INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Water Supply Systems Efficiency

Application of Renewable Energy Sources

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Thesis to obtain the Master degree in

Civil Engineering

Jury

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September 2007

Acknowledgement

This project has been developed during master degree in Civil Engineering at Instituto Superior Técnico, in an Erasmus semester, partly at Lund Technical University, in the Division of Energy and Building Design (EBD) and another part at DECivil of Instituto Superior Técnico.

I would like to thank everyone who helped me during this project with their time, effort and knowledge. I would like to express my gratitude to Professor Helena Ramos, my thesis supervisor in my home town university (IST) for the advice and knowledge given that allowed me to work and study water supply systems.
I would like to leave a special thank to Dr. Bengt Perers, my thesis co-supervisor at EBD, whose knowledge and advice made it possible to make the bridge between my field of studies and the project's subject. I would also like to thank Professor Björn Karlsson and the Energy and Building Design department for all the help given regarding PV technolodgy knowledge.
I would like to thank my family whose support was very important in a time of adaptation to a new reality and my friends, whose encouragement was very important in some difficult times.

Abstract

This work has the objective of studying the possible application of renewable energy sources to supply water pumps.

The increase in price of conventional fossil energy sources is making developing and developed countries resort renewable energy. Since water demand is increasing, the pumps energy demand increases as well forcing a solution for this situation.

A preliminary study of a deep well in Lusaka, Zambia was done using the PVSYST software. This preliminary study revealed that a PV powered deep well pump (as a stand-alone system) would be a good solution since the water cost would be 1,07 €/m^3, which is a competitive value.

A water supply system to a Portuguese village was also analyzed. Water pumped between the source and a village reservoir was connected to different power sources, using the Homer software. The pump power and operating conditions were determined using EPANET. Firstly a stand-alone system was tested to compare with the cost of extending the electrical grid. The breakeven grid distance obtained for average values of PV cost, grid extension cost and pump power, was 31,6 km.

Two grid connected systems were tested: with a water turbine and without. For the water turbine to exist an extra flow has to be pumped (increasing the pump power and cost) during the night so that during the day there is enough water for the turbine. The system without a water turbine proved to be more cost-effective. The increase in pump power and consequent power source system increase proved not to be cost-effective when compared to a case with no water turbine. However, for different energy tariffs and hydro turbine cost the system with the water turbine can be cost-effective when compared with the system without.

Keywords: efficiency, water pump, PV/solar powered pump, solar energy, renewable energies, renewable resources, wind turbines, deep well pumping, PV technologies.

Resumo

Este trabalho tem como objectivo o estudo da possível aplicação de energias renováveis a bombas hidráulicas.

O aumento do preço da energia de origem fóssil está a levar países desenvolvidos e países em vias de desenvolvimento a recorrer a energias renováveis. Uma vez que o consumo de água também tem vindo a aumentar, o consumo por bombagem consequentemente também tem aumentado.

Um estudo preliminar de bombagem de um poço em Lusaka, Zâmbia, foi realizado usando o PVSYST. O estudo revelou que o custo de venda de água para consumo humano seria de 1,07 €/m^3, o que é um valor relativamente baixo.

Um sistema de abastecimento a uma vila de Portugal, também foi sujeito a análise, sendo constituído por um hidropressor, com bomba entre uma ETA e um reservatório populacional, que está ligado a diferentes fontes de energia. Na análise recorreu-se ao software HOMER. A potência da bomba e as condições de escoamento foram determinadas com o recurso ao software EPANET. Primeiro foi testado um sistema isolado da rede, para comparar com o custo de prolongar a rede eléctrica com ligação à rede nacional. Para valores médios actuais de custo de fotovoltaicos (sem considerar possíveis subsídios financeiros), a distância mínima à rede para o sistema ser economicamente vantajoso tem de ser no mínimo 31,6 km.

Foram testados dois sistemas ligados à rede eléctrica: um com uma turbina hidráulica e outro sem turbina. Para se poder usar a turbina é necessário bombear um maior caudal (só no período nocturno) para depois turbinar durante as horas de ponta (i.e., durante o dia). Isto tem como consequência um aumento da potência da bomba e respectivo custo. A implementação de uma turbina e respectivo aumento da potência da bomba revelou não ser tão vantajoso em relação ao caso em que não há turbina. No entanto esta situação pode ser invertida se o tarifário da rede eléctrica apresentar diferenças significativas entre o período nocturno e o diurno e o preço da turbina reduzir.

Palavras-chave: eficiência, bombas hidráulicas, bombas hidráulicas solares, energia solar, energias renováveis, turbinas eólicas, bombas submersíveis, tecnologias PV.

LIST OF PUBLICATIONS

During the period of time this thesis was being done, some articles based on this project were submitted for publication:

(i) Ramos, J., Ramos, H. M. (2007). “Renewable energy sources to power water pumps: application to a real water supply system. IWA – World Water Congress - Vienna 2008 - 8-12 September 2008 | The Austria Centre Vienna (submitted to IWA – WWC, September 2007);

(ii) Ramos, J., Ramos, H. M. (2007). “Water supply systems efficiency – Application of renewable energy sources”, in progress (to submit for Renewable and Sustainable Energy Reviews, November 2007);

(iii) Ramos, J., Ramos, H. M. (2007). “Energias renováveis no aumento da eficiência energética dos sistemas de abastecimento por bombagem”, in progress. (to submit for SEREA-Seminário Ibero-Americano, 2008).

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NOMENCLATURE

Notation

Wp (Watt peak) = Photovoltaic power capacity (measured as maximum power output) under standardized test conditions;
DC = Direct Current;
AC= Alternating Current;
PV= Photovoltaic;
MPPT= Maximum Power Point tracker.

Terminology

PV array = A number of PV modules connected together in a system to give a common DC output;
PV efficiency = the factor between PV output and the total energy available from the sun;
Wind turbine = Equipment that converts the wind mechanical energy into electric energy;
Charge Controller = Charges the battery or battery bank and often also manages the supply to the load in a PV system;
Inverter = DC / AC converter for example from 24 Volt DC to 230V AC;
Rectifier = AC / DC converter;
Loss of Load Probability (LOL or LLP) = Percentage of time in which the system does not operate due to the lack of power supply;
Autonomy = Time that the system can work without PV or wind energy supply (work on batteries or water tank);
Pipe pressure drop or friction losses = Pressure loss due to friction in the pipes;
Pump Head = Extra energy given by the pump to the flow;
Flow Rate = Volume of water passing by a certain section per time unit;
Grid extension = The electric grid can be extended by an electric cable in the ground or electric wire on poles. The latter solution is less expensive but needs much more maintenance in remote areas. Both technologies are sensitive to theft in unstable or less developed areas. This technology also requires a marginal investment in enlargement of the power station production and power.
Primary load = Pump power (kW);
Breakeven grid distance = Minimum distance from the national electrical grid from which the stand alone system is cost effective;
Net present cost (or net present value) = the sum in year zero of all discounted cash-flows (profits were considered as negative cash-flows and vice versa);
COE (cost of electricity) = it is the cost of each useful kWh delivered. The useful term means that the energy that is not used (excess energy that exists in stand-alone systems) is not taken into account;
Percentage of renewable sources = the percentage of energy supplied by renewable sources (wind, solar and hydro);
Sellback rate = it is the price per kWh that the grid purchases the excess energy produced by the system.

1. INTRODUCTION

1.1. Scope

Water pumping is one of the most important infrastructures where ever mankind is settled. It allows getting water from a location where it exists in large quantities to a location where it is needed. Water is a natural resource and a basic need for humans and animals. Also industry and agriculture may use large amounts of pumped water.

The need for saving energy has become one of the world's main concerns over the last years and it will become more and more important in the near future. New strategies must be developed and implemented in the major energy consumption systems (adapted from [20] and [21]).

To transport water from the source to the destination, usually a large infrastructure is needed (pipes, pumps, dams, tanks) when the supplied population has a considerable size. For the water to flow to the destination point it will need to have boosts of energy along the way, otherwise the flow energy will not be enough for the water to reach its destination. Water pumps give the flow the extra energy needed (head). Pumps are also commonly used to extract water from deep wells to supply small populations.

Pumps have been used along the history of mankind as: hand pumps, animal driven pumps, hydraulic pumps, wind pumps, diesel and gasoline pumps and more recently solar powered pumps.

Several years ago the energy consumption of a pump was most of the time forgotten due to the low energy price. Water losses in the pipes and the efficiency of pumps were not the main aim in the design project as they represented a small portion of the total budget. In locations where the electrical grid was not available it was usually used diesel, gasoline or wind mill pumps (adapted from [20] and [30]).

Nowadays the energy price is rising and the water supply companies need to invest in cheaper systems. Pumps are becoming more and more efficient. Water losses in the pipes are being reduced as much as possible. However, demand is also getting higher, forcing companies to find different new sources of energy. The rising of the diesel and gasoline prices is also forcing small users to change to alternative sources of energy. The environmental concerns regarding polluting emissions are also increasing. These factors are forcing an evolution of the renewable energy sources.

The fast evolution of PV and the already highly developed wind power technologies is making it one of the possible energy solutions for water pumping. Also, the environmental concerns are making these systems very appealing.

Solar water pumps are currently being used to irrigate crops, water livestock and provide drinkable water. The solar pump produces the most water when needed the most (when the weather is sunny and dry). Solar pumps commonly use direct current motors since they are more efficient (adapted from [14]).

They can be installed in valleys and forest areas or other locations where wind exposure is poor.

1.2. Objectives

The main objective of this thesis is to determine whether it is economically viable to use renewable energy sources, such as solar and hybrid (wind-solar) systems to power water pumps that supply water to a village. The water supply systems are very important infrastructures and in the majority of the cases, intensive consuming systems of energy. The energy incumbencies of a supply system represent a significant part of expenses during the exploitation of the system. Two case studies with viability analysis of the implementation of renewable energy sources in a water supplying system are presented. A water supplying system adapted from a Portuguese Village is analyzed. For this case study the water pumped is located between a water source and a village reservoir and it is connected in different ways to renewable power sources. Feasibility and alternative analysis are developed. It was also done a small study about a deep well water pump in Zambia (sizing and economical study).

One secondary objective is to guarantee an adequate technique performance based on a global evaluation of the system, which includes different scenarios for different restrictions of each component. In this way, only through integrated analysis based on several support instruments regarding the system behaviour, it will be able to answer to the necessary requirements to attain the maximum efficiency. This work presupposes a learning process and tests developments about the usefulness of some simulation available software, such as EPANET, PVSYST4 and HOMER recently applied in this area.

2. STATE-OF-THE-ART

2.1. Advantages of PV powered pumping

Traditionally the water pumping technology of choice has been the wind pump. Wind pumps provide long lasting solutions with a quite simple technology which is easily understood and can be locally maintained. However, even wind pumps have become expensive to install and to replace.

Diesel water pumping is an attractive solution due to the large power range of the pumps and the availability of water when it is needed. It can pump water for different demands over the day. This technology is already highly developed and evolved. However recent increase of fuel price and an intense and skilled maintenance need of the diesel motor can make these systems a costly solution in the long run.

Although normal water pumps are becoming more and more efficient, the demand is also getting higher making pumps high energy consumption equipment. PV systems have come down in price in the last 30 years, and are now available in almost every country in the world. The PV technology is also very reliable if well designed and installed and a local infrastructure is created for long term maintenance. The weak point today is often the battery and battery managing system if low quality technology is chosen. PV pumping has the best cost effectiveness in small distributed stand alone situations outside the electric grid.

All these factors together have solar powered pumps to emerge in the market.

Solar water pumps are often thought as being an expensive technology, not being able to pump enough water and not being reliable enough. But these pumps and systems have evolved much in the last years. It exists currently in the market solar pumps with different capabilities:

- Submersible pumps which can pump up to 200 m heads;
- Pumps that are able to deliver at 100 m a flow of 10.000 l/day or at 50 m a flow of 20000 l/day;

According to [14] one of the strong points of solar powered pumps is its reliability. It usually requires little maintenance (3 to 5 years is the gap period between check ups). Pumps designed for these systems have a high efficiency allowing the decrease of solar array and therefore the upfront cost is lower.

Although there are no limits to how large solar pumps can be built, they become more cost effective the smaller they are (when combustion engines are less economical). For example, the smallest solar pump requires less than 150 W and can lift water from depths exceeding 65 m at 5,7 l/min. In 10 hours of sunny day it can lift 3400 litres which is enough for several families.

The most effective way to minimize the cost of solar pumping is to decrease the demand through flow control. Drip irrigation, lower water consuming toilets can reduce considerably the pumped water.

In this thesis work it was simulated the usage of solar energy to supply a pump of a water supplying system (i.e. system that transports water from the source to the destination). These types of pumps are larger than a regular deep well pump and do not yet exist in the market combined with solar modules[14].

2.2. Applications of PV powered pumps

PV powered pumps have now proven their good performance and reliability. However they are mainly used as stand-alone systems in large and rural countries. As it will be mentioned further ahead in this report, PV powered systems are more cost-effective for low power consumption equipments. Therefore PV powered pumps are still generally used for small demands of water.

According to [11], solar water pumps currently have the following applications:

- Village water supply;
- Life stock watering;
- Irrigation;

In Figure 2.1 it is possible to see a scheme of each of these applications:

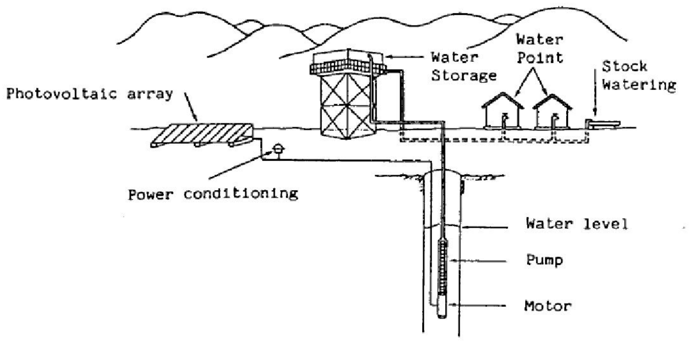
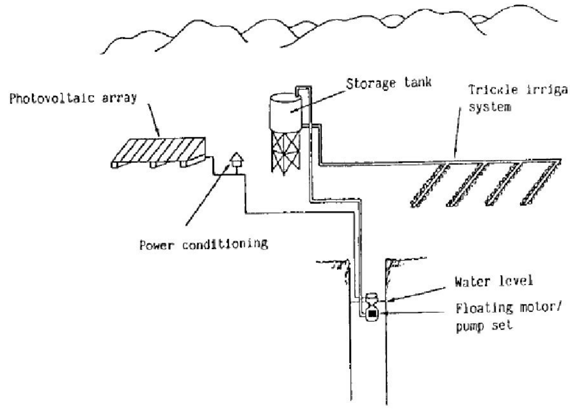
Village supply and life stock watering	
Irrigation	

Figure 2.1– Scheme of different types of water pump applications (adapted from [11])

In a PV pump it is necessary to have a storage tank for regulation when there is not much sunlight available, otherwise the water would only be available during the time when there is sunlight. Instead of these storage tanks, battery packs can also be used to provide energy to the pump when the sunlight is not enough. Even so, storage tanks have the advantage of taking some stress off the pump (it will work continuously with some long stops instead of working every time the demand requires), being more economical and a simpler solution.

For a village water supply it is usually required storage capability for a few days of demand (this depends on the weather history of the location). The system has to be as efficient as possible, and water losses should also be decreased as much as possible. It is advisable to have a rain gathering system to supplement pumping when sunshine is scarce. Individual metering and a cost for each m^3 is also recommended to limit the water use to the design range.

For irrigation purposes, solar powered pumps are used on small farms, vineyards and gardens. So far it is more economical to pump directly from the PV array (without a battery system) and store the water in a tank. The tank has to be high enough to provide the pressure needed for irrigation.

These systems need to take into account that the demand of water will vary throughout the year. Peak demand is sometimes double the year average. This means that the pump will be under-utilized for most of the year.

For livestock watering it is also important to have a tank to store the pumped water. In this case the tank does not need to be placed in a very high altitude since the pressure requirements are less demanding. Sometimes the animals can drink directly from the water storage. This system also can add to the hygiene and health of the cattle by filtering the water and preventing the cattle to walk in the water source area if it is a small pond for example[11].

2.3. Wind Powered Pumps

Usually the term "wind powered pumps" refers to wind mills that use the wind to mechanically extract water from a well. The use of a wind turbine to produce electric energy to then power the water pump is not yet very common. However, these systems are now starting to be used and are being financed in some locations by state institutions.

Before applying wind turbines the local wind data should be carefully measured and analysed. It is possible that the terrain morphology may reduce more than expected the energy output. However, if the wind speed is actually higher than expected most likely the output will increase roughly exponentially. This is shown in Figure 2.2:

Figure 2.2 - Correlation between wind turbine Furhländer 250 output and wind speed (adapted from [8])

A hybrid PV/Wind is expected to have a higher output when compared to a PV or Wind stand alone system. This is due to the fact that usually when there is little or no wind, in opposition there is normally good sun exposure and vice versa.

2.4. Pump Technology

According to [10], water pumps can be divided in two groups:

- Rotodynamic pumps (centrifugal pumps);
- Positive displacement pumps;

According to [2], the centrifugal pump is a pump that uses a rotating impeller to increase the pressure of a fluid. It works on the principle of converting kinetic energy of a flowing fluid into static pressure. The rotation of the pump impeller accelerates the fluid. As the fluid exits the impeller, part of the momentum is converted into static pressure.

In a positive displacement pump, the pump causes the liquid to move by a trapping fixed amount of liquid and then forces (displacing) that trapped volume into the discharge pipe, as shown in Figure 2.3:

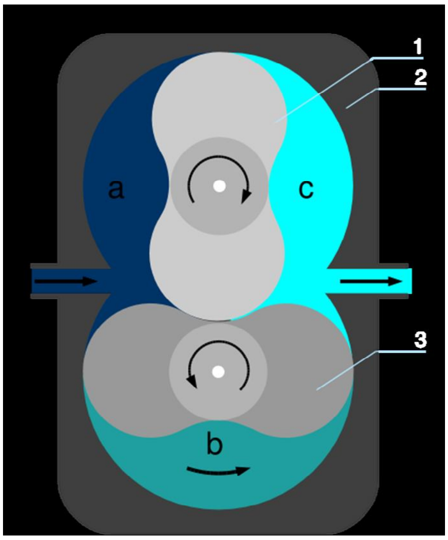


Figure 2.3 – Positive displacement pump (adapted from [10])

Therefore, the centrifugal pumps add energy continuously by increasing pressure, and positive displacement pumps give a periodic increase of energy by fluid displacement [2].

According to [11], although solar panels can be applied to all types of water pumps, they are more commonly applied only to some of those types. The following pumps vary in head, flow and efficiency. These are presented in Chapter 2.4.1, 2.4.2, 2.4.3, 2.4.4 and 2.4.5..

2.4.1. Submerged multistage centrifugal motor pump set

This type is probably the most common type of solar pump used for village water supply. It has the advantage that it is easy to install and the motor of the pump is submerged away from potential damage. Both AC and DC motors can be used making an inverter necessary in case an AC motor is chosen. If a brushed DC motor is used then the equipment will need to be pulled up from the well, approximately every 2 years, to replace brushes. It can also be used a brushless DC motor, but in this case an electronic commutation will be required.

For this kind of pumpset it is usual to use an AC motor with an inverter and a photovoltaic array of less than 1500 Wp. A scheme of this configuration is presented in Figure 2.4:

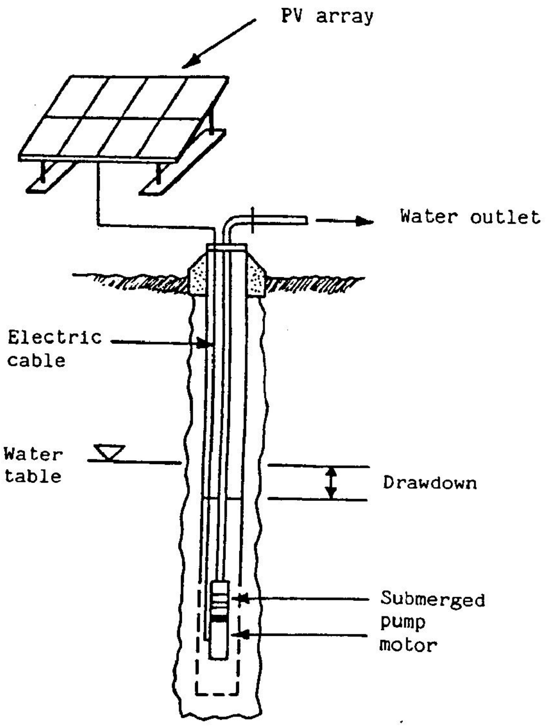


Figure 2.4 – Submerged multistage centrifugal motor pumpset (adapted from [11])

2.4.2. Floating motor pump set

This type of pump is more commonly used for irrigation pumping for canals and open wells. The set is easily portable. Most of these use a single stage submersed centrifugal pump. The most common uses a brushless (electronically commutated) DC motor. Often the solar array support incorporates a handle or "wheel barrow" type trolley to enable transportation, as in Figure 2.5:

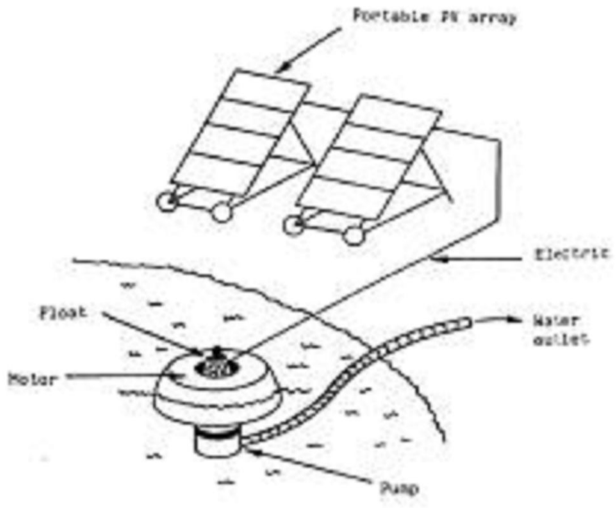


Figure 2.5 – Floating pump set (adapted from [11])

2.4.3. Submerged pump with surface mounted motor

This configuration was widely installed in the Sahelian West Africa during the 1970's. It gives easy access to the motor for brush changing and other maintenance.

However this kind of installation offers poor efficiency due to power losses in the shaft bearings and it has a high cost of installation associated. This configuration is being replaced by the submersible motor and pumpset. A scheme is presented in Figure 2.6:

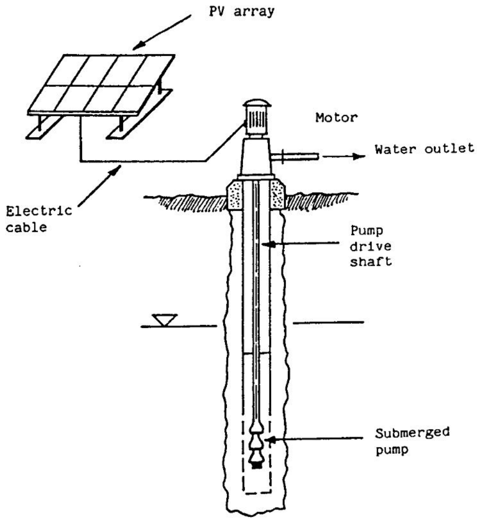


Figure 2.6 – Submerged pump with surface mounted motor (adapted from [11])

2.4.4. Reciprocating positive displacement pump

This type of pump is very suitable for high head and low flow applications. The output is proportional to the speed of the pump. At high head, the frictional forces are low compared to the hydrostatic forces, making positive displacement pumps more efficient than centrifugal for these situations. Reciprocating positive displacement pumps create a cyclic load on the motor which, for efficient operation, needs to be balanced. A scheme is presented in Figure 2.7:

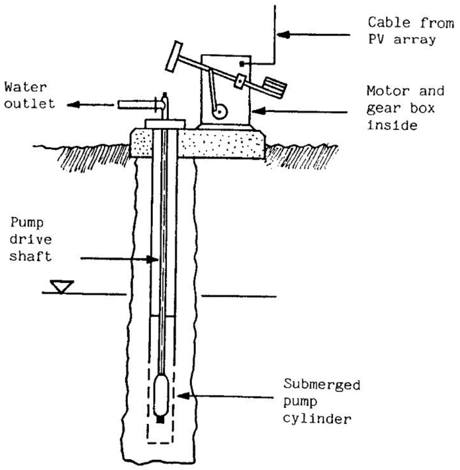


Figure 2.7 – Reciprocating positive displacement pump (adapted from [11])

2.4.5. Surface suction pump set

This type of pump set is not recommended except when an operator is present for supervision. Although the use of primary chambers and non-return valves can prevent loss of prime, in practice self-start and priming problems are experienced. It is not possible to have suction heads of more than 8 meters. A scheme is presented in Figure 2.8:

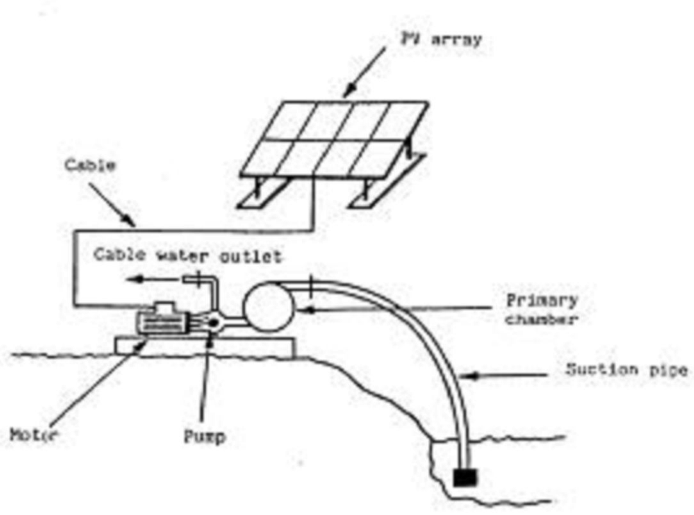


Figure 2.8 – Surface suction pumpset (adapted from [11])

2.4.6. Pump and PV system configuration

According to [7], [10] and [1], the Photovoltaic power source can be connected to the pump motor by the following ways:

- Direct coupling;
- Direct coupling with array reconfiguration;
- Direct coupling with booster;
- Fixed DC input converter (MPPT);
- AC coupling with an inverter

Direct coupling between the PV array and the pump is only possible with DC motor pumps. The I-V operating point results of the intersection of the pump curve with the PV array curve. If the pump curve is too high (array current undersized), the pumping threshold will be high, penalizing the low irradiances (low season, bad days and morning/evening). If it is too low, the full potential power of the array is not used during bright hours. The optimal sizing is therefore depending either on the irradiance distribution (i.e. location, orientation, meteo data), and on the periods at which the water needs are the more important.

Direct coupling with array configuration. Mismatch losses may be improved by performing a PV-array reconfiguration: if we consider two identical groups of PV-modules, at low irradiance all groups are connected in parallel, providing the high currents necessary to the pump starting. From a given irradiance level, the groups are connected in series, doubling the voltage and reducing the current of the PV array. This requires an electronic switch of rather simple technology.

The direct coupling with booster is an improvement of the direct coupling configuration, often necessary with DC displacement pumps. Most displacement pumps require a significant peak of current (at low voltage) when starting, in order to overcome the internal friction forces. The PV array current may not able to provide the peak unless by waiting very high insolation, increasing the irradiance threshold. Help is usually provided by an electronic device named "Booster", which stores the PV energy in a big capacity and gives it back as a peak of current.

Use of a DC-DC converter (MPPT – maximum power point tracker) shows a much favourable figure than direct coupling. This cheap electronic device absorbs the power of the PV array at a fixed voltage and current (for maximum output), and behaves as a current generator for feeding the DC-motor of the pump (for higher pump output). At the input side, the voltage may be chosen close to the maximum power point, and stays quite near for any irradiance. On most commercial DC-DC devices, the input voltage may be adjusted by hardware. At the output side, the power is supposed to be transmitted to the motor at the optimal current/voltage point corresponding to the available power and the motor needs.

For AC pumps, a PCU (DC/AC often including a MPPT converter) suited for a given pump is usually proposed by the pump's manufacturer. It is supposed to fit the inputs requirements (voltage and frequency) for proper operation of the pump.

2.5. Cases of success – performance and economical analysis

Although developed countries are turning to PV grid connected systems, for countries still in development a prominent shift to PV stand alone systems is occurring. This is also happening in systems for water pumping. Water PV pumps are being used mainly in the agriculture sector, and although the more sceptical do not believe they are reliable, the experience obtained in some countries has proven otherwise.

2.5.1. India

According to [13], an agrarian country like India is gradually shifting to stand alone solar water pumping. The DC floating pump system has found big acceptance among small farmers in the Southern states of India and more and more states are implementing water solar pumping programs. In 2002 the total number of electric grid connected pumps was about 13 million with a potential for 7 million more. Most of them are installed in wells. It is becoming increasingly uneconomical to extend the electrical grid due to the high capital involved, low tariffs in the farm sector and low collection of farmer’s dues.

Due to these limitations, a DC floating pump targeted at small farmers owning open wells has been developed by The Polvene Group.

A study revealed that the income of the farmers has increased since using water solar pumping four to five fold.

PV pumping has an immense potential in a country like India in terms of volume application, reduction of costs providing clean and reliable power. It is also a sector that has created employment and that so far has improved farmers life.

2.5.2. México

According to [12], between 1994 and 2000, 206 PV water pumps systems were installed in México as part of the Mexican Renewable Energy Program (MREP). Most of them were installed in the northern México in rural areas that suffer from severe water shortages. Traditional water pumping systems powered by diesel or gasoline engines have been used for decades but the cost, transportation of fuel and engine maintenance make conventional water pumping expensive for people living in rural areas. One of the solutions used to reduce total system and operational costs was to replace them with PV powered pumps. The common systems implemented was a PV array of 500 Wp (on average), controller, over current protection devices and an inverter when an AC motor was used.

After 10 years of the implementation of the PV pump system a review was conducted to 1/5 of installed PV water pumping to determine technical status, reliability and user acceptance. In that survey, 55 % of users agreed that PV pump systems are very economical has 39 % said it to be economical and the rest 6 % considered these systems as non economically viable. Regarding reliability, 49 % considered it with excellent reliability, 37 % classified the systems as reliable and 2 % considered it not to be reliable. Regarding water production, 48 % of the users classified water production as excellent, 46 % classified water production as good, 4 % considered it adequate while 2 % were not satisfied with water production.

According to [12], and as mentioned previously, in many Mexican states, due to the Mexican Renewable Energy Program, PV powered pumps were installed. At 1994, when the program started, the government co-shared 80% of the costs. After 2 years most of the users were convinced of the effectiveness of these types of pumps, so the shared costs by the program decreased to 15 % in the year of 2000. Figure 2.9 shows the cost per Watt of power installed for the different states in México:

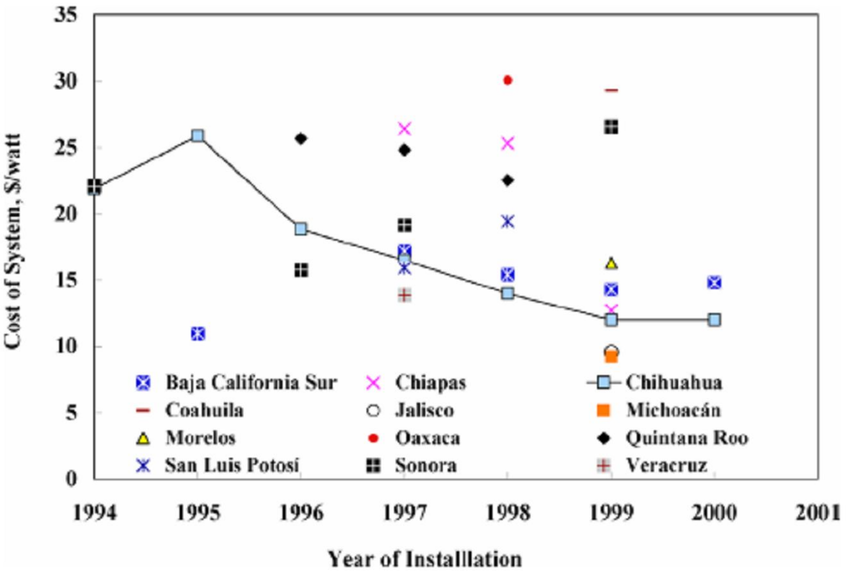
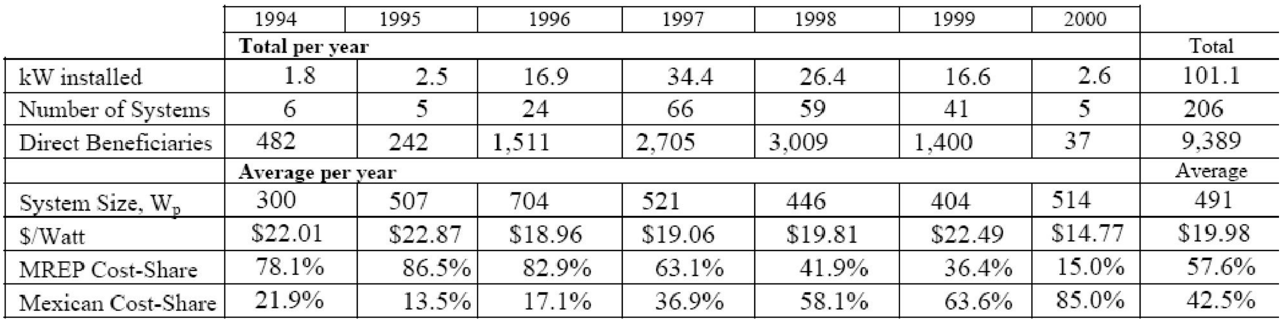


Figure 2.9 – Cost of water powered pump per Watt by state in Mexico (adapted from [12])

In some states the cost of the system per Watt got quite low, reaching the 12 $/Watt in the state of Chihuahua while in some other states the cost is still above 20 $/Watt. It is believed that this high price in some states is due to the lack of maturity of the PV sector when the pumps were installed.

In Table 2.1 an average over the years is shown:

Table 2.1 – Total MREP water PV powered pumps installed in México (adapted from [12])



	1994	1995	1996	1997	1998	1999	2000	
	Total per year							Total
kW installed	1.8	2.5	16.9	34.4	26.4	16.6	2.6	101.1
Number of Systems	6	5	24	66	59	41	5	206
Direct Beneficiaries	482	242	1,511	2,705	3,009	1,400	37	9,389
	Average per year							Average
System Size, W_p	300	507	704	521	446	404	514	491
$/Watt	$22.01	$22.87	$18.96	$19.06	$19.81	$22.49	$14.77	$19.98
MREP Cost-Share	78.1%	86.5%	82.9%	63.1%	41.9%	36.4%	15.0%	57.6%
Mexican Cost-Share	21.9%	13.5%	17.1%	36.9%	58.1%	63.6%	85.0%	42.5%

Since the implementation of these pumps the income of the farmers/users has increased along the years and living conditions have improved much.

2.5.3. Namibia

According to [14], Namibia has more than 40.000 boreholes in use, from which water is pumped for households, farming, tourism and agriculture activities.

A cost comparison study was conducted for solar and diesel water pumps over a range of pumping heads (10 to 200 m) and a range of daily flow rates (3 to 50 m^3/day). The all-inclusive costs were calculated taking into account the following aspects:

- The initial upfront cost;
- The operating costs;
- Maintenance costs;
- Replacement costs;

Calculating the all-inclusive cost allows solar pumps (with a higher upfront cost) to compete with diesel pumps (usually lower upfront but with ongoing diesel and intensive maintenance costs). The all-inclusive cost takes a long approach and was calculated using a 20 years study period which is the minimum life expectancy of a solar panel. Another measure chosen for comparison was the years to breakeven (the number of years for one solution to become cheaper than the other).

Figure 2.10 shows an example for a pumping solution (80 m head and 12 m^3/day):

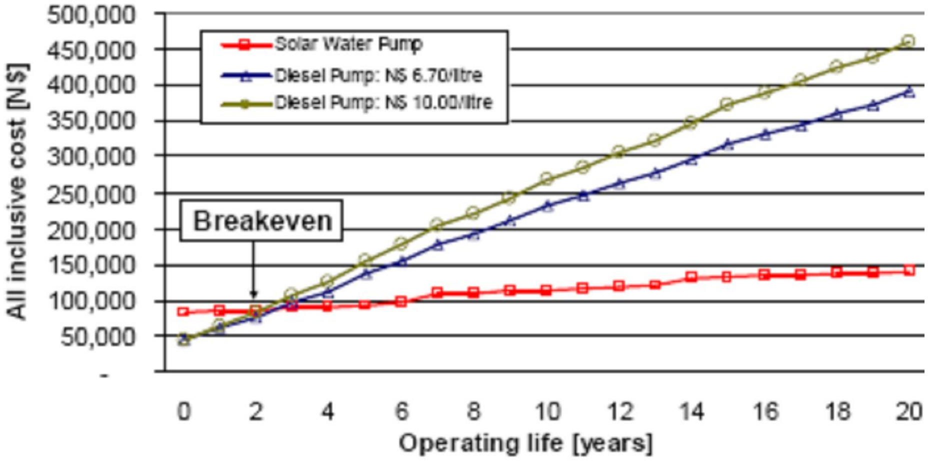
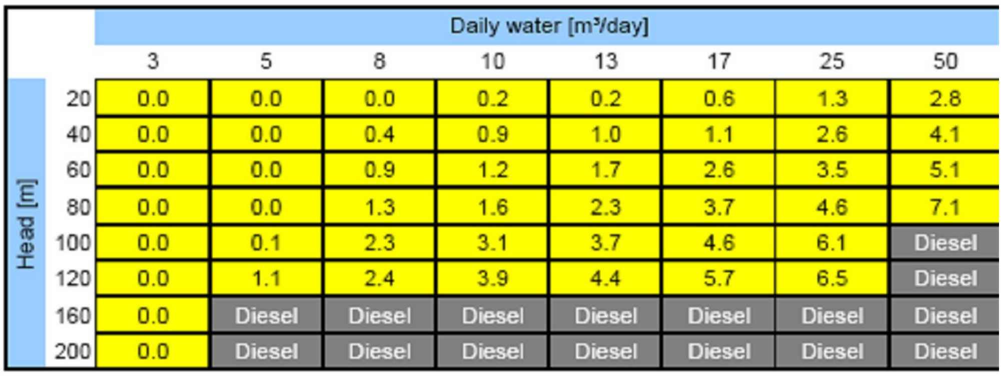


Figure 2.10 – All inclusive cost for solar powered pump and diesel powered pump (adapted from [14])

It is possible to see in the graphic that the breakeven occurs after only 2,6 years. The all-inclusive cost over 20 years reaches N$ 139.000 for solar pump and N$390.000 for diesel pump. If the diesel price increased to N$ 10,00 per litre then the total cost would rise to N$ 461.000.

For other operating conditions (flow rate and head) Table 2.2 shows the years for solar pumping to breakeven:

Table 2.2 – Years to solar powered pump to breakeven when compared to diesel (adapted from [14])



	Daily water [m^3/day]							
Head [m]	3	5	8	10	13	17	25	50
20	0.0	0.0	0.0	0.2	0.2	0.6	1.3	2.8
40	0.0	0.0	0.4	0.9	1.0	1.1	2.6	4.1
60	0.0	0.0	0.9	1.2	1.7	2.6	3.5	5.1
80	0.0	0.0	1.3	1.6	2.3	3.7	4.6	7.1
100	0.0	0.1	2.3	3.1	3.7	4.6	6.1	Diesel
120	0.0	1.1	2.4	3.9	4.4	5.7	6.5	Diesel
160	0.0	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
200	0.0	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel

As it is possible to see in the table, all solar pumps available in the market have a breakeven of less than 7 years. The smaller the pump is (smaller flow and head demand) the more cost effective as its breakeven is zero. The spaces marked with diesel refer to flow rates and heads that are not yet available in the market for PV pumps.

The calculations make use of the optimal solar and diesel pumping systems and assume a constant water demand. In applications where the water demand varies significantly (irrigation for example) diesel may present a more cost effective solution. Solar powered pumps are more cost effective when it is used on a continuous basis, or the water need is correlated to solar energy availability.

2.7. Market

Since the concern associated with the green house effect due to polluting gases has increased, the market regarding renewable energies has been increasing with it as well. Nowadays there is a big market offering many different systems of water solar pumps. Many companies have invested in this new rising market, making prices decrease due to competitiveness between them. From the large number of companies, several were chosen and are mentioned next:

- Solco Ltd

This company sells products related with water and power sustainable systems. It manufactures products such as water heaters, solar pumps and many other power systems. It is specialized in decentralised sustainable water and power solutions. It has acquired other companies working in the same area making it possible to distribute in every continent.

More information regarding this company can be found in the following site:

- http://www.solco.com.au/;

- Solar Water Technologies Inc

This is a small North American company that only works with PV powered water pumps. It has several systems available for different heads and flow pumping. More information can be found in the following site:

- http://www.solarwater.com/;

- Conergy Inc

This is also a North American company. It distributes products related with sustainable energy such as PV modules, solar water pumping, solar thermal and small wind power solutions. Regarding solar powered pumps, they offer solutions for surface and submersible pumps. More information can be found in the following site:

- http://www.conergy.us/DesktopDefault.aspx;

- Sunmotor International Ltd

This is a Canadian company, and as the name suggests, it uses the energy provided by the sun to operate motors and other electrical system. It offers solutions of floating pumps and groundwater pumps. More information can be found in the internet site:

- http://www.sunpump.com/;

- Kyocera Solar Inc

This company is one of the largest companies of production and distribution of solar energy products. It has its headquarters in the United States and affiliates also in Australia. It offers several solutions regarding water solar pumping. More information can be found in:

- http://www.kyocerasolar.com/;

There are several companies that have developed systems of solar powered water pumps but most of them are small companies. This market is growing as more and more companies invest in this area.

There was also done a research of the market of solar panels and other needed equipment.

- PV Enterprise

PV Enterprise is one of Sweden's leading manufacturers of solar cells. The head office is located at Vilshult in Blekinge, where most of the production also takes place. The company also has a smaller production plant at Tarnow in Poland.

This company supplies both modules and complete system solutions. The product range includes solar cell modules with powers from 25 to 185 W, connection boxes and installation equipment.

- http://www.pv-enterprise.com/pv/

- Dutch Solar

Dutch Solar is primarily a wholesale/manufacturing company of electronics and of PV solar modules for electricity from daylight.

This company sells solar panels, inverters and some mounting structures.

  - http://www.dutchsolar.com/

Other large companies such as BP and GE also produce and sell components for PV systems:

  - http://www.bp.com/modularhome.do?categoryId=4260
  - http://www.gepower.com/prod_serv/products/solar/en/index.htm

- Studer Innotec

Based in Switzerland, Studer Innotec is a manufacturer of inverters. Its products convert a battery voltage of 12, 24 or 48Vdc into 230Vac sinewave voltage, therefore suitable for any kind of AC appliance.

  - http://www.studer-inno.com/SITESTUDER/page/ALLEMAND/DescriptionD/HomeD.php

- SPS Energy Solutions

With offices across North America, SPS Energy Solutions manufactures its own products, has in-house engineering and marketing capabilities, and is a master distributor for world-class companies. It sells products such as solar modules, inverters, batteries, wind turbines among others

  - http://www.spsenergy.com/

- Fuhrländer

This company is established in Germany. It produces and sells wind turbines with an output range between 30 kW and 2500 kW.

  - http://www.fuhrlaender.de/

- WES BV

Wind Energy Solutions BV (WES BV) was established in 2003 by Teamwork Technology, a company specialised in technical solutions for energy problems, especially for developing countries. WES uses the former windturbine product range from Teamwork Technology and the turbines up to 250 kW from the well-known Dutch company Lagerwey the Windmaster.

  - http://www.windenergysolutions.nl/

- Bergey Wind Power

This American company produces and sells wind turbines. It has a 30 year experience and it is mainly specialized in small wind turbines.

  - http://www.bergey.com/

2.8. Warnings on applying deep well pumps

2.8.1. Contamination issues

According to [15], bacteria are microscopic organisms that can be found everywhere. Most of them are harmless but certain types can cause disease, sickness or other health problems.

Groundwater and aquifers are widely seen has being bacteriologically pure. Although this type of water has much fewer micro organisms it is not sterile. The soil through which the ground water passes filters it but also contains micro organisms that can adapt to the aquifer conditions and therefore become residents in the water.

Properly constructed and adequately cased and grouted water well usually obtains its water at a depth at which bacteria are no longer present. Bacteria are found in the upper soil layers of most streams, lakes and ponds. There can also be bacteria sources related to septic systems, farm animals and storm runoff. The bigger the depth of the aquifer the more the infiltrated water is filtered.

According to [16], there are many reasons that can lead to infected water, of which some are mentioned here:

- Shallow or dug well that is constructed from boards, bricks, stone or tile is vulnerable to surface water contaminations;
- In large diameter wells insect infestation is hard to control. The falling dead insect will contaminate the water with bacteria;
- In the event of flood or storm runoff, surface water could enter the top of the well and contaminate it. The rise of the aquifer level due to flood can reach levels at which bacteria are present;
- Bacteria can be introduced when a well is being drilled or maintained. Contractors must ensure that their equipment is sterile and should not be left in the ground while use;
- The well casing should be checked, and repaired if necessary after an earthquake to avoid bacteria contamination;
- Sometimes the contamination can be due to abandoned boreholes or wells used by engineering investigation or construction sites that affect the same aquifer.

There are more reasons that can cause contaminated groundwater but these are the more relevant.

2.8.2. Health issue

According to [19], the water extracted from a well should be tested in a laboratory for coliform bacteria. Coliform is a group of several types of bacteria from the same family that are commonly found in soil, on vegetation and in surface water. They also live in the intestines of warm-blooded animals. Because these type of bacteria are associated with sewage or surface waters they are used as an indicator group to determine the sanitary quality of drinking water. Most coliform do not cause illness, however, their presence in a water system is a public health concern due to the potential disease-causing strains of bacteria, viruses and protozoa that can also be present. These organisms typically cause flu-like symptoms such as nausea, vomiting, fever and diarrhea. Coliform can also indicate the presence of bacteria and viruses that can cause cholera and typhoid fever, dysentery and hepatitis.

2.8.3. Operational Issues

Bacterial contamination of a water supply is not always harmful for human health. Some types of bacterial contamination create problems in the system components instead of human health. The most common of these are the iron and sulphur bacteria that attack well pump components (neither of them harmful to humans).

According to [17] and [18], iron bacteria are generally more common than sulphur bacteria, because iron is more abundant in ground water. These bacteria are "oxidizing agents" which means that they combine iron or manganese dissolved in ground water with oxygen. This process creates a foul smelling brown slime that can coat well screens, pipes and plumbing fixtures. This slime can cause unpleasant odours, coloured water (yellow, red or orange water), corrode plumbing equipment and clog well pipes. This bacterium has a high rate of growth. It is also possible that slime deposits may form in toilet tanks. A smell of sewage or resembling fuel oil may be noticeable.

There are two categories of sulphur bacteria: sulphur oxidizers and reducers.

Sulphur oxidizing bacteria has effects similar to those of iron bacteria. They convert sulphide into sulphate, producing a dark slime that can clog plumbing.

Sulphur reducing bacteria live in oxygen deficient environments. They break down sulphur compounds producing hydrogen sulphide gas in the process. This gas is foul smelling and highly corrosive.

The sulphur reducing bacteria is the most common of both. The most obvious symptom of a sulphur bacteria problem is the smell of "rotten egg" due to the hydrogen sulphide gas.

Iron and sulphur bacteria contaminations are often difficult to tell apart because their symptoms are similar. However both bacteria can be treated using the same method.

2.8.4. Bacterial Prevention/Treatment

When planning to supply water from a well, preventing bacterial infection of water should be taken into consideration very seriously. Before considering possible forms of treatment of possible bacteria infestation, a detailed planning of procedures during the construction of the well should be done.

According to [16], to prevent bacterial infestation the following procedures should be done:

- When drilling the well every piece of equipment (drilling and pumping equipment) should be disinfected and should be handled with care (not to be left in the ground when it is not being used). The disinfection can be done with a 200 milligrams per litre of chlorine solution;
- The casing of a well should be properly sealed so that water from the soil does not leak down into the well;
- The casing should be extended above ground level to prevent water from penetrating the well in case of flood;
- Well casing deterioration over time should be checked periodically and consequents repairs should be done;
- Backflow prevention devices should be installed to avoid water from returning to the well when the pump is not working.

In case the well gets infected there are processes that solve the problem but if the contamination has reached a considerable size most of the treatments will only make the contamination controllable.

Bacteria are most effectively eliminated from drinking water by chlorine disinfection, filtration, ultraviolet irradiation or ozonation.

- *Filters*

Filtration does not remove bacteria or viruses from drinking water. This method can be a very effective mean of straining out large organisms like protozoan cysts and worm eggs. It has to be complimented with disinfection to eliminate bacteria. Filters must be checked and changed regularly.

- *Chlorine*

Chlorine is the most widely used method in the United States for disinfecting municipal and individual water supplies. It destroys bacteria by oxidizing their internal enzymes. However if the water has a high organic level dangerous chlorinated organics can be produced (carcinogenic to humans). The dispersing equipment should be automatic, require minimal maintenance and treat all water entering the house.

For severe cases, treatment with a strong acid and salt solution following thorough shock chlorination may be required. The acid solution may be able to penetrate thick incrustations of bacteria that the chlorine solution was unable to eliminate.

- *Iodine*

Iodine is chemically more stable than chlorine but also more expensive. Iodine can impart a slight taste to the water.

- *Ultraviolet Light*

Ultraviolet irradiation eliminates bacteria by creating photochemical changes in its DNA. No chemicals are added to the water in this method. The equipment has to be carefully installed and the temperature can not be very low otherwise the UV lamp will lose most of its effect.

- *Ozone*

Ozone contains three oxygen atoms. It is more effective than chlorine and adds no chemicals to the water. It can not be stored which means that an ozone generator is required. Ozonation equipment and operating costs are higher when compared with other treatment procedures.

3. FIRST CASE STUDY – DEEP WELL IN ZAMBIA

A small deep well pump connected to a solar module to supply water to a village in Lusaka, Zambia was tested. These systems (deep well pump connected to a solar module) have proven their cost-effectiveness, especially in rural countries with good sun exposure.

3.1. System information

A small study of a deep well supply system in Lusaka, Zambia was done using the preliminary sizing option of the software PVSYST4.

The case considered was a supply system that would serve 10 families with a consumption of 100 l/day each. The deep well was considered to have a depth of 100 meters.

The software has a database regarding solar irradiation for a vast number of locations, including Lusaka. It was assumed for the location in study a free horizon, which means that there is no object between the sun beam and the solar panel (shadows can decrease greatly the solar output).

After defining the system location it is necessary to specify the water needs and system configuration as shown in Table 11.1:

Table 3.1 – Deep well pump system inputs in PVSYST4 for a deep well located in Lusaka, Zambia

Water needs	$\frac{10 \cdot 100}{1000} = 1(m^3 / day)$
Head	110 m
Pipe length	112 m
Pipe internal diameter	70 mm
Pump technology	DC positive displacement
Power converter	MPPT converter
Pump layout	Deep well
Optimization on	Winter (Oct. – March)
Tilt	35º
Azimuth	0º

The head was defined assuming that the tank would be 10 meters above ground level, so the pump will need to give a head of 100 meters of well depth and an extra 10 meters for the water to get to the tank.

The pipe length was assumed to be the 110 meters of needed head and an extra 2 meters for possible elbows and curves.

After researching in the internet for deep well pump configurations an internal diameter of 70 mm was defined, has it was seen to be a reasonable value. After doing several simulations, a DC positive displacement pump and an MPPT converter were the components that lead to a lower system cost and size.

It was chosen a winter optimization since this is a stand alone system and therefore should be sized for the season with the less favourable conditions.

The software presents a tool that allows the user to optimize the tilt and azimuth (depending on the optimization season chosen).

3.2. Software used - PVSYST4

PVSYST4 is a PC software package for the study, sizing and data analysis of complete PV systems. It deals with grid-connected, stand-alone, pumping and DC-grid (public transport) PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools.

PVSYST4 offers 3 levels of PV system study, roughly corresponding to the different stages in the development of real project:

- Preliminary design;
- Project design;
- Measured data analysis.

In this work only the Preliminary design was used for deep well pumping sizing.

Besides designing the system, PVSYST4 also does some economical calculations based on the following values:

- Equipment
  - Module cost
  - Pump and accessories
  - Regulator cost
  - Transport/Fitting
  - Total investment
- Loan
  - Annuities
  - Maintenance cost
  - Total yearly cost
  - Water cost

Appendix 1 shows the results window from PVSYST software.

3.3. Results

When the results page is shown it comes with some predefined values for autonomy (that is depended on the tank volume) and required loss of load (that is the percentage of time in which we accept that the load is not satisfied). It was assumed autonomy of 6 days and a loss of load of 2%.

For the conditions defined, the PVSYST4 software presented the system displayed in Table 3.2 and Figures 3.1 and 3.2:

Table 3.2 – System configuration results for deep well pump is Lusaka, Zambia

PV size (Wp)	195
Pump Power (W)	154
Investment cost (€)	3019
Water cost (€/m^3)	1,07

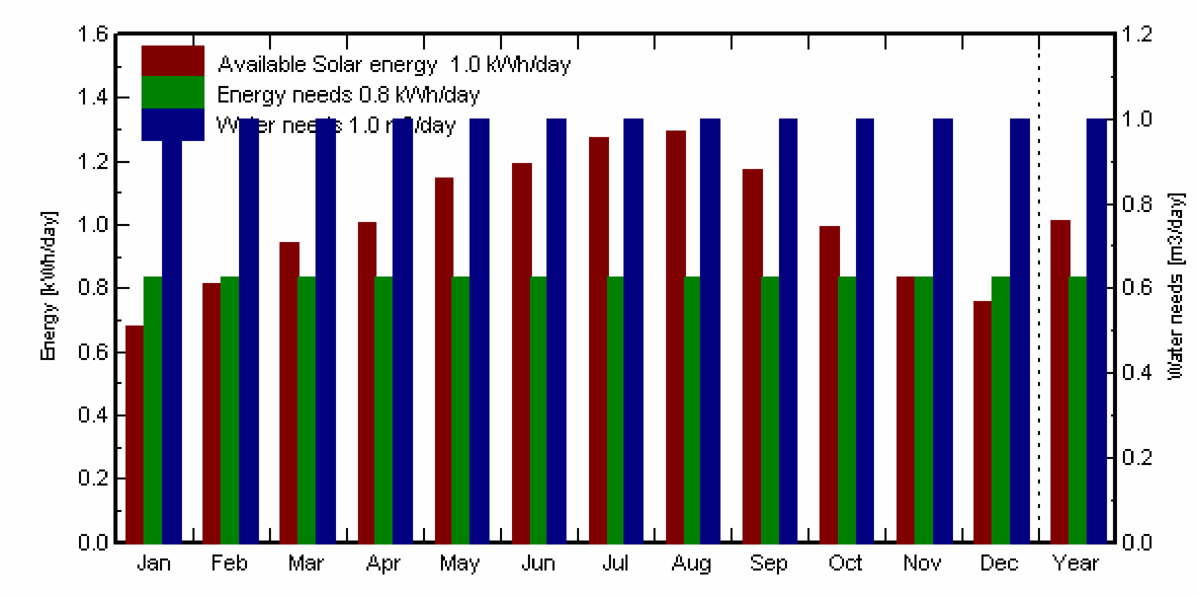


Figure 3.1 – Monthly energy and water needs. The blue columns indicate de daily water needs per day, the red the available solar energy per day and the green the necessary solar energy per day

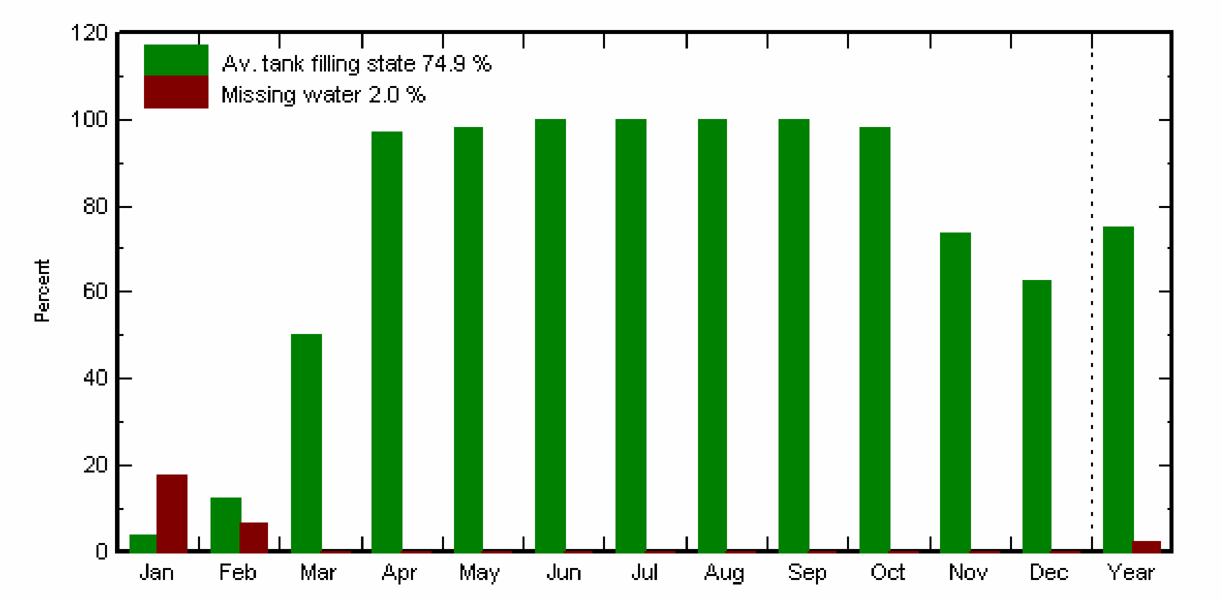


Figure 3.2 – Percentage of missing water due to loss of load and monthly average filling tank state

As it is possible to see, there is a loss of load during the months of January and February when there is less sunlight available leading to 2.0% of missing water for a whole year.

This loss of load could be inexistent if a larger system was defined or by using a hybrid system (with a diesel generator) as shown in Table 3.3:

Table 3.3 – System specifications and fuel needs

	Incid. (kWh/m^2 day)	PV available (kWh/day)	PV needs (kWh/day)	PV excess (kWh/day)	Pumped water (m^3/day)	Missing water (m^3/day)	Missing load (%)	Fuel (l)
Jan	3.90	0.70	0.80	0.00	0.80	0.20	17.70	3.10
Feb	4.70	0.80	0.80	0.00	1.00	0.10	6.50	1.00
Mar	5.40	0.90	0.80	0.00	1.10	0.00	0.00	0.00
Apr	5.80	1.00	0.80	0.20	1.00	0.00	0.00	0.00
May	6.60	1.10	0.80	0.30	1.10	0.00	0.00	0.00
June	6.80	1.20	0.80	0.40	1.00	0.00	0.00	0.00
July	7.30	1.30	0.80	0.40	1.00	0.00	0.00	0.00
Aug	7.40	1.30	0.80	0.50	1.00	0.00	0.00	0.00
Sep	6.70	1.20	0.80	0.30	1.00	0.00	0.00	0.00
Oct	5.70	1.00	0.80	0.20	1.00	0.00	0.00	0.00
Nov	4.80	0.80	0.80	0.00	1.00	0.00	0.00	0.00
Dec	4.30	0.80	0.80	0.00	0.90	0.00	0.00	0.00
Year	5.80	1.00	0.80	0.20	1.00	0.00	2.00	4.10

As it is possible to see in the table, the PV available is not enough to supply with the needed water during January and February meaning that if a diesel generator was to be added 4.10 l of diesel would be needed on a yearly basis.

The economic evaluation is the following presented in Table 3.4:

Table 3.4 – Economical analysis of the optimized system

Economic gross evaluation	
Module cost	902 €
Pump and accessories	701 €
Regulator cost	252 €
Transport/Fitting	1164 €
Total Investment	3019 €
Loan	
Annuities	241 €/year
Maintenance cost	138 €/year
Total yearly cost	380 €/year
Water cost	1,07 €/m^3

It is possible to determine a rule of thumb for water pumping from a deep well in Zambia and the surrounding African countries.

The rules of thumb based on the results determined, presented in Table 3.2, are shown in equation (3.1):

$$Rule\ of\ Thumb = \begin{cases} \dfrac{195}{1} = 195Wp/m^3 \\ \dfrac{195}{154} \approx 1{,}27Wp/Wload \\ \dfrac{154}{1} = 154Wload/m^3 \end{cases} \quad (3.1)$$

These rules of thumb facilitate the pre-sizing of a system of this kind. It allows the user to know rough values regarding the size of the solar module and water pump depending on the water needs (these values are accurate for locations with similar solar conditions to Lusaka).

3.4. Sensitivity

The sensitivity of the results regarding system autonomy and acceptable loss of load was studied. The values obtained are presented in Table 3.5:

Table 3.5 – Sensitivity study of autonomy and loss of load

Autonomy (days)	**6**	**6**					**3**	**4**	**5**	**6**	**7**
LOL (%)	**2**	**1**	**2**	**3**	**4**	**5**	**2**				
PV Size (Wp)	195	205	195	183	177	172	198	196	195	195	192
Pump Power (W)	154	162	154	145	140	135	157	155	155	154	152
Investment cost (€)	3.019	3.161	3.019	2.857	2.767	2.677	3.072	3.040	3.043	3.019	2.980
Water cost (€/m3)	1,07	1,11	1,07	1,02	0,99	0,97	1,08	1,07	1,07	1,07	1,05
Rule of Thumb (Wp/Wload)	1,27	1,27	1,27	1,26	1,26	1,27	1,26	1,26	1,27	1,27	1,26

These results are also displayed in Figures 3.3 to 3.6:

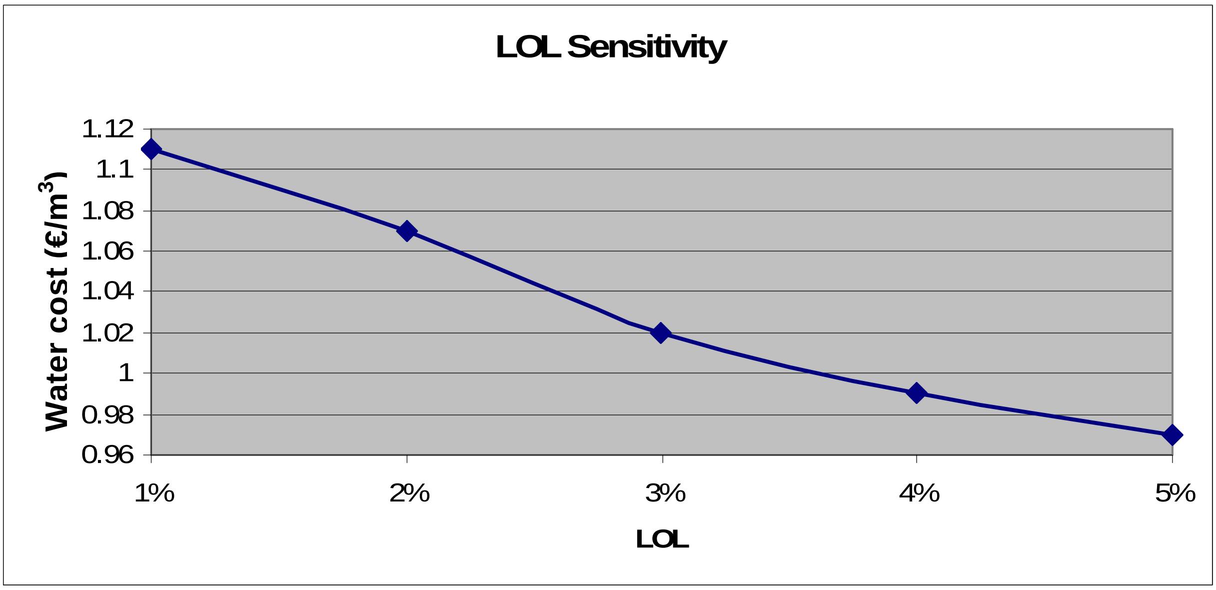


Figure 3.3 – Water cost of the system dependence on loss of load

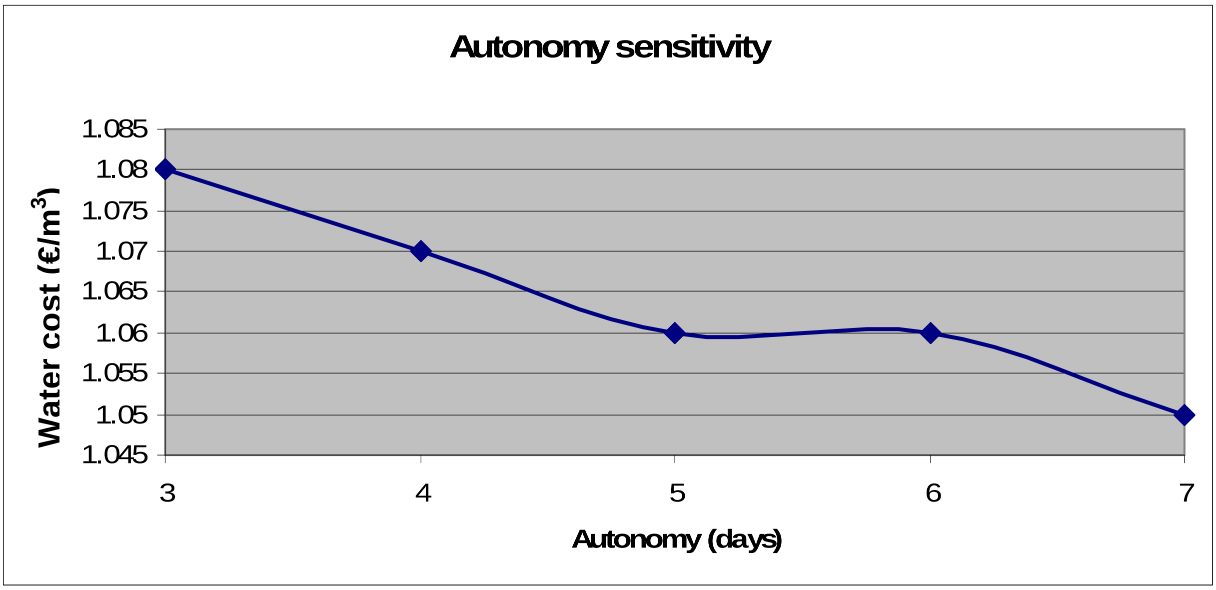


Figure 3.4 – Water cost of the system dependence on autonomy

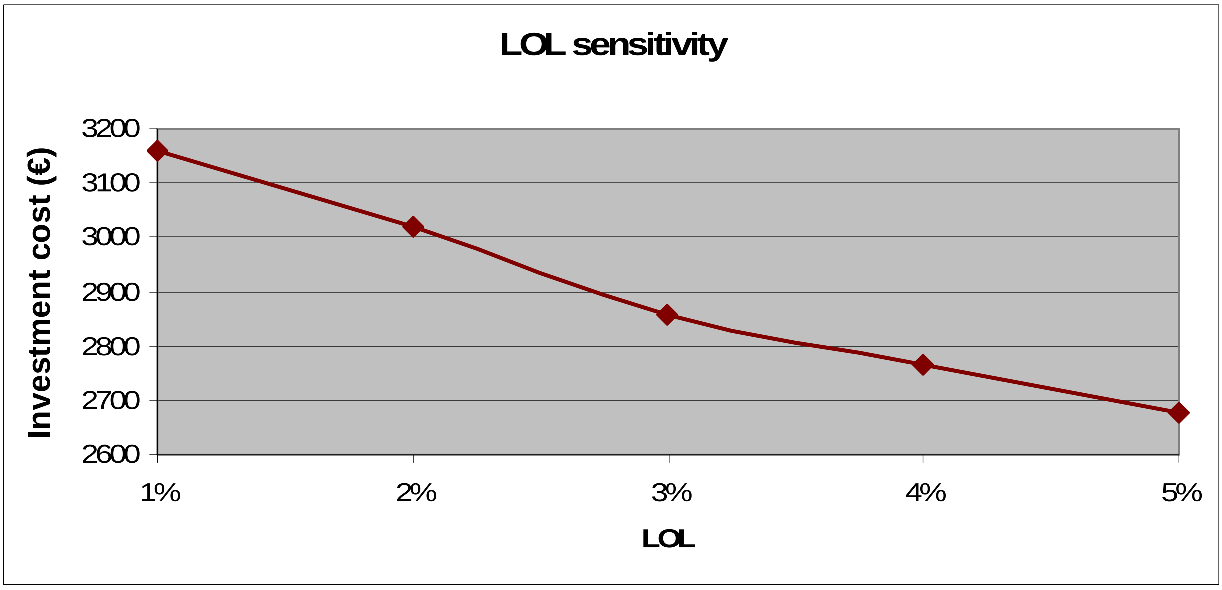


Figure 3.5 – Investment cost of the system dependence on loss of load

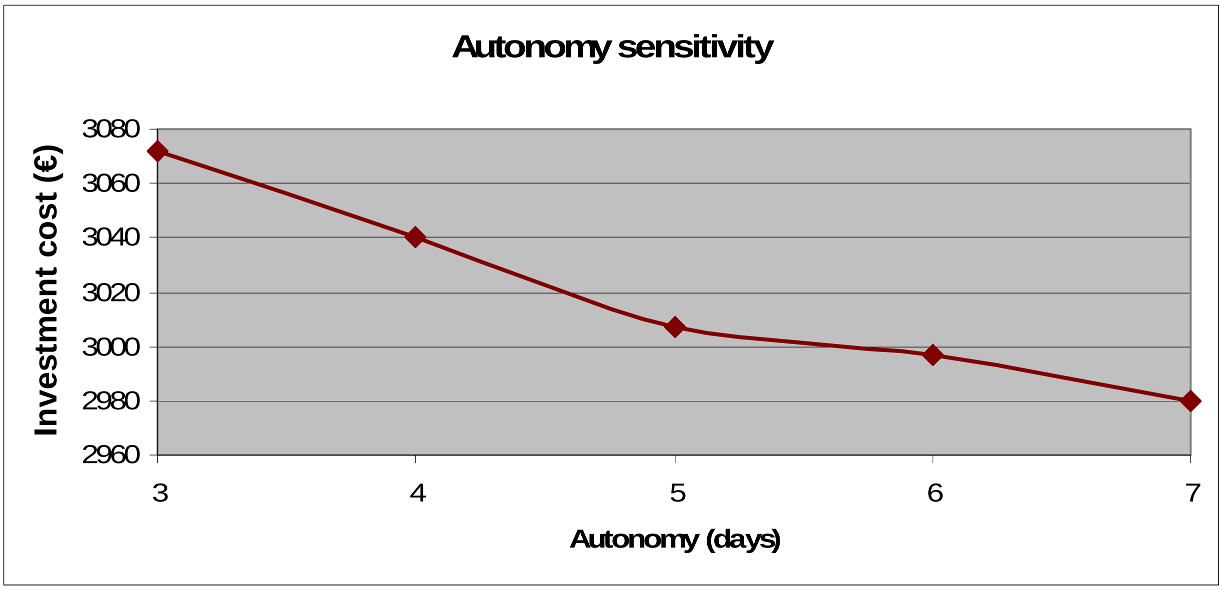


Figure 3.6 – Investment cost of the system dependence on autonomy

As it is possible to verify, for lower percentages of accepted loss of load the investment and the water cost get higher. This is due to the need of increasing pump power and PV array size for the system to pump the necessary water to reduce the loss of load.

When the autonomy is increased the tank volume consequently increases as well. The investment and water cost get lower for higher tank volumes (higher autonomy) due to the fact that higher tank volume leads to a smaller pump and PV array. The increase of tank size is cheap when compared to the decrease and savings in the pump and PV array.

4. SECOND CASE STUDY - WATER SUPPLY SYSTEM IN A PORTUGUESE VILLAGE

A supply system in Portugal, composed of pipes, a water pump, a water source and a village reservoir, was analysed. It was simulated the connection of an energy supply system (wind, solar and hydro energy) to the hydraulic pump.

Two types of energy supply system were tested: a stand-alone system and a grid connected system. In the grid connected system two possibilities were simulated, one with a hydro turbine and another without (for the water turbine to exist an extra flow has to be pumped to increase the available water in the end stream reservoir, as it will be explained further ahead in this work).

4.1. Software used in the analysis

4.1.1. EPANET

This system was simulated by using hydraulic specific software named EPANET. According to [9], this software performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank and the concentration of chemical species throughout the network during a simulation period comprised of multiple time steps. In addition to chemical species, water age and source tracing can also be simulated.

EPANET's hydraulic simulation model computes hydraulic heads at junctions and flow rates through links for a fixed set of reservoir levels, tank levels and water demands over a succession of points in time. From one time step to the next reservoir levels and junction demands are updated according to their prescribed time patterns while tank levels are updated using the current flow solution. The solution for heads and flows at a particular point in time involves solving simultaneously the conservation of flow equation for each junction and the head loss relationship across each link in the network. This process, known as hydraulically balancing the network, requires using an iterative technique to solve the nonlinear equations involved. EPANET employs the Gradient Algorithm for this purpose.

Appendix 2 shows some pressure values on the supply system (Figures A2.1 to A2.3, copied from the software).

4.1.2. HOMER

According to [8], HOMER, the micropower optimization model, simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications. When a power system is designed, many decisions about the configuration of the system must be made. The large number of technology options and the variation in technology costs and availability of energy resources make these decisions difficult. HOMER's optimization and sensitivity analysis algorithms make it easier to evaluate the many possible system configurations.

The user provides the model with inputs, which describe technology options, component costs, and resource availability. HOMER uses these inputs to simulate different system configurations, or combinations of components, and generates results that you can be viewed as a list of feasible configurations sorted by net present cost. HOMER also displays simulation results in a wide variety of tables and graphs that help comparing configurations and evaluate them on their economic and technical merits. Tables and graphs for use in reports and presentations can be exported.

When someone wants to explore the effect that changes in factors, such as resource availability and economic conditions might have on the cost-effectiveness of different system configurations, the model can be used to perform sensitivity analyses.

The total net present cost is HOMER's main economic output. All systems are ranked according to net present cost, and all other economic outputs are calculated for the purpose of finding the net present cost. The net present cost is calculated according to equation (4.1):

$$C_{NPC} = \frac{C_{ann,total}}{CRF(i, R_{Proj})} \tag{4.1}$$

where C_{NPC} is the net present cost, $C_{ann,total}$ is the total annualized cost, i is the annual interest rate, R_{proj} the project lifetime and *CRF* the capital recovery factor. The net present cost (or net present value) is the sum of the discounted cash-flows to year zero. Negative cash flows mean profits and vice versa. The lower this value is the more cost effective the solution is. More information regarding this can be found in Homer's help menu.

However, Homer software also determines the cost per useful kWh delivered (COE). The useful term means that the energy that is not used (excess energy that exists in stand-alone systems) is not taken into account.

Homer determines the breakeven grid distance for stand-alone systems. This parameter is the minimum distance to the national electrical grid from which the stand alone system is cost effective when compared to the national grid.

As mentioned, Homer is a software that simulates power systems. It simulates all possible combinations of configurations inputted. For example, if for PV array it is inputted 0, 100 and 200 kWp in the quantity box, the software will test all combinations of these three values with the ones inputted for the rest system components.

In Appendixes 3 to 5 the input windows from the software are shown (Figures 4.1 to 4.4 and 5.1 to 5.6)

4.2. Supplying system data

The system that is going to be analysed refers to a semi-theoretical case, so some parameters of the system were assumed to simplify calculations and simulations. The system has the following characteristics presented in Table 4.1:

Table 4.1 – Water supply system characteristics

Location	Lisbon
Pipe Length	2999 m
Darcy-Weibach Coefficient	0,0115
Pump Efficiency	80 %
Initial Point Elevation	130
Middle Point Elevation	80
Final Point Elevation	170

The outline of the supply system can be seen in Figure 4.1:

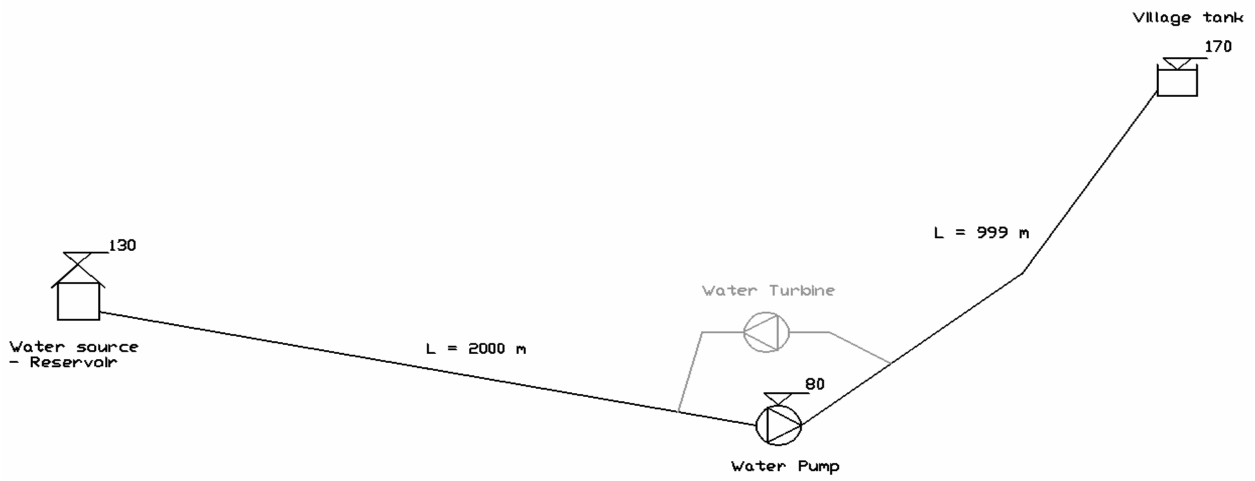


Figure 4.1 - Outline of the supply system in Portugal

Figure 4.1 is not a scaled design. It is only a scheme for analysis purposes. It shows the location of the pump and the water turbine (it was tested a system with and without a water turbine). The position of the water turbine in the system has no influence in its power output. Although it is represented next to the water pump it could be located somewhere else in the system.

The village has an hourly demand has shown in Figure 4.2:

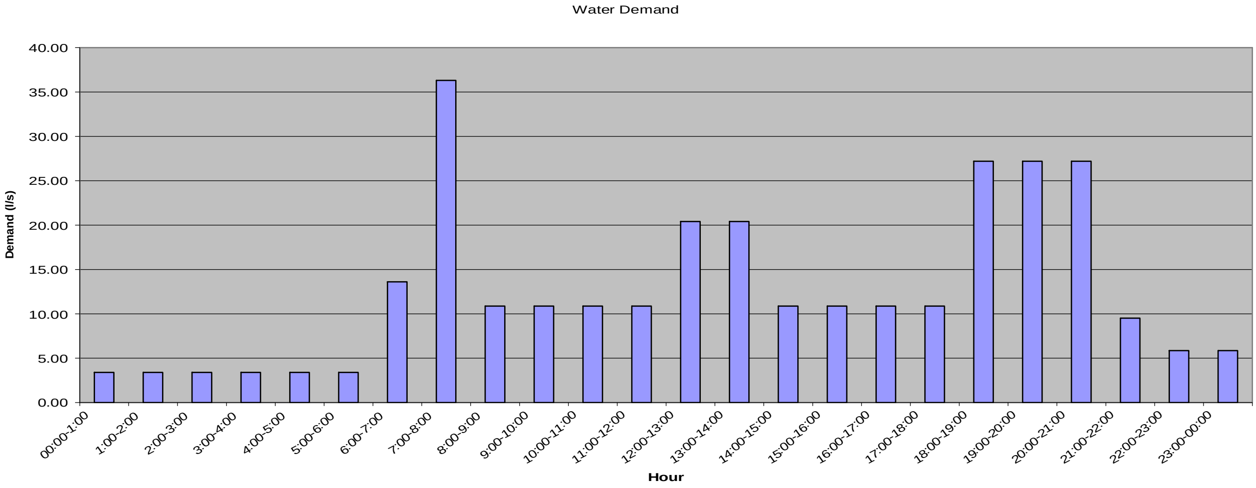


Figure 4.2 - Village daily water demand

The water supply system described above was simulated in EPANET which, with the input of the village demand, friction losses and altitude of each node and reservoir, determines the head necessary for the pump. Knowing the daily hour consumption of the village it is possible to determine the necessary flow to pump.

The results are presented in Table 4.2:

Table 4.2 - Flow to pump for a pump working period of 18h per day

Hour	Duration (h)	Duration (s)	Consumption (l/s)	Consumption per hour (l)	Consumption per day (l)	Q (l/s)	Qpump (18h) (l/s)
00:00-1:00	1	3600	3,40	12240,00	1083484,80	12,54	16,72
1:00-2:00	1	3600	3,40	12240,00			
2:00-3:00	1	3600	3,40	12240,00			
3:00-4:00	1	3600	3,40	12240,00			
4:00-5:00	1	3600	3,40	12240,00			
5:00-6:00	1	3600	3,40	12240,00			
6:00-7:00	1	3600	13,60	48960,00			
7:00-8:00	1	3600	36,31	130723,20			
8:00-9:00	1	3600	10,88	39168,00			
9:00-10:00	1	3600	10,88	39168,00			
10:00-11:00	1	3600	10,88	39168,00			
11:00-12:00	1	3600	10,88	39168,00			
12:00-13:00	1	3600	20,40	73440,00			
13:00-14:00	1	3600	20,40	73440,00			
14:00-15:00	1	3600	10,88	39168,00			
15:00-16:00	1	3600	10,88	39168,00			
16:00-17:00	1	3600	10,88	39168,00			
17:00-18:00	1	3600	10,88	39168,00			
18:00-19:00	1	3600	27,20	97920,00			
19:00-20:00	1	3600	27,20	97920,00			
20:00-21:00	1	3600	27,20	97920,00			
21:00-22:00	1	3600	9,52	34272,00			
22:00-23:00	1	3600	5,85	21052,80			
23:00-00:00	1	3600	5,85	21052,80			

It was considered on Table 4.2 that the pump would have a rest period of 6 hours per day (the previous table refers to the supply system without a water turbine).

According to the Portuguese legislation the velocity of the flow in a pumped part of a supply system has to be between 0,6 and 1,5 m/s. For a penstock (hydropower hydraulic circuit) the maximum limit can attain 5 m/s. These limitations allow determining the pipes diameters with equations (4.2):

$$\begin{aligned} Q &= V \cdot A \\ Q &= V \cdot \frac{\pi \cdot D^2}{4} \\ D &= \sqrt{\frac{4 \cdot Q}{\pi \cdot V}} \end{aligned} \tag{4.2}$$

This supply system was tested as stand-alone system and as a grid connected system. In a grid-connected system it was used a water turbine since it is possible to sell the energy to the grid. In the stand-alone system this possibility was not tested since it is not possible to sell the energy (in this specific case to have a water turbine it is necessary to increase the pump size and therefore its cost).

4.3. System components

The Homer software already contains a list of equipments for some system components (wind turbines and batteries). The software also requires several equipment inputs. These values are presented in Chapters 4.3.1 to 4.3.6 and 4.4 adapted from [1] and [4].

4.3.1. PV array

The characteristics of the PV array are presented in Table 4.3:

Table 4.3 – PV array inputs in Homer software

Slope	53º (latitude plus 15º)
Ground reflectance	0,2
Azimuth	0º
Lifetime	25 years

The tilt was checked with PVSYST4 which has a tool that indicates the optimum tilt and azimuth.

4.3.2. Battery bank

Homer offers a list of battery models (already containing its electrical information). The largest battery present is “Surrette 4KS25P” that has a capacity of 7,6 kWh. This battery has a lifetime of 12 years.

4.3.3. Converter

The converter transforms DC current in AC and vice versa. It has an average lifetime of 15 years and an efficiency of 90 % when performing as an inverter and 85 % efficiency when performing as a rectifier.

4.3.4. Wind turbine

The Homer software contains a list of wind turbines. The turbine chosen for this work was the Fuhrländer 250. The average lifetime expectancy for a wind turbine is 25 years. The hub height used was 60 meter above terrain level. Its power output is related to wind speed as shown in Figure 4.3:

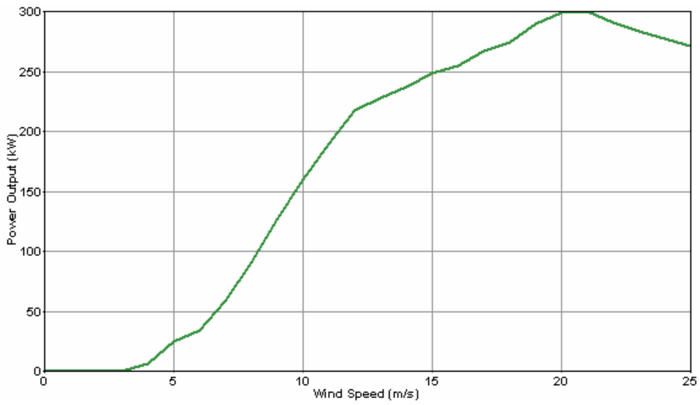


Figure 4.3 – Correlation of wind turbine Fuhrländer 250 output with wind speed (adapted from [8])

4.3.5. Water turbine

For the water turbine it was assumed a lifetime expectancy of 25 years. The efficiency was assumed of 85 %. The costs of this component depend on the head and flow of the turbine and are presented in Chapter 4.4.

4.3.6. System costs

The system has a total cost that is the sum of the cost of each component in its lifetime. The costs used for each component are presented in Table 4.4:

Table 4.4 – Costs of each component of the energy system (adapted from [1], [4] and [5])

Component	Initial cost	Replacement cost	Operation and maintenance cost (€/yr)
Fuhrländer 250	250.000 (1000 €/kW)	0	12.500 (0,5 % initial cost)
PV array	5000 €/kWp	0	50 €/kWp (1 % initial cost)
Converter	500 €/kW	500 €/kW	5 €/kW (1 % initial cost)
Battery	200 €/kWh	200 €/kWh	2 €/kWh (1 % initial cost)

The replacement cost is zero for the wind turbine and the PV array due to the fact that these components have lifetime expectancy equal to the study period (25 years). On the other hand the converter and battery bank have a lifetime expectancy of 15 and 12 years, respectively, and therefore need to be replaced.
These costs already include expenses with specialized personnel and mounting equipment.

The pump and water turbine costs will be mentioned in Chapter 4.4 and the Appendix 6.

4.4. Sensitivity analysis

Some sensitivity analysis was done to provide more accurate results. This sensitivity was done on the PV array, battery and converter costs and also on the population reservoir (when a water turbine was used). For a larger reservoir the flow that can be used by the water turbine can be higher, however the water to be pumped also has to be higher.

For the PV array, battery bank and converter a linked multiplier was used, that multiplies with the initial, replacement and operation and maintenance cost defined in the program. These values will multiply by these components costs. Therefore a lower PV capital multiplier should offer a cheaper and mores cost-effective solution. These values are presented in Table 4.5:

Table 4.5 – PV capital multiplier values for sensitivity analysis

PV capital multiplier	1,0
	0,85
	0,7
	0,3

The different reservoir sizes used are presented in Table 4.6:

Table 4.6 – Different village reservoir sizes for sensitivity analysis

Diameter	20 m						
Initial level	8 m	10 m	14 m	18 m	22 m	26 m	30 m
Volume (m^3)	2513,27	3141,59	4398,23	5654,87	6911,50	8168,14	9424,78

A minimum volume of 832,52 m^3 was established for the population reservoir. Therefore, for higher volumes, a larger flow can be used by the turbine and a larger pump will also be necessary. Further reservoir information is presented in Appendix 7. The turbine's size, price and cost are presented in Table 4.7a:

Table 4.7a – Hydro turbine cost and power for different village reservoir sizes (adapted from [25] and [26])

Flow (l/s)	**Head (m)**	**Power (kW)**	**Price (€/kW)**	**Price (€)**	**O&M (€/yr)**
20,70	49,00	8,62	3000,00	25864,65	258,65
27,77	48,70	11,50	2900,00	33336,64	333,37
51,04	47,00	20,39	2800,00	57093,34	570,93
74,32	44,00	27,80	2600,00	72268,77	722,69
97,59	41,00	34,01	2400,00	81624,28	816,24
120,86	36,00	36,98	2300,00	85061,27	850,61
144,13	31,00	37,98	2300,00	87349,99	873,50

The flow values presented in Table 4.7a are different than the ones displayed on the figures exported from Homer. This is due to the fact that Homer software displays the flows for the 24h. However the turbine only work 15 hours a day. Therefore the values are different. Nevertheless, Homer uses the values presented in Table 4.7 for a 15 hour period. The values in Table 4.7a are for pipes diameter of 326 mm.

When the flow of the turbine is higher, the pumped water will also have to be higher in order to re-establish the water volume. The pump costs can be calculated by Figure 4.4 (adapted from [25]):

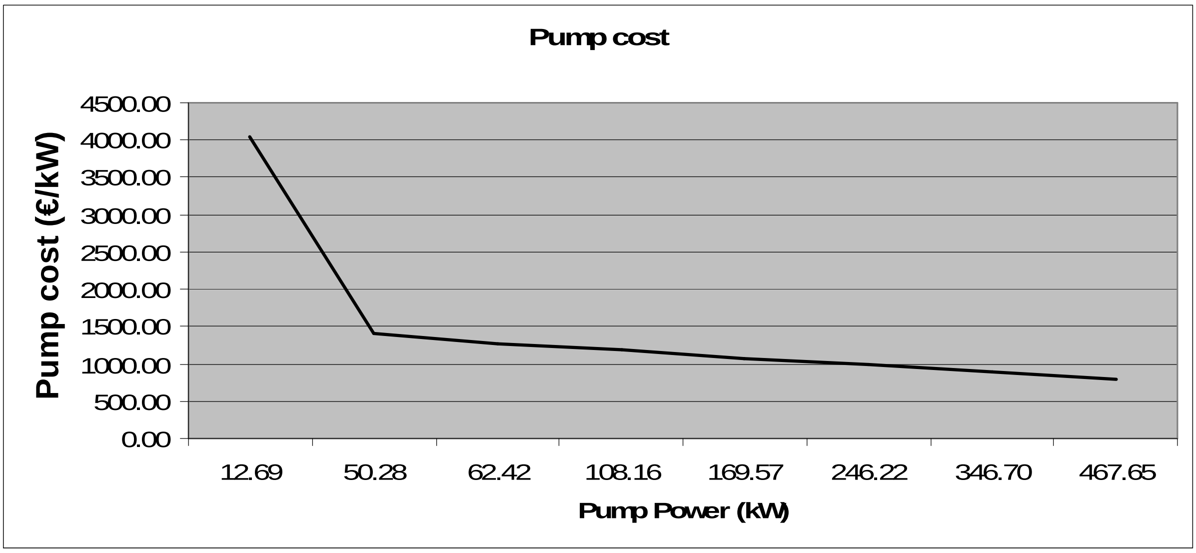


Figure 4.4 – Pump cost per kW of power

The cost associated with the pump is presented in Table 4.7b:

Table 4.7b – Pump adapted cost and power for different village reservoir sizes

Flow (l/s)	**Head (m)**	**Power (kW)**	**Cost/kW**	**Total (€)**	**Difference (€)**
16,72	61,95	12,69	4048,03	67683,13	0
66,88	61,37	50,28	1400,00	93632,00	25948,87
79,73	63,91	62,42	1269,58	101223,92	33540,79
118,51	74,50	108,16	1189,86	141010,42	73327,29
157,30	88,00	169,57	1079,03	169730,79	102047,66
196,09	102,50	246,22	993,35	194786,87	127103,74
234,87	120,50	346,70	885,37	207947,43	140264,30
273,66	139,50	467,65	791,61	216630,92	148947,79

It will have to be analysed if a larger water turbine will bring benefits (energy sold to the grid) when compared with the increase in pump and turbine cost.

As mentioned before, the pipes diameter chosen for the system with a hydro turbine was the largest available in the market, 326 mm.

For the stand-alone system and the grid connected system without a hydro turbine, it was also tested a variation in diameter of the pipes. This variation is presented in Table 4.8:

Table 4.8 – Pipes diameters studied for sensitivity analysis on the stand-alone system

Velocity (m/s)	**Diameter (m)**	**Dcommercial (mm)**
0.6	0.188	130
1.5	0.119	145
		163
		181

The diameters tested were the three largest (the 130 mm was not tested). Different diameters for the pipes mean that the pump power will also vary (larger diameters mean lower velocity and therefore smaller friction losses). This is presented in Table 4.9:

Table 4.9 – Variation in pump power due to variation in pipes diameters on the stand-alone system

D (mm)	**Pump Power (kW)**
145	14.32
161	12.69
181	11.87

The values presented in Table 4.9 are different from the ones presented in Homer imported figures. This is due to the fact that Homer calculates the average daily energy used by the pump (kWh/day).

For the grid connected system the largest diameter available in the market (326 mm) was chosen, as mentioned before, and therefore a variation in diameter size was not studied.

Also for grid connected systems it was done a sensitivity analysis for the sell back energy rate. The values used are in Table 4.10:

Table 4.10 – Sell back rate sensitivity values for grid connected systems

Sell back rate (€/kWh)	0,078
	0,1
	0,15
	0,2

The lowest value is an average of the sell back rate in Portugal. However, with new environmental policies, it is expected that this value will increase when the energy provided is from renewable sources.

A sensitivity study for the grid energy price was also done. The current grid prices are presented in Table 4.11:

Table 4.11 – National electrical tariff in Portugal

	Summer	Winter	Price (€/kWh)
Low consumption hours (LCH) – identified as Vazio in figures	23h-9h	22h-8h	0.043
Medium consumption hours	9h-10:30 12:30-8h 22h-23h	8h-9:30 11:30-19h 21h-22h	0.073
Peak consumption hours	11h-12h 20h-22h	10h-11h 19h-21h	0,128

A larger gap between these prices was tested. These values are presented in Table 4.12:

Table 4.12 – Difference between consumption periods

	Price (€/kWh)
Low consumption hours (LCH) – identified as Vazio in figures	0.043 (1) 0,035 (2) 0,030 (3)
Medium consumption hours	0.073 (1) 0,080 (2) 0,090 (3)
Peak consumption hours	0,128 (1) 0,130 (2) 0,140 (3)

These values were linked as the numbers in Table 4.12 indicate.

In the stand-alone system it was also taken in to account as a sensitivity parameter the grid extension cost. The values used are presented in Table 4.13:

Table 4.13 – Sensitivity values for the grid extension cost for the stand-alone system

Grid extension cost (€/km)	10.000
	15.000
	20.000
	25.000
	30.000

This parameter is used to determine the breakeven grid distance, that is, the minimum distance from the national electrical grid from which the stand alone system is cost effective.

4.5. Weather data

4.5.1. Irradiation

Portugal is one of the warmest countries in Europe. It is located in the South West of Europe and it presents high levels of sun irradiation. Even during the winter period, although temperature may get quite low it is common to have a considerable amount of days with good sunlight exposure.

The Homer software can import solar data through the latitude and longitude of a certain location. This data is imported from NASA's Surface Solar Energy Data Set which provides monthly average solar radiation data for everywhere on earth.

Lisbon is at 38º 42'N and 9º 05'W. For these coordinates Homer imported the following data, presented in Table 4.14 and Figure 4.5:

Table 4.14 – Solar data retrieved from Homer software (adapted from [8])

Month	**Clearness Index**	**daily radiation (kWh/d/m2)**
January	0.529	2.360
February	0.539	3.150
March	0.598	4.650
April	0.595	5.780
May	0.609	6.730
June	0.603	6.980
July	0.627	7.080
August	0.670	6.820
September	0.655	5.520
October	0.611	3.910
November	0.521	2.480
December	0.505	2.040

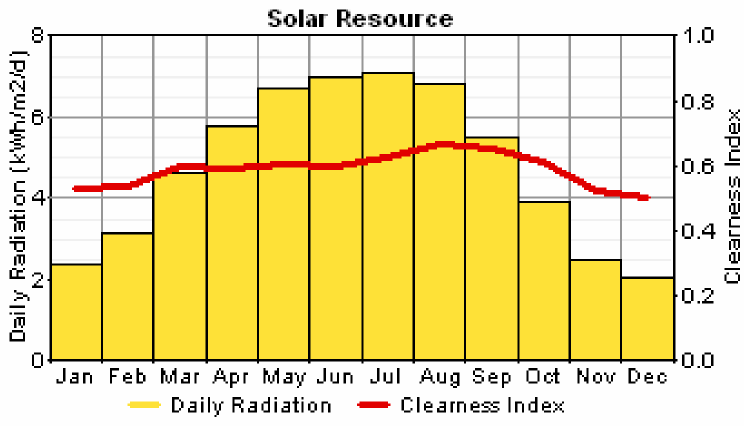


Figure 4.5 – Solar data retrieved from Homer software

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth.

4.5.2. Wind

Hybrid systems, composed of solar and wind energy, were simulated. Wind turbines are already able to deliver energy at a price that can compete with conventional sources. There are wind turbines designed for low wind velocity, moderate velocity and high velocity.

In theory, a solar/wind hybrid system will have a better performance then a PV stand alone system due to the fact that low solar irradiation seasons are associated with high wind velocity seasons and vice-versa.

The wind data was retrieved from Meteonorm, which is a global climatologic database combined with a synthetic weather generator. The outputs are climatologic means as well as time series of typical years for any point on earth.

Meteonorm supplies monthly averages of wind speed. The Homer software then generates hourly data using those monthly averages and taking into consideration the following factors:

- The weibull k values;
- The autocorrelation factor;
- The diurnal pattern strength;
- The hour of peak wind speed.

Due to the lack of information regarding these factors, the pre-defined values were used. Those values are presented in Table 4.15:

Table 4.15 – Predefined wind data from Homer software

Weibull value	2
Autocorrelation factor	0,85
Diurnal pattern strength	0,25
Hour of peak wind speed	15

The wind speed also varies with altitude (logarithmic, according to Homer). It was defined an altitude of 80 meters.

The wind data used is relative to Lisbon, Portugal and the values used are presented in Table 4.16:

Table 4.16 – Wind average speed for Lisbon (adapted from [6])

Month	Wind speed average (m/s)
January	3.60
February	3.90
March	3.80
April	4.00
May	4.10
June	3.90
July	4.00
August	4.10
September	3.30
October	3.30
November	3.40
December	3.60

From these values, Homer then generates hourly values using an algorithm. The wind maximum, minimum and average monthly values are presented in Figure 4.6:

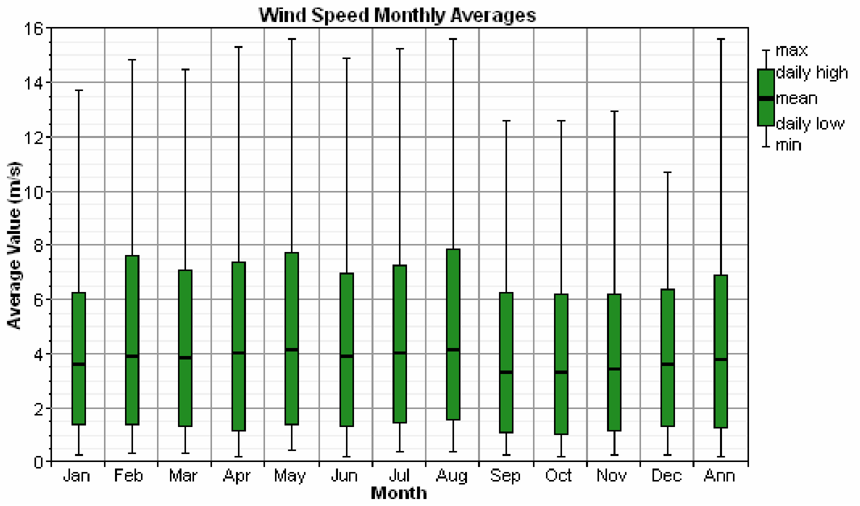


Figure 4.6 – Wind monthly variation generated by Homer software

As it is possible to see although the averages values are quite low, there are large variations of wind speed. The output of a wind turbine increases roughly cubically to the increase in wind speed.

There is an increase in wind speed for higher altitudes such as presented in Figure 4.7:

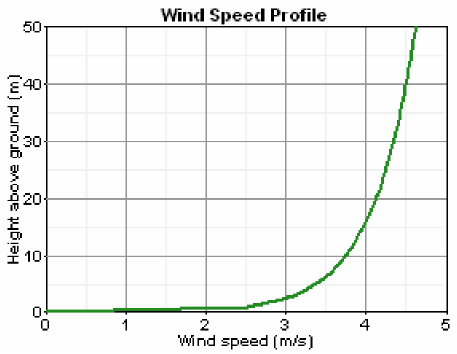


Figure 4.7 – Correlation between wind speed and height above ground

4.6. Stand-alone system

As mentioned before a water turbine was not used in the stand-alone system. In this case it was assumed the pump would have a rest period of 6 hours per day. Therefore, as mentioned in Chapter 4.4, for a flow of 16,72 l/s the water pump power is 12,69 kW. This is shown in Figure 4.8:

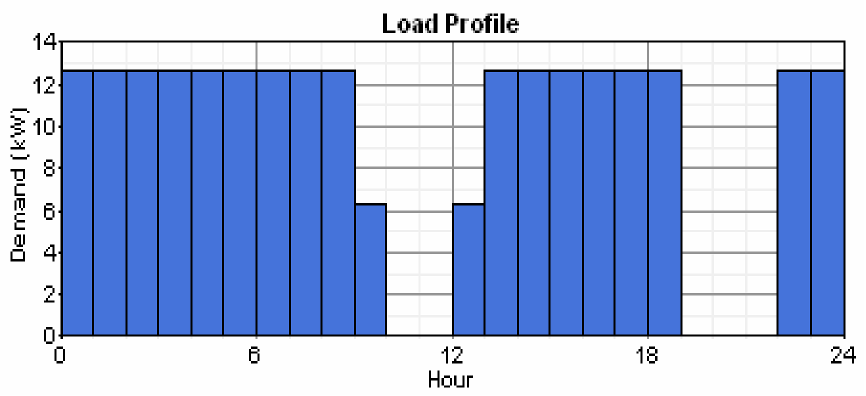


Figure 4.8 – Daily distribution of pump power

The intermediate value between 9 and 10h and between 12 and 13h is due to the fact that the pump only works for half an hour (the Homer software only accepts one value for a whole hour therefore, to simulate half an hour of working period the power was reduced to half).

4.6.1. Results

For this system configuration and for average values of load (diameter of 163 mm – pump power of 12,69 kW), a PV cost multiplier of 1,0 (average PV cost of 5000 €/kWp) and a grid extension cost of 20.000 € the results are presented in Table 4.17:

Table 4.17 – Optimized system configuration and costs for average sensitivity values for a stand-alone system

Number of wind turbines	1
PV power (Wp)	30
Battery (Nº/kWh)	110/836
Converter (kW)	20
Total Net Present Cost (€)	902692
Cost of electricity (€/kWh)	0,774
Breakeven distance to grid (km)	31,6

4.6.2. Sensitivity

The system configuration depends on the sensitivity values that were defined. This means that, for example, for different PV capital multipliers the system presented will be different. The same happens with the variation in load size. This correlation is presented in Figure 4.9:

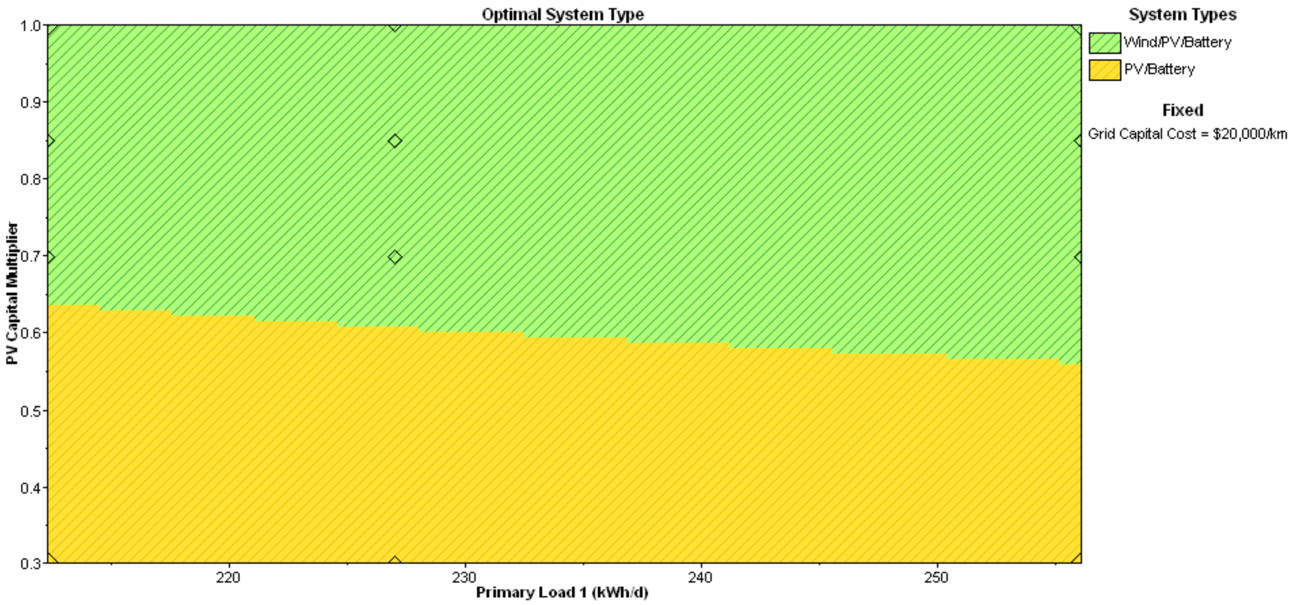


Figure 4.9 – Optimized system configuration for different pump power and PV multiplier values

In Figure 4.9 it is possible to see when a system composed of PV and batteries is more cost effective than one composed of Wind, PV and batteries for different pump power and PV capital multiplier values. For example, for normal PV costs (PV multiplier of 1,0) and average pump power the optimized system would be composed of Wind, PV and battery bank (green area of the diagram). If the PV cost reduced by 60 % (PV multiplier of 0,4) for an average pump power the optimized system would be composed of only PV and battery bank (yellow area of the diagram).

Has expected, for lower PV multipliers the optimized system is composed of just PV and battery. This is due to the fact that for lower multipliers the initial, replacement and maintenance cost of PV, batteries and converter is lower and therefore this configuration tends to get cheaper when compared to the wind solution.

4.6.2.1. PV capital multiplier

As mentioned before, the PV cost multiplier is linked to the battery and converter costs as well. This sensitivity value has the purpose of simulating possible subsidies for these systems and probable decrease in price in the next years for PV systems.

Table 4.18 displays the different system configurations and economic calculations for different PV multipliers for a pump load of 12,69 kW and a grid extension price of 20.000 €/km:

Table 4.18 – PV capital multiplier influence in the system configuration and cost

PV multiplier		
1,0	**System configuration**	1 wind turbine; 30 kWp PV; 836 kWh battery; 20 kW converter
	Total Net Present Cost (€)	902692
	Cost of electricity (€/kWh)	0,774
	Breakeven distance to grid (km)	31,6
0,85	**System configuration**	1 wind turbine; 30 kWp PV; 836 kWh battery; 20 kW converter
	Total Net Present Cost (€)	831214
	Cost of electricity (€/kWh)	0,712
	Breakeven distance to grid (km)	28,8
0,70	**System configuration**	1 wind turbine; 30 kWp PV; 836 kWh battery; 20 kW converter
	Total Net Present Cost (€)	759737
	Cost of electricity (€/kWh)	0,651
	Breakeven distance to grid (km)	26,0
0,30	**System configuration**	0 wind turbine; 100 kWp PV; 1710 kWh Battery; 20 kW converter
	Total Net Present Cost (€)	353753
	Cost of electricity (€/kWh)	0,303
	Breakeven distance to grid (km)	10,1

These results can also be presented in a graphic form in Figures 4.10 to 4.13:

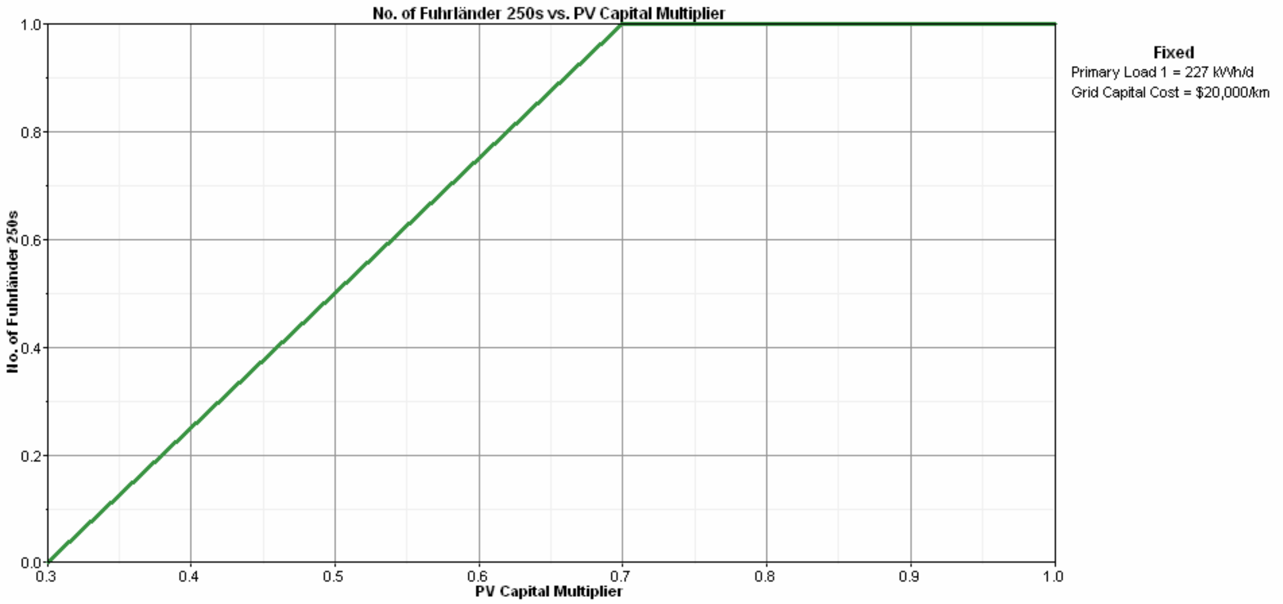


Figure 4.10 – Number of wind turbines vs. PV capital multiplier for a stand-alone system

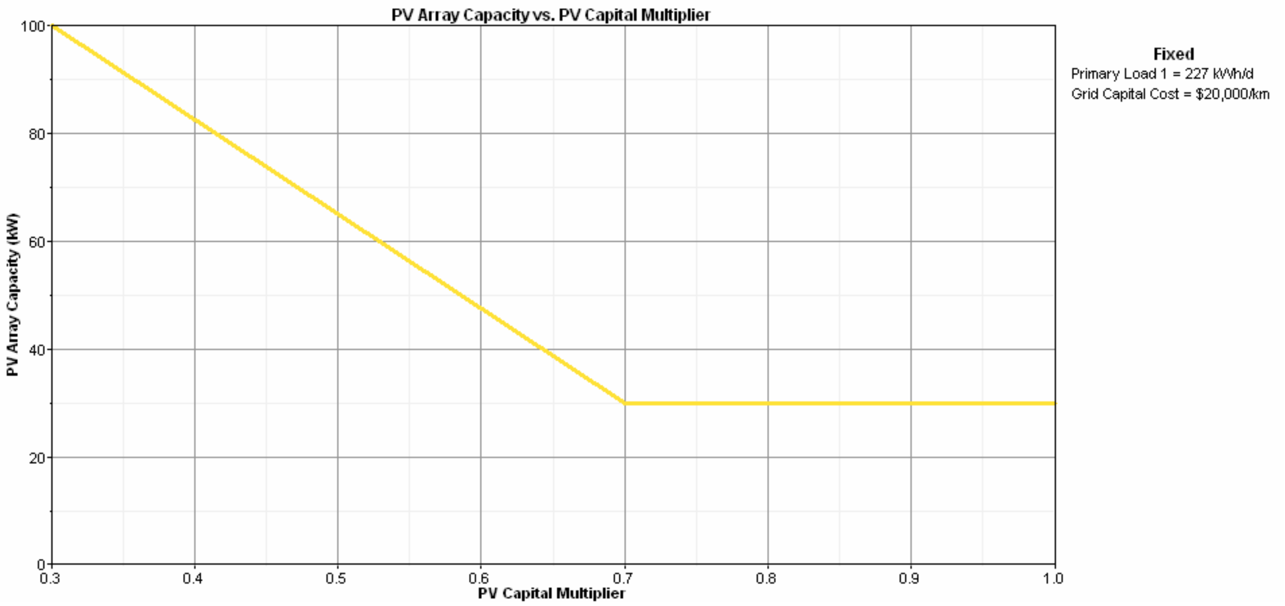


Figure 4.11 – PV array capacity vs. PV capital multiplier for a stand-alone system

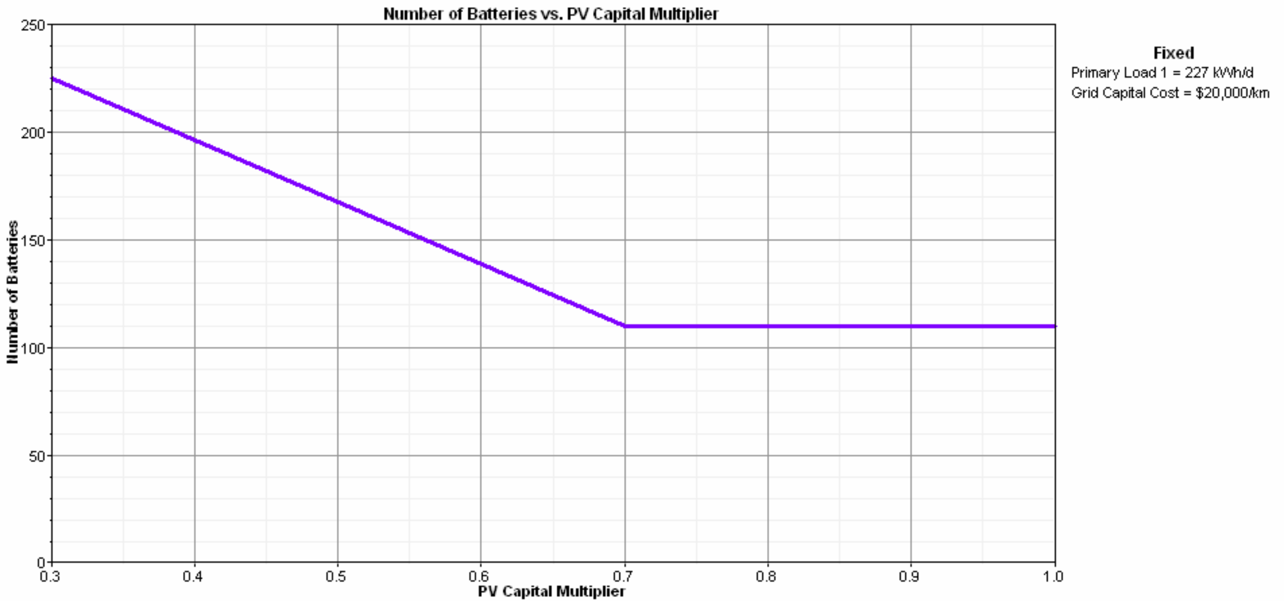


Figure 4.12 – Number of batteries vs. PV capital multiplier for a stand-alone system

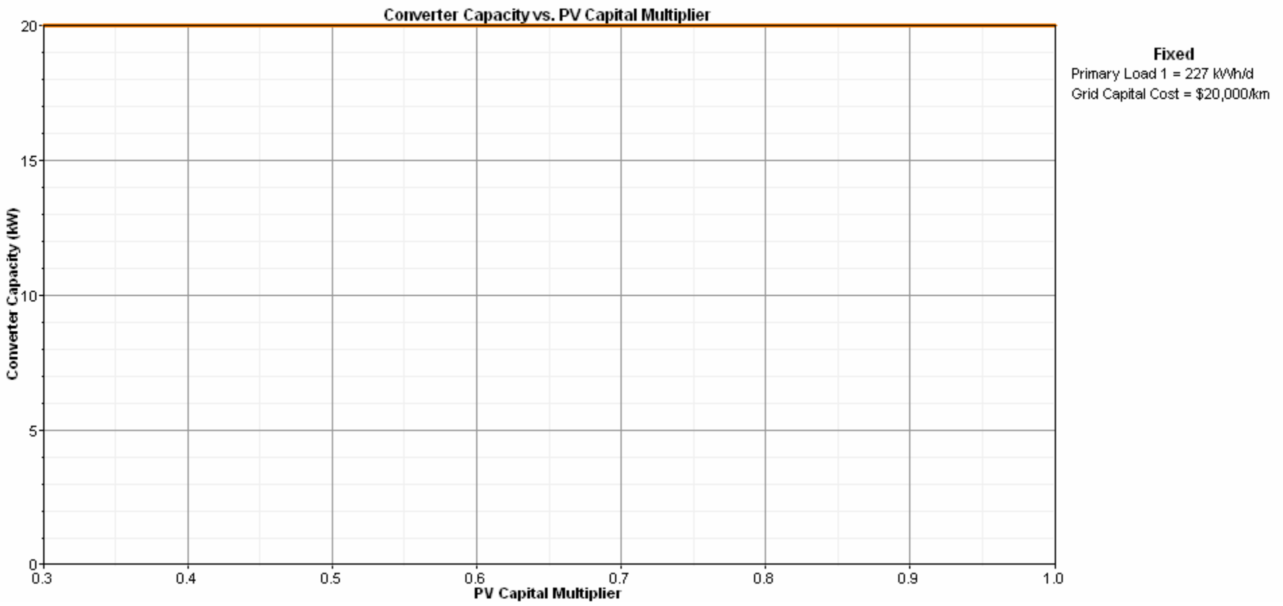


Figure 4.13 – Converter capacity vs. PV capital multiplier for a stand-alone system

The previous figures show the different system configurations for different PV capital multipliers. As expected, for a lower multiplier the optimum system is composed of a larger PV array and battery bank and a smaller number of wind turbines. For higher values the wind has a larger portion of the energy production since nowadays wind energy technology is more cost effective when compared to PV technology.

Figures 4.14 and 4.15 show the economic results for different PV capital multipliers:

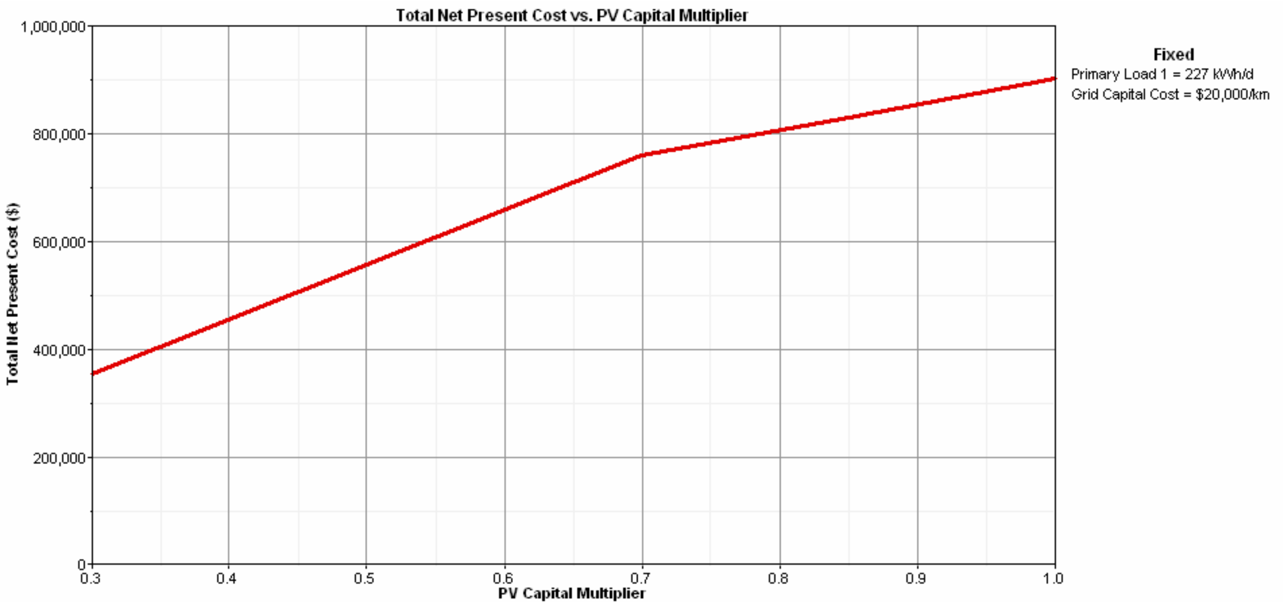


Figure 4.14 – Net present cost vs. PV capital multiplier for a stand-alone system

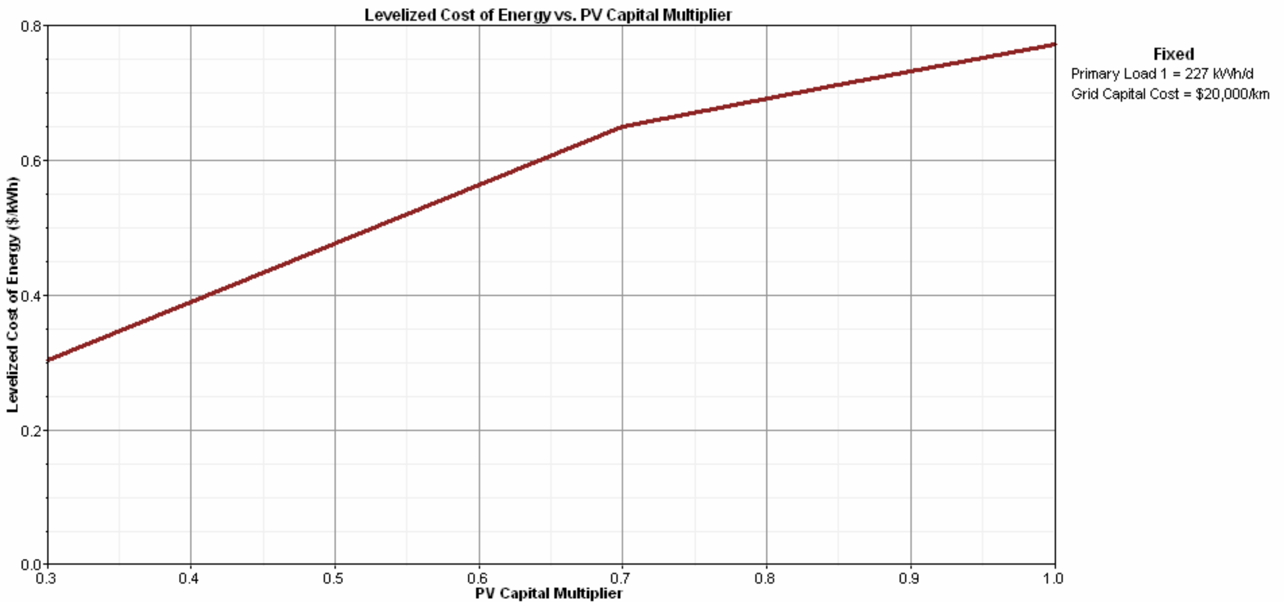


Figure 4.15 – Cost of energy vs. PV capital cost multiplier for a stand-alone system

The two main economic parameters are lower for a lower PV multiplier and vice versa, as expected.

One of the main factors in a stand-alone system is the breakeven distance for the electrical grid. This is displayed in Figure 4.16:

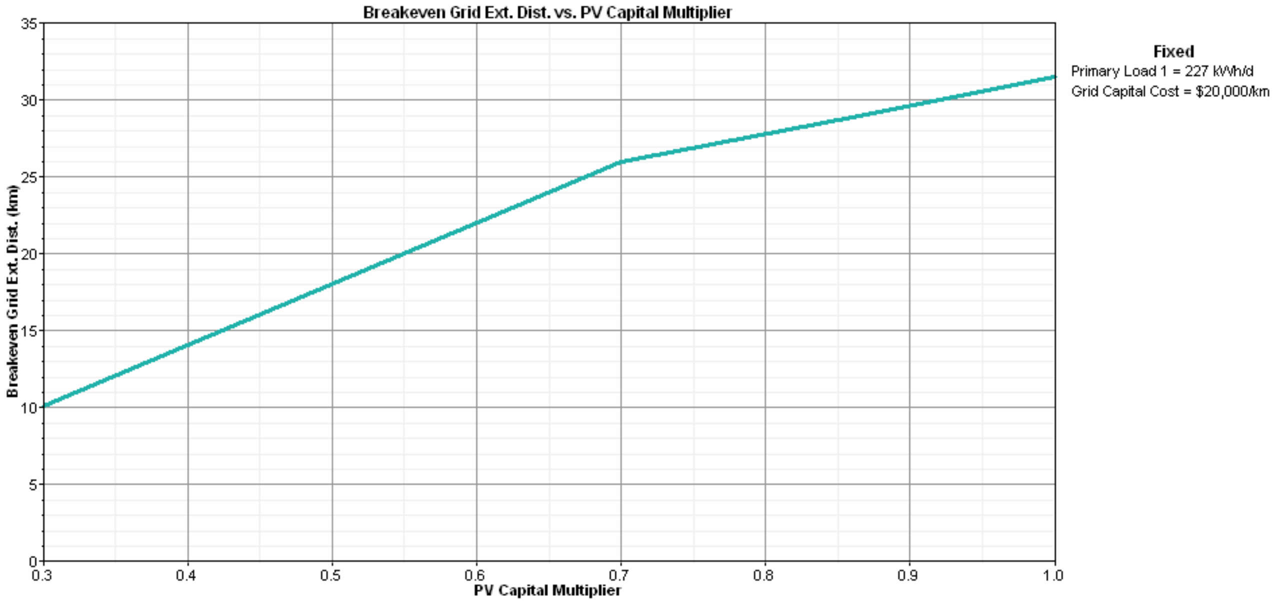


Figure 4.16 – Breakeven grid distance vs. PV capital multiplier for a stand-alone system

The breakeven distance is lower for lower PV multipliers. When the multiplier is 0,3 (as it happens in Sweden) the distance is roughly 10 km which is a very attractive value.

4.6.2.2. Pump Power

The pump power variation is due to the variation in pipes diameter size. Although a larger diameter will mean a smaller load and therefore a more cost effective solution, the decrease in the system cost would need to be compared with the increase pipes costs. The results presented in Table 4.19 refer to a 20.000 €/km of grid extension and a PV capital multiplier of 1,0:

Table 4.19 – Pump power influence in the stand-alone system configuration and cost

Pump Power		
11,87	**System configuration**	1 turbine; 20 kWp PV; 836 kWh battery; 20 kW converter
	Total Net Present Cost (€)	845645
	Cost of electricity (€/kWh)	0,775
	Breakeven distance to grid (km)	29,6
12,69	**System configuration**	1 turbine; 30 kWp PV; 836 kWh battery; 20 kW converter
	Total Net Present Cost (€)	902692
	Cost of electricity (€/kWh)	0,774
	Breakeven distance to grid (km)	31,6
14,32	**System configuration**	1 turbine; 30 kWp PV; 1026 kWh battery; 25 kW converter
	Total Net Present Cost (€)	972442
	Cost of electricity (€/kWh)	0,739
	Breakeven distance to grid (km)	33,8

These results can also be presented in a graphic form in Figures 4.17 to 4.20:

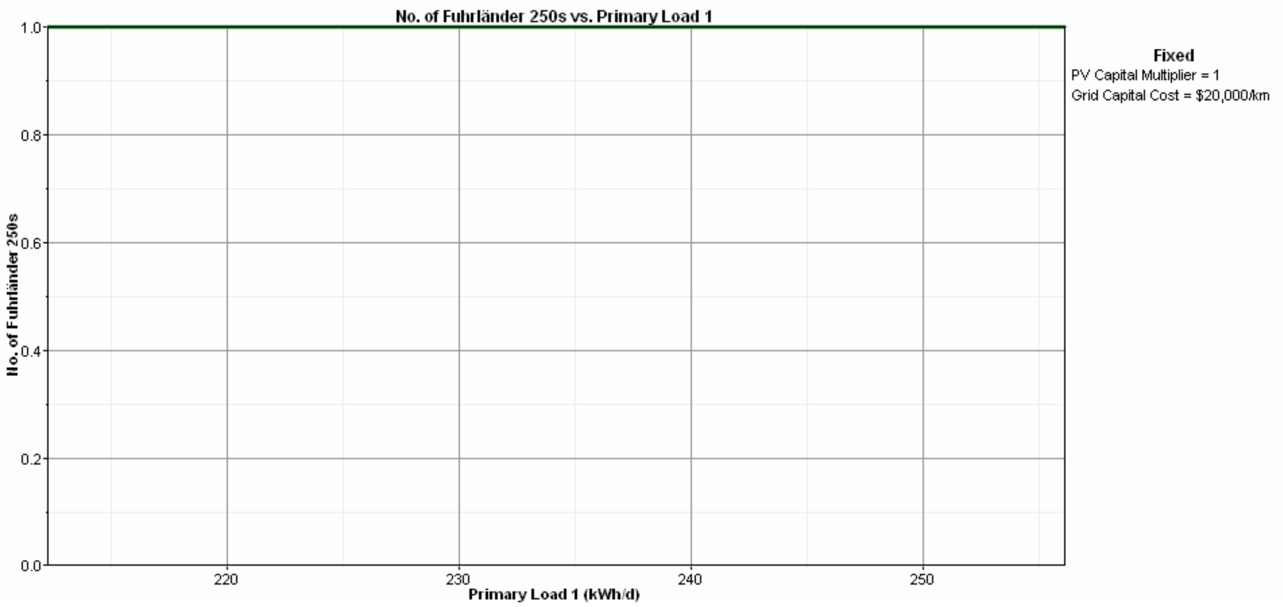


Figure 4.17 – Number of wind turbines vs. pump power for a stand-alone system

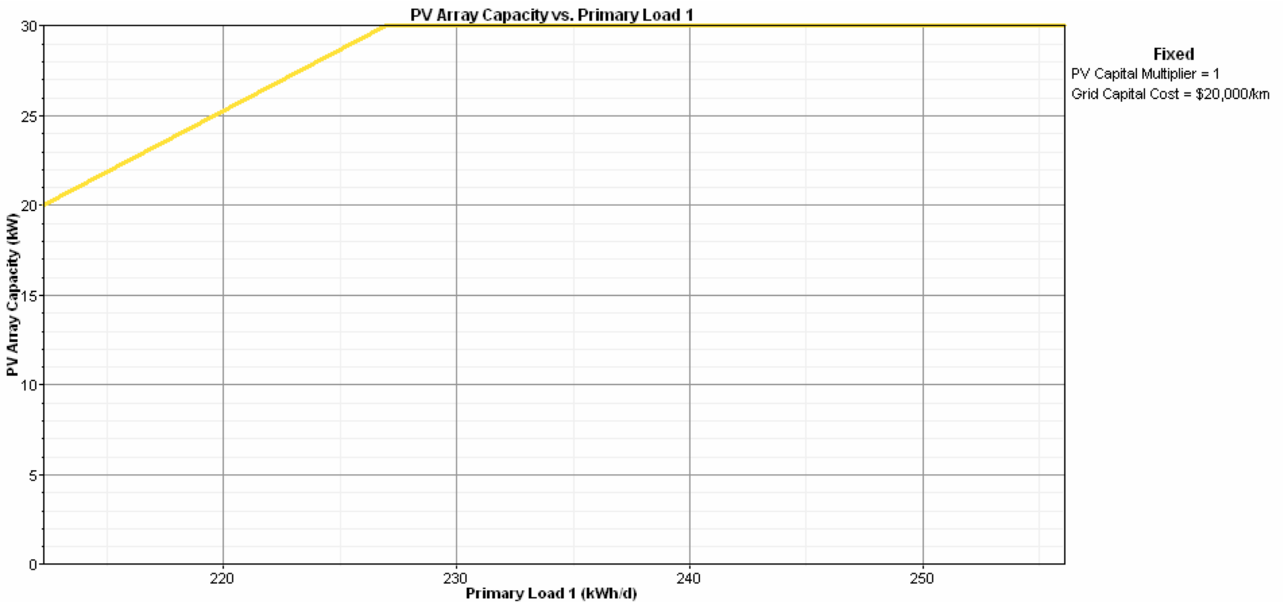


Figure 4.18 – PV array capacity vs. pump power for a stand-alone system

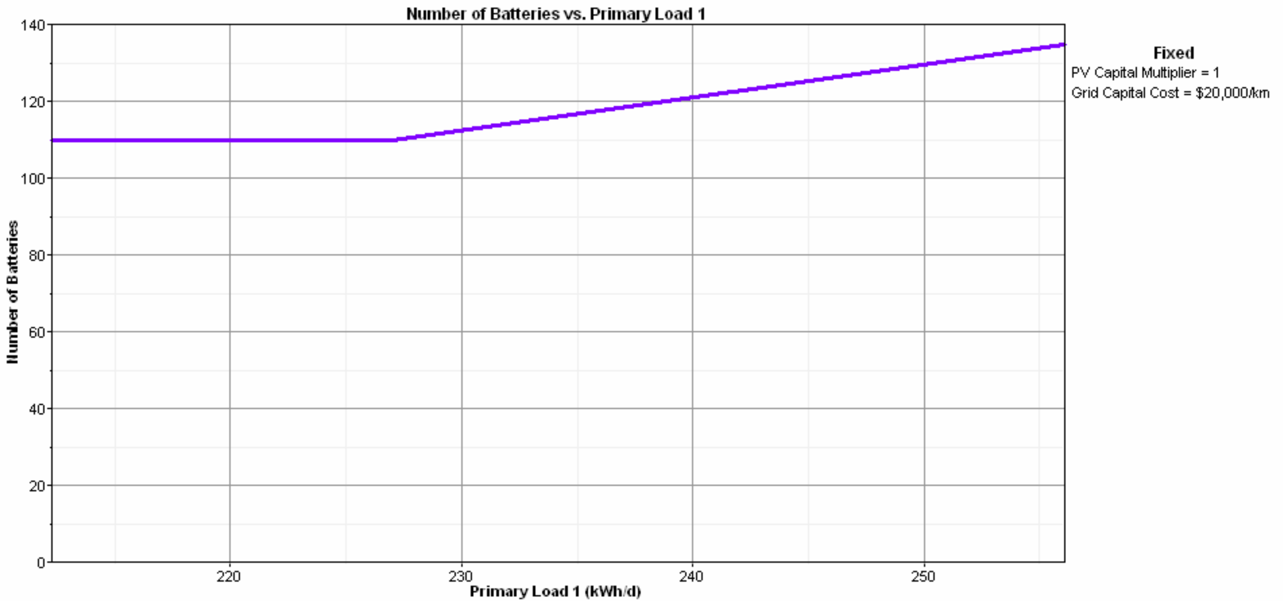


Figure 4.19 – Number of batteries vs. pump power for a stand-alone system

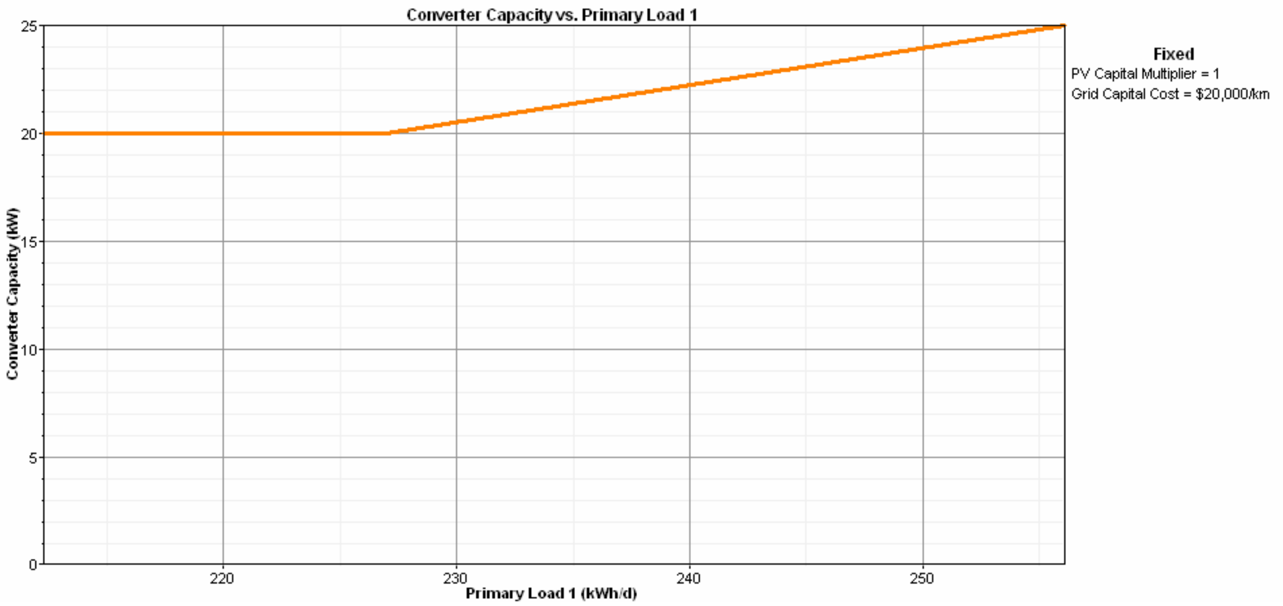


Figure 4.20 – Converter capacity vs. pump power for a stand-alone system

As expected for a lower pump power the system configuration tends to get smaller. On the other hand for higher energy consumption the system gets larger.

The economic results are displayed in Figures 4.21 and 4.22:

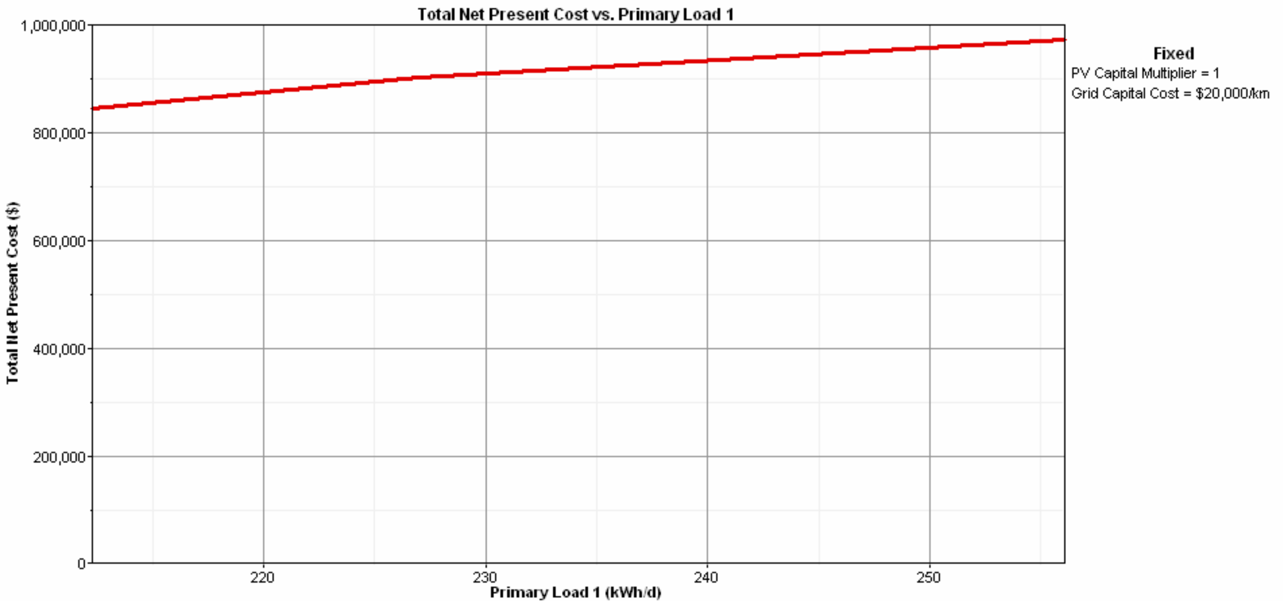


Figure 4.21 – Net present cost vs. pump power for a stand-alone system

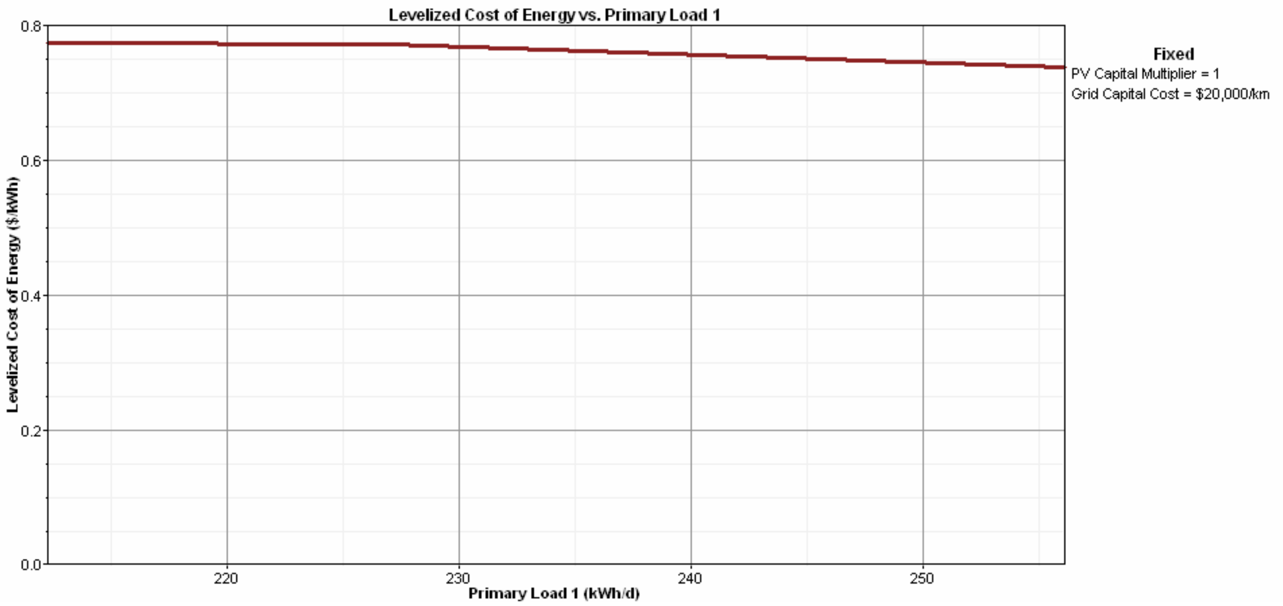


Figure 4.22 – Cost of energy vs. pump power for a stand-alone system

As expected the net present cost decreases for lower loads and increases for higher ones.
However, the cost of energy is lower for higher pump loads. This is due to the fact that the cost of energy is relative to useful produced energy and not to the whole energy production (there is a very large portion of excess energy). Knowing that in all pump power situations the system includes only one wind turbine, the excess energy is lower when the load is higher and therefore the cost of energy is lower as well.

In Figure 4.23 it is shown the influence of the pump power variation in the breakeven distance to the electric grid:

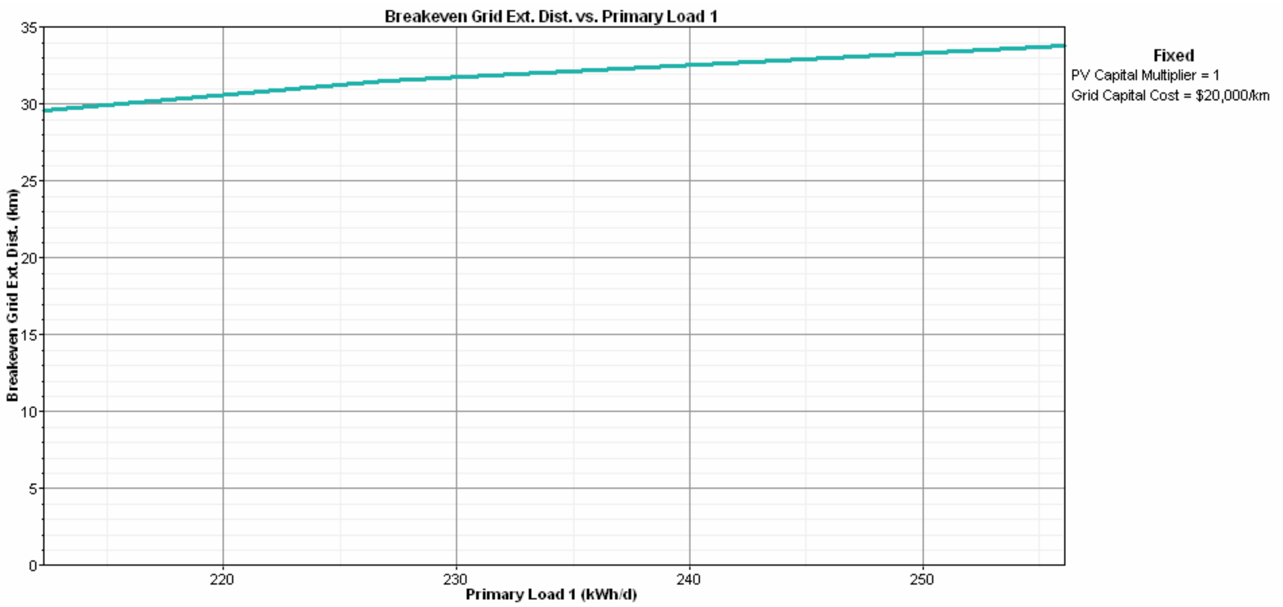


Figure 4.23 – Breakeven distance to grid vs. pump power for a stand-alone system

Due to the fact that higher load values mean a more expensive system, the breakeven distance to grid will also increase for higher loads.

4.6.2.3. Grid extension cost

The grid extension cost has no influence on the economic results of the system. It only causes variations in the breakeven distance to the electric grid. These changes are shown in Table 4.20 (for a PV multiplier of 1,0 and a pump power of 12,69 kW):

Table 4.20 – Grid extension cost influence in the stand-alone system breakeven distance to grid

Grid extension cost (€/km)	Breakeven distance to grid (km)
10.000	51,7
15.000	39,2
20.000	31,6
25.000	26,4
30.000	22,7

These results can also be displayed in the form of graphic, in Figure 4.24:

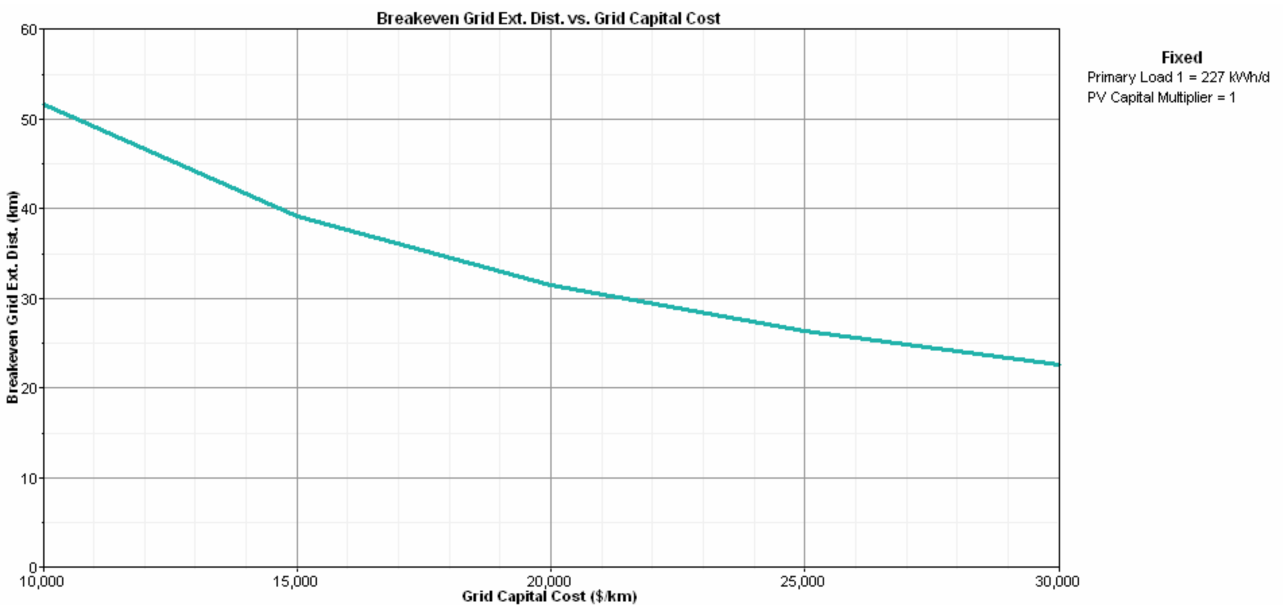


Figure 4.24 – Breakeven grid extension vs. grid capital cost for a stand-alone system

Has expected for higher cost of grid extension the breakeven distance to the grid tends to get smaller. This graphic is not linear since the price of the grid energy is also taken into consideration and does not vary.

4.7. Grid connected system

For the grid connected system it was necessary to input the tariff of the grid energy. The tariff is presented in Table 4.21:

Table 4.21 – National electrical tariff in Portugal

	Summer	Winter	Price (€/kWh)
Low consumption hours (LCH) – identified as Vazio in figures	23h-9h	22h-8h	0.043
Medium consumption hours	9h-10:30 12:30-8h 22h-23h	8h-9:30 11:30-19h 21h-22h	0.073
Peak consumption hours	11h-12h 20h-22h	10h-11h 19h-21h	0,128

Two grid connected systems were tested: one with a water turbine and another without the water turbine. This is due to the fact that in order to have a water turbine the pump energy consumption needs to increase causing an energy increase in the system configuration and cost as well.

In grid connected systems, in opposition to stand alone systems, there is no excess energy because all energy that is not used is sold to the national electrical grid.

As mentioned in Chapter 4.4 the variations in energy sell back and in the water turbine size were introduced in Homer software as sensitivity values.

4.7.1. System with a water turbine

In order to use the turbine a larger amount of water is necessary to be pumped (water pumped during the night when the energy tariff is lower to fill the village tank and used during the day for the hydro turbine). This correlation is presented in Table 4.22 (adapted from [25] and [26]):

Table 4.22 – Hydro turbine and pump characteristics for different reservoir levels (different flows) (adapted from [25] and [26])

Turbine (15h)						**Pump**					
									Price		
Flow (l/s)	**Head (m)**	**Power (kW)**	**Price (€/kW)**	**Price (€)**	**O&M (€/yr)**	**Flow (l/s)**	**Head (m)**	**Power (kW)**	**Cost/kW**	**Total (€)**	**Difference (€)**
20,70	49,00	8,62	3000,00	25864,65	258,65	66,88	61,37	50,28	1400,00	93632,00	25948,87
27,77	48,70	11,50	2900,00	33336,64	333,37	79,73	63,91	62,42	1269,58	101223,92	33540,79
51,04	47,00	20,39	2800,00	57093,34	570,93	118,51	74,50	108,16	1189,86	141010,42	73327,29
74,32	44,00	27,80	2600,00	72268,77	722,69	157,30	88,00	169,57	1079,03	169730,79	102047,66
97,59	41,00	34,01	2400,00	81624,28	816,24	196,09	102,50	246,22	993,35	194786,87	127103,74
120,86	36,00	36,98	2300,00	85061,27	850,61	234,87	120,50	346,70	885,37	207947,43	140264,30
144,13	31,00	37,98	2300,00	87349,99	873,50	273,66	139,50	467,65	791,61	216630,92	148947,79

The Difference column is the difference between the cost of the pump in question and the pump cost when there is no water turbine (pump power distributed along the day) as it happened in the stand-alone system. These calculations are for a working period of 15 hours and 9 hours for the turbine and pump, respectively. The pump power is presented in Figure 4.25:

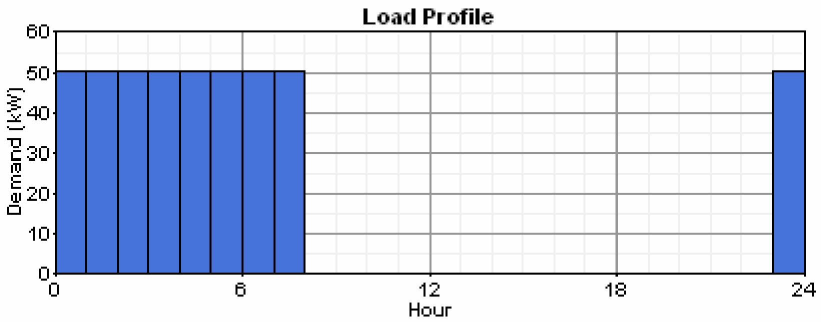


Figure 4.25 – Pump load for a flow of 66,88 l/s

As shown in Table 4.22 the pump power has to increase in order to increase the turbine's flow as well.

4.7.1.1. Results

For a PV cost multiplier of 1,0 and a sellback rate of 0,078 €/kWh the most cost effective system is composed of just a water turbine. The results of this system are presented in Table 4.23:

Table 4.23 – System configuration and cost for a grid connected system without a hydro turbine

Number of wind turbines	0
PV power (Wp)	0
Battery (N°/kWh)	0/0
Converter (kW)	0
Grid Annual Purchase (kWh)	164250
Total Net Present Cost (€)	79711
Cost of electricity (€/kWh)	0,027
Percentage of renewable source (%)	21,5

The results presented in Table 4.24 refer to a sellback rate of 0,10 €/kWh:

Table 4.24 - System configuration and cost for a grid connected system with a hydro turbine for a sellback rate of 0,10 €/kWh

Number of wind turbines	6
PV power (Wp)	0
Battery (N°/kWh)	0/0
Converter (kW)	0
Grid Annual Purchase (kWh)	79780
Total Net Present Cost (€)	-82090
Cost of electricity (€/kWh)	-0,003
Percentage of renewable source (%)	95,6

4.7.1.2. Sensitivity analysis

The system configuration varies for different sell back prices and stream flows. This variation (for an average pump power of 50,28 kW) is shown in Figure 4.26 and 4.27:

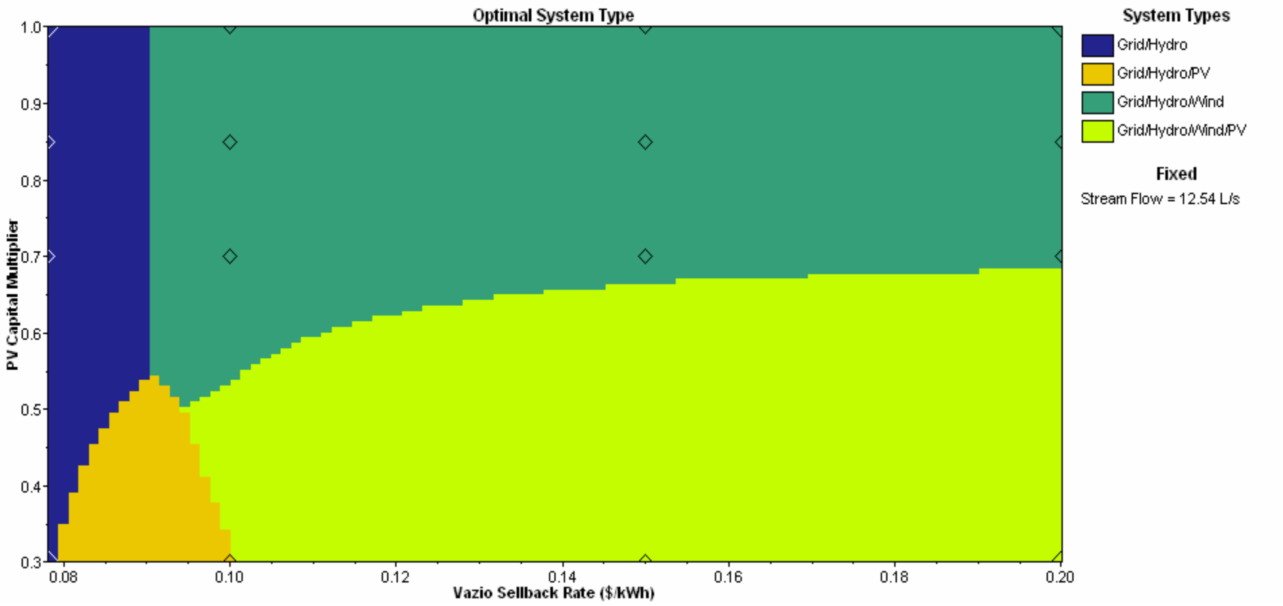


Figure 4.26 – Optimized system configuration for different PV and sellback rate values for a grid connected system with a hydro turbine

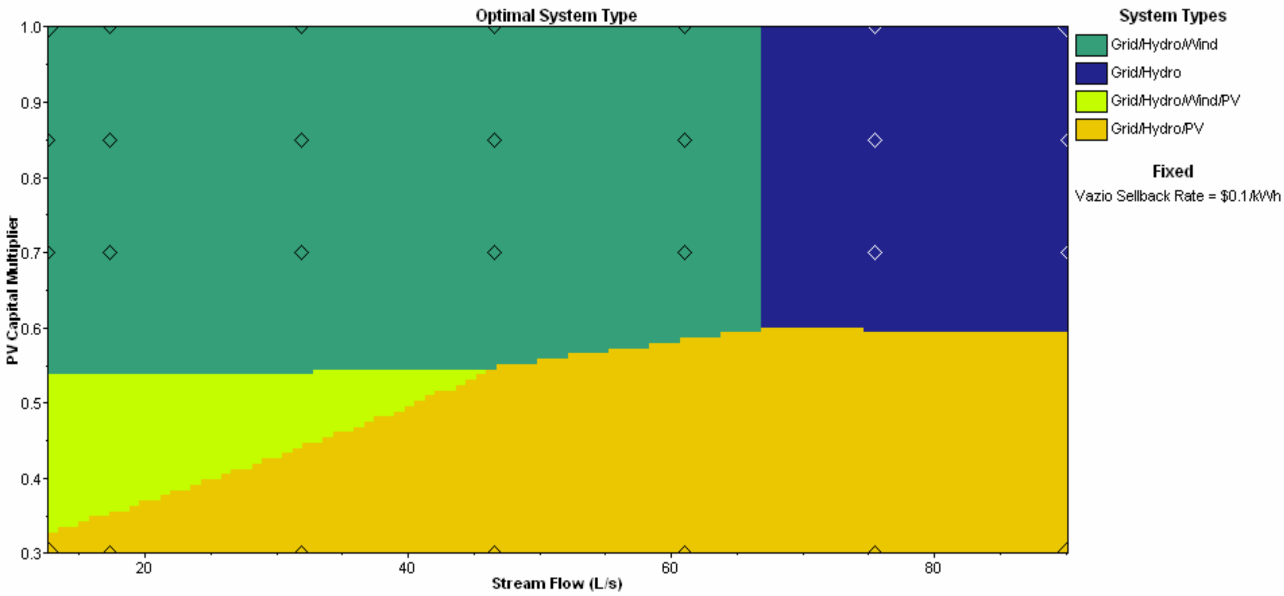


Figure 4.27 – Optimized system configuration for different PV and stream flow values for a grid connected system with a hydro turbine

Figure 4.27 is for a energy sellback price of 0,10 €/kWh since for a price of 0,078 €/kWh the only system configuration is the grid/turbine system. Figure 4.27 displays the optimized system configuration for different PV multipliers and stream flows. For example, for a stream flow of 20,07 l/s (correspondent to 12,54 l/s presented by Homer, as mentioned in Chapter 4.4).and a reduction of 60 % in PV cost (PV multiplier of 0,4) the optimized system is composed of grid connection, hydro turbine, wind turbines and PV (yellow area). If the cost reduction of PV was only of 20 % (PV multiplier of 0,8) than the optimized system would no longer be composed of PV source (green area). The same type of correlation is done between the PV capital multiplier and the sellback rate in Figure 4.26.

4.7.1.2.1. Stream flow

The stream flow determines the power of the water turbine used. Table 4.25 displays the system configuration and main economic values for the different stream flow values for a PV multiplier of 1,0 and energy sellback price of 0,078 €/kWh:

Table 4.25 – Hydro flow influence in the system configuration and cost for a grid connected system

Stream flow (l/s)		
20,70	**System configuration**	164250 kWh/yr grid; 8,20 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	79711
	Cost of electricity (€/kWh)	-0,027
	Percentage of renewable source (%)	21,5
27,77	**System configuration**	203911 kWh/yr grid; 11,35 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	93538
	Cost of electricity (€/kWh)	0,025
	Percentage of renewable source (%)	23,3
51,04	**System configuration**	353316 kWh/yr grid; 20,39 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	158870
	Cost of electricity (€/kWh)	0,024
	Percentage of renewable source (%)	23,7
74,32	**System configuration**	553942 kWh/yr grid; 27,80 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	253875
	Cost of electricity (€/kWh)	0,026
	Percentage of renewable source (%)	21,2
97,59	**System configuration**	804325 kWh/yr grid; 34,01 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	379746
	Cost of electricity (€/kWh)	0,027
	Percentage of renewable source (%)	18,5
120,86	**System configuration**	1132577 kWh/yr grid; 36,98 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	565184
	Cost of electricity (€/kWh)	0,030
	Percentage of renewable source (%)	14,9
144,13	**System configuration**	1527700 kWh/yr grid; 37,98 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	801227
	Cost of electricity (€/kWh)	0,033
	Percentage of renewable source (%)	11,8

When the hydro flow increases the system tends to get more expensive due to the increase in pump power which the leads to higher energy purchases from the grid (the values presented do not take into account the increase of pump price which would increase the system cost – this is presented in Appendix 6).This is due to the fact that the pipes diameter does not vary, and therefore the friction losses increase in a quadratic way. As mentioned before for a sellback price of 0,078 €/kWh, PV and wind technologies can not compete with the grid energy.

These results are also presented in the form of graphic, in Figures 4.28 to 4.30:

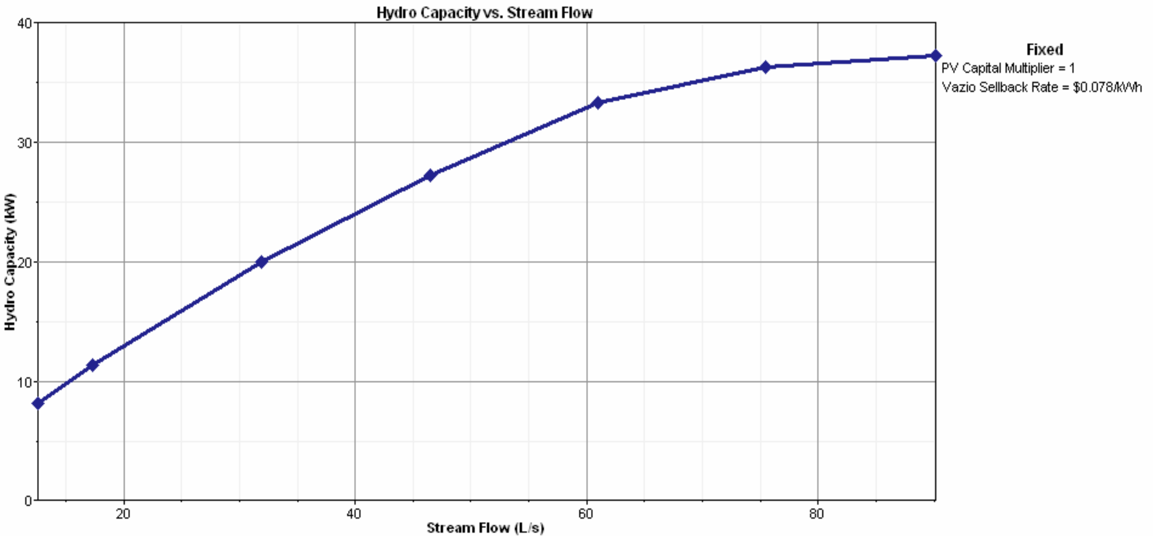


Figure 4.28 – Hydro capacity vs. stream flow for a grid connected system

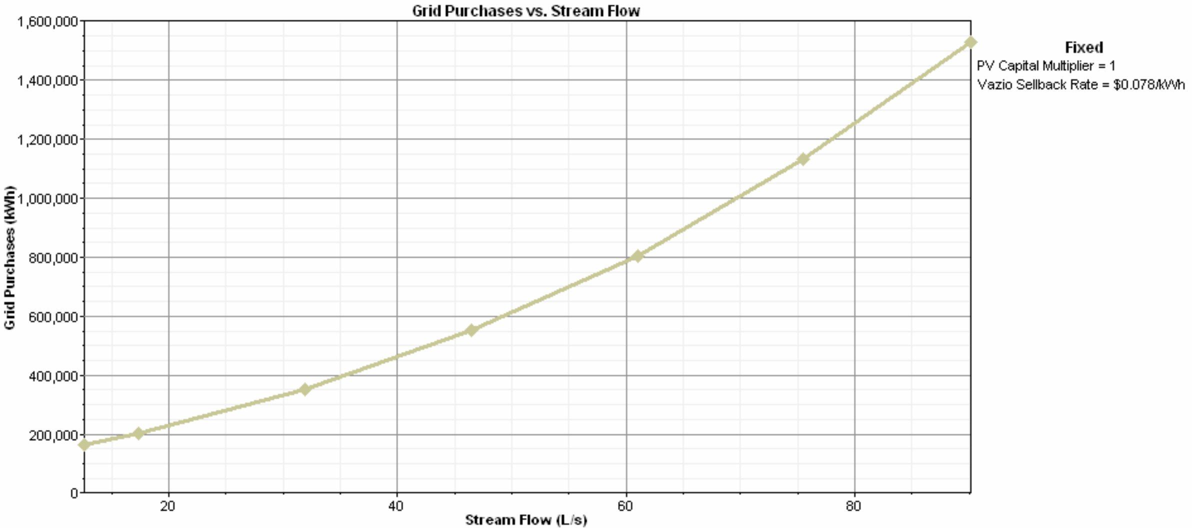


Figure 4.29 – Grid purchases vs. stream flow for a grid connected system

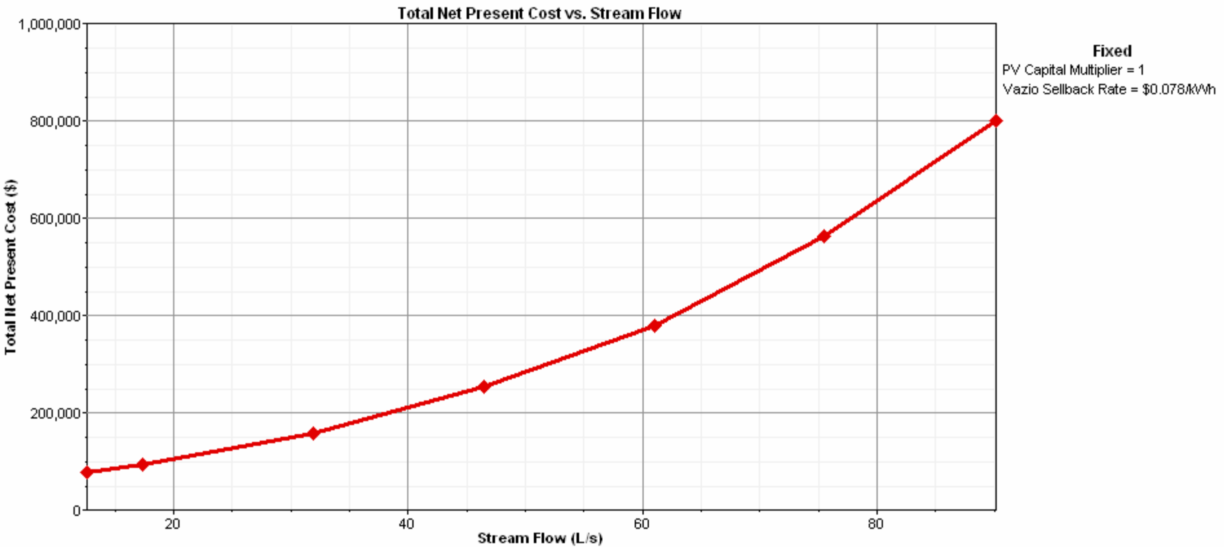


Figure 4.30 – Net present cost vs. stream flow for a grid connected system

As expected the net present cost and grid purchases increases with the increase of the stream flow. This is due to the fact that the pipes diameter was maintained for all stream flows and therefore the friction losses increase in a quadratic way, increasing the pump's head and decreasing the hydro turbine's head.

4.7.1.2.2. PV capital multiplier

As mentioned, the PV multiplier has no influence in the system for a sellback rate of 0,078 €/kWh. Therefore the results presented in Table 4.26 and Figures 4.31 to 4.34 are for a sellback price of 0,10 €/kWh (and a stream flow of 20,70 l/s since it was found to be the cheapest hydro turbine size):

Table 4.26 - PV multiplier influence in the grid connected system configuration and cost

PV multiplier		
1,0	**System configuration**	79780 kWh/yr grid; 6 wind turbines; 8,20 kW hydro; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-82090
	Cost of electricity (€/kWh)	-0,003
	Percentage of renewable source (%)	95,6
0,85	**System configuration**	79780 kWh/yr grid; 6 wind turbines; 8,20 kW hydro; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-82090
	Cost of electricity (€/kWh)	-0,003
	Percentage of renewable source (%)	95,6
0,70	**System configuration**	79780 kWh/yr grid; 6 wind turbines; 8,20 kW hydro; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-82090
	Cost of electricity (€/kWh)	-0,003
	Percentage of renewable source (%)	95,6
0,30	**System configuration**	145150 kWh/yr grid; 0 turbine;8,20 kW hydro; 1000 kWp PV; 0 kWh battery; 850 kW converter
	Total Net Present Cost (€)	-237045
	Cost of electricity (€/kWh)	-0,010
	Percentage of renewable source (%)	92,6

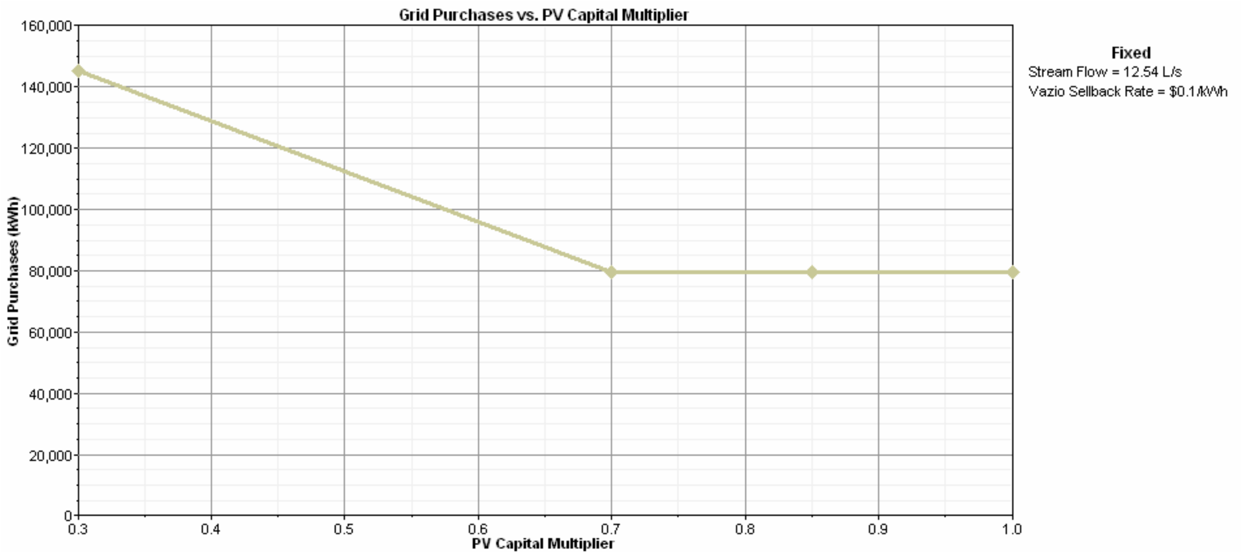


Figure 4.31 – Grid purchases vs. PV capital multiplier for a grid connected system

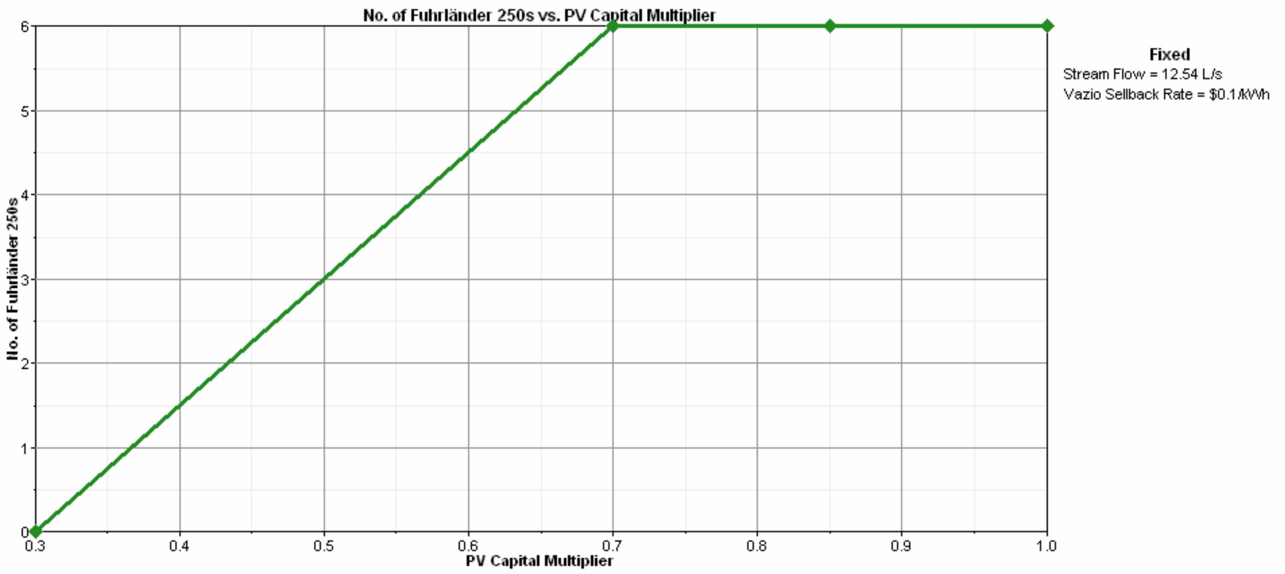


Figure 4.32 – Number of wind turbines vs. PV capital multiplier for a grid connected system

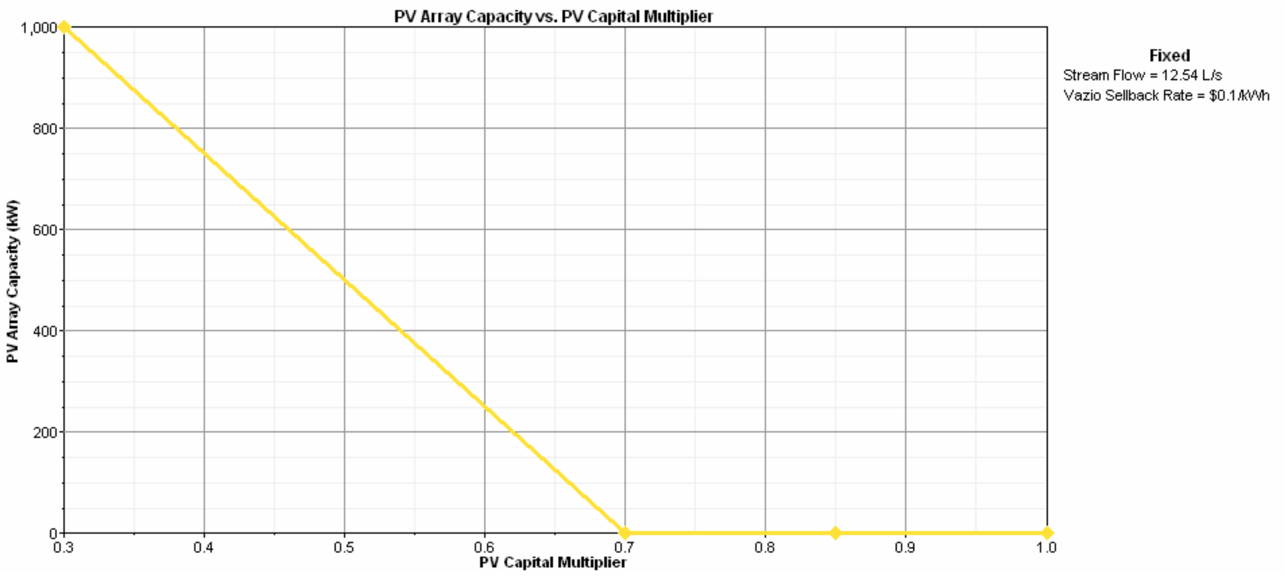


Figure 4.33 – PV array capacity vs. PV capital multiplier for a grid connected system

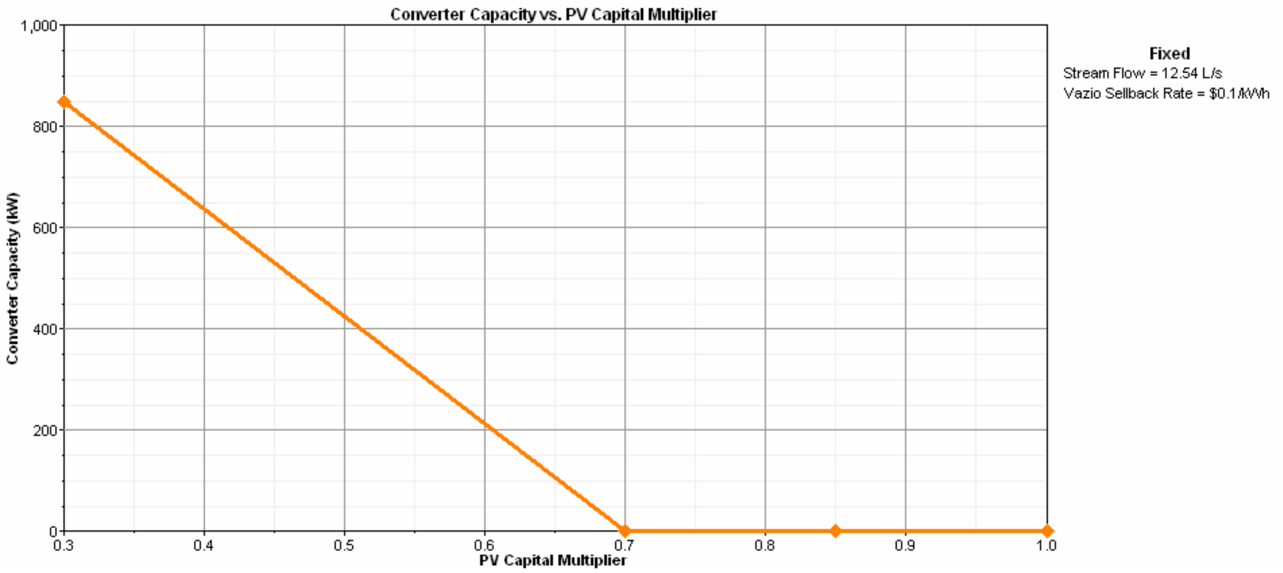


Figure 4.34 – Converter capacity vs. PV capital multiplier for a grid connected system

The two main economic parameters are presented in Figures 4.35 and 4.36 (under the same conditions):

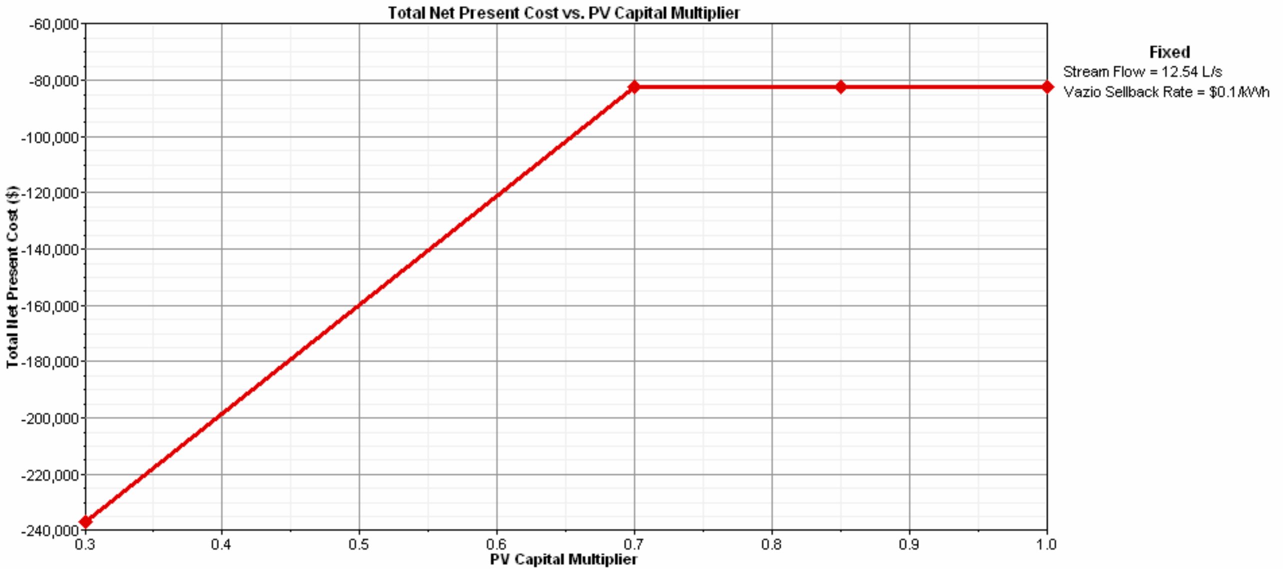


Figure 4.35 – Net present cost vs. PV capital multiplier for a grid connected system

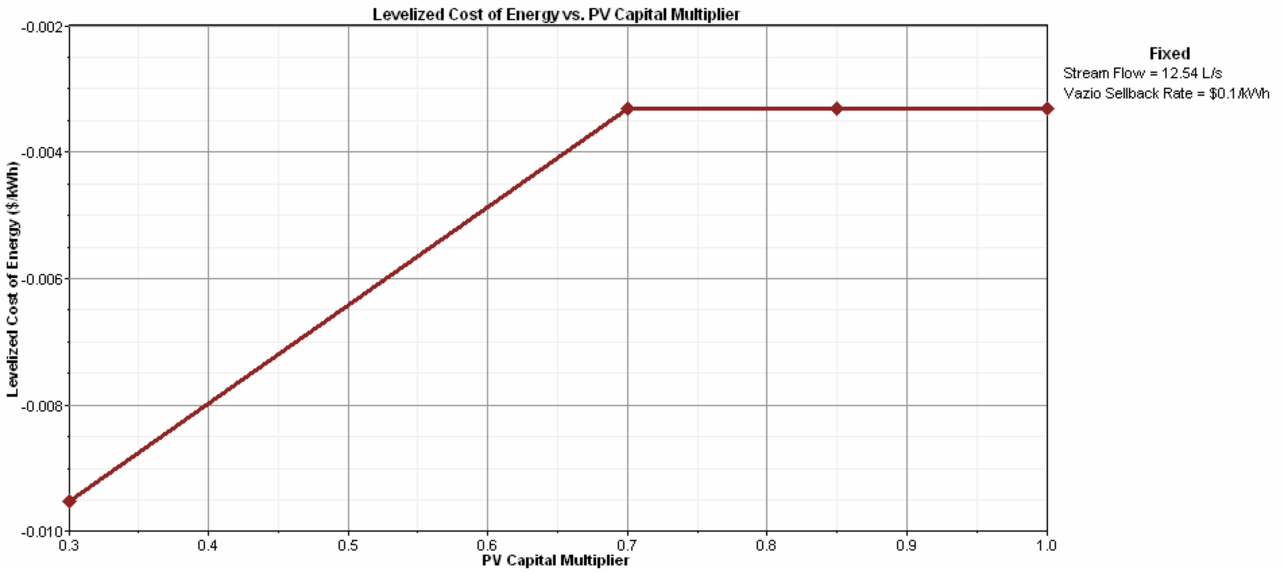


Figure 4.36 – Cost of energy vs. PV capital multiplier for a grid connected system

As expected, for lower PV multipliers the cost of the system tends to get lower, the PV array increases and the number of wind turbines decreases. The net present cost is in this case negative which means the system is profitable.

4.7.1.2.3. Energy sellback price

The energy sell back price is very important in determining the size of the renewable sources used and costs of the system. The variations caused are presented in Table 4.27 (for a PV multiplier of 1,0 and a stream flow of 20,70):

Table 4.27 - Sell back price influence in the grid connected system configuration and cost

Sell back price (€/kWh)		
0,078	**System configuration**	164250 kWh/yr grid; 8,20 kW hydro; 0 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	79711
	Cost of electricity (€/kWh)	0,027
	Percentage of renewable source (%)	21,5
0,10	**System configuration**	79780 kWh/yr grid; 8,20 kW hydro; 6 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-82090
	Cost of electricity (€/kWh)	-0,003
	Percentage of renewable source (%)	95,6
0,15	**System configuration**	72936 kWh/yr grid; 8,20 kW hydro; 9 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-1479057
	Cost of electricity (€/kWh)	-0,045
	Percentage of renewable source (%)	97,2
0,20	**System configuration**	65660 kWh/yr grid; 8,20 kW hydro; 15 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-3393347
	Cost of electricity (€/kWh)	-0,075
	Percentage of renewable source (%)	98,5

These results are also presented in Figures 4.37 and 4.38:

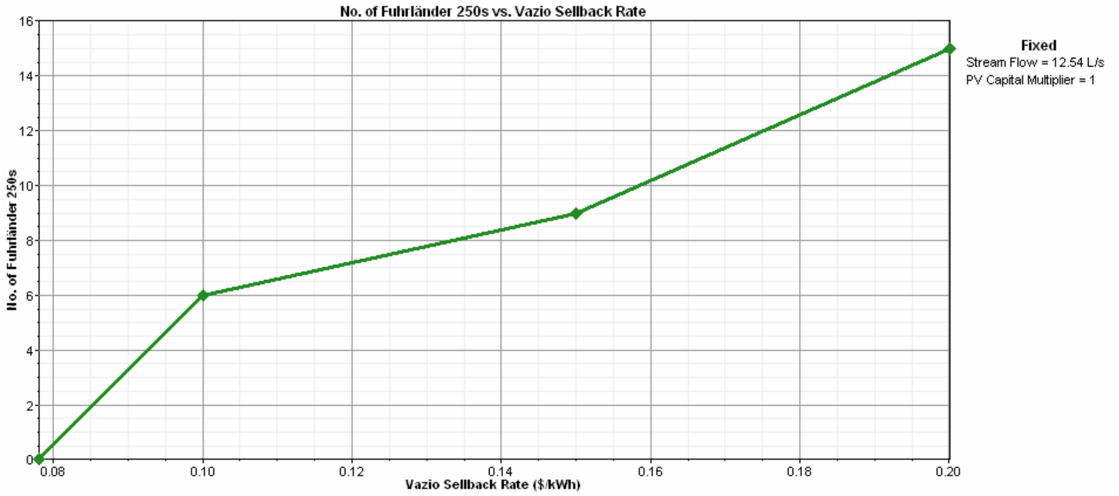


Table 4.37 – Number of wind turbines vs. sellback rate for a grid connected system

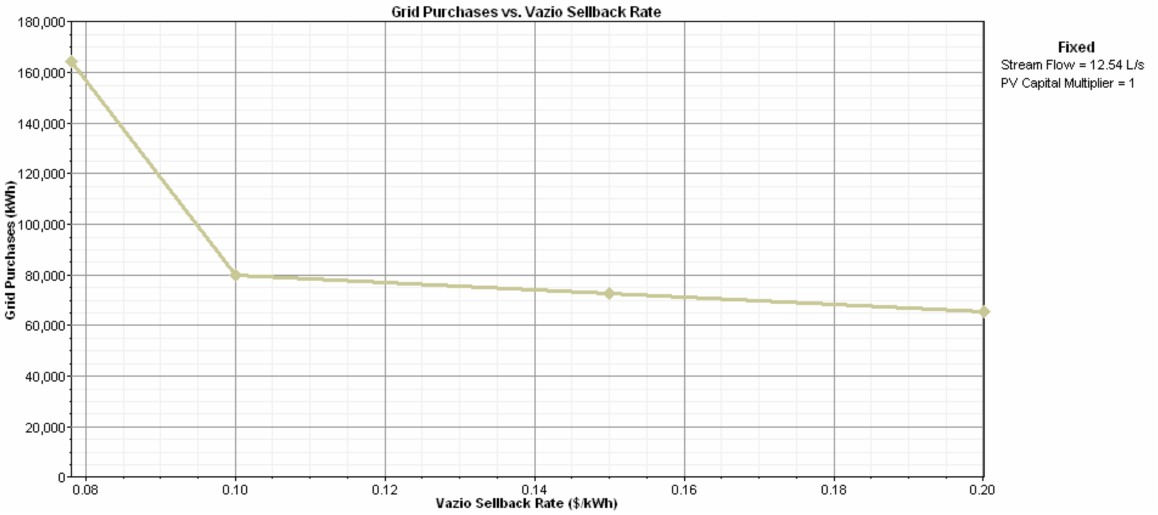


Figure 4.38 – Grid purchases vs sellback rate for a grid connected system

The two main economic parameters are presented in Figures 4.39 and 4.40:

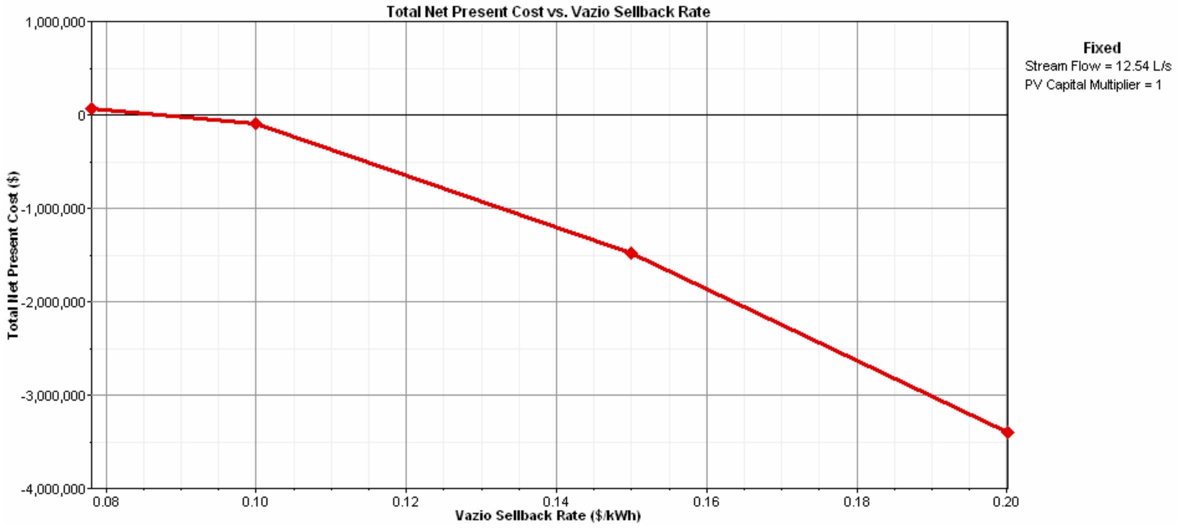


Figure 4.39 – Net present cost vs. sellback rate for a grid connected system

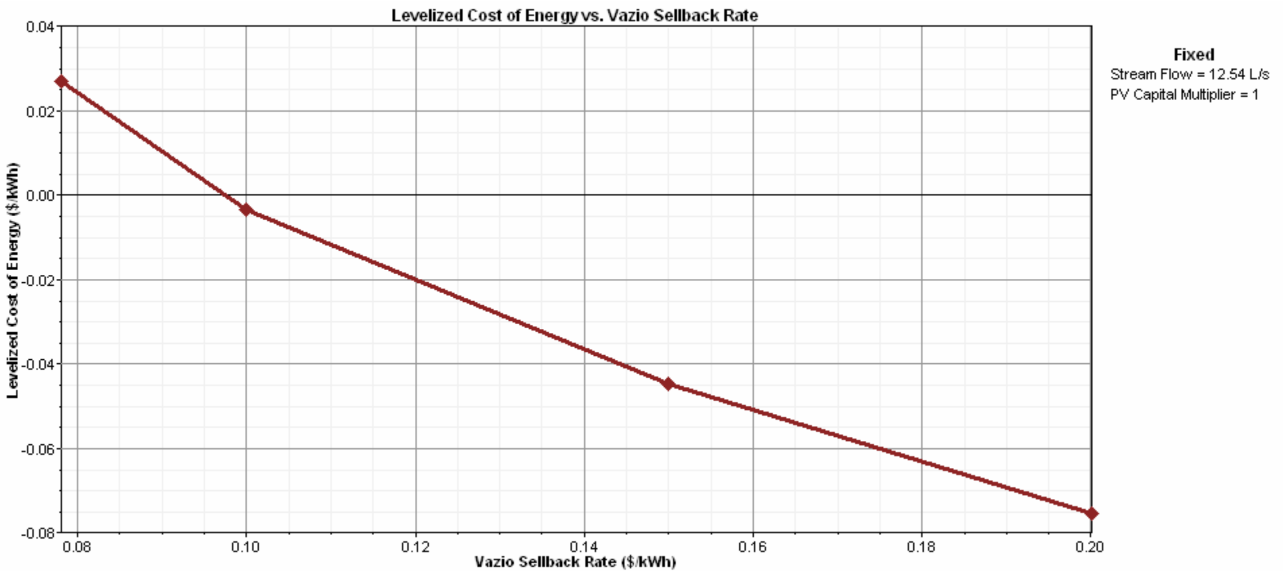


Figure 4.40 – Cost of energy vs. sellback rate for a grid connected system

As expected, for higher sellback rates the renewable fraction of the system increases since renewable sources tend to be more cost-effective. The system cost tends to get lower due to the profits from the energy sold to the national electrical grid. The grid energy purchases by the system also decrease for higher sellback rates since the system tends to have more alternative sources of energy for higher sellback rates.

4.7.2. System without a water turbine

As mentioned before this simulation was done to be compared with the previous one (with a water turbine), to check if there are benefits in using a water turbine in this study case.

Not having a water turbine allows the decrease in pump power. The pump's power and flow are presented in Table 4.28 and Figure 4.41:

Table 4.28 – Pump characteristics for a grid connected system without a hydro turbine

Usage (hours)	Flow (l/s)	Power (kW)
18	16,72	12,69

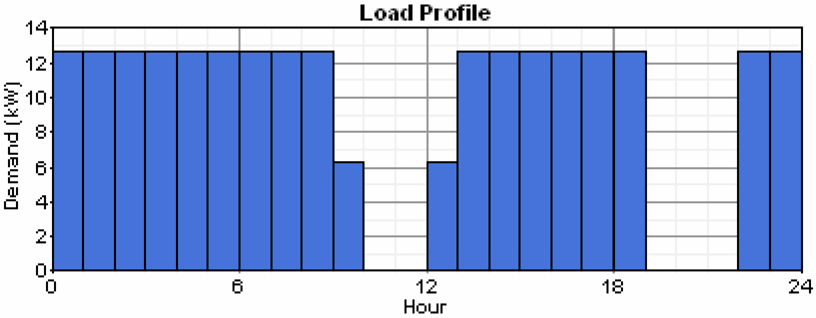


Figure 4.41 – Pump daily usage for a grid connected system without a hydro turbine

This reduction in pump power may, cost effectively, reduce the whole system cost (although the pump is used in periods of the day when the grid tariff is higher – medium consumption period).

4.7.2.1. Results

For the average sell back energy price of 0,078 €/kW the system is cheaper using only the electrical grid as power supply (regardless of the PV capital multiplier or load values) This result is presented in Table 4.29:

Table 4.29 – Optimized system configuration and cost for a grid connected system without a hydro turbine for a sellback rate of 0,078 €/kWh

Number of wind turbines	0
PV power (Wp)	0
Battery (Nº/kWh)	0/0
Converter (kW)	0
Grid Annual Purchase (kWh)	93.460
Total Net Present Cost (€)	75.109
Cost of electricity (€/kWh)	0,057
Percentage of renewable source (%)	0,0

The results presented in Table 4.30 refer to a sellback rate of 0,10 €/kWh:

Table 4.30 - Optimized system configuration and cost for a grid connected system without a hydro turbine for a sellback rate of 0,10 €/kWh

Number of wind turbines	6
PV power (Wp)	0
Battery (Nº/kWh)	0/0
Converter (kW)	0
Grid Annual Purchase (kWh)	22328
Total Net Present Cost (€)	-177220 €
Cost of electricity (€/kWh)	-0,005
Percentage of renewable source (%)	98,7

4.7.2.2. Sensitivity

The optimized system configuration varies for different sell back rates. This variation (for an average load of 12,69 kW) is shown in Figure 4.42:

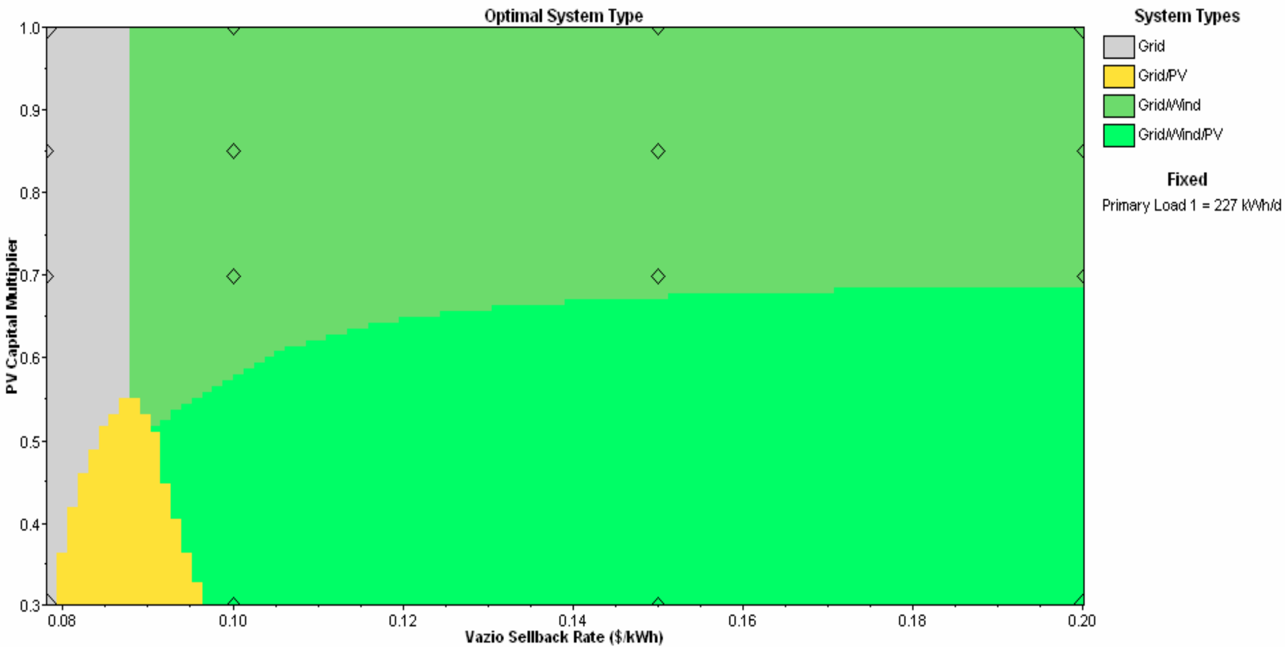


Figure 4.42 – Optimized system configuration for different sellback rates and PV capital multipliers for a grid connected system without a hydro turbine

As expected, the PV gains relevance for lower PV capital multipliers and both renewable energy sources (wind and PV) gain relevance for higher sell back rate. If the sell back rate is 0,14 €/kWh and there is a reduction of PV costs by 60 % (PV multiplier equal to 0,4) the optimized system is composed of a grid connection, wind turbines and PV source (light green area). If there is no reduction in PV cost (PV multiplier equal to 1,0) for the same sellback rate the system is no longer composed of PV source (dark green).

4.7.2.2.1. PV capital multiplier

The PV cost multiplier is linked to the battery and converter costs as well. This sensitivity value has the purpose of simulating possible subsidies for these system and probable decrease in price in the next years for PV systems.

As mentioned previously, for the average value of sellback energy price the PV multiplier has no influence on the optimized solution (the optimized solution is always just the electrical national grid connection). Therefore, the following presented results will be for a sell back price of 0,10 €/kWh.

Table 4.31 displays the different optimized system configuration and economic calculations for different PV multipliers for a pump load of 12,69 kW and a energy sell back price of 0,10 €/kWh:

Table 4.31 – System configuration and cost for different PV capital multiplier for a grid connected system without a hydro turbine

PV multiplier		
1,0	**System configuration**	22328 kWh/yr; 6 wind turbines; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-117220
	Cost of electricity (€/kWh)	-0,005
	Percentage of renewable source (%)	98,7
0,85	**System configuration**	22328 kWh/yr; 6 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-117220
	Cost of electricity (€/kWh)	-0,005
	Percentage of renewable source (%)	98,7
0,70	**System configuration**	22328 kWh/yr; 6 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-117220
	Cost of electricity (€/kWh)	-0,005
	Percentage of renewable source (%)	98,7
0,30	**System configuration**	16476 kWh/yr; 4 turbine; 970 kWp PV; 0 kWh battery; 800 kW converter
	Total Net Present Cost (€)	-260670
	Cost of electricity (€/kWh)	-0,007
	Percentage of renewable source (%)	99,4

These results can also be presented in a graphic way through Figures 4.43 to 4.46:

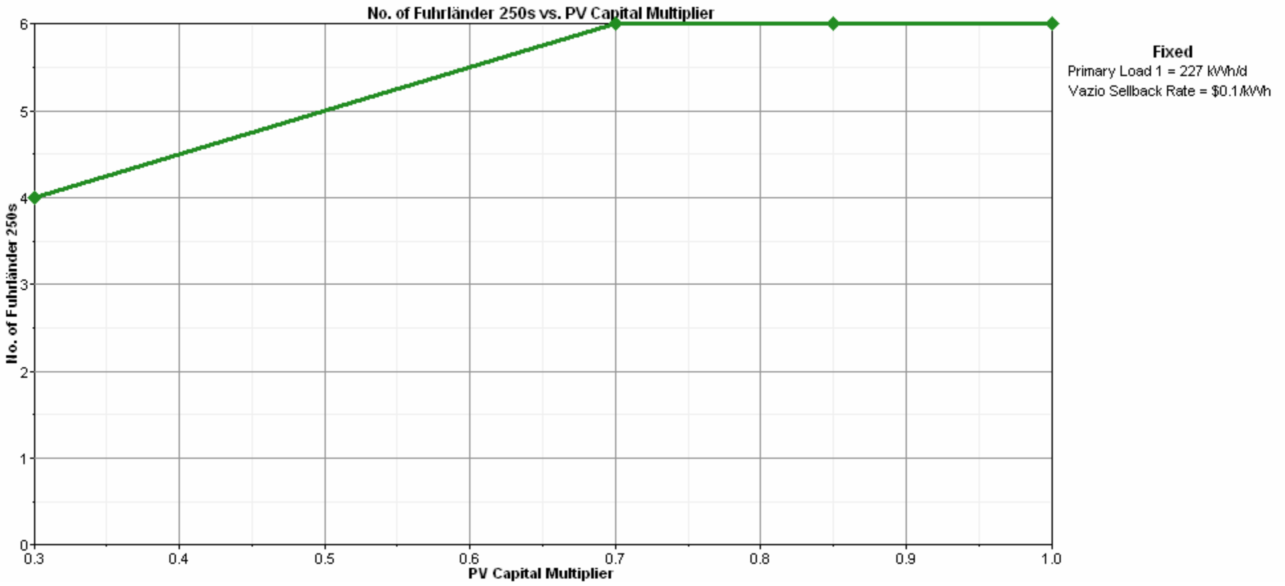


Figure 4.43 - Number of wind turbine vs. PV capital multiplier for a grid connected system without a hydro turbine

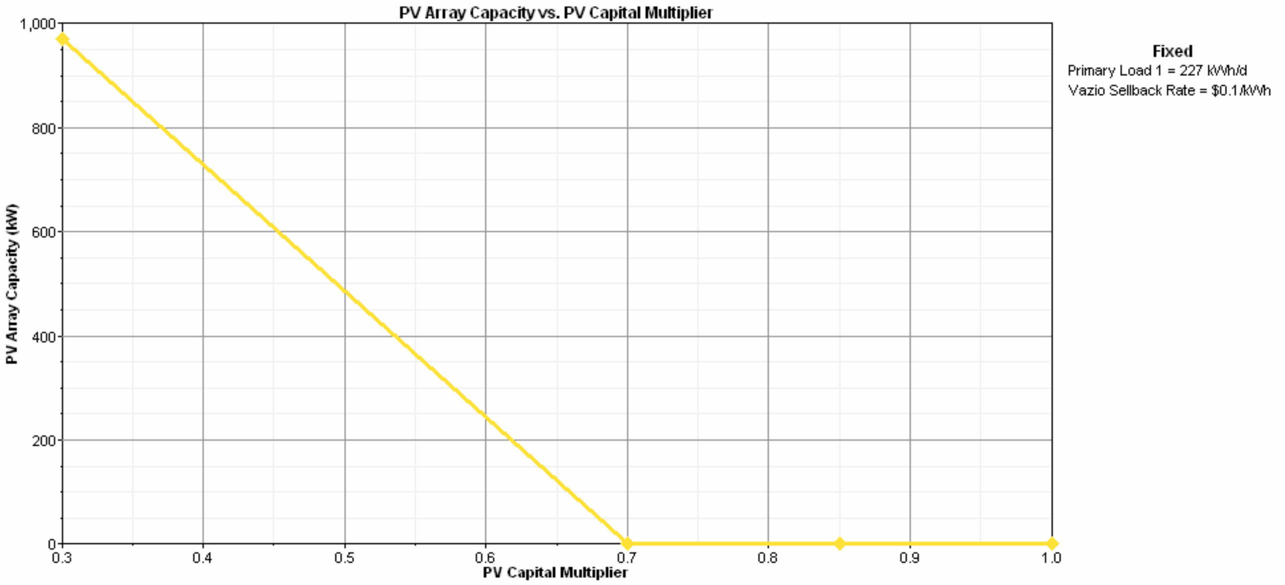


Figure 4.44 - PV array capacity vs. PV capital multiplier for a grid connected system without a hydro turbine

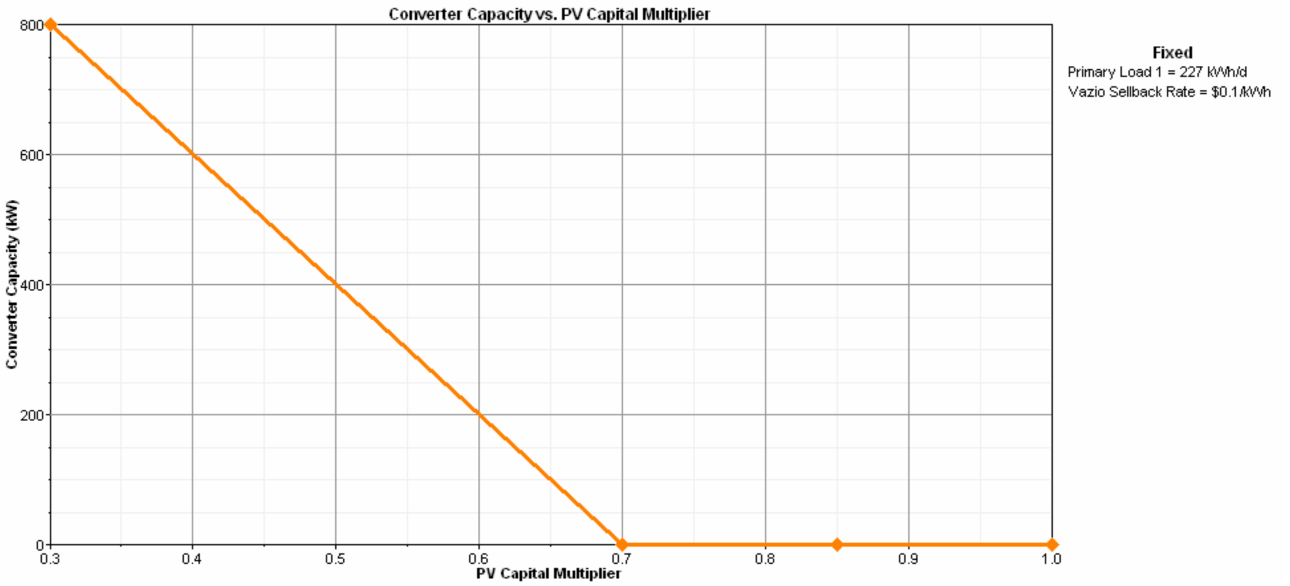


Figure 4.45 - Converter capacity vs. PV capital multiplier for a grid connected system without a hydro turbine

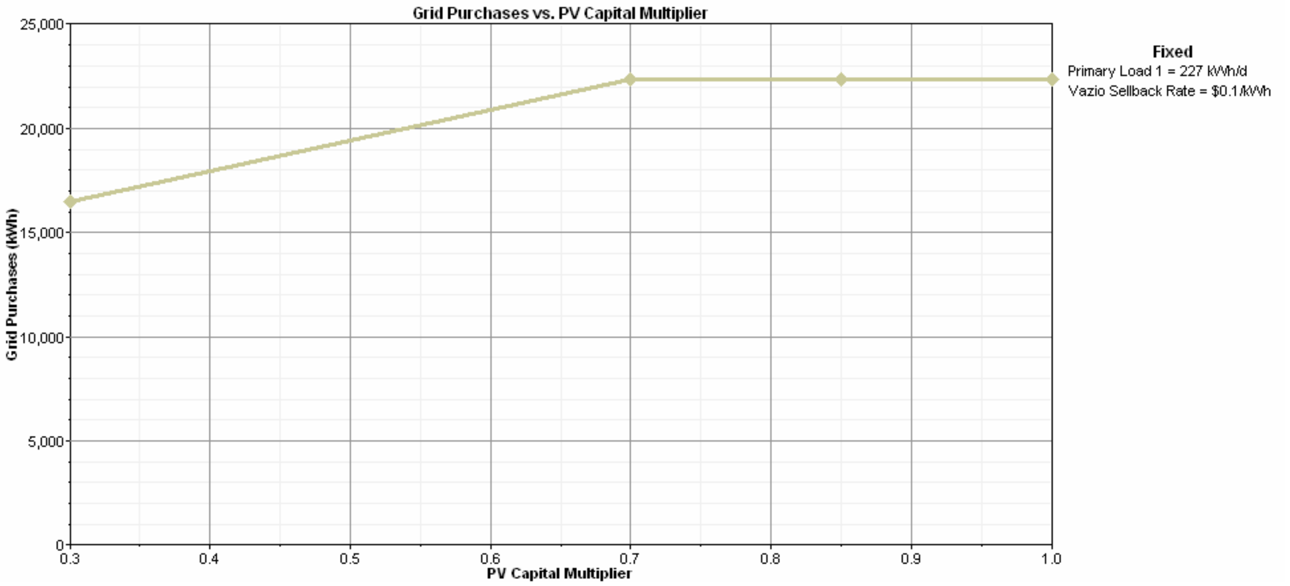


Figure 4.46 – Grid purchases vs. PV capital multiplier for a grid connected system without a hydro turbine

The previous figures show the different system configurations for different PV capital multipliers. As expected, for a lower multiplier the optimum system is composed of a larger PV array and a smaller number of wind turbines. For higher values the wind has a larger portion of the energy. The grid energy purchases also get lower for lower values of PV multipliers.

Figures 4.47 and 4.48 show the economic results for different PV capital multipliers:

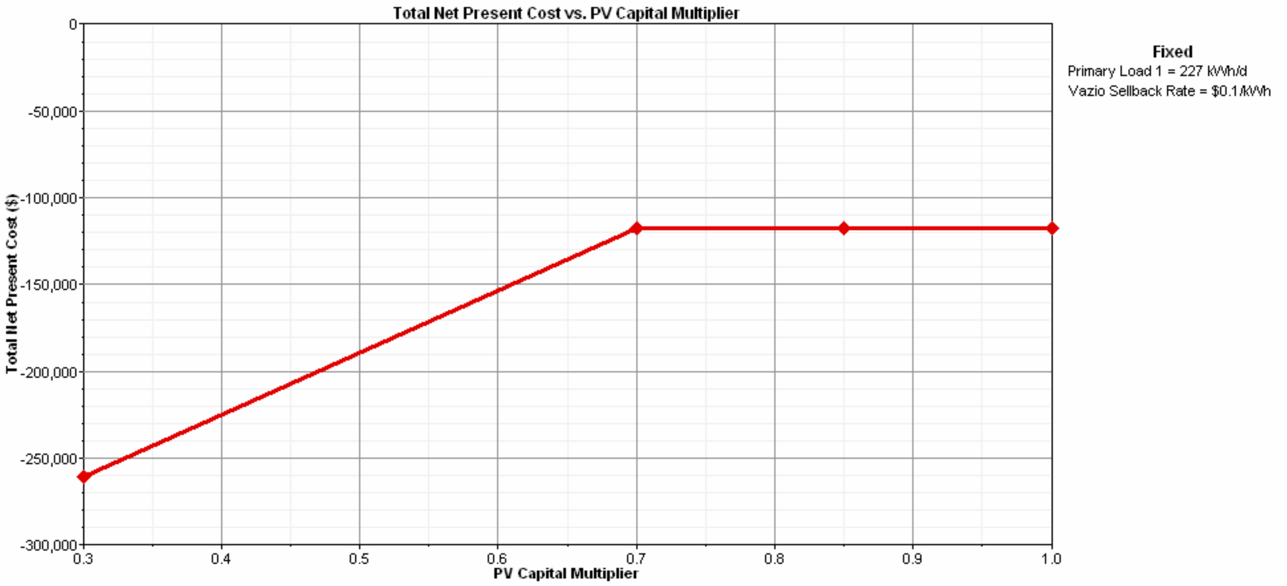


Figure 4.47 - Net present cost vs. PV capital multiplier for a grid connected system without a hydro turbine

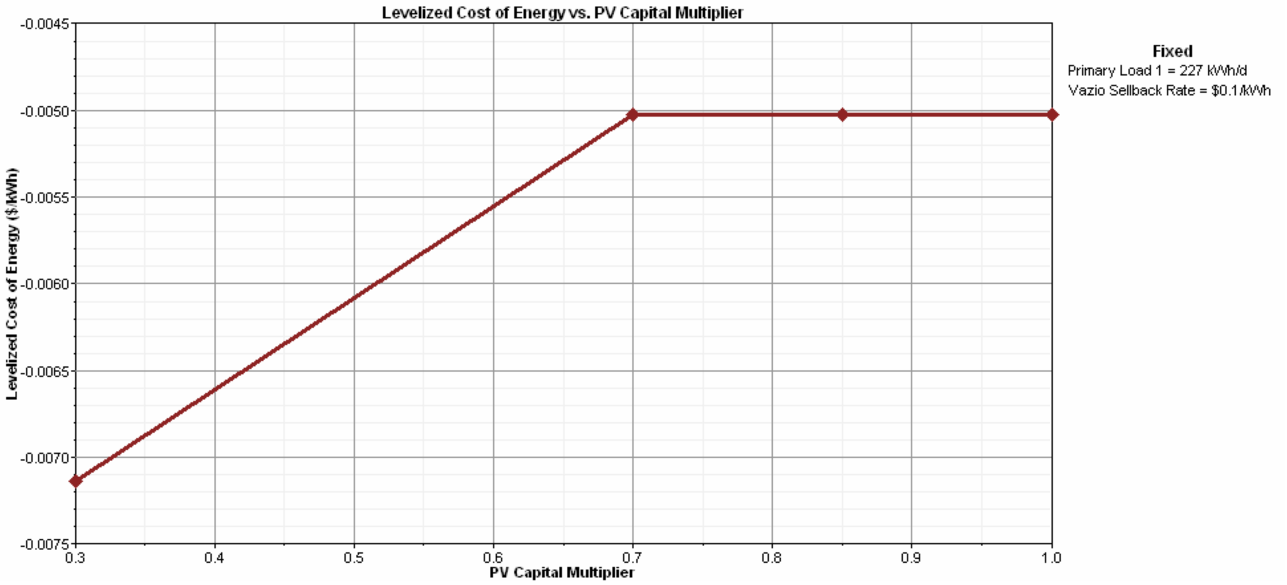


Figure 4.48 - Cost of energy vs. PV capital cost multiplier for a grid connected system without a hydro turbine

The two main economic parameters are lower for a lower PV multiplier and vice versa, as expected.

4.7.2.2.2. Pump power

The pump power variation is due to the variation in diameter size as mentioned previously. The results presented in Table 4.32 refer to an energy sell back price of 0,10 €/kWh and a PV capital multiplier of 1,0:

Table 4.32 – Optimized system configuration and cost for different pump power values for a grid connected system without a hydro turbine

Pump Power		
11,87	**System configuration**	20557 kWh/yr; 6 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-123435
	Cost of electricity (€/kWh)	-0,005
	Percentage of renewable source (%)	98,8
12,69	**System configuration**	22328 kWh/yr; 6 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-117220
	Cost of electricity (€/kWh)	-0,005
	Percentage of renewable source (%)	98,7
14,32	**System configuration**	25884 kWh/yr; 6 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-105021
	Cost of electricity (€/kWh)	-0,004
	Percentage of renewable source (%)	98,5

As it was shown in Table 4.32 the system configuration does not vary for different pump loads. Therefore, only some of the graphics will be presented. Figures 4.49 to 4.51 show the main characteristics of the system:

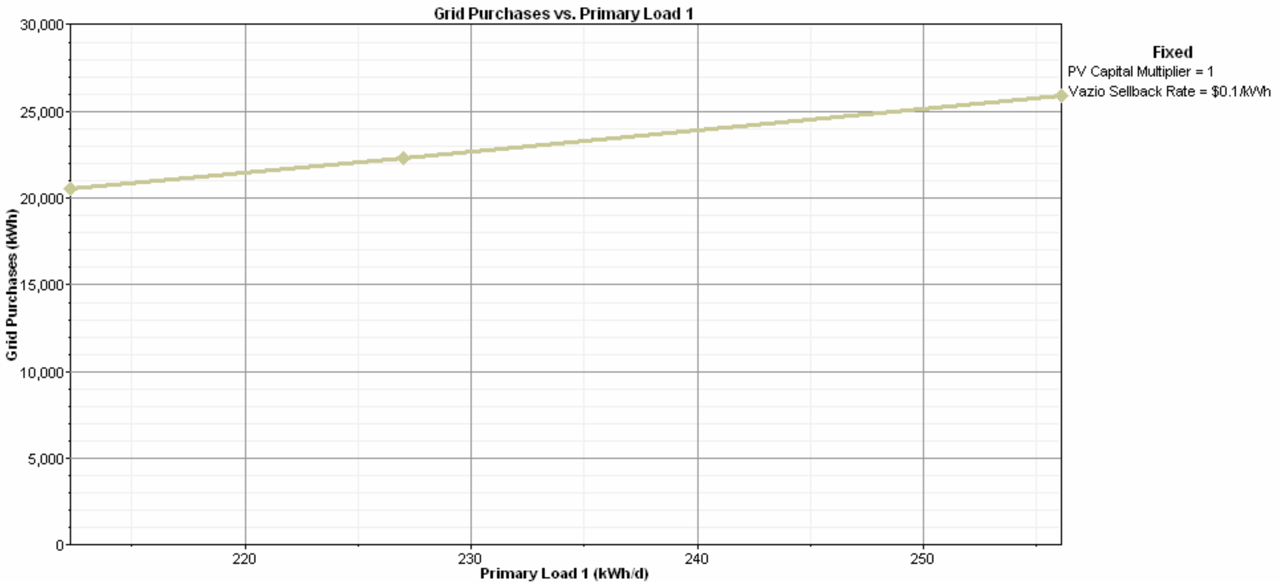


Figure 4.49 – Grid purchases vs. pump power for a grid connected system without a hydro turbine

Figure 4.50 - Net present cost vs. pump power for a grid connected system without a hydro turbine

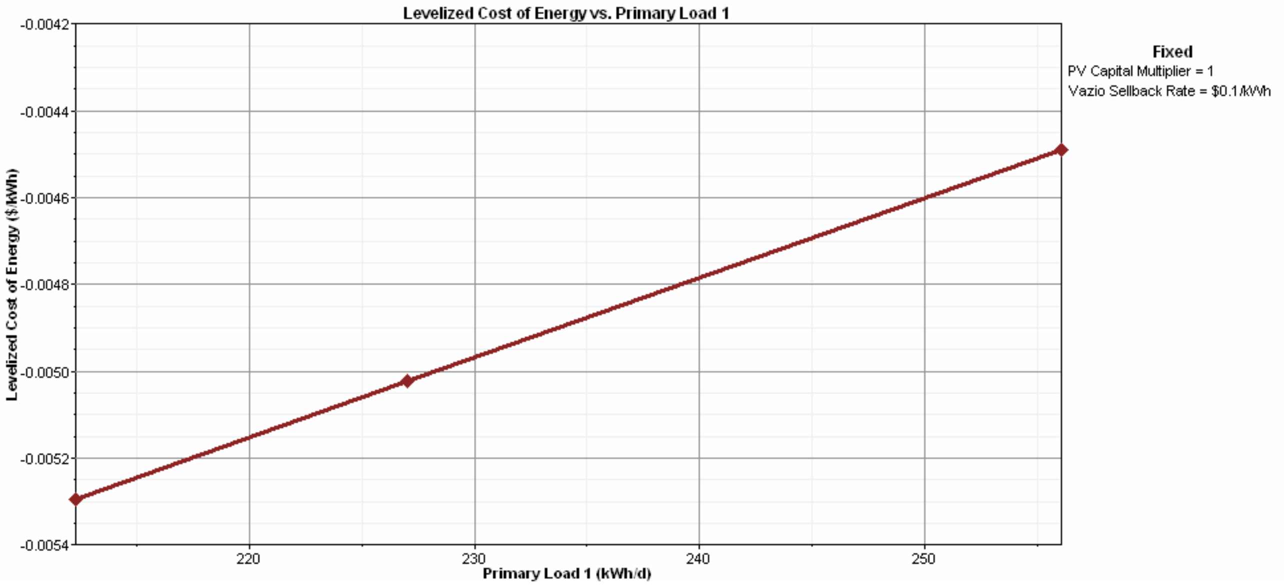


Figure 4.51 - Cost of energy vs. pump power for a grid connected system without a hydro turbine

As expected, the grid purchases increase for higher load values and vice versa (since the number of wind turbines is always the same). The net present cost and cost of energy are higher for higher load values (they have negative values, which means that for a 25 year project-life the system gives profits) and vice-versa.

4.7.2.2.3. Energy sellback price

The energy sell back price is very important in determining the size of the renewable sources used and costs of the system. The variations caused are presented in Table 4.33 (for a PV multiplier of 1,0 and a pump power of 12,69):

Table 4.33 – Sellback rate influence in the configuration and cost for a grid connected system without a hydro turbine

Sell back price (€/kWh)		
0,078	**System configuration**	82855 kWh/yr grid; 0 wind turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	66586
	Cost of electricity (€/kWh)	0,057
	Percentage of renewable source (%)	0,0
0,10	**System configuration**	22328 kWh/yr grid; 6 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-117220
	Cost of electricity (€/kWh)	-0,005
	Percentage of renewable source (%)	98,7
0,15	**System configuration**	19.710 kWh/yr grid; 10 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-1538049
	Cost of electricity (€/kWh)	-0,045
	Percentage of renewable source (%)	99,3
0,20	**System configuration**	17896 kWh/yr grid; 14 turbine; 0 kWp PV; 0 kWh battery; 0 kW converter
	Total Net Present Cost (€)	-3440114
	Cost of electricity (€/kWh)	-0,082
	Percentage of renewable source (%)	99,5

Due to the fact that the PV array, converter capacity and battery bank do not exist for any of these values, the correspondent graphics will not be presented. The main results are shown in Figures 4.52 to 4.55:

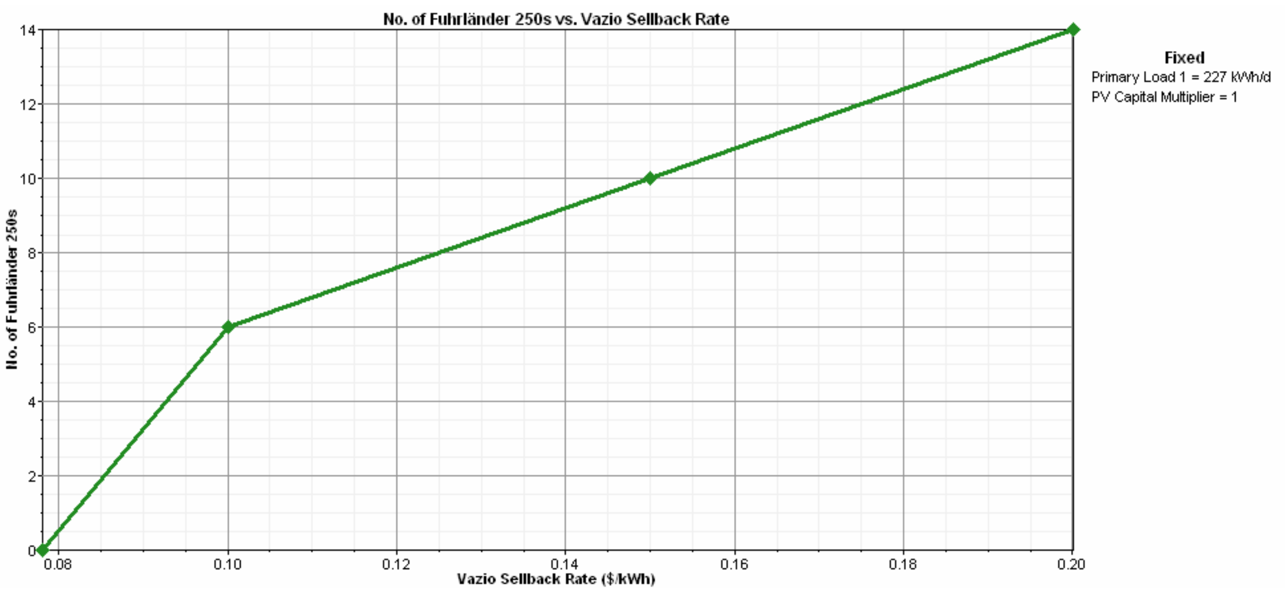


Figure 4.52 – Number of wind turbines vs. sell back rate for a grid connected system without a hydro turbine

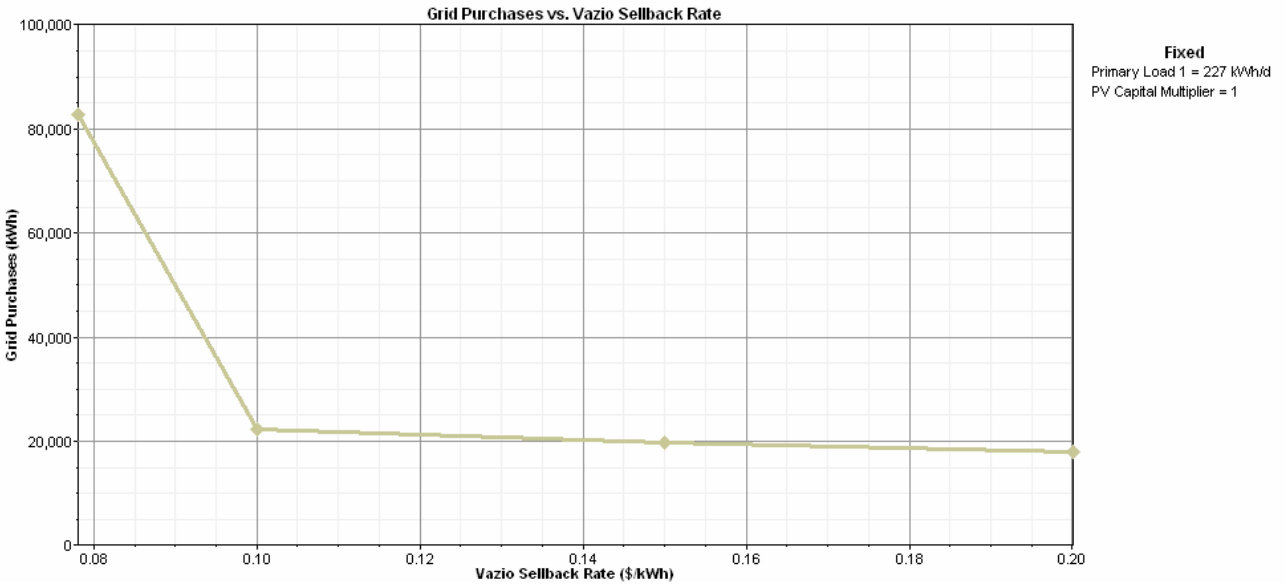


Figure 4.53 – Grid purchases vs. sellback rate for a grid connected system without a hydro turbine

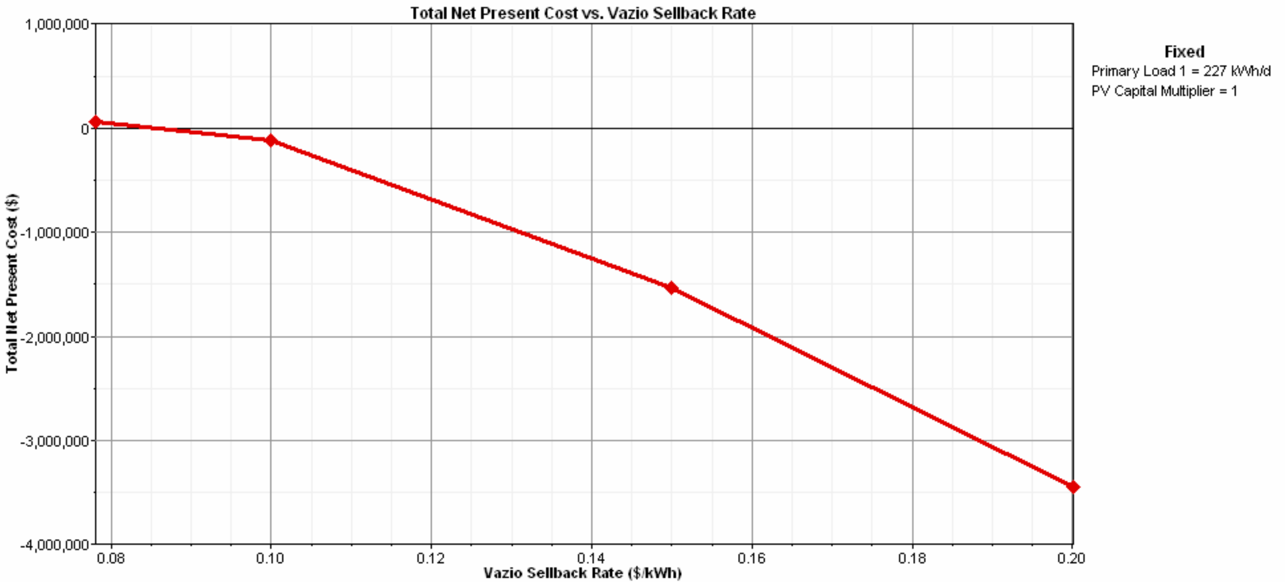


Figure 4.54 – Net present cost vs. sellback rate for a grid connected system without a hydro turbine

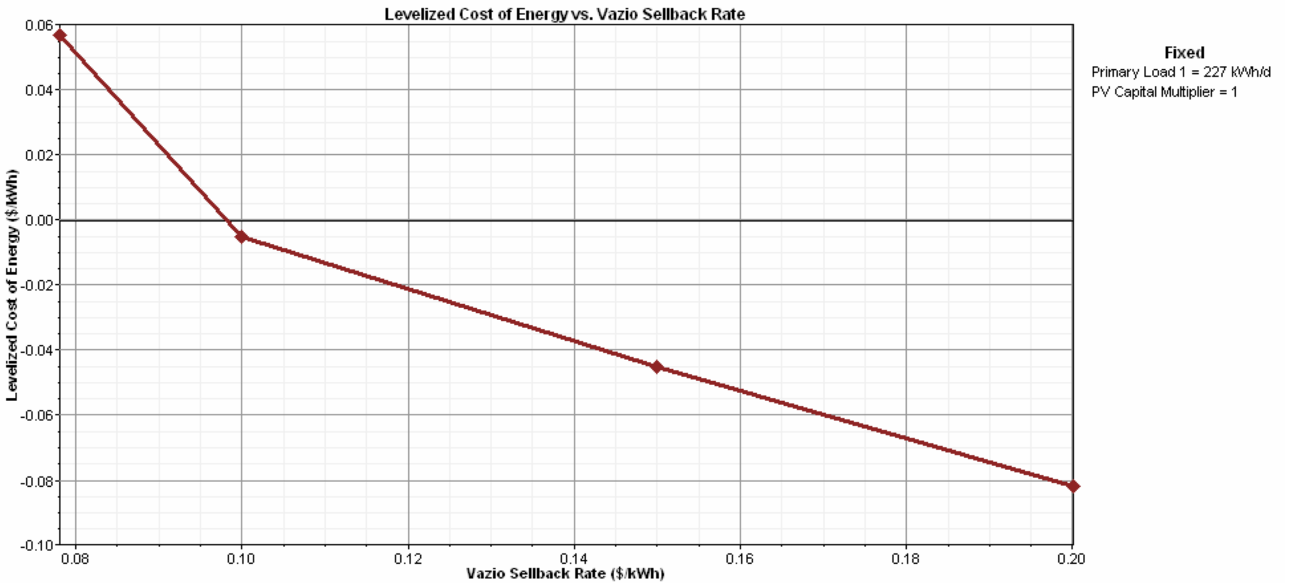


Figure 4.55 – Energy cost vs sellback rate for a grid connected system without a hydro turbine

As expected, for higher sell back rates the number of wind turbines increase since the excess energy produced can be sold to the grid at higher prices. Therefore the total net present cost increases and energy cost decreases for higher sell back rates as well. For a larger number of wind turbines the total energy purchased to the grid is lower.

4.7.3. Variation in grid energy price and turbine cost

A variation in grid price was studied as mentioned in Chapter 4.4. Also a decrease in the water turbine cost was tested. These two sensitivity studies were done to try and conclude when the water turbine system is cost-effective when compared to the system without a water turbine. It was considered the smallest water turbine since it presented the lowest system cost (8,62 kW of power). The reduction done in the water turbine cost is presented in Table 4.34:

Table 4.34 – Sensitivity values used for the water turbine initial cost

Initial cost (€)	Percentage of reduction (%)	Cost (€)
25864,65	15	21984,95
	30	18105,26

The variation values for the grid energy price are mentioned in chapter 4.4. The variation in grid energy price was tested in both systems with and without a water turbine.

4.7.3.1. Results

The results obtained from both simulations (with and without a water turbine) are presented in Table 4.35. The grid energy prices are indicated by reference numbers that are explained in chapter 4.4.

Table 4.35 – Net present cost for different grid energy prices for systems with and without a water turbine for an energy sellback rate of 0,078 €/kWh

Grid energy price	System without a water turbine	System with a water turbine
(1)	NPC = 66.586 €	NPC = 79.711 €
(2)	NPC = 67.663 €	NPC = 61.192 €
(3)	NPC = 68.991 €	NPC = 49.616 €

For the system with a water turbine there is also a variation in total system cost. This variation is presented in Table 4.36:

Table 4.36 – Net present cost for different hydro turbine costs and different grid energy prices for a sellback rate of 0,078 €/kWh

Hydro turbine reduction in cost (%)	Initial turbine cost (€)	Grid energy price	Net present cost (€)
0	25864,65	(1)	79.711
		(2)	61.192
		(3)	49.616
15	21984,95	(1)	75.831
		(2)	57.311
		(3)	45.737
30	18105,26	(1)	71.951
		(2)	53.432
		(3)	41.857

As it is possible to see in both Table 4.35 and 4.36 as the grid energy price and turbine cost vary the net present cost varies as well. If the difference between the energy price of the low consumption, medium consumption and peak consumption period increases the system with a water turbine tends to get cheaper (in this system the pump only operates during the low consumption period) when compared with the system without a hydro source (in this case the system operates during multiple consumption periods). As it is possible to see, for a decrease in 30 % in initial turbine cost and for a grid energy price indicated as (3) the system with a water turbine is cheaper roughly 25.000 €. The difference between both water pumps is 25948,87 €. This situation would have to be carefully studied. More accurate values for pump cost would need to be determined.

4.8. Comparison of systems

Table 4.37 shows the comparison of different possible solutions:

Table 4.37 – Comparison of different types of energy systems

System	**Stand-alone (without a water turbine)**	**Grid connected without water turbine (sellback rate = 0,078 €/kWh)**	**Grid connected without water turbine (sellback rate = 0,10 €/kWh)**	**Grid connected with water turbine (sellback rate = 0,078 €/kWh)**	**Grid connected with water turbine (sellback rate = 0,10 €/kWh)**	**Grid connected with a water turbine (30 % reduction in cost and tariff (3)) for a sellback rate of 0,078 €/kWh**
Total Net present cost (€)	902692	66586	-117220	79711	-82090	41857
Energy cost (€/kWh)	0,774	0,057	-0,005	0,027	-0,003	0,014
Grid purchases (kWh/yr)	0	82855	22328	164250	79780	164250
Breakeven grid extension distance (km)	31,6	(N.A.)	(N.A.)	(N.A.)	(N.A.)	(N.A.)
Renewable fraction (%)	100	0	98,7	21,5	95,6	21,5
Pollution gases emitted (Yes/No)	No	Yes if considered that energy grid can come from fossil energy	Yes if considered that energy grid can come from fossil energy	Yes if considered that energy grid can come from fossil energy	Yes if considered that energy grid can come from fossil energy	Yes if considered that energy grid can come from fossil energy

All the results presented in Table 4.37 refer to normal values situation (no subsidies, no reduction in the pump power, for a grid extension price of 20.000€/km and for a flow stream of 20,70 l/s). This investigation was done using the Homer and the EPANET software.

5. CONCLUSIONS

5.1. Deep well in Lusaka-Zambia

The preliminary simulation done to study the possibility of a water supply system of a deep well in Lusaka, Zambia showed that these type of water supply systems could have a big positive impact in African economy and help the large number of population that do not have access to drinkable water. The system presented a quite low cost per cubic meter of water pumped which means that the system would easily be paid with a small price for the users for each cubic meter of water consumed.

As mentioned before, in deep well pumping is cheaper to have a water tank rather than a battery bank. Batteries are more expensive, require specialized workers and a maintenance and operation cost. A water tank is a simple and cheap solution when compared to batteries.

For this preliminary study one assumption was made that might not be completely accurate. It was assumed by the software that the water demand is the same all year. This is probably not true since it is most likely for the demand to be higher during the summer season and lower in the winter season.

5.2. Supply system to a Portuguese Village

Some conclusions were taken from the supply system tested. The peak output of the wind turbines is roughly around a wind speed of 20 m/s. The average values found for Lisbon (3,75 m/s annual average – retrieved from Meteonorm software) seem quite small compared to what was the ideal. This reduces greatly the output of the wind turbines. The values obtained was 10,3 % of the total possible output when it was expected at least a value of roughly 20 %. If the wind averages used are lower than in reality, this factor would decrease significantly the total cost of the system.

In the analyses presented in this work, the PV array tends to get very large when the PV multipliers is 0,3. A large PV array has the inconvenient of being hard to implement due to the fact that it would occupy a large area of terrain. For a PV module efficiency of 16,7 %, 1 kWp will occupy, in average, around 6 m^2 which means that 1000 kWp would occupy 6000 m^2 (adapted from [4]). This is a very large area and therefore a different solution would need to be found.

Most of the electric production in these systems come from wind source rather than PV. This proves that wind energy is nowadays cheaper than PV energy. Even so a hybrid system was chosen by the Homer software

All the solutions presented in this work could be improved by changing some input values. Homer simulates various systems using all possible configurations with the values inputted by the user for the quantity of each component. Therefore the system will only use the values inputted and not the intermediate ones. Once the optimized solution is found new values could be inserted to optimize the solution, however simulations for a small system like this took around 50 hours, therefore this optimization was not developed in detail.

It is also difficult to simulate a general case like the one in this thesis project since the parameters used are average values. If a more specific project had to be studied more interactive solutions could be obtained.

A stand-alone system is a possible alternative for a grid extension. Grid extension cost is tending to get higher along with the grid energy price (adapted from [5] and [13]).

In a stand-alone system it is necessary to reduce the load power as much as possible. These systems tend to be more cost effective when they are small sized, therefore the load has to be decreased as much as possible. The pump working time was increased to 18 hours for the power to be lower.

After running a simulation of a stand-alone system the software displayed an optimized solution containing both wind and solar energy. A solar and wind hybrid solution displays a better performance since low wind seasons are usually good solar times and vice versa (adapted from [1]). Even so, the software choose more wind energy rather than solar. This is due to the fact that nowadays wind energy is more developed than solar, presenting a price per kWh delivered lower than PV modules.

A stand-alone system is cost-effective if the sum of the cost of the grid extension and its energy price is higher than the renewable system cost, in the long run. The results showed that for the system analysed to be cost effective the grid would need to be at a distance of at least 31,6 km. This value would decrease to 10 km if there were subsidies.

Due to the fact that it was not acceptable loss of load (lack of water is not acceptable) the system presented a very high value of excess energy (226.348 kWh/yr – 70 % of total production). This energy could be used for a maintenance facility in the pump surroundings.

Grid connected systems were also tested. These systems are harder to implement because the national grid still has low energy prices that are hard to compete with. However this situation is expected to change. The increase in fossil fuels price will most likely cause the increase of the national grid energy price.

In these systems all energy produced by the system that is not consumed by the water pump is sold to the electric national grid.

The system without a water turbine is composed only of a grid connection for a sellback rate of 0,078 €/kWh. Wind energy source is only cost-effective when the sellback rate is 0,10 €/kWh and PV only when its multiplier is equal to 0,30. This shows that it is still difficult for renewable sources to compete with the electric grid. Renewable systems in a case like this are still dependent on subsidies and other forms of support from the government, especially PV source. This system proved to be more cost-effective when compared with the system with a water turbine.

For the water turbine system the pump power had to be increased significantly (although for less working hours) in order to turbine greater flows. This causes an increase in the power source configuration. In this case the optimized system is composed of a grid connection and a water turbine for a sellback rate of 0,078 €/kWh. The smaller the turbine is the cheaper the system gets. This is due to the fact that the pipes diameter is always the same, therefore for a larger turbine (higher flow) the friction losses are higher. Also, for a larger hydro turbine to exist, an increase in pump power is necessary.

Also in this case, when the sellback rate is 0,10 €/kWh (instead of 0,078 €/kWh) wind turbines get cost-effective and are part of the optimized system. PV is only an option when subsidies are given.

It was possible to conclude that it is still difficult to have renewable energy compete with conventional energy sources from an economical point of view. However, with the predictable increase in oil price (energy cost increases as well) and decrease in the cost of wind and solar power in the near future, it is believed that these systems will rapidly become cost-effective even without any special economical support.

It was concluded that the variation studied in grid energy price for the different consumption periods and the reduction in hydro turbine prices brings benefits for the water turbine system, since it gets cheaper. The difference between water pump costs would have to be more accurately determined to more accurately compare both systems with and without a water turbine.
It was possible to conclude that between a system with and without a water turbine, the more cost effective solution is without a water turbine although it depends on the turbine cost and energy tariff. If there was a water source on the population reservoir that would permit an increase in stream flow for the hydro turbine and probably this system would be more cost-effective.
Has shown and mentioned, if the energy tariff and turbine cost were to vary the hydro system could be cost-effective when compared with the system with no water turbine

It is difficult to simulate a general case like the one in this thesis project since the values used are average values. If a more specific project was to be studied more precise results could be obtained. Also, before applying a system of this kind a previous study based on measurements of solar irradiation and wind speed would be necessary since there is still a lack of this kind information in our country.

Different types of results can be retrieved from the Homer software, however, due to lack of space permitted for this report only the more important were presented in this work

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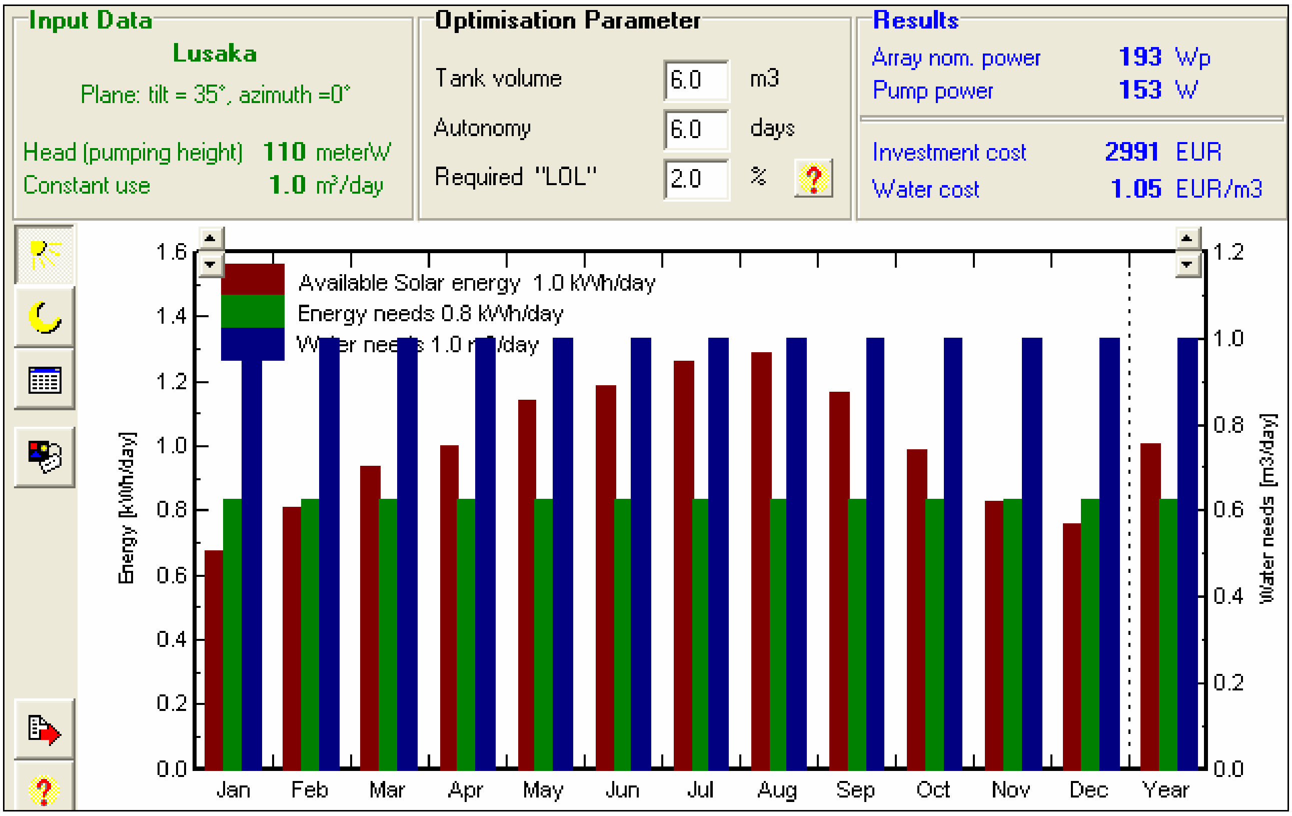
Appendixes

Appendix 1 – PVSYST4 results and inputs

Table A1 – Predefined values of PVSYST4 software

Loan duration (expected lifetime)	20 years
PV modules specific cost, <1 kWp	5,00 €/Wp
PV modules specific cost, <10 kWp	4,50 €/kWp
PV modules specific cost, <100 kWp	3,90 €/kWp
PV modules specific cost, >100 kWp	3,50 €/kWp
Custom modules overcost ratio	1,30
Inverters specific cost, <5 kWp	800 €/kW
Inverters specific cost, >5 kWp	700 €/kW
Inverters specific cost, >20 kWp	600 €/kW
Free mounting specific cost	0,60 €/W
Scale exponential factor (mounting and maintenance) ratio	0,80
Specific cost of submersible well pumps	4,50 €/W
Specific cost of controllers for pumping (basis 500 W)	0,80 €/W
Specific cost of Controller/Inverter for pumping	1,30 €/W
Specific transport and mounting costs (stand alone 500 Wp)	6.000 €/kW
Scale exponential factor (stand alone mounting and regul.) ratio	0,70



Input Data

Lusaka

Plane: tilt = 35°, azimuth =0°

Head (pumping height) **110** meterW

Constant use **1.0** m³/day

Optimisation Parameter

Tank volume 6.0 m3

Autonomy 6.0 days

Required "LOL" 2.0 %

Results

Array nom. power **193** Wp

Pump power **153** W

Investment cost **2991** EUR

Water cost **1.05** EUR/m3

Figure A1 – PVSYST4 results

Appendix 2 – Pressure in the supply system nodes (EPANET)

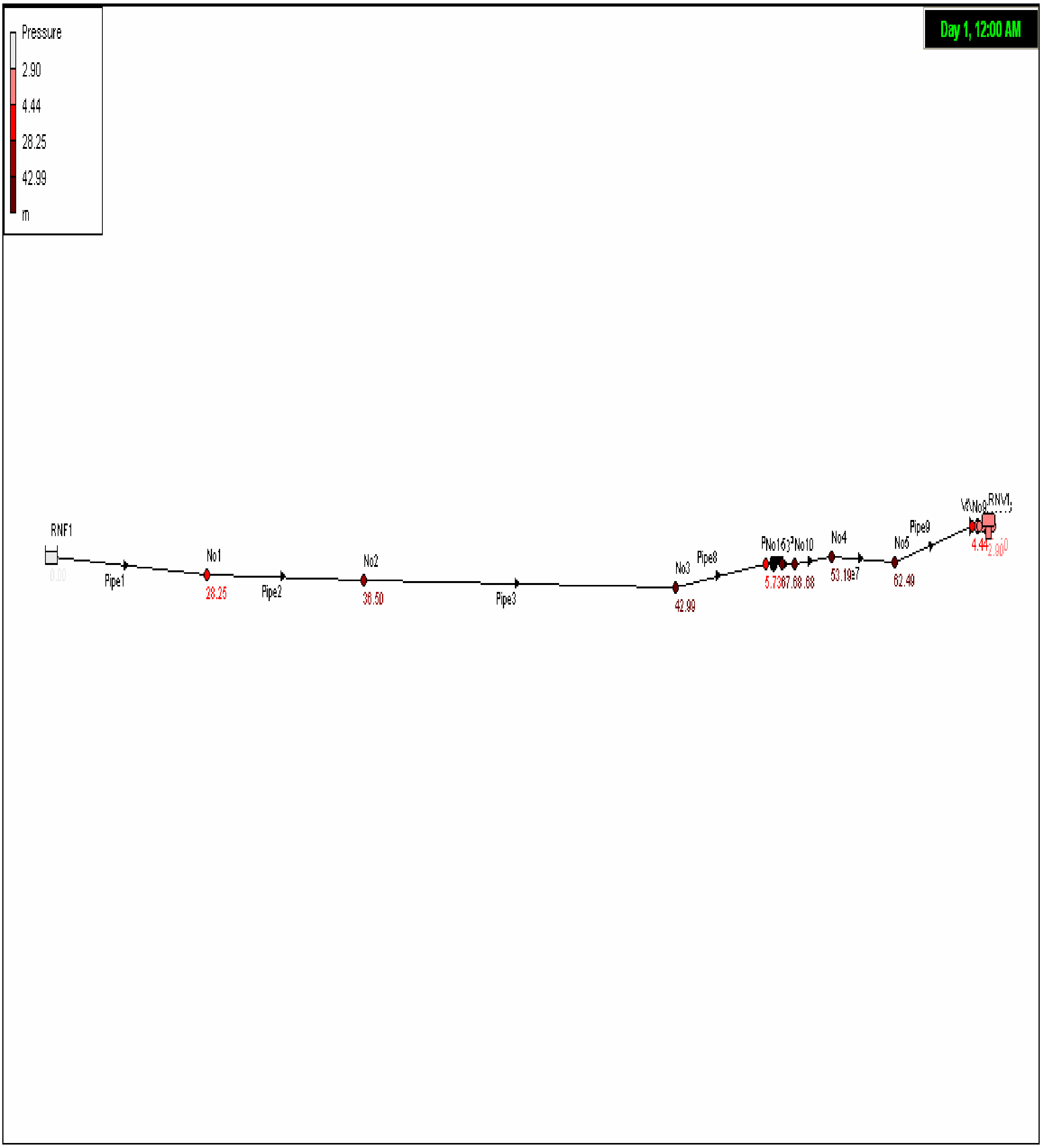


Figure A2.1 – Pressure in system nodes for the stand-alone situation (no water turbine present)

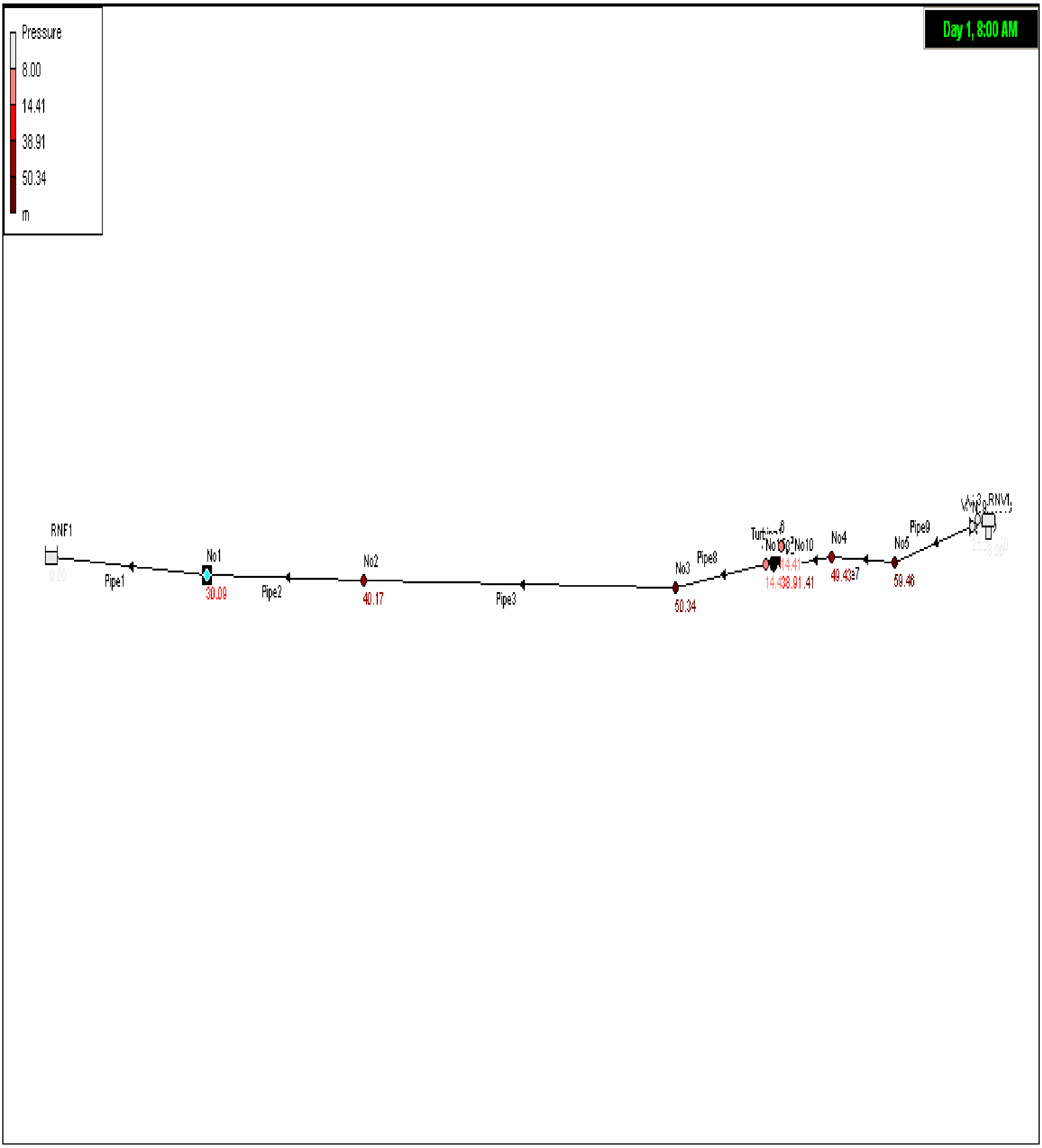


Figure A2.2 - Pressure in system nodes for a grid connected situation (with a water turbine) for a reservoir size of 1926,20 m^3 (first situation)

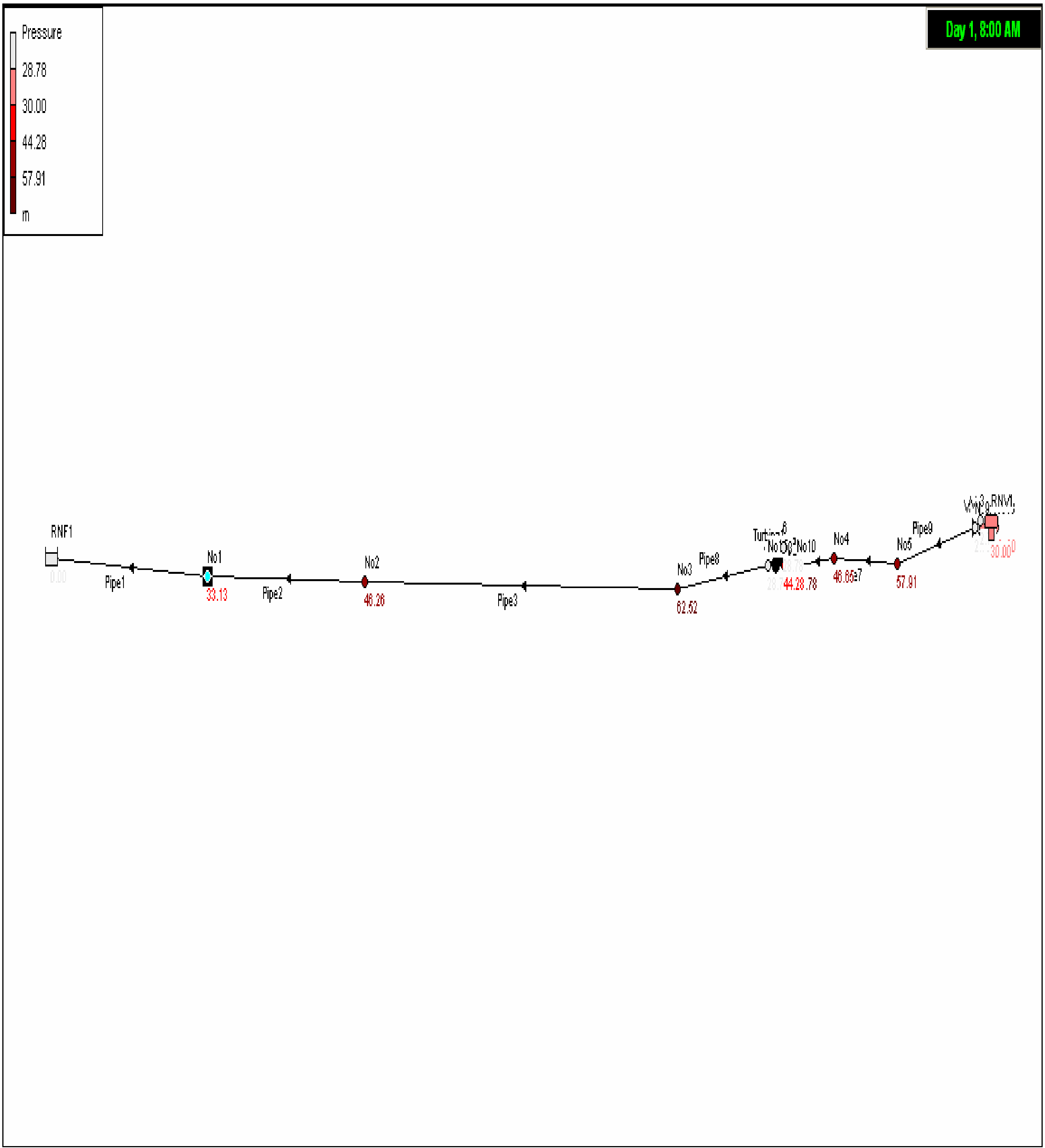
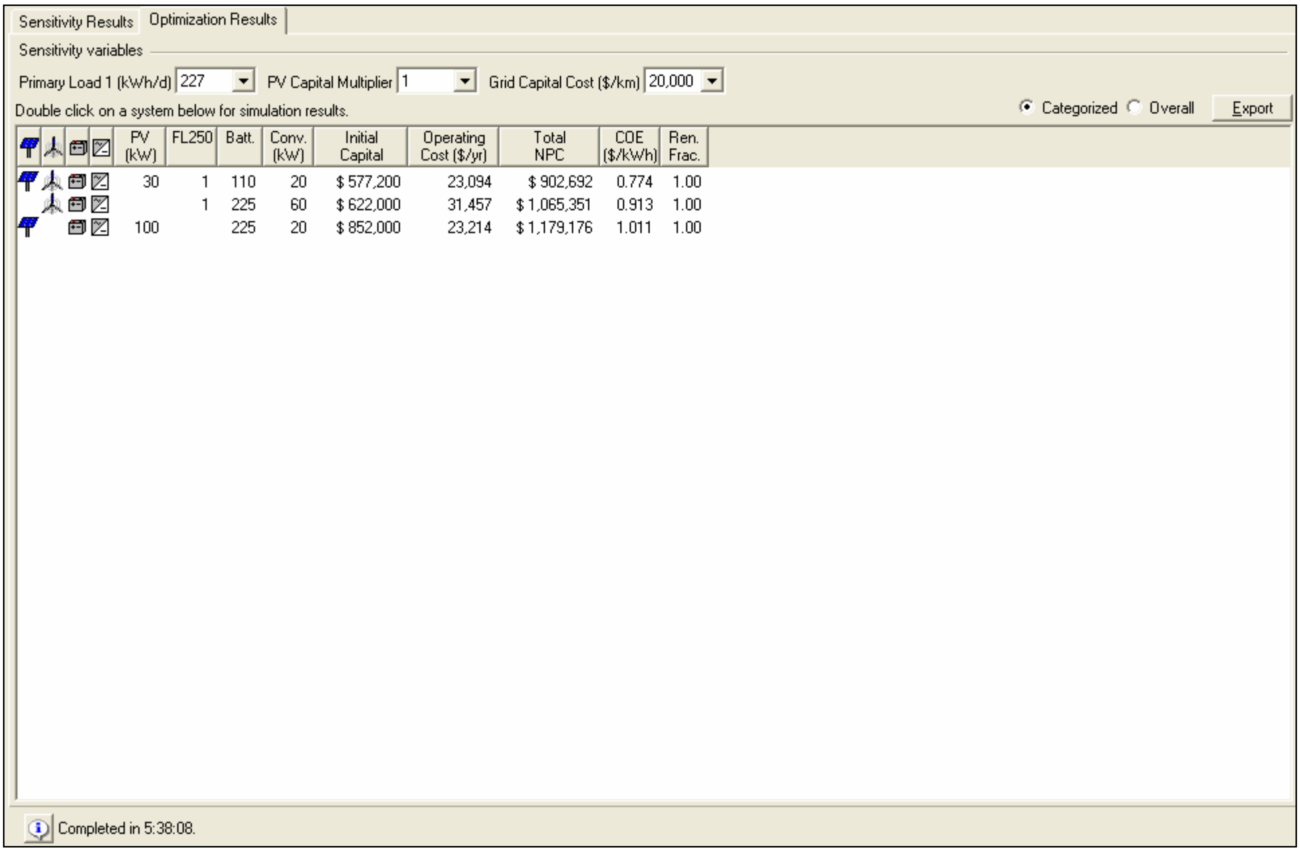


Figure A2.3 - Pressure in system nodes for a grid connected situation (with a water turbine) for a reservoir size of 9424,78 m^3 (seventh situation)

Appendix 3 – Stand-alone system



Sensitivity variables

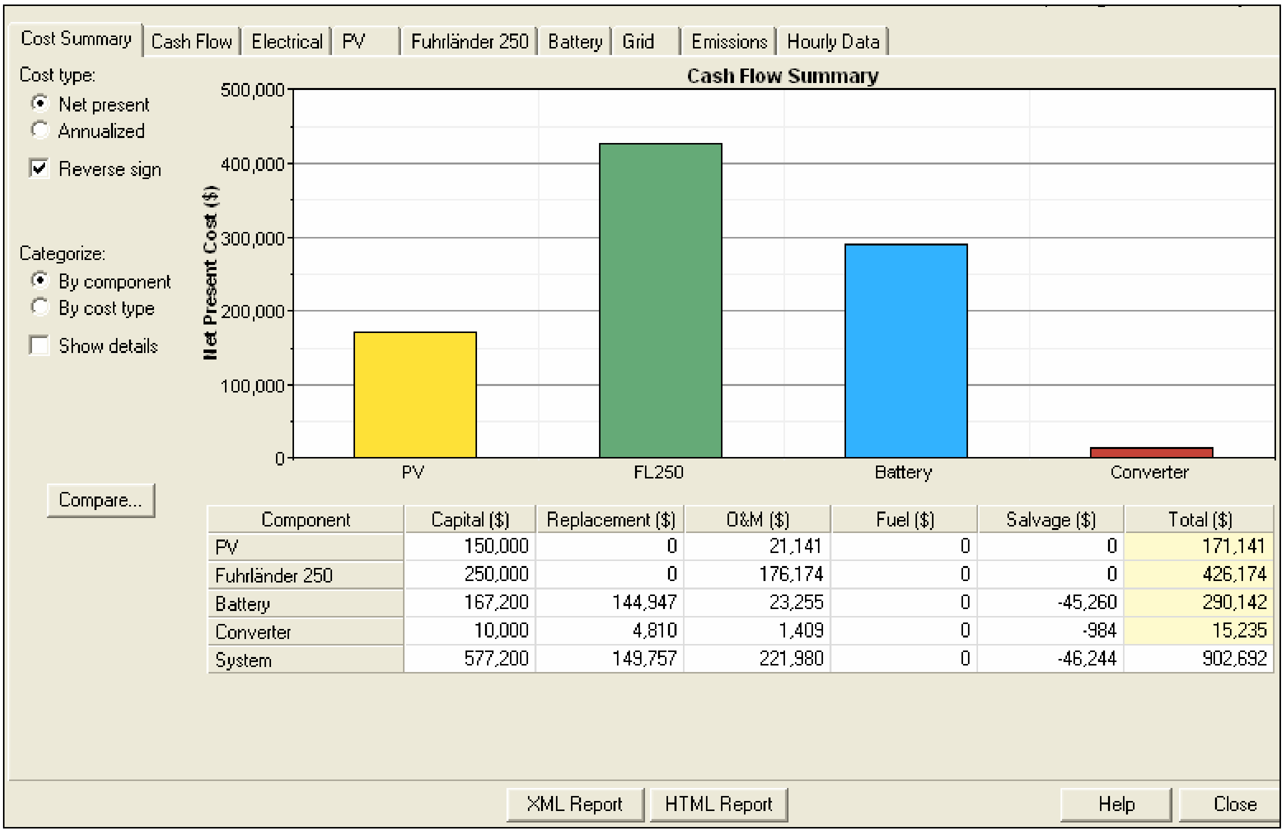
Primary Load 1 (kWh/d) 227 PV Capital Multiplier 1 Grid Capital Cost ($/km) 20,000

Double click on a system below for simulation results.

● Categorized ○ Overall

PV (kW)	FL250	Batt.	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
30	1	110	20	$ 577,200	23,094	$ 902,692	0.774	1.00
	1	225	60	$ 622,000	31,457	$ 1,065,351	0.913	1.00
100		225	20	$ 852,000	23,214	$ 1,179,176	1.011	1.00

Figure A3.1 – Optimized solutions for each type of system, displayed in net present cost order

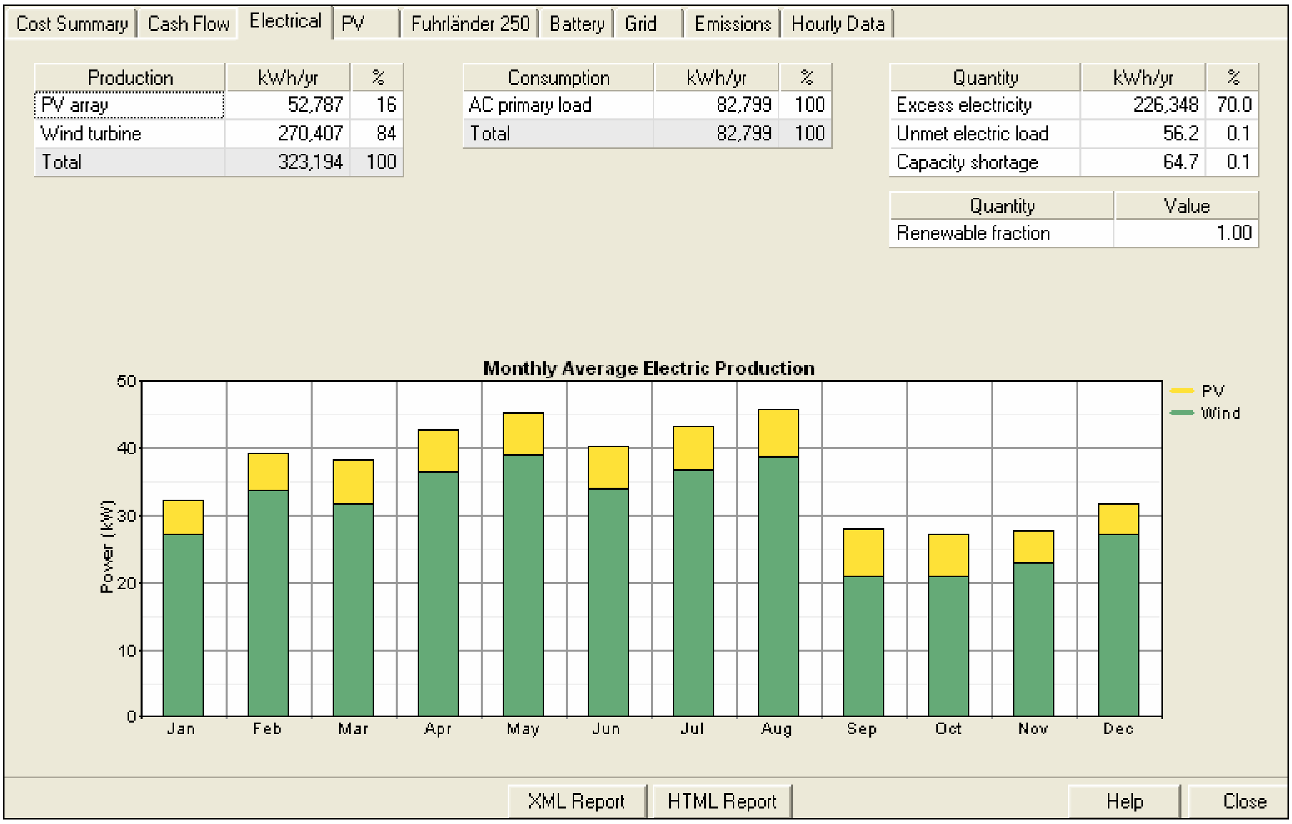


Cost type:
● Net present
○ Annualized
☑ Reverse sign

Categorize:
● By component
○ By cost type
☐ Show details

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	150,000	0	21,141	0	0	171,141
Fuhrländer 250	250,000	0	176,174	0	0	426,174
Battery	167,200	144,947	23,255	0	-45,260	290,142
Converter	10,000	4,810	1,409	0	-984	15,235
System	577,200	149,757	221,980	0	-46,244	902,692

Figure A3.2 – System components weigh in the net present cost for the optimized solution



Production	kWh/yr	%
PV array	52,787	16
Wind turbine	270,407	84
Total	323,194	100

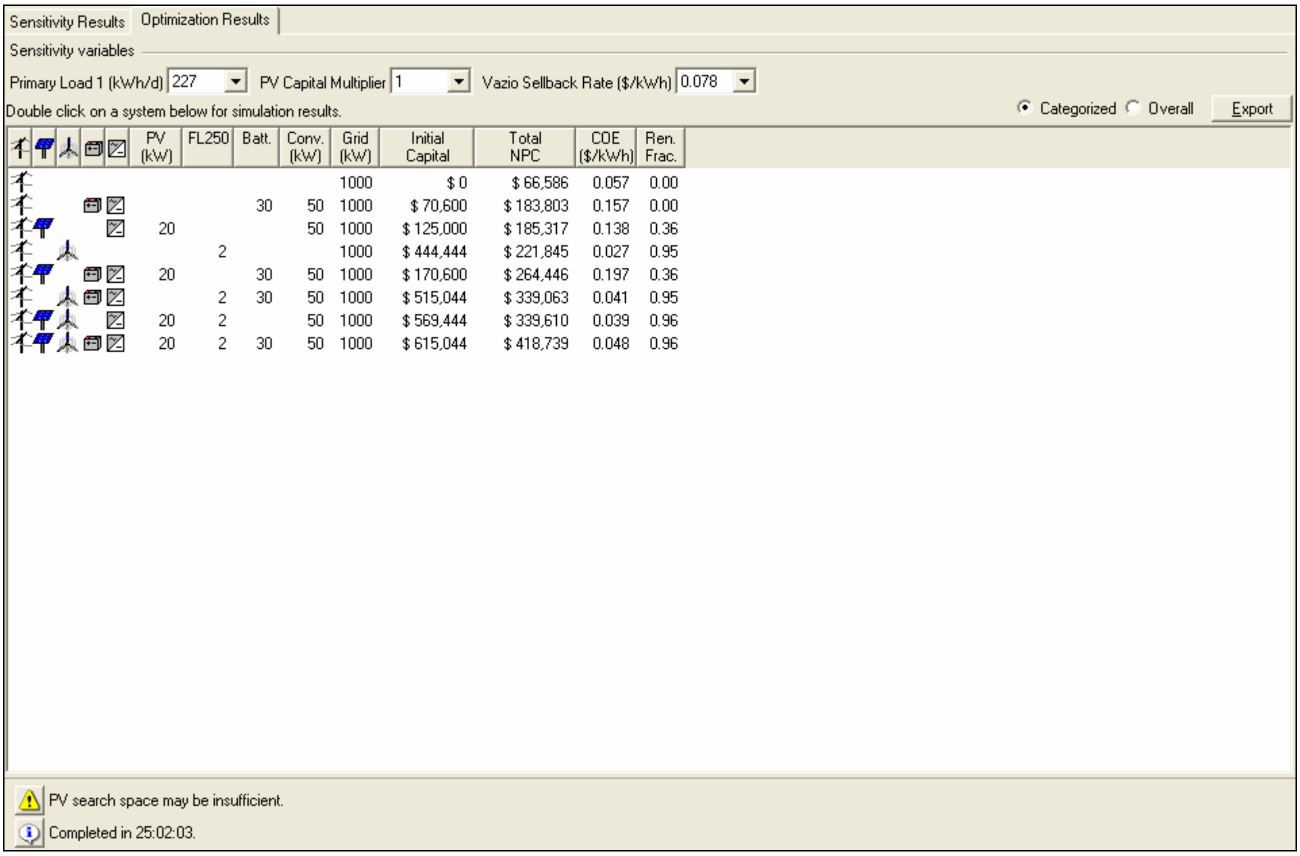
Consumption	kWh/yr	%
AC primary load	82,799	100
Total	82,799	100

Quantity	kWh/yr	%
Excess electricity	226,348	70.0
Unmet electric load	56.2	0.1
Capacity shortage	64.7	0.1

Quantity	Value
Renewable fraction	1.00

Figure A3.3 – Monthly average electric production of wind and PV source in the optimized solution

Appendix 4 – Grid connected system without a water turbine



Sensitivity variables

Primary Load 1 (kWh/d) 227 PV Capital Multiplier 1 Vazio Sellback Rate ($/kWh) 0.078

Double click on a system below for simulation results.

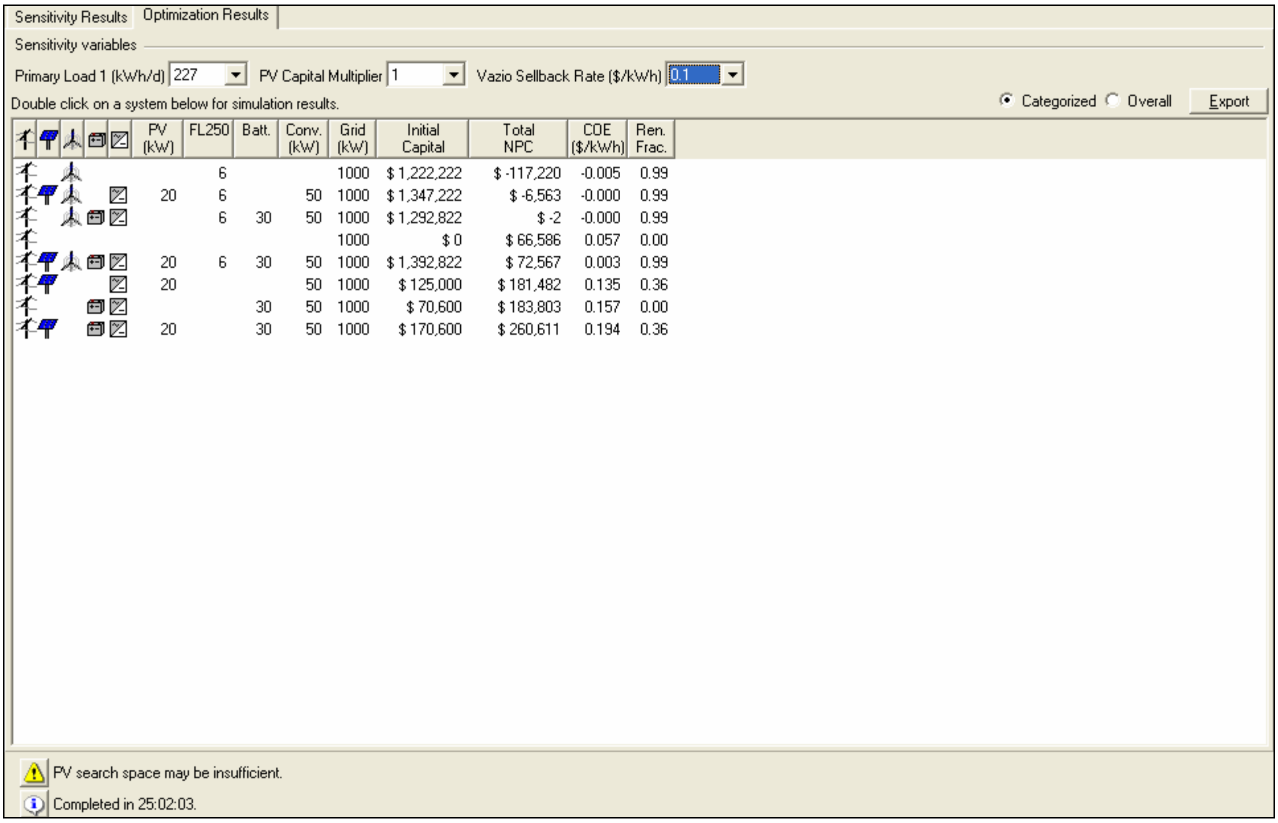
● Categorized ○ Overall

					PV (kW)	FL250	Batt.	Conv. (kW)	Grid (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.
✓									1000	$ 0	$ 66,586	0.057	0.00
✓			✓	✓			30	50	1000	$ 70,600	$ 183,803	0.157	0.00
✓	✓			✓	20			50	1000	$ 125,000	$ 185,317	0.138	0.36
✓		✓				2			1000	$ 444,444	$ 221,845	0.027	0.95
✓	✓		✓	✓	20		30	50	1000	$ 170,600	$ 264,446	0.197	0.36
✓		✓	✓	✓		2	30	50	1000	$ 515,044	$ 339,063	0.041	0.95
✓	✓	✓		✓	20	2		50	1000	$ 569,444	$ 339,610	0.039	0.96
✓	✓	✓	✓	✓	20	2	30	50	1000	$ 615,044	$ 418,739	0.048	0.96

⚠ PV search space may be insufficient.

ⓘ Completed in 25:02:03.

Figure A4.1 - Optimized solutions for each type of system, displayed in net present cost order for a sellback rate of 0,078€/kWh



Sensitivity variables

Primary Load 1 (kWh/d) 227 PV Capital Multiplier 1 Vazio Sellback Rate ($/kWh) 0.1

Double click on a system below for simulation results.

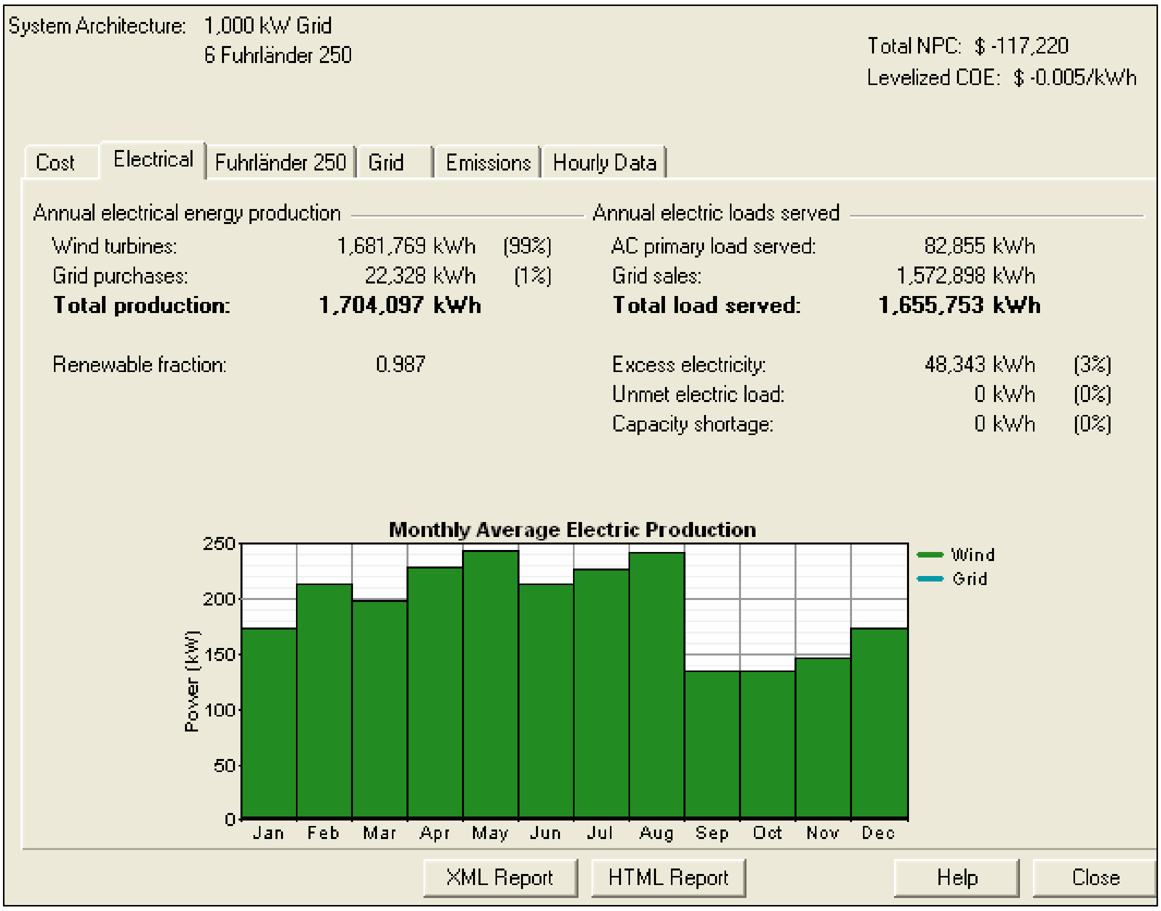
● Categorized ○ Overall

					PV (kW)	FL250	Batt.	Conv. (kW)	Grid (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.
✓		✓				6			1000	$ 1,222,222	$ -117,220	-0.005	0.99
✓	✓	✓		✓	20	6		50	1000	$ 1,347,222	$ -6,563	-0.000	0.99
✓		✓	✓	✓		6	30	50	1000	$ 1,292,822	$ -2	-0.000	0.99
✓									1000	$ 0	$ 66,586	0.057	0.00
✓	✓	✓	✓	✓	20	6	30	50	1000	$ 1,392,822	$ 72,567	0.003	0.99
✓	✓			✓	20			50	1000	$ 125,000	$ 181,482	0.135	0.36
✓			✓	✓			30	50	1000	$ 70,600	$ 183,803	0.157	0.00
✓	✓		✓	✓	20		30	50	1000	$ 170,600	$ 260,611	0.194	0.36

⚠ PV search space may be insufficient.

ⓘ Completed in 25:02:03.

Figure A4.2 - Optimized solutions for each type of system, displayed in net present cost order for a sellback rate of 0,10€/kWh



System Architecture: 1,000 kW Grid
6 Fuhrländer 250

Total NPC: $ -117,220
Levelized COE: $ -0.005/kWh

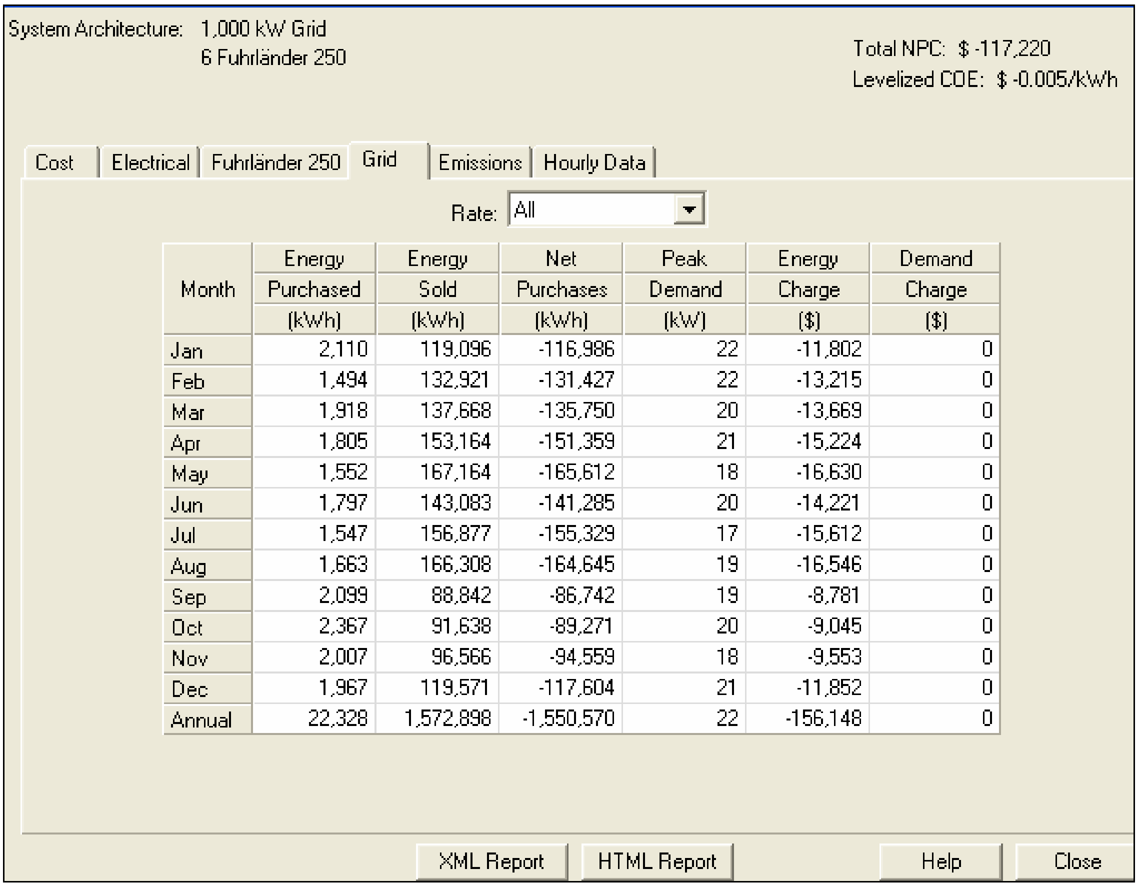
Annual electrical energy production

Wind turbines:	1,681,769 kWh	(99%)
Grid purchases:	22,328 kWh	(1%)
Total production:	**1,704,097 kWh**	
Renewable fraction:	0.987	

Annual electric loads served

AC primary load served:	82,855 kWh	
Grid sales:	1,572,898 kWh	
Total load served:	**1,655,753 kWh**	
Excess electricity:	48,343 kWh	(3%)
Unmet electric load:	0 kWh	(0%)
Capacity shortage:	0 kWh	(0%)

Figure A4.3 - Monthly average electric production of wind and grid source in the optimized solution for a sellback rate of 0,10 €/kWh



System Architecture: 1,000 kW Grid
6 Fuhrländer 250

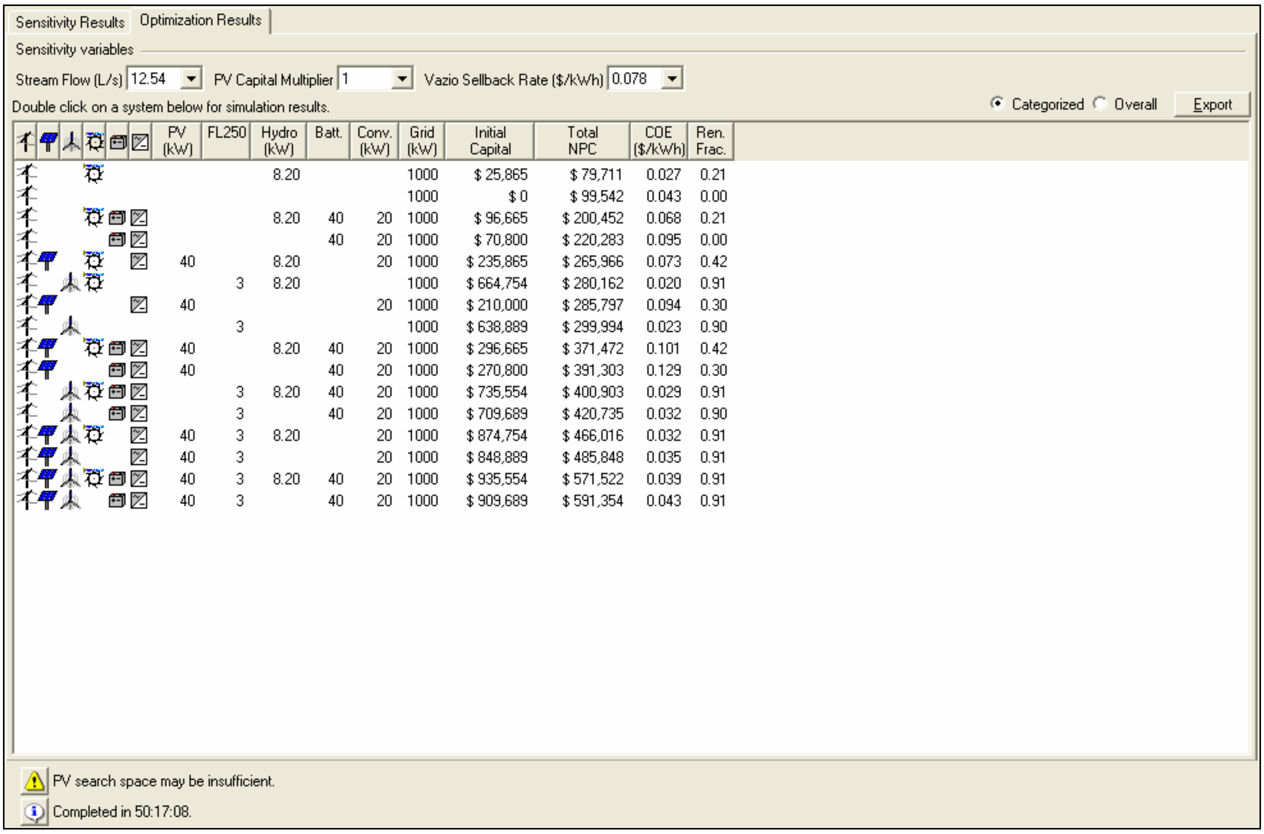
Total NPC: $ -117,220
Levelized COE: $ -0.005/kWh

Rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	2,110	119,096	-116,986	22	-11,802	0
Feb	1,494	132,921	-131,427	22	-13,215	0
Mar	1,918	137,668	-135,750	20	-13,669	0
Apr	1,805	153,164	-151,359	21	-15,224	0
May	1,552	167,164	-165,612	18	-16,630	0
Jun	1,797	143,083	-141,285	20	-14,221	0
Jul	1,547	156,877	-155,329	17	-15,612	0
Aug	1,663	166,308	-164,645	19	-16,546	0
Sep	2,099	88,842	-86,742	19	-8,781	0
Oct	2,367	91,638	-89,271	20	-9,045	0
Nov	2,007	96,566	-94,559	18	-9,553	0
Dec	1,967	119,571	-117,604	21	-11,852	0
Annual	22,328	1,572,898	-1,550,570	22	-156,148	0

Figure A4.4 – Data regarding the electric national grid for a sellback rate of 0,10 €/kWh

Appendix 5 – Grid connected system with a water turbine



Sensitivity Results | Optimization Results

Sensitivity variables

Stream Flow (L/s) 12.54 | PV Capital Multiplier 1 | Vazio Sellback Rate ($/kWh) 0.078

Double click on a system below for simulation results.

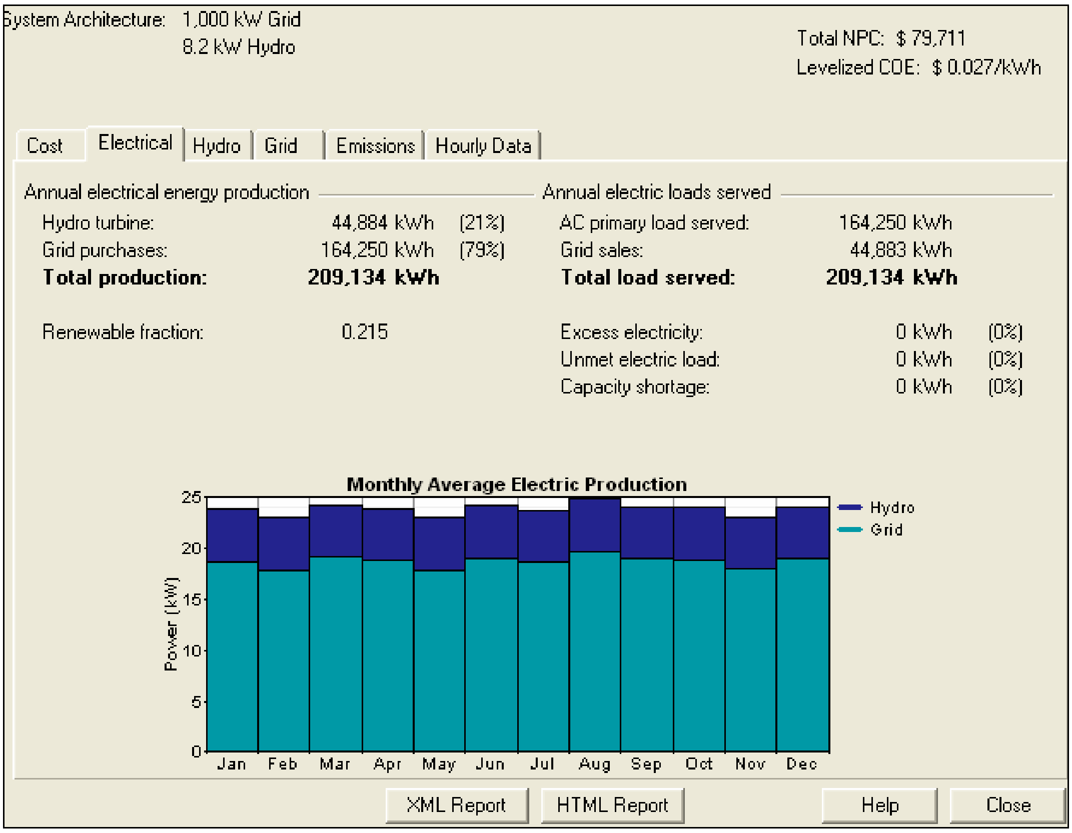
● Categorized ○ Overall | Export

PV (kW)	FL250	Hydro (kW)	Batt.	Conv. (kW)	Grid (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.
		8.20			1000	$ 25,865	$ 79,711	0.027	0.21
					1000	$ 0	$ 99,542	0.043	0.00
		8.20	40	20	1000	$ 96,665	$ 200,452	0.068	0.21
			40	20	1000	$ 70,800	$ 220,283	0.095	0.00
40		8.20		20	1000	$ 235,865	$ 265,966	0.073	0.42
	3	8.20			1000	$ 664,754	$ 280,162	0.020	0.91
40				20	1000	$ 210,000	$ 285,797	0.094	0.30
	3				1000	$ 638,889	$ 299,994	0.023	0.90
40		8.20	40	20	1000	$ 296,665	$ 371,472	0.101	0.42
40			40	20	1000	$ 270,800	$ 391,303	0.129	0.30
	3	8.20	40	20	1000	$ 735,554	$ 400,903	0.029	0.91
	3		40	20	1000	$ 709,689	$ 420,735	0.032	0.90
40	3	8.20		20	1000	$ 874,754	$ 466,016	0.032	0.91
40	3			20	1000	$ 848,889	$ 485,848	0.035	0.91
40	3	8.20	40	20	1000	$ 935,554	$ 571,522	0.039	0.91
40	3		40	20	1000	$ 909,689	$ 591,354	0.043	0.91

PV search space may be insufficient.

Completed in 50:17:08.

Figure A5.1 - Optimized solutions for each type of system, displayed in net present cost order for a sellback rate of 0,078€/kWh



System Architecture: 1,000 kW Grid
8.2 kW Hydro

Total NPC: $ 79,711
Levelized COE: $ 0.027/kWh

Cost | Electrical | Hydro | Grid | Emissions | Hourly Data

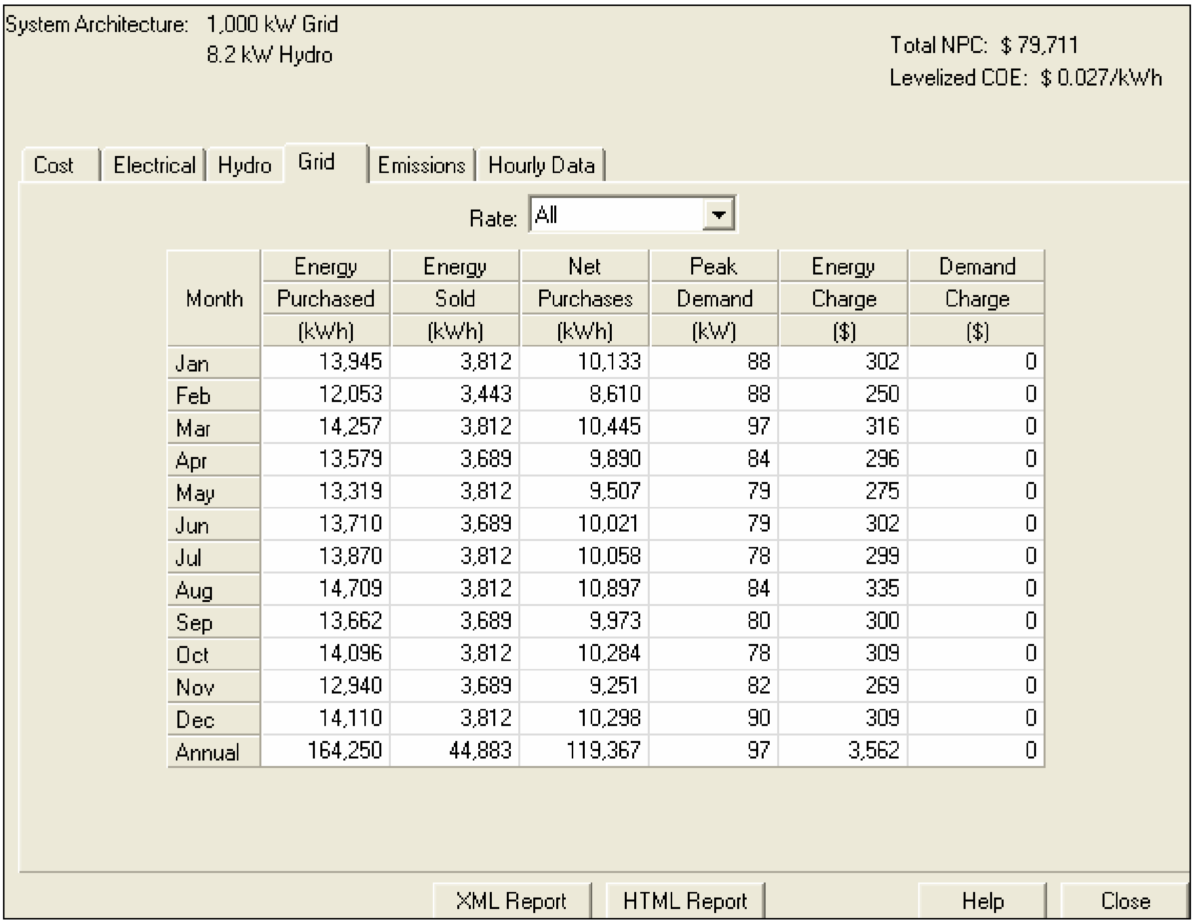
Annual electrical energy production

Hydro turbine:	44,884 kWh	(21%)
Grid purchases:	164,250 kWh	(79%)
Total production:	**209,134 kWh**	
Renewable fraction:	0.215	

Annual electric loads served

AC primary load served:	164,250 kWh	
Grid sales:	44,883 kWh	
Total load served:	**209,134 kWh**	
Excess electricity:	0 kWh	(0%)
Unmet electric load:	0 kWh	(0%)
Capacity shortage:	0 kWh	(0%)

Figure A5.2 - Monthly average electric production of hydro and wind source in the optimized solution for a sellback rate of 0,078 €/kWh



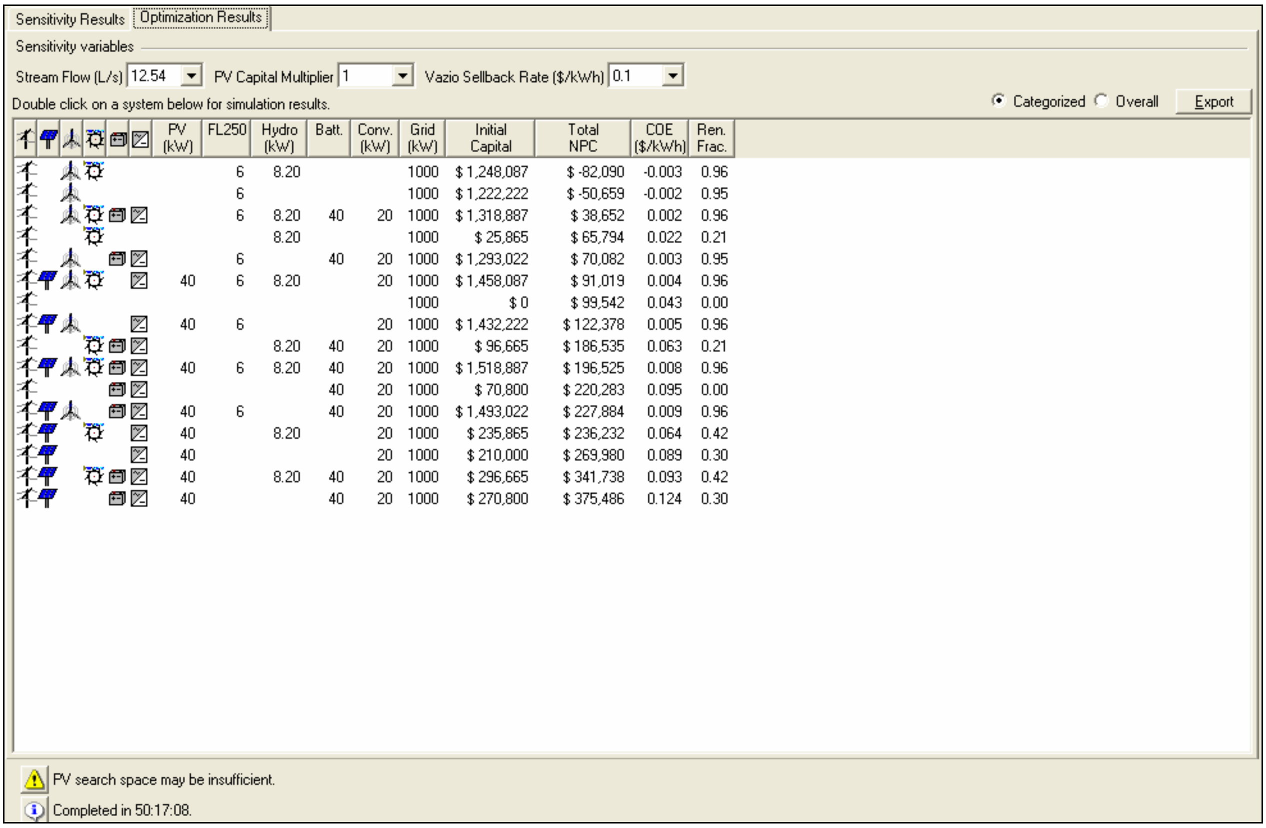
System Architecture: 1,000 kW Grid
8.2 kW Hydro

Total NPC: $ 79,711
Levelized COE: $ 0.027/kWh

Rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	13,945	3,812	10,133	88	302	0
Feb	12,053	3,443	8,610	88	250	0
Mar	14,257	3,812	10,445	97	316	0
Apr	13,579	3,689	9,890	84	296	0
May	13,319	3,812	9,507	79	275	0
Jun	13,710	3,689	10,021	79	302	0
Jul	13,870	3,812	10,058	78	299	0
Aug	14,709	3,812	10,897	84	335	0
Sep	13,662	3,689	9,973	80	300	0
Oct	14,096	3,812	10,284	78	309	0
Nov	12,940	3,689	9,251	82	269	0
Dec	14,110	3,812	10,298	90	309	0
Annual	164,250	44,883	119,367	97	3,562	0

Figure A5.3 - Data regarding the electric national grid for a sellback rate of 0,078 €/kWh



Sensitivity variables

Stream Flow (L/s) 12.54 PV Capital Multiplier 1 Vazio Sellback Rate ($/kWh) 0.1

Double click on a system below for simulation results.

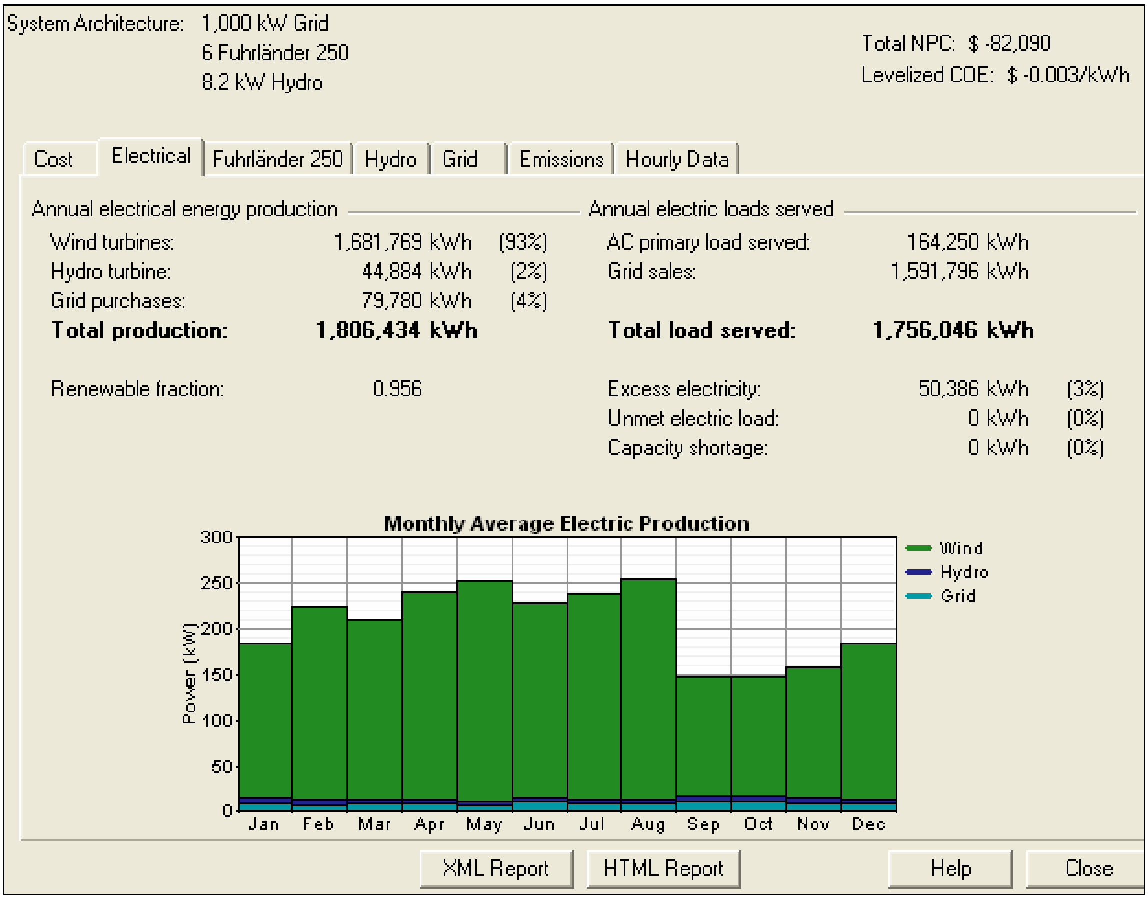
● Categorized ○ Overall

						PV (kW)	FL250	Hydro (kW)	Batt.	Conv. (kW)	Grid (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.
●		●	●				6	8.20			1000	$ 1,248,087	$ -82,090	-0.003	0.96
●		●					6				1000	$ 1,222,222	$ -50,659	-0.002	0.95
●		●	●	●	●		6	8.20	40	20	1000	$ 1,318,887	$ 38,652	0.002	0.96
●			●					8.20			1000	$ 25,865	$ 65,794	0.022	0.21
●		●		●	●		6		40	20	1000	$ 1,293,022	$ 70,082	0.003	0.95
●	●	●	●		●	40	6	8.20		20	1000	$ 1,458,087	$ 91,019	0.004	0.96
●											1000	$ 0	$ 99,542	0.043	0.00
●	●	●			●	40	6			20	1000	$ 1,432,222	$ 122,378	0.005	0.96
●			●	●	●			8.20	40	20	1000	$ 96,665	$ 186,535	0.063	0.21
●	●	●	●	●	●	40	6	8.20	40	20	1000	$ 1,518,887	$ 196,525	0.008	0.96
●				●	●				40	20	1000	$ 70,800	$ 220,283	0.095	0.00
●	●	●		●	●	40	6		40	20	1000	$ 1,493,022	$ 227,884	0.009	0.96
●	●		●		●	40		8.20		20	1000	$ 235,865	$ 236,232	0.064	0.42
●	●				●	40				20	1000	$ 210,000	$ 269,980	0.089	0.30
●	●		●	●	●	40		8.20	40	20	1000	$ 296,665	$ 341,738	0.093	0.42
●	●			●	●	40			40	20	1000	$ 270,800	$ 375,486	0.124	0.30

PV search space may be insufficient.

Completed in 50:17:08.

Figure A5.4 - Optimized solutions for each type of system, displayed in net present cost order for a sellback rate of 0,10€/kWh



System Architecture: 1,000 kW Grid
6 Fuhrländer 250
8.2 kW Hydro

Total NPC: $ -82,090
Levelized COE: $ -0.003/kWh

Annual electrical energy production

Wind turbines:	1,681,769 kWh	(93%)
Hydro turbine:	44,884 kWh	(2%)
Grid purchases:	79,780 kWh	(4%)
Total production:	**1,806,434 kWh**	

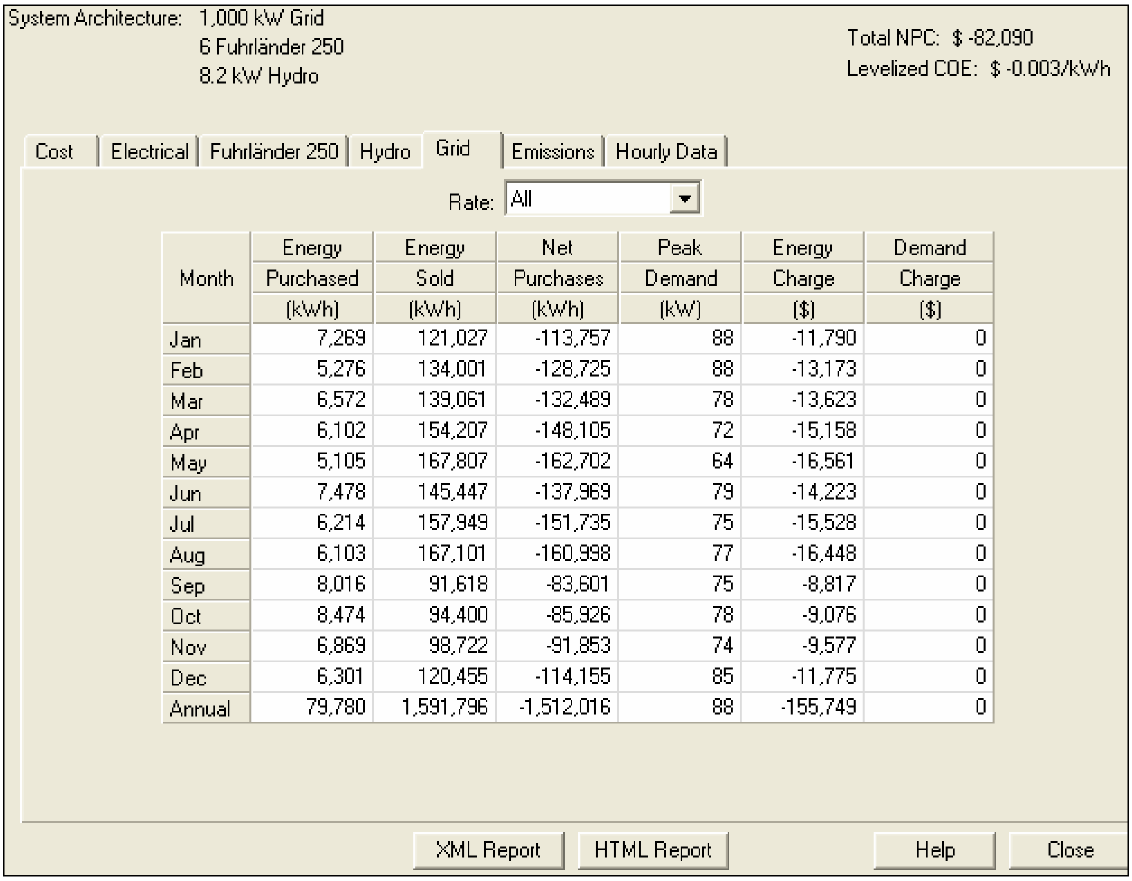
Renewable fraction: 0.956

Annual electric loads served

AC primary load served:	164,250 kWh
Grid sales:	1,591,796 kWh
Total load served:	**1,756,046 kWh**

Excess electricity:	50,386 kWh	(3%)
Unmet electric load:	0 kWh	(0%)
Capacity shortage:	0 kWh	(0%)

Figure A5.5 - Monthly average electric production of hydro, wind and grid source in the optimized solution for a sellback rate of 0,10 €/kWh



System Architecture: 1,000 kW Grid
6 Fuhrländer 250
8.2 kW Hydro

Total NPC: $ -82,090
Levelized COE: $ -0.003/kWh

Rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	7,269	121,027	-113,757	88	-11,790	0
Feb	5,276	134,001	-128,725	88	-13,173	0
Mar	6,572	139,061	-132,489	78	-13,623	0
Apr	6,102	154,207	-148,105	72	-15,158	0
May	5,105	167,807	-162,702	64	-16,561	0
Jun	7,478	145,447	-137,969	79	-14,223	0
Jul	6,214	157,949	-151,735	75	-15,528	0
Aug	6,103	167,101	-160,998	77	-16,448	0
Sep	8,016	91,618	-83,601	75	-8,817	0
Oct	8,474	94,400	-85,926	78	-9,076	0
Nov	6,869	98,722	-91,853	74	-9,577	0
Dec	6,301	120,455	-114,155	85	-11,775	0
Annual	79,780	1,591,796	-1,512,016	88	-155,749	0

Figure A5.6 - Data regarding the electric national grid for a sellback rate of 0,10 €/kWh

Appendix 6 – Pump and hydro turbine characteristics for different village tank reservoir levels

Table A6.1 – Pump and turbine characteristics for different reservoir sizes (different flows and head)

Turbine (15h)						**Pump**					
Flow (l/s)	**Head (m)**	**Power (kW)**	**Cost (€/kW)**	**Cost (€)**	**O&M (€/yr)**	**Flow (l/s)**	**Head (m)**	**Power (kW)**	**Cost (€/kW)**	**Total (€)**	**Difference**
(N.A.)	(N.A.)	(N.A.)	(N.A.)	(N.A.)	(N.A.)	16.72	61.95	12.69	4048.03	67683.13	0
20.70	49.00	8.11	3000.00	24343.20	243.43	66.88	61.37	50.28	1400.00	93632.00	25948.87
27.77	48.70	10.82	2900.00	31375.66	313.76	79.73	63.91	62.42	1264.01	100779.65	33096.52
51.04	47.00	19.19	2800.00	53734.91	537.35	118.51	74.50	108.16	1189.86	141010.42	73327.29
74.32	44.00	26.16	2600.00	68017.66	680.18	157.30	88.00	169.57	1079.03	169730.79	102047.66
97.59	41.00	32.01	2400.00	76822.85	768.23	196.09	102.50	246.22	993.35	194786.87	127103.74
120.86	36.00	34.81	2300.00	80057.66	800.58	234.87	120.50	346.70	885.37	207947.43	140264.30
144.13	31.00	35.74	2300.00	82211.75	822.12	273.66	139.50	467.65	791.61	216630.92	148947.79

Appendix 7 – Reservoir sensitivity analysis

Table A7.1 – Minimum reservoir operation conditions

Minimum level (m)	2,65
Diameter (m)	20
Minimum Volume (l)	832522,05
Minimum Volume (m^3)	832,52

Table A7.2 – Reservoir sizes sensitivity analysis

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Pump flow (l/s)	66,88	79,73	118,51	157,30	196,09	234,87	273,66
Turbine flow (l/s)	20,06	27,77	51,04	74,32	97,59	120,86	144,13
Volume (l)	2513274,12	3141592,65	4398229,72	5654866,78	6911503,84	8168140,90	9424777,96
Volume (m^3)	2513,27	3141,59	4398,23	5654,87	6911,50	8168,14	9424,78
Diameter (m)	20,00	20,00	20,00	20,00	20,00	20,00	20,00
Nível (m)	8,00	10,00	14,00	18,00	22,00	26,00	30,00