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Cost Calculation Algorithm for Photovoltaic Systems

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1. Introduction

The electric energy is directly correlated with vital elements for countries of today's world. These elements can be divided into four sub-titles of production, national income, health and education. It is almost impossible for countries that lack of electric energy to ensure positive developments in such parameters. It is known that, even these days, at least 1.6-2 million people not to consume electricity in the world. Besides, in some countries, there exist great differences between the poor and the rich in obtaining energy (Belfkira et al., 2008).
In that situation, the most benefit in the future of electricity generation sources, expected to be renewable energy sources especially solar and wind. It is also expected that the technical, economic, social and political barriers of widespread use of these resources will decline over time and these resources will own a very important share in the production of electricity at the end of this century. In this chapter, features of sustainable energy production and sustainability parameters of photovoltaic (PV) systems are summarized. This chapter focused on a life cycle cost analysis (LCCA) method that used in PV system design. In this point, apart from conventional cost analysis, calculable "external costs and benefits" are taken into account. In addition, effect of the capacity utilization (CU) on unit energy cost is explained particularly in stand-alone PV systems. Thus, detailed analysis of life cycle and unit energy costs -which the most disadvantaged parameter of PV within the parameters of sustainability- was, carried out. The topics discussed are supported with sample applications at the end of chapter.

1.1 Expectations for the future of energy production

Energy plays a very important role for the peace of world, in addition to its role being an element that effects development of a country. For this reason, the World's Energy Council has resolved to act with understanding of "energy for people, energy for peace". Electric energy demand is increasing very rapidly with each passing year. According to the forecasts of the International Energy Agency, the energy need of world will increase two times in 2020 when compared to 1997 (WEC Handbook, 2004).
World Energy Council (WEC) has been forecast over the various scenarios related to the amount of future energy consumption and energy production technologies. These scenarios are divided into two classes as A and C group characteristically (Table 1).
In these scenarios, it is estimated the world population will be 10.2 billion in 2050. According to the A-group scenario, economic growth and energy demand of the world will

increase because of globalization. It is also expected the annual energy consumption that was 420EJ in 2000, will be 1040EJ in 2050. In addition, it is indicated that using of the world's fossil energy sources will continue in a high percentage, so the annual carbon dioxide (CO_2) emissions will rise up form 6.4Gt to 9-15Gt. C-group scenarios suppose in a highly unusual that the international community will focus on ecological protection and international equity and as a result of this energy consumption will reduce. According to the scenario, primary energy consumption will be 600EJ in 2050. Especially small power, reliable and advanced technology production nuclear reactors and renewables will be used in electrical production and as a result the annual carbon dioxide emissions will fall from 6.4Gt to 5Gt. Fossil fuels will be used only as a transitional fuel. The said scenarios are divided into sub-groups among themselves that differ in some respects. For example, in A-1 scenario it is forecast that percentage of fossil fuels will be high in energy production, will not be a major advance in coal and nuclear energy technologies, trend of technological development will focus on oil and natural gas systems, in particular these two fossil fuels will be preferred instead of coal in 21st century. In another scenario (scenario A-3), is proposed to especially biomass, renewables and new-generation nuclear energy technologies will have the largest share in electrical energy production (WEC Report, 2004).

PARAMETER		SCENARIO -A-		SCENARIO -C-	
DATE		2000	2050	2000	2050
World population [billion]		6.2	10.2	6.2	10.2
The world's economic assets (GWP) [trillion $]*		30	110	30	84
Primary energy consumption [Exa Joule]		420	1040	420	600
Resource availability	Fossil	High	High	High	Low
	Renewable	High	High	High	High
Technology intensity	Fossil	High	High	High	Medium
	Renewable	Low	High	Low	High
Net Carbon Emissions [Gigatonnes]		6.4	9 - 15	6.4	5
* With the dollar exchange rate in 2000					

Table 1. Change expectations in parameters that affect the world's energy needs

In all of these scenarios, particularly in the residential-office and transportation the use of coal will be completely abandoned, and the share of petroleum products is projected to decline to 10% of today's level. From these knowledge has clearly emerged to invest in alternative energy sources is to make investment in the future of the countries

2. Sustainable electrical energy production

The environmental impacts of energy development scenarios should be very well explained and focused on the sustainable energy production applications to guide future investments.

Fig. 1. shows that distribution of resources used for electric energy production of the world in 2007. "Other renewables" term includes energy sources except hydropower such as wind, photovoltaic, geothermal. It is known that coal has the highest emissions of CO_2 and other pollutants per kWh. However, because of low cost and easily accessible, coal dominated energy market and is standing against the principles of sustainability. If these trends continue, the number of coal power plants will increase and only the developing countries will be producing carbon dioxide much more than the sum of all OECD countries since 2030. Here, a cost term has emerged that usually cannot measured clearly. These costs are expressed with the "external costs" term. In a study was made by Sovacool in 2009, has suggested that coal (19cents/kWh), oil (12cents/kWh) and nuclear (11cents/kWh) power plants are in the first three rows respectively in terms of the highest ranking of the negative costs. These values were calculated as 6-7cents/kWh for natural gas and biomass power plants and 5cents/kWh for hydroelectric power plants. Wind, geothermal and solar plants have been identified as the most advantageous systems because of 1cent/kWh and below external cost (Sovacool, 2009).

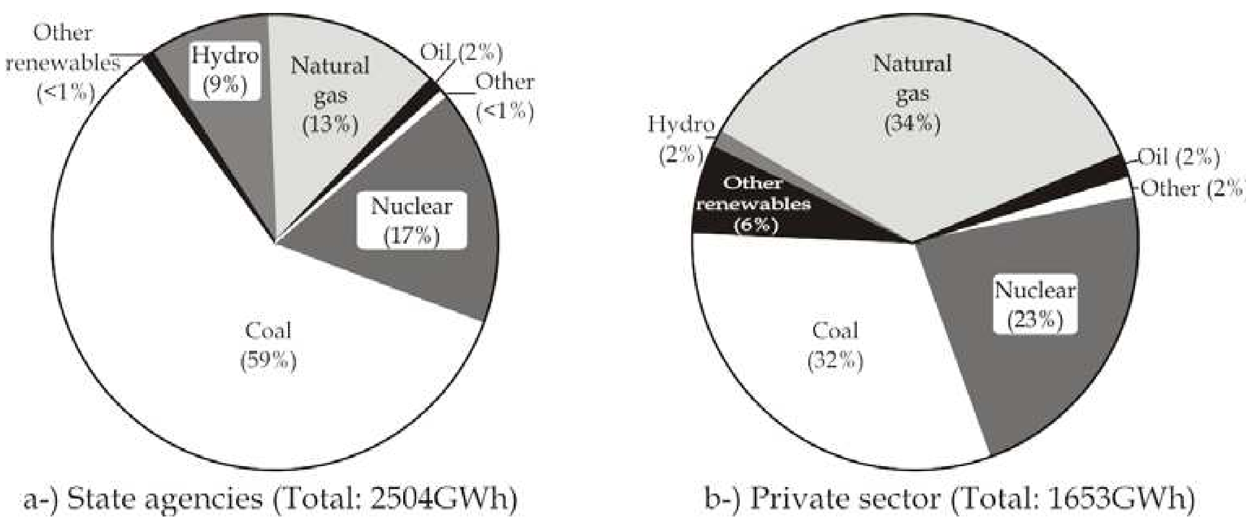

Fig. 1. Distribution of resources used for electric energy production of the world in 2007 (EIA, 2007)

Environmental effects of an energy production system is a process in which various stages such as mining and processing of mineral, to the amount of direct and indirect emissions, reuse or recycling of waste facilities. Assessment of each stage of this process, main indicators should be identified to measure possible impacts. These indicators will be some values such as environmental and social impacts, greenhouse gas emissions, consumption of raw materials, availability and economical benefits of renewable energy resources. Measurement of external costs will greatly reduced the problem of high costs which is the most important parameter adversely affecting the competitiveness of renewables.

2.1 Sustainability ranks of PV systems

There are many important parameters that must be taken into account in the sustainability analysis of energy generation technologies. The effects of power generation should not be considered with the traditional method only results in environmental and climatic conditions. Social and economical environment of community using generated energy also significantly affects the choice of production method. Due to the increasing worldwide communication and information sharing, public awareness of the environmental and climatic changes rapidly increases. This awareness is manifested in the field of energy production as in all areas. According to the analysis of the WEC, since 2030 the amount of energy derived from renewable sources will increase rapidly and have a large share of world energy markets at the end of this century. As shown in Fig. 2., electricity generation will be met largely from renewables and especially PV systems (approximately 60%) in 2100. Today, this estimate may be perceived as utopian. However, remember that developments in nanotechnology and semiconductor technology have put innovation into our lives which recognized the utopia just 20 years ago. In the PV module industry, hot-carrier and quantum dots based cells which are product of nanotechnology are seen as the most competitive technologies in terms of sustainability (Manna & Mahajan, 2007; Azzopardi & Mutale, 2010).

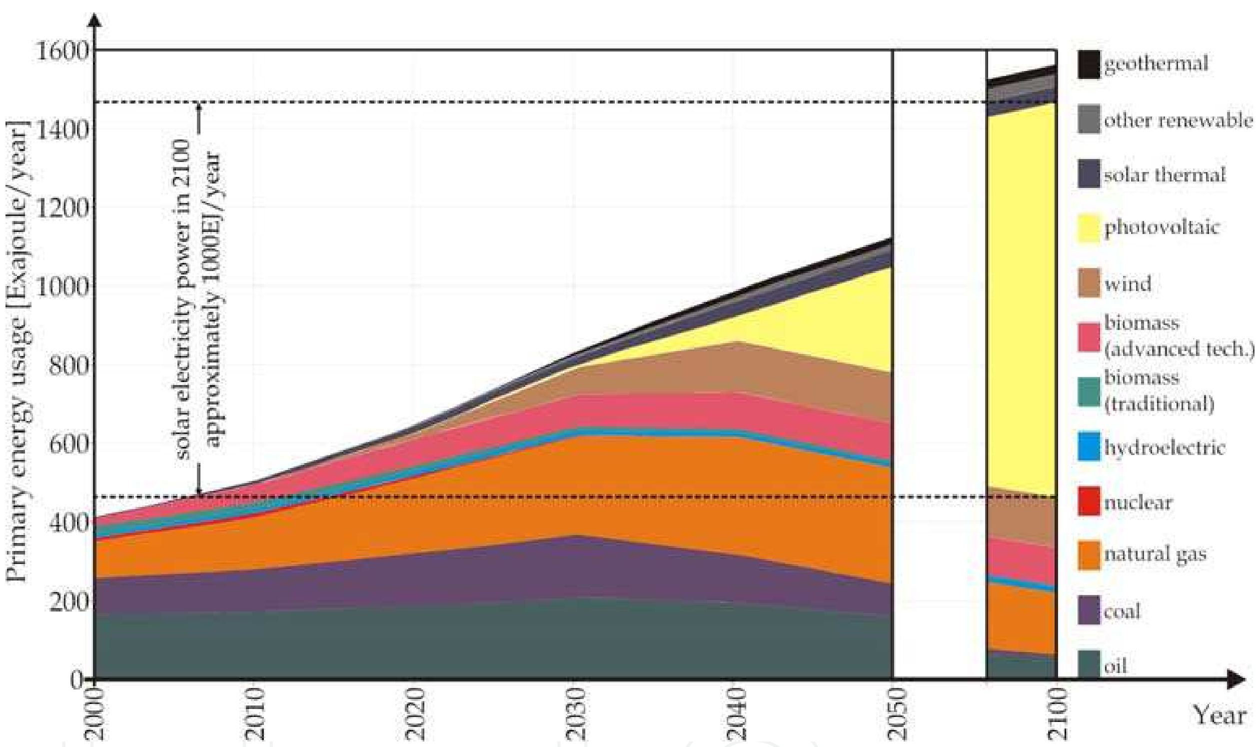

Fig. 2. Change expectations of WEC for usage of primary energy in electricity generation (WEC Report, 2007)

Comparing of PV systems in terms of sustainability parameters is given in Table 2. As seen, PV systems have important advantages to compete with other energy generation systems for sustainability such as availability, CO_2 emission, land use, fresh water consumption, social and environmental impacts. However, especially high initial and unit energy costs are major disadvantages although decreases with each passing year as a result of technological developments and investment (Varun et al., 2009). It is expected that the unit cost of PV energy will be half of present day value until 2025 that decline is quite high compared to other renewable systems (Fig. 3.) (Winkler et al., 2009).

Especially, the unit energy cost of a stand-alone PV plant quite varies depending on life cycle and capacity utilization of the system. This issue will be discussed again in later sections.

Production Technology	Unit Energy Cost [$/kWh]	CO_2 Emission [g/kWh]	Availability	Efficiency [%]	Fresh Water Consumption [kg/kWh]	Land Use [km2/GW]	Social and Environmental Effects
Nuclear	0.0172 - 0.0273	10 - 50	280 years (99% of all world reserves are within boundaries only 10 countries)	30 - 45	30 -100	1 - 4	- Danger of radioactive leaks - Public reaction - Nuclear waste issues
Coal	< 0.1	1000	185 - 260 years (50% of all world reserves are within boundaries of only 3 countries) (26% USA, 16% Russia and 11.5 %China)	30 - 45	15 - 30	10 - 20	- High toxic gas emissions - The public's negative perception - The effects of environmental pollution and greenhouse gas - Mining difficulties
Natural Gas	< 0.1	500 - 600	120 years 41% of total reserves are within Middle East and 27% are within Russia boundaries)	45 - 55	15 -30	1 - 4	- Be imported fuel for many countries - The public's negative perception because of dependence on foreign sources - High CO2 emissions
Wind	0.4 - 0.5	10 - 50	Infinite	24 - 54	< 1	50 -100	- Noise pollution - Visible pollution (minor) - Adverse effects on wildlife (bird deaths) - Positive public perception - Low CO2 emission
Hydroelectric	0.1 - 0.3	1 - 100	Infinite	> 90	65 - 70	75 - 750	- Climate change - Major land use and because of its negative effects on natural environment
Photovoltaic	0.8 - 1.2	15 - 100	Infinite	12 - 22	< 1	28 - 64	- The toxic waste created during the module production - Visible pollution (minor) - Positive public perception - Low CO2 emission - Quiet operation

Table 2. Sustainability indicators of energy generation systems (Evans et al., 2009; Meier, 2002; Green, 2005; Fthenakis & Kim, 2009; Kaygusuz, 2009; Abdeen, 2008)

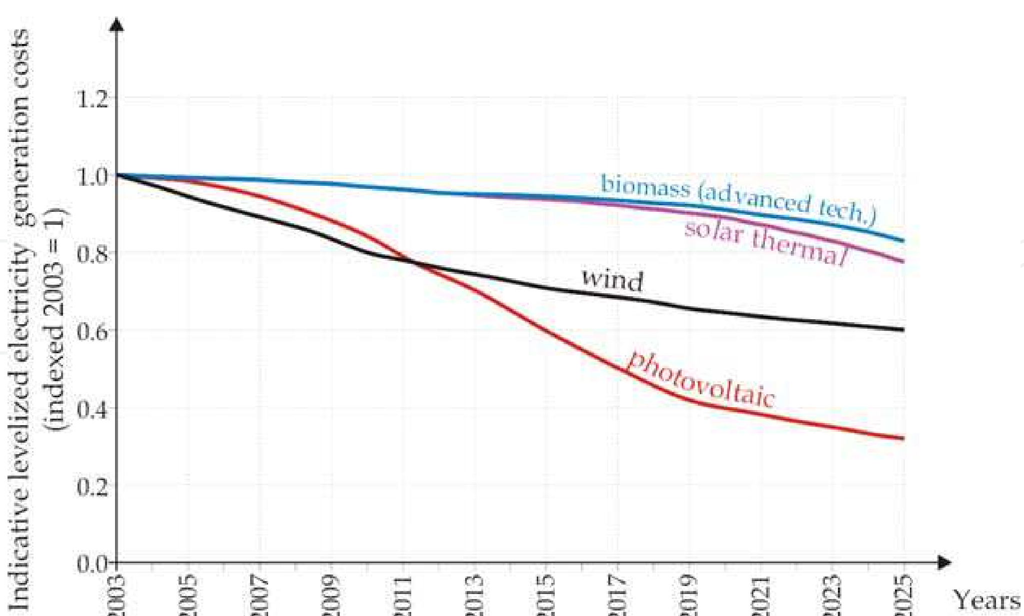

Fig. 3. Unit energy cost estimations of advanced energy generation technologies

According to the International Energy Agency (IEA) reports, changing of the installed PV power in member countries of IEA Photovoltaic Power System Programme (PVPS) between

1992 and 2008 is given in Fig. 4. Growth rates in recent years are particularly noteworthy. While the amount of the total installed power is 105MW in 1992, it has been increased by 127.8 times until 2008 and reached 13425MW. The total installed capacity of 7866MW in 2007 increased 71% in only one year. By the end of 2008, the share of stand-alone PV Systems (that are shown as black columns in Fig. 4) in total installed power was realized as 5.5% (741MW).

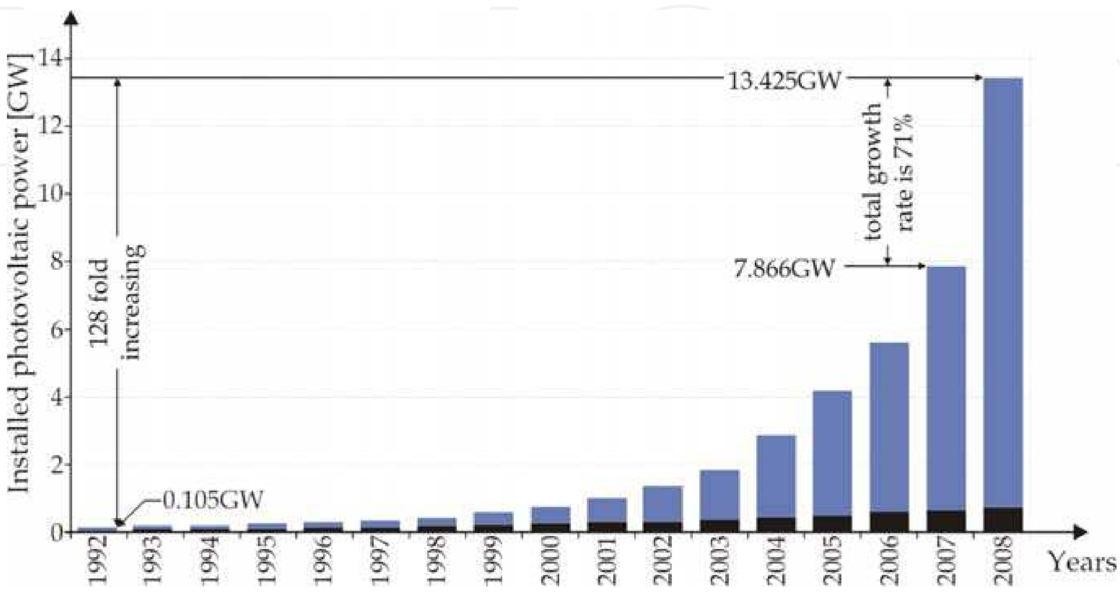

Fig. 4. Cumulative installed grid-connected and off-grid PV power in IEA_PVPS countries (IEA, 2010)

3. Photovoltaic system design

The sun actually constitutes the source of all energy in the world. Sun power converts to other energy sources in various ways. These relationships are seen in Fig. 5. But, only PV systems which convert solar energy directly into electricity are entered into the topic of this section.
Modular structures of PV systems provide a great flexibility in terms of many parameters. The power spectrum ranges from a few miliwatts for wristwatches or scientific calculators, to kilowatt systems in remote area power supplies, for example, for mountaineering lodges or water pumps, to large central PV power stations in the megawatt range (Presier, 2003). PV cells are generally considered to be an expensive method of electricity production. However, in off-grid situations photovoltaics are very often the most economic solution to provide the required electricity service (Hongbo et al., 2009). The growing market all over the world indicates that solar electricity has entered many areas in which its application is economically viable. Additionally, the rapidly growing application of PV systems in grid-connected situations shows that photovoltaic's are very attractive for a large number of private people, companies and governments who want to contribute to the establishment of a new and more environmentally being electricity supply system.
PV systems may contain different components and specifications by use. In Fig. 6., block diagrams of stand-alone and grid-connected PV systems are shown. Battery groups are used in both systems. If desired, grid-connected systems can be designed without batteries. However, stand-alone systems as usually include storage units (Chaar, 2006). In following sections, design processes of a PV system are investigated.

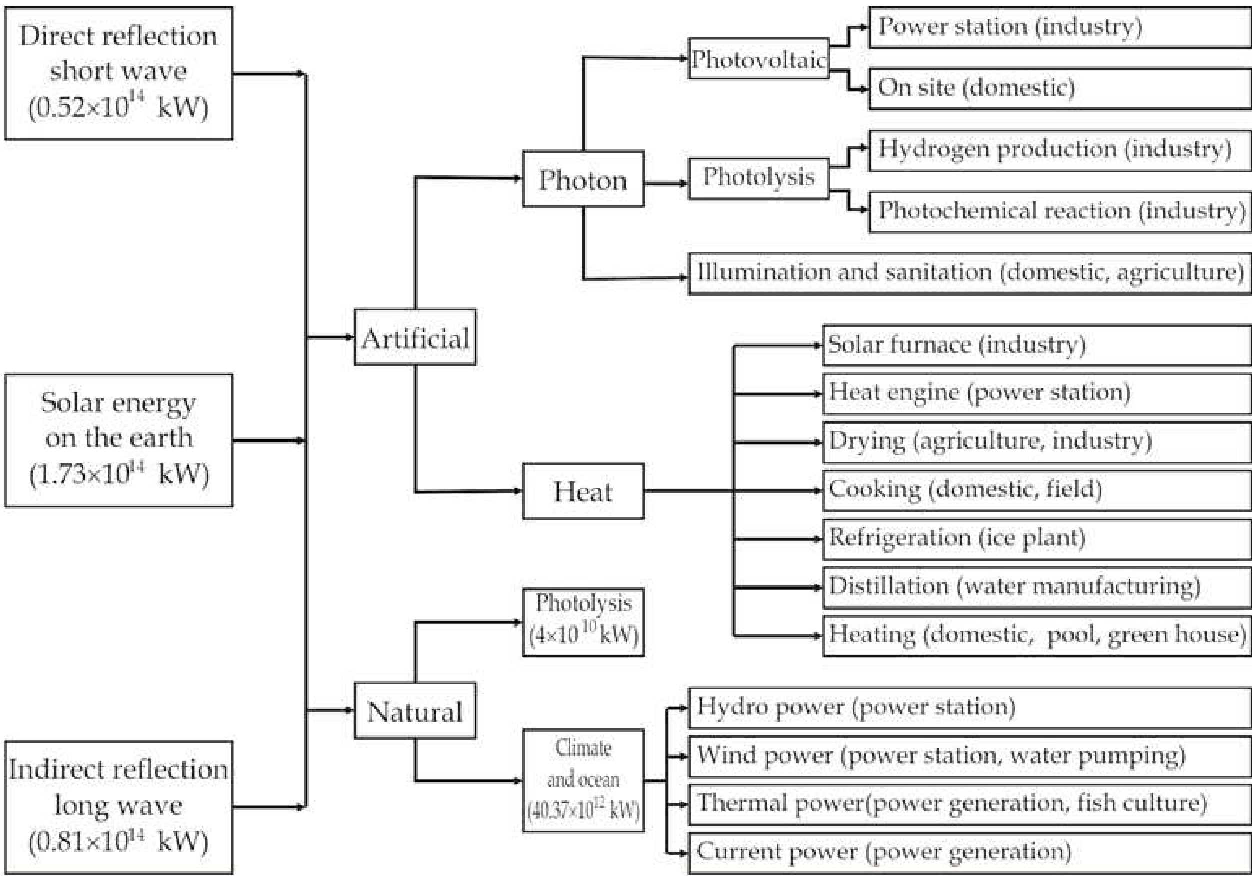

Fig. 5. The relationship between solar energy and other energy sources (Sen, 2004)

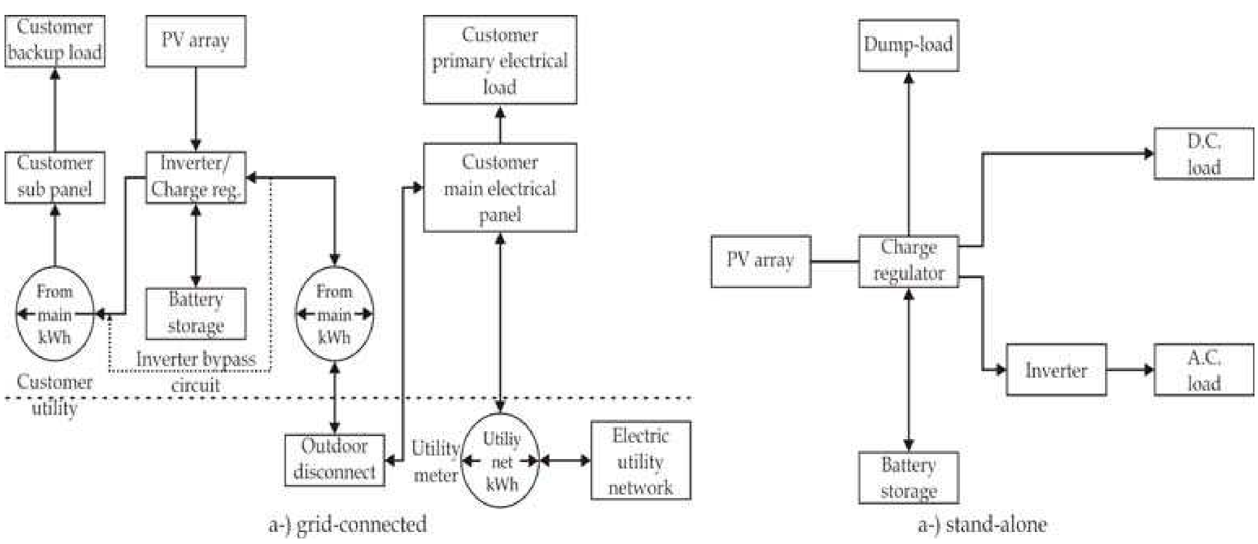

Fig. 6. Block diagram of PV systems with battery storage

3.1 Determination of the load amount

Load determination is the first and most important stage of PV system design. Generally, storage capacity is given as ampere-hour (Ah). Therefore, the amount of energy demanded by load must be denominated in this unit. Correct identification of load is crucial to the reliability of the system. For this purpose, all loads are supplied from the PV panel should be defined and power, current, operating voltage, and especially the daily working hours of each load are determined. In some cases, load amount may be varied as seasonal, monthly or daily and should be recalculated for each change period. For an accurate result, the amounts of AC loads in watts and DC loads in Ah (W_{AC} and W_{DC}) must be calculated separately. At the next stage the total amount of load is determined by adding of these two values. Inverter sizing should be made for AC loads. Wire sizing is realized for each load by using their power. At this stage, a precise voltage drop calculation can be made if required. However, wiring efficiency can be assumed as a constant value such as 0.98 in most cases. Efficiencies of other components (inverter and charge regulator) also must be known. Finally, if the system contains a battery group, battery losses that occur during charging and discharging events must be taken into consideration. Thus the total current demand from the PV panels would be designated. Following equations can be written for load sizing.

$$L_{AC} = W_{AC} \cdot \left[\frac{1}{V_{ii}} \cdot \frac{1}{\eta_i} \cdot \frac{1}{\eta_w} \cdot \frac{1}{\eta_b} \cdot \frac{1}{\eta_{ch}} \right] \tag{1}$$

$$L_{DC} = W_{DC} \cdot \left[\frac{1}{\eta_w} \cdot \frac{1}{\eta_b} \cdot \frac{1}{\eta_{ch}} \right] \tag{2}$$

$$\sum L = L_{AC} + L_{DC} \qquad [\mathrm{Ah}] \tag{3}$$

Here, η_i, η_w, η_b and η_{ch} shows inverter, transmission line, battery group and charge regulator efficiencies respectively. V_{ii} is the value of DC input voltage of inverter. If the operating voltage of the load is different from system voltage, a convertor circuit should be added to the system. The efficiency of this element should be also added to the equation (Messenger & Ventre, 2000). In some cases, to calculate the amount of load, practically total power values of the loads multiplied by a constant coefficient after being converted to Ah. This coefficient varies between 1.1 and 1.5. Designer must be taken in to account all system parameters correctly to obtain this coefficient (Chel et al., 2009).

3.2 Determination of storage capacity and battery number

PV systems usually include a storage system because of modules produce energy in the only daytime hours. Storage systems typically consist of rechargeable batteries. In addition to energy storage, batteries also undertake additional tasks, such as to pause the system when overload times, to provide voltage regulation and to be a current source.

Location of PV systems is significantly effect on the performance. Depending on location, less storage may be required even during the worst season of year. If the minimum peak sun hours value (T_{min}) of system location is known during the operation times of load, autonomous day number (D) calculates by using of the equations (4) and (5).

$$D_{critic} = -1.9 \cdot T_{min} + 18.3 \tag{4}$$

$$D_{noncritic} = -0.48 \cdot T_{min} + 4.58 \tag{5}$$

Here, T_{min} value is daily sunshine duration and measured as meteorological data. These equations are only valid for regions where T_{min} value is at least one hour in a day. If the sun does not appear, D value should be also more than these values (18.3 for critical loads, 4.58 for noncritical loads) (Messenger & Ventre, 2000). Total battery storage (B) is calculated with equation (6) using the D value obtained from above formulas.

$$B = \sum L \cdot \left(\frac{D}{D_T \cdot D_{ch} \cdot (disch)} \right) \quad (6)$$

In this equation, D_T represents the capacity reduction of batteries depending on temperature and discharge amount. If the load current will exceed the specified discharge rate for more than 10 minutes, additional correction factor should be applied to B value. This factor is called as charge-discharge correcting factor and represented with D_{ch}. The amount of discharge expressed as a fraction has been identified with (disch) symbol. Practically, assuming as $D_T \cdot D_{ch} \cdot (disch) \cong 0.8$ provides sufficient accuracy (Messenger and Ventre, 2000). In studies that realized by Chel et al. for India-New Delhi and Able-Thomas and Hill for Gambia, D value was assumed as three days practically (Chel et al, 2009; Able-Thomas & Hill, 1996). In a similar study, Deshmukh has indicated that this value could be two or three days (Deshmukh & Deshmukh, 2008). This approach is applicable for location where not too many climate change during year. After this stage, to calculate the number of batteries (N_B) is sufficient to know capacity value the selected battery (Ah). Number of batteries in parallel (N_B) is obtained by equation (7). If required, this value multiplied by battery numbers that connected in serial.

$$N_B = \frac{B}{Ah} \quad (7)$$

A no integral quantity is found as a result of this calculation. The exact number obtained by rounded of this value up or down. Other factors in the battery selection are additional connection requirements in case of too many battery using and additional maintenance times. Increasing the number of connections increases the risk of failure. On the other hand, insufficient number of batteries may require more outages in case of a fault. In addition, weight and commercially availability of batteries must be taken in to account for a good choice. Battery unit is usually the second biggest part of the total cost of PV system after modules. Storage costs are closely related to the life of selected battery. According to a detailed study by Jossen et al., if battery life is less than 3.5 years, storage units are becoming the most expensive element of PV systems due to increased replacement costs (Jossen et al., 2004).

3.3 PV panel array sizing

After making the calculation about amount of load, photovoltaic array (panel) can be sized. In that phase, to provide the aim of minimum PV module usage, appropriate tilt and number of parallel modules are determined. If the system voltage is greater than the chosen module's output voltage, additional modules can be needed for series connection.

The main thing is working of the system under the worst conditions (Messenger & Ventre, 2000; Able-Thomas & Hill, 1996). In that case, calculation can be made like that separate for every day or every month, in addition to that if the system will work during the whole year or whole month just for the worst conditions the current taken from the PV module (I_{PV}) and number of modules (N_M) can be determined. The number of modules needed for the system is determined after taking into consideration of modules' dirty surface due to usage or depreciation loss, total design current is divided to one module's current. Especially crystalline modules are more sensitive to dirty surface and slope of sunshine than amorphous modules. Besides, the temperature changes on surface during the daytime also affect the efficiency of module (Gregg et al, 2005). For this reason, a correction factor is implemented to that calculated module current. To choose that value as 0.9 is enough to provide accuracy (Messenger & Ventre, 2000). According to chosen number of modules multiplication of the power of module (P_M) and number of modules gives the power of the installed PV (P_{PV}) panel.

$$I_{PV} = \frac{\sum L}{T_{min} \cdot 0.9} \tag{8}$$

$$N_M = \frac{I_{PV}}{I_M} \tag{9}$$

$$P_{PV} = P_M \cdot N_M \tag{10}$$

If the tilt of the panel can be changed monthly or seasonally, a new table that gives the optimum design current can be made. To form that table, a database should be made according to tilt for every month. But in that case module save can be failed because the system is designed for the worst conditions. This method provides the calculation of the extra energy produced from the PV modules and this energy can be consumed by additional consumers.

3.4 Selection of inverter and charge controller

Under the nominal working conditions the necessary inverter power to feed the A.C. load can be chosen the 110% of PV panel power. However if the system feeds a motor load, the choice should meet the start up and maximum load current. According to an experimental study made by Onat et al. in 2009, especially start up currents of A.C. machines such as induction motor and transformers have some important effects on PV systems. According to the study, induction motor has been the most compelling electrical machine for PV system that has demanded a startup power that is 2.14 times higher than nominal power value. In addition, such demand for quite high power (transient operation period) has lasted for a long time of 8.2 seconds. On the other hand, startup power of transformers has been 1.3 times higher than nominal value. Moreover, the time required to complete transient operation has been 5.3sec. However, if the startup current is not taken into consideration, particularly in the systems that are frequently connected and disconnected, high power drawn may result in overheating of the modules and decrease of the efficiency of the photovoltaic system (Onat et al., 2009).

In charge controller selection, generally simple ones are preferred. Some safety problems can be occurred because of complexity. Charge controller should keep the battery current that comes from the panels equal to the load current. In that case inverter power (P_{inv}) and controller current (I_{ch}) can be found by following formulas.

$$P_{inv} = P_{PV} \times 1.1 \tag{11}$$

$$I_{ch} = \frac{P_{PV}}{V_b} \tag{12}$$

In that formula, V_b shows the battery group’s D.C. output voltage. In the selection of inverter and controller the efficiency affects the system’s working directly and that has been stated in the design phase of load determination. In the selection of those equipments, the efficiency cost relation should be checked. Especially in inverter market, simple, cheap but it creates until the 10% loss, additionally expensive but working with 98% efficiency models are also available (Gregg et al., 2005).

3.5 Auxiliary components (BOS) and assembly

Wire sizing must be made separately for every part of the system. Generally, panel-battery, battery-controller, or inverter and controller-load are the main parts. But this can be extended according to the specifications of the load and system. In consideration with maximum current of every part and line length, voltage drops can be calculated.

In the selection of fuse, generally standard fuses that have as a current value 125% of the nominal line current are preferred. All fuses that are going to be used in DC should be suitable for that type current.

Switches and breakers in the system that makes the on-off operations should be suitable for the maximum current values controlled by them. Besides they should be suitable for the current type (AC or DC) that used for. In inductive currents, sudden current interruption may cause high voltage in switches. If the controlled load is inductive, they should be durable to high voltage and arcs that are formed when the circuit is interrupted.

Sub components of the systems, such as plugs, fuse clips, protection systems, ground rods, battery cabins, electric boards...etc should be considered in design phase.

These equipments' cost is named as BOS (Balance of System). In practical calculations, this cost is taken as 10% of the total panel cost (Messenger & Ventre, 2000). However, if enough data is available this calculation can be made in more detail. Besides, the assembly cost also should be considered in the design phase. Assembly costs change according to land conditions and system characteristics.

4. Cost calculation of PV systems

Costs in photovoltaic systems include purchase, operating, maintenance and change costs. If the firm should borrow money to buy a property, then this cost also should be added to this cost. In most of the cases, to meet all cost of the first purchase from the capital stock is not economical. Especially, for an accuracy cost calculation of PV systems, considering of external costs is important. External cost is generally not measurable and does not have direct relation with the system. For example many people know that acid rains are occurred due to sulphur emission from the factory chimneys. Also acid rains cause damages in buildings and this is also known. But the cost of this damage does not paid directly by the companies that cause the emission (Messenger & Ventre, 2000). External cost value can also be negative. For example, if the system has a benefit that is not directly have a positive effect on the system, this value can have an effect to decrease the total system cost. Generally when to determine the cost the following four methods are used.

1. Heuristic or experience based method; In that method estimated cost is determined by experienced people.
2. Analogical method; this method includes stereotypes about cost estimation systems and structures.
3. Parametric method; uses equations to define the relation between a system's measurable aspects and its cost.
4. Analytical method; is also called as detailed model. Every step in construction phase of the system is included in cost. Like labor force rate, labor force time, material amount

and price. This method also called as bottom-up method (Du et al., 2009). In Table 3. these methods' implementation parts are seen.

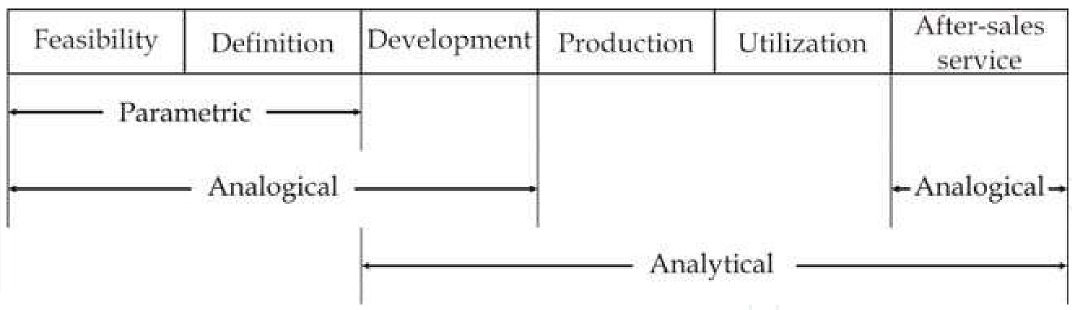

Table 3. Use of cost calculation methods and application areas

4.1 Life cycle cost analysis (LCCA) of PV systems

Purchase of any properties or construction of a facility, the first and most important step is creating the design project. Design steps of photovoltaic systems are focused in previous parts. In some situations, the aesthetic and ergonomic characteristics of the design are also examined in this scope. Second step is to determine how the design can be carried out. "How long does it take to set up the system?" and "What is the first cost in construction phase?" are this step's two important questions and should be answered after the first step. The third step is calculation of the total cost of purchase/construction during the life of the system. This information also includes operating, maintenance, replacement and disposal (salvage) costs in addition to the first setup and design costs and especially affects the investors' decision. Many effective methods are developed to calculate this value before the construction phase by the use of economic theories with computer technologies (Mearig et al., 1999). LCCA is generally used to compare a few different project alternatives. PV systems can also be including these different alternatives. For example, like a PV system working separately or a hybrid PV/Wind system's preference, to chose one of the load from two loads those make the same work, to compare the module and battery options those are going to be used in PV systems according to their costs for the different options as a result of LCCA well decisions can be made. In electric producing systems, the other aim of LCCA is to determine the energy cost per unit. This value can affect the system's set up preference. This also gives clue in determination of sales cost of the produced electrical energy.

4.2 Stages of LCCA

In litterateur, different implementation methods are developed for LCCA. Barringer explained the 11 steps to complete the LCCA. According to this study, "the basic tree for LCC combines acquisition and sustaining costs as shown in Fig. 7. Acquisition and sustaining costs are not mutually exclusive. If you acquire equipment, you must sustain the acquisition, and you can't sustain without someone having acquired the item. Acquisition and sustaining costs are found by gathering the correct inputs, building the input database, evaluating the LCC and conducting sensitivity analysis to identify cost drivers" (Barringer & Barringer, 2003).

According to the study of Jeromin et al, LCC analysis includes there main stages as investment, operating and recycling. In addition to that the information, for every stage which costs are calculated, is also included in detail (Jeromin et al., 2009). Some parameters used in LCCA have been explained below.

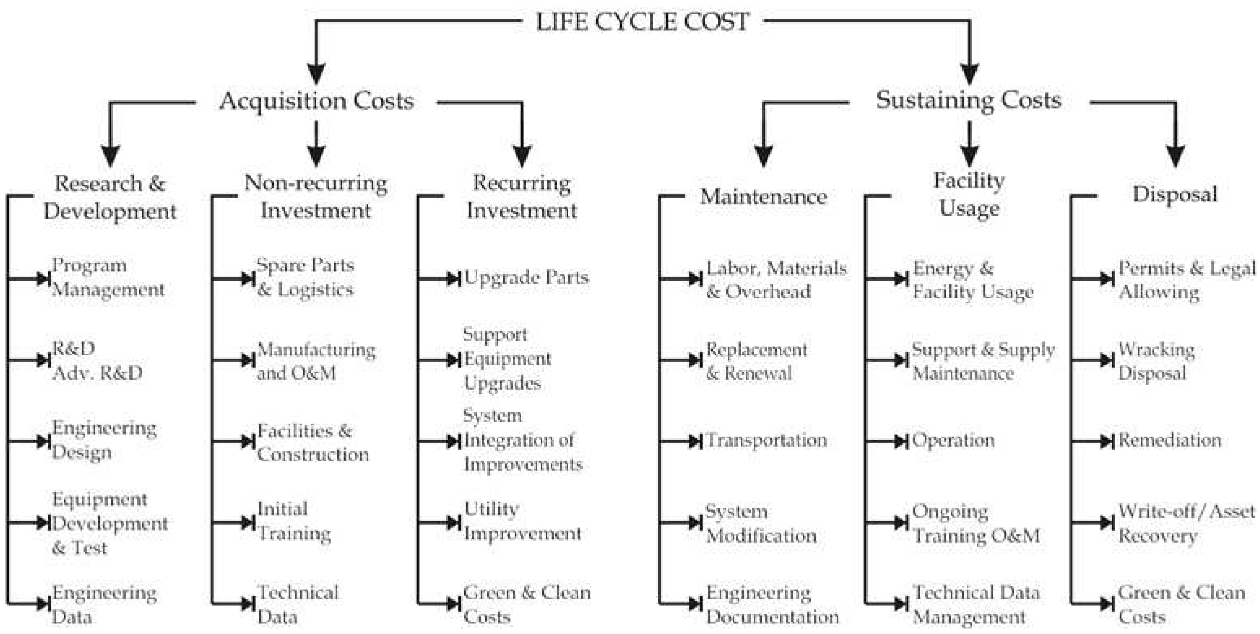

Fig. 7. Main components of LCC

4.3 The monetary Impact of time

Life cycle cost (LCC) of an item includes the sum of operating and trading costs during the life time. Some of these costs occur in the purchasing period, while others engaged in next time. To compare two similar products which taken at different times and at different costs is a convenient way to reduce all costs to purchasing time. This process is known as the "present worth method". The two events will determine the value of money over time.

Inflation rate (i) is a measure of the decline in the value of money. For example, in a country where annual inflation rate of 5%, then the items will cost more than 5% next year. So that, more money will be required to buy the same product. In fact, there is decreasing the value of cash. Beside this, the inflation rate is valid for any product does not have to equal to the general inflation rate. Annual price increase on certain products may be too high or low according to the average value.

Interest (discount) rate (d) is associated with the amount of profit that obtained from saving capital. If the money is being deposited in a bank account, interest rate of that is a positive value. The -n- year's later value of a currency lent at interest annually at a d% rate is calculated by (13).

$$N_n = N_0(1+d)^n \quad (13)$$

Therefore, the amount of money in cash will increase. However, incoming money (N_n) will not be equal to initial value (N_0) in terms of purchasing power by reason of changes in the inflation rate. Inflation increases the purchasing cost of a product. For this reason, the purchase cost of an item -n- years later will be:

$$C_n = C_0(1+i)^n \quad (14)$$

In this case, if the cost of an item increases more than incoming money from bank account, it may be profitable to buy the product immediately. If the opposite that inflation rate lower than discount rate then should wait before making the purchase. However, this purchasing manner is not valid often because of cannot be benefit from the item until it is purchased. Finally, in the purchasing period of an item economy may not always be in the forefront. Only needs or personal requests may be reasons of purchase. If the initial purchasing cost and investment cost are equal to each other $(C_0 = N_0)$, C_n/N_n ratio is a dimensionless value. This ratio determine the present worth coefficient (P_R) of money. Accordingly, P_R of an item that will purchase -n- year later is;

$$P_R = \left(\frac{1+i}{1+d}\right)^n \tag{15}$$

Thus, the present value of the item (P_{Worth}) is calculated by following equation.

$$P_{Worth} = P_R \cdot C_0 \tag{16}$$

In the calculation of P_{Worth} of recurring expenses in each or certain years such as operating and maintenance costs (O&M) or replacement costs etc., above equation (16) is rewritten for each purchasing year and their sum is taken as in equation (17).

$$P_{Worth} = C_0 + C_0\left(\frac{1+i}{1+d}\right) + C_0\left(\frac{1+i}{1+d}\right)^2 + C_0\left(\frac{1+i}{1+d}\right)^3 + ... + C_0\left(\frac{1+i}{1+d}\right)^{n-1} \tag{17}$$

If assumed that $x = \left(\frac{1+i}{1+d}\right)$, equation (17) can be written as follows (Messenger & Ventre, 2000; Kolhe et al., 2002).

$$P_{Worth} = C_0(1 + x + x^2 + ... + x^{n-1}) \tag{18}$$

4.4 Calculation of life cycle cost

Life cycle cost (LCC) is defined as the sum of present values of all components in the system. Basically, the calculated LCC should be included purchasing, replacement, maintenance, fuel and operating costs of each component. Additionally, if there is a sales value of the system at the end of the operating life, this fee will be added as a negative cost to LCC. In some cases, destruction, transportation or disposal expenses may also be required. These values should be added as a positive life costs.

In this study, fossil fuel saving amounts that obtained by the use of PV systems are taken into consideration. This value can be determined by the calculation of required fossil fuel to produce the energy equal to PV system. Here, lower heating value (H [kcal/kg]) of used fossil fuels and efficiency of power plant ($\eta_{ü}$) should be known. In this case, to calculate the saved fuel amount (M_F), following equation can be used.

$$M_F = \frac{1}{H}\left(\sum_{i=1}^{t}\frac{X \cdot Y_i}{\eta_{ü}}\right) \text{ [tonnes]} \tag{19}$$

Here, X indicates power of the system (MW) and Y_i represents the percentage value of solar power in total during lifetime (Amit et al., 1995). If PV provides all power consumption of load, then assumed Y_i=1. "t" is the total time (hours) of the system in operation. Another point to note here that the fossil fuel consumed during the production of solar cells or the carbon dioxide emissions is taken into account. With the adding of these values in the calculations more accurate results are obtained. In a detailed study realized by Stoppato, recycling period of toxic gas emissions that occur during the PV module production was calculated. Recycling period was obtained as 3.5 and 4.91 years for two different systems which have 28 year lifetime and 10MW power (Stoppato, 2008). These values correspond to the 13.5% and 17.5% of total module life respectively. So, for accurate calculation of -t- in equation (19), system life should be assumed lower than approximately 15% of real value. In this case, saving the cost of fossil fuels (C_F) can be easily calculated by multiplying the calculated value in (19) by the unit price of fuel (C_{fuel}) (Amit et al., 1995).

$$C_F = M_F \cdot C_{fuel} \tag{20}$$

As a result, data needed to write a comprehensive LCC equation can be obtained. LCC value will be the sum of present worth of the costs detailed above.

$$LCC = C_0 + C_{O\&M_{PWorth}} + C_{R_{PWorth}} - C_{S_{PWorth}} - C_{F_{PWorth}} \quad [c.u.] \tag{21}$$

Here, C_0, $C_{O\&M}$, C_R, C_S, and C_F represent the sum of initial purchasing, operation and maintenance, replacement, salvage and fuel costs respectively. All the values are calculated in currency unit (c.u.) of purchase. In grid-connected PV systems, selling value of produced electricity is also added to LCC. Depending on the size of the system, design and construction phase may take one or two years. This period is the stage of initial purchasing at the same time. Fig. 8. shows cash flows of a sample system that's total life is 27 year (including the design and installation period) (Whisnant et al., 2002). Note that, cost of saving fuel has participated in the seventh year to LCC as stated above.

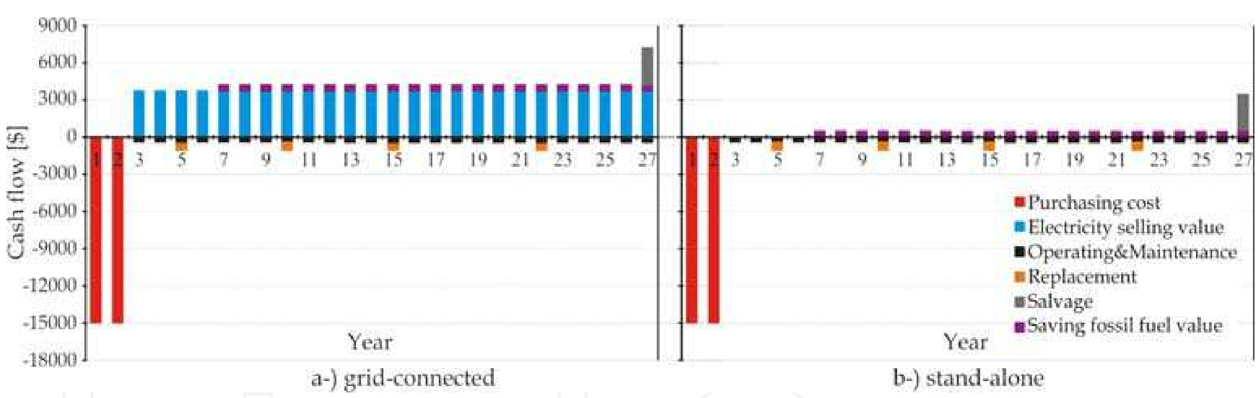

Fig. 8. Sample cash flows of PV systems

Finally, the choice to be made between different alternatives, a table is prepared containing LCC values of all components and options for a healthy comparison. Thus, LCCA is completed. But generally the unit cost of energy is also calculated in power systems. Especially in stand-alone systems, knowing of unit energy cost provides important advantages.

4.5 Unit energy cost calculation

The unit energy cost (C_E) can be calculated as simple dividing by annual life cycle cost (ALCC) to annual energy consumption of loads feeding by system. Here, total energy consumption of loads (ΣE) during life time of the system is obtained by multiplying ΣL that calculated by equation (3) and total time (t) of the system in operation. Equation (23) is used to calculate ALCC value (Chel et al., 2009). In this case, annual energy production and unit energy cost of PV system are founded from equation (24) and (25) respectively.

$$\sum E = \sum L \cdot t \qquad [kWh] \tag{22}$$

$$ALCC = LCC \cdot \left[\frac{\left((1+d)^n \cdot d\right)}{\left((1+d)^n - 1\right)} \right] \qquad \left[{CU}/{year} \right] \tag{23}$$

$$E = \frac{\sum E}{n} \qquad \left[{kWh}/{year} \right] \tag{24}$$

$$C_E = \frac{ALCC}{E} \qquad \left[{CU}/{kWh} \right] \tag{25}$$

ALCC re-calculated for each system, but it is a constant value. Therefore, according to the equation (25), the most effective way of reducing the unit cost of energy is increase the load as possible as feeding by system.

4.6 Other parameters that affect LLC and the unit energy cost of PV systems

In the calculation of LCC and unit energy cost can be various positive and negative factors in addition to the above-mentioned parameters. Capacity utilization rate (CU), the loan has been received and not received (credit use) to meet the initial investment cost, conditions and amount of borrowed money, incentives and subsidies given by the state or otherwise applied additional taxes can be considered as the most important ingredients that create these effects. These parameters are described briefly below.

4.6.1 Capacity utilization rate

Capacity utilization (CU) is one of the most important parameters that directly affect the unit cost of PV energy systems. CU is a measurable value depending on consumed percentage of total generated energy and changes with technical, geographical and climatic parameters in PV systems. However, in grid-connected wind and PV systems, depending on the region's conditions if the CU rate is above 20% is considered suitable for investment (EIE, 2009).

CU rate is largely depending on amount of load feeding from PV system. System design should be made taking into account the worst conditions in operating period of the load. Otherwise, reliability problems and loss of load probabilities will arise. Panel sizing and storage unit calculations are also made according to the worst climatic data as given previous sections. So, resulting in usage of excess energy is important in the better climatic conditions when the system is in operation. Usually, excess energy is wasted with dump loads or some modules are disabled. However, these methods do not make a positive impact on unit energy cost. If the excess energy uses to feed other loads or it is possible to sell to the real consumers, unit energy costs can be reduced greatly in (Eltawil & Zhao, 2010). In a sample application realized by Ersöz and Onat for İstanbul-Turkey, effect of CU on unit energy cost was calculated. According to this paper, CU of a PV system designed for a load that is in operation whole year was determined as 2.48% in case of only load feeding. Unit energy cost is 1.16$/kVAh. In case of only 5% of excess energy consumed in a useful way, unit energy cost decreases approximately three times and is 0.394$/kVAh (Ersöz & Onat, 2010). The relationship between capacity utilization rate and the unit cost of energy is seen in Fig. 9.

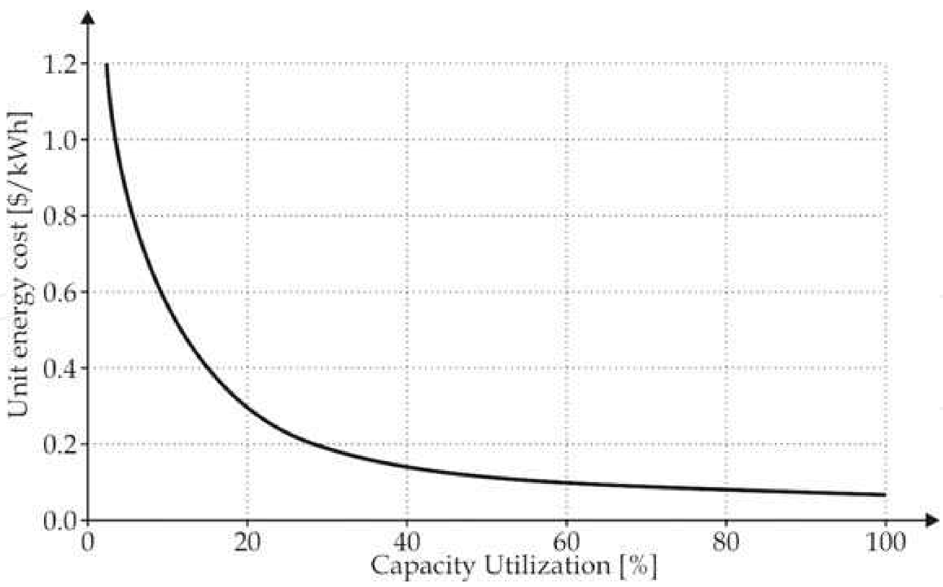

Fig. 9. Changing of unit energy cost with capacity utilization

4.6.2 Borrowed money (credit usage)

Sometimes do not enough money in hand to get a desired product. In this case, often borrowing is taken from banks and other credit institutions. So, the amount of borrowed money and interest on borrowings is also important and affects the cost of items. If bank loan will be used to buy a product, it must be known how will affect the LCC of the product. To do so, tables would prepare showing the annual repayment of borrowed money. This process has become very easy with computer technology.

If enough money is available for any purchase, it is really easy to decide whether spending or saving. Otherwise if the money is not available, the only option is to borrow. Even if the money is available, it should be taken into consideration that interest of the borrowing is lower or higher than bank account interest. In some cases, credit usage may be more advantageous (Messenger & Ventre, 2000).

4.6.3 Subsidies (incentives) and taxes

Additional factors that should be taken into consideration in cost analysis are effects of subsidies (government aids) in various ways. While some of subsidies are included into the cost directly, others occur as external costs. Today, in most countries various subsidy mechanisms have been established to encourage the use of renewable energy sources. Rarely, some governments are taking some extra taxes during the installation of the system or over produced energy. Therefore, effects of these taxes and subsidies on LCC vary between countries. For example according to the law on "**Use of Renewable Energy Resources for Production of Electric Energy**" dated May 10, 2005 in Turkey;

- For the energy to be produced from renewable energy resources by companies that fulfill the conditions given in the regulation, a purchasing guarantee will be ensured.
- In case the natural and judicial persons establish plants with maximum 1MW installed power to meet their own needs, regardless of whether it is a network supported or individual system, for the projects of which definite project, planning, master plan, preliminary survey or first study are prepared by the General Directorate of State Hydraulic Works (DSI) or (EIE), no service fee will be charged.

- The necessary plant investments to establish such systems, supplying of electro-mechanic systems domestically as production, research and development (R&D) and production investments to be made under scope of electric production systems that use solar cells and focusing units and R&D plant investments related to electric energy or fuel production by using biomass resources will be benefit from incentives,
- In case immovable assets under property of the forestry and treasury departments or disposition and jurisdiction of the state are used to make electric energy production from renewable energy resources under scope of law, the required usage permits for such lands will be given and in case of leasing; various tax deductions will be awarded (Official Gazette of Turkish Republic, 2005).

After all these steps LCC analysis are completed. Designer should try to make an accurate calculation as possible using all of or only necessary steps above-mentioned, depending on economic, social and geographical conditions of the country.

5. Examples

5.1 Sample application-1

For a PV system planned in İzmir-Turkey, cost-effective option will be chosen from among alternatives in Table 4. Duration of the project and installation of the system is given as one year. Operating cycle is determined as 25 years duration of the project except. Let's calculate LCC and unit energy cost of each alternatives.

System Location	:	İzmir - TURKEY
Life Cycle of System	:	25 year
Inflation Rate	:	5%
Interest Rate	:	10%
Operating and Maintenance Cost	=	150$/year
Balance of System Cost (BOS)	=	10% of module cost
Assembly Cost	=	5% of module cost
Salvage Value	=	15% of total initial purchasing cost

Component Alternatives	Specifications	Price [$]	Life [Year]
Load - 1 (AC Load) (fan motor)	voltage: 220VAC, daily power consumption: 2kWh/day	150	15
Load - 2 (DC Load) (fan motor)	voltage: 24VDC, daily energy consumption: 100Ah/day	250	10
Module	voltage: 12V, power: 120W, current: 10.84A	638	= system life
Battery - 1	voltage: 12V, capacity: 210Ah, efficiency: 90%	313	10
Battery - 2	voltage: 12V, capacity: 102Ah, efficiency: 90%	153	15
Inverter	voltage: 24VDC-input / 220VAC-output efficiency:95%	500	10
Charge Regulator	Input voltage: 24VD, efficiency: 95%	145	5
Wiring	efficiency: 98%	BOS includes	= system life

Table 4. System specifications for sample application

5.1.1 Solution

Let us first determine the amount of the system daily load. Using equations (1) and (2), L values are determined as below.

For AC load, L_{AC}=104.68Ah/day, and DC load, L_{DC}=119.35Ah/day

According to the average of 30 years meteorological data measured by Turkish State Meteorological Service, the peak sun hours of Izmir are given in Table 5.

Months	January	February	March	April	May	June	July	August	September	October	November	December
Peak sun hours [h/day]	4.3	5.1	6.6	7.4	9.6	11.8	12.2	11.6	10.0	7.5	5.3	3.8

Table 5. Average peak sun hors of Izmir for each month

The worst time-slot of average daily sunlight duration for İzmir is stated as December 3.8h/day. Voltage of PV module is half of load voltage. Therefore, two modules should connect in serial. Accordingly, demanded current, number of modules and power of PV panel are calculated by taking twice of values determined from equations (8), (9) and (10).

$I_{PV(AC\text{-}load)}$=27.552A, $N_{M(AC\text{-}load)}=5.08 \Rightarrow 6$, $P_{PV(AC\text{-}load)}$=720W

$I_{PV(DC\text{-}load)}$=31.41A, $N_{M(DC\text{-}load)}=5.78 \Rightarrow 6$, $P_{PV(DC\text{-}load)}$=720W

Note that, total module number (N_M) can not be odd number because of parallel connection requirements. Autonomous day number is calculated as D=2.756days, by using of the equation (5). From equation (6), total battery capacity is determined as, $B_{AC\text{-}load}$=360.62Ah and $B_{DC\text{-}load}$=411.16Ah. In this case, numbers of batteries for each option are calculated by using equation (7). (The battery number will be doubled and N_M can not be odd number).

$N_{B(1)AC\text{-}load}=4$, $N_{B(2)AC\text{-}load}=8$, $N_{B(1)DC\text{-}load}=4$, $N_{B(2)DC\text{-}load}=8$,

In battery selection, consideration of only initial purchase cost does not give accurate results. To make an acceptable choice, LCC analysis must be realized for two batteries given in the problem. By the use of inflation and interest rates, "x" value is found as x=0.9545. Accordingly, the cost calculation results are given as outlined in Table 6. Despite containing more connection, Battery-2 (12V, 102Ah) should be preferred that is advantageous approximately 28% in terms of total LCC.

Cost [$]	Battery - 1	Battery - 2
Initial	1252	1224
Pworth of 10th year replacement	785.89	
Pworth of 15th year replacement		608.72
Pworth of 20thyear replacement	493.31	
TOTAL LCC	**2531.2**	**1832.72**

Table 6. LCCA of battery alternatives

Inverter power is calculated as approximately 400W from equation (11). Current value of charge regulator is also determined as 15A by the use of equation (12). After these stages, LCC calculation can be realized. For this, showing of all calculations in a table is a preferred way. In this study, Table 7. has been established using the same method.

Component		AC - LOAD			DC - LOAD		
		Purchasing Cost [$]	Present Worth [$]	Per. of in the LCC [%]	Purchasing Cost [$]	Present Worth [$]	Per. of in the LCC [%]
Initial Investment Costs							
Load		150	150	1.63	250	250	2.94
Module		3828	3828	41.6	3828	3828	45.1
Batteries		1224	1224	13.3	1224	1224	14.4
Charge Regulator		145	145	1.58	145	145	1.71
Inverter		500	500	5.44			
BOS		382.8	382.8	4.16	382.8	382.8	3.00
Montage		191.4	191.4	2.08	191.4	191.4	4.51
Total Initial Investment Costs			**6421.2**	**69.85**	**6021.2**	**6021.2**	**71**
Operating and Maintenance Costs							
Yearly Operating& Maintenance Costs		100	**1542.92**	**16.78**	100	**1542.92**	**18.2**
Replacement Costs							
5^{th} Year	Charge Reg.	145	114.88	1.25	145	114.88	1.35
10^{th} year	Load				250	156.93	1.85
	Inverter	500	313.86	3.41			
	Charge Reg.	145	91.02	0.99	145	91.02	1.07
15^{th} year	Batteries	1224	608.72	6.62	1224	608.72	7.17
	Load	150	74.60	0.81			
	Charge Reg.	145	72.11	0.78	145	72.11	0.97
20^{th} year	Load				250	98.51	1.16
	Inverter	500	197.01	2.14			
	Charge Reg.	145	57.13	0.62	145	57.13	0.67
Total Replacement Costs		**1529.33**		**16.64**	**1198.82**		**14.13**
Salvage Cost		300.68		3.27	281.95		3.32
Life Cycle Cost (LCC)			**9192.77**	**100.0**	**8481.5**		**100.0**

Table 7. LCC calculation details of two load alternatives

Looking at the LCC values obtained seems to be very close to each other. The difference between the two systems is below 10%. In such a case, the design engineer may also decide which option is more appropriate by looking parameters other than cost. For instance, a load may be preferred that require fewer battery or module. Sometimes, because of market conditions in the country, availability or being domestic production may be preferred for a system. In this application, only the life cycle costs will be considered only. In this case, to choose the DC load is obviously necessary. If accepted, this selection is made; the unit cost of energy can be calculated. From equation (22), useful amounts of energy will be produced by the system is determined as 26137.65kWh in 25 years. Note that, it should also be considered in this calculation that system voltage is 24VDC. By the substituting of this value in equation (23), ALCC is obtained as 934.4$/year. (24) After the calculation of E value as 1045.5kWh/year from equation (24), unit energy cost (C_E) can be determined using of the equation (25) as 0.894$/kWh.

5.2 Sample application-2

In this application, we calculate the system's capacity utilization rate selected in previous example. In addition, we determine the amount of produced excess energy and show the effect of consuming 5%, 15%, 25% and 35% of this excess energy on unit energy cost.

5.2.1 Solution

The amount of produced PV energy can be calculated for each month. PV panel consist of three parallel circuits with two modules in serial connection as calculated above. The current of each circuit is 10.84A. In this case, for instance, according to T_{min} value is 4.3h for the month of January, produced energy in this month can be calculated as $E_{January}$=3*4.3*10.84*31=4334.92Ah. Table 8. is formed from similar calculations made for other months.

Months	Peak sun hours [h/day]	I_{PV} [A]	E_{PV} [Ah/month]	E_{Load} [Ah/day]
January	4.3	32.52	4334.92	3699.85
February	5.1		4643.86	3341.8
March	6.6		6653.59	3699.85
April	7.4		7219.44	3580.5
May	9.6		9677.95	3699.85
June	11.8		11512.08	3580.5
July	12.2		12299.064	3699.85
August	11.6		11694.192	3699.85
September	10		9756	3580.5
October	7.5		7560.9	3699.85
November	5.3		5170.68	3580.5
December	3.8		3830.856	3699.85
Yearly Total [Ah/year]			**94353.528**	**43562.75**
25 years TOTAL [Ah]			**2358838.2**	**1089068.75**
Capacity Utilization			**%46.17**	

Table 8. Produced energy and CU values of the system for each month

As shown in Table 8. during the total life cycle (25 years), approximately 1270kVAh=30480kWh excess energy will be produced in case of feeding DC load only. Useful consumption of this amount in rates of given in the problem, then the following results are obtained.

5% is consumed; ⇒ E=1106.44kWh/year ⇔ C_E=0.84$/kWh

15% is consumed; ⇒ E=1228.39kWh/year ⇔ C_E=0.76$/kWh

25% is consumed; ⇒ E=1350.3kWh/year ⇔ C_E=0.69$/kWh

35% is consumed; ⇒ E=1472.23kWh/year ⇔ C_E=0.63$/kWh

Unit cost of energy has fallen by increasing of the capacity utilization.

5.3 Sample application-3

Let's calculate the amount of fuel consumption and its financial value and let's draw a cash flow diagram. Low heating value and unit price of diesel are given as H_{diesel}=10000kcal/kg and C_{diesel}=2000$/ton. Efficiency of diesel power plant will be accepted as 35%.

5.3.1 Solution

First we calculate the amount of fuel saving with equation (19). LCC of the system assumed as 15% lower than actual value as mentioned under heading 4.4 $(25 \cdot 0.85 = 21\text{year})$. According to utility energy amount that will be produced by the PV panel is 26137.65kW=26.14MW, saving diesel fuel amount is calculated as

$$M_{Diesel} = \frac{1}{H_{Diesel}} \left(\sum_{i=1}^{t} \frac{X \cdot Y_i}{\eta_{diesel}} \right) = \frac{26.14 \cdot 1}{10000 \cdot 0.35} \cdot 21 = 2.184\,\text{tonnes} .$$

By dividing of this value to life of the system, annual saving amount is obtained as 103.8kg. In this case, present worth of saving can be calculated. For this, by the using of "x" value that have already calculated before as $x = 0.9545$, Table 9 is formed. Here, unit price of diesel (2$/kg) should be taken into account. Although, purchasing cost of diesel in first year is $2 \cdot 103.8 = 207.6\$$, calculation should start from 5th year.

Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total
M_{diesel} [kg]					103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	103.8	**2179.8**
C_{diesel}[$/kg]	2																									
Pworth of ΣC_{diesel}[$]					164.5	157	149.9	143	136.5	130.3	124.4	118.7	113.3	108.2	103.2	98.5	94.1	89.8	85.7	81.8	78.1	74.5	71.1	67.9	64.8	**2255.4**

Table 9. LCC analysis of fuel savings

Here, the calculated value of $2255.1 in the amount of savings is the only measurable benefit. It does not include the environment and human health benefits. Even considering of this value only, the calculated value of LCC in example-1 decreases to the 6226.4$. Finally, annual LCC and unit energy cost are calculated as 685.95$/kWh and 0.656$/kWh respectively. As a result of these calculations, cash flow diagram is also seen in Fig. 10.

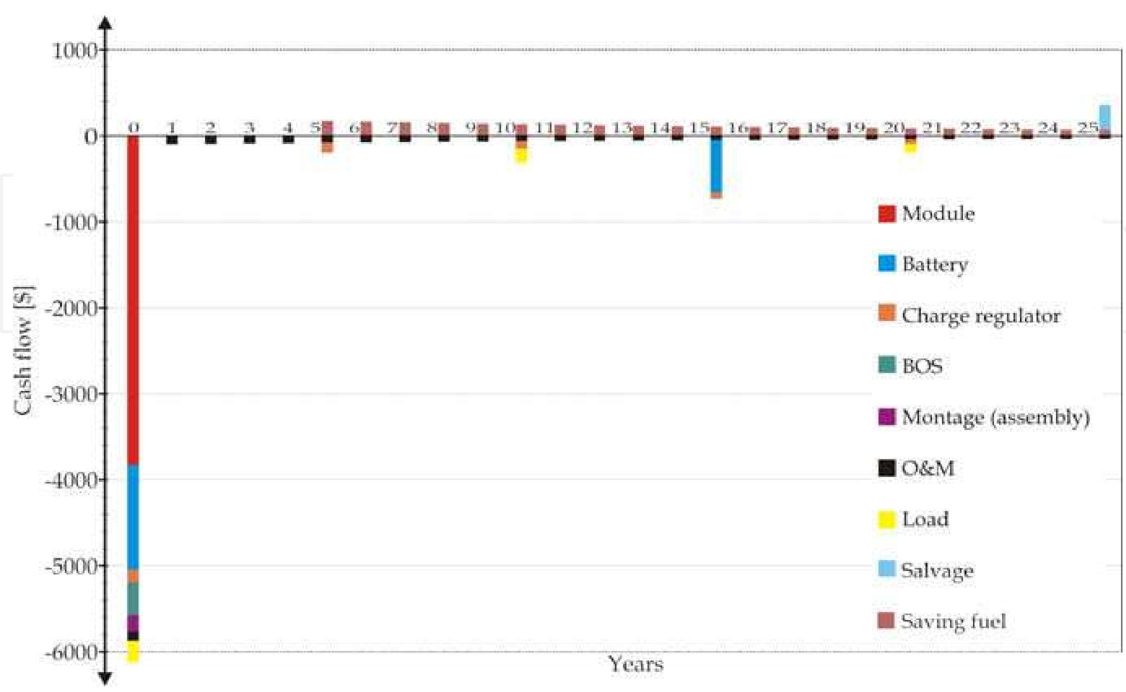

Fig. 10. Cash flow diagram of PV system with DC load

6. Conclusions

In this chapter, it has been supported by the results of various researches that PV systems should take place within the sustainable energy policies. This is an accepted fact by international energy agencies that PV systems will have an important share in the second half of 21st century especially.

In today's economic conditions, cost is the most disadvantaged sustainability parameter of PV systems. This negativity can be reduced by taking into account the external benefits in cost calculations. In this chapter, PV system design processes are described in detail. All necessary parameters are also defined to make an accurate LCC calculation. In addition, the impacts of capacity utilization and fossil fuel savings on the LCC are discussed and methods of calculating these values are added to the topics.

Other important disadvantage of PV system in terms of sustainability is power quality depending on the reliability problems. Both high cost and short life span of batteries used to reduce the reliability problems are emerging as negative barriers. Low efficiencies of commercial PV modules (between 12% and 20%) are also an important technical drawback. Depending on technological developments on these issues, the share of PV system in electrical energy production will increase substantially.

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The world's reliance on existing sources of energy and their associated detrimental impacts on the environment- whether related to poor air or water quality or scarcity, impacts on sensitive ecosystems and forests and land use - have been well documented and articulated over the last three decades. What is needed by the world is a set of credible energy solutions that would lead us to a balance between economic growth and a sustainable environment. This book provides an open platform to establish and share knowledge developed by scholars, scientists and engineers from all over the world about various viable paths to a future of sustainable energy. It has collected a number of intellectually stimulating articles that address issues ranging from public policy formulation to technological innovations for enhancing the development of sustainable energy systems. It will appeal to stakeholders seeking guidance to pursue the paths to sustainable energy.