

Cost Calculation Algorithm for Stand-Alone Photovoltaic Systems

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Abstract: - Photovoltaics are the technology that generates direct current (DC) electrical power measured in watts or kilowatts from semiconductors when they are illuminated by photons. Photovoltaics are the technological symbol for a future sustainable energy supply system in many countries. A considerable amount of money is invested in research, development and demonstration; several governments set up substantial market introduction programs and industry invests in larger production facilities. Life Cycle Cost Analysis (LCCA) is an economic method of project evaluation in which all costs arising from owning, operating, maintaining and ultimately disposing of a project are considered to be potentially important to that decision. Doing a LCCA gives the total cost of a PV system -including all expenses incurred over the life of the system. LCCA is particularly suitable for the evaluation of building design alternatives that satisfy a required level of building performance, but that may have different initial investment costs; different operating, maintenance and repair (OM&R) costs; and possibly different lives. In this study, a software computer program for educational purposes is designed to determine initial, life cycle and unit energy costs of a stand-alone photovoltaic system in Turkey. Depending on the selected location, material and criteria, the proposed software implements the life cycle analysis of the system. The database and fixed constants of proposed software can be updated and new elements can be added at any time. Present value algorithm is described in previous section is used for cost calculation. Inappropriate selection of components is blocked by the software. Also, too large selection of particular elements such as inverter and batteries is blocked for optimal sizing of the system. As a result of the calculations were performed using software designed, in terms of lifetime cost and unit energy costs of PV systems most suitable provinces are Mersin, Antalya, Adana, Mardin, Van, Adıyaman, Aydın and Kilis respectively. In the opposite, the highest costs are in Gümüşhane, Yalova, Ağrı, Çankırı and Kastamonu provinces.

Key-Words: - Photovoltaic cell, Life Cycle Cost, Present Worth, PV System Design, Software, Unit Energy Cost.

1 Introduction

Renewable energy sources are an almost unlimited supply of energy if one considers the energy required by mankind, compared with the extremely large amount of energy we receive from the sun. Modern energy services require the growing inclusion of renewable energy into the sustainable energy mix.

The technologies used for conversion of renewable energy sources to heat, electricity and/or fuels are plentiful. Their development has contributed to the gradual lowering of technology prices on the one hand and to improvement in their efficiency on the other. Gradually renewable energy and its different energy conversion technologies have become economically viable, capable of competing with fossil-fuelled technologies in the energy market.

The economic case for renewables has been improving rapidly over the past few years. Some renewable energy technologies are maturing rapidly and becoming increasingly cost competitive. For example, wind, hydro, and geothermal power are already competitive in many wholesale electricity markets. Other technologies, such as solar PV, solar water heaters and biomass are often cost-effective options to provideservices in off-grid areas in developing countries. Solar powered devices, such as emergency roadside telephones, roadside crossing sites, parking meters or traffic lights, can be found in remote as well as urban areas. Other competitive market examples include green electricity markets, which respond to willingness by the consumer to pay a premium for environmentally clean energy services.

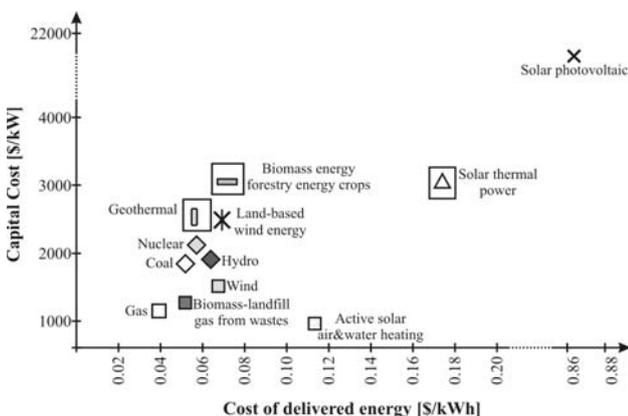


Figure 1 Specific Daily Delivered Electricity/Specific Capital Cost

Figure 1 compares the costs of electricity generating systems. The cost competitiveness of renewables is increasing steadily and is expected to continue improving in the future, as their market

shares grow. Solar energy costs today can only be acceptable in “niche markets”, where other alternatives are for some reason unattractive or not feasible. The wind energy industry has made significant progress in decreasing costs to become economically viable. Large wind-farms will contribute even more to this trend in the future. Geothermal energy is already economically viable and can compete in the electricity markets, as is hydro and some types of biomass (e.g. landfill gas utilisation) [1].

Although fuel of solar PV generators is free, but price of PV electricity is far above the price of electricity from conventional fossil fuel power plants. And also PV electricity is the most expensive amongst the other renewable electricity prices. This has been clearly shown in Figure 1. This high capital cost is affected by some technical factors such as efficiency, technology, reliability, location, orientation, tilt, as well as some non-technical factors, which are often overlooked. Non-technical factors are classified as

- Awareness, attitudes and acceptance of customers and energy providers
- Financing
- Research and development
- Demonstration and marketing
- Regulatory measures
- Market-based factors
- Electricity infrastructure factors [2].

1.1 Photovoltaics

Photovoltaics are the technology that generates direct current (DC) electrical power measured in watts or kilowatts from semiconductors when they are illuminated by photons. As long as light is shining on the solar cell (the name for the individual PV element), it generates electrical power. When the light stops, the electricity stops. Solar cells never need recharging like a battery. Some have been in continuous outdoor operation on Earth or in space for over 30 years [3].

Photovoltaics are the technological symbol for a future sustainable energy supply system in many countries. A considerable amount of money is invested in research, development and demonstration; several governments set up substantial market introduction programs and industry invests in larger production facilities. No other renewable energy technology receives such a strong appreciation by the public and to an increasing extent also by the politicians and the industrial and financial sectors. This is a remarkable situation since at the same time photovoltaic (PV) electricity is regarded as much too expensive

compared to conventional grid electricity. The high and justified recognition of photovoltaics may be understood on the basis of a description of the main positive features of this kind of solar electricity conversion [1].

1.2 Characteristics of Photovoltaic Energy Conversion

Photovoltaics aim at two areas of application. One is the power supply for off-grid professional devices and supply systems (e.g. telecommunication equipment, solar home systems) and the other is large-scale electricity generation as a substitute for and a complement to today's non sustainable energy processes. With respect to the latter, the global potential of PV electricity is of key importance. Table 1 shows the technical and the theoretical potential of several renewable energy sources. The theoretical potential does not take into account land use restrictions, conversion efficiencies, storage requirements and so on. The technical potential on the other hand must not be confused with short-term economic potentials, since price situations and capital requirements for activating these energy sources on a large scale are not considered [1, 4].

Many photovoltaic systems operate in a stand-alone mode. Such systems consist of a PV generator, energy storage (for example a battery), AC and DC consumers and elements for power conditioning – as shown in Figure 2.

Table 2 lists some of the advantages and disadvantages of photovoltaics. Note, that they include both technical and nontechnical issues. Often, the advantages and disadvantages of photovoltaics are almost completely opposite of conventional fossil-fuel power plants. Notice that several of the disadvantages are nontechnical but relate to economics and infrastructure. They are partially compensated for by a very high public acceptance and awareness of the environmental benefits. During the late 1990s, the average growth rate of PV production was over 33% per year [5, 6].

Table 1 Current use and potential of main renewable energy sources

RESOURCE	Current Use	Technical Potential	Theoretical Potential
	[Exa Joule / year]		
Hydropower	9	50	147
Biomass Energy	50	>276	2900
Solar Energy	0.1	>1575	3900000
Wind Energy	0.12	640	6000

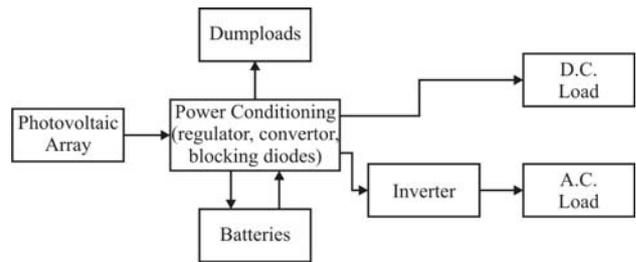


Figure 2 Major components of a stand-alone PV system

The solar cell is a semiconductor device that converts the solar insolation directly to electrical energy. The cell is a non-linear device and can be represented by the $I-V$ terminal characteristics, or by an approximate electrical equivalent circuit as shown in Figure 3.

The cells are connected in series and in parallel combinations in order to form an array of the desired voltage and power levels. Figure 4 represents the $I-V$ and $P-V$ characteristics of the solar-cell generator for five insolation levels (in percentages).

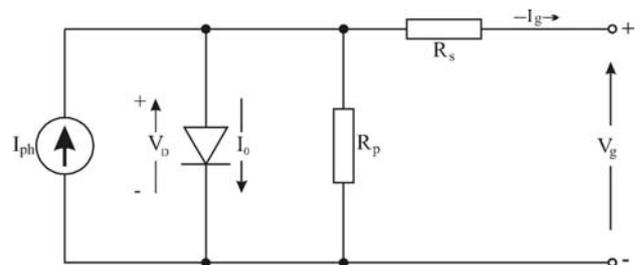


Figure 3 Photovoltaic cell equivalent circuit

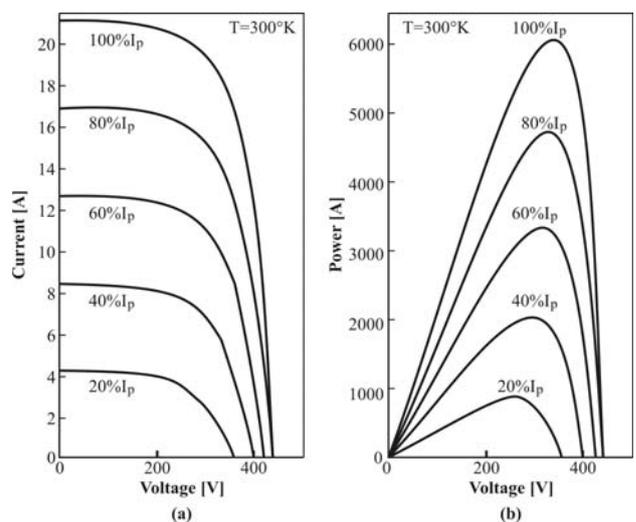


Figure 4 a) $I-V$ and b) $P-V$ Characteristics of a photovoltaic cell

The $I_g - V_g$ equation of the solar cell generator, which consists of N_s cells in series and N_p cells in parallel, is given by:

$$V_g = I_g R_s \frac{N_s}{N_p} \ln \left(1 + \frac{N_p I_{ph} - I_g}{N_p I_0} \right) \quad (1)$$

$$I_g = I_{ph} - I_0 \left(e^{\frac{qV_g}{kT}} - 1 \right) \quad (2)$$

Where, I_{ph} is cell photocurrent (amps), proportional to the insolation; I_0 is cell reverse saturation current; R_s is cell series resistance; $q = 1.602 \cdot 10^{-19} C$ is electron charge, $k = 1.3806 \cdot 10^{-23} J/K$ is the Boltzmann's constant; and T is absolute temperature [7-11].

Table 2 Advantages and Disadvantages of PV Systems

Advantages of photovoltaics	Disadvantages of photovoltaics
Fuel source is vast and essentially infinite	Fuel source is diffuse (sunlight is a relatively low density energy)
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	
Low operating costs (no fuel)	High installation costs
No moving parts	
Ambient temperature operation	
High reliability in modules (>20 years)	Poorer reliability of auxiliary (BOS) elements including storage
Modular (small or large increments)	
Quick installation	
Can be integrated into new or existing building structures	Lack of widespread commercially available system integration and installation so far
Can be installed at nearly any point of use	
Daily output peak may match local demand	Lack of economical efficient energy storage
High public acceptance	
Excellent safety record	

2 Life Cycle Cost Analysis of a PV System

Life Cycle Cost Analysis (LCCA) is an economic method of project evaluation in which all costs arising from owning, operating, maintaining and ultimately disposing of a project are considered to be potentially important to that decision. LCCA is particularly suitable for the evaluation of building design alternatives that satisfy a required level of building performance, but that may have different initial investment costs; different operating, maintenance and repair (OM&R) costs; and possibly different lives [12]. Doing a LCCA gives the total cost of a PV system -including all expenses incurred over the life of the system. There are two reasons to do an LCC analysis: 1) to compare different power options, and 2) to determine the most cost-effective system designs. For some applications there are no

options to small PV systems so comparison of other power supplies is not an issue.

The PV system produces power where there was no power before. For these applications the initial cost of the system is the main concern. However, even if PV power is the only option, a LCCA can be helpful for comparing costs of different designs and/or determining whether a hybrid system would be a cost-effective option. Some might want to compare the cost of different power supply options such as photovoltaics, fueled generators, or extending utility power lines. The initial costs of these options will be different as will the costs of operation, maintenance, and repair or replacement. A LCC analysis can help compare the power supply options. The LCC analysis consists of finding the present worth of any expense expected to occur over the reasonable life of the system. To be included in the LCC analysis, any item must be assigned a cost, even though there are considerations to which a monetary value is not easily attached. For instance, the cost of a gallon of diesel fuel may be known; the cost of storing the fuel at the site may be estimated with reasonable confidence; but, the cost of pollution caused by the generator may require an educated guess. Also, the competing power systems will differ in performance and reliability. To obtain a good comparison, the reliability and performance must be the same. This can be done by upgrading the design of the least reliable system to match the power availability of the best. In some cases, you may have to include the cost of redundant components to make the reliability of the two systems equal. For instance, if it takes one month to completely rebuild a diesel generator, you should include the cost of a replacement unit in the LCC calculation. A meaningful LCC comparison can only be made if each system can perform the same work with the same reliability [7, 13].

2.1 LCC Calculation

The life-cycle cost of a project can be calculated using the formula:

$$LCC = C + M_{PW} + E_{PW} + R_{PW} - S_{PW} \quad (3)$$

where the PW subscript indicates the present worth of each factor. The initial cost (C) of the system consists of the components prices such as PV array, DC-AC converter (maximum power-point trackers), storage batteries, electronic control and battery charger, the cost of civil work, installation and the connections cables. Operation and maintenance cost includes taxes, insurance, maintenance, recurring costs, etc [14, 15].

Two phenomena affect the value of money over time. The inflation rate (i) is a measure of decline in value of money. The discount rate (d) relates to the amount of interest that can be earned on principal that is saved. If money is invested in an account (N_0) that has a positive interest rate, the principal will increase from year to year. After n years, the value of the investment will be

$$N(n) = N_0(1 + d)^n \tag{4}$$

However, in terms of the purchasing power of this investment, for example $N(n)$ dollars will not purchase the same amount as this amount of money would have purchased at the time the investment was made. In order to account for inflation, note that if the cost of an item at the time investment was made is (C_0), then the cost of the item after n years will be

$$C(n) = C_0(1 + i)^n \tag{5}$$

If $C_0 = N_0$, the ratio of $C(n)$ to $N(n)$ becomes a dimensionless quantity (Pr), which represents the *present worth factor* of an item that will be purchased n years later, and is given by

$$Pr = \left(\frac{1 + i}{1 + d} \right)^n \tag{6}$$

The present worth factor of an item is defined as the amount of money that would need to be invested at the present time with a return of $100d\%$ in order to be able to purchase the item at a future time, assuming an inflation rate of $100i\%$. Hence, for the item to be purchased n years later, the present worth is given by

$$PW = (Pr)C_0 \tag{7}$$

Sometimes it is necessary to determine the present worth of a recurring expense, such as fuel cost, OM&R costs and replacement costs. For example, if the first year's supply of fuel is purchased at the time the system is put into operation, and each successive year's fuel supply is purchased at the beginning of the year, the present worth of the fuel acquisitions will be

$$PW = C_0 + C_0 \left(\frac{1+i}{1+d} \right) + C_0 \left(\frac{1+i}{1+d} \right)^2 + C_0 \left(\frac{1+i}{1+d} \right)^3 + \dots + C_0 \left(\frac{1+i}{1+d} \right)^{n-1} \tag{8}$$

Letting $x = \left(\frac{1+i}{1+d} \right)$, equation (8) becomes

$$PW = C_0 (1 + x + x^2 + \dots + x^{n-1}) \tag{9}$$

This expression can be simplified by observing that $\frac{1}{1-x} = 1 + x + x^2 + x^3 + \dots = \sum_{i=0}^{\infty} x^i$. The cumulative present worth factor (Pa) can be defined as

$$Pa = \frac{PW}{C_0} = \frac{1}{1-x} - \sum_{i=n}^{\infty} x^i = \frac{1}{1-x} - x^n \sum_{i=0}^{\infty} x^i \tag{10}$$

or,

$$Pa = \frac{1 - x^n}{1 - x} \tag{11}$$

2.2 Social Costs

In addition, with the use of photovoltaic cell, environment pollution and greenhouse gas impact that called social cost of conventional fuels is almost zero. This is one of the important advantages to encourage the using of photovoltaics. By the Fraunhofer Institute in Germany for a detailed study of the electrical energy produced from fossil sources will bring total social cost to be at least $0.27\$/kWh$ and social cost of nuclear power plants have been reported in at least $0.04\$/kWh$ [16].

When we replace the conventional units with photovoltaic units, the fuel which would have been used for power generation will be saved due to the use of the PV system. The cost of the conventional fuel that saved is the part of the social costs as above mentioned. The quantity (M_{fuel}) and cost of fuel (C_{fuel}) saved in this wise can be calculated by following equations:

$$M_{fuel} = \frac{1}{LHV} \left(\sum_{i=1}^t \frac{X \cdot Y_i}{\eta_{ii}} \right) [ton] \tag{12}$$

$$C_{fuel} = \frac{C_p}{LHV} \left(\sum_{i=1}^t \frac{X \cdot Y_i}{\eta_{ii}} \right) [CU] \tag{13}$$

Where,

LHV = lower heating value of fuel used at the input of conventional unit in $\left[\frac{kJ}{kg} \right]$,

X = power in MW which is replaced by photovoltaic units,

η_{ii} = efficiency of conventional generation unit,

Y_i = percentage of full rated capacity which is generated by photovoltaic unit for a particular hour,

C_p = cost of fuel in Currency unit/ton [17].

3 Photovoltaic System Design

In any photovoltaic system design, the first task is normally to determine the load. Once the load has been determined, then the amount of battery back-up needs to be determined. Some systems will not need batteries, some will have minimal storage and some will require sufficient battery storage to meet critical performance requirements.

After battery selection, the size of the photovoltaic array must be determined. Then the electronic components of the system, such as charge controllers, inverters and maximum power point trackers are selected. Finally, the balance of system (BOS) components are selected, including the mounting for the array, the wiring, switches, fuses, battery compartments, lightning protection and if necessary, monitoring instrumentation.

3.1 Load Determination

In photovoltaic system design, since battery capacity will be determined in ampere-hour (Ah), it makes sense to determine the load energy requirements in Ah . Most PV systems are used for direct current (DC) electrical appliances because the current produced by a PV cell is basically of the DC type. However, DC electrical appliances are rarely found in everyday usage, and, moreover, it is not worthwhile converting existing alternating current (AC) electrical appliances for a PV power supply. Instead, an inverter is added to the PV system in order to convert the DC generated by the PV modules into AC type suitable for AC appliances. Daily energy demand (W) can be calculated by following equations for DC and AC loads [18].

$$W_{AC} = \left(\frac{(kWh/year)}{365} \cdot 1000 \right) \cdot \frac{1}{V_{ii}} \cdot \frac{1}{\eta_i} \cdot \frac{1}{\eta_w} \cdot \frac{1}{\eta_b} \quad (14)$$

$$W_{DC} = \left(\frac{(Ah/year)}{365} \right) \cdot \frac{1}{\eta_w} \cdot \frac{1}{\eta_b} \quad (15)$$

3.2 Battery Sizing

The number of days of autonomy required for critical need applications depends on the location and operating period of the system. In locations with relatively high average insolation, even during the worst part of the year, less storage is needed. If the minimum peak sun hours (T_{min}) over the period of operation of the load are known for a location, the number of days of autonomy (D) can be estimated from the following equations:

$$\begin{aligned} D_{critic} &= -1,9T_{min} + 18,3 \\ D_{noncritic} &= -0,48T_{min} + 4,58 \end{aligned} \quad (16)$$

These equations are only valid for T_{min} of about one hour per day. These equations are only valid for minimum peak sun hours about one hour per day. Obviously if the sun doesn't shine, more than 18.3 days of storage will be needed.

Sizing of the batteries must take into account the loss of capacity under conditions of low temperature, high rate of discharge, or high rate of charge. Battery size (B) is thus determined from,

$$B_{Ah} = W \left(\frac{D}{D_T \cdot D_{ch} \cdot (disch)} \right) \quad (17)$$

where D_T , D_{ch} and $(disch)$ represent temperature derating factor, charge/discharge derating factor and the depth of discharge expressed as a fraction respectively. In this study, assumed unity value for $D_T \cdot D_{ch} \cdot (disch) \cong 0.8$. Once the battery capacity is determined, the number of batteries in parallel required for the system is calculated by dividing the total capacity to capacity of single battery [7, 19].

3.3 Array Sizing

After the system load has been determined, the PV array can be sized. Choosing an adequate number of modules without choosing more than needed to improve system requirements depends upon knowledge of average insolation conditions at the site for months during which the system will be in use.

The number of modules for the system is determined by dividing the array design current by the current available from a selected module, after correcting for module degradation from aging or dirt accumulation. The derated design current of the array is the design current divided by a degradation factor, which is commonly about 0.9. Additional series modules may be needed if the system voltage higher than module output voltage (generally 12V).

3.4 Controller, Inverter and/or Converter Selection

The D.C. loads will require a battery charge controller as a part of the system and the A.C. loads will require both controller and inverter. In the present case, relatively simple controllers are preferred because complexity sometimes leads to reliability problems. For a motor-driven appliance, the designer must determine whether the motor will be damaged by D.C. or by harmonics.

3.5 BOS Components, Wire, Fuse and Switch Selection

Remaining system parts will typically include a container for the batteries, conduit, plugs and receptacles, fuse holders, surge protectors, ground rods, wire nuts, terminal lugs, etc. The cost of BOS components will typically be about 10% of the cost of array.

Proper wire sizing depends on the current to be carried by the wire, but at low voltages primarily on the length of the wire. To allow for cloud focusing, the rated array current is multiplied by 1.25 to obtain the maximum current from array to controller. Fuse sizes are then chosen to be next higher value above the maximum current from array to controller [7].

4 Life Cycle Cost Calculation Software for Stand-Alone PV Systems

In this study, computer software for educational purposes is designed to determine initial, life cycle and unit energy costs of a stand-alone photovoltaic system in Turkey. Depending on the selected location, material and criteria, the proposed software implements the life cycle analysis of the system. Replacement number and costs are also calculated. Additionally, the quantity and cost of conventional fuel savings by the using of PV system are calculated.

The database and fixed constants of proposed software can be updated and new elements can be added at any time. Present value algorithm is described in previous section is used for cost calculation. Inappropriate selection of components is blocked by the software. Also, too large selection of particular elements such as inverter and batteries is blocked for optimal sizing of the system. All calculated values can be saved and printed. Delphi programming language is used in the software design. Information for database has been obtained from the internet and Turkish State Meteorological Service [20].

Flowchart of the program is shown in Figure 5. Figure 6, and 4 shows the editing windows of constants and database respectively. Main window of proposed software and an example calculation are given in Figure 8.

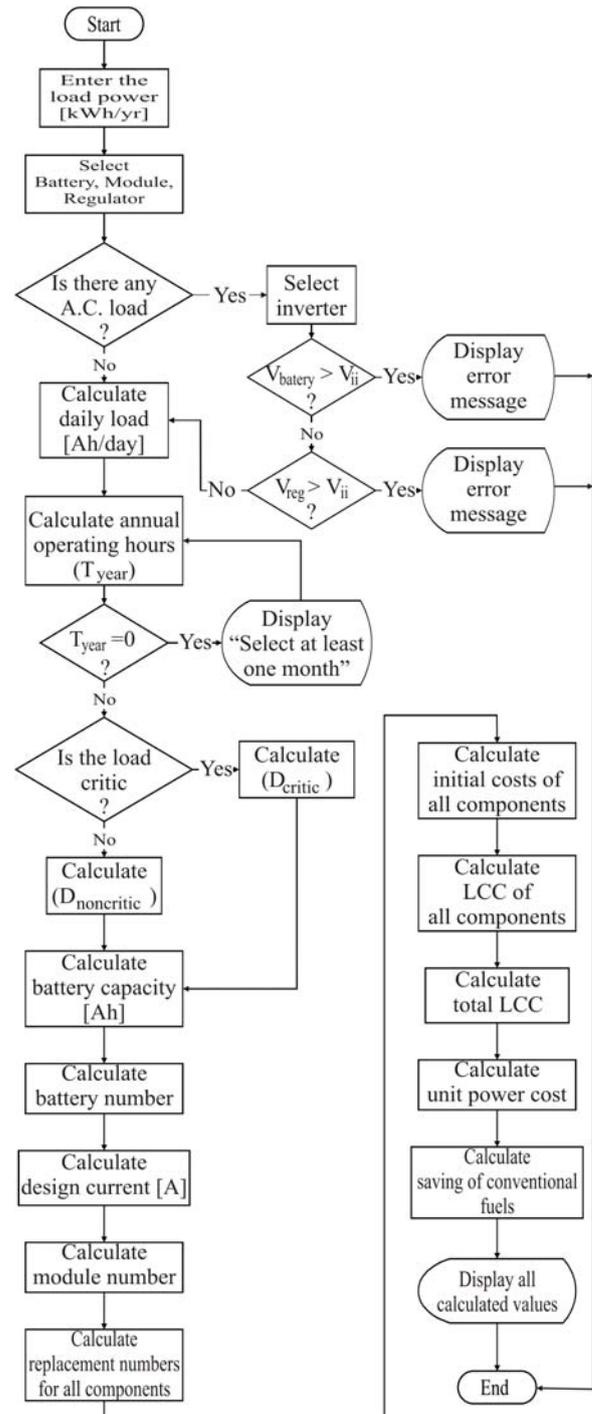


Figure 5 Flowchart of software

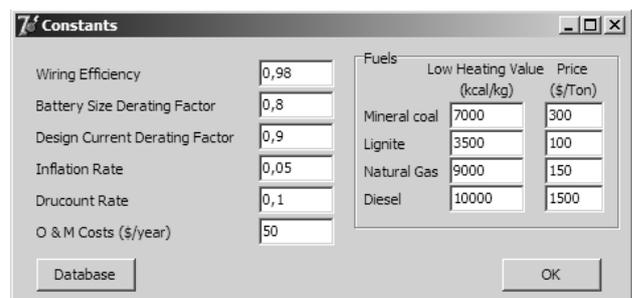


Figure 6 Fixed values editing window of software

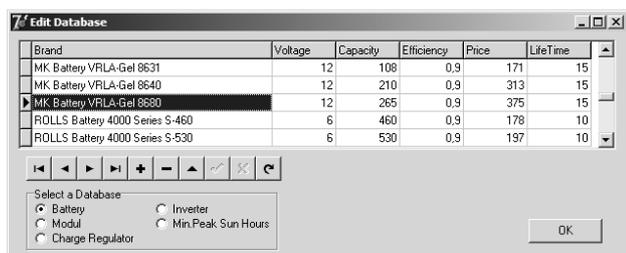


Figure 7 Database editing window

5 Conclusions

In this study, software designed to perform the life cycle cost analysis for stand-alone PV systems installed in Turkey. For system design, daily minimum peak sun hours values are used that has been obtained from statistical data of the Turkish State Meteorological Service. Cost analysis method is based on the present worth algorithm. Additionally, the quantity and cost of conventional fuel savings by the using of PV system are calculated by the proposed software.

As a result of the calculations were performed using software designed, in terms of lifetime cost and unit energy costs of PV systems most suitable provinces are Mersin, Antalya, Adana, Mardin, Van, Adıyaman, Ayduun and Kilis respectively. In the opposite, the highest costs are in Gümüşhane, Yalova, Ağrı, Çankırı and Kastamonu provinces. Figure 9 shows that location of the system has a significant impact on unity energy cost. In Turkey, difference between the lowest energy cost (Mersin) with the highest (Gümüşhane) is approximately 4.56 times.

Designed software can be used for educational purposes in PV system design courses. By expand of database the analysis can be made for any region in the world. The results of the cost effects of various system parameters and the environmental impact of conventional fuel savings may be analyzed.

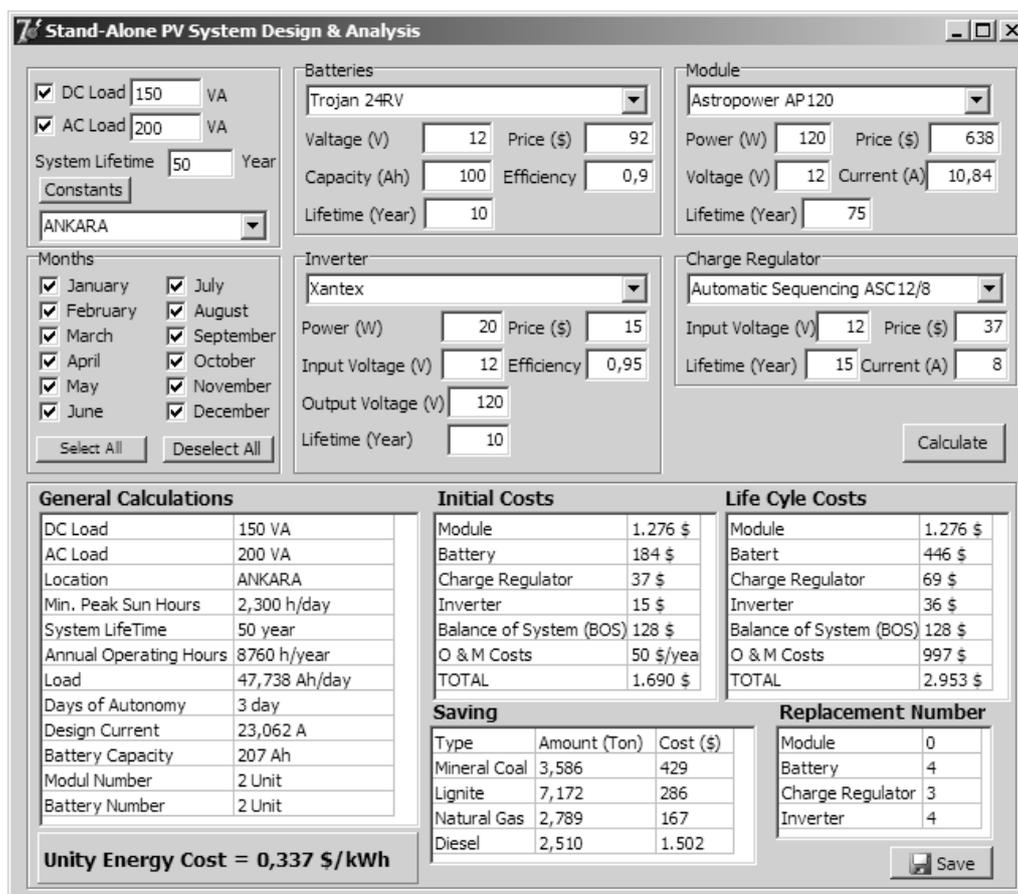


Figure 8 Main window of proposed software

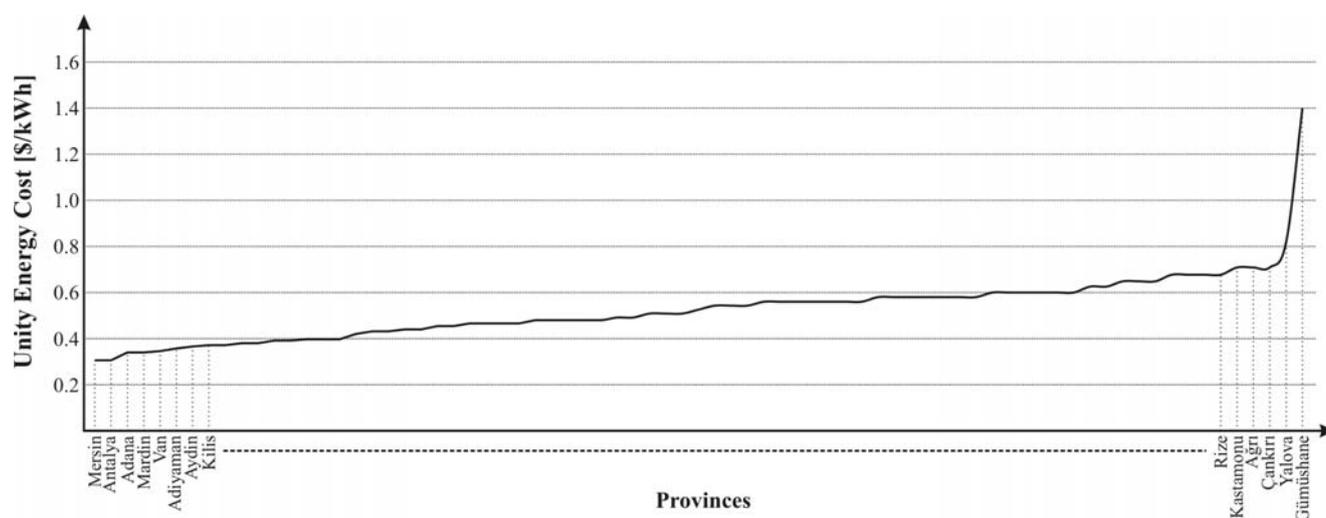


Figure 9 Changing of the unit energy cost of provinces in Turkey

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