NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF MECHANICAL ENGINEERING
SECTION OF FLUIDS

DIPLOMA THESIS

Simulation, design study and optimization of small hybrid RES energy systems for electrification of remote communities

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Athens 2011

CONTENTS

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ABSTRACT

Small-sized hybrid power systems may be designed to solve the power supply problem in some rural areas. In most of these areas the energy production is mainly based on energy-intensive and polluting autonomous diesel generator units or on a really expensive and hardly advantageous grid extension. Therefore, the development of hybrid systems that combine different but complementary renewable energy technologies can offer solutions both in the environmental pollution and the economical problem.

The subject of this diploma thesis, is the electrification of remote areas. In the first part, the theoretical background of the electrification of such areas is presented, as well as the main characteristics of hydropower, wind power and photovoltaics. In the second one, the operation of a hybrid wind-hydro-solar power generation system with batteries for power storage and diesel generators for emergencies is analyzed and optimized.

In order to find the combinations of the hybrid system's components that can provide 24h electrification of a remote area, an iterative algorithm written in FORTRAN was developed. The proposed method has been tested by taking into consideration the annual average hourly values of the load demand, wind speed, insolation and water flow that the hybrid generation system would meet in Western Ghats (Kerala), India. The results of this algorithm depict the power distribution throughout an average day and other data like the costs of the combinations, which prove the advantages of the system over constructing an extension to the nearest existing distribution line or using diesel generators.

Furthermore, an optimization software (EASY) was used to find the optimal combination that would minimize the cost per kWh and the use of diesel generators. Comparison between the results of the algorithm and the optimization procedure was made.

INTRODUCTION

Many isolated areas, especially in developing countries, are not connected to grid electricity mainly because of capacity shortage and difficult terrain and environmental considerations. Usually, diesel generators (DG) are utilized to feed power to those areas due to their compact design and high specific power. The compact design makes it easy to install the unit in non-prepared and small area locations. The high specific power means that the ratio of output power to the weight of the unit is considerably high.

However, as an independent power source, the DG unit is facing significant problems. The maximum efficiency can only be achieved when the DG unit is operated close to the rated capacity and it is not recommended for it to operate below its minimum power specified by the manufacturer. This might be a problem in remote area applications since the load profiles during day and night times are very different, depending on daily activities. Since the fuel price has been increasing in the last decades, the generation cost has also increased. On top of that, several other problems can occur regarding their hard maintenance, as well as the extra cost to transport fuel to these remote areas. The transportation system may have problems such as it is difficult to support the fuel consumption continuously. Moreover, there is a necessity to reduce the combustion of fossil fuels and the consequent CO_2 emissions which is the principal cause of the greenhouse effect/global warming. These global environmental concerns and the ever increasing need for energy, coupled with a steady progress in renewable energy technologies have opened up many opportunities for utilization of renewable energy resources. Hence, applications of inexhaustible, renewable and clean energy sources like wind, hydro and solar energy, are becoming more and more popular to solve the power shortage problem in these areas.

Micro-hydro, wind and solar technologies operating in a stand-alone mode have long ago entered the commercial phase and, in many situations, have proved their reliability and cost effectiveness. Yet research and development in these energy technologies continue in order to improve their performance, establish techniques for accurate prediction of their output and reliably integrate them with other conventional generating sources. Moreover, at present, the economic aspects of these renewable energy technologies are sufficiently promising to include the development of their market.

Hybrid energy systems are pollution free, take low cost and less gestation period, user and social friendly. Such systems are important sources of energy supply, especially in remote areas. Hybrid systems can provide high quality electricity at a comparatively economic price.

However, the output power generated by the renewable power sources always fluctuates depending on the weather conditions. Therefore, isolated operation of these power units may not be effective in terms of efficiency and reliability. So, a hybrid energy system combining different renewable energy sources is a viable solution that offers energy balance and stability, due to the complementary strengths of each type of sources. In this respect, the hybrid power systems have greater flexibility, higher efficiency and lower costs for the same quantity of energy production than a PV-only system, a diesel-only system etc. Thus, many non urban communities are already electrified from stand-alone systems.

The performance of a hybrid system is remarkably increased when storage devices are available. The integration of the hybrid power systems with battery storage provides a reduction in the operational costs and emitted air pollutants in the atmosphere.

A case study is conducted in a typical remote village of Western Ghats in Kerala, India. In order for the hybrid system to supply electricity reliably and at an economical price, its design must be based on energy balance. So, only specific combinations of hydro turbines, wind turbines and PV panels can be acceptable and the task of the developed code is to find these combinations.

Based on the available load profile, the hourly average data on wind speed, insolation, and the power demand, the generation capacity is determined to best match the power demand by minimizing the difference between generation and load (ΔP) over a 24-hour period. The capacity of the storage needed to make the system operate independently as a stand-alone system is determined from the hourly information obtained from ΔP.

A cost comparison is given for the different combinations of the hybrid energy system. In this comparison, the economical benefit from installing a stand-alone system is clear. Moreover, the optimal configuration based on cost per kWh and use of the diesel generators is determined.

However, because annual average hourly wind and insolation data are used, periods of time (days) with no wind and/or solar generation, which do occur in real-life situations, do not show up in this study. To account for these situations, a backup diesel generator is also used as a part of the system to respond to the emergency cases where renewable energy generation and battery banks are not sufficient to supply the load.

It should be noted that when comparing the energy supplied by a stand-alone system with that supplied by a utility grid extension, in addition to a cost comparison, the "quality of energy supply" from the two sources should also be studied. Such a study should include issues such as power quality, reliability, protection and ability for motor starting. A study of these issues is beyond the scope of this diploma thesis.

Use of other renewable sources, such as biomass, geothermal etc. is not considered in this work. Besides, batteries are the only storage technology that is used, despite the advancements in fuel cell technology, which have opened up the option for using hydrogen in the energy storage procedure.

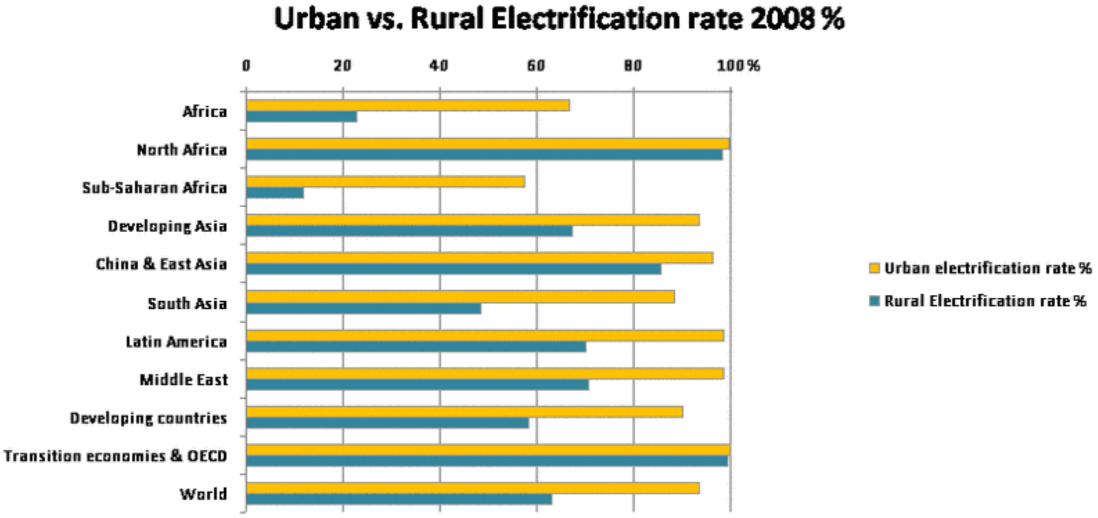
PART I
THEORETICAL BACKGROUND

CHAPTER 1: ELECTRIFICATION OF REMOTE AREAS

1.1. Introduction

Rural electrification, mainly in the form of grid extension, has been high on the development agenda since the 1950's. Electricity is a fundamental factor for any society and it is, implicitly, a precondition for economic development anywhere. People in developing countries quite rightly have the demand of sharing some of the modern amenities taken for granted in developed nations and urban populations. The provision of electricity enables the use of many modern labour saving electric products and appliances, not the least of which is basic electric lighting and water pumping.

All countries - whether industrialized, middle or low income - place a high priority on providing their citizens access to electricity. Despite this policy and the expenditure of billions of dollars, there are still nearly 1,6 billion people - more than 300 million households in both urban and rural areas - who have no access to electricity services today. The vast majority of these households (approximately 260 millions) are rural households, which reside in isolated communities, difficult to access and therefore to connect to national or regional grids, mainly in Sub-Saharan Africa and South Asia. This can be explained by the fact that the rate of urban electrification is significantly greater that the rural one in most of the areas, as seen below in a diagram created by the International Energy Agency at 2008:



These so-called “off-grid” communities are generally small and dispersed, consisting of low-income households, characteristics economically unattractive to potential private-sector energy providers or even government electrification programs that must prioritize the allocation of scarce resources.

To meet their lighting and other basic energy needs, many of these households continue to depend on expensive fossil fuel–based sources, such as diesel or kerosene, which are energy inefficient and polluting. Grid extension, diesel-powered minigrids and mini-hydropower generators were, for the most part, the only electrification options available to rural communities. With the commercial maturation of various small-scale, renewable energy-based technologies - from solar photovoltaic systems to small wind generators and micro hydropower - along with the evolution of innovative service delivery models, off-grid or stand-alone service provision has emerged as a viable alternative for increasing electricity access, especially in remote and dispersed communities. The dramatic rise in fuel prices has further highlighted the economic attractiveness of these technology options.

Of course technology is not the only factor that determines the long-term sustainability of off-grid electrification. It requires effective prioritization and planning to enable economic choices of technology, appropriate infrastructure to ensure that services are provided over the long run and sustainable financing to make these capital-intensive technologies affordable.

Poor rural households are not the target of all electrification policies. Some policies also target a mix of farms, big villages and small towns all of which call for different technologies. In fact, rural electrification policies are shaped according to the various energy needs, resources and target groups. Electrifying the suburb of a major city obviously poses problems that are different from those of a remote village in the inland. So a different analysis has to be carried for each case, since the circumstances can greatly change from place to place.

1.2. Main Challenges and Benefits

1.2.1. General challenges faced by rural communities

Remote or rural regions lacking electricity supply often pose well identified challenges. They may lie at a reasonable distance from national or regional electricity grids (i.e. remote villages in the Amazon), may be difficult to access (far from urban centers, with a difficult terrain such as large rivers, inaccessible gorges, etc.) or may suffer harsh climatic conditions that render electrification through grid extension a really hard task. The population of most rural communities has a low density and is also characterized by a low level of education, low load density (which is generally concentrated at evening peak hours) and low revenues.

The provision of electric services to rural and remote communities in the developing world is a financial challenge. Assuming all current rural and remote communities in the developing world would be electrified with a grid-based modest service, the associated generation, transmission and distribution systems would require huge costs. To a large extent the investment has to come from utilities, governments and private investors. Though the multilateral development banks and donors are influential, they are relatively modest investors in rural electrification.

However, the developing world is facing more rural development challenges than the provision of electricity services: clean water, sanitation, health services and safety are more important priorities. On the other hand, access to electricity facilitates these services.

Continuous technology innovation is necessary in order to cope with the electrification challenge, particularly in the rural context. In the past, many rural electrification programs have focused on expanding central grids managed by national or regional utilities. In several cases the technical standards for the rural electricity schemes were not adjusted to local conditions. In some cases technical standards appropriate for urban areas were used or in other cases, standards applicable in the donor countries. Cost reduction is a critical issue because one of the biggest obstacles in extending electrification to rural communities are the "up-front" costs of the investment. To reduce costs, further developments in this area are needed.

Therefore, the concept of off-grid electrification through a hybrid system is gaining more and more viability, even though they need further development and cost reduction. In many cases, they can prove to be really more advantageous than grid expansion.

Just providing the rural communities with electricity is hardly enough. Infrastructure, local technicians and appliance shops are needed, and the customer base must be properly informed and educated. To that end cooperation between a utility, the local government and a community-based organization is needed.

In the past, many donor supported rural electrification programs focused on the poor segment of the communities. There is a growing understanding that electricity used for productive applications is equally or sometimes even more important because of its positive effects on local employment and income generation for the poor. Planning and funding of the electrification program should therefore be based on the whole potential consumer base, taking the development objectives into account.

In light of these challenges, electricity provision to the world's rural poor calls for a committed and long-term action plan. The benefits that electricity access brings to households and communities are justified not only on social and economic grounds but also on grounds of equity objectives.

1.2.2. Social benefits of electrification

At the household level, electricity is mainly used for powering light bulbs, fans, television sets, computers and phones. The use of computers and phones can provide access to information and facilitate communication and health care. Electricity can significantly improve the living conditions inside the house, while the household chores tend to become less tedious, the light bulbs can provide better brightness for studying and reading and fans and television sets increase the increasing the general welfare and the comfort of all members of the household.

School in South Africa powered by a photovoltaic system

Electrification of a rural community leads of course to many health benefits, presumably through improvements of health facilities, reduced air pollution from light sources, improved knowledge through increased access to information broadcasted on radio and television (better knowledge of diseases and how to avoid them) and better nutrition from improved knowledge and access to refrigeration and non-spoiled food.

Moreover, education benefits are also certain, through improvement of schools and more time spent studying due to availability of electric light. The citizens will be educated and well-informed about history and timeliness, so they won’t be easily manipulated.

1.2.3. Economic benefits of electrification

Besides the social benefits, access to electricity will definitely have a huge economic impact on the community. Electricity use is expected to lead to more productive processes. The growth of businesses or farms using electricity will subsequently increase the demand for electricity, leading to a virtuous growth cycle profitable to both electricity providers and rural communities. Such economic growth is obviously an important achievement of any rural electrification program.

Obviously, electricity cannot by itself guarantee the economic growth of a newly electrified community. While it is undoubtedly an important input to rural businesses, farms or other small rural structures, adequate local conditions such as organized rural markets and sufficient credit are necessary for these businesses to grow. Lack of such complementary development programs in these regions may hinder their economic growth. Nevertheless, higher availability of jobs, productivity increases or improved economic opportunities are the effect that can be expected from better energy services.

In general, rural electrification investments can often generate sufficient benefits to be warranted from an economic standpoint. The value of these benefits to households (who constitute the vast majority of the connections in rural electrification schemes) is frequently above the average long-run supply cost.

1.3. Technologies commonly used in rural electrification policies

The main challenge of electrifying rural or remote areas is the choice of the appropriate technology for each occasion.

The choice of a specific energy technology for rural electrification depends on the targeted country and on whether it is a whole region, community, business, farm or household that is to benefit from the process. Except from the load type, the load growth should be taken into consideration. So, a study of current and future demand for electricity on site is critical to avoid power shortage. The adoption of flexible system design that can be expanded as load demand increases can mitigate risks associated with unpredictable load growth rates.

Furthermore, issues of customer density, relative distance to the national or regional grid, landscape, availability of natural resources such as wind, sun, water, forests, economic and financial aspects, availability and maturity of any chosen technology, are the factors which must be taken into consideration for the choice of the technology or technology mix.

The variety of potential energy technologies for rural electrification projects is quite large and each technology naturally differs in its generation technique, its costs and in the quality of the service it delivers. These technologies generally involve national or regional grid extension, diesel generators, liquefied petroleum gas, disposable batteries, kerosene lamps, renewable energies (including photovoltaic systems, wind energy, hydropower, and new wave energy and hydrogen) or hybrid systems.

In this thesis, details regarding other technologies than hybrid systems are not presented.

1.3.1. Hybrid systems

Hybrid systems are basically a combination of two or more different but complementary energy supply systems located on the same site. The advantage of hybrid systems is their ability to avoid fluctuations in the system's energy supply, since the different energy generators have the ability of complementing one another, unlike the stand-alone renewable energy technologies such as wind and PV. The most common types of renewable energy are wind, micro hydropower and photovoltaic systems. By using the strengths of each type of sources, a hybrid system will provide a relatively constant delivery of energy even when one of the supply devices of the system is unable to generate power (lack of wind in the case of a wind turbine or of sunlight in the case of a PV). Hybrid systems are able to provide 'grid-quality' electricity with a power range between several kilowatts and several hundred kilowatts, without requiring much supervision and attention.

Solar-diesel hybrid station

Renewable energy sources are widely available throughout the developing world:

- *Sub-Saharan Africa:* There exist numerous natural advantages, like extremely favorable sun and wind conditions, big hydro potential and important sustainable biomass potential. Even though, the off-grid renewable sector is far from reaching its potential, something that may happen in the future due to better technology prices and increased awareness of governments.

  Northern Africa: Most places have a really important solar and wind potential and the development of renewable energy projects is rather widespread.

  East Africa: This region boasts enormous potential for wind energy generation due to its favorable climatic conditions.
- *Asia:* Many Asian countries present the highest solar irradiations in the world, whereas others are already familiar with wind, biomass and hydro energy systems. Nevertheless, the electrification of the rural areas has not yet reached a satisfying level despite the great PV potential. On the contrary, the urban electrification rate, especially in South and East Asia, is really high.

  Middle East: The countries without fossil fuel reserves are turning towards renewable energies and more particularly towards solar technologies.

- *Latin and Central America:* Latin American countries have demonstrated strong commitment and invested a lot to reduce the number of people without access to electricity. Except from Brazil and its enormous hydro and biomass industry, renewable energies in Latin America are mostly limited to off-grid projects which have been the main drivers of the market so far. The taking off of the wind continental industry, the extremely favorable indigenous conditions, as well as the economic growth of the continent will probably change this within the next years whereas the continent will remain a very interesting market, as well as a good case study, for the off-grid sector.

Except, from allowing the use of indigenous natural resources, the hybrid systems offer on site power generation, thereby avoiding transmission losses and long distribution chains and satisfying energy demand directly. The standardization and modularity of the technology (for example PV systems) provides a high degree of flexibility to adapt to different locations and environments and at the same time allows the installed technology to be scaled up when demand increases. Furthermore, the simple installation and maintenance combined with minimal running costs, facilitate local training and income generation opportunities, which in turn guarantee the sustainability of the system.

Apart from the renewable energy units, hybrid systems usually also include battery banks and diesel generators in order to circumvent the problem of intermittent resources. Of course, hybrids with diesel generators are possible only where diesel fuel can be reliably transported to the site and users can afford fuel costs that may escalate over time.

At favorable weather conditions, the renewable part of the system is able to meet the energy demand, using the energy surplus to charge the battery. The batteries act as “buffers”, maintaining a stable energy supply during short periods of time i.e. in cases of low sunlight or low wind. Moreover, the battery serves to meet peak demands, when the renewable energy units maybe cannot satisfy the demand. A charge controller is responsible for regulating the state of load of the battery, controlling the battery not to be overloaded or too deeply discharged. The complementary resource produces the required energy at times of imminent deep discharge of the battery, at the same time loading the battery.

The main drawbacks of a hybrid system are the following:

- ❖ Renewable energy production is dependent on natural cycles, i.e. PV doesn't work at night.
- ❖ Initial cost of these systems is higher than comparably sized conventional generators.
- ❖ They don't handle peak loads well without energy storage.

The choice of which energy technology or mix of technologies to use depends not only on the local ambient and economical conditions, but also on whether the energy produced will be used for lighting or cooling purposes in a single household, or for productive processes (irrigation pumping, water supplies, crop processing, refrigeration, etc.) of businesses, agro-industries, small shops, and so on. Another issue that needs to be taken into consideration is whether the system is going to be installed in a region which is likely not to be connected to conventional grid during the lifetime of the system. In this case, the growth in demand during the whole lifetime has to be accounted. Hybrid systems can technically be designed for almost any purpose at any capacity.

1.3.1.1. Components of a typical hybrid system

A typical hybrid system for the application in developing countries generally consists of the following main components:

- *A primary source of energy, i.e. a renewable energy resource:*
  The different renewable energy technologies that can be used are mentioned in the next section.
- *A secondary source of energy for supply in case of shortages, i.e. diesel generators:*
  The application of diesel generating sets in hybrid systems results in less frequent start-up and shut-down procedures than in stand-alone diesel generators. The prevention of the non-continuous use of the diesel generators results is beneficial for their lifetime.
  Motor generating sets have a wide range of operating hours, with figures that vary from 1.000 to 80.000 hours for generators with capacities less than 30 kW, and strongly depend on the way of operation.

Moreover, geographic conditions also affect the diesel generating sets' output. The decrease in efficiency is approximately 1% for every 100 m above sea level and another 1% for every 5,5°C above a temperature of 20 °C.

- *A storage system to guarantee a stable output during short times of shortages:* The storage device of hybrid systems, in most cases lead-acid batteries, is a very sensitive and crucial part of the system. The optimal performance of this component highly influences not only the system's performance, but also the overall costs of the system. Optimal performance of the battery bank results in a longer lifetime of the battery and in lower overall costs. The performance of a battery bank is controlled with the help of a charge controller, which guarantees that the battery is neither over-charged nor discharged too deeply.
  The batteries offer support in times of peak demands, which cannot be met by the renewable energy units alone and provide the ability to bypass short times of power shortages.
  The lead-acid battery technology is currently the most viable alternative in developing countries. Other technologies (NiMH, NiCd, Li-ion etc.) are not so easily available and are currently much more expensive. However, in some applications and conditions their life cycle cost may be lower than for lead-acid. The development of especially Li-ion technology is quite fast at present.

The following major aspects need to be considered when designing a battery bank for hybrid systems:

- Capacity Design. When designing a battery bank installation, it is important to note that a battery's capacity decreases over lifetime. The end of life of a battery is reached when capacity has declined to 80% of the nominal value, where the nominal value is given by the manufacturer. Thus, a battery installation should be designed based on the 80% of the nominal battery capacity.
- Effect of temperature. The nominal capacity is usually given at a battery temperature of 20°C. Low temperatures slow down the chemical reactions inside the battery, thus significantly reducing the capacity. High temperatures result in an increase of corrosion velocity of the battery's electrodes, thus reducing the battery's lifetime significantly. Therefore, both high and low temperatures should be avoided as much as possible.

- Deep discharge (less than 70% of the nominal capacity), overcharge and a low electrolyte level should be avoided. In order to guarantee this, the application of a charge controller is essential. Furthermore, regular control both of battery acid level and voltage are fundamental, too.

- *A charge controller:*

  The charge controller has two fundamental objects:

  - Regulation of the current from the renewable energy units so that the battery is not overcharged.
  - Regulation of the current to the load in order to protect the battery from discharge.

  The charge controller is one of the least costly components in renewable energy systems, but is a key factor for the system's reliability and maintenance costs. An optimally working charge controller can significantly increase the performance and lifetime of the batteries.

  The operation of the charge controller depends on the type of the hybrid system: In case the hybrid system relies only on renewable energy for power supply (for example, PV/wind hybrid systems), the charge controller is responsible for maximizing the batteries' lifetime. On the other hand, if the hybrid system also contains diesel generators, the charge controller has the additional objective of minimizing the diesel fuel and maintenance costs.

  From the aspect of charge control, there are some major differences between the above two cases:

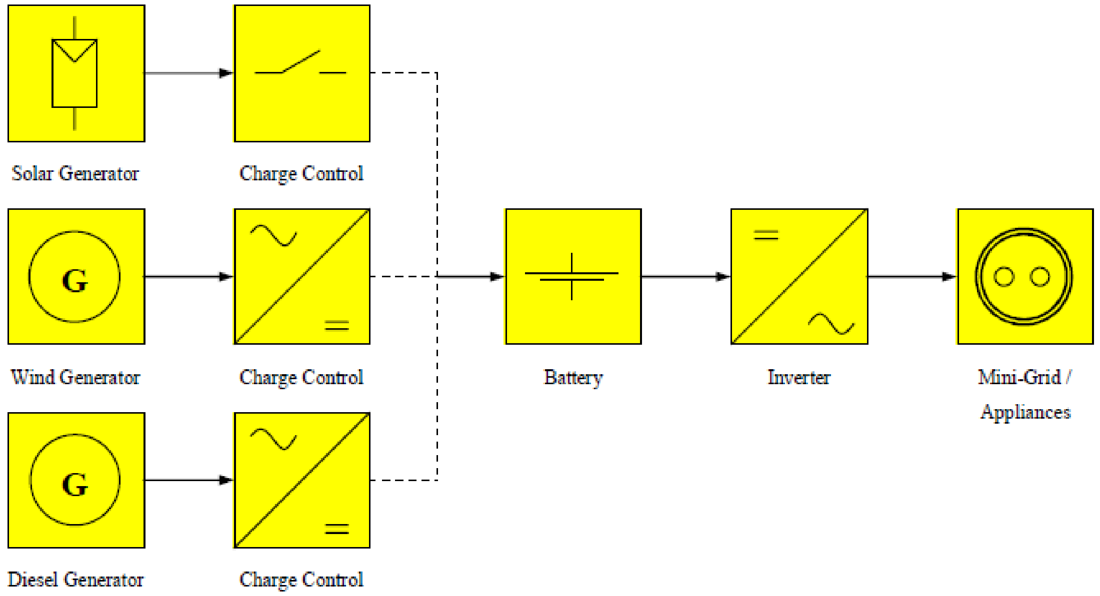
  - ✓ Battery banks in hybrid systems are generally relatively smaller and cycled more than 'simple' systems with renewable energy technologies alone. That increases the importance of regular equalization and makes the cycle life the main factor determining the battery lifetime. A typical cycle life of hybrid systems' battery banks consists of 2.000 – 3.000 cycles.
  - ✓ The fact that power is available on demand in diesel generators supported hybrid systems eliminates the fluctuations which emanate from the renewable energy resources. Therefore, the charge controller's usage becomes simpler.

- ✓ Since hybrid systems are typically designed for higher loads than pure renewable systems, charge controllers have a smaller contribution in the costs of the overall system. So more costly and higher efficiency and functionality controllers can be used, without increasing the overall costs significantly.

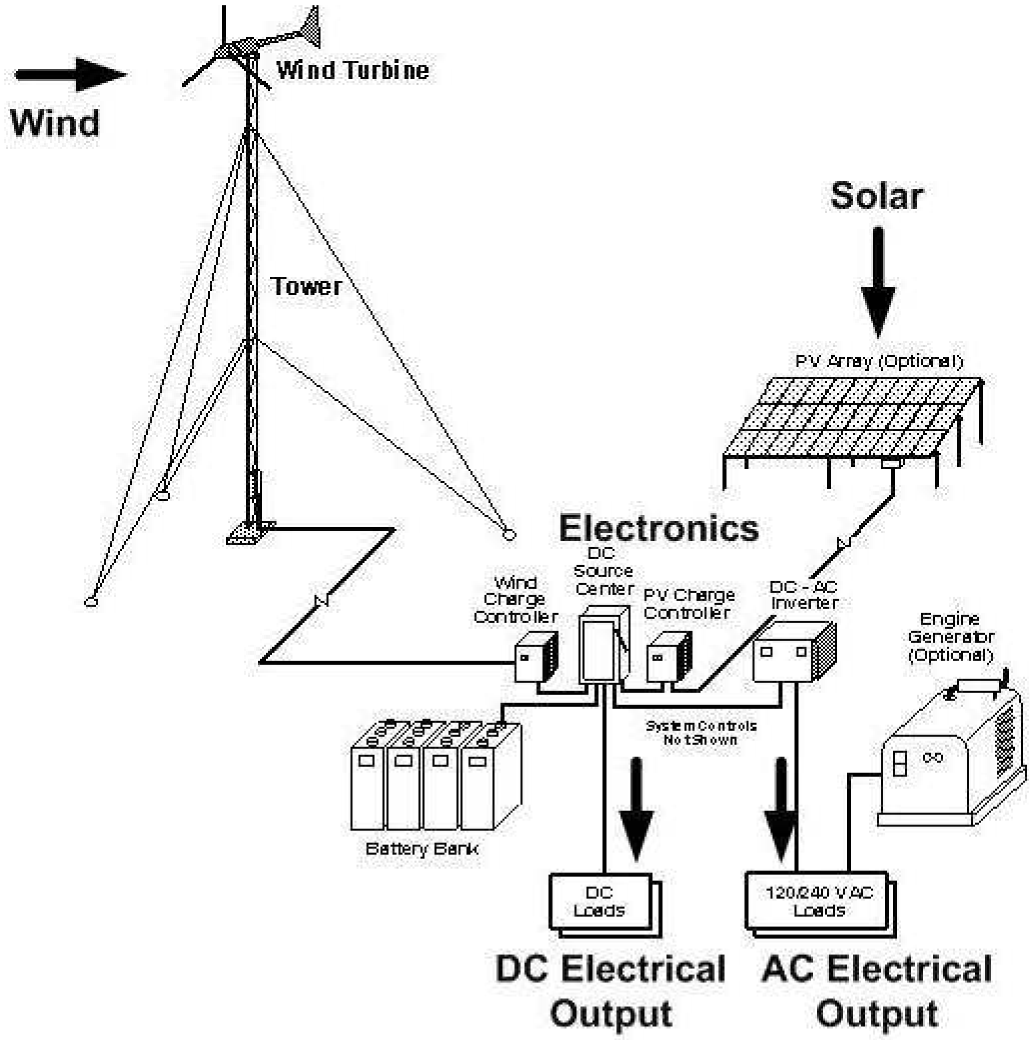
Main problems related to batteries and the charge controller, include temperature control, which is often difficult. Many charge controllers cannot be properly adjusted.

- *Installation material (safety boxes, cables, plugs, etc.)*
- *The appliances (lighting, TV/radio, etc.)*
- *A DC/AC inverter:*

In cases that the power supplied by the renewable energy unit is given in DC, a DC/AC-inverter needs to be installed. This is due to the fact that most appliances needing AC current are less costly than those requiring DC current.
Some inverter technologies integrate the charge control functions to the inverter. These appliances allow with their integrated system management an automatic control of the energy sources, the charging state of the battery and the power demand of the loads.



Principle circuit of a PV/Wind/Diesel hybrid system



Example of a hybrid system with both AC and DC output

1.3.1.2. Renewable energy technologies used for rural electrification

The most widely used renewable energy technologies for rural electrification are described below:

❖ **Wind energy** has a very high potential for rural electrification. Wind energy units do not necessitate long-term centralized planning for their development as their installation is rather simple. In most rural settings, several smaller wind turbines are installed instead of fewer but larger ones, making it easier for the grid to absorb wind generation.

Successful examples of remote wind power installations are the Atlantic islands of Canary, Azores and Cape Verde, where the developing of the high wind resource establishes these renewable energy units as one of the most cost-effective power plants to install and operate.

- **Photovoltaic (PV)** power systems already provide electricity in developing countries to about 1 million off-grid households. Particularly recommended for countries with ample sunlight and poorly developed rural electricity grid, PV systems can provide electricity to relatively dispersed populations but also to groups of houses or entire villages. The most common systems used in remote areas are solar home systems, which can power light bulbs and small appliances such as televisions, radios, fans, etc. Generally the capacity of the units used in rural households ranges from 30 to 100 Watts.
- **Small hydropower** projects already provide electricity to millions of people throughout the world. These power plants can vary in size from less than 500 kW to about 10 MW and most are developed at the community level or for small industry. Additionally, they can also provide mechanical energy for small businesses, drinking water and irrigation through canals or pumps.
  However, mini-hydropower plants are often criticized for not providing sufficient power to meet peak demand or for providing excess capacity during off-peak periods.
- **Bioenergy** already provides the main source of energy for heating and cooking for many millions of people in rural communities. Biomass raw materials - for example from crop or forest residues – can be used to generate electricity. This can be done in conjunction with larger plants which also use energy to process crops. Alternatively smaller-scale systems based on biomass combustion or small-scale gasification can be used to generate electricity for local use.

Bioenergy comes in many different forms, based on different feedstocks, such as:

- Organic fractions of municipal waste, sewage sludge or demolition waste.
- Agricultural waste, such as stalks, straw, etc.
- Forestry waste such as branches, roots, tops of trees, wood from thinning operations etc.
- Waste from wood processing industry.
- Energy crops such as suitable grasses, trees or oil seeds.

- **Ocean energy** could play a significant role in rural coastal and island regions of the developing countries by generating electricity, producing drinking water through desalination, or food through aquaculture, and cooling. Currently, project development activities are at an early stage in China, India and Indonesia for providing electricity to rural households by harnessing energy from ocean waves and tidal currents. The installation of tidal current projects in remote villages is currently being planned in China and the Philippines. A 2 MW tidal current plant is being considered by India to bring electricity to a remote area near Sunderban in West Bengal. A low-temperature ocean thermal desalination plant has been operating since 2005 at Kavaratti in Lakshadweep islands in Western India and that provides 100 m^3 of drinking water per day to a local community. There are also significant opportunities to take advantage of wave and tidal current energy of remote coastal areas in Mexico, Brazil and South Africa and activities are already under way in these countries.
- **Fuel cell technology** offers a number of attractive characteristics, among which are: very high efficiency, good part load characteristics, and very low emissions. However, effort to introduce this technology to commercial markets for power generation continues. The technology is considered too immature for use in rural areas in developing countries, but once a commercial product emerges, the technology may be suitable, at least in special situations.
- **Hydrogen** may well play a key role in distributed energy generation. Diesel generators can be substituted by hydrogen "generators" (small-scale portable power devices such as reformers and fuel cells). Hydrogen can also be used as fuel to power backup devices (larger fuel cells) and to provide combined heat and power. Nowadays, there are about 400 stationary hydrogen demonstrations in the world.

  Hydrogen can be produced locally, it permits long term, loss free storage of energy, it can be combusted with very small pollution, and if used in a fuel cell, overall cycle energy recovery (generation of hydrogen and use of the hydrogen for power generation) can be around 30%.

  However, isolated hydrogen systems are considerably more complicated and demanding to operate than they appear from system sketches in reports. The cost is also extremely high and the availability of suitable components (electrolysers, fuel cells) very limited.

1.3.1.3. Technical aspects

The factors that determine the success of the hybrid system from a technical point of view are the following:

- ✓ The design of hybrid systems should keep the use of diesel fuel in a low level by utilizing the local resources. However, oversizing of the renewable energy generator is not an option, since it increases system costs.
- ✓ Key requirement from a technical point of view is simplicity and reliability. For hybrid systems, this issue is a major challenge, since these systems are rather sophisticated. Most technical problems observed with hybrid system are not result of failures of single components itself, but are due to rather frequent failures of components' integration.

CHAPTER 2: HYDROPOWER

Hydropower is the power derived from the natural movement or flow of masses of water. Most commonly, this power is harnessed by taking advantage of the fall of water from one level to another, thus exploiting the effect of gravity. The energy of the falling water is converted to mechanical energy by the use of a turbine. Micro hydropower turbines come in many shapes and sizes - from waterwheels, to pumps used as turbines (where water is forced through the pump in the opposite direction), to squirrel cage turbines, called Cross-flow turbines. Once the turbine is used to convert water energy to mechanical energy, the mechanical energy in turn can be used to perform work or converted to some other form of energy, such as electrical energy (called hydroelectric energy). The energy-producing potential at any given hydropower site depends on the energy of the water, which in turn depends on the distance the water falls, called the head, and on the amount of water flowing.

The actual amount of mechanical or hydroelectric energy produced at such a site also depends on the efficiency at which the turbine or turbine-generator unit can convert the water energy to the other forms of energy.

Hydroelectric power is the most widely used form of renewable energy. Once a hydroelectric complex is constructed, the project produces no direct waste, and has a considerably lower output level of the greenhouse gas carbon dioxide (CO_2) than fossil fuel powered energy plants.

2.1. Generating methods

- *Conventional (dams):* Most hydroelectric power comes from the potential energy of dammed water driving a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. A large pipe (the "penstock") delivers water to the turbine.
- *Pumped storage:* This method produces electricity to supply high peak demands by moving water between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine. Pumped-storage schemes currently provide

the most commercially important means of large-scale grid energy storage and improve the daily capacity factor of the generation system.

- *Run-of-the-river:* Run-of-the-river hydroelectric stations are those with small or no reservoir capacity, so that the water coming from upstream must be used for generation at that moment, or must be allowed to bypass the dam.
- *Tide:* A tidal power plant makes use of the daily rise and fall of ocean water due to tides. Such sources are highly predictable, and if conditions permit construction of reservoirs, can also be dispatch able to generate power during high demand periods. Less common types of hydro schemes use water's kinetic energy or undammed sources such as undershot waterwheels.
- *Underground: A*n underground power station makes use of a large natural height difference between two waterways, such as a waterfall or mountain lake. An underground tunnel is constructed to take water from the high reservoir to the generating hall built in an underground cavern near the lowest point of the water tunnel and a horizontal tailrace taking water away to the lower outlet waterway.

2.2. Function

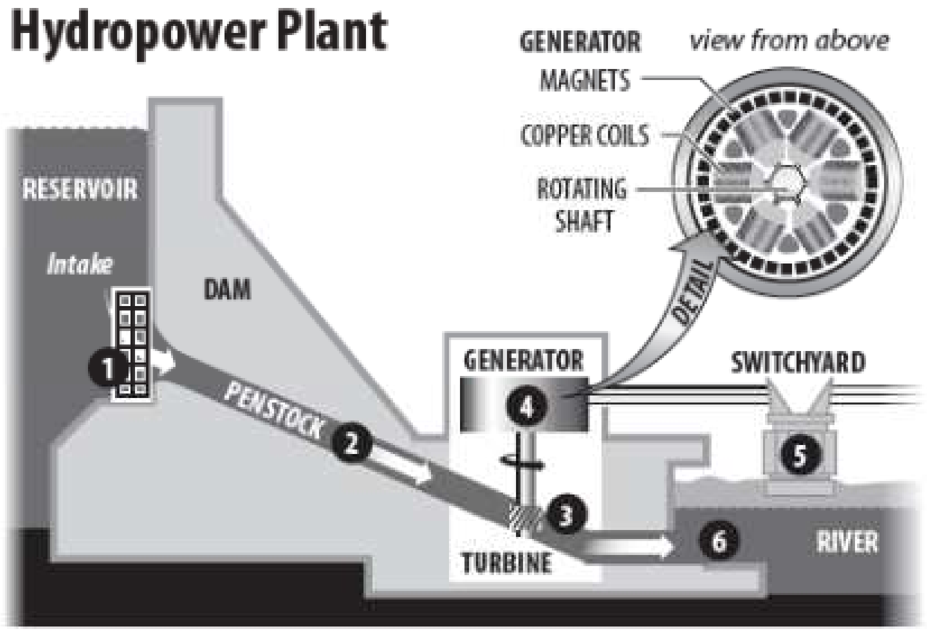
Hydropower functions by converting the energy in flowing water into electricity. The volume of water flow and the height (head) from the turbines in the power plant to the water surface created by the dam determines the quantity of electricity generated. Simply, the greater the flow and the taller the head means the more electricity produced.

The simple working of a hydropower plant has water flowing through a dam, which turns a turbine, which then turns a generator. A hydropower plant (including a powerhouse) generally includes the following:

1. The dam holds water back and stores water upstream in a reservoir, or large artificial lake. In case of run-of-the-river stations, the dams do not impound water, but instead use the power of the flowing river.
2. Gates open on the dam, allowing gravity to pull the water down through the penstock. An intake conduit carries water from the reservoir to turbines inside the powerhouse. Pressure builds up as water flows through the pipeline.
3. The water then hits the large blades of the turbine, making them turn. The vertical blades are attached through a shaft to a generator located above. Each

turbine can weigh as much as 172 tons and turn at a rate of 90 revolutions per minute.

4. The turbine blades turn in unison with a series of magnets inside the generator. The large magnets rotate past copper coils, which produce alternating current (AC).
5. The transformer inside the powerhouse takes the AC and converts it to higher-voltage current so as to allow electricity to flow to customers. Out of every power plant exit four power lines consisting of three wires (associated with three power phases) and a neutral (ground) wire.
6. Used water is carried through outflow pipelines, which reenters the river downstream.



Hydropower is also readily available. Engineers can control the flow of water through the turbines to produce electricity on demand. In addition, reservoirs may offer recreational opportunities, such as swimming and boating.

2.3. Sizes and capacities of hydroelectric facilities

- *Large and specialized industrial facilities:*

  Although no official definition exists for the capacity range of large hydroelectric power stations, facilities from over a few hundred megawatts to more than 10 GW are generally considered large hydroelectric facilities. Large-scale hydroelectric power stations are more commonly seen as the largest power producing facilities in the world, with some hydroelectric facilities capable of generating more than double than the installed capacities of the current largest nuclear power stations.

The construction of these large hydroelectric facilities, and their changes on the environment, are also often on grand scales, creating as much damage to the environment as help by being a renewable resource. Many specialized organizations, such as the International Hydropower Association, look into these matters on a global scale.

- *Small:*

  Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 MW is generally accepted as the upper limit of what can be termed small hydro. This may be stretched to 25 MW and 30 MW in Canada and the United States.

  Small hydro plants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. Since small hydro projects usually have minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro. This decreased environmental impact depends strongly on the balance between stream flow and power production.

- *Micro:*

  Micro hydro is a term used for hydroelectric power installations that typically produce up to 100 KW of power. These installations can provide power to an isolated home or small community, or are sometimes connected to electric power networks. There are many of these installations around the world, particularly in developing nations as they can provide an economical source of energy without purchase of fuel. Micro hydro systems complement photovoltaic solar energy systems because in many areas, water flow, and thus available hydro power, is highest in the winter when solar energy is at a minimum.

- *Pico:*

  Pico hydro is a term used for hydroelectric power generation of under 5 KW. It is useful in small, remote communities that require only a small amount of electricity. For example, to power one or two fluorescent light bulbs and a TV or radio for a few homes. Even smaller turbines of 200-300W may power a single home in a developing country with a drop of only 1 m. Pico-hydro setups typically are run-of-the-river, meaning that dams are not used, but rather pipes divert some of the flow, drop this down a gradient, and through the turbine before returning it to the stream.

2.4. Calculating the amount of available power

A simple formula for approximating electric power production at a hydroelectric plant is:

$$P = \rho * H * Q * g * n$$

where:

P is Power in watts,
ρ is the density of water (~1000 kg/m^3),
H is the head in meters,
Q is flow rate in m^3/s,
g is acceleration due to gravity of 9,81 m/s^2,
$n=n_p n_t n_d n_g$ is the total efficiency ranging from 0 to 1, where n_p=penstock efficiency, n_t=turbine efficiency, n_d=drive mechanism efficiency, n_g=generator efficiency.

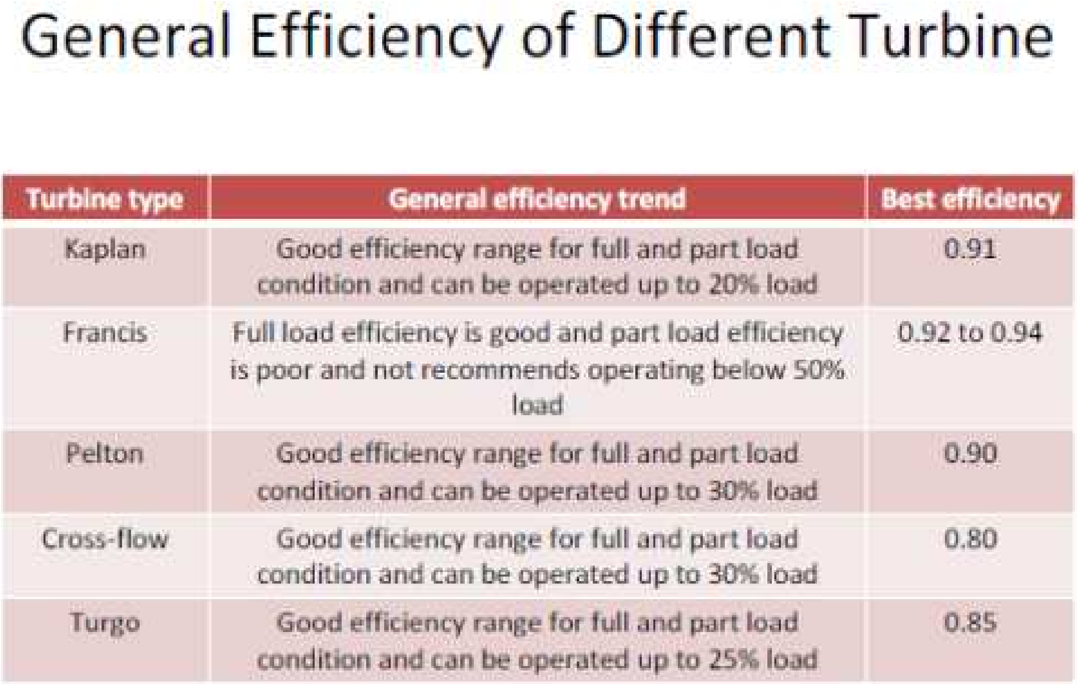
Annual electric energy production depends on the available water supply. In some installations the water flow rate can vary by a factor of 10:1 over the course of a year.

2.5. Turbine types

A water turbine is a rotary engine that takes energy from moving water. Flowing water is directed on to the blades of a turbine runner, creating a force on the blades. Since the runner is spinning, the force acts through a distance (force acting through a distance is the definition of work). In this way, energy is transferred from the water flow to the turbine.

The precise shape of water turbine blades is a function of the supply pressure of water, and the type of impeller selected.

Water turbines are classified as impulse turbines or reaction turbines according to the process by which the water head and flow are converted to mechanical power.



General Efficiency of Different Turbine

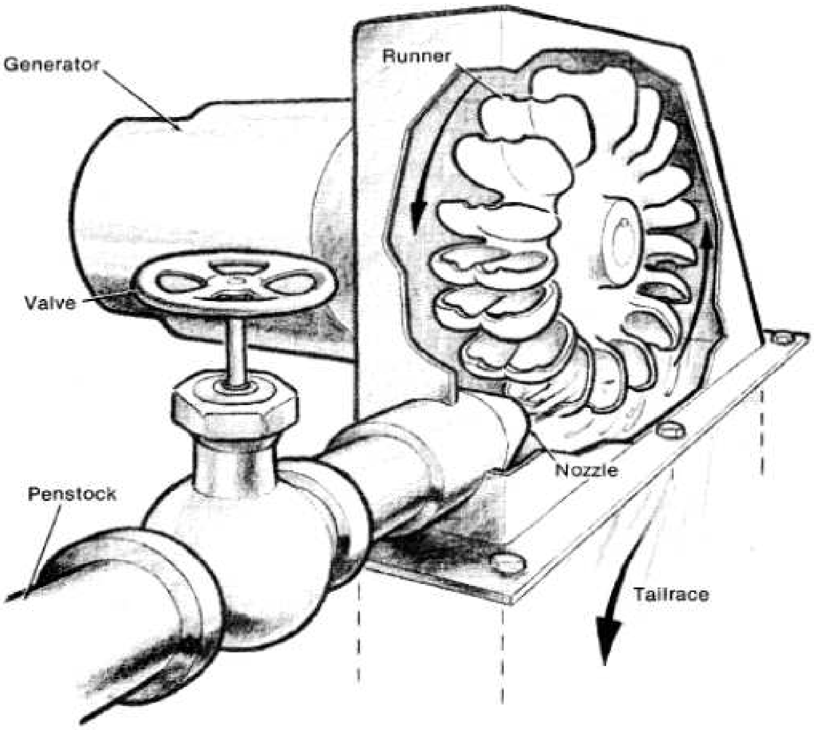
Turbine type	General efficiency trend	Best efficiency
Kaplan	Good efficiency range for full and part load condition and can be operated up to 20% load	0.91
Francis	Full load efficiency is good and part load efficiency is poor and not recommends operating below 50% load	0.92 to 0.94
Pelton	Good efficiency range for full and part load condition and can be operated up to 30% load	0.90
Cross-flow	Good efficiency range for full and part load condition and can be operated up to 30% load	0.80
Turgo	Good efficiency range for full and part load condition and can be operated up to 25% load	0.85

2.5.1. Impulse turbines

In impulse turbines, the head is converted to velocity in a stationary nozzle directed toward the turbine wheel (runner). The water jet from the nozzle is directed against curved buckets on the runner, which deflect the jet and reduce its velocity. The force resulting from this deflection is applied to the turbine runner, creating the turbine torque and power. Since the turbine is spinning, the force acts through a distance (work) and the diverted water flow is left with diminished energy.

In the impulse turbines, no pressure change occurs at the turbine blades, and the turbine doesn't require housing for operation.

Impulse turbines are most suited for applications with relatively high (>300m) head and low flow. This is because the high head and corresponding high water velocity concentrates the available water power into a small flow area. The concentrated power is most efficiently converted by directing one or more water jets against buckets on the runner. The runner deflects the jet and reduces its velocity. The best efficiency in impulse turbines, occurs when the speed of the runner is about 1/2 that of the water jet as it leaves the nozzle.



Impulse turbine (Pelton wheel)

An advantage of impulse turbines over the reaction turbines is that since the head is converted to velocity in the stationary nozzles, there is no pressure drop across the runner. Consequently, no close-clearance seals are needed between the runner and the turbine housing. This makes the impulse turbines simpler to manufacture and maintain, and more tolerant of less-than-clean water conditions.

The main types of impulse turbines are Pelton (High head and low discharge), Turgo (Medium head and medium discharge) and Cross-flow (Low to medium head and low discharge) turbines:

2.5.1.1. Pelton turbine:

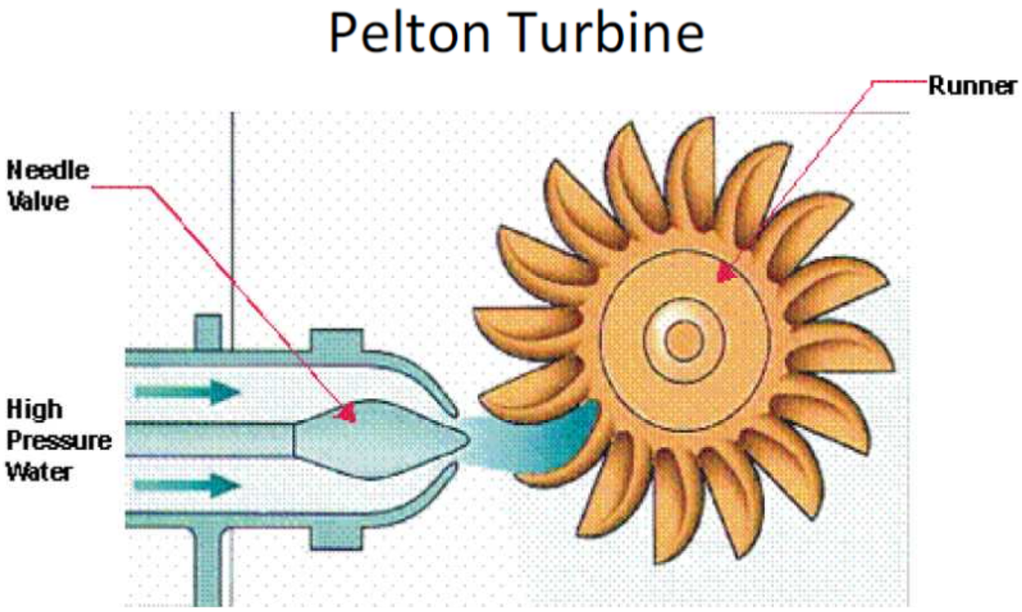
The Pelton wheel is an impulse turbine which is among the most efficient types of water turbines. It was invented by Lester Allan Pelton in the 1870s. The Pelton wheel extracts energy from the impulse (momentum) of moving water, as opposed to its weight like traditional overshot water wheel.

Although many variations of impulse turbines existed prior to Pelton's design, they were less efficient than Pelton's design. The water leaving these wheels typically still had high speed, and carried away much of the energy. Pelton's paddle geometry was designed so that when the rim runs at 50% of the water jet’s speed, the water leaves the wheel with very little speed, extracting almost all of its energy, and allowing for a very efficient turbine.

Function:

The water flows along the tangent to the path of the runner. The spoon-shaped buckets mounted around the edge of the runner split the flow from the nozzle into two streams that are discharged from the sides of the runner. As water flows into the bucket, the direction of the water velocity changes to follow the contour of the bucket. When the water-jet contacts the bucket, the water exerts pressure on the bucket and the water is decelerated as it does a "u-turn" and flows out the other side of the bucket at low velocity. In the process, the water's momentum is transferred to the turbine. This "impulse" does work on the turbine. For maximum power and efficiency, the turbine system is designed such that the water-jet velocity is twice the velocity of the bucket. A very small percentage of the water's original kinetic energy will still remain in the water. However, this allows the bucket to be emptied at the same rate it is filled, thus allowing the water flow to continue uninterrupted. Often two buckets are mounted side-by-side, thus splitting the water jet in half. This balances the side-load forces on the wheel, and helps to ensure smooth, efficient momentum transfer of the fluid jet to the turbine wheel.

An inherent limitation on the flow rate that a Pelton wheel can handle is the size of water jet that can be efficiently diverted by the runner buckets. Several jets can be employed around the periphery of the runner to increase power. Under optimum conditions, a Pelton turbine can achieve up to 90% efficiency, due to the simple flow path through this type of turbine.



Because water and most liquids are nearly incompressible, almost all of the available energy is extracted in the first stage of the hydraulic turbine. Therefore, Pelton wheels have only one turbine stage, unlike gas turbines that operate with compressible fluid.

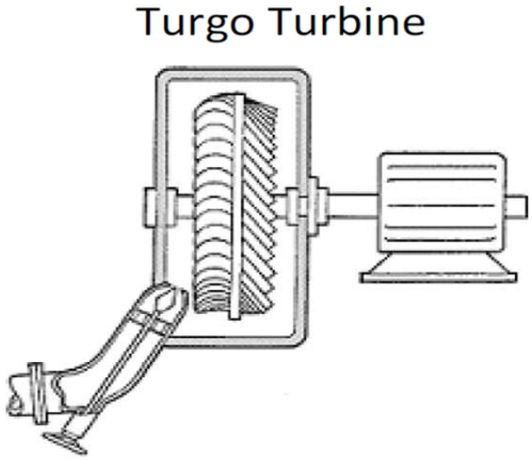
Applications:

Pelton wheels are the preferred turbine for hydro-power, when the available water source has relatively high hydraulic head at low flow rates. Pelton wheels are made in all sizes. There exist multi-ton Pelton wheels mounted on vertical oil pad bearings in hydroelectric plants. The largest units can be up to 200 megawatts. The smallest Pelton wheels are only a few inches across, and can be used to tap power from mountain streams having flows of a few liters per minute. Some of these systems utilize household plumbing fixtures for water delivery. These small units are recommended for use with thirty meters or more of head, in order to generate significant power levels. Depending on water flow and design, Pelton wheels operate best with heads from 15 meters to 1800 meters, although there is no theoretical limit.

The Pelton wheel is most efficient in high head applications. Thus, more power can be extracted from a water source with high-pressure and low-flow than from a source with low-pressure and high-flow, even though the two flows theoretically contain the same power. Also a comparable amount of pipe material is required for each of the two sources, one requiring a long thin pipe, and the other a short wide pipe.

2.5.1.2. Turgo turbine:

The Turgo turbine is an impulse water turbine designed for medium head applications. Operational Turgo Turbines achieve efficiencies of about 87%. In factory and lab tests Turgo Turbines perform with efficiencies of up to 90%.



Developed in 1919 by Gilkes as a modification of the Pelton wheel, the Turgo has some advantages over Francis and Pelton designs for certain applications.

First, the runner is less expensive to make than a Pelton wheel. Second, it doesn't need an airtight housing like the Francis. Third, it has higher specific speed and can handle a greater flow than the same diameter Pelton wheel, leading to reduced generator and installation cost.

Turgos operate in a head range where the Francis and Pelton overlap. While many large Turgo installations exist, they are also popular for small hydro where low cost is very important.

Like all turbines with nozzles, blockage by debris must be prevented for effective operation.

Theory of operation:

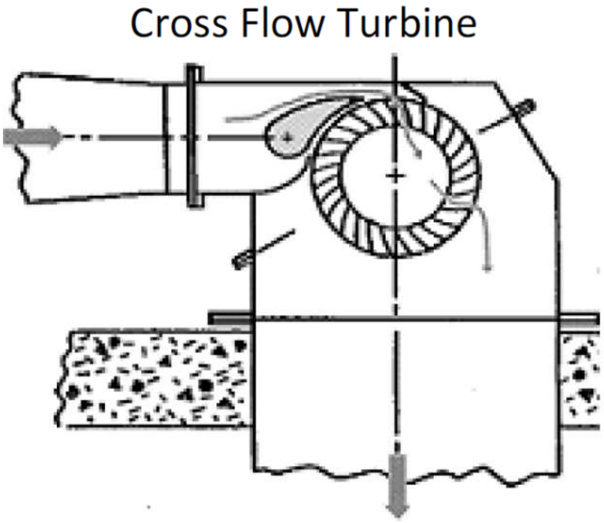
The Turgo turbine is an impulse type turbine. Water does not change pressure as it moves through the turbine blades. The water's potential energy is converted to kinetic energy with a nozzle. The high speed water jet is then directed on the turbine blades which deflect and reverse the flow. The resulting impulse spins the turbine runner, imparting energy to the turbine shaft. Water exits with very little energy. Turgo runners may have an efficiency of over 90%.

A Turgo runner looks like a Pelton runner split in half. For the same power, the Turgo runner is one half of the diameter of the Pelton runner, and so twice the specific speed. The Turgo can handle a greater water flow than the Pelton because exiting water doesn't interfere with adjacent buckets.

The specific speed of Turgo runners is between the Francis and Pelton. Single or multiple nozzles can be used. Increasing the number of jets increases the specific speed of the runner by the square root of the number of jets (four jets yield twice the specific speed of one jet on the same turbine).

2.5.1.3. Cross-flow turbine:

A cross-flow turbine, Banki-Michell turbine or Ossberger turbine is a water turbine developed by the Australian Anthony Michell, the Hungarian Donát Bánki and the German Fritz Ossberger. It was invented to accommodate larger water flows and lower heads than the Pelton Wheel turbine. Today, the company founded by Ossberger is the leading manufacturer of this type of turbine.

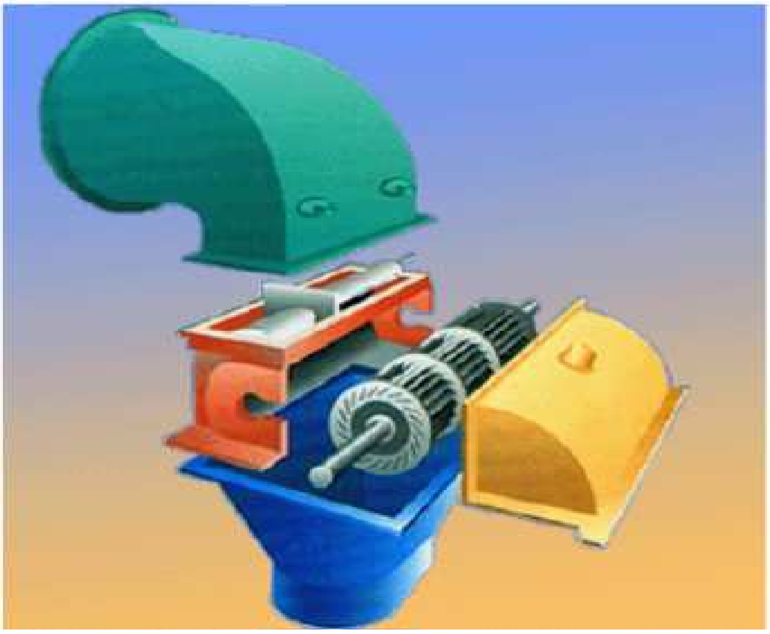

Cross Flow Turbine

Cross-flow turbine uses an elongated, rectangular-section nozzle directed against curved vanes on a cylindrically shaped runner. The water jet is slowed down in two stages, encountering the runner vanes twice as it passes through the horizontal runner. The elongated design of the runner and inlet nozzle increases the turbine flow capacity, which permits accommodation to lower heads. When the water leaves the runner, it also helps clean the runner of small debris and pollution. However, the more complex flow path through the crossflow turbine results in a lower efficiency, about 65%. Most practical cross-flow turbines have two nozzles, arranged so that the water flows do not interfere.

Cross-flow turbines are often constructed as two turbines of different capacity that share the same shaft. The turbine wheels are the same diameter, but different lengths to handle different volumes at the same pressure. The subdivided wheels are usually built with volumes in ratios of 1:2. The subdivided regulating unit, the guide vane system in the turbine's upstream section, provides flexible operation, with 33, 66 or 100% output, depending on the flow. Low operating costs are obtained with the turbine's relatively simple construction.

Details of design:

The turbine consists of a cylindrical water wheel or runner with a horizontal shaft, composed of numerous blades (up to 37), arranged radially and tangentially. The blade's edges are sharpened to reduce resistance to the flow of water. A blade is made in a part-circular cross-section (pipe cut over its whole length). The ends of the blades are welded to disks to form a cage like a hamster cage and are sometimes called "squirrel cage turbines". Instead of the bars, the turbine has trough-shaped steel blades.The water flows first from the outside of the turbine to its inside. The regulating unit, shaped like a vane or tongue, varies the cross-section of the flow.



The water jet is directed towards the cylindrical runner by nozzle. The water enters the runner at an angle of about 45/120 degrees, transmitting some of the water's kinetic energy to the active cylindrical blades.

The regulating device controls the flow based on the power needed, and the available water. Water admission to the two nozzles is throttled by two shaped guide vanes. These divide and direct the flow so that the water enters the runner smoothly for any width of opening. The guide vanes should seal to the edges of the turbine casing so that when the water is low, they can shut off the water supply. The guide vanes therefore act as the valves between the penstock and turbine. Both guide vanes can be set by control levers, to which an automatic or manual control may be connected.

The turbine geometry (nozzle-runner-shaft) assures that the water jet is effective. The water acts on the runner twice, but most of the power is transferred on the first pass, when the water enters the runner. Only ⅓ of the power is transferred to the runner when the water is leaving the turbine.

The water flows through the blade channels in two directions: outside to inside, and inside to outside. Most turbines are run with two jets, arranged so two water jets in the runner will not affect each other. It is, however, essential that the turbine, head and turbine speed are harmonised.

The cross-flow turbine is of the impulse type, so the pressure remains constant at the runner.

Advantages:

The peak efficiency of a cross-flow turbine is somewhat less than a Kaplan, Francis or Pelton turbine. However, the cross-flow turbine has a flat efficiency curve under varying load. With a split runner and turbine chamber, the turbine maintains its efficiency while the flow and load vary from 1/6 to the maximum.

Since it has a low price and good regulation, cross-flow turbines are mostly used in mini and micro hydropower units of less than two thousand kW and with heads less than 200 m.

Particularly with small run-of-the-river plants, the flat efficiency curve yields better annual performance than other turbine systems, as small rivers' water is usually lower in some months. The efficiency of a turbine determines whether electricity is produced during the periods when rivers have low flows. If the turbines used have high peak efficiencies, but behave poorly at partial load, less annual performance is obtained than with turbines that have a flat efficiency curve.

Due to its excellent behavior with partial loads, the cross-flow turbine is well-suited to unattended electricity production. Its simple construction makes it easier to maintain than other turbine types: only two bearings must be maintained, and there are only three rotating elements. The mechanical system is simple, so repairs can be performed by local mechanics.

Another advantage is that it can often clean itself. As the water leaves the runner, leaves, grass etc. will not remain in the runner, preventing losses. Therefore, although the turbine's efficiency is somewhat lower, it is more reliable than other types. No runner cleaning is normally necessary, e.g. by flow inversion or variations of the speed. Other turbine types are clogged more easily, and consequently face power losses despite higher nominal efficiencies.

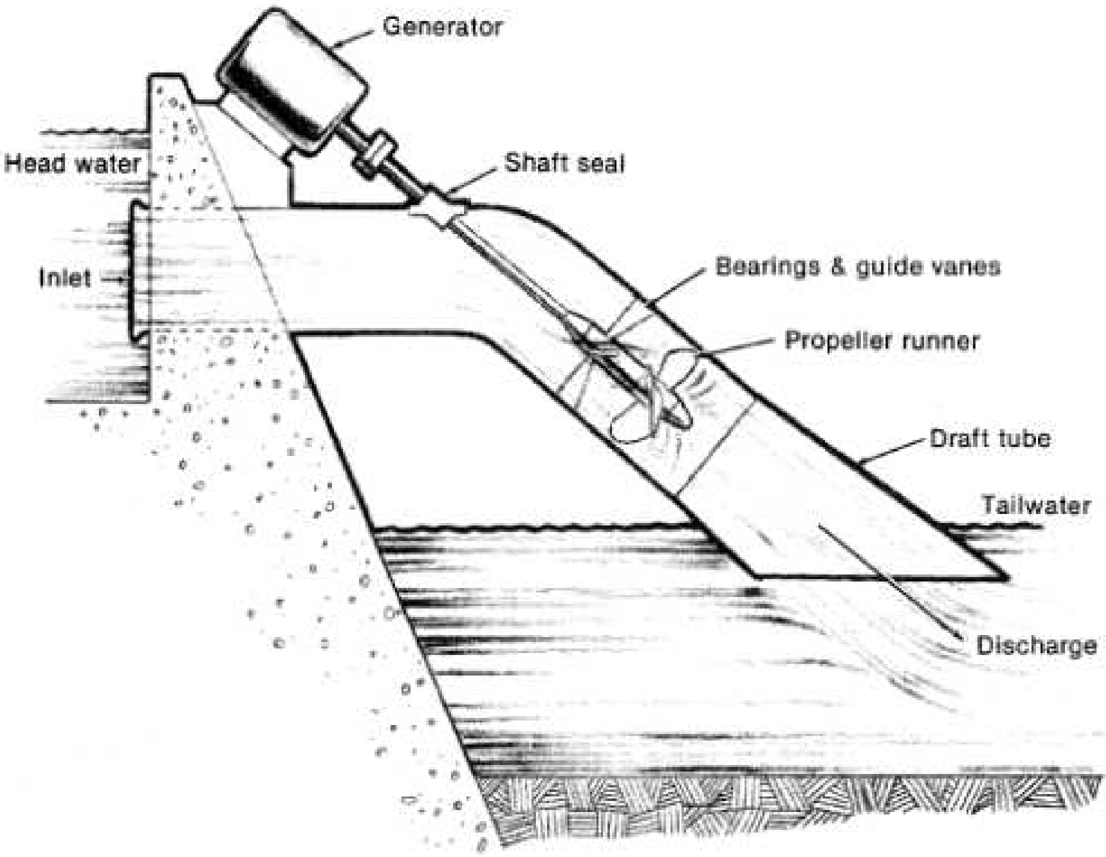
2.5.2. Reaction turbines

In reaction turbines, part of the available head may be converted to velocity within stationary parts of the casing, and the remainder or all of the head is converted to velocity within the turbine runner. The forces resulting from the velocity change act on the turbine runner, creating torque and power.

In reaction turbines, unlike the impulse ones, pressure drop occurs in both fixed and moving blades. The water changes pressure as it moves through the turbine and gives up its energy.

In terms of mechanical design, an important feature of reaction turbines is that to maintain good efficiency, a close running clearance seal must be maintained between the runner and the casing. This is because reaction turbines operate with the head applied across the runner, and leakage past the runner is lost power. For this reason, the performance and efficiency of reaction turbines is more likely to be degraded by entrained sand and silt in the water causing seal wear than is that of an impulse-type turbine. However, for low head applications, reaction turbines offer smaller turbine diameters and higher rotational speed than traditional impulse turbines. This advantage of a smaller runner for a given flow is offset by the fact that more flow is needed because of the lower head.

Most water turbines in use are reaction turbines and are used in low (<30m) and medium (30-300m) head applications.



Reaction turbine

The main types of reaction turbines are Francis (Medium head and medium discharge) and Kaplan (Low head and high discharge) turbines.

2.5.2.1. Francis turbine:

The Francis turbine is a type of water turbine that was developed by James B. Francis in Lowell, Massachusetts. It is an inward-flow reaction turbine that combines radial and axial flow concepts.

Francis turbines are the most common water turbine in use today. They operate in a head range of ten meters to six hundred and fifty meters and are primarily used for electrical power production. The power output ranges from 10 to 750MW, mini-hydro excluded. Runner diameters are between 1 and 10 meters. The speed range of the turbine is from 83 to 1000 rpm. Medium size and larger Francis turbines are most often arranged with a vertical shaft. Vertical shaft may also be used for small size turbines, but normally they have horizontal shaft.

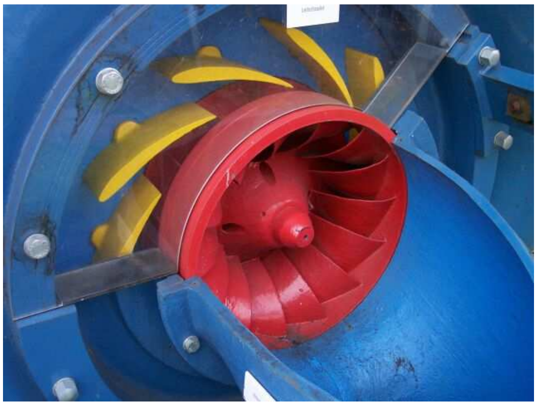
Francis Turbine attached to a generator

Theory of operation:

The Francis turbine is a reaction turbine, which means that the working fluid changes pressure as it moves through the turbine, giving up its energy. A casement is needed to contain the water flow. The turbine is located between the high-pressure water source and the low-pressure water exit, usually at the base of a dam.

The inlet is spiral shaped. The flow is generally controlled by wicket gates. There are usually 12 to 24 wicket gates, and they are connected, by links to a gate ring to move in a coordinated fashion. The gates control flow and, alter the angle of that flow into the runner. This radial flow acts on the runner's vanes, causing the runner to spin.

Cut-away view, with guide vanes (yellow) at minimum flow setting



Cut-away view, with guide vanes (yellow) at full flow setting

As the water moves through the runner, its spinning radius decreases, further acting on the runner. This property, in addition to the water's pressure, helps Francis and other inward-flow turbines harness water energy efficiently.

Francis turbine runner

Application:

Francis turbines may be designed for a wide range of heads and flows. This, along with their high efficiency, has made them the most widely used turbine in the world. Francis type units cover a head range from 20 meters to 700 meters, and their output power varies from just a few kilowatts up to one GW. Large Francis turbines are individually designed for each site to operate at the highest possible efficiency, typically over 90%.

In addition to electrical production, they may also be used for pumped storage, where a reservoir is filled by the turbine (acting as a pump) during low power demand, and then reversed and used to generate power during peak demand.

2.5.2.2. Kaplan turbine:

The Kaplan turbine is a propeller-type water turbine which has adjustable blades. It was developed in 1913 by the Austrian professor Viktor Kaplan, who combined automatically adjusted propeller blades with automatically adjusted wicket gates to achieve efficiency over a wide range of flow and water level.

The Kaplan turbine was an evolution of the Francis turbine. Its invention allowed efficient power production in low-head applications that was not possible with

Francis turbines. The head ranges from 10-70 meters and the output from 5 to 120 MW. Runner diameters are between 2 and 8 meters. The range of the turbine is from 79 to 429 rpm. Kaplan turbines are now widely used throughout the world in high-flow, low-head power production.

Kaplan Turbine

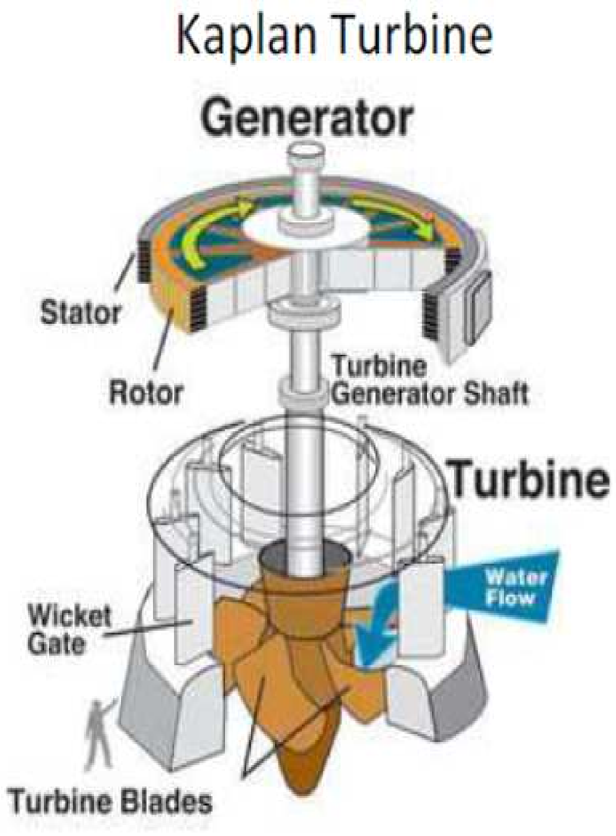
Theory of operation:

The Kaplan turbine is an inward flow reaction turbine, which means that the working fluid changes pressure as it moves through the turbine and gives up its energy. The design combines radial and axial features.

The inlet is a scroll-shaped tube that wraps around the turbine's wicket gate. Water is directed tangentially through the wicket gate and spirals on to a propeller shaped runner, causing it to spin.

The outlet is a specially shaped draft tube that helps decelerate the water and recover kinetic energy.

The turbine does not need to be at the lowest point of water flow as long as the draft tube remains full of water.



A higher turbine location, however, increases the suction that is imparted on the turbine blades by the draft tube. The resulting pressure drop may lead to cavitation. Variable geometry of the wicket gate and turbine blades allow efficient operation for a range of flow conditions. Kaplan turbine efficiencies are typically over 90%, but may be lower in very low head applications.

Current areas of research include CFD driven efficiency improvements and new designs that raise survival rates of fish passing through.

Because the propeller blades are rotated by high-pressure hydraulic oil, a critical element of Kaplan design is to maintain a positive seal to prevent emission of oil into the waterway.

Applications:

Kaplan turbines are widely used throughout the world for electrical power production. They cover the lowest head hydro sites and are especially suited for high flow conditions.

Inexpensive micro turbines on the Kaplan turbine model are manufactured for individual power production with as little as two feet of head.

Large Kaplan turbines are individually designed for each site to operate at the highest possible efficiency, typically over 90%. They are very expensive to design, manufacture and install, but operate for decades.

Variations:

The Kaplan turbine is the most widely used of the propeller-type turbines, but several other variations exist:

- Propeller turbines have non-adjustable propeller vanes. They are used in where the range of head is not large. Commercial products exist for producing several hundred watts from only a few feet of head. Larger propeller turbines produce more than 100 MW.
- Bulb or Tubular turbines are designed into the water delivery tube. A large bulb is centered in the water pipe which holds the generator, wicket gate and runner. Tubular turbines are a fully axial design, whereas Kaplan turbines have a radial wicket gate.
- Pit turbines are bulb turbines with a gear box. This allows for a smaller generator and bulb.
- Straflo turbines are axial turbines with the generator outside of the water channel, connected to the periphery of the runner.
- S-turbines eliminate the need for a bulb housing by placing the generator outside of the water channel. This is accomplished with a jog in the water channel and a shaft connecting the runner and generator.
- VLH turbine is an open flow, very low head "Kaplan" turbine slanted at an angle to the water flow. It has a large diameter, is low speed using a permanent magnet alternator with electronic power regulation and is very fish friendly (<5% mortality).
- Tyson turbine is a fixed propeller turbine designed to be immersed in a fast flowing river, either permanently anchored in the river bed, or attached to a boat or barge.

2.5.3. Pumps used as turbines

When the flow in a centrifugal pump is reversed by applying head to the discharge nozzle, the pump becomes a hydraulic turbine. Pumps are usually manufactured in larger quantities and may offer a significant cost advantage over a hydraulic turbine. The potential advantage of using a pump as a turbine should be carefully evaluated by comparing cost, operating efficiency, and the value of the electric power produced with the same values for a traditional hydraulic turbine under the same head and flow conditions.

When a pump is used as a turbine, to operate at the rated pump speed, the operating head and flow rate must be increased over the rated head and flow rate for normal pumping operation. A common error in selecting a pump for use as a turbine is to use the turbine design conditions in choosing a pump from a catalog. Because pump catalog performance curves describe pump duty, not turbine duty, the result is an oversized unit that fails to work properly.

Since turbine performance curves for pumps are rarely available, you must use manufacturer's correction factors that relate turbine performance with pump performance at the best efficiency points. For pumps with specific speeds up to about 3500, these factors vary from 1.1 to 2.5 for head and flow and from 0.90 to 0.99 for efficiency. These values are the turbine performance characteristics and must be converted to pump characteristics in order to properly select a pump. This is done as follows:

$$Q_p = \frac{Q_t}{C_Q}$$

$$H_p = \frac{H_t}{C_h}$$

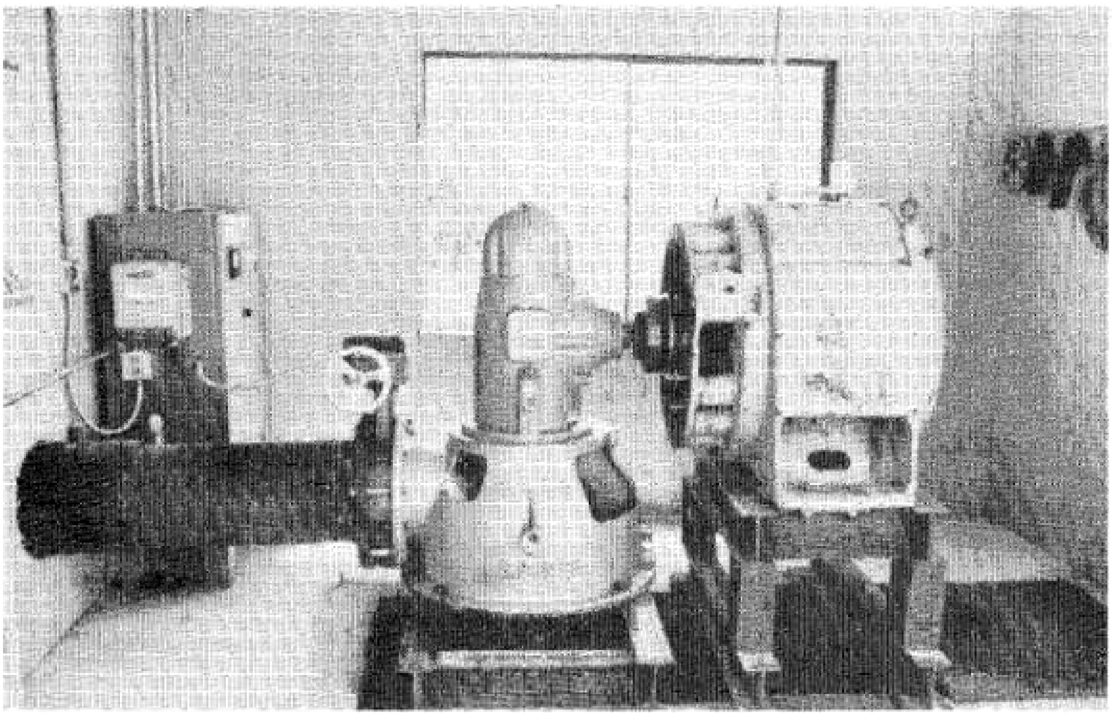
$$e_t = e_p * C_E$$

Where:

Q_p = *capacity of the pump* (m^3/s)
Q_t = *capacity of the turbine* (m^3/s)
C_Q = *capacity correction factor*
H_p = *head of the pump* (m)
H_t= *net effective head of the turbine* (m)
C_h = *head correction factor*
e_t = *turbine efficiency at best efficiency point*
e_p = *pump efficiency at best efficiency point*
C_E = *efficiency correction factor*

Once you have determined Q_p and H_p, you can review manufacturer's pump curves and select a pump that has these characteristics at best efficiency and operates at the desired speed.

Since pumps are not specifically designed for reversed flow or for coupling with generators, consideration must be given to determining if the pump and generator bearings can support the reversed loads. This is particularly important in the case of vertical shaft pumps, which normally transfer their shaft weight and hydraulic thrust load to a thrust bearing in the drive motor. In this case, the generator must be designed for vertical mounting and have a thrust bearing capable of supporting the thrust loads.



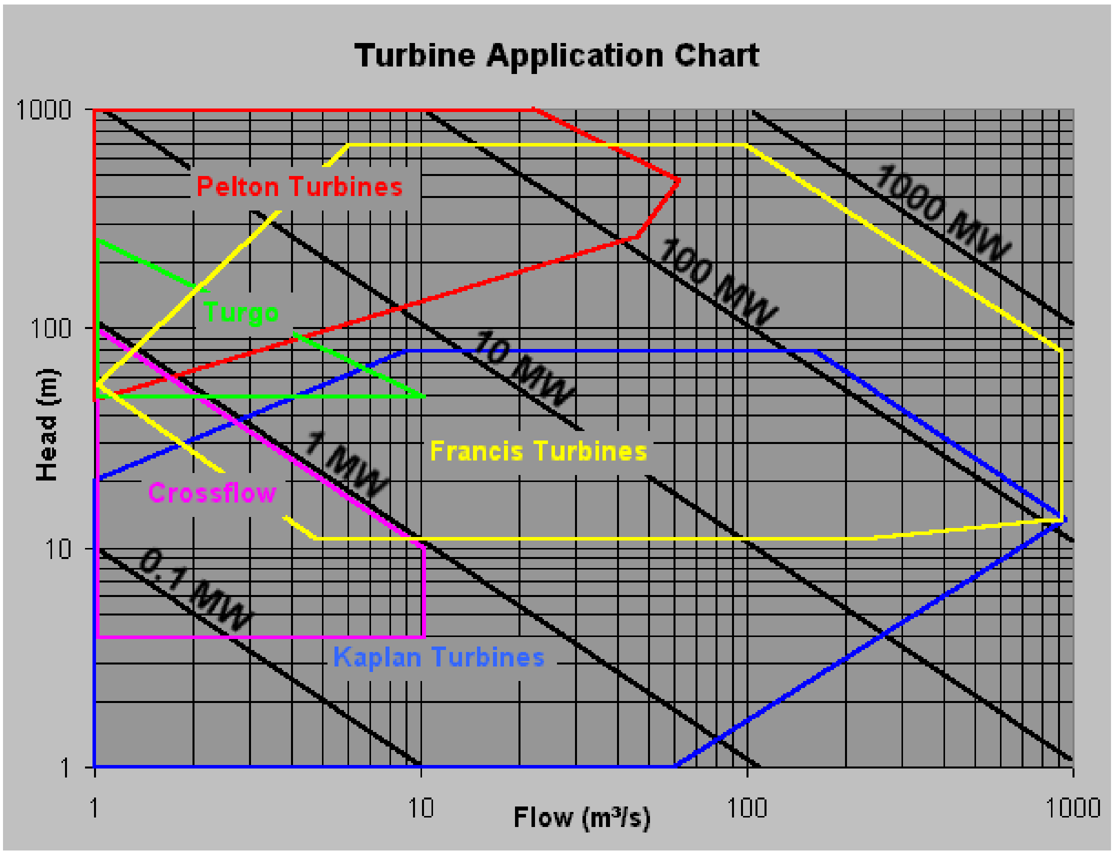
Vertical shaft pump used as a turbine, with 9O-degree gear box

2.6. Design and application

Turbine selection is based mostly on the available water head, and less so on the available flow rate. In general, impulse turbines are used for high head sites, and reaction turbines are used for low head sites.

Hydropower Turbine Application Chart is a graphical chart that shows which type of turbine is to be used depending on the effective head and flow rate.

Particular combinations of site head and flow dictate the type of turbine that will efficiently produce power. For conditions where different types of turbines overlap, the selection process should be based on a comparison of equipment costs and performance quotations from competing manufacturers of several suitable turbines. In general, the turbine offering the highest shaft speed for the given head and flow should result in the lowest equipment cost.



If the head and flow allow the use of either impulse or reaction type turbines, the selection should be based on an evaluation of the following factors:

- If the water is sand or silt laden, an impulse turbine should be favored to avoid performance loss due to wear in the reaction turbine seals.
- If the turbine must be located some height above the tailwater level, a reaction turbine with a draft tube at the outlet should be favored to make use of the maximum head available.
- If the head and flow rate can be maintained relatively constant, using a pump with reverse flow as a turbine should be considered since the initial cost and availability may be advantageous.
- A turbine that turns fast enough for direct coupling to the generator shaft should result in a more compact installation and less long-term maintenance than one coupled through drive belts or a transmission.
- If the flow rate is at the upper end of the impulse turbine range, the Cross-flow (Banki) or Turgo-type impulse turbines should be evaluated. They offer higher speed than the Pelton Wheel, handle more flow, and do not require the close running seals needed by the Francis turbine and other reaction-type turbines.

Specific speed:

The specific speed N_s of a turbine is the primary numerical classification of the turbine. This value describes the speed of the turbine at its maximum efficiency with respect to the power and flow rate. The specific speed is derived to be independent of turbine size. Given the fluid flow conditions and the desired shaft output speed, the specific speed can be calculated and an appropriate turbine design selected.

The specific speed, along with some fundamental formulas can be used to reliably scale an existing design of known performance to a new size with corresponding performance.

The specific speed is also the main criteria for matching a specific hydro site with the correct turbine type. By calculating the specific speed of a turbine, it is possible to make accurate calculations of the turbine's performance for a range of heads.

The relationship between specific speed and turbine speed is as follows:

$$Ns = \frac{N * P^{0,5}}{H_d^{1,25}}$$

Where:

N_s = *specific speed*
N = *turbine speed (rpm)*
H_d = *design head of the turbine (m)*
P = *turbine power (kW)*

Well-designed efficient machines typically use the following values: Impulse turbines have the lowest N_s values: a Pelton turbine ranges from 10 to 30, Turgo turbines have a value between 20 and 70, while Cross-flow turbines vary from 20 to 200. Francis turbines have a range of 30 to 400, while Kaplan and Propeller turbines are at least 200 or more.

Runaway speed:

The runaway speed of a water turbine is the speed at which the turbine exceeds its designed maximum rotational speed. The turbine will be designed to survive the massive centrifugal forces of this speed.

2.7. Generators

A generator is an electromechanical device that converts mechanical energy (torque) into electrical energy. This is accomplished by driving a coil through magnetic lines of force, so that the coil interacts with those lines of force to produce a voltage at the coil terminals.

The generator used in a micro/pico hydroelectric installation can either produce alternating current (AC) or direct current (DC). The most common generator types, which are used in these applications, are synchronous generators and induction (asynchronous) motors, which both produce AC.

The synchronous speed of a generator is determined as follows:

$$n_g = \frac{f * 120}{p}$$

where:

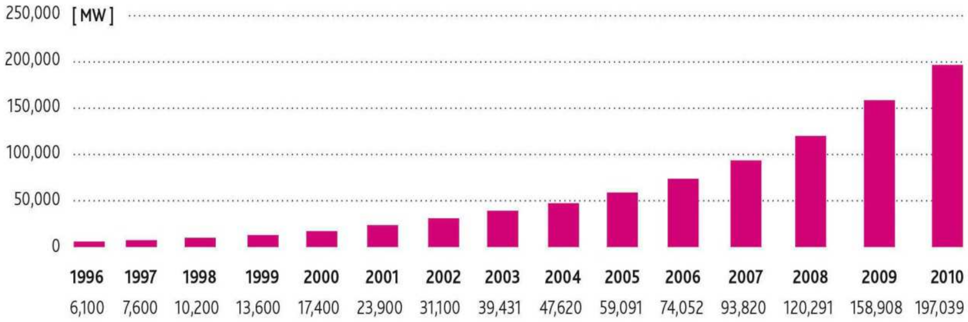
n_g = *synchronous speed (rpm)*
f = *frequency (Hz)*
p = *number of stator poles*

As can be seen from the equation, the frequency and poles interact to determine the speed of a generator.

Standard speeds of regularly manufactured generators are 3600, 1800, 1200, and 600 rpm. However, because of over speed considerations, most generators for micro hydropower applications are specified in the 900 to 1800 rpm range.

CHAPTER 3: WIND POWER

Wind power is produced by using wind generators to harness the kinetic energy of wind. For the past two decades, wind energy has increased with the highest ratio of all renewable energy technologies, with growth rate of 30 % percentage per year. As of June 2011, worldwide nameplate capacity of wind-powered generators was 215 GW.



Global cumulative wind capacity (1996-2010)

Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface and rotation of the earth. The sun's heat warms the air in patches, resulting in some patches becoming warm and some other remaining cold. Hot air gets lighter in weight and it leaves its place moving upwards, while heavier cold air patches fill up the space left. This continuous movement of air produces the winds.

Wind flow patterns depend on the earth's terrain, bodies of water and vegetation. Therefore, the wind resource is highly variable, both geographically and temporally, something that causes great variation of wind energy produced.

3.1. Turbine sizes

Wind generation equipment is categorized into three general classifications:

- *Utility-Scale:* Corresponds to large turbines (more than 900 kW) intended to generate bulk energy for sale in power markets. They are typically installed in large arrays or wind energy projects,

2MW Sewind wind turbine

but can also be installed in small quantities on distribution lines, otherwise known as distributed generation.

- *Industrial-Scale:* Corresponds to medium sized turbines (50 kW to 750 kW) intended for remote grid production, often in conjunction with diesel generation or load-side generation (on the customer's side of the meter) to reduce consumption of higher cost grid power and possibly to even reduce peak loads.

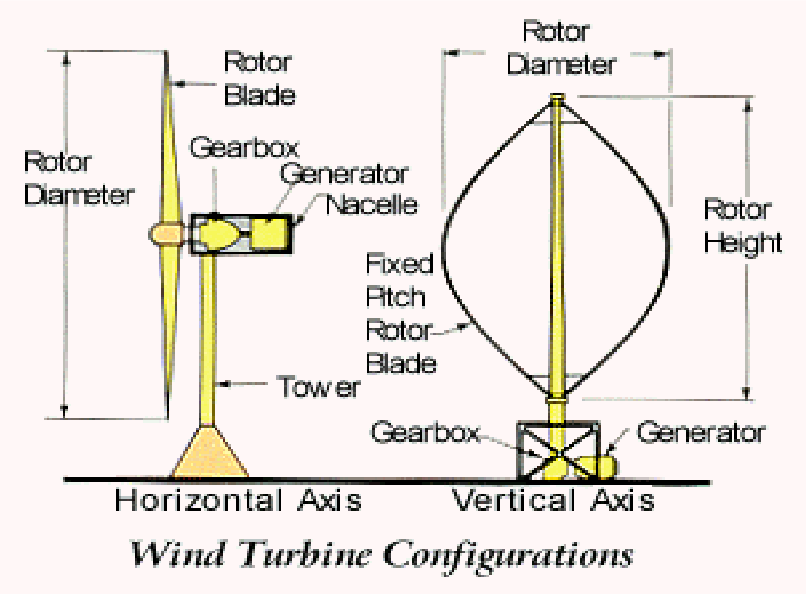
50kW Benz wind turbine

- *Residential-Scale:* Corresponds to micro- and small-scale turbines (400 watts to 50 kW) intended for remote power, battery charging, or net metering type generation. The small turbines can be used in conjunction with solar photovoltaics, batteries, and inverters to provide constant power at remote locations where installation of a distribution line is not possible or is more expensive.

Residential wind power installation

3.2. Types of wind turbines

The separation of wind turbines has to do with the axis about which they can rotate. This is either a horizontal or a vertical axis, the former being older and more common.



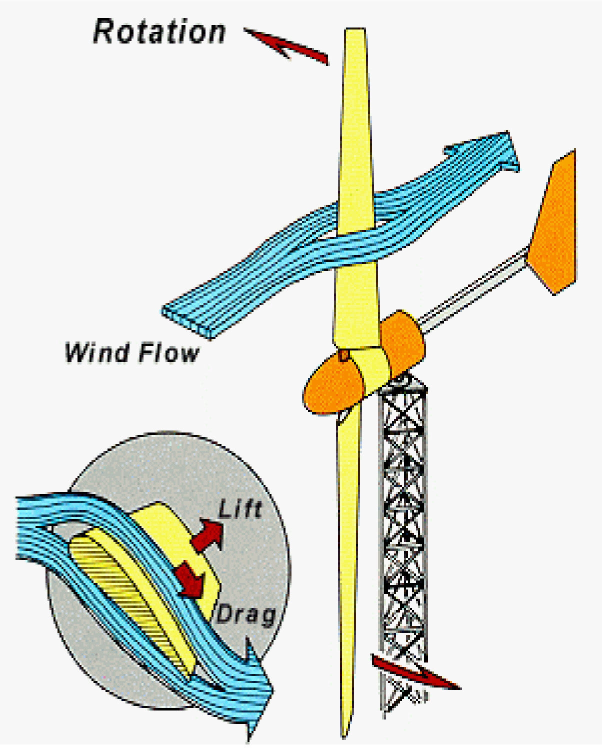
3.2.1. Horizontal axis wind turbines

In the horizontal axis wind turbines (HAWTs) the axis of the rotor's rotation is parallel to the wind stream and the ground. The main rotor shaft and electrical generator are at the top of the tower and they have to be pointed to the wind. A wind vane can point a small turbine towards the wind, while large turbines generally use a wind sensor coupled with a servo motor. A gearbox is also installed, in order for the slow rotation of the blades to turn into a quicker rotation that is more suitable to drive an electrical generator.

All grid-connected commercial wind turbines today are built with a propeller-type rotor on a horizontal axis. Most horizontal axis turbines built today have two or three blades.

A horizontal axis wind turbine

The wind passes over both surfaces of the airfoil shaped blade but passes more rapidly over the longer (upper) side of the airfoil, thus creating a lower-pressure area above the airfoil. The pressure differential between top and bottom surfaces results in aerodynamic lift. Since the blades of a wind turbine are constrained to move in a plane with the hub as its center, the lift force causes rotation about the hub. In addition to the lift force, a drag force perpendicular to the lift force impedes rotor rotation. A prime objective in wind turbine design is for the blade to have a relatively high lift-to-drag ratio. This ratio can be varied along the length of the blade to optimize the turbine's energy output at various wind speeds.



Principles of wind turbine aerodynamic lift

HAWTs can be subdivided into upwind wind turbines and downwind wind turbines:

3.2.1.1. Upwind wind turbines:

In upwind wind turbines the rotor faces the wind. The basic advantage of upwind designs is that one avoids the wind shade behind the tower. The vast majority of wind turbines have this design. Anyhow, even if the tower is round and smooth, the wind starts bending away from the tower before it reaches the tower itself, resulting in the power of the wind turbine to drop slightly. The basic drawback of upwind designs is that the rotor needs to be made rather inflexible to prevent being pushed into the tower by high winds and placed at some distance from the tower and sometimes tilted forward into the wind a small amount. This increases efficiency by avoiding turbulence created by the tower. In addition an upwind machine needs a yaw mechanism to keep the rotor facing the wind.

3.2.1.2. Downwind wind turbines

In downwind wind turbines the blades are mounted behind the tower (lee side). Downwind machines have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. A more important advantage in terms of the weight and the structural dynamics of the tower is that the rotor may be made more flexible, meaning that the blades will bend at high wind speeds, thus taking part of the load off the tower. The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower. This may give more fatigue loads on the turbine, something that makes the downwind design less reliable than the upwind one.

3.2.2. Vertical axis wind turbines

In vertical axis wind turbines (VAWTs) the axis of rotation is perpendicular to the wind stream and the ground. Although they have existed for centuries, they are not in such wide use as their horizontal counterparts. The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as much as horizontal axis turbines. The basic vertical axis designs are the Darrieus, which has curved blades, the Giromill, which has straight blades, and the Savonius, which uses scoops to catch the wind.

Savonius wind turbine

Darrieus wind turbine

A vertical axis machine does not need to be oriented with respect to wind direction to be effective, something that is useful on sites with a highly variable wind direction. Moreover, because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier accessibility and servicing and a lighter weight and lower cost tower. Another advantage offered by the VAWTs is that they can be packed closer together in wind farms, allowing more in a given space. This is not because they are smaller, but rather due to the slowing effect on the air that HAWTs have, forcing designers to separate them by ten times their width. They also do not require as much wind to generate power, thus allowing them to be closer to the ground. By being closer to the ground they are easily maintained and can be installed on chimneys and similar tall structures.

On the other hand, VAWTs are sensitive to off-design conditions and have a low installation height limiting the operation to lower wind speed environments, what makes them less efficient at collecting energy from the wind than the horizontal machine designs. Furthermore, the blades of a VAWT are prone to fatigue as the blade spins around the central axis, sometimes leading to catastrophic failure.

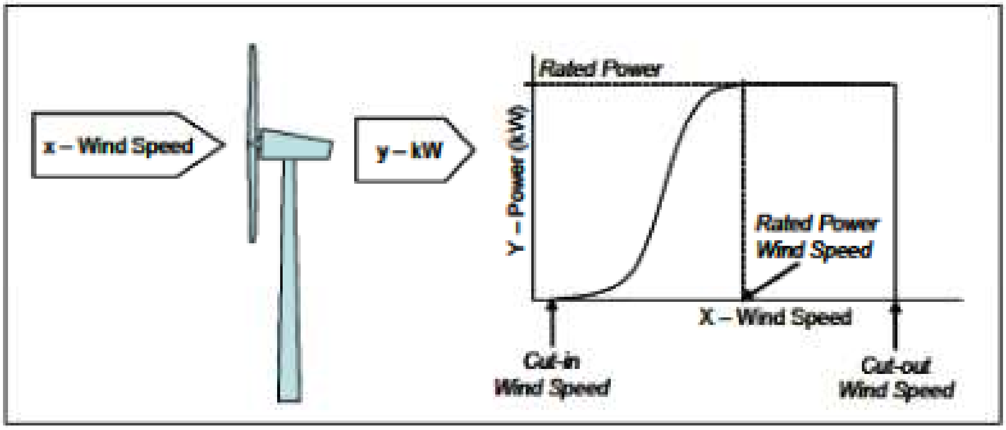
3.3. Operating characteristics and power curve of a wind turbine

Power production from a wind turbine is a function of wind speed. The relationship between wind speed and power is defined by a power curve, which is unique to each turbine model and, in some cases, unique to site-specific settings. Variability in the wind resource results in the turbine operating at continually changing power levels. All wind turbines share certain operating characteristics, such as start-up, cut-in, rated and cut-out wind speeds, which define the power curve of a wind turbine:

- *Start-up Speed*: The speed at which the rotor and blade assembly begins to rotate.
- *Cut-in Speed*: The minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 3 m/s and 5 m/s for most turbines.
- *Rated Speed:* The minimum wind speed at which the wind turbine will generate its designated rated power. For instance, a 5kW wind turbine cannot generate 5kW until wind speeds reach its rated speed value. Rated speed for most machines is in the range of 11 to 16 m/s. For wind speeds between the cut-in and

rated speed values, the power output from a wind turbine increases as the wind increases. The output of most wind turbines remains stable for wind speeds above the rated speed.

- *<u>Cut-out Speed:</u>* At very high wind speeds, typically between 20 and 35 m/s, most wind turbines cease power generation and shut down in order to prevent being damaged. The wind speed at which shut down occurs is called the cut-out speed, or sometimes the furling speed. Shut down may occur in one of several ways: In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind. Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. When the speed of the wind drops back to safe levels, the normal operation of the wind turbine resumes.



Wind turbine power curve

3.4. Calculation of wind power output

The power from a wind turbine is calculated (in Watts) from the following equations (depending on the wind speed):

- $u<u_c$: $P_w=0$
- $u_c \le u \le u_r$: $P_w=1/2 * C_p * \rho * A * u^3 * n_t$
- $u_r \le u \le u_f$: $P_w=P_{rated}$
- $u>u_f$: $P_w=0$

where:

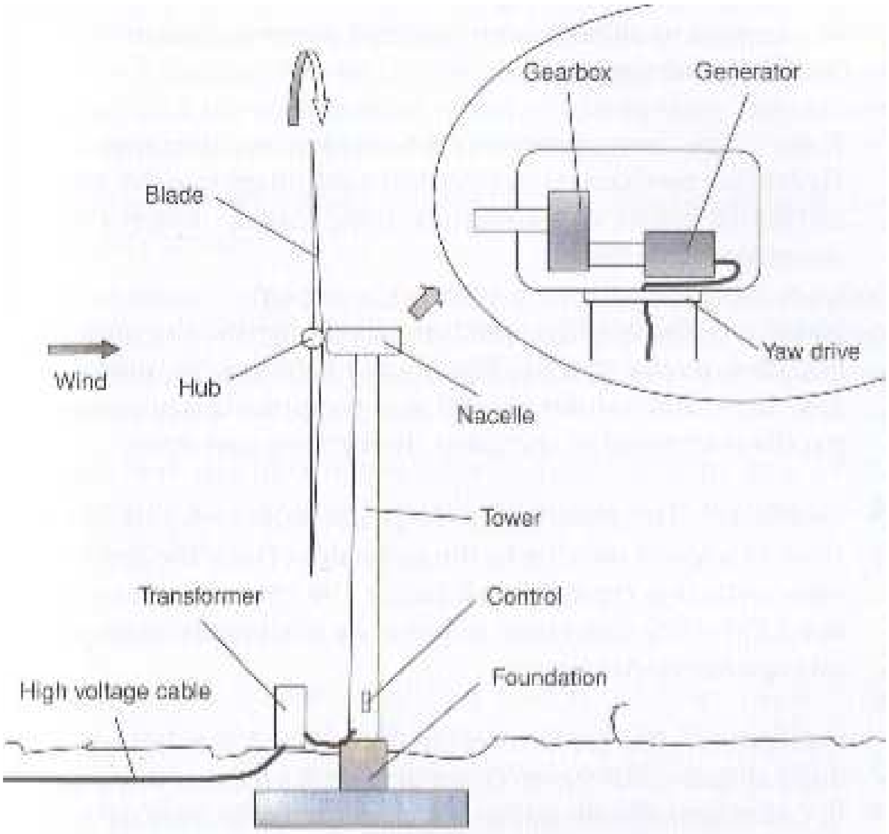
- *ρ: Air density (kg/m^3)*
- *A: Swept area of rotor (m^2). As it can be easily perceived, the larger the rotor, the more energy it can capture.*
- *u: Wind speed (m/s)*

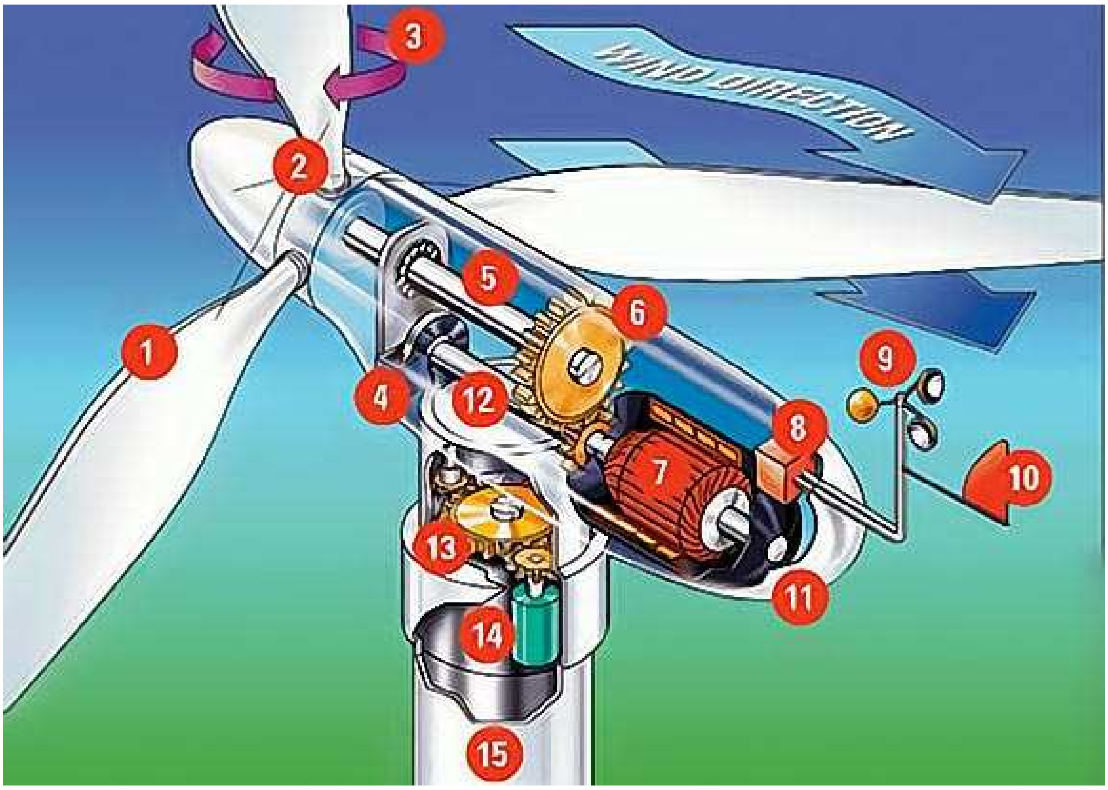
- C_p: *Power coefficient, ranging from 0,25 to 0,45. This dimensionless number is the percentage of the kinetic energy of the wind that will be converted into mechanical energy, turning a rotor, and it depends on the design. The theoretical maximum power efficiency of any design of wind turbine is 0,59 (Betz limit).*
- n_t: *Efficiency (%) of the whole wind turbine system (the generator, bearings, power transmission etc.).*
- u_c: *Cut-in speed*
- u_r: *Rated speed*
- u_f: *Cut-out (furling) speed*
- P_{rated}: *Rated power of the wind turbine*

Horizontal axis wind turbines (HAWT) theoretically have higher power efficiencies than vertical axis wind turbines (VAWT) however wind direction is not important for a VAWT and so no time (and power) is wasted chasing the wind. In turbulent conditions with rapid changes in wind direction more electricity will be generated by a VAWT despite its lower efficiency.

3.5. Components of a wind turbine

The diagrams above depict the components of a typical upwind wind turbine:





Major turbine components

1) *Blades:* Blades are designed aerodynamically to capture the maximum surface area of wind in order to spin the most ergonomically. They are lightweight, durable and corrosion-resistant material. The best materials are composites of fiberglass and reinforced plastic. They also come in various sizes and have tended to grow over the years. In the early 1980s, a typical blade was likely to be 10 meters long and such a wind turbine could generate about 45 MWh per year. By 1990 the typical blade measured 27 meters and could produce 550 MWh per year. In the early twenty-first century blades as long as 70 meters can generate 5600 MWh per year.
2) *Rotor:* The rotor is the hub around which the blades are connected. Often, however, "rotor" is used to refer to the hub and the blades as a single unit. It is easy to comprehend that it is the key component, as it transforms the wind's kinetic energy into torque, which is translated into wind power.
3) *Pitch:* Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low.
4) *Brake:* A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in case of emergency.

5) *Low-speed shaft:* The rotor turns the low-speed shaft at about 30 to 60 rpm.

6) *Gear box:* Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 40 to 400 rpm to about 1.000 to 1.800 rpm, the rotational speed required by most generators to produce electricity. Nonetheless, because it is a costly and heavy part of the wind turbine, alternatives that omit the gear box are explored, like the use of direct-drive generators for DC-type wind turbines which can operate at lower rotational speeds. The use of these generators reduces the complexity and the maintenance requirements of the system, but a much larger generator is required to deliver the same power output as the AC-type wind turbines.

7) *Generator:* Converts the turning motion of a wind turbine's blades into electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades.

The choice of the right type of generator is really important. Most home and office appliances operate on 120 volt (or 240 volt), 60 cycle AC. Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC. Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts.

Generators that produce AC are generally equipped with features to produce the correct voltage (120 or 240 V) and constant frequency (60 cycles) of electricity, even when the wind speed is fluctuating.

DC generators are normally used in battery charging applications and for operating DC appliances and machinery. They also can be used to produce AC electricity with the use of an inverter, which converts DC to AC.

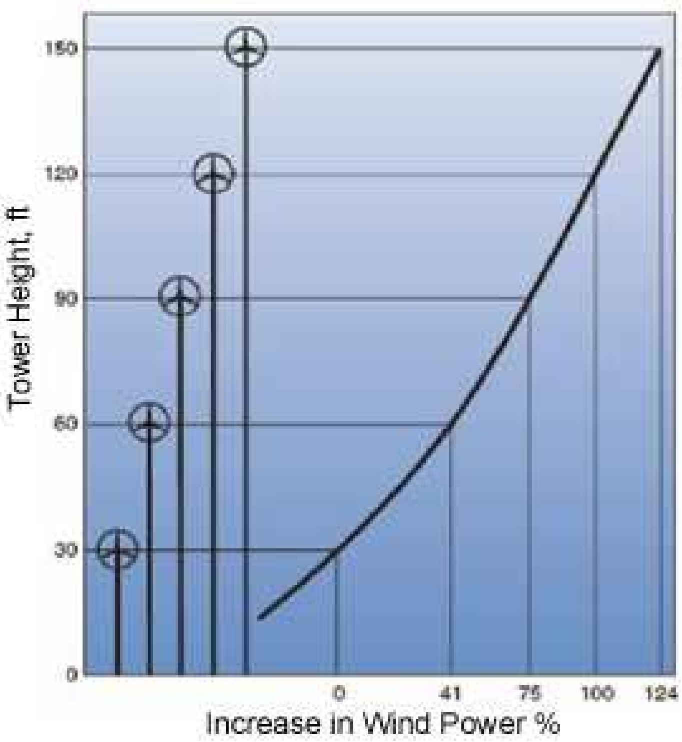
8) *Controller:* The controller starts up the machine when the wind speed reaches the start-up speed value and shuts it off when the cut-out speed is reached, for safety reasons.

9) *Anemometer:* Measures the wind speed and transmits wind speed data to the controller.

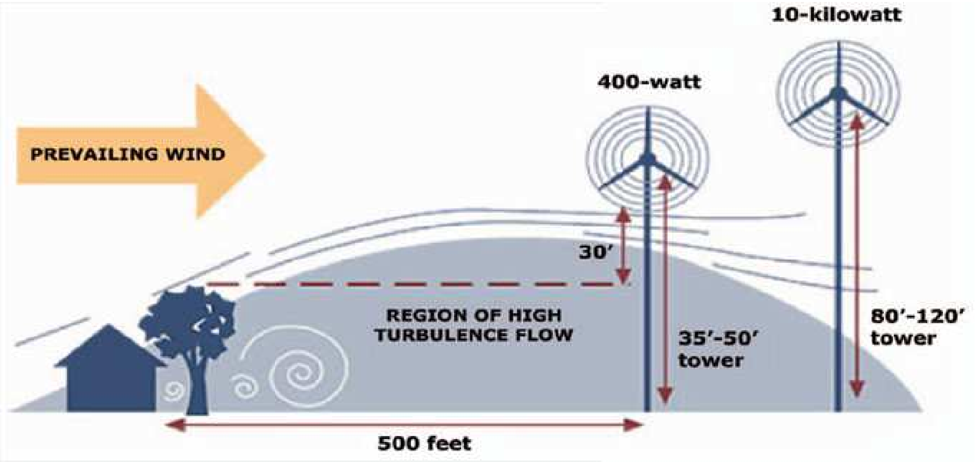
10) *Wind vane:* Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind in order to gather maximum wind energy.
11) *Nacelle:* The enclosure that houses the turbine's drive train, including the gearbox, the yaw mechanism, and the electric generator. It can be easily removed for maintenance of the wind turbine.
12) *High-speed shaft:* It drives the generator.
13) *Yaw drive:* The yaw mechanism automatically senses the direction of the wind and rotates the rotor to keep it facing into the direction of the wind. It only exists in upwind turbines, while downwind turbines don't require a yaw drive, because the wind blows the rotor downwind.
14) *Yaw motor:* Powers the yaw drive.
15) *Tower:* Towers for small wind systems have guy wires anchored to the ground on three or four sides to hold it erect. These towers cost less than freestanding towers, but require more land area to anchor the guy wires. Some of these towers are erected by tilting them up. This operation can be quickly accomplished using only a winch, with the turbine already mounted to the tower top. This simplifies not only installation, but maintenance as well. Towers can be constructed of a simple tube, a wooden pole or a lattice of tubes, rods, and angle iron. Large wind turbines may be mounted on lattice towers, tube towers or guyed tilt-up towers.

3.6. Height and ideal placing of the wind turbine

Tall towers enable turbines to access faster in better quality winds, and even small increases in wind speed translate to exponentially more energy the turbine can generate, since the power output is proportional to the cube of the wind speed.



The best sites for turbines are those where the wind is least obstructed, which is often the highest point on a property. The bottom of the turbine rotor should clear the highest wind obstacle (rooftop, mature tree, etc.) within a 150 meters (500 ft) radius by at least 10 meters (30 ft). Doing so ensures the turbine reaches consistent, fast wind speeds and prolongs the life of the turbine by avoiding stressful air turbulence.



Except from the cost parameters, placing a wind turbine in a low height also produces more sound, since taller towers raise the generator high above the ground, diluting sound considerably. Sound decreases four-fold with every doubling of distance from the turbine (including distance above the ground) so taller towers are better for their owners as well as neighbors.

It is also important to keep in mind that a turbine's generator size is independent of the tower's height. Appropriate tower height is matched to a turbine depending on surrounding terrain, trees and buildings, and wind resource and tower height restrictions, if any, should only reflect sound and safety concerns rather than be designed to correspond to a system's generating capacity.

3.7. Offshore wind power

Offshore wind power refers to placing wind farms in bodies of water to take advantage of the better wind speeds available offshore compared to on land and generate more electricity from wind.

Aerial view of a wind farm located in the English Channel with 100 wind turbines of 300MW total capacity (area covered: 35km²)

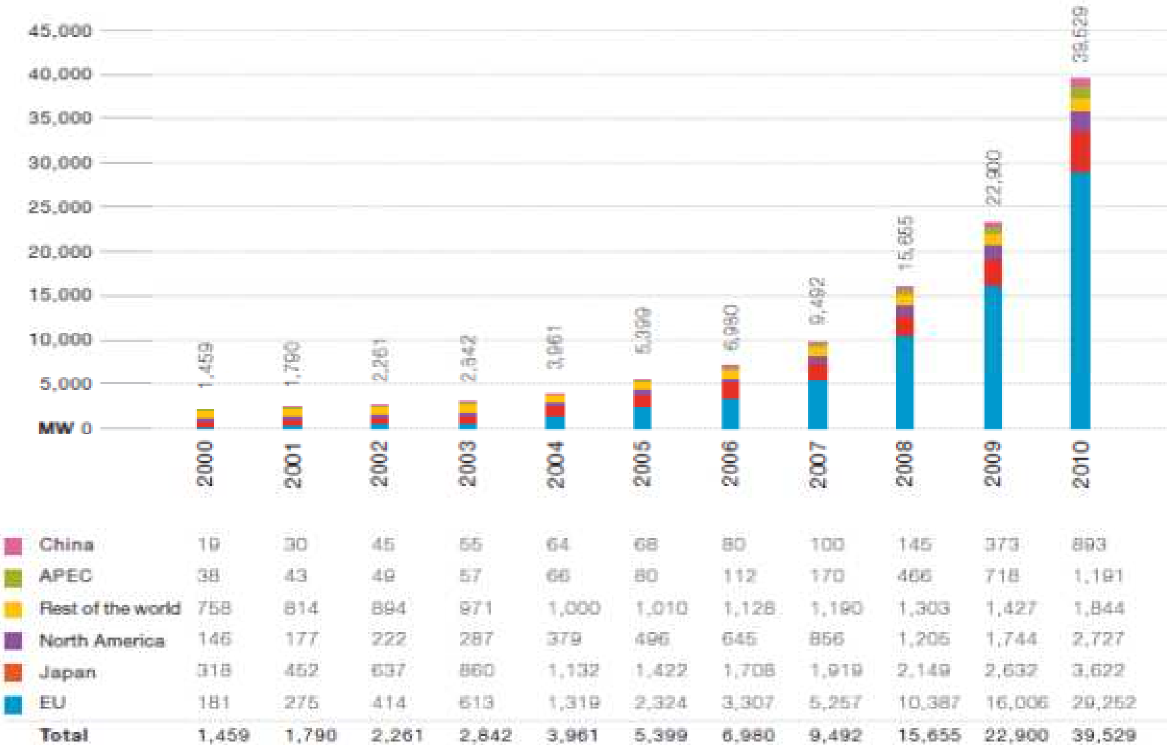
Siemens and Vestas are the leading turbine suppliers for offshore wind power, while DONG Energy, Vattenfall and E.ON are the leading offshore operators. As of 2010, 3,16 GW of offshore wind power capacity was operational, mainly in Northern

Europe. Offshore wind power capacity is expected to reach a total of 75 GW worldwide by 2020, with significant contributions from China and the US.

The offshore wind farm Middelgrunden near Copenhagen with 20 large 2MW wind turbines (total length 3,4 km)

CHAPTER 4: PHOTOVOLTAICS

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current. This takes place in solar panels which are composed of a number of solar cells, some non mechanical devices containing one or two layers of a semiconductor material that exhibits the photovoltaic effect and creates an electric field across the layers. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide. PV modules have no moving parts, are virtually maintenance-free, and have a working life of 20 to 30 years.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
China	19	30	45	55	64	68	80	100	145	373	893
APEC	38	43	49	57	66	80	112	170	466	718	1,191
Rest of the world	758	814	894	971	1,000	1,010	1,128	1,190	1,303	1,427	1,844
North America	146	177	222	287	379	496	645	856	1,205	1,744	2,727
Japan	318	452	637	860	1,132	1,422	1,708	1,919	2,149	2,632	3,622
EU	181	275	414	613	1,319	2,324	3,307	5,257	10,387	16,006	29,252
Total	1,459	1,790	2,261	2,842	3,961	5,399	6,980	9,492	15,655	22,900	39,529

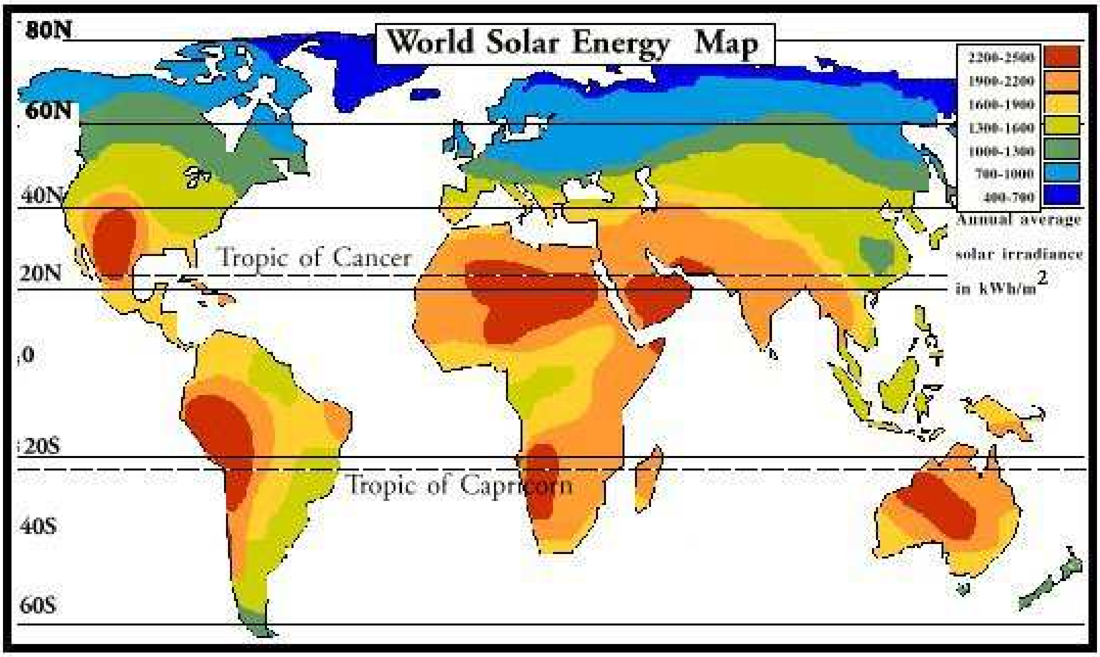
Evolution of global cumulative annual installed capacity (2000-2010)

From the first PV applications in space to the GW systems planned today, more than 40 years have passed. Over the last decade, PV technology has acquired the potential to become a major source of power generation for the world. The PV production has been increasing by an average of more than 20% each year since 2002, making it the world's fastest-growing energy technology and that robust and continuous growth is expected to continue in the years ahead. At the end of 2008, the world's cumulative installed PV capacity was approaching 16 GW. One year later it was 23 GW. At the end of 2010, almost 40 GW are installed globally and produce some 50 TWh of electricity every year, with the three leading countries (Germany, Japan and the US) representing nearly 80% of the total installed capacity. Such installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building, known as Building Integrated Photovoltaics (BIPV) or even added to the building long after construction, known as Building Applied Photovoltaics (BAPV). The EPIA/Greenpeace Advanced Scenario shows that by the year 2030, PV systems could be generating approximately 1,8 TW of electricity around the world.

The cost of photovoltaics has significantly declined over the past years, because of the advances in technology and increases in manufacturing scale and sophistication. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported the installation of solar panels in many countries.

Because of their modularity, PV systems can be designed to meet any electrical requirement, no matter how large or small. The simplest systems can power small calculators and wrist watches, while more complicated systems provide electricity for pumping water, powering communications equipment and lighting homes and running appliances. PV power has proven to be the cheapest form of electricity for performing these tasks in many cases. The photovoltaic cell is the basic building block of a PV system. Individual cells can vary in size from about 1 cm to about 10 cm across. However, one cell only produces 1 or 2 Watts, which isn't enough power for most applications. To increase power output, solar cells (about 40) are electrically connected into a packaged weather-tight photovoltaic module or solar panel. PV modules range in output from 10 to 300 Watts. If more power is needed, several modules can be installed on a building or at ground-level in a rack to form a PV array. About 10 to 20 PV arrays can provide enough power for a household. The term array refers to the entire generating plant, whether it is made up of one or several thousand modules. An array can consist of as many modules as necessary to meet the power output needed.

4.1. The solar resource



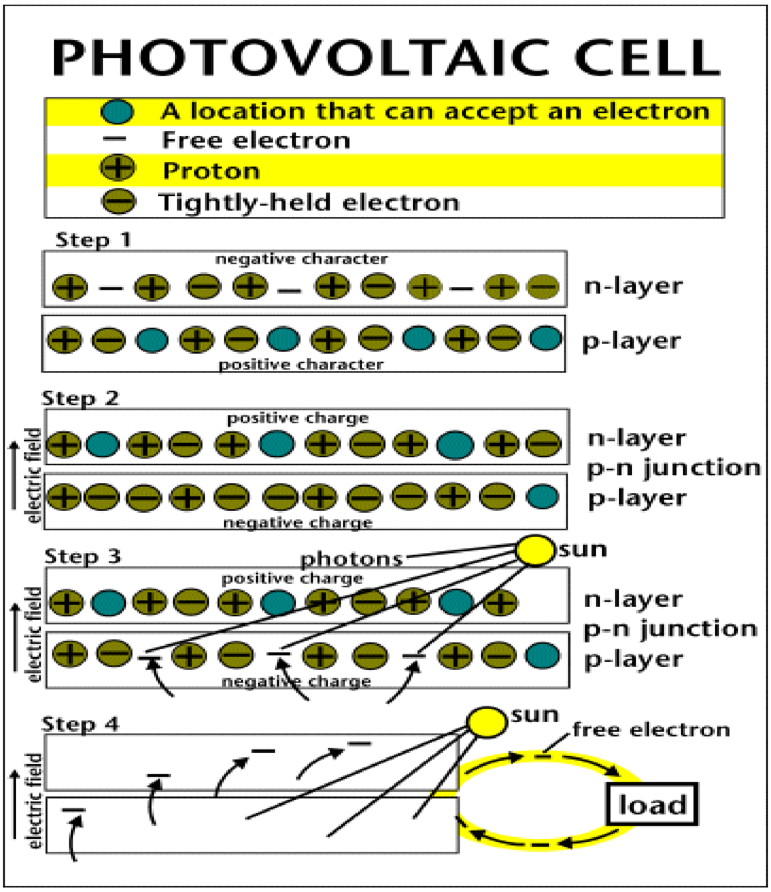
When sunlight reaches the Earth, it is distributed unevenly in different regions. Not surprisingly, the areas near the equator receive more solar radiation than anywhere else on Earth.

Sunlight varies with the seasons, as the rotational axis of the Earth shifts to lengthen and shorten days with the changing seasons. For example, the amount of solar energy falling per square meter on Yuma, Arizona, in June is typically about nine times greater than that falling on Caribou, Maine, in December. The quantity of sunlight reaching any region is also affected by the time of day, the climate (especially the cloud cover, which scatters the sun's rays), and the air pollution in that region. Likewise, these climatic factors all affect the amount of solar energy that is available to PV systems.

4.2. Photovoltaic effect

In order for the photovoltaics to generate electric power, they need a flow of electrons that will act as charge carriers for an electric current. This is done by exploiting the photovoltaic effect, which refers to photons of light exciting electrons into a higher state of energy. This phenomenon was discovered in 1839 by French physicist Edmund Becquerel.

Sunlight is composed of photons, which contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a photovoltaic cell, they may be reflected, pass right through or be absorbed. The absorbed photons are those that provide energy to generate electricity. So, only sunlight of certain wavelengths will work efficiently to create electricity. PV systems can still produce electricity on cloudy days, but not as much as on a sunny day, except from slightly cloudy days which can result in higher energy yields than days with a completely cloudless sky.



When enough sunlight (energy) is absorbed by the semiconductor, electrons, that have received the energy of the photons, are able to be dislodged from the material's atoms. The positions left free by each electron, that has escaped an atom, act as positive charges and take the name of "holes". The photovoltaic cells generally consist of two thin regions, one above the other. Due to the electrons moving freely in the semiconductor, one region is of "type n", with an excess of electrons (negative), while the other is of "type p", with an excess of positive holes. This 2-region structure, called a p-n junction, produces an internal electric field. When the photons create free electrons and holes in proximity to the p-n junction, the internal electric field makes them move in opposite directions: the electrons move towards the side n, where they are available for the electrical circuit, and the holes move towards the side p, where they await incoming electrons. So a tension (electromotive force) is generated between the p and n regions, with p positive and n negative. When the two surfaces are connected through an external load, electricity flows.

4.3. Performance and efficiency of a PV system

The performance of a photovoltaic array is dependent upon sunlight. Climate conditions (e.g., clouds, fog) have a significant effect on the amount of solar energy received by a PV array and, in turn, its performance.

For best performance, terrestrial PV systems aim to maximize the time they face the sun. Solar trackers aim to achieve this by moving PV panels to follow the sun. The increase can be by as much as 20% in winter and by as much as 50% in summer. Static mounted systems can be optimized by analysis of the sun path. Panels are often set to latitude tilt, an angle equal to the latitude, but performance can be improved by adjusting the angle for summer or winter.

Even partial shading can have a surprisingly large effect on the output of the panel. Not only will the cells that are shaded be producing less power, but as the cells within a panel are normally all wired in series, the shaded cells affect the current flow and the output of the whole panel. Therefore in a situation where partial shading cannot be avoided, there may be a case for not having the panels wired in series to produce the higher voltages that can be used with some inverters.

Generally, as with other semiconductor devices, temperatures above room temperature reduce the performance of photovoltaics. As a result the power output will be reduced by between 0,25% (amorphous cells) and 0,5% (most crystalline cells) for each Celsius degree of temperature rise. Panel temperatures in the summer in warm climates can easily reach 50^oC resulting in a 12% reduction in output compared to the rated output at 25^oC. This reduction in efficiency can be a decisive factor, in case of a high electricity demand in the summer.

In terms of the solar cell itself, its conversion efficiency is what mainly determines the general efficiency of the PV system. The conversion efficiency of a PV cell is the proportion of sunlight energy that the cell converts to electrical energy and it is the main factor that determines the reliability of the cell. What is really important is that the p layer absorbs as many incoming photons as possible and frees as many electrons as possible. Furthermore, another challenge is to keep the electrons from meeting up with holes and "recombining" with them before they can escape the cell. Therefore, the material has to be designed in order for the electrons to be freed as close to the junction as possible, so that the electric field can help send them through the conduction layer and out into the electric circuit. So the higher the absorption and the minimum the reflection and the recombination are, the higher the conduction and the solar cell's efficiency will be.

The record at the moment stands at an efficiency of around 40%, using multi junction cells (multiple layers of silicon), each layer tuned to trap different frequencies (colors) of light. This type of cell will however be expensive to produce and in the past has been mainly used in space where efficiency may be more important. Cells used in photovoltaic panels for electricity production are usually single junction type with an efficiency of somewhere around 15%.

4.4. Calculation of output power of a PV array

The simplest, but fairly accurate equation that calculates the power output (in Watts) of a PV array is:

$$P_{PV} = n * A_p * N_{PV} * Ins$$

Where:

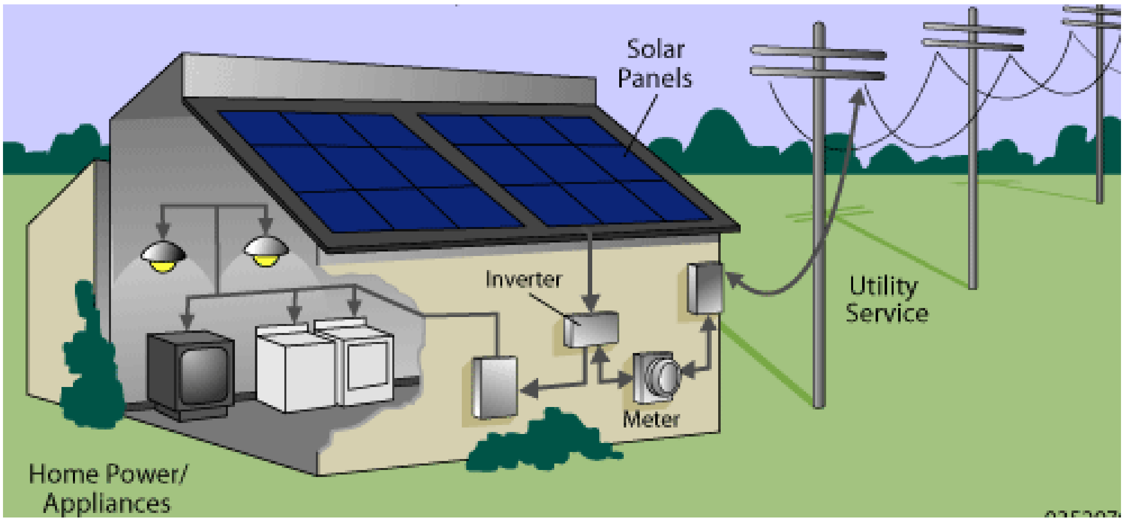
n: Energy conversion efficiency, (%)
A_P*: Area of single PV panel,* (m^2)
N_{PV}*: Number of PV panels*
I_{ns}*: Insolation,* (W/m^2)

4.5. Photovoltaic applications

The photovoltaic technology can be used in several types of applications:

- *Grid-connected domestic systems:*
  This is the most popular type of solar PV system for homes and businesses in developed areas. Connection to the local electricity network allows any excess power produced to feed the electricity grid and to sell it to the utility. Electricity is then imported from the network when there is no sun. An inverter is used to convert the direct current (DC) power produced by the system to alternative current (AC) power for running normal electrical equipments.

In case of buildings, arrays are most often retrofitted into existing buildings, usually mounted on top of the existing roof structure or on the existing walls. Alternatively, an array can be located separately from the building but connected by cable to supply power for the building. Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings as a principal or ancillary source of electrical power.



Residential grid connected PV system

- *Grid connected power plants:*

These systems produce a large quantity of photovoltaic electricity in a single point. The size of these plants ranges from several hundred kilowatts to several megawatts. Some of these applications are located on large industrial buildings such as airport terminals or railway stations. This type of large application makes use of already available space and compensates a part of the electricity produced by these energy-intensive consumers.

Sarnia PV power plant in Canada (97MWp)

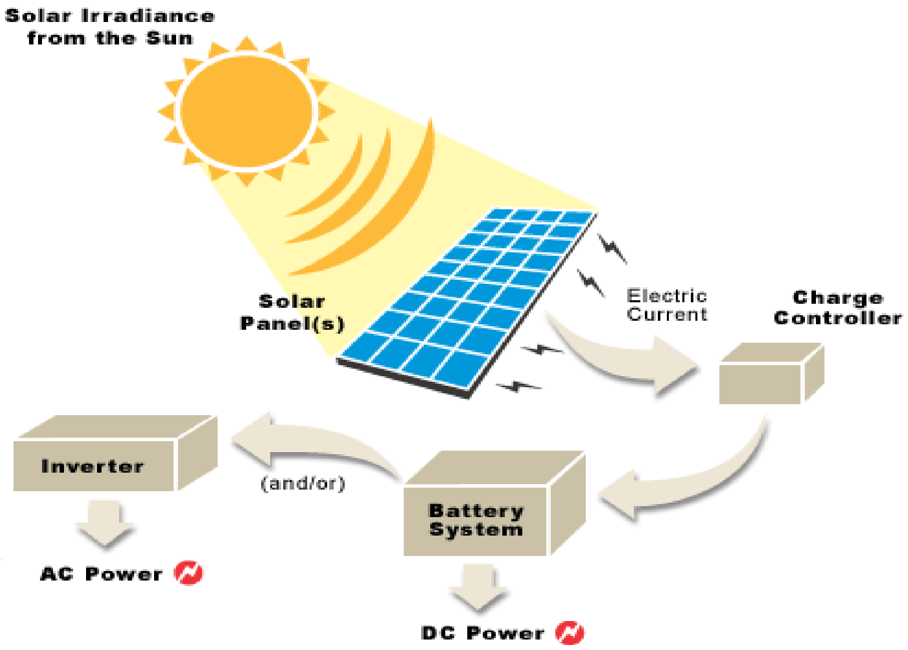
Many solar photovoltaic power stations have been built all over the world, with Europe having the biggest part of the installed capacity. As of December 2010, the largest photovoltaic (PV) power plants in the world are the Sarnia Photovoltaic Power Plant (Canada, 97 MWp), Montalto di Castro Photovoltaic Power Station (Italy, 84,2 MWp) and Finsterwalde Solar Park (Germany, 80,7 MWp).

Many of these plants are integrated with agriculture and some use innovative tracking systems that follow the sun's daily path across the sky to generate more electricity than conventional fixed-mounted systems facing south. These power stations operate without any fuel costs or emissions.

- *Off-grid systems for rural electrification:*

Especially in terms of off-grid locations a significant market for solar power and battery based solutions has emerged. The use of solar energy or other renewable energy technology along with batteries as power storages is often the only way to bring access to electricity to remote areas (mountain huts, developing countries).

The system is connected to the battery banks via a charge controller and an inverter can be used to provide AC power, enabling the use of normal electrical appliances.



Operation of a PV system with DC and/or AC output

Rural electrification means either small solar home system covering basic electricity needs in a single household, or larger solar mini-grids, which provide enough power for several homes. The first commercial installation of this kind was in 1966 on Ogami Island in Japan to transition Ogami Lighthouse from gas torch to fully self-sufficient electrical power.

- *Off-grid industrial applications:*

  Solar energy is frequently used in the telecommunications field for remote applications in order to link remote rural areas to the rest of the country. Repeater stations for mobile telephones powered by PV or hybrid systems also have a large potential. Other applications include traffic signals, marine navigation aids, security phones, remote lighting, highway signs and waste water treatment plants. These applications avoid the high cost of installing cabled networks and therefore, they are cost competitive in bring power in areas far away from electric mains.

PV used for a remote telecommunication station

- *Consumer goods:*

  Photovoltaic cells are used in many daily electrical appliances and standalone devices, including watches, calculators, toys, battery chargers, professional sun roofs for automobiles etc. Other applications include power for services such as water sprinklers, road signs, lighting and phone boxes.

Sun roof system used to cool down the car

4.6. Available photovoltaic technologies

The most common photovoltaic technologies are crystalline silicon technology and thin film technology:

4.6.1. Crystalline silicon technology

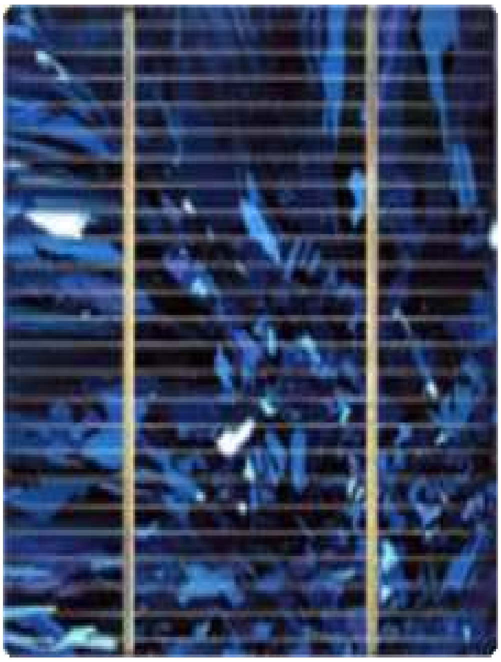
Crystalline silicon cells are made from thin slices cut from a single crystal of silicon (monocrystalline) or from a block of silicon crystals (polycrystalline). Their efficiency ranges between 12% and 17% and this is the most common technology, representing about 90% of the market today.

Three main types of crystalline cells can be distinguished: Monocrystalline (Mono c-Si), Polycrystalline (or Multicrystalline) (multi c-Si) and Ribbon sheets (ribbon-sheet c-Si).

- *Monocrystalline cells:* They are made in long cylinders and sliced into round or hexagonal wafers. As a result of being cut from cylindrical ingots, the silicon wafers do not entirely cover the surface of a square solar cell module without a substantial waste of refined silicon. Hence most mono-crystalline panels have uncovered gaps at the four corners of the cells. While this process is expensive, energy-intensive and wasteful of materials, it produces the highest-efficiency cells, typically around 15 percent and as high as 25 percent in some laboratory tests. Because these high-efficiency cells are more expensive, they are sometimes used in combination with concentrators such as mirrors or lenses. Concentrating systems can boost efficiency to almost 30 percent. Monocrystalline cells account for 29 percent of the global market for PV.

Monocrystalline silicon cell

- *Polycrystalline cells:* They are made of molten silicon cast into ingots or drawn into sheets, then sliced into squares. While the manufacturing process is simpler and the production costs are lower, the cells tend to be slightly less efficient, with average efficiencies of around 12 percent, creating a granular texture. Because the cells are square, they can be packed more closely together. Polycrystalline cells make up 62 percent of the global PV market.



Polycrystalline silicon cell

- *Ribbon sheets (ribbon-sheet c-Si):* Ribbon silicon is a type of mono-crystalline silicon. It is made by drawing flat thin films from molten silicon that has a multi-crystalline structure. These cells are less efficient than poly-crystalline silicon, however the significant reduction in silicon waste indicates lower production costs.

4.6.2. Thin film technology

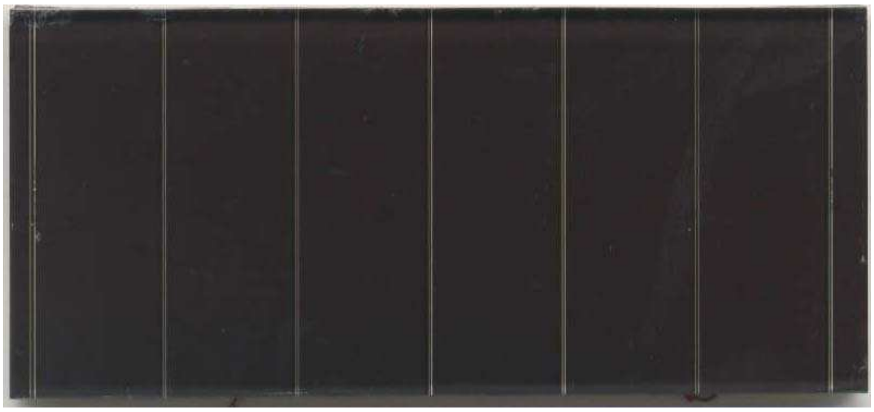
Thin film modules are constructed by depositing extremely thin layers of photosensitive material on to a low-cost backing such as glass, stainless steel or plastic. Once the deposited material is attached to the backing, it is laser-cut into multiple thin cells.

Thin Film modules are normally enclosed between two layers of glass and are frameless. If the photosensitive material has been deposited on a thin plastic film, the module is flexible. This creates opportunities to integrate solar power generation into the fabric of a building or end-consumer applications.

The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers. Four types of thin film modules (depending on the active material used) are commercially available at the moment: Amorphous silicon (a-Si), Cadmium telluride (CdTe), Copper, Indium, Gallium (di)selenide/(di)sulphide (

CIGS), Copper, Indium (di)selenide/(di)sulphide (CIS) and multi junction cells (a-Si/m-Si).

- *Amorphous silicon (a-Si):* Silicon is essentially sprayed onto a glass or metal surface in thin films, making the whole module in one step and reducing the manufacturing costs. The semiconductor layer is only about 1 µm thick. Amorphous silicon can absorb more sunlight than c-Si structures. However, a lower flow of electrons is generated which leads to efficiencies that are currently in the range of 4 to 8%. An increasing number of companies are developing light, flexible a-Si modules perfectly suitable for flat and curved industrial roofs.



Amorphous silicon cell

- *Cadmium telluride (CdTe):* This is the most reliable thin film technology available, because it combines low manufacturing costs and a module efficiency of up to 11%. The two main raw materials are cadmium and tellurium, which are by-products of zinc mining and copper processing, respectively. Tellurium is produced in far lower quantities than cadmium. Availability in the long-term may depend on whether the copper industry can optimize extraction, refining and recycling yields.
- *Copper, indium, gallium (di)selenide/(di)sulphide (CIGS) and copper, indium (di)selenide/(di)sulphide (CIS) :* CIGS and CIS have achieved efficiencies of 20% in the laboratory, making them the thin film with the highest efficiencies. Current module efficiencies are in the range of 7 to 12%. However, the manufacturing costs are increased, while the manufacturing process is more complex and less standardised than for other types of cells. There are no long-

term availability issues for selenium and gallium, Indium is available in limited quantities but they are no signs of an incoming shortage.

- *Multi junction cells (a-Si/m-Si):* They consist of an a-Si cell with additional layers of a-Si and micro-crystalline silicon (µc-Si) applied onto the substrate. The µc-Si layer absorbs more light from the red and near-infrared part of the light spectrum. This increases efficiency by up to 10%. The thickness of the µc-Si layer is in the order of 3 µm, making the cells thicker but also more stable.

Table: Record efficiencies of thin film technologies

Thin film technology	Record commercial module efficiency (%)	Record lab efficiency (%)
a-Si	7,1	10,4
a-Si/µ-Si	10	13,2
CdTe	11,2	16,5
CIGS/CIS	12,1	20,3

4.6.3. Other technologies

Except from the cell types mentioned above, there are several other types of photovoltaic technologies developed today starting to be commercialized or still at the research level, the main ones are:

- Concentrated photovoltaic: Some solar cells are designed to operate with concentrated sunlight. These cells are built into concentrating collectors that use a lens to focus the sunlight onto the cells. The main idea is to use very little of the expensive semiconducting PV material while collecting as much sunlight as possible. Efficiencies are in the range of 20 to 30%.

Concentrated photovoltaic module

- Flexible cells: Based on a similar production process to thin film cells, when the active material is deposited in a thin plastic, the cell can be flexible. This opens the range of applications, especially for building integration (roofs-tiles) and end-consumer applications.

4.7. Advantages

The 89.000 TW of sunlight reaching the Earth's surface is plentiful – almost 6000 times more than the 15 TW equivalent of average power consumed by humans. Additionally, solar electric generation has the highest power density (global mean of 170 W/m^2) among renewable energies.

Solar power is pollution-free during use and the importance of using clean energy alternatives instead of fuel consuming generators is obvious. Furthermore, by burning no fuel and having no moving parts, PV systems are clean and silent. Also, most photovoltaic cells are made from silicon, and silicon is an abundant and nontoxic element (the second most abundant material in the earth's mass).

PV Modules can be recycled and therefore the materials used in the production process (silicon, glass, aluminium, etc.) can be reused. Recycling is not only beneficial for the environment but also for helping to reduce the energy needed to produce those materials and therefore the cost of fabrication.

PV cells were originally developed for use in space, where repair is extremely expensive, if not impossible. PV still powers nearly every satellite circling the earth because it operates reliably for long periods of time with virtually no maintenance. In general, PV installations have no moving parts and they can operate for many years with little maintenance or intervention after their initial set-up, so after the initial capital cost of building any solar power plant, operating costs are extremely low compared to existing power technologies. The estimated lifetime of a PV module is 30 years and the modules' performance is very high providing over 80% of the initial power after 25 years which makes photovoltaics a very reliable technology in the long term. Furthermore, the energy payback time of a module is constantly decreasing. This means that the time required for a PV module to produce as much energy as it needs to be manufactured is very short, it varies between 1,5 years to 3 years. A module therefore produces 6 to 18 times more energy than is needed to manufacture it. Therefore, PV systems are low-maintenance and cost-effective solutions, ideal for supplying power to communications stations on mountain tops, navigational buoys at sea, or homes far from utility power lines.

In terms of aesthetics, photovoltaics can be easily integrated in buildings. Systems can cover roofs and facades contributing to reduce the energy buildings consume. They don't produce noise and can be integrated in very aesthetic ways. European building legislations have been and are being reviewed to make renewable energies as a required energy source in public and residential buildings. This fact is accelerating the development of ecobuildings and positive energy buildings (E+ Buildings) which opens up many opportunities for a better integration of PV systems in the built environment.

Moreover, as of 2011, the price of PV modules per MW has fallen by 60 percent since the summer of 2008, according to Bloomberg New Energy Finance estimates, while technological improvements suggest that they will get even cheaper and more attractive in the next few years. So, as time progresses and fossil fuels get more expensive, solar and other renewable energy technologies are becoming strong competitors, posing a growing threat to the dominance of conventional power sources in the next few years.

The room for improvement in the development of solar cells is fairly considerable, while the research money invested on them are very little compared to fossil and nuclear energy sources. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% in case of concentrating photovoltaic cells and efficiencies are rapidly rising while mass-production costs are rapidly falling.

4.8. Disadvantages

Solar electricity is usually intermittent, because it is not produced at night and is greatly reduced in cloudy conditions requiring alternate sources of power. While many buildings with photovoltaic arrays are tied into the power grid which absorbs any excess electricity generated throughout the day and provides electricity in the evening, such systems use a grid tie inverter to convert direct current (DC) to alternating current (AC) incurring an energy loss of about 4 to 12 percent. Off-grid systems use either storage batteries or diesel generators, with the former incurring significant energy losses and requiring regular maintenance and the latter consuming costly and pollutant fuel.

Despite the significant drop in the PV modules’ price, solar electricity is more expensive than most other forms of small-scale alternative energy production. Without governments mandating "feed-in tariffs" for green solar energy, solar PV is less affordable to homeowners than solar hot water or solar space heating.

PART II
ANALYSIS OF THE HYBRID SYSTEM CASE STUDY

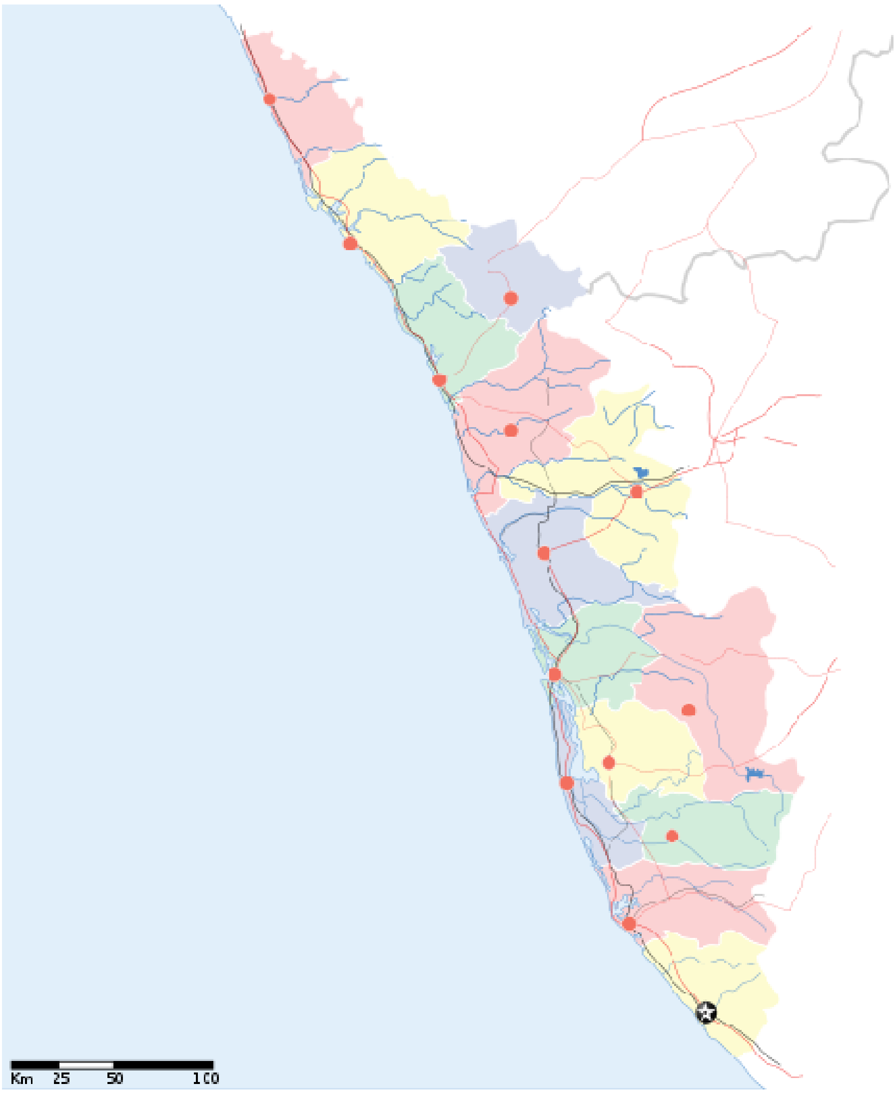
CHAPTER A: METHODOLOGY

A.1 Case study

This diploma thesis deals with a stand-alone hybrid system that contains solar photovoltaic, wind energy, micro-hydro, diesel generators and batteries. The main objective is to find all the combinations of these components that provide reliable electrification to a remote community.

The data that the algorithm will use in order to find the acceptable combinations belong to a typical farming village of Western Ghats in Kerala, India. Western Ghats is a mountain range along the western side of India, which runs approximately 1600 km through the states of Maharashtra, Goa, Karnataka, Tamil Nadu and Kerala ending at Kanyakumari, at the southern tip of India. Kerala is an Indian state located on the Malabar coast of south-west India.

Location of Kerala in India



Map of Kerala

The data is retrieved from S. Ashok's paper: 'Optimised model for community-based hybrid energy system'. According to it: "This village is around 110 km away from the nearest local town. The mode of transportation is limited to jeeps (that too to certain areas only) and distance to the existing grid line is around 15 km. The hilly terrain and the nature of landscape make it expensive and complex to extend the grid. The village has 120 families with a population of over 600. A 6.25 kVA community-based diesel generator (DG) unit supplies power to about 35% of the population. DG set operates six hours a day during peak hours. During emergencies and festival seasons, the DG operation is extended to remaining hours of the day. Individuals for their typical household applications own other small units of diesel generators of ratings 1kVA and less. About 40% of the population is deprived of electricity. The principal demand of electricity is for lighting and radio. The electrical appliances in the village include 11 and 20W compact fluorescent lamps, 60W fan and 35W radio set."

In order to face the electricity problem, different ways of electrification, instead of diesel generators, must be examined. As mentioned above, grid extension is a hardly feasible and not at all economical solution. According to estimations, the cost of electricity in that case would be Rs. 7,11/kWh=0,107€/kWh[1]. So a way must be found to supply the necessary power to elevate the living standards of the people without access to the electricity grid. That can be done by harnessing the abundant energy available in nature and converting it to electricity, guaranteeing 24h, reliable and less expensive supply to the village.

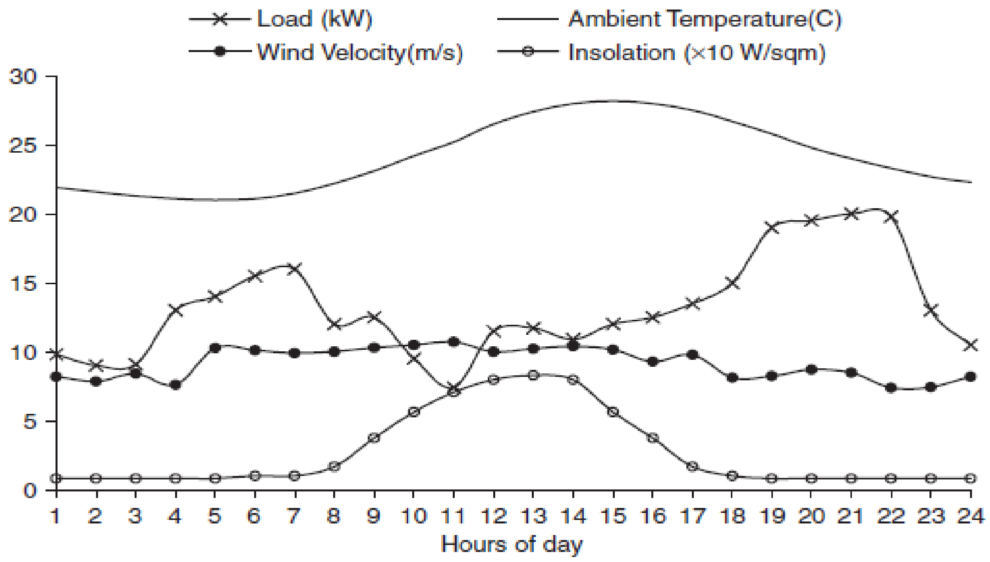
According to the data, it is estimated that there exists potential for utilizing renewable energy sources like several water streams flowing down hills, wind and solar energy. Therefore, at first sight, it seems an appropriate location for the discussed hybrid system to be placed. Because of the fact that it combines more than one renewable energy technologies along with batteries for energy storage and diesel generators for back-up, a balanced and stable output is ensured.

It should be made clear, that this thesis only uses the numerical data available for this region in order to work out the optimal combinations. Other factors, like land-planning, space requirements, social impacts etc. are not taken into consideration and they need a completely different approach that would demand knowing details on the location and making on-site studies.

A.2 Hourly load profile and renewable energy data of the village

The next diagram shows the average hourly load profile of the village for the typical day, as well as the variations of ambient temperature (^{o}C), wind velocity (m/s) and insolation (*10 W/m^{2}).

Note that the curves are shown as continuous plots. Therefore, the power curves that will result from them will also be shown as continuous plots. If the hourly data was assumed to be discontinuous (constant during each hour), then all of the power curves would be stair case plots.



Using a digitizing program, like WinDig, that converts hard copy graphs to data, we are able to determine the values of these diagrams as follows:

Hours of day	Insolation	Wind velocity	P_{load}	Ambient Temperature
1	0	8,25	9,9	22,05
2	0	7,8	9	21,6
3	0	8,4	9,15	21,3
4	0	7,65	13,05	21,15
5	0	10,2	14,1	21,15
6	10,5	10,05	15,6	21,15
7	10,5	9,9	16,05	21,45
8	18	10,05	12	22,2
9	37,5	10,35	12,6	23,1
10	57	10,5	9,45	24,15
11	70,5	10,65	7,5	25,2
12	81	10,05	11,4	26,55
13	84	10,35	11,7	27,3
14	81	10,5	10,95	27,9
15	55,5	10,2	12	28,2
16	37,5	9,3	12,45	28,05
17	16,5	9,9	13,5	27,45
18	10,5	8,1	15	26,7
19	0	8,25	19,05	25,8
20	0	8,7	19,5	24,75
21	0	8,55	20,1	24
22	0	7,35	19,8	23,25
23	0	7,5	13,05	22,65
24	0	8,25	10,5	22,35

The micro-hydro scheme is supposed to have a stable water flow Q=35 l/s with head H=45m.

A.3 Size of the system components and cost parameters

Locally available standard micro-hydro, wind and solar PV units suitable to the resource measurements are selected for unit sizing for the benefit of service and maintenance. 15kW, 3 Phase Kaplan-Induction-type micro-hydro turbo units, 5kW 3 Phase AEP 5000 asynchronous wind units, 120WBP Solar 33 V, 3.56A PV units, 5 kW 3 Phase DG sets and 360 AH, 6V battery units are used for calculation [1].

- *Wind turbines model(5kW 3 Phase AEP 5000 asynchronous wind units):*

  The appropriate output of wind turbines depends on the wind speed at the location of wind turbines, air density, swept area of rotor and efficiency related to energy conversion from wind energy to electrical energy. In this simulation, mathematical model of each wind turbine is designed to convert hourly wind speed to be electrical power using following equation:

$$P_w(t) = 0{,}5 * n_t * n_g * \rho_\alpha * C_p * A * V_r^3(t)$$

Where:

$V_r(t)$=*wind velocity (m/s)*
ρ_α=*air density (kg/m^3)*
C_p=*power coefficient of wind turbine*
A=*wind turbine rotor swept area (m^2)*
n_t=*wind turbine efficiency*
n_g=*generator efficiency.*

- *Photovoltaic model(120W BP Solar 33 V, 3.56A PV units):*

  The output power from PV panels is influenced by insolation. In order to simplify the calculations, in this simulation the hourly power produced by each PV module is based on the hourly insolation and the panel's efficiency according to the following equation:

$$Ppv(t) = n * A_p * Ins(t)$$

Where:

n=*energy conversion coefficient (%)*
Ap=*Area of a single PV panel (m^2)*
$Ins(t)$=*Insolation (W/m^2).*

- *Micro-hydro turbines (15kW, 3 Phase Kaplan-Induction-type micro-hydro turbo units):*

  The hourly electrical power generated by the micro-hydro unit is calculated as follows:

$$P_h(t) = n_h * \rho_{water} * g * H_{net} * Q(t)$$

Where:

n_h=hydro efficiency
ρ_{water}=density of water (kg/m^3)
g=acceleration due to gravity (m/s^2)
H_{net}=effective head(m), Q(t)=flow rate (l/s).

- *Battery model (360 AH, 6V battery units):*

  The power generated by micro-hydro, wind turbines and PV panels and delivered to the load, at any hour t, can be expressed by the following equation:

$$P_{genfinal}(t) = N_h * P_h(t) + [N_w * P_w(t) + N_{pv} * P_{pv}(t)] * n_i$$

Where: n_i=efficiency of AC/DC inverter.

Power from batteries is required whenever the power generated ($P_{genfinal}$) is unable to supply the load demand. On the other hand, the power is stored whenever the supply from renewable energy units exceeds the load demand. At each hour the state of charge of batteries is related to the previous state of charge, the energy production and consumption situation of the system during the time from t-1 to t. Two cases are considered in expressing the energy stored in the batteries at hour t.

Case 1: During charging process, the available batteries capacity at hour t can be described by the following equation:

$$P_b(t) = P_b(t-1) \cdot (1-\sigma) + (P_{gen}(t) - P_{load}(t) / n_i) \cdot n_b$$

Case 2: During discharging process, the available batteries capacity at hour t can be expressed as follow:

$$P_b(t) = P_b(t-1) \cdot (1-\sigma) - (P_{load}(t) - P_{gen}(t) / n_i)$$

Where:

$P_b(t)$, $P_b(t\text{-}1)$ are the available capacity of battery banks at hour t and at previous time t-1, respectively. The term σ is the self-discharge rate of the battery banks, in study it is assumed 0,002. The terms n_i, n_b are the inverter efficiency and battery efficiency, respectively.

Some constraints must be considered under battery banks operation. The value of $P_b(t)$ cannot be lower than minimum allowed energy level remained in battery banks (P_{bmin}), and it cannot be higher than maximum allowable energy level (P_{bmax}) during charging operation. These constraints mean that the battery banks should not be discharged or charged over their limit operation points in order to protect the battery banks against damage and to prolong their life time operation. Mathematically, the constraint of the batteries operation can be expressed as follows:

$$P_{b\min} \le P_b(t) \le P_{b\max}$$

The value of P_{bmin} is determined by the maximum permissible depth of discharge (DOD):

$$P_{b\min} = (1 - DOD) * P_{b\max}$$

In this study, the value of maximum DOD is 80% so that the minimum energy level of the battery banks is 20% of P_{bmax}. P_{bmax} can be considered as the nominal storage capacity:

$$C_{batn} = 6 * 360 / 1000 = 2,16kW$$

- *Diesel generators (5 kW 3 Phase DG sets):*

Diesel generators are operated, when necessary, to meet the load demand and the fuel consumption of DG unit is related to the rated power and its generated power. The hourly fuel consumption (in liters/hour) is calculated as follows:

$$F(t) = (0,246 * P_d(t) + 0,08415 * P_{drated})$$

Where:

$P_d(t)$=Power generated by diesel generators at hour t (kW), $P_{drated}(t)$= Rated power of diesel generators (kW).

From this equation, the rated power and the power generated influence the fuel consumption of DGs. Therefore, in order for the DG to reach the maximum efficiency of operation, the unit should be operated within rated power and specified minimum value. The operating condition must be in the range of:

$$P_{d\min} \le P_d(t) \le P_{d\max}$$

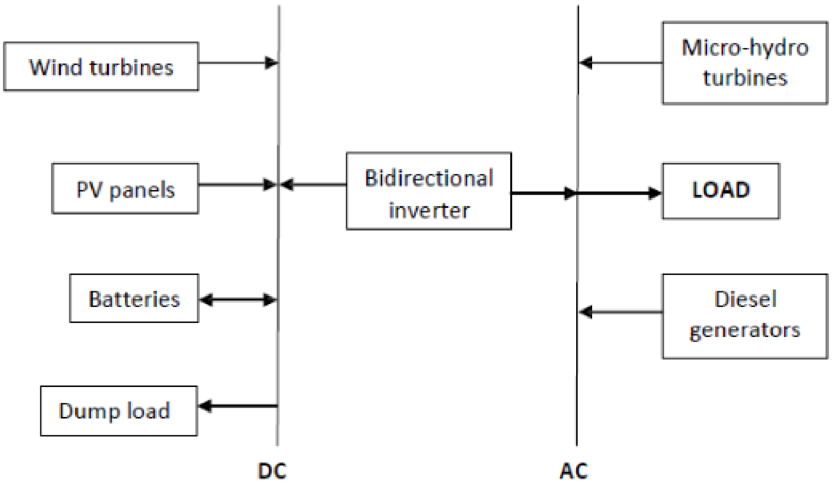
Usually, the manufacturer of the DGs gives the recommendation to set the minimum point of diesel operation, as well as suggestions for a better operation technique. On the other hand, the maximum efficiency of DGs corresponds to their rated power.

❖ Cost parameters:

The annual cost of the proposed hybrid energy system is computed based on capital and operating costs of different energy components. The capital costs of micro-hydro, wind, solar PV, DG units and batteries are Rs. 90/W=1,35€/W, Rs. 125/W=1,88€/W, Rs. 200/W=3,01€/W, Rs. 15/W=0,22€/W and 500€/battery, respectively. The operating costs of micro-hydro, wind, solar PV and batteries are Rs. 0,15/kWh=0,0022€/kWh, Rs.0,1/kWh=0,0015€/kWh, Rs.0,05/kWh=0,0007€/kWh and 0,2€/kWh , respectively. The operating cost of DG units includes fuel cost (Rs. 24/l=0,36€/l) and operation and maintenance cost of Rs. 0,2/kWh=0,003€/kWh. The project lifetime is taken as 20 years with 15% interest rate [1].

A.4 Hybrid system configuration

The hybrid micro-hydro/wind/solar power generation system consists of hydro turbines, wind turbines, PV panels, battery banks as energy storage, an inverter and cables, as shown in the next figure. The diesel generators are connected at AC bus so that they can directly supply the load demand without any converter unit.



When the power from renewable energy sources cannot meet the load demand, power from the batteries will be used. If the power generated from the renewable energy units is not able to satisfy the load and the battery storage is depleted, the diesel back-up system will be operated. The existence of battery storage and its priority in use (the DGs are used when the batteries are fully discharged) results in a significant lessening of the diesel generators' start/stop cycles (frequent start ups/stops promote wear and increase CO_2 emissions). Hence it can be inferred that with increasing the number of days of battery storage, the non-operating months of the diesel system increase.

Furthermore, despite increasing the complexity and the cost of the system, the batteries provide storage of the surplus energy, whenever the generated energy exceeds the load. When the batteries are fully charged and the generated energy still exceeds the load, the excess generation is dumped to an external voltage-controlled resistive load. The purpose of incorporating a dumped load into the system is to preserve the stability of the system frequency and voltage. If the excess energy cannot be dissipated usefully (for example in water pumping or space heating), then it must be disposed as heat by a controlled resistor.

A.5 Acceptable combinations

The hybrid energy system integrates various combinations of renewable energy units, applicable depending on availability. The target of the algorithm, which is a FORTRAN code, is to determine the combinations of renewable energy units, which provide energy balance between the generation and the demand. The number of batteries and the capacity of the diesel generators will be later calculated, so that 24h electrification is assured.

Depending on the criterion that we chose or a trade-off between more of them (minimum cost, minimum use of diesel generators, etc.) we can define the most appropriate one among these different combinations.

CHAPTER B: DETAILED ALGORITHM DESCRIPTION

B.1 Table dimensioning, files opening, explanatory text, input reading

The input data that the program will use to make the needed calculations are the wind velocity, the insolation, the load demand and the water flow for each hour during the day. Therefore the tables V(24), aI(24), aLoad(24), Q(24) respectively, are dimensioned to store these values. Caution was taken so that the names of the tables begin with letters that allow storage of real numbers.

The code will use three text files, one that contains the input data, one in which the results will be presented and another one which will have the same results in a different format, facilitating the procedure of making diagrams later. The first one is “input.txt” and is referred to with the number 1, the second one is “RESULTS.txt” and is referred to with the number 5 and the third one is “OUTPUT.txt” and is referred to with the number 10.

After the opening of these files, the code contains some commands so that this explanatory text appears in the beginning of file 5:

Pht = total power generated from hydro units(kW)
Pwt = total power generated from wind units(kW)(inverter losses are included)
Ppvt = total power generated from solar units(kW)(inverter losses are included)
Pgenfinal = total power generated from all renewable energy units(kW)(inverter losses are included)
Pbatgen = power generated by the batteries(inverter losses are included)
Pd = total power generated from DGs(kW)
Fuel = liters of fuel consumed by DGs
Dumped = Total power dumped(kW)

With a simple do command (for each hour of the day, which means from n=1 to n=24), all the input values are stored in the corresponding tables.

B.2 Setting of the parameters

According to the given facts, the parameters of the units are defined. The following tables include the value that was given to each parameter.

- Micro-hydro unit parameters:

Density of the water (kg/m^3)	1000.0
Gravity (m/s^2)	9.81
Head of the micro-hydro scheme (m)	45.0
Efficiency of the hydro turbine	0.83
Rated power (kW) of the hydro turbine	15.0

- Wind unit parameters:

Efficiency of the wind turbine	0.98
Generator efficiency	0.98
Air density (kg/m^3)	1.22521
Wind wheel diameter (m) (d)	5.0
Swept area (m^2)	$\pi*d^2/4$
Power coefficient of wind turbine	0.4
Rated power (kW) of the wind unit	5.0

- PV unit parameters:

Efficiency of a PV module	0.15
Area of a single PV panel (m^2)	14.5542*7.3152
Rated power (kW) of the PV unit	0.12

- Battery unit parameters:

Self-discharge factor	0.002
Battery charging efficiency	0.98
Maximum depth of discharge (DOD)	0.8
Maximum power of the battery (kW) (P_{bmax})	6.0*360.0/1000.0
Minimum power of the battery (kW) (P_{bmin})	(1.0-DOD)*P_{bmax}

- Inverter parameters:

Inverter efficiency	0.98

- Diesel generator parameters:

Rated power of the diesel generator (kW)	P_{drated}	5.0

- Cost parameters:

Interest rate (i)	0.15
Project lifetime (years) (N)	20.0
Capital Recovery Factor	$(i*(1+i)^N)/((1+i)^N-1)$
Capital cost of micro-hydro units (€)	1355.4*Phrated
Capital cost of wind units (€)	1882.5*Pwrated
Capital cost of PV units (€)	3012*Ppvrated
Capital cost of battery (€)	500
Capital cost of DG units (€)	225.9*Pdrated
Operational costs of micro-hydro units (€/kWh)	0.0026
Operational costs of wind units (€/kWh)	0.001506
Operational costs of PV units (€/kWh)	0.000753
Operational costs of batteries (€/kWh)	0.2
Operational costs of DG units (€/kWh)	0.003
Fuel cost (€/l)	0.36

Note: The part of the cost calculations is explained later, in the section 'Rest of calculations'.

B.3 Initialization

The combination number indicator and the number of micro-hydro, wind and PV units are initialized: icombination=0, N_h=0, N_w=0, N_{pv}=0. So do the values, which represent the total power generated by each unit per day: $P_{unittotalh}$=0.0, $P_{unittotalw}$=0.0, $P_{unittotalpv}$=0.0.

B.4 Finding the acceptable combinations

The condition for a combination to be acceptable, is that generation and load balance over the period of one day. That means that the curve of ΔP versus time, where ΔP is the difference between the generated power that serves the demand and the load, must have an average of zero or more over the day. Note that positive values of ΔP indicate the availability of generation and negative ΔP indicates generation deficiency.

The procedure to determine all the acceptable combinations is as follows:

1) The power produced by each renewable energy unit for each hour during the day is calculated (in kW), using the formulas described in paragraph A.3. There is a condition that tests if the calculated power of each unit exceeds the rated one. If so, the generated power becomes equal to the rated one, which is the maximum power that can be generated. The results are stored in the corresponding tables. The values $P_{unittotalh}$, $P_{unittotalw}$, $P_{unittotalpv}$ are the sum of the 24 values of generated power of each micro-hydro, wind and PV unit, respectively.
2) The next iterative procedure calculates the total generated power from renewable energy units (P_{gen}), the total power that is delivered to the load ($P_{genfinal}=n_i*P_{gen}$) and the difference $\Delta P= P_{genfinal}-P_{load}$ for each hour. The variable "sum" is used to represent the sum of the 24 values of ΔP (See Fig.1):

$$sum = \sum_{t=1}^{24} \Delta P(t)$$

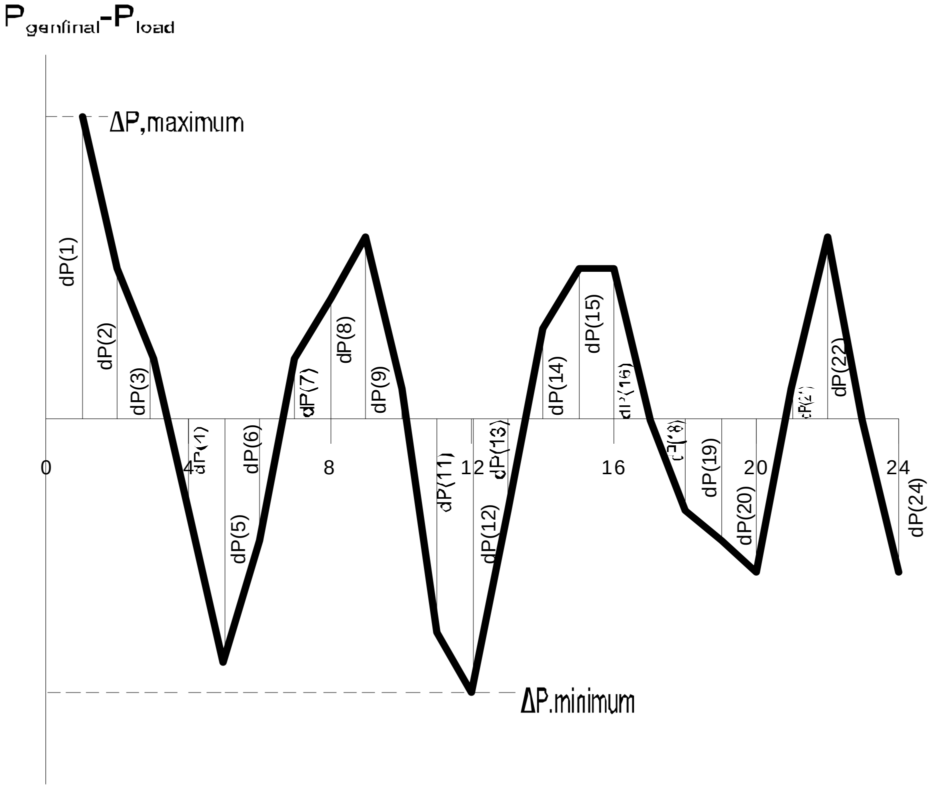


Fig.1: Example of ΔP versus time

3) If sum is less than zero then the combination is not acceptable, as it can’t meet the load demand. Therefore the number of renewable energy units must be increased. Since the energy density of the micro-hydro and wind, far exceeds that of a single solar PV module, the number of wind turbines and micro-hydro are fixed at each iteration of the procedure and the number of PV modules is incremented until the system is balanced.
4) Once sum turns greater than zero, it means that the combination produces more power than the load demand. This is the condition that needs to be fulfilled in order for the combination to be acceptable. The number of the combination (icombination) increases by 1 and it now represents the number of this combination.
5) After all the needed calculations (mentioned in paragraph B.5 Rest of calculations) are made, the condition that checks if the number of the PV units is not zero takes place. If N_{pv} is not zero, the number of the wind turbines increases by one, the number of PV is initialized at zero and the previous steps are repeated to find the next combination that guarantees balance between the generation and the load.
6) When there is a combination with no PV units, step 5 is skipped and the last condition takes place. This condition leads to either continuation of the procedure or to the end of the program. The condition consists of two arguments: if the number of micro-hydro units is zero **OR** the number of wind units is not zero. If one or both of them are true, then the number of micro-hydro units increases by one, the numbers of wind and PV units are initialized at zero and all the previous steps are repeated for the new combination.
7) When the last condition is not true, step 6 is skipped and that means that all the acceptable combinations are found and all the needed calculations are made. The program ends.

The form, which the acceptable combinations should have, is the following one:

- ✓ **N_h=0:**

  N_h=0, N_w=0, N_{pv}=a
  N_h=0, N_w=1, N_{pv}=b
  N_h=0, N_w=2, N_{pv}=c
  N_w=N_w+1 until: N_h=0, N_w=d, N_{pv}=0

- ✓ **N_h=1:**

  N_h=1, N_w=0, N_{pv}=e
  N_h=1, N_w=1, N_{pv}=f
  N_h=1, N_w=2, N_{pv}=g
  N_w=N_w+1 until: N_h=1, N_w=h, N_{pv}=0

- ✓ **N_h=2:**

  N_h=2, N_w=0, N_{pv}=j
  N_h=2, N_w=1, N_{pv}=k
  N_w=N_w+1 until: N_h=2, N_w=l, N_{pv}=0

- ✓ **N_h=N_h+1** until: N_h=m, N_w=0, N_{pv}=0

B.5 Rest of calculations

When a combination with specific N_h, N_w, N_{pv} numbers is considered as an acceptable one, all the rest values are calculated based on these numbers. That means that the numbers of renewable energy units are fixed for the rest of the calculations (until they change in order to find the next acceptable combinations). The numbers of batteries and the power needed to be provided by the DGs are calculated so that they fit the storage and extra power needs of a specific combination, so that 24h coverage of the load demand is met.

<u>Number of batteries:</u>

From the ΔP versus time diagram the values of the maximum power difference and the minimum one are determined. The difference between them is the required storage capacity for the hybrid system. It is so, because we need to determine how large our "power storage" should be in order to include both the maximum power that will be stored and the maximum power that will be retrieved from the batteries.

The number of batteries required for the needed storage capacity can be found as follows:

Required Storage Capacity= ΔP,maximum-ΔP,minimum

Number of batteries=Required Storage Capacity/(DOD*rated capacity of each battery)

The term DOD*rated capacity of each battery indicates the difference between the maximum power (P_{rated}) and the minimum one ((1-DOD)*P_{rated}) of the battery, so it is actually the available power that a battery can supply.

Note: If the number of batteries has decimal digits, it will become equal to the next integer.

In the code, the Required Storage Capacity is represented by the variable 'capacity', while ΔP,maximum and ΔP,minimum by 'dpmax' and 'dpmin'. $P_{batteriesmax}$ represents the maximum power of all the batteries ($P_{batteriesmax} = N_b * P_{bmax}$) and $P_{batteriesmin}$ represents the minimum one ($P_{batteriesmin} = N_b * P_{bmin}$).

Power flow scenario and charging/discharging process of the hybrid system:

P_{bo} is the power level of the batteries at t=0 (when the batteries are considered fully charged: $P_{bo}=P_{bmax}$) and $P_{batterieso}$ is the total power of the batteries at t=0 ($P_{batterieso}=N_b * P_{bo}$).

The values that represent the total power supplied by the diesel generators, the total dumped power per day and the maximum hourly power generated from the DGs are initialized before the charging/discharging process: $P_{unittotald}$=0, totaldump=0 and d_{max}=0, respectively.

As said before, the power from the renewable sources through the inverter is hourly measured as follows: $P_{genfinal}(t) = n_i * P_{gen}(t)$

Principles of charging and discharging scenarios are dependent on the state of $P_{genfinal}(t)$ and the load power demand at hour t.

- If ΔP<0, the batteries are discharged to cover the gap between the generation and the demand. The power level of the batteries is now:

$$P_b(t) = P_b(t-1)\cdot(1-\sigma) - (P_{load}(t) - P_{gen}(t)/n_i)$$

If they reach the minimum power level, they stop discharging ($P_b(t) = P_{batteries\min}$) and the diesel generators supply the remaining power needed:

$$P_d(t) = P_{load}(t) - P_{genfinal}(t) - (P_{batteries0} * (1-\sigma) - P_{batteries\min}) * n_i$$

If not, the DGs don't need to work: $P_d(t)=0$

No power is dumped, of course.

- If ΔP>0, the batteries are charged. The power level of the batteries is determined:

$$P_b(t) = P_b(t-1) \cdot (1-\sigma) + (P_{gen}(t) - P_{load}(t) / n_i) \cdot n_b$$

If they reach their rated capacity ($P_b(t) = P_{batteries\max}$), the rest of the power generated by the renewable energy units is dumped:

$$Dump(t) = P_b(t) - P_{batteries\max}(t) .$$

If not, no power needs to be dumped: Dump(t)=0

Diesel generators produce no energy and no fuel is consumed.

One oddity of this part of the algorithm is that the calculations for the first hour (t=1) are made separate from the rest (t=2 to t=24). The reason is that, in order to calculate the power of the batteries at hour t, the previous one (at hour t-1) is needed. While $P_b(t)$ is calculated based on the previous one ($P_b(t-1)$) for t=2 to 24, $P_b(1)$ is based on $P_{batteries0}$:

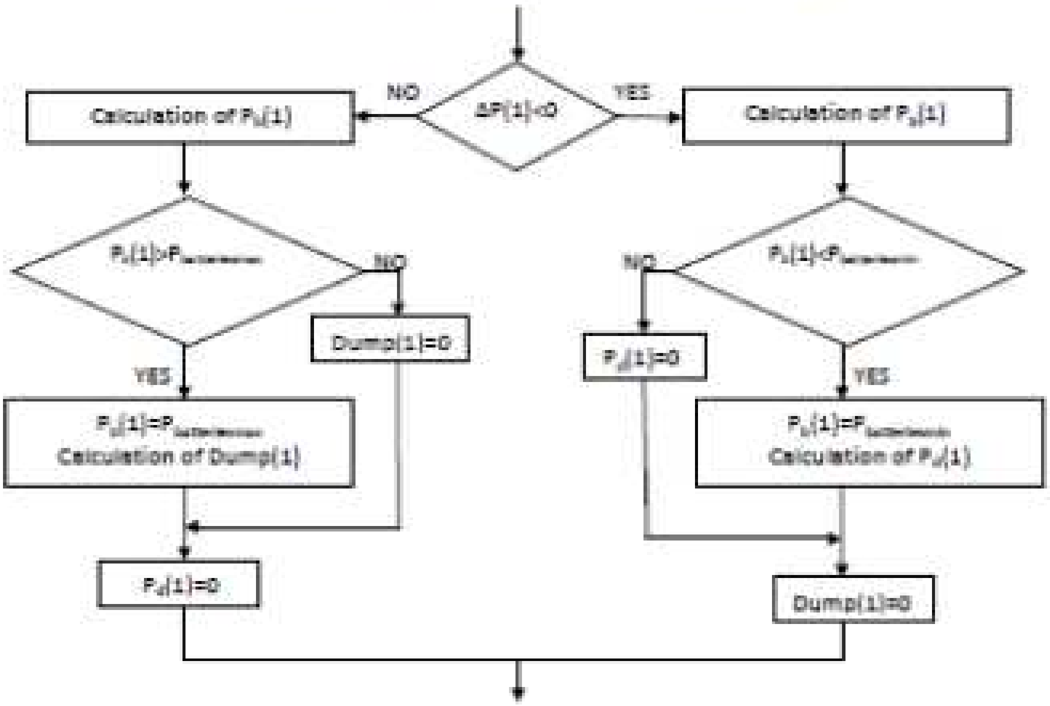
- If ΔP<0:

$$P_b(1) = P_{batteries0} * (1-\sigma) - (P_{load}(1) / n_i - P_{gen}(1))$$

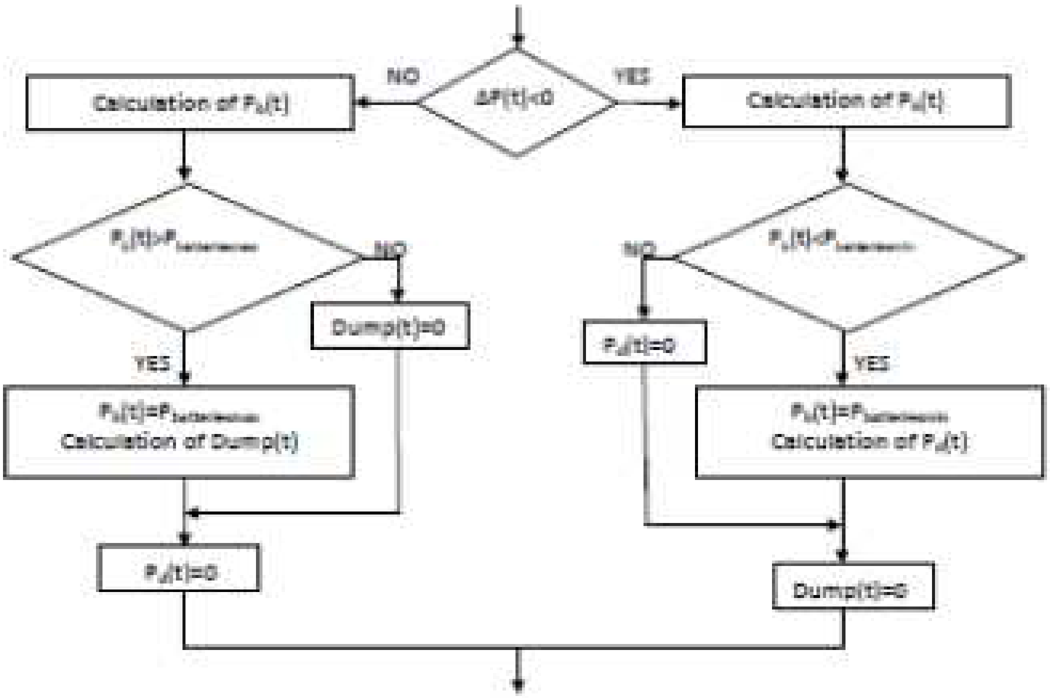
- If ΔP>0:

$$P_b(1) = P_{batteries0} * (1-\sigma) + n_b(P_{gen}(1) - P_{load}(1) / n_i)$$

BATTERIES CHARGING/DISCHARGING FLOWCHART:



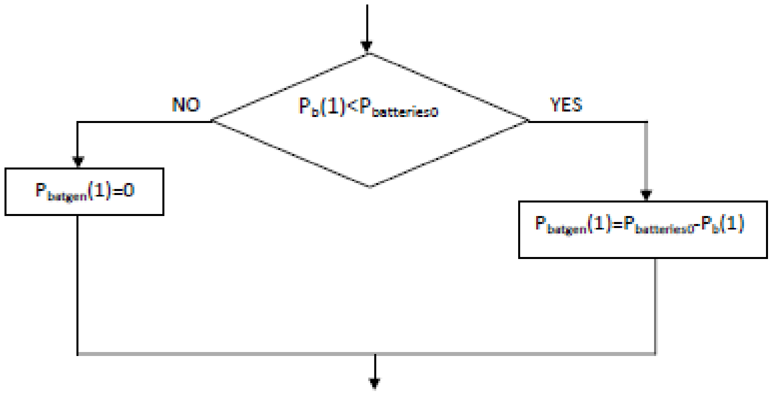
For the rest hours of the day:



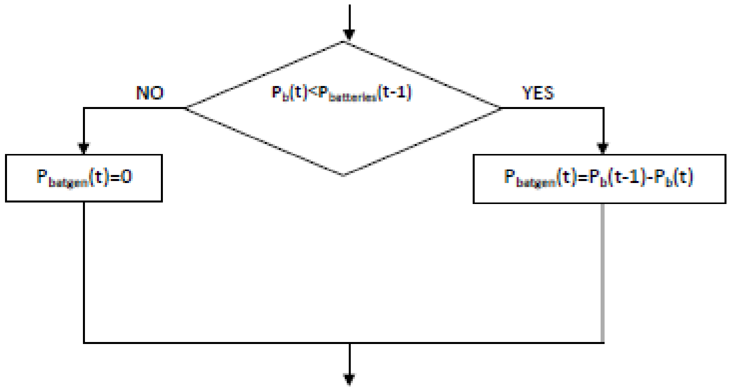
Afterwards, with a simple do command (again from t=2 to 24, because the calculation for t=1 is separate), the power that the batteries generate is calculated and stored in the table $P_{batgen}(24)$:

- If $P_b(1)<P_{batteries0}$, then $P_{batgen}(1)=P_{batteries0}-P_b(1)$.
  If not, then $P_{batgen}(1)=0$
- If $P_b(t)<P_b(t-1)$, t=2,...,24, then
  $P_{batgen}(t)=P_b(t-1)-P_b(t)$.
  If not, then $P_{batgen}(t)=0$

POWER GENERATED FROM BATTERIES CALCULATION FLOWCHART:



For the rest hours of the day:



The results of these iterations are stored in the corresponding tables. The highest hourly power supplied by the DGs ('d_{max}' value), the daily dumped power ('totaldump' value) and the daily power from the DGs ('$P_{unittotald}$' value) are determined.

Number of DGs calculation:

Diesel generators are installed to take action when both the renewable energy units and the batteries cannot meet the demand. This happens because the number of batteries is limited and in some hours (that the batteries are fully charged and the generated power exceeds the load demand) power is dumped.

In our case, that we consider fully charged batteries in the beginning, if the generated power exceeds the load in the first hours of the day, it will all be dumped. Only when the batteries are discharged, will we be able to store energy. This can be shown in the next diagram:

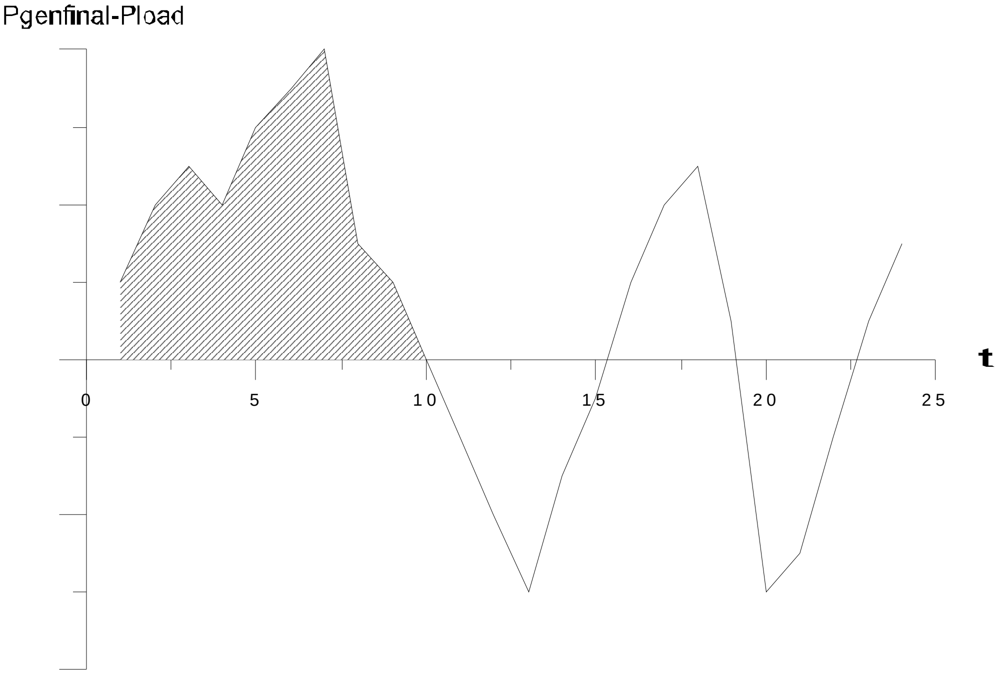


Figure 2: Dumped power

The area with the hatch represents the energy that will be dumped for sure, while the batteries cannot store anymore power.

If the batteries were so many that no power needed to be dumped, then the condition that checks if a combination is acceptable ($sum = \sum_{t=1}^{24} \Delta P(t) > 0$) would mean that there is no need for DGs, because the exceeding generated power (that is stored in the batteries) is larger than the deficient power (which will be supplied by the batteries). This can be seen in the next figure:

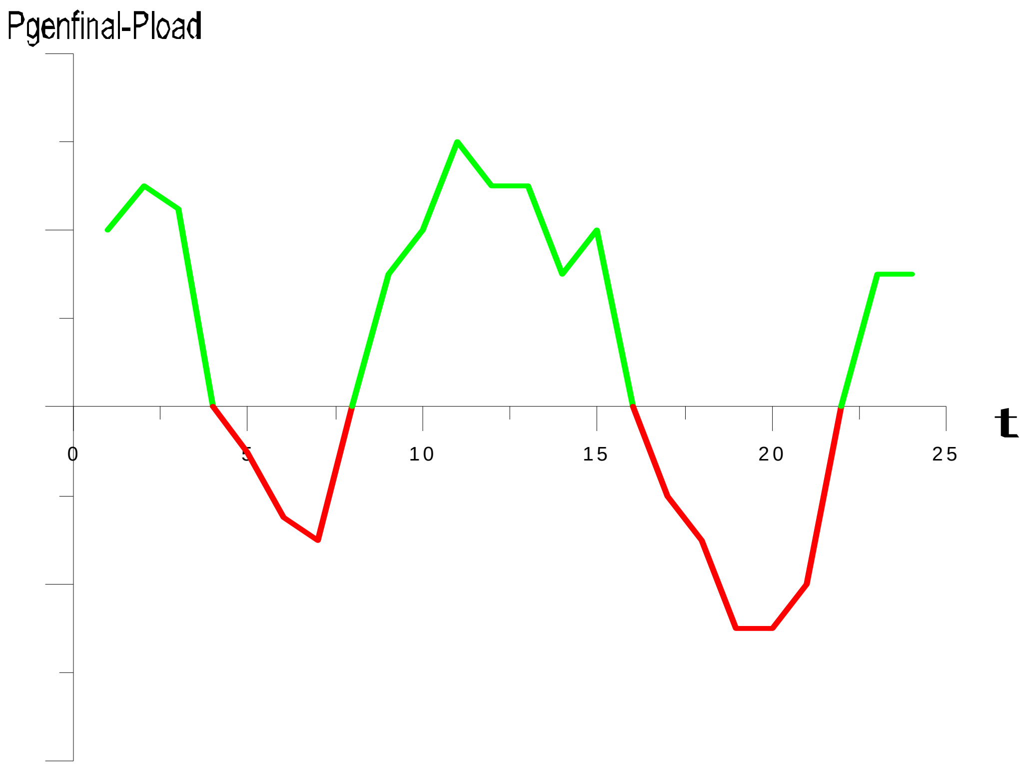


Figure 3: No dumped power

This diagram depicts an example of an acceptable combination. Once the storage we have is enough, all the surplus power (green line) is stored. Therefore, it can be used to cover the power shortage (red line) just by itself, without any need for diesel generators.

Of course this would mean that significantly more batteries should be installed, something that would elevate the cost of the hybrid system.

The number of DGs required is found as follows:

$$N_d = \frac{d_{\max}}{P_{drated}}$$

We consider that the diesel generators cannot generate more power than the rated one, so we define how many of them are needed to cover the peak demand for diesel power.

Note: If the number of DGs has decimal digits, it will become equal to the next integer.

Fuel consumption calculation:

The fuel consumption is calculated for each hour that the diesel generators are working:

$Fuel(t) = 0,246 * P_d(t) + N_d * 0,08415 * P_{drated}, t = 1, 2, ..., 24$

Furthermore, the total fuel consumed per day ('Fueltotal' value).

*Note: This is the equation that displays the fuel consumption of all the DGs at each hour that they operate. The fuel consumption for each DG is: 0,246*P_d+0,08415*P_{drated}, where P_d is the power generated by the diesel unit and P_{drated} is its rated power.*

Cost calculation:

The total annual cost (TC) of the system is composed of annual capital cost (ACC_{total}) and annual operational cost (AOC):

$$TC = ACC_{total} + AOC$$

- Calculation of Annual Capital Cost (ACC_{total}):

ACC_{total} consists of the annual capital costs of the units that do not need replacement during the project lifetime (renewable energy, DG units, batteries). The annual capital cost of each unit can be calculated as follows:

$$ACC = CC * CRF$$

Where: CC=Capital cost of each component, which is the rated power (kW) multiplied by the capital cost per kW. According to our facts the capital costs are calculated (in €) as follows:

$$CC_h = 1355,4 * P_{hrated}$$
$$CC_w = 1882,5 * P_{wrated}$$
$$CC_{pv} = 3012 * P_{pvrated}$$
$$CC_d = 225,9 * P_{drated}$$
$$CC_b = 500$$

CRF=Capital Recovery Factor, a ratio to calculate the present value of a series of equal cash flows. It can be calculated as follows:

$$CRF = \frac{i*(1+i)^N}{(1+i)^N - 1}$$

Where: i=interest rate=15%, N=Project lifetime=20 years

So, the annual capital cost of the hybrid system is:

$$ACC_{total} = (CC_h * N_h + CC_w * N_w + CC_{pv} * N_{pv} + CC_d * N_d + CC_b * N_b) * CRF$$

- Calculation of annual operational cost (AOC):

  AOC is the sum of the daily operational costs (DOC) throughout a year:

$$AOC = \sum_{d=1}^{365} DOC(d)$$

Our case study is based on one average day of the year, which is supposed to be repeated. Thus, the AOC is:

$$AOC = 365 * DOC$$

The daily operational cost (DOC) consists of the daily operational costs of the renewable energy units, the batteries and the diesel generators. Each one of them is calculated by multiplying the generated power with the operational cost per kWh.

So the DOC is calculated as follows:

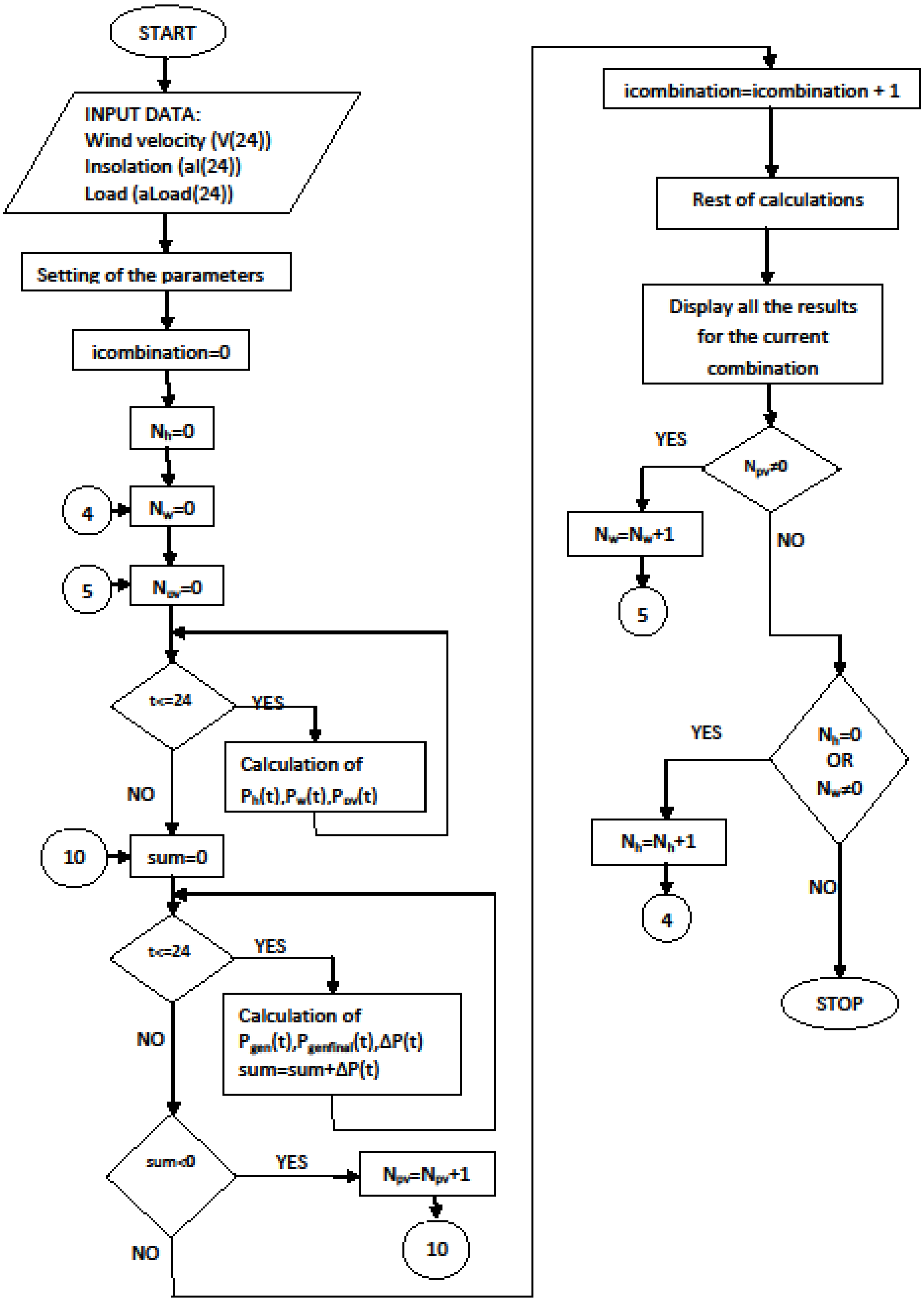
$$DOC = OC_h * N_h * P_{unittotalh} + OC_w * N_w * P_{unittotalw} + OC_{pv} * N_{pv} * P_{unittotalpv} + OC_b * P_{batgentotal} + OC_d * P_{unittotald} + FC * Fueltotal$$

B.6 Results presentation

All the results are presented in file 5 with the corresponding format. They include all the power and cost information about all the acceptable combinations. The columns depict the generated power of the different renewable energy units ($P_{ht}(t)=N_h*P_h(t)$, $P_{wt}=N_w*P_w(t)$, $P_{pvt}(t)=N_{pv}*P_{pv}(t)$), the batteries, the DGs, the fuel liters consumed and the dumped power for each hour. Afterwards, cost information, the total dumped power and the percentages of the renewable energy and the diesel generation are presented.

On the other hand, file 10 presents only the energy results in a slightly different format. Each column depicts a different sum between the amounts of generated power. The last column is the sum of all the powers from all the units. This format is easier to use, in order to produce diagrams which add to each other.

GENERAL FLOWCHART OF THE ALGORITHM:



CHAPTER C: RESULTS AND DIAGRAMS OF THE ALGORITHM

C.1 Numerical results

After the algorithm was executed files 5 (RESULTS.txt) and 10 (OUTPUT.txt) were created. As we see the acceptable combinations are the following eight:

#	N_h	N_w	N_{pv}	N_b	N_d
1	0	0	208	22	5
2	0	1	151	20	4
3	0	2	95	18	4
4	0	3	38	16	3
5	0	4	0	15	3
6	1	0	7	8	2
7	1	1	0	9	1
8	2	0	0	0	0

File 5 presents the following results:

Pht = total power generated from hydro units(kW)
Pwt = total power generated from wind units(kW)(inverter losses are included)
Ppvt = total power generated from solar units(kW)(inverter losses are included)
Pgenfinal = total power generated from all renewable energy units(kW)(inverter losses are included)
Pbatgen = power generated by the batteries(inverter losses are included)
Pd = total power generated from DGs(kW)
Fuel = liters of fuel consumed by DGs
Dumped = Total power dumped(kW)

Combination N= 1
Nh=0, Nw= 0, Npv=208, Nb=22, Nd=5, dPmax= 16.96, dPmin= -20.10

hour	Pht	Pwt	Ppvt	Pgenfinal	Load	Pbatgen	Pd	Fuel	Dumped
1	0.00	0.00	0.00	0.00	9.90	9.99	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	9.00	9.07	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	9.15	9.21	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	13.05	8.98	4.10	3.11	0.00
5	0.00	0.00	0.00	0.00	14.10	0.00	14.12	5.58	0.00
6	0.00	0.00	24.46	24.46	15.60	0.00	0.00	0.00	0.00
7	0.00	0.00	24.46	24.46	16.05	0.00	0.00	0.00	0.00
8	0.00	0.00	24.46	24.46	12.00	0.00	0.00	0.00	0.00
9	0.00	0.00	24.46	24.46	12.60	0.00	0.00	0.00	3.39
10	0.00	0.00	24.46	24.46	9.45	0.00	0.00	0.00	14.92
11	0.00	0.00	24.46	24.46	7.50	0.00	0.00	0.00	16.87
12	0.00	0.00	24.46	24.46	11.40	0.00	0.00	0.00	12.97
13	0.00	0.00	24.46	24.46	11.70	0.00	0.00	0.00	12.67
14	0.00	0.00	24.46	24.46	10.95	0.00	0.00	0.00	13.42
15	0.00	0.00	24.46	24.46	12.00	0.00	0.00	0.00	12.37
16	0.00	0.00	24.46	24.46	12.45	0.00	0.00	0.00	11.92
17	0.00	0.00	24.46	24.46	13.50	0.00	0.00	0.00	10.87
18	0.00	0.00	24.46	24.46	15.00	0.00	0.00	0.00	9.37
19	0.00	0.00	0.00	0.00	19.05	19.14	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	19.50	18.11	1.44	2.46	0.00
21	0.00	0.00	0.00	0.00	20.10	0.00	20.12	7.05	0.00
22	0.00	0.00	0.00	0.00	19.80	0.00	19.82	6.98	0.00
23	0.00	0.00	0.00	0.00	13.05	0.00	13.07	5.32	0.00
24	0.00	0.00	0.00	0.00	10.50	0.00	10.52	4.69	0.00

Total dumped power per day=118.73kW
Total fuel consumed per day=35.19liters
Capital Cost=14670.42Euro
Annual operational cost=10354.63Euro
Total annual cost=25025.05Euro
Total power generated per day(served and dumped)=407.67kW
Renewable(%)= 71.21
DG(%)= 28.79
Total cost per kWh=0.237Euro/kWh

Combination N= 2

Nh=0, Nw=1, Npv=151, Nb=20, Nd=4, dPmax=15.16, dPmin= -18.00

hour	Pht	Pwt	Ppvt	Pgenfinal	Load	Pbatgen	Pd	Fuel	Dumped
1	0.00	2.54	0.00	2.54	9.90	7.44	0.00	0.00	0.00
2	0.00	2.15	0.00	2.15	9.00	6.92	0.00	0.00	0.00
3	0.00	2.68	0.00	2.68	9.15	6.52	0.00	0.00	0.00
4	0.00	2.03	0.00	2.03	13.05	11.07	0.00	0.00	0.00
5	0.00	4.81	0.00	4.81	14.10	1.92	7.40	3.50	0.00
6	0.00	4.60	17.76	22.35	15.60	0.00	0.00	0.00	0.00
7	0.00	4.39	17.76	22.15	16.05	0.00	0.00	0.00	0.00
8	0.00	4.60	17.76	22.35	12.00	0.00	0.00	0.00	0.00
9	0.00	4.90	17.76	22.66	12.60	0.00	0.00	0.00	0.00
10	0.00	4.90	17.76	22.66	9.45	0.00	0.00	0.00	11.68
11	0.00	4.90	17.76	22.66	7.50	0.00	0.00	0.00	15.07
12	0.00	4.60	17.76	22.35	11.40	0.00	0.00	0.00	10.87
13	0.00	4.90	17.76	22.66	11.70	0.00	0.00	0.00	10.87
14	0.00	4.90	17.76	22.66	10.95	0.00	0.00	0.00	11.62
15	0.00	4.81	17.76	22.56	12.00	0.00	0.00	0.00	10.48
16	0.00	3.64	17.76	21.40	12.45	0.00	0.00	0.00	8.86
17	0.00	4.39	17.76	22.15	13.50	0.00	0.00	0.00	8.57
18	0.00	2.41	17.76	20.16	15.00	0.00	0.00	0.00	5.08
19	0.00	2.54	0.00	2.54	19.05	16.59	0.00	0.00	0.00
20	0.00	2.98	0.00	2.98	19.50	16.57	0.00	0.00	0.00
21	0.00	2.83	0.00	2.83	20.10	0.71	16.58	5.76	0.00
22	0.00	1.80	0.00	1.80	19.80	0.00	18.02	6.12	0.00
23	0.00	1.91	0.00	1.91	13.05	0.00	11.16	4.43	0.00
24	0.00	2.54	0.00	2.54	10.50	0.00	7.97	3.64	0.00

Total dumped power per day= 93.09kW
Total fuel consumed per day=23.45liters
Capital Cost=12542.54Euro
Annual operational cost= 8307.70Euro
Total annual cost=20850.25Euro
Total power generated per day(served and dumped)=385.20kW
Renewable(%)= 79.07
DG(%)= 20.93
Total cost per kWh=0.196Euro/kWh

Combination N= 3

Nh=0, Nw=2, Npv=95, Nb=18, Nd=4, dPmax=13.47, dPmin= -16.20

hour	Pht	Pwt	Ppvt	Pgenfinal	Load	Pbatgen	Pd	Fuel	Dumped
1	0.00	5.09	0.00	5.09	9.90	4.89	0.00	0.00	0.00
2	0.00	4.30	0.00	4.30	9.00	4.77	0.00	0.00	0.00
3	0.00	5.37	0.00	5.37	9.15	3.84	0.00	0.00	0.00
4	0.00	4.05	0.00	4.05	13.05	9.04	0.00	0.00	0.00
5	0.00	9.61	0.00	9.61	14.10	4.52	0.00	0.00	0.00
6	0.00	9.19	11.17	20.37	15.60	0.00	0.00	0.00	0.00
7	0.00	8.79	11.17	19.96	16.05	0.00	0.00	0.00	0.00
8	0.00	9.19	11.17	20.37	12.00	0.00	0.00	0.00	0.00
9	0.00	9.80	11.17	20.97	12.60	0.00	0.00	0.00	0.00
10	0.00	9.80	11.17	20.97	9.45	0.00	0.00	0.00	9.10
11	0.00	9.80	11.17	20.97	7.50	0.00	0.00	0.00	13.39
12	0.00	9.19	11.17	20.37	11.40	0.00	0.00	0.00	8.89
13	0.00	9.80	11.17	20.97	11.70	0.00	0.00	0.00	9.19
14	0.00	9.80	11.17	20.97	10.95	0.00	0.00	0.00	9.94
15	0.00	9.61	11.17	20.78	12.00	0.00	0.00	0.00	8.71
16	0.00	7.28	11.17	18.46	12.45	0.00	0.00	0.00	5.93
17	0.00	8.79	11.17	19.96	13.50	0.00	0.00	0.00	6.38
18	0.00	4.81	11.17	15.99	15.00	0.00	0.00	0.00	0.91
19	0.00	5.09	0.00	5.09	19.05	14.04	0.00	0.00	0.00
20	0.00	5.96	0.00	5.96	19.50	13.58	0.00	0.00	0.00
21	0.00	5.66	0.00	5.66	20.10	2.86	11.60	4.54	0.00
22	0.00	3.60	0.00	3.60	19.80	0.00	16.22	5.67	0.00
23	0.00	3.82	0.00	3.82	13.05	0.00	9.24	3.96	0.00
24	0.00	5.09	0.00	5.09	10.50	0.00	5.43	3.02	0.00

Total dumped power per day= 72.44kW
Total fuel consumed per day=17.19liters
Capital Cost=10652.86Euro
Annual operational cost= 6729.28Euro
Total annual cost=17382.15Euro
Total power generated per day(served and dumped)=367.73kW
Renewable(%)= 85.61
DG(%)= 14.39
Total cost per kWh=0.161Euro/kWh

Combination N= 4
Nh=0, Nw=3, Npv=38, Nb=16, Nd=3, dPmax=11.67, dPmin=-14.41

hour	*Pht*	*Pwt*	*Ppvt*	*Pgenfinal*	*Load*	*Pbatgen*	*Pd*	*Fuel*	*Dumped*
1	0.00	7.63	0.00	7.63	9.90	2.34	0.00	0.00	0.00
2	0.00	6.45	0.00	6.45	9.00	2.62	0.00	0.00	0.00
3	0.00	8.05	0.00	8.05	9.15	1.16	0.00	0.00	0.00
4	0.00	6.08	0.00	6.08	13.05	7.02	0.00	0.00	0.00
5	0.00	14.42	0.00	14.42	14.10	0.00	0.00	0.00	0.00
6	0.00	13.79	4.47	18.26	15.60	0.00	0.00	0.00	0.00
7	0.00	13.18	4.47	17.65	16.05	0.00	0.00	0.00	0.00
8	0.00	13.79	4.47	18.26	12.00	0.00	0.00	0.00	0.00
9	0.00	14.70	4.47	19.17	12.60	0.00	0.00	0.00	3.75
10	0.00	14.70	4.47	19.17	9.45	0.00	0.00	0.00	9.65
11	0.00	14.70	4.47	19.17	7.50	0.00	0.00	0.00	11.60
12	0.00	13.79	4.47	18.26	11.40	0.00	0.00	0.00	6.79
13	0.00	14.70	4.47	19.17	11.70	0.00	0.00	0.00	7.40
14	0.00	14.70	4.47	19.17	10.95	0.00	0.00	0.00	8.15
15	0.00	14.42	4.47	18.89	12.00	0.00	0.00	0.00	6.82
16	0.00	10.93	4.47	15.40	12.45	0.00	0.00	0.00	2.88
17	0.00	13.18	4.47	17.65	13.50	0.00	0.00	0.00	4.08
18	0.00	7.22	4.47	11.69	15.00	3.38	0.00	0.00	0.00
19	0.00	7.63	0.00	7.63	19.05	11.48	0.00	0.00	0.00
20	0.00	8.95	0.00	8.95	19.50	10.59	0.00	0.00	0.00
21	0.00	8.49	0.00	8.49	20.10	1.64	9.98	3.72	0.00
22	0.00	5.39	0.00	5.39	19.80	0.00	14.42	4.81	0.00
23	0.00	5.73	0.00	5.73	13.05	0.00	7.33	3.07	0.00
24	0.00	7.63	0.00	7.63	10.50	0.00	2.89	1.97	0.00

Total dumped power per day= 61.12kW
Total fuel consumed per day=13.57liters
Capital Cost= 8524.99Euro
Annual operational cost= 4979.42Euro
Total annual cost=13504.41Euro
Total power generated per day(served and dumped)=359.46kW
Renewable(%)= 88.40
DG(%)= 11.60
Total cost per kWh=0.124Euro/kWh

Combination N= 5

Nh=0, Nw=4, Npv=0, Nb=15, Nd=3, dPmax=12.10, dPmin= -12.61

hour	Pht	Pwt	Ppvt	Pgenfinal	Load	Pbatgen	Pd	Fuel	Dumped
1	0.00	10.17	0.00	10.17	9.90	0.00	0.00	0.00	0.21
2	0.00	8.60	0.00	8.60	9.00	0.47	0.00	0.00	0.00
3	0.00	10.74	0.00	10.74	9.15	0.00	0.00	0.00	1.05
4	0.00	8.11	0.00	8.11	13.05	5.00	0.00	0.00	0.00
5	0.00	19.22	0.00	19.22	14.10	0.00	0.00	0.00	0.00
6	0.00	18.39	0.00	18.39	15.60	0.00	0.00	0.00	2.68
7	0.00	17.58	0.00	17.58	16.05	0.00	0.00	0.00	1.46
8	0.00	18.39	0.00	18.39	12.00	0.00	0.00	0.00	6.32
9	0.00	19.60	0.00	19.60	12.60	0.00	0.00	0.00	6.94
10	0.00	19.60	0.00	19.60	9.45	0.00	0.00	0.00	10.09
11	0.00	19.60	0.00	19.60	7.50	0.00	0.00	0.00	12.04
12	0.00	18.39	0.00	18.39	11.40	0.00	0.00	0.00	6.92
13	0.00	19.60	0.00	19.60	11.70	0.00	0.00	0.00	7.84
14	0.00	19.60	0.00	19.60	10.95	0.00	0.00	0.00	8.59
15	0.00	19.22	0.00	19.22	12.00	0.00	0.00	0.00	7.16
16	0.00	14.57	0.00	14.57	12.45	0.00	0.00	0.00	2.06
17	0.00	17.58	0.00	17.58	13.50	0.00	0.00	0.00	4.01
18	0.00	9.63	0.00	9.63	15.00	5.44	0.00	0.00	0.00
19	0.00	10.17	0.00	10.17	19.05	8.93	0.00	0.00	0.00
20	0.00	11.93	0.00	11.93	19.50	7.61	0.00	0.00	0.00
21	0.00	11.32	0.00	11.32	20.10	3.43	5.37	2.58	0.00
22	0.00	7.19	0.00	7.19	19.80	0.00	12.62	4.37	0.00
23	0.00	7.64	0.00	7.64	13.05	0.00	5.42	2.60	0.00
24	0.00	10.17	0.00	10.17	10.50	0.00	0.34	1.35	0.00

Total dumped power per day= 77.34kW
Total fuel consumed per day=10.89liters
Capital Cost= 7754.58Euro
Annual operational cost= 3951.67Euro
Total annual cost=11706.26Euro
Total power generated per day(served and dumped)=377.83kW
Renewable(%)= 92.09
DG(%)= 7.91
Total cost per kWh=0.107Euro/kWh

Combination N= 6

Nh=1, Nw=0, Npv=7, Nb=8, Nd=2, dPmax= 6.15, dPmin= -7.28

hour	Pht	Pwt	Ppvt	Pgenfinal	Load	Pbatgen	Pd	Fuel	Dumped
1	12.82	0.00	0.00	12.82	9.90	0.00	0.00	0.00	2.63
2	12.82	0.00	0.00	12.82	9.00	0.00	0.00	0.00	3.53
3	12.82	0.00	0.00	12.82	9.15	0.00	0.00	0.00	3.38
4	12.82	0.00	0.00	12.82	13.05	0.52	0.00	0.00	0.00
5	12.82	0.00	0.00	12.82	14.10	1.57	0.00	0.00	0.00
6	12.82	0.00	0.82	13.65	15.60	2.24	0.00	0.00	0.00
7	12.82	0.00	0.82	13.65	16.05	2.68	0.00	0.00	0.00
8	12.82	0.00	0.82	13.65	12.00	0.00	0.00	0.00	0.00
9	12.82	0.00	0.82	13.65	12.60	0.00	0.00	0.00	0.00
10	12.82	0.00	0.82	13.65	9.45	0.00	0.00	0.00	0.00
11	12.82	0.00	0.82	13.65	7.50	0.00	0.00	0.00	4.77
12	12.82	0.00	0.82	13.65	11.40	0.00	0.00	0.00	1.96
13	12.82	0.00	0.82	13.65	11.70	0.00	0.00	0.00	1.66
14	12.82	0.00	0.82	13.65	10.95	0.00	0.00	0.00	2.41
15	12.82	0.00	0.82	13.65	12.00	0.00	0.00	0.00	1.36
16	12.82	0.00	0.82	13.65	12.45	0.00	0.00	0.00	0.91
17	12.82	0.00	0.82	13.65	13.50	0.14	0.00	0.00	0.00
18	12.82	0.00	0.82	13.65	15.00	1.64	0.00	0.00	0.00
19	12.82	0.00	0.00	12.82	19.05	6.51	0.00	0.00	0.00
20	12.82	0.00	0.00	12.82	19.50	5.25	1.44	1.20	0.00
21	12.82	0.00	0.00	12.82	20.10	0.00	7.28	2.63	0.00
22	12.82	0.00	0.00	12.82	19.80	0.00	6.98	2.56	0.00
23	12.82	0.00	0.00	12.82	13.05	0.00	0.23	0.90	0.00
24	12.82	0.00	0.00	12.82	10.50	0.00	0.00	0.00	0.00

Total dumped power per day= 22.60kW
Total fuel consumed per day= 7.29liters
Capital Cost= 4652.27Euro
Annual operational cost= 2762.81Euro
Total annual cost= 7451.08Euro
Total power generated per day(served and dumped)=334.64kW
Renewable(%)= 94.89
DG(%)= 5.11
Total cost per kWh=0.065Euro/kWh

Combination N= 7

Nh=1, Nw=1, Npv=0, Nb= 9, Nd=1, dPmax=10.22, dPmin= -5.18

hour	*Pht*	*Pwt*	*Ppvt*	*Pgenfinal*	*Load*	*Pbatgen*	*Pd*	*Fuel*	*Dumped*
1	*12.82*	*2.54*	*0.00*	*15.37*	*9.90*	*0.00*	*0.00*	*0.00*	*5.17*
2	*12.82*	*2.15*	*0.00*	*14.97*	*9.00*	*0.00*	*0.00*	*0.00*	*5.68*
3	*12.82*	*2.68*	*0.00*	*15.51*	*9.15*	*0.00*	*0.00*	*0.00*	*6.06*
4	*12.82*	*2.03*	*0.00*	*14.85*	*13.05*	*0.00*	*0.00*	*0.00*	*1.51*
5	*12.82*	*4.81*	*0.00*	*17.63*	*14.10*	*0.00*	*0.00*	*0.00*	*3.23*
6	*12.82*	*4.60*	*0.00*	*17.42*	*15.60*	*0.00*	*0.00*	*0.00*	*1.53*
7	*12.82*	*4.39*	*0.00*	*17.22*	*16.05*	*0.00*	*0.00*	*0.00*	*0.87*
8	*12.82*	*4.60*	*0.00*	*17.42*	*12.00*	*0.00*	*0.00*	*0.00*	*5.13*
9	*12.82*	*4.90*	*0.00*	*17.72*	*12.60*	*0.00*	*0.00*	*0.00*	*4.83*
10	*12.82*	*4.90*	*0.00*	*17.72*	*9.45*	*0.00*	*0.00*	*0.00*	*7.98*
11	*12.82*	*4.90*	*0.00*	*17.72*	*7.50*	*0.00*	*0.00*	*0.00*	*9.93*
12	*12.82*	*4.60*	*0.00*	*17.42*	*11.40*	*0.00*	*0.00*	*0.00*	*5.73*
13	*12.82*	*4.90*	*0.00*	*17.72*	*11.70*	*0.00*	*0.00*	*0.00*	*5.73*
14	*12.82*	*4.90*	*0.00*	*17.72*	*10.95*	*0.00*	*0.00*	*0.00*	*6.48*
15	*12.82*	*4.81*	*0.00*	*17.63*	*12.00*	*0.00*	*0.00*	*0.00*	*5.33*
16	*12.82*	*3.64*	*0.00*	*16.47*	*12.45*	*0.00*	*0.00*	*0.00*	*3.72*
17	*12.82*	*4.39*	*0.00*	*17.22*	*13.50*	*0.00*	*0.00*	*0.00*	*3.42*
18	*12.82*	*2.41*	*0.00*	*15.23*	*15.00*	*0.06*	*0.00*	*0.00*	*0.00*
19	*12.82*	*2.54*	*0.00*	*15.37*	*19.05*	*3.98*	*0.00*	*0.00*	*0.00*
20	*12.82*	*2.98*	*0.00*	*15.81*	*19.50*	*3.98*	*0.00*	*0.00*	*0.00*
21	*12.82*	*2.83*	*0.00*	*15.65*	*20.10*	*4.72*	*0.00*	*0.00*	*0.00*
22	*12.82*	*1.80*	*0.00*	*14.62*	*19.80*	*2.50*	*2.69*	*1.08*	*0.00*
23	*12.82*	*1.91*	*0.00*	*14.73*	*13.05*	*0.00*	*0.00*	*0.00*	*0.00*
24	*12.82*	*2.54*	*0.00*	*15.37*	*10.50*	*0.00*	*0.00*	*0.00*	*0.00*

Total dumped power per day= 82.32kW
Total fuel consumed per day= 1.08liters
Capital Cost= 5651.24Euro
Annual operational cost= 1583.18Euro
Total annual cost= 7234.43Euro
Total power generated per day(served and dumped)=398.99kW
Renewable(%)= 99.15
DG(%)= 0.85
Total cost per kWh=0.063Euro/kWh

Combination N=8

Nh=2, Nw=0, Npv=0, Nb=0, Nd=0, dPmax=18.15, dPmin=5.55

hour	Pht	Pwt	Ppvt	Pgenfinal	Load	Pbatgen	Pd	Fuel	Dumped
1	25.65	0.00	0.00	25.65	9.90	0.00	0.00	0.00	15.24
2	25.65	0.00	0.00	25.65	9.00	0.00	0.00	0.00	16.14
3	25.65	0.00	0.00	25.65	9.15	0.00	0.00	0.00	15.99
4	25.65	0.00	0.00	25.65	13.05	0.00	0.00	0.00	12.09
5	25.65	0.00	0.00	25.65	14.10	0.00	0.00	0.00	11.04
6	25.65	0.00	0.00	25.65	15.60	0.00	0.00	0.00	9.54
7	25.65	0.00	0.00	25.65	16.05	0.00	0.00	0.00	9.09
8	25.65	0.00	0.00	25.65	12.00	0.00	0.00	0.00	13.14
9	25.65	0.00	0.00	25.65	12.60	0.00	0.00	0.00	12.54
10	25.65	0.00	0.00	25.65	9.45	0.00	0.00	0.00	15.69
11	25.65	0.00	0.00	25.65	7.50	0.00	0.00	0.00	17.64
12	25.65	0.00	0.00	25.65	11.40	0.00	0.00	0.00	13.74
13	25.65	0.00	0.00	25.65	11.70	0.00	0.00	0.00	13.44
14	25.65	0.00	0.00	25.65	10.95	0.00	0.00	0.00	14.19
15	25.65	0.00	0.00	25.65	12.00	0.00	0.00	0.00	13.14
16	25.65	0.00	0.00	25.65	12.45	0.00	0.00	0.00	12.69
17	25.65	0.00	0.00	25.65	13.50	0.00	0.00	0.00	11.64
18	25.65	0.00	0.00	25.65	15.00	0.00	0.00	0.00	10.14
19	25.65	0.00	0.00	25.65	19.05	0.00	0.00	0.00	6.09
20	25.65	0.00	0.00	25.65	19.50	0.00	0.00	0.00	5.64
21	25.65	0.00	0.00	25.65	20.10	0.00	0.00	0.00	5.04
22	25.65	0.00	0.00	25.65	19.80	0.00	0.00	0.00	5.34
23	25.65	0.00	0.00	25.65	13.05	0.00	0.00	0.00	12.09
24	25.65	0.00	0.00	25.65	10.50	0.00	0.00	0.00	14.64

Total dumped power per day=285.02kW
Total fuel consumed per day= 0.00liters
Capital Cost= 6496.22Euro
Annual operational cost= 507.77Euro
Total annual cost= 7004.00Euro
Total power generated per day(served and dumped)=615.56kW
Renewable(%)=100.00
DG(%)= 0.00
Total cost per kWh=0.058Euro/kWh

C.2 Diagrams

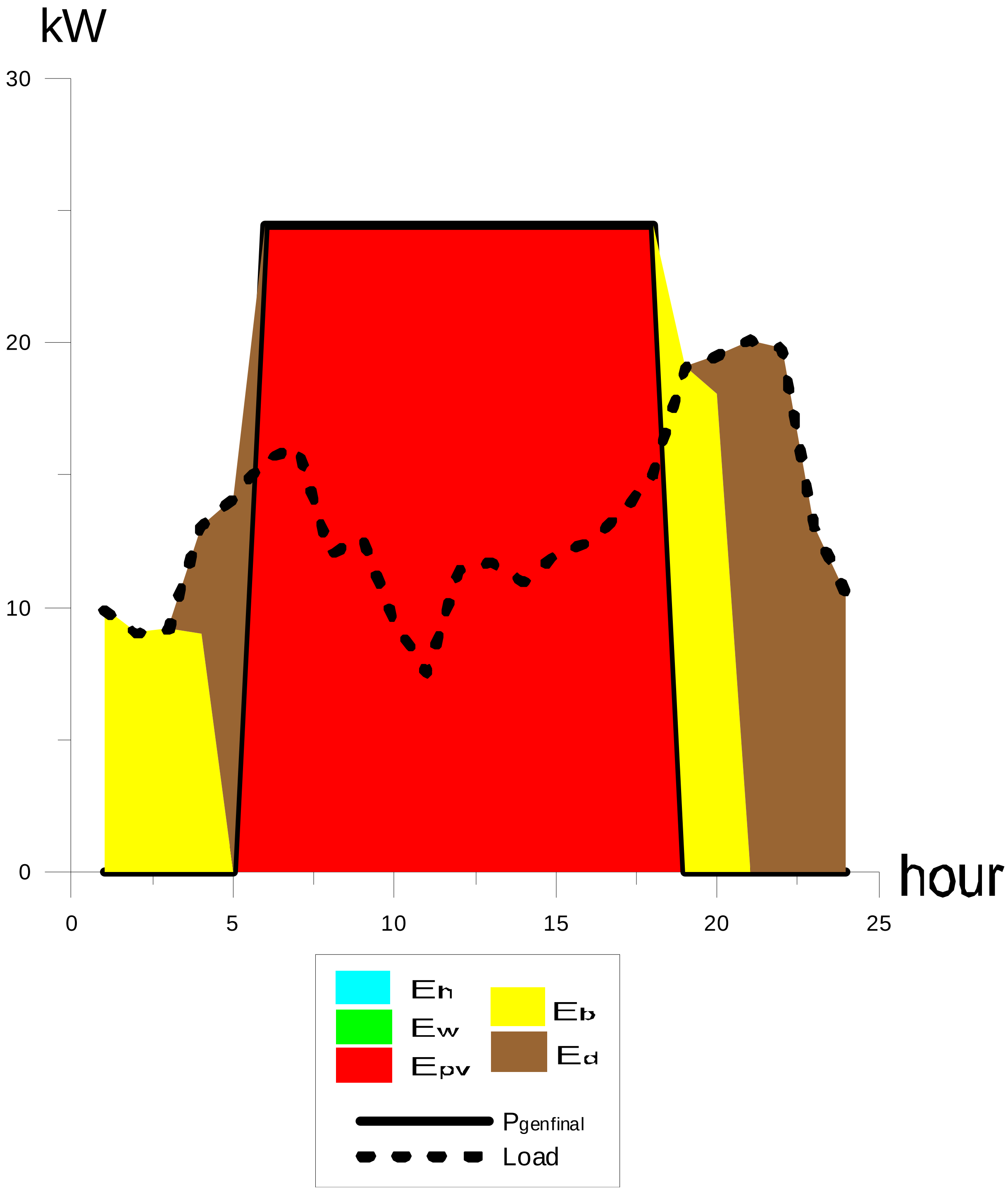
Grapher 8 is the program used for creating the diagrams. It reads the data included in file 10 (‘OUTPUT.txt’) and it depicts the curves of the generated power and the load versus time for each combination. The bold black line is the curve of the power that serves the load (meaning that the losses of the inverter are included) and is generated by the renewable energy units ($P_{genfinal}$) versus time, while the dashed one depicts the variation of the load throughout the day.

The colored areas of the diagrams represent the amounts of energy that each group of units supplied. So, the blue area is the energy produced by hydro turbines over the day (E_h), the green one by wind turbines (E_w), the red one by photovoltaics (E_{pv}), the yellow one is the energy retrieved by the batteries (E_b) and the brown one is supplied by the diesel generators (E_d).

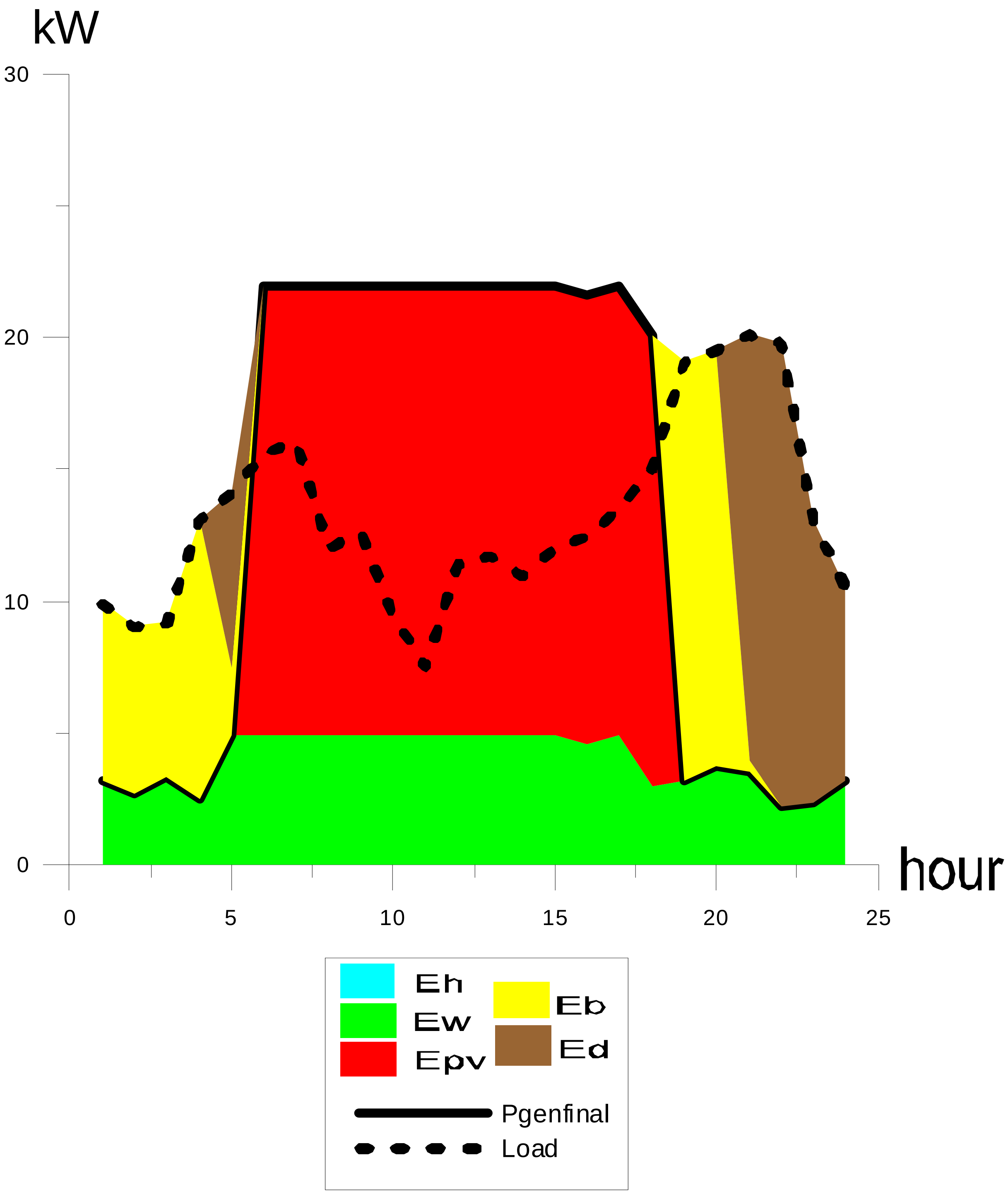
As it can be easily observed, when the demand curve exceeds the power generation one, the area between them is the energy supplied by the batteries and the diesel generators (yellow and brown color).

Note: Some inaccuracies in the diagrams are due to the fact that each power curve is a function with 24 known values (one for each hour of the day) and a line that connects them. Therefore , the line of the function between two hours is just a line connecting two points and is not representing the value that the power really has between these two points. Of course, this problem could be limited if more than 24 power calculations were made for the day.

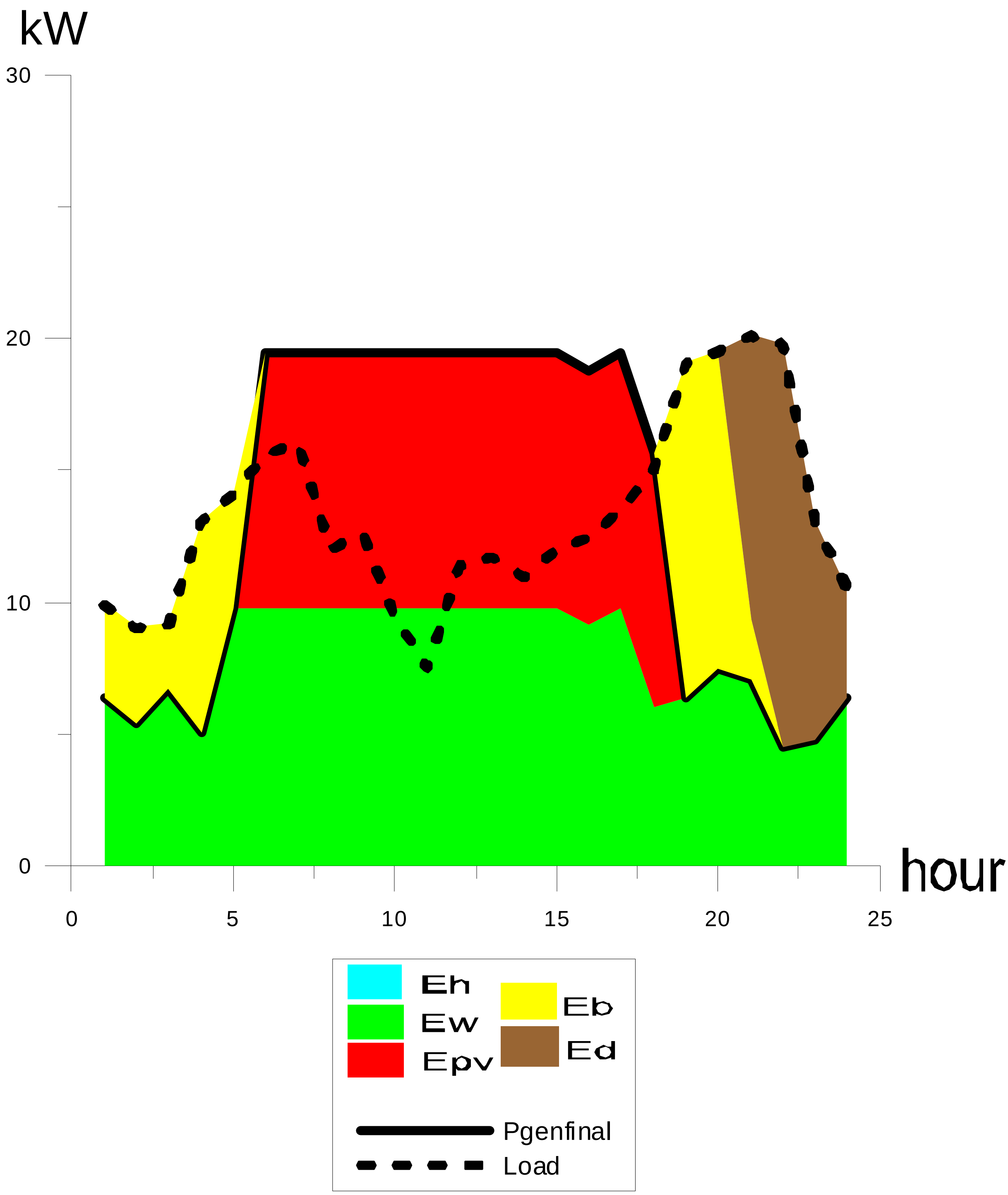
- *Combination 1 (N_h=0, N_w=0, N_{pv}=208):*



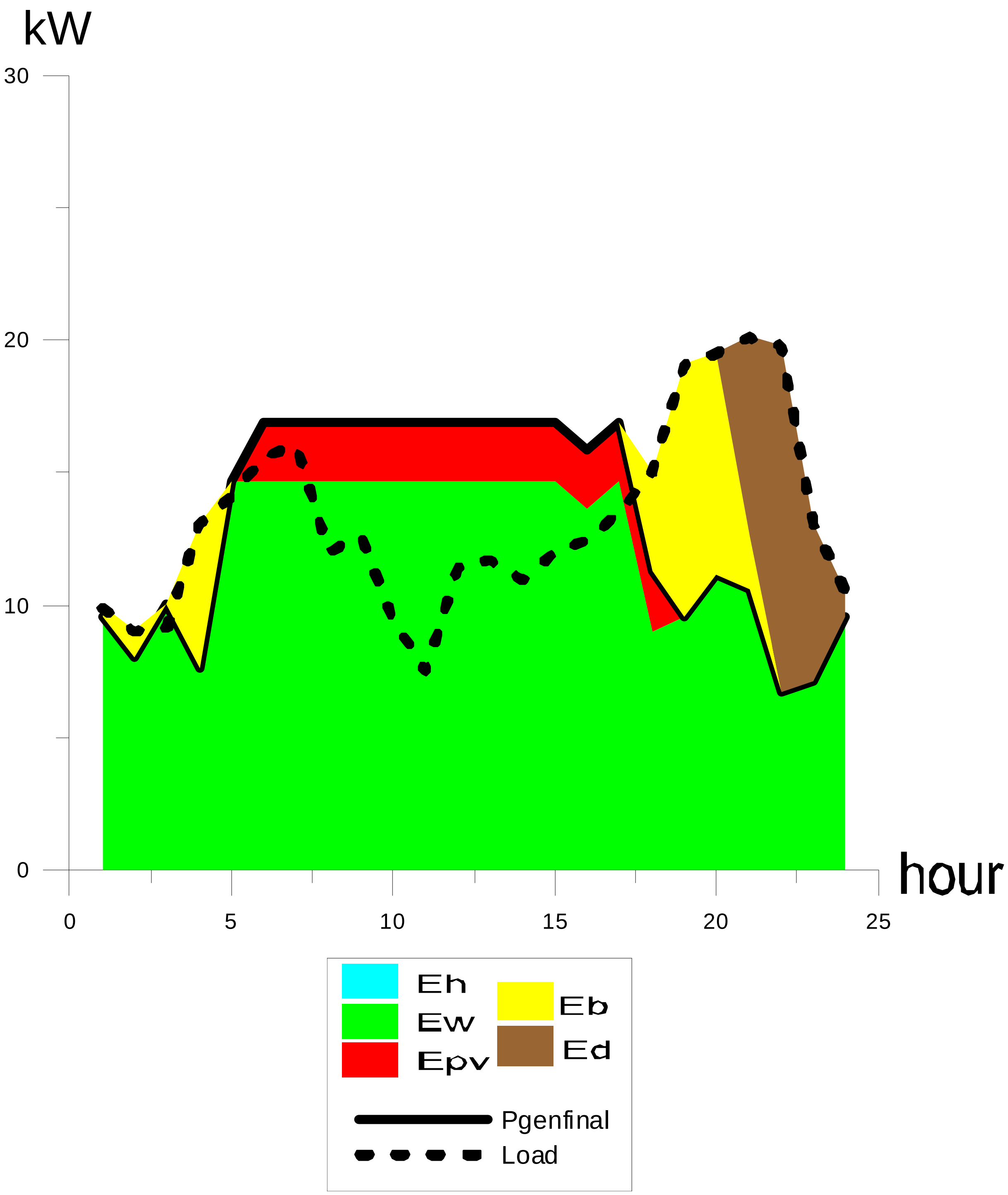
- *Combination 2 (N_h=0, N_w=1, N_{pv}=151):*



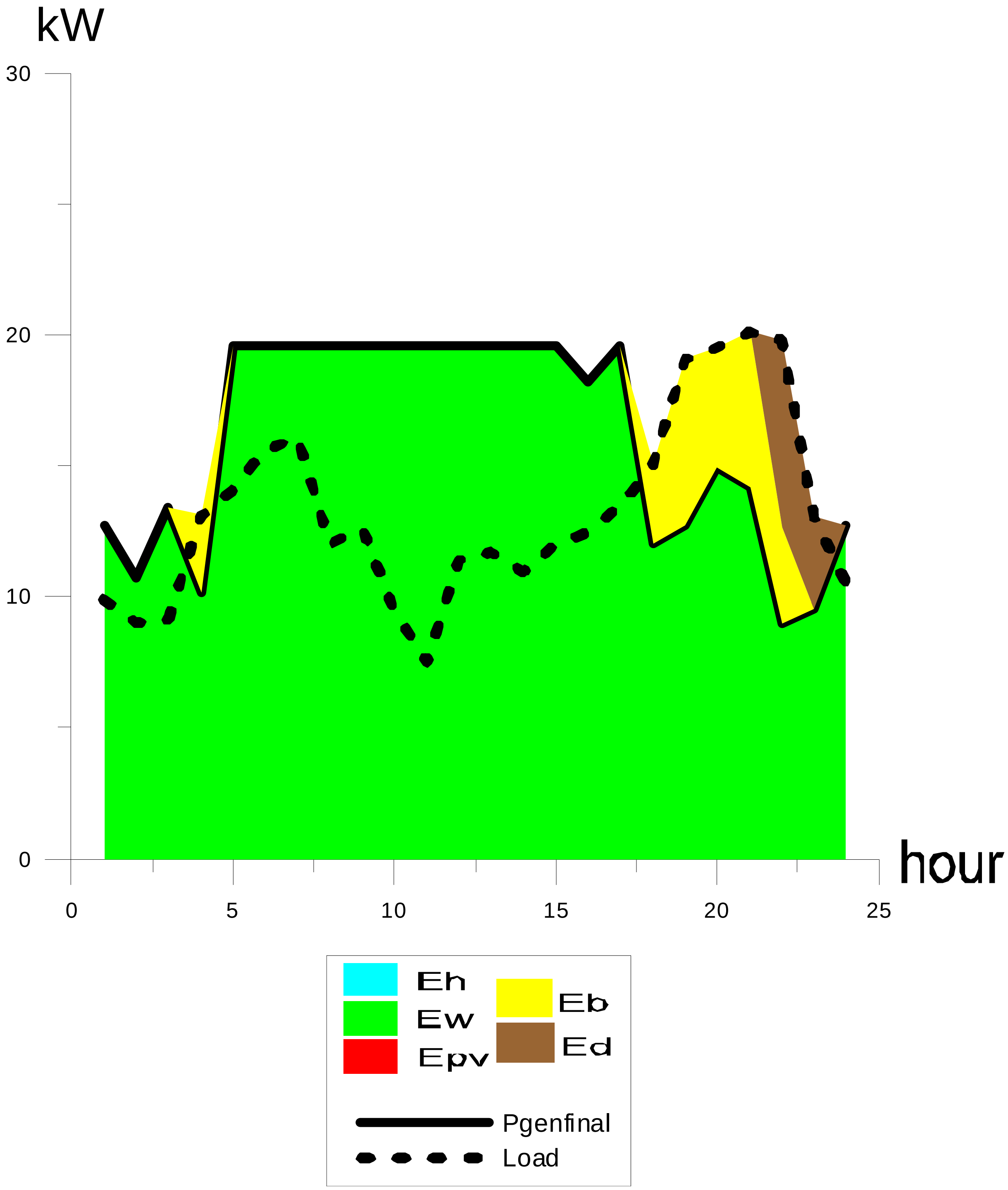
- *Combination 3 (N_h=0, N_w=2, N_{pv}=95):*



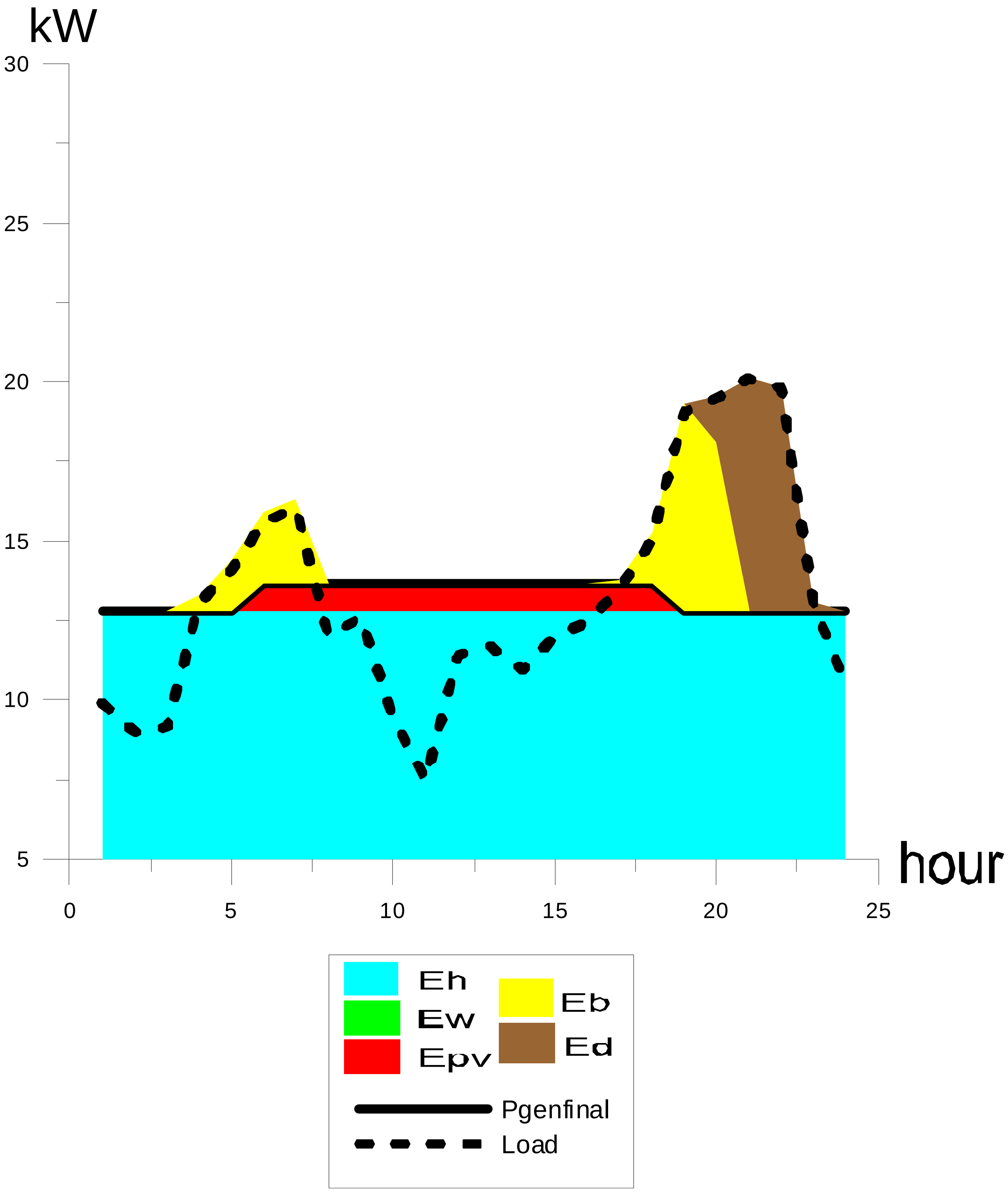
- *Combination 4 (N_h=0, N_w=3, N_{pv}=38):*



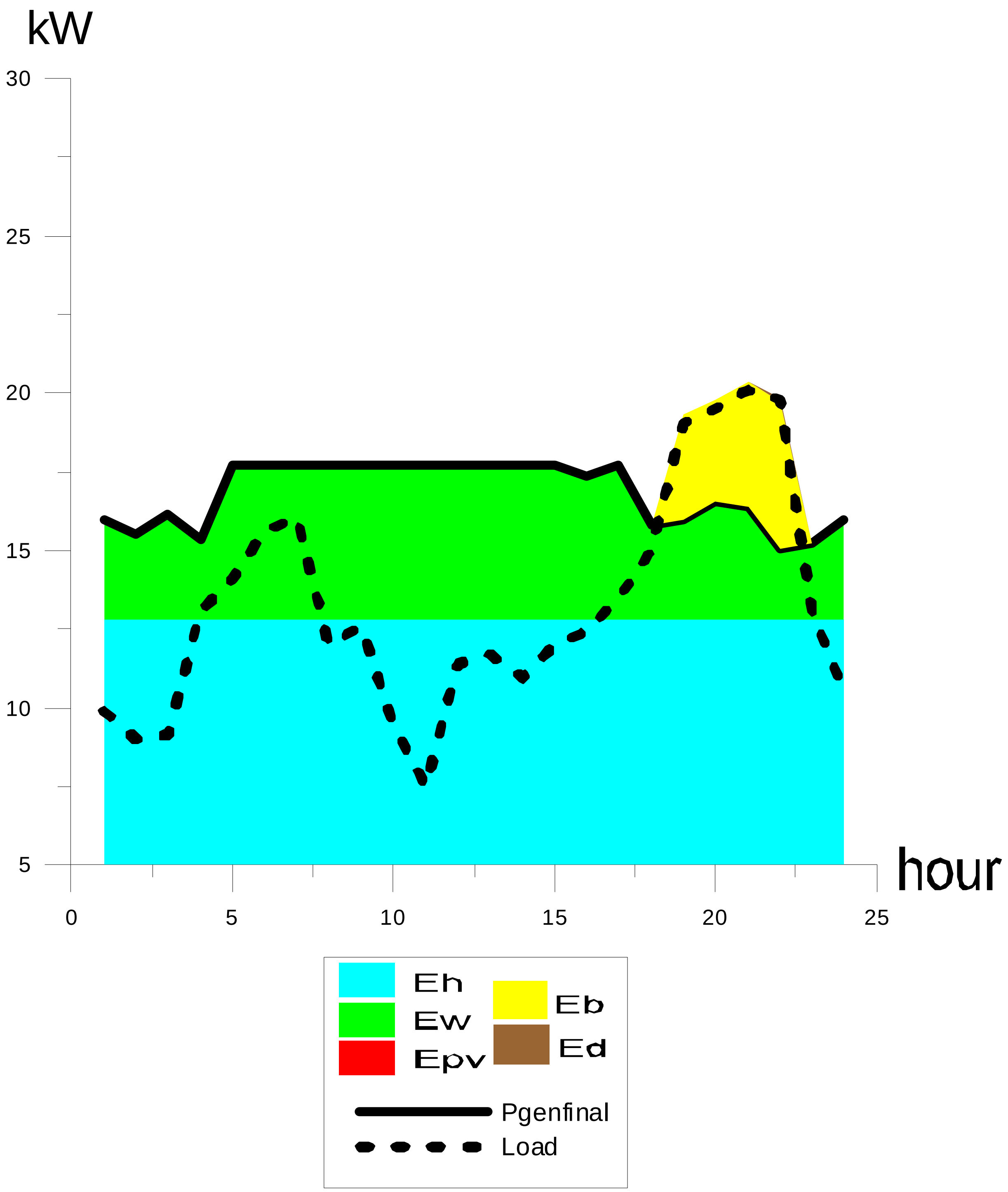
- *Combination 5 (N_h=0, N_w=4, N_{pv}=0):*



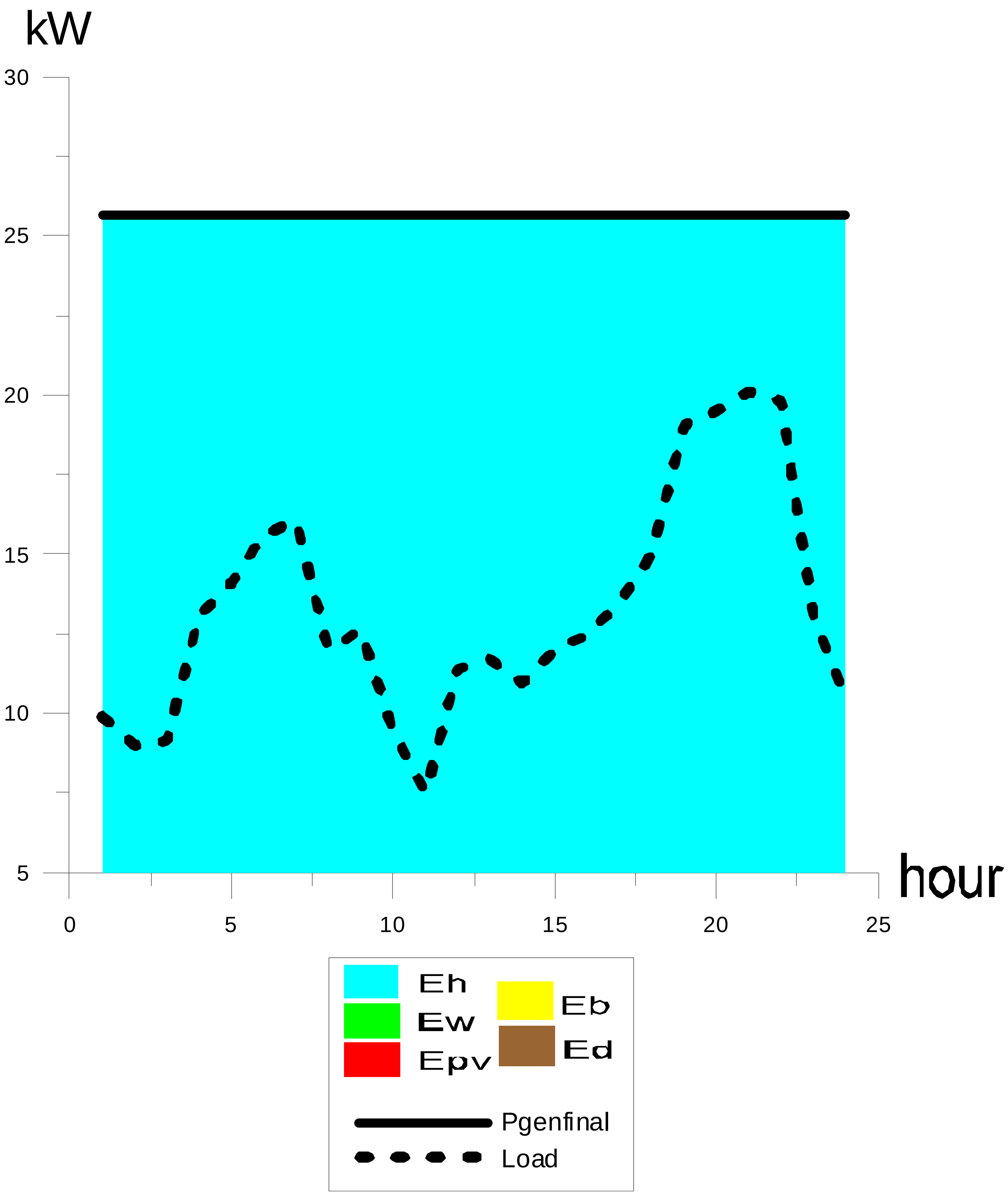
- *Combination 6 (N_h=1, N_w=0, N_{pv}=7):*



- *Combination 7 (N_h=1, N_w=1, N_{pv}=0):*



- *Combination 8 (N_h=2, N_w=0, N_{pv}=0):*



C.3 Cost comparison

- *Cost comparison between the hybrid system combinations:*

The main factor that determines the competitiveness of each combination is its cost and more specifically the price of each kWh it offers to the load. The total power that serves the load during one day is the sum of the daily power produced by the renewable energy units and the diesel generators, minus the dumped power per day. Taking into consideration that this day is an average one, the power that serves the load for the whole year is the daily one multiplied by 365:

$$P_{day,load} = \mathrm{P}_{renew} + P_{DG} - P_{dumped}$$

$$P_{year,load} = 365 * P_{day,load}$$

When the total annual cost of the system is divided by $\mathrm{P}_{\mathrm{year,load}}$, it results to the kWh price.

$$€ / kWh = \frac{TC}{P_{year,load}}$$

Here it should be clarified, that even though the unit of $\mathrm{P}_{\mathrm{year,load}}$ is kW, once the analysis made was considering hourly values, the number of kW in a year is equal to the number of kWh in a year.

It can be easily understood that the more power a system dumps, the more expensive the kWh price gets. This happens because the size of a hybrid system should be corresponding to the demand. If it greatly exceeds it, then the load may be absolutely served, but with more units – and subsequently more costs - than it should.

In the table below are the kWh price and the cost information that each combination has:

#	1	2	3	4	5	6	7	8
Capital cost(€)	14670,42	12542,54	10652,86	8524,99	7754,58	4652,27	5651,24	6496,22
Annual operational cost(€)	10354,63	8307,70	6729,28	4979,42	3951,67	2762,81	1583,18	507,77
Total annual cost(€)	25025,05	20850,25	17382,15	13504,41	11706,26	7415,08	7234,43	7004,00
€/kWh	0,237	0,196	0,161	0,124	0,107	0,065	0,063	0,058

Therefore, the combination with the best kWh price (0,058€/kWh) is the eight one that includes only two hydro turbines. Its low cost can be explained by the fact, that the hydro turbines have the highest rated power (15kW) and the lowest capital cost per rated Watt out of all renewable energy units, and that it does not any other units that would increase the cost of the system. As a matter of fact, this combination has by far the lowest operational cost and subsequently the lowest total annual cost. Combination 8 depicts a configuration that produces much more energy than needed and it might be more suitable for an area with a greater demand. This can be seen by the amount of dumped power (285,85kW per day) which is by far the largest of all the combinations'. Nevertheless, the kWh price is still the lowest and it has the ability of corresponding to a possible population and subsequently demand inflation. The fact that two hydro turbines can be so efficient and in no need of any other renewable energy units, batteries and diesel generators, is the stable water flow (35 l/s) during the average day and subsequently throughout the whole year. This is almost unattainable to occur in real life situations.

Combinations 6 and 7 also provide low kWh prices and they have a greater variety of components. Combination 6 has the least dumped power and the lowest capital cost out of all the combinations but its operational cost exceeds that of combination 8 and it is the reason that its kWh price is not the best. However their versatility can make them more suitable solutions in reality.

An important remark is that the more photovoltaics and batteries a combination has, the more expensive it is. This is due to the high capital cost and the high operational cost that the PV panels and the batteries have and it can be highlighted in combinations 1 to 5, which are the combinations with the greatest sum of PV modules and batteries. The less the sum of PV modules and DGs is, the lower the kWh price gets.

In general it can be said that using a hydro turbine of this specific rated power is better than using an equal, in terms of power, variation of wind turbines and PV panels of these specific powers, because it offers the best power to cost proportion unlike a PV panel that has a low rated power (120W) and not proportionally low costs.

- *Cost comparison between different energy supply schemes*

Based on the current situation in Western Ghats, the diesel generators operate for an average of 6 hours per day and they supply power to about 35% of the population. On top of that, they provide a relatively expensive electricity, as the kWh price reaches up to 0,1524€[1]. The option of grid extension is cheaper than the diesel generators, as it provides a kWh price of up to 7,11Rs=0,107€ [1] but the topographical characteristics of the area make it a hardly feasible enterprise.

The table below presents the kWh price of combination 8, the grid extension and the diesel generator units:

Description	**Daily hours of operation**	**Population electrified (%)**	**kWh price (€/kWh)**
Combination 8 (N_h=2)	24	100	0,058
Grid extension	24	100	0,107
Diesel generators	6	35	0,152

The profit that the community would have with an installation of a hybrid micro-hydro, wind , PV system instead of extending the grid supply or keeping the diesel generators is obvious in cases of combinations 6, 7 and 8. Any of them, offers significantly cheaper electrification, 24 hours per day and with no part of the population being deprived of it. Especially if combination 8 was installed, the difference in kWh price between the hybrid system and the grid extension would be huge: 0,107-0,058=0,049€.

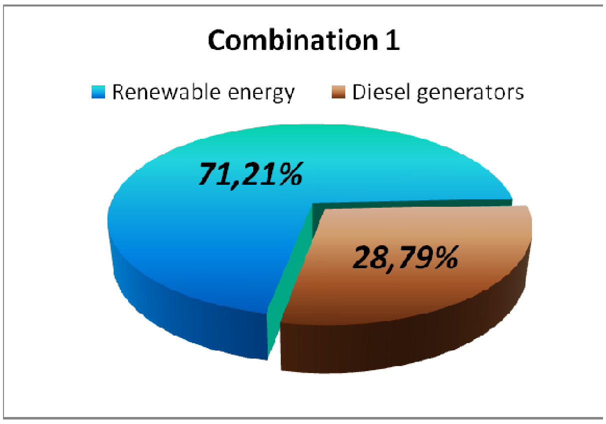
Combination 5 provides the same kWh price with the grid extension but it is an environmentally friendly solution and maybe a more feasible option. Compared to the existing electrification through diesel generators, combination 4 also offers cheaper electricity with much less emissions too.

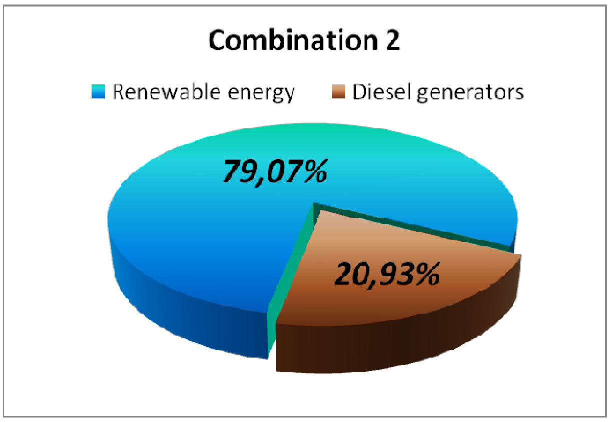
This diploma thesis does not include any analysis over the quality of the electricity supplied by the hybrid system. The term quality of electrical supply refers to a minimal number of interruptions and their duration kept to a minimal period of time. In general it can be said, that a safe and satisfactory operation is ensured when the devices are connected to voltage which is within the prescribed tolerances for voltage and frequency. For this a separate research should be done in order to find out the quality of the electricity that each energy scheme provides, something that can prove to be a really important parameter.

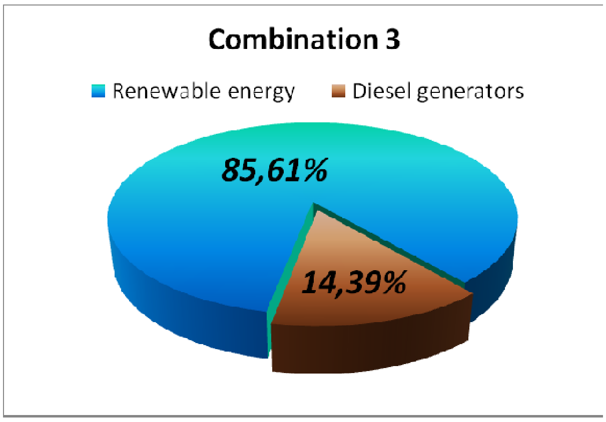
C.4 Use of diesel generators and fuel consumption

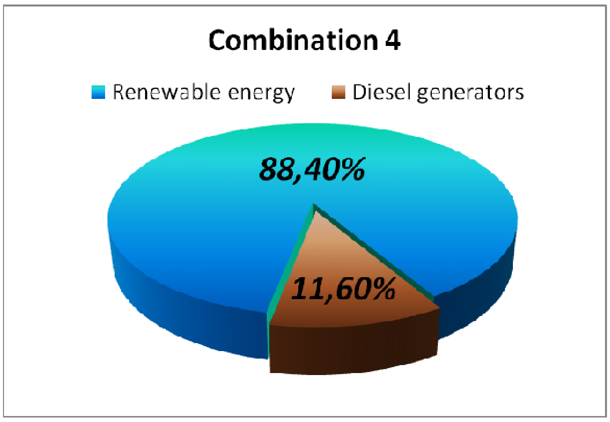
A characteristic of a successful hybrid system installation is its impact on the environment and one of the main reasons, except from the economical one, to switch to a hybrid system is to minimize the use of the diesel generators and subsequently the combustion of fossil fuels and the pollutant emissions.

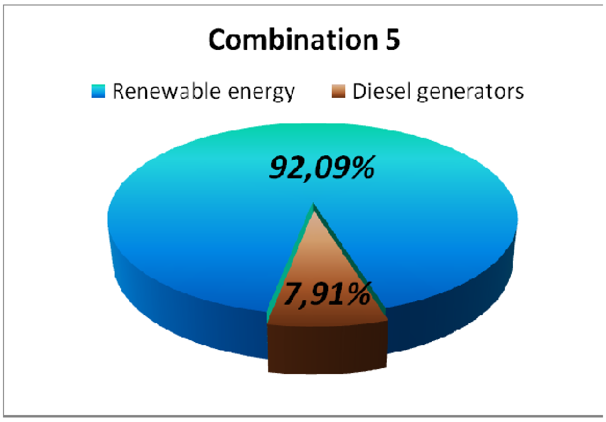
Below are the energy distributions between the renewable energy units and diesel generators that each combination has:

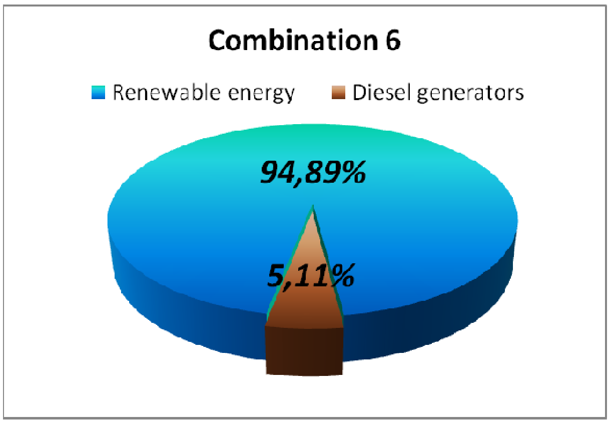


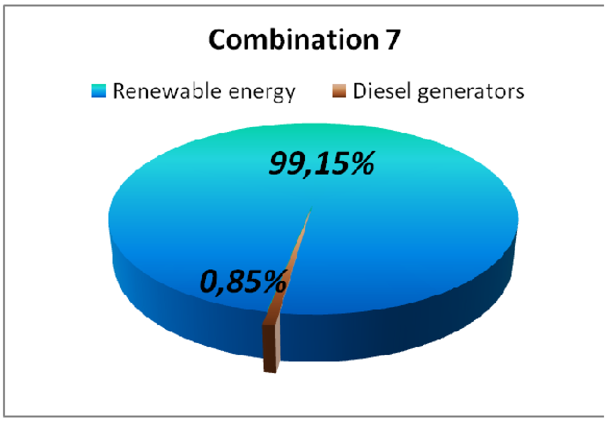


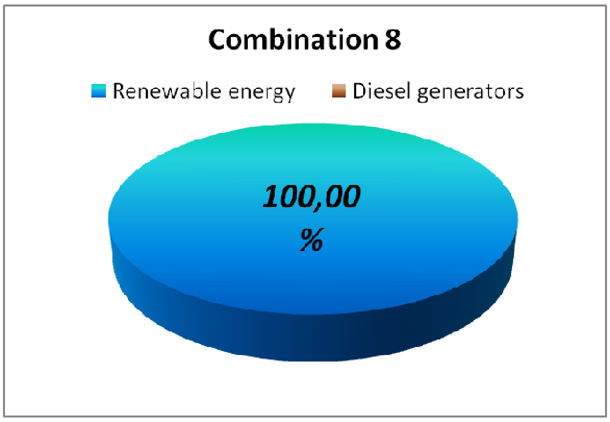












Combination 8 has no need for a back-up diesel generator, since its two hydro turbines cover the demand totally. Therefore, in environmental terms, this is the ‘cleanest’ combination that produces no CO_2 or other gases responsible for the greenhouse effect.

Combination 7 is also almost emission-free, while it includes only one diesel generator that only supplies 0,85% of the total power to the load, i.e. only 2,69kW per day (at 22:00), as seen in the data created from the algorithm.

What can be observed in the rest combinations is that the more PV panels and the less wind or hydro turbines a combination has, the more power from diesel generators it needs. Combinations 1 and 2 are the two combinations with the most PV modules (208 and 151 respectively) and their renewable energy units supply 71,21% and 79,07% of the load.

In general, the diesel generators turn on during and right after the time of the main peak demand (19:00-22:00), that the batteries run out of power, and the wind turbines and the photovoltaics produce less power and no power respectively, because of lower wind speeds and no sunlight. This shortcoming of the photovoltaics to supply power during the peak demand, assigns the serving of the whole load to the batteries and the diesel generators and it explains the fact that the more PV panels a combination has, the more the diesel generators will operate.

The second greatest peak demand of the load during the day takes place from 4:00 to 7:00 in the morning. It partially happens at the same time with no sunshine and lower wind speeds, but the batteries are able to supply the power needed, except from the first two combinations, where diesel generators are used too.

A consequence of the use of diesel generators is the fuel consumption. So, the table below presents the liters of fuel consumed for each combination throughout the day:

#	1	2	3	4	5	6	7	8
Fuel consumed per day (liters)	5,19	3,45	7,19	3,57	0,89	,29	,08	,00

The amount of CO_2 and other gases emissions depend on the type of diesel generator used and are not calculated. This calculation should take into consideration the frequency that the diesel generator starts and stops, the limits that its power should be, its technical features etc. and needs further analysis.

CHAPTER D: OPTIMIZATION OF THE HYBRID SYSTEM

D.1 Introduction

The target of this chapter is to find out the optimal combination - meaning the number of hydro turbines, wind turbines, photovoltaics, batteries and diesel generators - that leads to the minimization of some specific parameters, using an optimization software.

This optimization software will be based on the algorithm developed and described in the previous chapters, but it will use a whole different procedure in order to test the propriety of the combinations. As analyzed before, the algorithm was finding the acceptable combinations by checking the energy balance that the renewable energy units were providing. If that was a positive one, the number of batteries and diesel generators that would provide the appropriate back up, were calculated. Therefore, the algorithm had three free variables (number of hydro turbines, wind turbines and photovoltaics) that were producing the combinations.

By using this optimization software we are able to determine as many variables as we want, something that will significantly broaden the group of the acceptable combinations, providing more possible solutions for our problem. In our case the variables that will be determined are the number of hydro turbines (N_h), wind turbines (N_w), photovoltaics (N_{pv}), batteries (N_b) and diesel generators (N_d). When the process comes to an end, the optimal selection that minimizes an objective, which is also specified by the user, will be found.

Two optimization procedures will take place. The first will have a single objective, which will be the minimization of the kWh price, meaning that the combination that provides the minimum kWh price is going to be determined. The second will have two objective which will be the minimum kWh price along with the minimum contribution of diesel generators. The combination that will result from this procedure is going to combine both economical and environmental advantages.

D.2 EASY (Evolutionary Algorithm SYstem) software

EASY is a general purpose optimization platform that has been extensively used in engineering applications. It can be used to solve either single- or multi-objective, constrained or unconstrained optimization problems and it was developed and brought to market from a research group in the National Technical University of Athens (NTUA).

EASY offers a variety of optimization tools and it supports both stochastic and deterministic (gradient- or non-gradient-based) optimization methods, as well as some smart hybrids of the above.

It readily accommodates external software for the purpose of evaluating candidate solutions and computing their constraint values, provided that these are brought to input-output compatibility with EASY. A (μ,λ) evolutionary algorithm, where μ and λ are the parent and offspring population sizes, serves as the key search tool within EASY.

In order for EASY to communicate with the external evaluation software, the user must create a .bat file, that consists of a sequence of calls to available executables, which determine the evaluation process for each and every individual. This approach is absolutely flexible and introduces a negligible overhead due to the creation of new processes as well as the parsing of the script file each time a candidate solution is evaluated. To perform an evaluation, EASY writes and saves an ASCII text file (.dat) for the population member under consideration, in the current directory. This file contains the arithmetic values of the design variables. The sequence of executable file(s) called by the batch file should read the .dat file and then create a .res file, with the objective function value(s), meaning the value of the parameter(s) to be minimized.

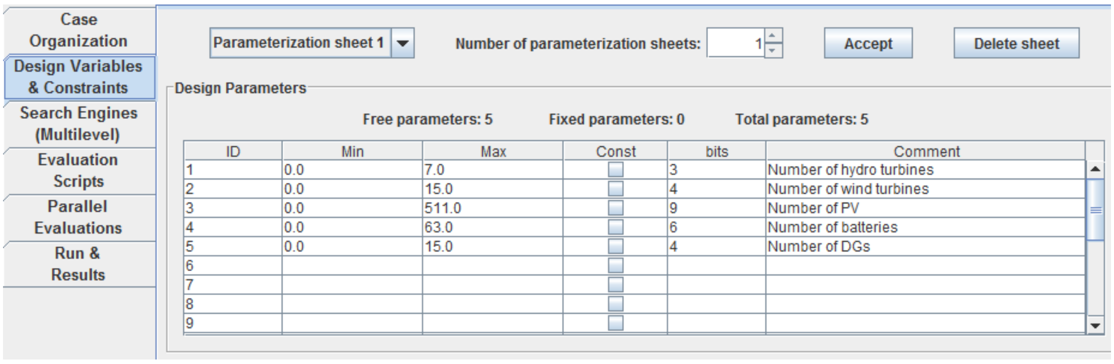
D.3 Optimal configuration that provides minimum kWh price (single objective)

✓ *Definition of design variables, further settings and progress of the optimization procedure:*

As mentioned above, the design variables in our case are the number of hydro turbines (N_h), wind turbines (N_w), photovoltaics (N_{pv}), batteries (N_b) and diesel generators (N_d), and their lower and upper bounds and the resolution in bits of binary encoded variables must be defined. In our case, the minimum and the maximum values of the design variables are the following:

- Number of 15kW hydro turbines: 0-7
- Number of 5kW wind turbines: 0-15
- Number of 120W PV panels: 0-511
- Number of 360AH, 6V batteries: 0-63
- Number of 5kW diesel generators: 0-15

Obviously, the value of these variables can only be integer. Therefore, the number of bits per variable must be equal to the possible integer numbers in the domain of definition of the variable. For instance, in the case of the batteries (0-63) $2^6=64$ values have to be produced. So, the number 6 fills the 'bits' cell, as seen below in the 'Design Variables & Constraints' tab of EASY:



Parameterization sheet 1

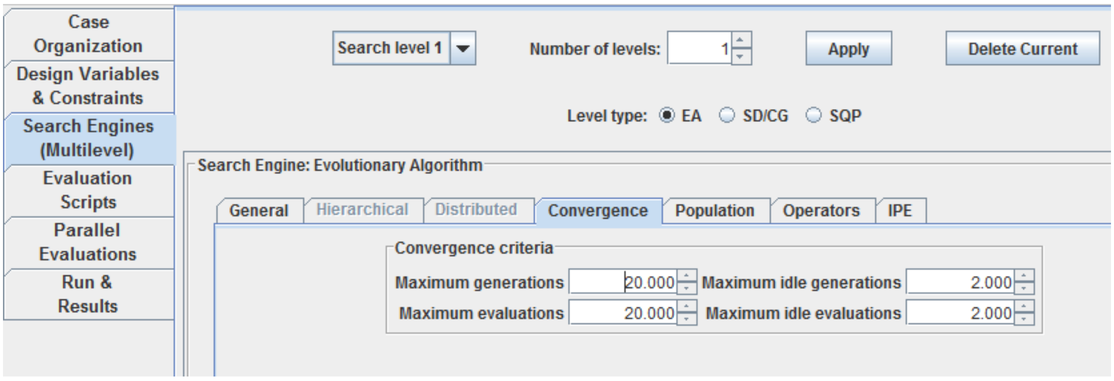
Number of parameterization sheets: 1

Design Parameters

Free parameters: 5 Fixed parameters: 0 Total parameters: 5

ID	Min	Max	Const	bits	Comment
1	0.0	7.0	☐	3	Number of hydro turbines
2	0.0	15.0	☐	4	Number of wind turbines
3	0.0	511.0	☐	9	Number of PV
4	0.0	63.0	☐	6	Number of batteries
5	0.0	15.0	☐	4	Number of DGs
6			☐		
7			☐		
8			☐		
9			☐		

Also, the Convergence Criteria are set as seen below:



Search level 1

Number of levels: 1

Level type: ● EA ○ SD/CG ○ SQP

Search Engine: Evolutionary Algorithm

Convergence criteria

Maximum generations 20.000

Maximum idle generations 2.000

Maximum evaluations 20.000

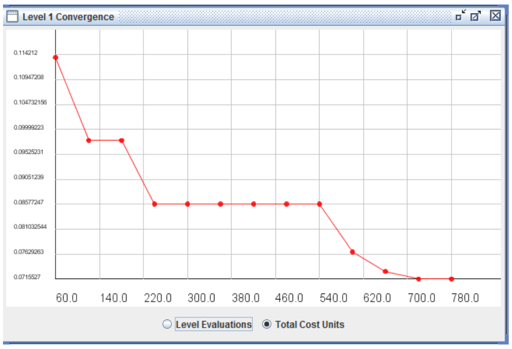
Maximum idle evaluations 2.000

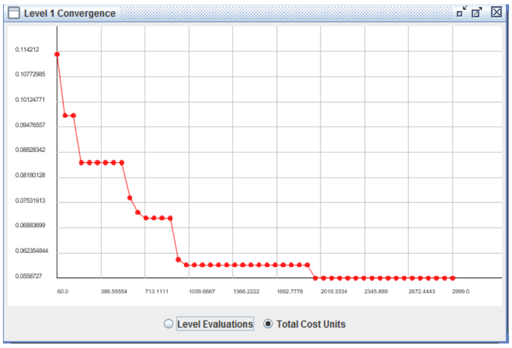
The maximum generations is the number of maximum generations each deme will evolve (20.000), the maximum evaluations is the maximum number of evaluations each deme is allowed to post (20.000), the maximum idle generations is the number of idle generations allowed for each deme (2.000) and the maximum idle evaluations is the number of idle evaluations allowed for each deme (2.000).

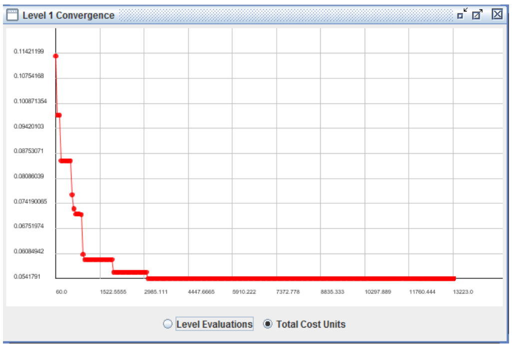
After setting initial population, simulations are performed to reach the final optimal configuration according to the proposed system. The best combination at every generation is obtained and the process is repeated until the pre-specified convergence is achieved or until the total generation specified is reached.

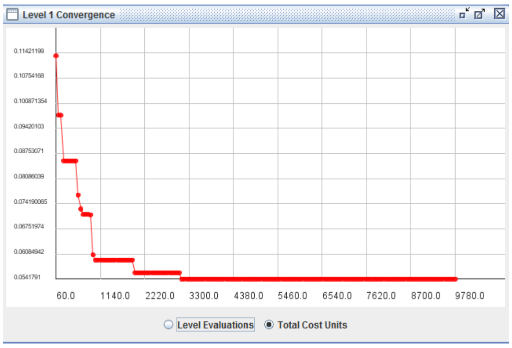
During the optimization procedure, the user can keep track of the convergence to the optimal configuration through some diagrams and tables available in EASY. The progress of the 'Variable trends' and the 'Convergence' diagrams during the process is depicted in the following images(they are created during the minimization of the kWh price.):

Convergence:

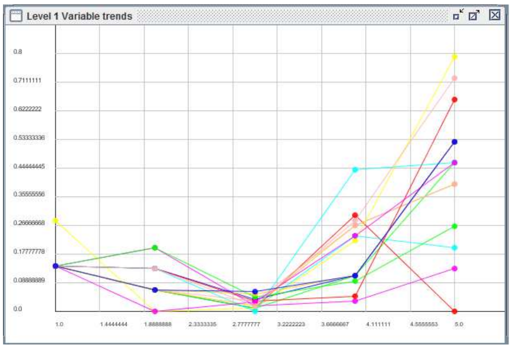


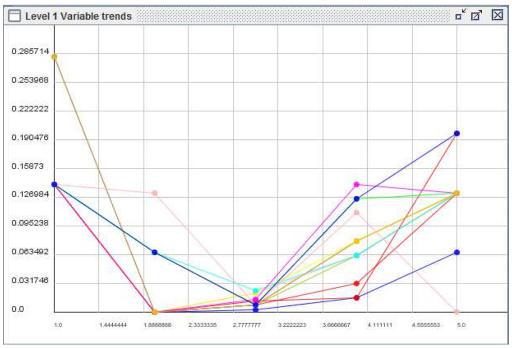


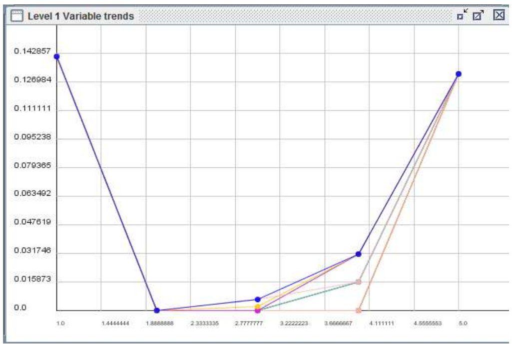


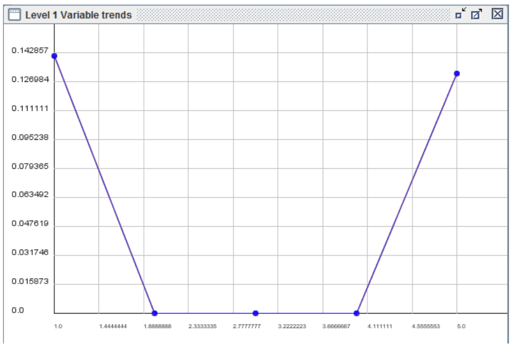


Variable trends:









By observing the progress of these diagrams, the user is able to change some of the settings that may delay the convergence. For example, by looking the 'Variable trends' diagrams, one can see that the values of the second (N_w), the third (N_{pv}) and the fourth (N_b) variables lie on the lower layers of their domain of definition. Therefore the user can interfere and narrow it down, so that the algorithm does not check solutions that are away from the optimal one.

In terms of the convergence, we can see that the kWh price has reached its minimum value after approximately 3000 evaluations.

- ✓ *Results:*

  The combination that provides the lowest kWh price, based on EASY, is the following one:

  Combination EASY1

N_h	N_w	N_{pv}	N_b	N_d	€/kWh
1	0	0	0	2	0,054

Combination EASY1 is a combination that did not turn up in the algorithm developed. It is obviously one of those combinations that were not tested, because of the less independent variables that leaded to less candidate solutions. As already highlighted, the evolutionary algorithms can test the whole group of combinations that this proposed system can have.

The details of this combination are the following:

Combination EASY1

Nh=1, Nw=0, Npv=0, Nb=0, Nd=2

hour	*Pht*	*Pwt*	*Ppvt*	*Pgen*	*Pgenfinal*	*Load*	*Pbatgen*	*Pd*	*Fuel*	*Dumped*
1	12.82	0.00	0.00	12.82	12.82	9.90	0.00	0.00	0.00	2.67
2	12.82	0.00	0.00	12.82	12.82	9.00	0.00	0.00	0.00	3.57
3	12.82	0.00	0.00	12.82	12.82	9.15	0.00	0.00	0.00	3.42
4	12.82	0.00	0.00	12.82	12.82	13.05	0.00	0.23	0.90	0.00
5	12.82	0.00	0.00	12.82	12.82	14.10	0.00	1.28	1.16	0.00
6	12.82	0.00	0.00	12.82	13.76	15.60	0.00	2.78	1.52	0.00
7	12.82	0.00	0.00	12.82	13.76	16.05	0.00	3.23	1.64	0.00
8	12.82	0.00	0.00	12.82	13.76	12.00	0.00	0.00	0.00	0.57
9	12.82	0.00	0.00	12.82	13.76	12.60	0.00	0.00	0.00	0.00
10	12.82	0.00	0.00	12.82	13.76	9.45	0.00	0.00	0.00	3.09
11	12.82	0.00	0.00	12.82	13.76	7.50	0.00	0.00	0.00	5.07
12	12.82	0.00	0.00	12.82	13.76	11.40	0.00	0.00	0.00	1.17
13	12.82	0.00	0.00	12.82	13.76	11.70	0.00	0.00	0.00	0.87
14	12.82	0.00	0.00	12.82	13.76	10.95	0.00	0.00	0.00	1.62
15	12.82	0.00	0.00	12.82	13.76	12.00	0.00	0.00	0.00	0.57
16	12.82	0.00	0.00	12.82	13.76	12.45	0.00	0.00	0.00	0.12
17	12.82	0.00	0.00	12.82	13.76	13.50	0.00	0.68	1.01	0.00
18	12.82	0.00	0.00	12.82	13.76	15.00	0.00	2.18	1.38	0.00
19	12.82	0.00	0.00	12.82	12.82	19.05	0.00	6.23	2.37	0.00
20	12.82	0.00	0.00	12.82	12.82	19.50	0.00	6.68	2.48	0.00
21	12.82	0.00	0.00	12.82	12.82	20.10	0.00	7.28	2.63	0.00
22	12.82	0.00	0.00	12.82	12.82	19.80	0.00	6.98	2.56	0.00
23	12.82	0.00	0.00	12.82	12.82	13.05	0.00	0.23	0.90	0.00
24	12.82	0.00	0.00	12.82	12.82	10.50	0.00	0.00	0.00	2.07

Total dumped power per day=24.78kW
Total fuel consumed per day=18.54liters
Capital Cost=3609.01€
Annual operational cost=2733.62€
Total annual cost=6342.63€
Total power generated per day=354.51kW
Renewable(%)= 88.23
DG(%)= 11.77
Total cost per kWh=0.054€/kWh

Combination EASY1 offers a better price than combination 8 (0,058€/kWh), something that was expected due to the larger group of combinations it tested. We can observe that they are similar, while combination 8 includes only 2 hydro turbines and combination EASY1 includes 1 hydro turbine and 2 diesel generators.

In terms of the environment, combination 8 that serves the load only with hydropower (no DG contribution) is the 'cleanest' combination possible. Combination EASY1 can also be considered as an environmentally friendly one, while its diesel generators only serve 11,7% of the load demand.

As observed in paragraph C.3, the main reason that these two combinations are the most economic ones is the stable water flow (35 l/s), that is really unlikely to happen in reality. The fact that these combinations do not include batteries gives them much less flexibility to cope with the inconstancies that may occur.

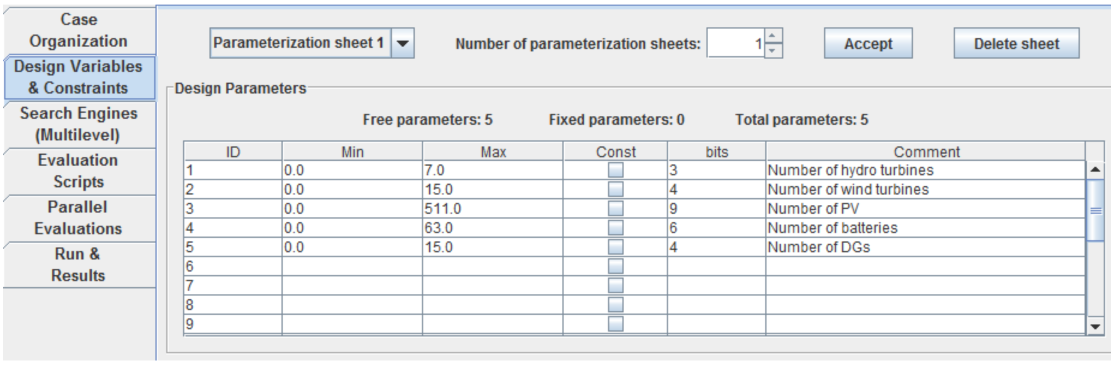
D.4 Optimal configuration that provides minimum kWh price and DG contribution (double-objective)

✓ *Definition of design variables, further settings and progress of the optimization procedure:*

The previous configuration (combination EASY1) was the optimal one in minimizing the kWh price, which was the single objective. By adding one more objective in the optimization process we will be able to determine the combinations that minimize two of the specified parameters (objectives), which will be the kWh price and the percentage of the load that is supplied by the diesel generators.

The results of this process will be really useful, because we will be able to realize if the economical and the environmental factors are opposed to each other or not. That is another advantage towards the algorithm that was just calculating the DG contribution that each of the eight acceptable combinations has.

The design variables that are going to be determined are the same with the single objective optimization, as seen below:



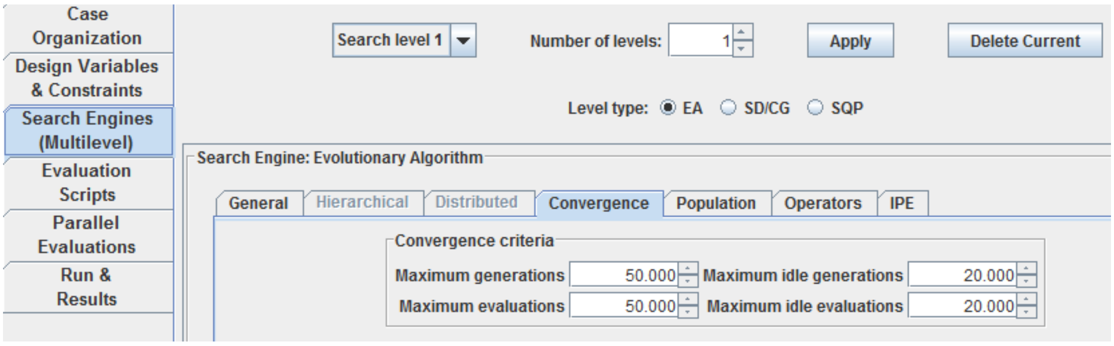
Number of parameterization sheets: 1

Design Parameters

Free parameters: 5 Fixed parameters: 0 Total parameters: 5

ID	Min	Max	Const	bits	Comment
1	0.0	7.0	☐	3	Number of hydro turbines
2	0.0	15.0	☐	4	Number of wind turbines
3	0.0	511.0	☐	9	Number of PV
4	0.0	63.0	☐	6	Number of batteries
5	0.0	15.0	☐	4	Number of DGs
6			☐		
7			☐		
8			☐		
9			☐		

Due to the fact that it is now a multi-objective task, the numbers of the maximum evaluations and generations are set at 50000, while the number of idle generations and evaluations are 20.000.



Number of levels: 1

Level type: ● EA ○ SD/CG ○ SQP

Search Engine: Evolutionary Algorithm

Convergence criteria

Maximum generations 50.000 Maximum idle generations 20.000

Maximum evaluations 50.000 Maximum idle evaluations 20.000

Another option that needs to be set in multi-objective tasks is the order of magnitude of each objective. In our case and after taking into consideration the importance of low emissions, the kWh price and the diesel contribution are considered equally important, so their order of magnitude will be the same.

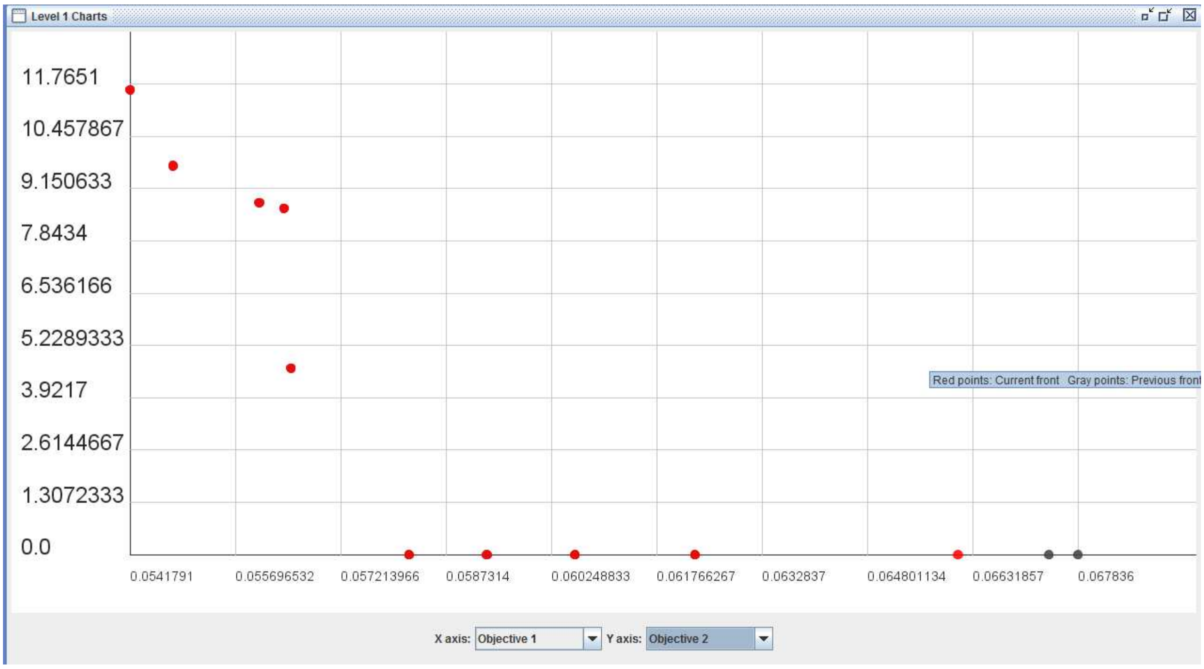
- ✓ *Results:*

The table below presents the ten combinations that were considered the optimal ones during the optimization process:

Combinations EASY2

#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
N_h	1	1	2	1	2	1	2	2	1	1
N_w	0	0	0	1	0	0	0	0	0	1
N_{pv}	0	1	0	2	1	2	5	1	1	2
N_b	0	3	0	1	1	3	0	1	2	11
N_d	2	2	0	2	0	2	0	2	2	1
€/kWh	0,0541	0,0560	0,0582	0,0565	0,0593	0,0564	0,0605	0,0623	0,0548	0,0661
%DG	11,76	8,91	0,00	4,72	0,00	8,76	0,00	0,00	9,84	0,00

The diagram depicting the values of the two objectives for each combination is the following one:



As we can see, the best combination that resulted from the double-objective optimization is the one (combination EASY1) that resulted from the single-objective one too. Now we have a much clearer image of this combination, as it proved to be the optimal one in terms of minimum cost and minimum use of diesel generators.

The combination that provided the best kWh based on the algorithm (combination 8) is the same with combination EASY2.3.

CHAPTER E: COMMENTS ON THE RESULTS AND SUGGESTIONS FOR FURTHER RESEARCH

The operation of a micro-hydro/wind/PV hybrid system was analyzed and optimized. An algorithm was developed in order to find the acceptable combinations, by changing the renewable energy units and adapting the needed batteries and diesel generators. The input data came from a rural village in Western Ghats in Kerala, India.

The developed numerical algorithm can be applied for any stand-alone hybrid system. The wind speed, the insolation, the load demand and the water flow daily data of any rural area could be used in order for the algorithm to determine the acceptable combinations and simulate the operation of the proposed micro-hydro/wind/PV hybrid energy system in this area. With a slight modification of the code, it would be able to read the above data for one year, and not for an average day. That would provide of course more accurate and realistic results. Furthermore, results that would take into consideration a non-stable water flow, would correspond better to the reality which cannot have an absolutely stable water flow. For that, nothing needs to be changed in the algorithm, as it can already read 24 values of water flow in the input file.

Based on that algorithm, an optimization software (EASY-Evolutionary Algorithm SYstem) was used to find the optimal configuration of the system in terms of cost and environmental behavior.

The results that occurred were really encouraging and they highlight the economical and environmental advantages that the installation of the hybrid system would have instead of extending the grid supply and using diesel generators:

		Combination name	Micro hydro (15kW)	Wind units (5kW)	PV panels (120W)	Batteries (360Ah, 6V)	Diesel generators (5kW)	€/kWh	DG (%)
Algorithm		1	0	0	208	22	5	0,237	28,79
		2	0	1	151	20	4	0,196	20,93
		3	0	2	95	18	4	0,161	14,39
		4	0	3	38	16	3	0,124	11,60
		5	0	4	0	15	3	0,107	7,91
		6	1	0	7	8	2	0,065	5,11
		7	1	1	0	9	1	0,063	0,85
		8	2	0	0	0	0	0,058	0,00
EASY	*Single-objective*	EASY1	1	0	0	0	2	0,054	11,76
	Double-objective	EASY2.1	1	0	0	0	2	0,054	11,76
		EASY2.2	1	0	1	3	2	0,056	8,91
		EASY2.3	2	0	0	0	0	0,058	0,00
		EASY2.4	1	1	2	1	2	0,056	4,72
		EASY2.5	2	0	1	1	0	0,059	0,00
		EASY2.6	1	0	2	3	2	0,056	8,76
		EASY2.7	2	0	5	0	0	0,060	0,00
		EASY2.8	2	0	1	1	2	0,062	0,00
		EASY2.9	1	0	1	2	2	0,054	9,84
		EASY2.10	1	1	2	11	1	0,066	0,00

The surplus of solutions that EASY software provided is more than obvious and the reason for that was explained in the previous chapter. Nevertheless, combination 8 that resulted from the algorithm, as well as combinations 6 and 7, offer extremely competitive kWh prices along with minimal use of diesel generators.

An advantage of the algorithm is that its sequence of results, gives us the opportunity to understand how the addition of some units affect the cost and the general operation of the hybrid system.

In terms of the system's components, the following observations are lined up:

The PV modules used in this case study have a low rated power (120W) and that has both negative and positive consequences. As observed in the previous paragraphs, the more PV panels a combination has, the higher costs it has and the more the diesel generators are used. The PV panels have the highest capital cost per Watt (Rs. 200=3,012€) compared to the hydro turbines, the wind turbines and the diesel generators, and the capital cost is the main part of the total cost calculated in the algorithm. The operational costs have a significantly smaller portion of the total cost, so the fact that the photovoltaics have the lowest operational cost per kWh (Rs. 0,05=0,0007€) does not balance their high capital cost. Furthermore, as highlighted before, the PV panels do not operate during the peak demands of the load, meaning that almost all the power must be retrieved from the batteries and the diesel generators at that time, causing the operational cost, the fuel cost and the emissions to increase.

Nevertheless, the PV modules' low rated power provides a greater accuracy for the method that the algorithm uses to find the acceptable combinations. Since the energy density of the micro-hydro and wind, far exceeds that of a single solar PV module, the number of wind turbines and micro-hydro are fixed and the number of PV modules is incremented until the system is balanced. This flexibility could not be provided by the other renewable energy units. For instance, in our case study, a combination that has just one hydro turbine wouldn't be acceptable, while one with two hydro-turbines is by far an acceptable one, that dumps lots of the produced energy. This happens because the leap of the installed capacity between these two combinations is the rated power of the hydro turbine which is 15kW. On the contrary, the power difference that an acceptable combination can have with its previous one, that has one PV module less and is not acceptable, is only 120W.

A plan that would keep this advantage and limit the cost problem would be to use two sizes of photovoltaics. The bigger size photovoltaics could be used to cover the main part of the installed capacity, while offering a better capital cost per Watt and operational cost per kWh. The smaller ones would be used so that the flexibility of the procedure, as described before, won't be lost.

In terms of the batteries, they are a parameter that elevates the cost (especially the operational one) of the system. Their presence though, remains indispensable for the operation of the hybrid system, or else there would be no energy storage capability. A correct strategy would minimize the number of the batteries in order to make the system more competitive, like the combinations that have few batteries.

Other forms of energy storage could provide a less expensive storage of energy that exceeds the demand. For example , the continuously developing technology of fuel cells may as well be a more competitive option than the battery banks. Furthermore, storing energy in the form of water, pumped from a lower elevation reservoir to a higher one (pumped storage) is a really large capacity form of energy storage available nowadays. Of course, the decision that would choose between different forms of energy storage demands extensive analysis that takes into consideration many parameters regarding the cost and the viability of the system.

The hydro turbines applied in our case study, have a great cost to production proportion. Furthermore, their stable output (as considered in the calculations) provides unceasing supply throughout the day. In order to oppose to the problem with the great amount of dumped power that occurs when two hydro turbines are installed (combination 8), a solution that uses one of the existing hydro turbines (15kW) and another one or two of smaller rated power could be looked into. Of course, an absolutely stable water flow throughout the year cannot occur in real life and a more detailed research can be made by having a variable flow during the average day.

The wind turbines of the system provide a decent supply throughout the day. As remarked in the theoretical part dealing with wind power, even a small variation of wind speed can result in a great fluctuation of output. That explains the fact that even though the daily wind speed data do not have great variations, the power diagrams show that there is a stable wind power production in the time between 5:00 and 15:00, when the wind turbines reach their rated power, but a significant drop at the rest hours. A way to take a better advantage of the wind potential is to use wind turbines with slightly bigger size than the current one (5kW).

A part of the general operation of the system, developed in this diploma thesis, that would need a further research is the operation strategy of the diesel generators according to the batteries. In our case study, the diesel generators turn on when the batteries reach their minimum power level. A better cooperation between the DGs and the batteries and a subsequent lessening of the cost and the pollutant emissions could be succeeded through a more complicated and sophisticated strategy, that would combine the options mentioned below:

- ✓ DGs start or/and stop: At specific battery level that is determined by the state of charge or battery terminal voltage **OR** at specific site load power which is measured as a percentage of the diesel generator or inverter rated capacity **OR** at specific renewable output power as a percentage of the peak power of the renewable energy units **OR** after a specific time period.
- ✓ DGs' operation: At fixed, at the full power rating **OR** they meet the entire load and charge the battery if required **OR** they meet the base load with battery supplying the transient load.
- ✓ Inverter's operation: To meet the transient load **OR** to meet all or part of the load.

- ✓ Batteries charging starts: At the beginning of the diesel operating **OR** at specific battery level during the running of the diesel generator **OR** at specific diesel operating power level **OR** at specific output of the renewable energy units.
- ✓ Batteries charging power level: Fixed at the full power rating of the charger **OR** varying to meet the maximum battery charging rate.
- ✓ Batteries charging stops: At specific battery level **OR** at specific diesel operating power level **OR** at specific output of the renewable energy units.

The selection of the best operation of the DGs and the batteries of the system requires further technical characteristics of these components to be known.

A more extensive cost analysis would also offer more information regarding the system and its components. In this work, the cost is calculated based on the capital and the operational cost and in case of further research more costs could be included. Annual customer damage cost, annual emission cost in order to capture the CO_2 emission generated from the DGs and the annual replacement cost are suggested. Battery units are likely to be replaced during the project's lifetime, what depends on both their cycle life, which is the length of time that the battery will last under normal cycles, and their float life, which is the maximum length of time that the battery will last , regardless of how much it is used.

Moreover, in this work no costs for the inverter, the charge controller and the minor parts of the equipment were considered. This is because the main target of this analysis is to compare the costs of the different combinations and not to provide a detailed and accurate cost presentation, and the costs of these parts would not affect this comparison, while they would be stable for each combination.

SYMBOLS USED IN THE ALGORITHM (IN ALPHABETICAL ORDER):

Tables:
aI(24): Insolation (W/m^2)
aLoad(24): Load demand (kW)
dP(24): Power difference ($P_{genfinal}$-P_{load}) (kW)
Dump(24): Power dumped (kW)
Fuel(24): Fuel consumption (liters)
Pbatgen(24): Power retrieved from the batteries (kW)
Pbatteries(24): Power level of all the batteries (kW)
Pd(24): Power produced by the diesel generators (kW)
Pgen(24): Power produced by all renewable energy units (kW)
Pgenfinal(24): Power produced by all renewable energy units, that serves the load (inverter losses are included) (kW)
Ph(24): Power produced by each hydro turbine (kW)
Ppv(24): Power produced by each PV panel (kW)
Pw(24): Power produced by each wind turbine (kW)
V(24): Wind speed (m/s)

Variables:
a: Efficiency of the hydro turbine
ab: Battery charging efficiency
ag: Efficiency of the wind generator
aHnet: Head of the micro-hydro scheme (m)
ainv: Efficiency of the inverter
AOC: Annual operational cost of the system (€)
Ap: Area of single PV panels (m^2)
apv: Efficiency of a PV panel
Area: Swept area of the wind turbine's rotor (m^2)
at: Efficiency of the wind turbine
capacity: Difference between the maximum and the minimum power difference ($P_{genfinal}$-P_{load}) (kW)
CCb: Capital cost of battery (€)
CCd: Capital cost of DG units (€)
CCh: Capital cost of micro-hydro unit (€)

CCpv: Capital cost of PV unit (€)
CCtotal: Annual capital cost of the system (€)
CCw: Capital cost of wind unit (€)
cp: Power coefficient of the wind turbine
CRF: Capital Recovery Factor
d: Wind wheel diameter (m)
DOC: Daily operational cost of the system (€)
DOD: Maximum depth of battery's discharge
dmax: Maximum hourly power generated by the diesel generators (kW)
dpmax: Maximum power difference ($P_{genfinal} – P_{load}$) (kW)
dpmin: Minimum power difference ($P_{genfinal} – P_{load}$) (kW)
FC: Fuel cost (€/l)
Fueltotal: Daily fuel consumption (liters)
g: Gravity (m/s^2)
icombination: Number of current combination
Nb: Number of batteries
Nd: Number of diesel generators
Nh: Number of hydro turbines
Npv: Number of PV panels
Nw: Number of wind turbines
OCb: Operational costs of batteries (€/kWh)
OCd: Operational costs of DG units (€/kWh)
OCh: Operational costs of micro-hydro unit (€/kWh)
OCpv: Operational costs of PV units (€/kWh)
OCw: Operational costs of wind units (€/kWh)
Pb0: Power level of each battery at t=0
Pbatgentotal: Daily power retrieved from the batteries (kW)
Pbatteries0: Power level of all the batteries at t=0
Pbatteriesmax: Maximum power stored in all the batteries (kW)
Pbatteriesmin: Minimum power stored in all the batteries (kW)
Pbmax: Maximum power of each battery (kW)
Pbmin: Minimum power of each battery (kW)
Pdrated: Rated power of the diesel generator (kW)
Phrated: Rated power of the hydro turbine (kW)

pi: the mathematical constant π
Ppvrated: Rated power of the PV panel (kW)
Ptotal: Daily power produced by renewable energy units and diesel generators (kW)
Punittotald: Daily power generated by all diesel generators (kW)
Punittotalh: Daily power generated by each micro-hydro turbine (kW)
Punittotalpv: Daily power generated by each PV panel (kW)
Punittotalw: Daily power generated by each wind turbine (kW)
Pwrated: Rated power of the wind unit (kW)
rate: Interest rate
rho: Density of the water (kg/m^3)
rhoair: Air density (kg/m^3)
sigma: Self-discharge factor of the battery
sum: Sum of all the power differences($P_{genfinal} - P_{load}$)*, measured for each hour of the day (kW)*
TC: Total annual cost of the system (€)
totaldump: Daily power dumped (kW)
Y: Project lifetime (years)

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