COMPARING MAINTENANCE COSTS OF RENEWABLE ENERGY SYSTEMS

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INTRODUCTION

Energy plays an indispensable role in any modern society. We all depend on a constant and reliable supply of energy - for our homes, businesses and for transportation. In the past few years there has been significant interest in the use of renewable energy sources to meet the growing global demand for energy. The interest in renewable sources of energy has been spurred by the limited availability of conventional energy sources, such as oil, gas and coal, resulting in high energy costs, and the environmental pollution caused by the Carbon emission from the combustion of fossil fuels that has direct implications on the global climate. Figure 1 shows one possible scenario of projections of the market shares of different types of renewable energy sources in 2020. Overall, using renewable energy can provide many benefits, including:

- Making use of secure, local and replenishable resources
- Reducing dependence on non – renewable energy sources
- Helping to keep the air clean
- Helping to reduce the production of carbon dioxide and other greenhouse gases
- Creating new jobs in renewable energy industries.

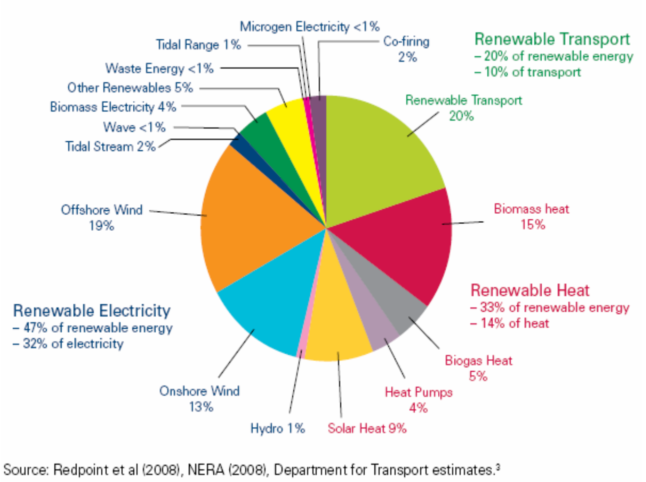

Figure 1 *Prediction of market share of different renewable energy sources in 2020*

Table 1 gives an overview of different sources of renewable energy and the corresponding technologies or applications developed to harvest these energy sources. A key issue in the widespread acceptance of renewable energy sources is the overall cost of energy production. Several of the technologies, such as wind energy, small–scale hydro power, energy from biomass and solar thermal applications are economically viable and competitive. The others, such as photovoltaic (PV) cells for solar energy conversion, which are comprised of silicon module panels that directly generate electricity from the Sun's light rather than heat, depend on increasing demand and large production volume to achieve the economies of scale necessary to be competitive with central generation.

Table 1 *Overview of renewable energy sources*

Renewable Energy Source	Technology/ Application
Solar	1. Photovoltaic (PV) cells to produce electricity; 2. Solar thermal system for heating water.
Wind	1. Wind turbine: single turbines or a number of turbines in a wind farm 2. Offshore: turbines in the water
Water	Hydro electric, wave and tidal systems to produce electricity
Biomass	Direct combustion of gas produced from biomass, or biogas, to generate electricity and/or heat – e.g. wood stoves or larger commercial operations
Geothermal	Using the temperature of the earth to produce electricity and/or heat, e.g. ground source heat pumps

Considerable attention has been given by the research and practitioner communities to installation, production and distribution costs. However, the issue of maintenance cost has not been addressed adequately. This paper focuses on the long term maintenance costs for photovoltaic solar energy systems and turbine based wind energy systems. We specifically have selected PV cells and turbine based wind energy systems since these technologies are mature enough to allow us to compare their maintenance costs, as opposed to nascent technologies such as fuel cells where the maintenance issues and associated costs have yet to be reliably estimated.

Solar Energy

Photovoltaic (PV) technology permits the transformation of solar energy directly into electric current. PV systems can deliver electric energy to a specific appliance and / or to the electric grid, as seen in Figure 2. PV has the potential to play an important role in the transition towards a sustainable energy supply in the 21st century, and to cover a significant share of future electricity needs. In addition, the technology could improve security of energy supply, provide environmentally benign energy services and enhance economic and social welfare. In combination with other renewable energy technologies and energy efficiency, PV technology is becoming a key technology for the future. Globally, the PV sector has grown by an average of 25% per year over the past two decades and by almost 50% per year over the past five years. This has happened because several countries have put in place successful market development policies. In Europe, these countries are Germany, Spain, Portugal, France, Italy, Greece and Belgium, who will most likely be joined by others. Outside Europe, Japan, Korea and the USA provide good examples of well-developed or emerging markets in PV.

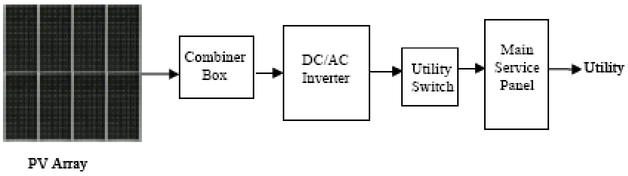

Figure 2 *Photovoltaic energy generation process*
Source: Solar Energy Technologies Program
(www.EERE.Energy.gov)

PV modules are generally divided into two broad categories:

- wafer-based crystalline silicon (c-Si);
- thin films, which include thin-film silicon, copper-indium/gallium-selenide/sulphide (CIGS), amorphous silicon (a-Si) and cadmium telluride (CdTe).

Thin film PVs can be highly efficient in material utilization, have relatively low labor requirements, and use comparatively less energy from start to finish. Wafer-based crystalline silicon (c-Si) is currently the dominant technology used in PV cells. The pervasive use of this type of PV cell technology is for several reasons: it is widely available; it has proven reliability; and it is well understood, since it is founded on the knowledge and technology originally developed for the electronics industry.
During normal operation, PV power systems do not emit substances that may threaten human health or the environment. In fact, through the savings in conventional electricity production they can lead to significant emission reductions. There are, however, several indirect environmental impacts related to PV power systems that require further consideration. The production of present generation PV power systems is relatively energy intensive, involves the use of large quantities of bulk materials and (smaller) quantities of substances that are scarce and/or toxic. During operation, damaged modules or a fire may lead to the release of hazardous substances. Finally, at the end of their useful life time PV power systems have to be decommissioned, and resulting waste flows have to be managed.

Maintenance and Operation Process

Solar electric systems are a proven technology and are extremely reliable. 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.
Composition of a solar panel array is shown in Figure 3. Solar panels have no moving parts, and therefore no potential points of mechanical failure. Recommended preventive maintenance is usually limited to semi–annual rinsing of the panels with water and monthly reading of inverter production. Grid-connected applications need better Balance of System (BOS) components. A variety of reliable components are available, but the efficiency, lifetime and operation of some components can be further improved, especially inverters and batteries. In addition, standardisation and quality assurance are crucial – for components as well as for the entire system. Ultimately, building integrated photovoltaic systems (BIPV) should be treated like almost any other building construction component, with similar lifetimes and installation requirements.

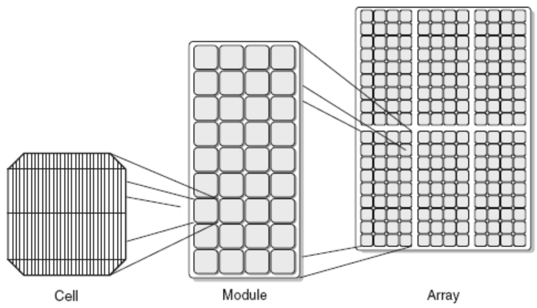

Figure 3 *Structure of a solar panel array*
Source: Solar Energy Technologies Program
(www.EERE.Energy.gov)

The common maintenance process for PV systems is:

- clean the module array;
- check all electrical connections;
- log lifetime, instantaneous power and energy output;
- check for any plant growth causing shading;
- write a report on system status and any corrective actions if necessary.

Overall, one can see that the maintenance operations required for PV arrays are quite basic and mostly manual, ranging from occasionally brushing any dust or grime from the panels to checking the electrical contacts. In fact if the panels are suitably angled, rain water accomplishes the task of keeping the panels clean quite effectively. However, inverters and batteries need to be replaced every five to ten years, or more frequently in hot climates. The solar modules are the most durable part of the system, with failure rates of only 1 in 10,000 per year. Operation and maintenance costs of PV installations are relatively low as compared to their initial installation costs, typically between 1% and 3% per year of installation costs over the 20- 30 years lifetime of PV modules.
We now present two case studies of real-world PV installations to compare maintenance costs for different capacity installations (50-500kw).

Figure 4 *Cleaning modules*
source: www.istarsolar.com

Case Study A

- solar photovoltaic system's power = 50 kw;
- location: Cesena (Italy);
- # of modules = 286;
- module's power = 175 Wp;
- dimension = 366.08 m²;
- # of inverters = 9;
- installation of 1 kWp = 7000 €;
- cost of total installation = 350 000 €.

Maintenance costs in this case were observed to be 1% of the total investment. The cost of scheduled maintenance for this system was 3.500,00 €/year. It is interesting to note how these costs were distributed among the various scheduled maintenance activities:

- clean the module array: 805,00 € / year (37 hours/year, 23% of annual cost);
- check all electrical connections, log lifetime, instantaneous power and energy output, write a report of system status and any corrective actions if necessary : 1.995,00 € /year (91 hours/year, 57% of annual cost);
- check for any plant growth causing shading : 700€ / year (32 hours/year, 20% of annual cost).

General costs for unscheduled maintenance were observed to be:
- replace an inverter = 25.000,00 € (500,00 €/kWp). MTBF (Mean time between failure) of inverter is 10 years;
- replace a module = 675,00 €

Case Study B

- solar photovoltaic system's power = 500 kw;
- location: unknown;
- # of modules = 1.680 (140 strings, 12 modules/string);
- module's power= 300 W/module;
- dimension: 2.135 m²;
- # of inverters = 1;
- installation of 1 kWp = 5.500 €;
- cost of total installation = 2.750.000 €.

Maintenance costs in this case were observed to be 0.5 % of the total investment. The cost of scheduled maintenance for this system is 13.750,00 €. These costs were distributed among the various scheduled maintenance activities as follows:
- Clean the module array: 3.163,00 € / year (144 hours/year, 23% of annual cost)
- Check all electrical connections, log lifetime, instantaneous power and energy output, write a report on system status and any corrective actions if necessary : 7.838,00 € /year (356 hours/year, 57% of annual cost)
- Check for any plant growth causing shading : 2.750,00 € / year (125 hours/year, 20% of annual cost)

General costs for unscheduled maintenance were observed to be:
- Replace an inverter = 200.000,00 € (400,00 kWp);
- Replace a module = 530,00 €

Wind Energy

Wind power is the most advanced, and commercially available of renewable energy technologies. A typical wind energy generation system is shown in Figure 5.

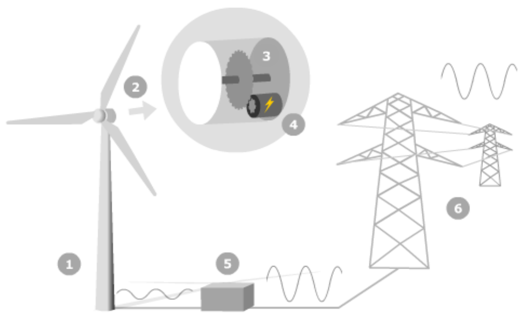

Figure 5 *Functioning of a wind energy system - 1) The wind blows on the blades and makes them turn; 2) The blades turns a shaft inside the nacelle (the box at the top of the turbine); 3) The shaft goes into a gearbox which increases the rotation speed; 4) The generator, which uses magnetic fields to convert the rotational energy into electrical energy. These are similar to those found in normal power stations; 5) The power output goes to a transformer, which converts the electricity coming out of the generator at around 700 Volts (V) to the right voltage for distribution system, typically 33,000 V; 6) The national grid transmits the power around the country - s*ource: Wind Force 10

A totally natural source, wind provides power which is both pollution-free and unlikely ever to run out. Wind power is also among the cheapest of the renewable energy sources. At good wind sites it is already fully competitive with traditional fossil fuel and nuclear generation. Its cost also continues to fall as the technology improves and the use of individual sites is maximised.

In recent years it has been the world's fastest growing energy source. By the end of 1998, more than 10,000 MW of electricity-generating wind turbines were operating in almost fifty countries around the world. Over the past six years the average annual growth in sales of wind turbines has been 40%. The most successful markets for wind energy in recent years have been in Europe, particularly Denmark, Germany and Spain. There has also been an upsurge in the use of the technology in the United States, as well as in many developing countries, including India, China, and countries in South America.

Maintenance and Operation Process

A wind turbine's reliability is dependent largely on the particular machine architecture, how well it is designed, and the quality of manufacture. Figure 6 shows a variety of potential component failure models, such as gearbox bearings, generator bearings and windings, power electronics, gearbox torque arms, pitch drive electronics. The reliability of a wind turbine also varies with the operating environment, since the machine's reaction to the wind environment determines the loading imposed on the components. The interactions between the operating conditions and the components of a wind turbine have not yet been fully understood.

An important issue that must be considered while discussing wind turbine repairs relates to safety. Large, modern wind turbines normally use conical tubular steel towers. The primary advantage of this tower over a lattice tower is that it makes it safer and far more comfortable for service personnel to access the wind turbine for repair and maintenance.

The primary danger in working with wind turbines is the height above ground during installation work and when doing maintenance work, as shown in Figure 7. New wind turbines are required to have fall protection devices, i.e. the person climbing the turbine has to wear a parachutist-like set of straps.

The straps are connected with a steel wire to an anchoring system that follows the person while climbing or descending the turbine.

The wire system has to include a shock absorber, so that persons are reasonably safe in case of a fall. Protection from the machinery, fire protection and electrical insulation protection is governed by a number of national and international standards. During servicing it is essential that the machinery be stopped completely. In addition to a mechanical brake, the rotor is locked in place with a pin, to prevent any movement of the mechanical parts whatsoever. Working conditions can be in extreme temperature conditions and may be curtailed by high winds. Some turbines are equipped with hoists and rigging equipment, but in general, all tools and equipment, in addition to spares, must be lifted into the nacelle. Space is limited inside the nacelle and working positions may be awkward. Work outside of the nacelle, including transitions into the hub on some turbines, requires working with a safety harness and lanyards.

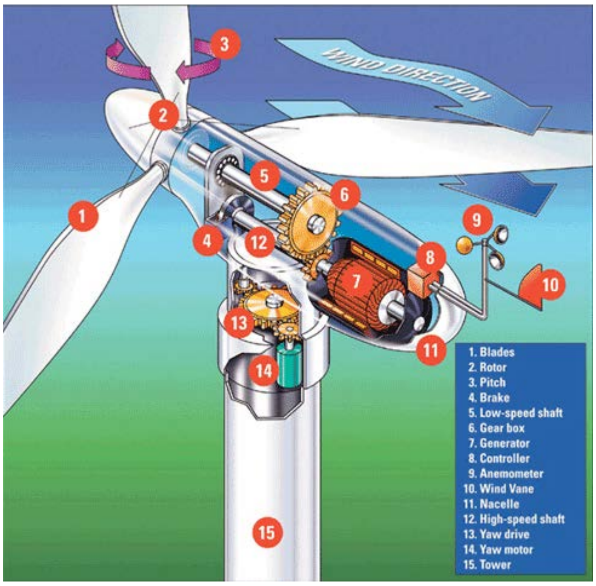

Figure 6 *Wind turbine potential failure modes*
Photo courtesy Clipper wind-power inc.

The maintenance activities for wind turbines fall under two categories: preventive maintenance and fault related maintenance. The objective of preventive maintenance is to replace components and refurbish systems that have exhausted useful lives, usually much shorter than the projected life of the turbine. Tasks associated with scheduled maintenance fall into this category. These tasks include periodic inspections of the equipment, bearing changes, calibration and adjustment of sensors and actuators, and replacement of consumables such as seals. Housekeeping and blade cleaning generally fall into this category. The specific tasks and their frequency are usually explicitly defined in the maintenance manuals supplied by the turbine manufacturer. On the other hand, a certain amount of unscheduled maintenance must be anticipated with any project. Commercial wind turbines contain a variety of complex systems that must all function correctly for the turbine to perform. Rarely are redundant components or systems incorporated. Failure or malfunction of a minor component will frequently shut down the turbine and require the attention of maintenance personnel.

Costs associated with planned maintenance can be estimated with reasonable accuracy, but can vary significantly with local labor costs, the location, and accessibility of the site.

Scheduled maintenance costs are also dependent on the type and cost of consumables used. Unscheduled costs can be separated into direct and indirect costs. The direct costs are associated with the labor and equipment required to repair or replace. The indirect costs result from lost revenue due to turbine downtime. In both cases, labor costs are driven by the difficulty of accessing and working on the components. With the exception of some switchgear and power conversion equipment, most the turbine equipment is accessed by climbing the tower (Figure 7). For safety reasons, a two-person crew is generally required for any up-tower activity. In remote locations, access to the turbine itself may be difficult and limited by weather.

Figure 7 *Personnel safety is an important maintenance and repair issue at existing wind installations*
Photo courtesy Clipper wind-power inc.

Labor cost estimates for major component replacement are developed from experience. Although some major components may be reworked in situ, this is not generally the case. Component replacement requires a crane to dismantle the drive train, and several personnel in addition to the crane operator. The equipment and procedures for disassembling the rotor or drive train are established during assembly. The actual cost, however, may vary due to accessibility to the turbine site, equipment availability, and wait time during high-wind conditions.
The availability of cranes capable of lifting turbine components in the MW capacity range is limited in many of the remote locations where wind farms are located, and mobilization costs alone can make up a major portion of the repair cost. As an example, the cost for replacing a gearbox in a 660 kW turbine on a 65 meter tower is on the order of 80.000 €, for a site with local hydraulic crane service. The bulk of this cost, perhaps 80%, is for procuring and overseas shipping the new gearbox, and the remainder is for crane, site labor and local shipping. Overhauling the gearbox at a local rebuild shop can reduce the total replacement cost to around 27.000 € - 34.000 €. These facilities are occasionally being established in areas with high concentrations of wind power projects. Replacing a gearbox in a 1.5 MW turbine on an 80 meter tower is substantially more expensive, even on a per-kW basis. A rebuilt gearbox costs 3 to 4 times as much as a rebuilt gearbox for a 660kW turbine. Since each boom section – 10 to 12 sections in all – and counterweights must be shipped on a dedicated truck, the mobilization cost is high, and total crane costs can reach 34.000 € to 46.000 €.
Labor for minor repairs, such as those associated with sensors, actuators or control components that fail or function intermittently, is generally accounted for by assigning a number of turbines to each technician. Due to the difficulty in accessing the equipment, travel and climbing time may be much higher than the actual time required to diagnose and repair. Intermittent malfunctions that are difficult to diagnose may require multiple trips. Most replacement parts used on a project are supplied by the turbine manufacturer. Many smaller components, such as electronic and hydraulic parts, are stock items that are available from multiple sources. But the bulk of the power-transmission and rotor components, and most of the controller and power conversion equipment, are special items that have to be sourced from the turbine vendor. Turbine models that have been in existence for more than ten years, and have large number of installations, have spawned an after-sales market in blades, and in generator and gearbox rebuild services.
We now present two case studies of real PV installations to compare maintenance costs for different capacity installations (20-3762 MW).

Case Study A

- wind system's power = 20 MW;
- location: Appennini;
- # of turbines: 10;
- installation of 1 kwp = 1800 €;
- cost of total installation = 36.000.000 €;
- lifetime = 20 years.

The 36.000.000 € for installation can be divided in the following categories:

- turbines installed: 23.760.000 € (66%);
- other parts of system: 5.400.000 € (15%);
- net connection: 1.800.000 € (5%);
- feasibility analysis: 5.040.000 € (14%).

During the first and the second year of installation, the maintenance costs were found to be 1% of 23.760.000 €, because most of the components were under warranty. Hence, the overall costs for schedule and unscheduled maintenance for the first two years were 238.000 € x 2 = 476.000 €. In the following 4 years, the maintenance costs were found to be 2% of 23.760.000 €, totalling 475.000 € x 4 = 1.900.000 for schedule and unscheduled maintenance. In the remaining 14 years, maintenance costs were found to be 4 % of 23.760.000 €, totalling 950.000 € x 14 = 13.300.000 for schedule and unscheduled maintenance. The total maintenance cost over a 20 year span were 15.676.000 €. Hence, the maintenance costs of this system were 33% of the installation investment. The overall maintenance cost can be divided into 3% for scheduled maintenance and 30% for unscheduled maintenance.

Case Study B

- wind system's power = 37,62 MW;
- location = Higueruela (Spain);
- # of turbines = 57;
- turbine's power = 660 kW each;
- installation of 1 kWp = 1500 €;
- cost of total installation = 56.600.000 €;
- lifetime = 20 years.

The 56.600.000 € for installation can be divided in the following categories:

- turbines installed: 38.000.000 € (67%);
- other parts of system: 8.464.000 € (15%);
- net connection: 2.800.000 € (5%);
- feasibility analysis: 7.336.000 € (13%)

During the first and the second year of installation, the maintenance costs were found to be 1% of 38.000.000 €, because most of the components were under warranty. Hence, the overall costs for schedule and unscheduled maintenance for the first two years were 380.000 € x 2 = 760.000 €. In the following 4 years, the maintenance costs were found to be 2% of 38.000.000 €, totalling 760.000 x 4 = 3.040.000 € for schedule and unscheduled maintenance. In the remaining 14 years, maintenance costs were found to be 4 % of 38.000.000 €, totalling 1.520.000 € x 14 = 21.280.000 € for schedule and unscheduled maintenance. The total maintenance costs over a 20 year span were 25.080.000 €.

Comparison of Maintenance Costs

We now use the data from the four case studies to compare the maintenance costs for PV and wind energy systems. Table 2 shows the comparison of quantitative and qualitative features of the maintenance requirements for both the renewable energy generation methods.

From the data we can observe that the maintenance cost of these systems is small as compared to the initial investment. It is very expensive, as much as 7000 €/kWp, to install a PV system. However, the maintenance cost of this system is only 0,5% of the total system cost. Hence, this implies that once the installation cost has been recouped, the costs of operating these systems beyond that point are negligible. From the case studies we can also observe that the same holds true for wind farms, with the unique difference that in this type of system, maintenance is far more complex.

Another interesting observation that can be made about both the renewable energy generation methods is that there are economies of scale in maintenance costs. The maintenance cost per kWp drops as the size of the power generation plant increases. This can be attributed to coordinated scheduled maintenance and also better maintenance tools that can be employed for larger scale systems. Moreover, larger power generation installations use sophisticated SCADA (Supervisory Control and Data Acquisition) systems, which reduce labor costs and also reduces maintenance costs.

On the qualitative side, one can see that PV systems are easier to access and maintain as compared to wind farms. The overall issue of safety and accessibility remains critical in the case of wind turbines.

CONCLUSIONS

Over the past few years, considerable attention has been given to installation, production and distribution costs for renewable energy systems. However, the issue of maintenance cost for such systems has not been addressed adequately. This paper focused on the maintenance costs for PV solar energy systems and turbine based wind energy systems. We presented a discussion of the maintenance issues relevant to these systems, and compared long term maintenance costs for PV and wind energy systems using two sets of case studies. From the case study data we can observe that wind energy systems are more difficult and expensive to maintain. However, when compared to the initial installation costs, the long term maintenance costs represent only a fraction of the initial investment.

During the last five years, industry RD&D has put emphasis on developing larger and more effective PV and wind turbine systems. Continued RD&D in maintenance and reliability is essential to ensure the necessary reductions in cost and uncertainty due to failures, to realise the anticipated and desired level of deployment. As renewable energy sources grow to be a significant part of the next generation energy grid, the reliability and availability of these systems will become critical factors in ensuring uninterrupted energy supply that meets society's needs.

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Table 2 *Comparison of maintenance operations for PV systems and wind farms*

	ACTIVITY	SOLAR SYSTEMS		WIND SYSTEMS	
		CASE A	CASE B	CASE A	CASE B
QUANTITATIVE	Power	50 kWp	500 kWp	20 MW	37,62 MW
	€/kWp	7.000 €/kWp	5.500 €/kWp	1.800 €/kWp	1.500 €/kWp
	Installation of system	350.000,00 €	2.750.000,00 €	36.000.000,00 €	56.600.000,00 €
	Management of system	unimportant	unimportant	~ 80.000 €/anno	~ 120.000 €/anno
	Schedule maintenance	3.500,00 €/year (1%)	13.750,00 €/year (0,5%)	150.000,00 €/year (0,8%)	225.720,00 €/year (0,6%)
	Unscheduled maintenance	2.800,00 €/year (0,8%)	11.000,00 €/year (0,4%)	650.000,00 €/year (3,2%)	526.680,00 €/ year (2.7%)

	ACTIVITY	SOLAR SYSTEMS	WIND SYSTEMS
QUALITATIVE	Ease of Installation	EASY	COMPLEX
	Ease of Localization	EASY	COMPLEX
	Access of the System	VERY EASY	MEDIUM DIFFICULTY
	Ease of Maintenance	VERY EASY	COMPLEX
	Ease of Monitoring	EASY	EASY
	Frequency of inspection	LOW	LOW
	Systems Reliability	HIGH	HIGH
	Maintenance Safety	SAFE	PERILOUS
	Enviromental impact	MINIMUN	MINIMUN
	Performance Estimate	HIGH	VERY HIGH
	Future Needs	VERY HIGH	VERY HIGH