOR DIAMETER	4.05 m	4.05 m
ROTOR SWEPT AREA	12.88 m^2	12.88 m^2
CUT IN SPEED	3 m/s	3 m/s
RATED SPEED	12 m/s	11,5 m/s
WEIGHT	165 kg	185 kg
TOTAL LENGTH	3.17 m	3.2 m
ESTIMATED ANNUAL ENERGY OUTPUT	3.945 – 6.622 kWh (5-7 m/s)	4.802 – 10.839kWh (5-7 m/s)
CO2 SAVED	2.621 – 4.966 kg (5-7 m/s)	3.610 – 7.350 kg (5-7 m/s)
GENERATOR	Synchronous, permanent magnets; 3 phases, 24-48-110-220 V, 50/60 Hz	Synchronous, permanent magnets, 3 phases, 48-110-220 V, 50/60 Hz
TYPE	Up-wind horizontal rotor	
YAW CONTROL	Passive system: yaw tail	
POWER CONTROL	Passive variable pitch system, centrifugal and absorbed (patented design)	
TRANSMISSION	Direct	
BRAKE	Electric	
CONTROLLER	On-grid or off-grid connection option	
BLADES	Polyurethane core + polyester resin +fiber glass	
INVERTER	Efficiency ≈ 95% ; Algorithm MPPT	
NOISE	37 dB (A) from 60 m (65 yd) with a wind speed of 8 m/s	
ANTI-CORROSION PROTECTION	Sealed design + e-coat + galvanizing + anodizing + UV resistant paint	
TOWER	12, 14 and 18 m (39, 46 and 59 ft); hydraulic or mechanical lay down system	
DESIGN	According to IEC61400-2	
SURVIVAL WIND SPEED	60 m/s (class 1 according to IEC 61400-2)	
TEMPERATURE RANGE	-20 C / 50 C (extreme conditions according to IEC 61400-2)	

WINDSPOT 1.5 power curve (According IEC 61400-12-1 standards)

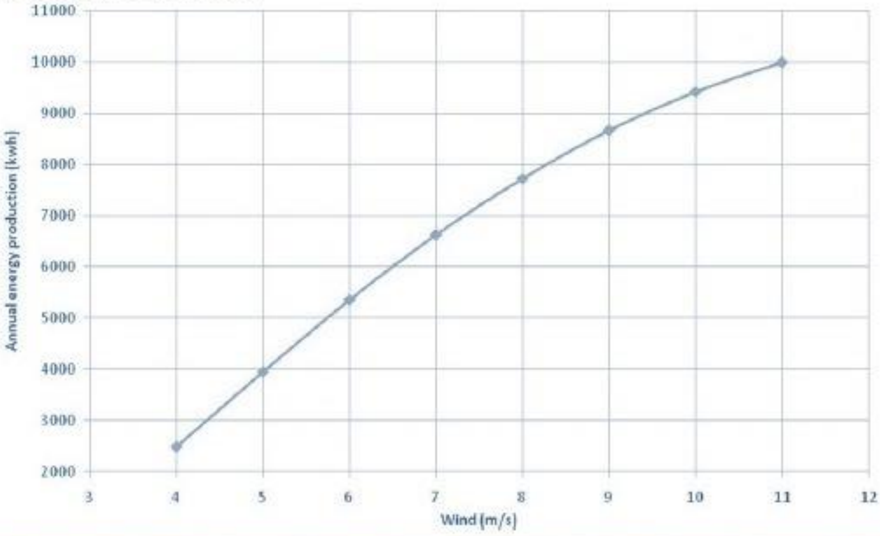
Power output at 11 m/s (24.6mph) at standard sea-level conditions is 1472 watts.



WIND SPEED (m/s)	POWER (W)
0	0
1	0
2	15
3	65
4	180
5	380
6	590
7	820
8	1050
9	1250
10	1350
11	1430
12	1500
13	1550
14	1590
15	1630
16	1670
17	1720
18	1755
19	1785
20	1800
21	1785
22	1783
23	1781
24	1779
25	1777

WINDSPOT 1.5 Annual Energy Production

Estimated annual energy production assuming annual an average wind speed of 5m/s (11.2mph) is 3.945 kwh.



Annual Energy Production (Kwh) 4 m/s Average wind speed	Annual Energy Production (Kwh) 5 m/s Average wind speed	Annual Energy Production (Kwh) 6 m/s Average wind speed	Annual Energy Production (Kwh) 7 m/s Average wind speed	Annual Energy Production (Kwh) 8 m/s Average wind speed	Annual Energy Production (Kwh) 9 m/s Average wind speed	Annual Energy Production (Kwh) 10 m/s Average wind speed	Annual Energy Production (Kwh) 11 m/s de Average wind speed
2410	3876	5295	6575	7696	8663	9489	10180

1.4 CERTIFICATIONS, TESTS AND STANDARDS

WINDSPOT has been designed according to the technical standards in force for the design of small wind turbines. Tests for data collection have been undertaken by outstanding international institutions.

Power curve and annual power output for WINDSPOT 3.5: obtained at the CIEMAT (Spanish Research Center for Energy, Environment and Technology) according to **IEC 61400-12-1** standard.

Power curve and annual power output for WINDSPOT 1.5: obtained at the **SEPEN** (Site Experimental Pour le Petit Eolien in Narbonne, France) according to **IEC 61400-12-1** standard.

WINDSPOT 3.5 acoustic noise level: Measurements done by the **Certification Institution GRONTMIJ CARL BRO** (Denmark) according to **IEC 61400-11** standard.

WINDSPOT 1.5 AND 3.5: **CE** Declaration of Conformity.

WINSPOT 1.5 AND 3.5 DESIGN: according to **IEC 61400-2 standard** (Class I), **IEC 61400-1** and **UNE-EN ISO 12100-1**.

SONKYO ENERGY: Quality Management System **ISO 9001**.

CE
2006/42/CE
2006/95/CE
200 /108/CE

LLOYD'S REGISTER QUALITY ASSURANCE
ISO9001
UKAS
MANAGEMENT SYSTEMS
001

B Definition of main inputs

RETScreen

Main input data in the “Start” sheet

Project location: This is the location of the project and is only used for reference purpose.

Project type: In this tab we have ten options in the drop-down list to select the type of the project. We only needed to use “Power” tab in our study which means “electricity generation” in the RETScreen software. Thus, we are able to compare a single clean energy technology with the other ones.

Technology: This is for selection of the technology used for the proposed case power system, which are wind turbine and photovoltaic in our study.

Grid type: By means of this cell we are able to choose the grid application type for the project. We have three options here; “Central-grid”, “Isolated-grid” and “Off-grid”.

Analysis type: Here we select the type of the analysis from “Method 1” and “Method 2”. Method 1 is used with less detailed information and is good for preliminary analysis, while method 2 needs more details from the project in order to perform a more precise analysis.

Units: Here we can select “Metric units”, which is standard unit for using in international wind energy industry, or “Imperial units” for expression of input and output data.

Climate data location: Here we select the location of the proposed case project and paste the data to the worksheet. Also, we can enter the climate data manually in the yellow and blue cells, appeared while we check the “Show data” box.

Input data in the “Energy Model” sheet

Fuel rate: It is the per-unit price of the fuel in the base case power system.

Annual O&M cost: It is the annual operation and maintenance cost for the base case power system.

Electricity rate-base case: It shows calculated value of the average electricity price for the base case power system, without including the installation cost of the base case power system.

Total electricity cost: It is calculated based on the annual electricity use and the electricity price for the base case power system and then added to the annual O&M cost.

Electricity-daily-DC: It is the weekly averaged daily amount of DC electricity consumption of the loads in kWh and in Method 1 we entered the related value for both the base case and the proposed case equally.

Electricity-daily-AC: It is the weekly averaged daily amount of AC electricity consumption of the loads in kWh. In Method 1 we enter the related value for both the base case and the proposed case equally.

Intermittent resource-load correlation: This tab has three options and defines the correlation between the load and intermittency of the resource. “Negative” is selected in cases where the load and availability of resource occurs in different time, thus the model assumes that the load demand is **always** covered by the battery. For example, a light for using only at night, when the PV system cannot work, falls into this group. In most cases this parameter will be considered as “Negative”. “Zero” is considered for steady loads which are constant during the day and partly covered by battery and partly directly by the power system. “Positive” is related to loads which are turned on only when we have enough electricity generated directly from the resource. In this category, the model assumes that the load is met straightly from the proposed case power system without using the battery.

Percent of month used: by checking this box we can define the variation of the load on a monthly basis from the daily average values. For a cottage which is only open in summer time, the values for winter would be entered 0 %, which means there is no load consumption during winter time.

Electricity-annual-DC: The model calculates the weekly averaged annual amount of DC electricity consumption by the load for both base case and proposed case power systems. If we choose “Method 1”, we should enter the incremental initial costs (negative value) for implementing the proposed case end-use energy efficiency measures.

Electricity-annual-AC: The model calculates the weekly averaged annual amount of AC electricity consumption by the load for both base case and proposed case power systems. If we choose “Method 1”, we should enter the incremental initial costs (negative value) for implementing the proposed case end-use energy efficiency measures and that is the sum of the design, purchase, construction and installation costs of all the elements of the power system less any "credits" for not having to design, or install base case equipment and materials.

Peak load-annual: It is the maximum power used at the peak load in one day. This value helps defining the capacity of the proposed case power system. This value would be the sum of AC and DC loads, if all the DC and AC loads happen at the same time.

Inverter

This component is an integral part of the wind power system that makes the power from battery charging system usable for our utilities, when there is no wind available. Wind inverter may enable the system to have optimum power characteristic curve even in low wind speeds.

Capacity: Here we should enter the nominal output of the inverter in kW (AC).

Efficiency: It is in percentage and shows that how effectively the inverter transforms the DC output to AC.

Miscellaneous losses: It is percentage of the losses through power conditioning, DC-DC converters, transformers etc. and in most cases this is considered zero.

Incremental initial costs: This is purchasing price of the inverter.

Battery

The battery storage enables the system to store surplus of energy produced at a favorable time and then use it when there is not enough production. The battery bank is charged when the total sum of wind and solar energy system is higher than the energy consumption. In this section the data about the battery system are identified.

Days of autonomy: It is the number of days that the batteries are able to supply the load from fully charged state, without using any extra generator. Therefore, the bigger the number of days of autonomy, the bigger the capacity of the battery must be. Depending on the design of the system and parameters like resources and system characteristics, values range up to 15 days. It is important not to overestimate this parameter, because values higher than what the system needs will impose extra costs to the system, due to bigger size of batteries.

Voltage: The nominal voltage of the batteries is used for the conversion of the battery capacity from Ah to Wh. Normal values given by the manufacturers are 6, 12, 18, 24, 36, 48, or 72 volts.

Maximum depth of discharge: It means the percentage of the capacity of the battery that can be discharged continuously without negative effect on the battery life. It depends on the size and type of the battery and can be requested from manufacturers.

Charge controller efficiency: It is the average efficiency of the charge controller. This value is higher in larger systems

Temperature control method: Here we have three options to select; “Ambient”, “Constant” and “Minimum”. This is the reduction of the battery capacity according to the temperature in its location. “Ambient” is used when the battery is located in non-insulated area and experiences fluctuations in outdoor temperature. We select “Constant” when the battery is kept at a constant temperature. “Minimum” is selected if the battery follows the fluctuations of the outdoor temperature. If batteries can be subject to freezing, “Constant” or “Minimum” is selected.

Average battery temperature derating: in this tab the model calculates the loss of rated capacity of the battery due to effect of the temperature variations. This value depends on the operating temperature of the battery and for lower temperatures that is larger than what it is in higher temperatures. If the battery is kept at constant temperature, the average temperature derating of the battery would be zero.

Capacity: Here we enter the annual rated capacity of the battery bank in Ah. The model then calculates its suggested nominal capacity of the battery bank in Ah and puts the calculated value in the right side of the input cell. This capacity provides the system with the specified days of autonomy and the model may reduce the capacity needed for a level of autonomy. The values can range from less than 100 Ah up to several thousand Ah for systems with high availability.

The capacity of the battery in kWh is considered in the "**Battery**" cell. This cell calculates the battery size in kWh on the basis of the "Capacity" and "Voltage". This helps us specify the cost of the battery system needed for the off-grid power system, which also depends on the type of the selected battery. Moreover, in more detailed studies maintenance cost (annual cost) as well as battery replacement cost (periodic cost) should be considered.

Resource data

Measured at: In this section we enter the height in which the average wind speeds are measured. This height is usually between 3 to 100 meters, with most common use of 10 meters. It correlates the wind speeds by considering the influence of the terrain roughness and obstacles.

Wind shear exponent: It is a dimensionless parameter used for showing the rate at which the wind speed changes with the elevation. Low values correspond to a smooth terrain, like snow, sea and sand, while high values used for terrains with obstacles, like urban areas. The value is typically changing from 0,10 to 0,40. It varies with the type of vegetation in the area, the topography and other parameters. The uncertainty in the wind shear exponent can be ± 0,10.

Wind turbine data

Power capacity per turbine: We enter here the rated power of the chosen wind turbine from the manufacturer data sheet. The rated capacity could be achieved at the rated wind speed.

Power capacity: This item shows the total output power of the wind project and is defined by multiplying the power capacity per turbine and number of turbines.

Hub height: Is the height of the rotor of the horizontal axis wind turbine, where the average wind speed is calculated. The higher the hub height, the better the energy output of the system.

Swept area per turbine: It is the area that rotor traverse during one complete rotation which is perpendicular to the wind direction. Swept area is directly related to the energy output of a wind turbine.

Energy curve data: In this part we select the energy curve data source to assign how the energy curve data is calculated for the selected wind turbine. It has two options; “Standard” and “custom” and by selecting each curve the calculation for the energy curve data differs. Using the “Standard” tab the model calculates the energy curve data based on the Rayleigh wind speed distribution and that is used if the wind speed distribution of the site is unknown. However, with “Custom” tab the model calculates the energy curve data based on a Weibull wind speed distribution.

Shape factor: It is a characteristic of the Weibull distribution and typically ranges from 1 to 3. A low shape factor implies a broad distribution of wind speed around the average wind speed, while a higher shape factor stands for a relatively limited distribution of wind speed about the average wind speed.

Wind speed m/s: In the show data section, this is a range of wind speeds that when used for calculating power curve data of a wind turbine, instantaneous wind speed is considered. When it is used for calculating energy curve data, it corresponds to the annual average values of the wind speed distribution.

Power curve data kW: It is the instantaneous power produced by the wind turbine in each wind speed at hub height at 15°C and 101,3 kPa. This shows the performance characteristic of the wind turbine which is provided by the manufacturer.

Energy curve data MWh: It is the amount of annual energy produced by the selected wind turbine over a range of annual average wind speeds.

Array losses: It is the effect of the interaction of the wind turbines with each other via their wakes, so the ones behind would hit by less wind speed and consequently produce less power. Losses are affected by the turbine orientation, spacing, characteristics of site etc. It is used in calculation of the “losses coefficient”. The value of array losses ranges from zero to 20 % of “Gross energy production”.

Airfoil losses: It accounts for accumulation of the ice, soils and bugs on the blades that affect the aerodynamic performance of the blades. The normal values are from 1 to 10 % of “Gross energy production” and that is used in the calculation of “Losses coefficient”.

Miscellaneous losses: It is losses of energy production due to start and stops, parasitic power requirement, cut-out and high wind speeds and losses through transmission lines. It helps with calculation of the losses coefficient and varies between 2 and 6 % of “Gross energy production”.

Availability: It is the average availability of the turbines in a wind farm considering the losses due to planned maintenance, power outage and failures of wind turbines. This value usually ranges from 93 to 98 % of gross energy production, but in harsh climates this value is lower.

Summary

Gross energy production: This represents the total annual energy produced from wind energy system without considering losses and that is presented in MWh.

Losses coefficient: This integrates all loss factors, from array losses to miscellaneous losses.

Specific yield: The model calculates the energy produced by a wind turbine by swept area of the rotor. In applicable projects it ranges from 150 to 1,500 kWh/m^2 where higher amounts stand for larger turbines in a site with good wind conditions.

Capacity factor: It is the ratio of the average power produced by the wind turbine system in a yearly basis to its rated power capacity. Typical good values range from 20 to 40 %. Low values stand for older technology or medium wind resource, whereas higher values show better technology or good wind regimes.

Electricity delivered to load: It shows the calculated electrical energy delivered to the load and also the percentage of the load demand that is covered by the proposed case power system. This is an important result and shows how much of the load is covered by the wind energy system.

Peak load power system

This section is description of the system which is designed to cover the rest of the load demand that is not met by the proposed case power system.

Emission Analysis

It is an optional part of clean energy project analysis that gives the estimated reduction of greenhouse gas emission by taking advantage of proposed case power system. Since our study only deals with financial and technical parts, we did not include this analysis in our study.

Financial Analysis

In this section, we enter input data, like inflation rate, debt ratio, etc. and then financial viability of the project can be evaluated by calculating output items such as IRR, simple payback, etc. This helps decision-makers to see effect of different financial parameters on the financial feasibility of the project.

Financial parameters

Inflation rate: It is the annual average rate of inflation during the life of the clean energy project.

Project life: It is the duration of proposed project, up to 50 years, over which the financial analysis is performed. It could be related to life cycle of the equipment, the term of the debt or the power purchase agreement.

Debt ratio: It is the ratio of debt over the sum of the debt and implies the created financial leverage for a project. Thus, the higher the debt ratio, the higher the financial leverage. This is used for calculating the equity investment which is required to finance the project. The values typically range from 0 to 90 %.

Initial costs

This section is about the total initial investment for the proposed case power system in order to produce energy, before it starts to make income. This is used as input in the calculation of the simple payback and equity payback.

Power system: This tab calculates the initial costs for the design, procurement and installation costs of the power system.

Other: It is used for putting other incremental costs other than the initial cost groups to bring a project to an operational stage.

Total initial costs: It is the sum of “Initial costs” and “Other” costs

Incentives and grants: This includes any subsidy or grant that is paid for the initial costs of the project and assumed as revenue during the construction year.

Annual costs and debt payment

This section includes the sum of operation & maintenance costs, fuel costs for the proposed case, debt payments and other costs.

O&M (savings) costs: It shows the incremental operation and maintenance costs or savings, in negative value of all sections of the power system.

Fuel cost-proposed case: It displays the total fuel cost for the proposed case and for each year the value is escalated at the inflation rate.

Total annual costs: This tab calculates the final value for the “Annual costs and debt payments”.

Annual savings and income

This section represents the yearly savings or/and income obtained from the implementation of the proposed case power system. As an example, it includes the savings from not paying for the grid electricity.

Fuel cost-base case: It is the total fuel cost for the base case and for each year the value is escalated at the inflation rate.

Total annual savings and income: This tab calculates the final value for the “Annual savings and income” which is the same as fuel cost in base case.

Financial viability

This section provides several financial indicators for the proposed case in order to evaluate economic aspects of the project.

Pre-tax IRR-assets: It also called return on asset (ROA) and is the true interest yield brought by the project finance over the life of a project before income tax. In a project we can compare the internal rate of return to its desirable rate of return.

Simple payback: It is the length of the time needed for a proposed project to recover its own initial cost from the savings or income of the project. The model uses pre-tax amounts of the total initial costs, the total annual costs, the total annual savings and income and grants for the calculation. Simple payback period implies how fast an investment is to get recovered; the smaller the calculated value, the more desirable is the investment in a project. It should not be used as the primary indicator of financial evaluation, but it is secondary indicator for defining the level of risk of financing a project. Also, it does not measure the time value of money and inflation of the costs. Meanwhile, it is useful for small projects to have a short payback period, with a low rate of return, than having one with a high rate of return and long payback period. This is because of the need of a faster refunding of its cash investment.

Equity payback: It calculates the length of the time needed for the owner of a project to refund its own initial investment (equity) out of the generated project cash flows. The equity payback is a better time indicator of the project, because it considers project cash flows from its beginning as well as the level of debt of the project. The equity payback is calculated by means of the year number and the cumulative after-tax cash flows.

PVsyst

Required autonomy: It is the period during lack of sunlight that the load could be supplied by only the battery.

Required LOL: It is the percentage of the load that cannot be supplied. This happens when the battery is disconnected because of low charge. The LOL is needed for identifying the size of the PV array for a known battery capacity.

HOMER

Derating Factor: It accounts for the effect of soiling, shading, snow cover, level of air pollution, etc. which result in fall in the output as well as efficiency of the PV system.

Ground reflectance: It stands for the reflected fraction of the solar radiation incident on the ground and its values differ with respect to natural cover of different areas.

Maximum annual capacity shortage: This means the maximum allowable value of the annual capacity shortage, as a percentage of total annual load.