East West University

Department of Electronics and Communications Engineering

On the Determination of Levelized Cost of Electricity for Solar PV System

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Declaration

This is certified that the project is done by us under the course “Project (ETE-498)”. The project ‘**On the Determination of Levelized Cost of Electricity for Solar PV System’** not been submitted elsewhere for the requirement of any degree or any other purpose except for publication.

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Abstract

As the solar photovoltaic (PV) matures, the economic feasibility of PV projects is increasingly being evaluated using the levelized cost of electricity (LCOE) generation in order to be compared to other electricity generation technologies. Unfortunately, there is lack of clarity of reporting assumptions, justifications and degree of completeness in LCOE calculations, which produces widely varying and contradictory results. This paper reviews the LCOE for solar PV, correcting the misconceptions made in the assumptions found throughout the literature. Then a template is provided for better reporting of LCOE results for PV needed to influence policy mandates or make invest decisions. A numerical example is provided with variable ranges to test sensitivity, allowing for conclusions to be drawn on the most important variables. Grid parity is considered when the LCOE of solar PV is comparable with grid electrical prices of conventional technologies and is the industry target for cost-effectiveness. Given the state of the art in the technology and preferable financing terms it is clear that PV has already obtained grid parity in specific locations and as installed costs continues to decline, grid electricity prices continue to escalate, and industry experience increases, PV will become an increasingly economically advantageous source of electricity over expanding geographical regions.

Acceptance

This Project paper is submitted to the **Department of Electronics and Communications Engineering, East West University** is submitted in partial fulfillment of the requirements for the degree of **B.Sc** in **ETE** under complete supervision of the undersigned.

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Chapter 1
Introduction

1.1 INTRODUCTION

This Thesis work represents some of effective ways to levelize the cost of electricity (i.e in short LCOE) for different Renewable Energy (RE) resources. Now here the term comes Renewable Energy (RE), simply, Renewable Energies are those generated from sources that do not have a finite end, or those that can be recycled, typically from natural sources – like solar power, wind power and water/hydro power.These are the examples that we think about most when we hear the term "Renewable Energy" but they are not the only sources.

Now, can we imagine a world without energy? It's not possible, right. Let's have a look on our daily lives – our electronic devices require electricity for power, our streetlights need the same for lighting, our vehicles require gasoline and diesel. We fuel our homes with domestic oil, propane or electricity from a national or local grid for lighting, heating and powering our devices. Also each website that is hosted on a server that needs power. The places where used to work, we use computers, phones, printers, scanner devices, security systems and servers, as do our shopping malls, parking lots, sports stadiums, cars, ships, airplanes and so on, all these things needs power.

Before the discovery and utilization of Coal around the time of Industrial Revolution, most of the energy we used for lighting and heating was from renewable sources. Then we discovered Coal that fueled the industrial revolution in the western world, and later on tap oil in greater quantities leading to an acceleration of technologies that would take us into the 20th century. Throughout most of human history and pre-history, we burned what would today be known as "biomass": plant material such as wood, grass, mosses and so on, to fuel our hearths and later, homesteads. It became an important fuel source. From one perspective, the discovery and utilization of fire is a history of civilization, and a history of the use of renewable energy. Humanity continued in that fashion for many thousands of years before the discovery of oils though obviously in smaller quantities and the mass drilling of oil during the industrial age. Other uses of renewables in antiquity include animal power (using cattle to drive ploughs or turn millstones) and wind for the sail that has driven trade for some 8,000 years of human history. The use of water sources, such as creating dams to harness the power of the fluid motion of water, is not a new idea either. It was in the 1970s that we began to look back towards some of these ancient methods and technologies to provide the power sources of tomorrow. Peak oil and peak coal was theorized as far back as the 1870s. some thinkers were theorizing on and developing concepts of solar technology to prepare for a post coal world. Theories and investment in solar technology lasted until the outbreak of WWI. Even in 1912, a paper in Scientific American hypothesized that soon, fossil fuels would run out leaving solar power our only option.

In 2015, at the Paris Climate Summit (or COP21) a new agreement came up with a vision of reducing the carbon emissions rate and also limiting the global average temperature change. To move forward, we also need to realize that there is only so much that can possibly be done in limiting Green House Gas (GHG) output as the human population only increases day-by-day and puts more demands on our energy infrastructure. To further, help the environment and secure the future of the planet for our next generations, we need to move to renewable sources for our energy generation. In corresponds to that thought, renewable energy became not just a scientific innovation for the future, but a necessity.

According to a report by the International Energy Agency, the increase of amount of electricity produced from renewable sources increased from just over 13% in 2012 to 22% the following year. They also predict that that figure should hit 26% by 2020. In terms of total generation, renewables accounts for 19% of our present usage. Most long-term forecast models predict that use will triple between 2012 and 2040. We can break these figures down even further and look at the divide between renewable energy types. These are:
9% from biomass
2% as non-biomass heat energy
8% from hydro electricity generation
2% of electricity generated from geothermal, biomass, wind and solar power

Domestically, the US produces just over 13% of its electricity from renewable sources. As one of the world's largest consumers of energy (at 11.4kw per person per year) and consuming around 25% of the world's production every year, the situation in the US is immediate. Exponential growth of production in China, and equal exponential growth in coal mining there, should not be permitted to outstrip renewable use and it seems we are winning that particular battle; a UN report concluded in 2015 that renewable technology is now being produced on an industrial scale.

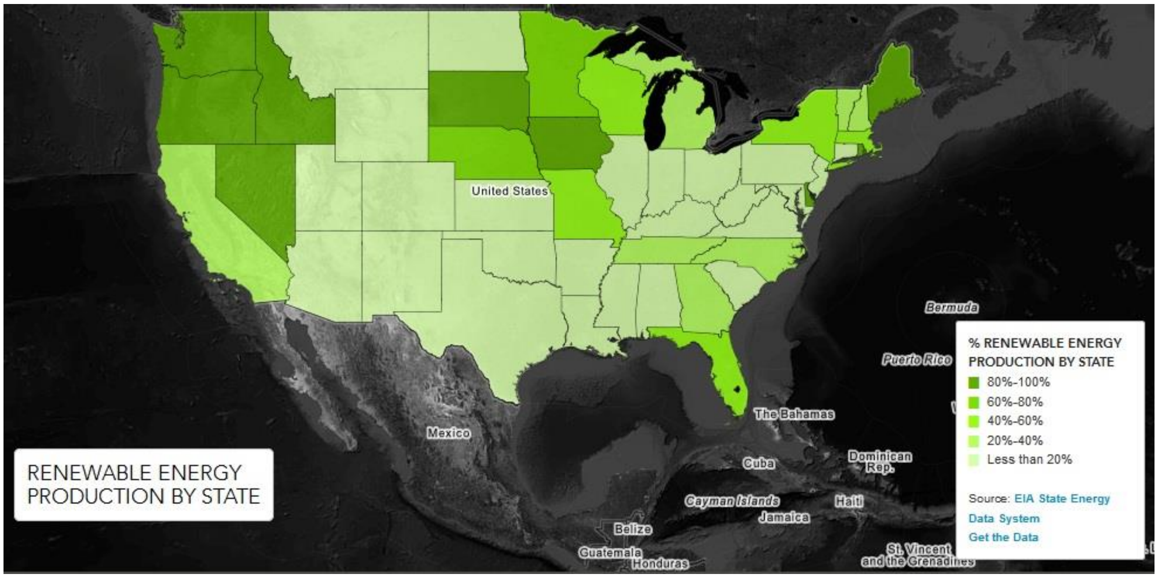


Fig.1.1 Renewable energy production indifferent states of USA

1.2 Motivation

During the last decades, renewable energy has known an remarkable development. Most people believe this is for fighting against global warming. The development of low-carbon technologies has become a strategic policy ratified by all the economic powers as it is a way to ensure they meet their energy needs while providing a competitive attitude within the race for technological leadership. Given the challenges linked to renewable, their development must be seen as a necessity rather than a luxury.

To Reduce the Greenhouse gas emissions, a necessity:

During the last decades, humanity awareness has raised about climate change problems and so far especially about global warming. To reduce greenhouse gas emissions has become a political willingness. As a result, several countries, led by the European Union, committed through Kyoto protocol and Doha amendment to legally binding reductions in their emissions during the periods 2008- 2012 and 2013-2020. The objective for the Community is to achieve, successively during the 1st and 2nd commitment periods, mean emissions of 95% and 80% of the emissions of base year 1990. Although being a noble cause, it has never been possible to reach an accord. China and the United States of America, two major greenhouse gas emitters, never ratified the Kyoto protocol while Canada withdrew its participation during the first period and Japan and Russia didn’t extend their participation to the second period of commitment. Renewable energy against climate change… not only EU has come with legislation intending to reach its 20-20- 20 targets : 20% reduction in greenhouse gas emissions, 20% improvement in energy efficiency and 20% share of energy from renewable sources in inclusive Community energy consumption by the end 2020. It is clear that renewable energy production is part of EU’s policy against climate change but it is not the only reason justifying the quick development of the sector. The gas crisis in 2006 and 2009 revealed EU's energy supply weaknesses. While being the world's biggest energy importer [6], the European Union is largely depending on foreign countries for its energy supply. In 2010, it imported 52,7% of all its fuel consumption. EU's position is still less comfortable since, for each fuel, importations rely on few partners. As a consequence, one of the most important objectives of EU's energy policy is to ensure its supply security. Of course, achieving a 20%- share of renewable energy in its final energy consumption by the end 2020 will lower its dependency on foreign countries. Another argument in favors of a strong development of renewable technologies is that they represent new industrial development perspectives and « Europe has some of the world's most successful renewable energy companies and research institutions – we must keep this leadership position and avoid being overtaken by our competitors ». Developing new low-carbon technologies is crucial for the economy and it is a way of getting out of the economic and financial crisis.

Toward a solar break away in renewable development?

The development of low-carbon sources of energy is a key factor in the fight against climate change but it has also strong connections with energy supply security and technological leadership. Therefore it has become an objective adopted by all the big economies. « The EU is facing fierce competition in international technology markets. Countries such as China, Japan, South Korea and the USA are pursuing an ambitious industrial strategy in solar, wind and nuclear markets » It is reflected in their investments in the sector as it can be observed on the figure. China and USA's investments reach respectively 50 and 80% of Europe's investments. The Ernst & Young study of the renewable energy country attractiveness ranked China, India, USA and Brazil in its top 10. The competition for technological lead is strong and everyone is trying to hold its own.

Renewable technologies at the center of lots of challenges:

Low carbon technologies are an important part of the solution in response to the global warming but it is also a key factor in energy security of supply policies and technological lead. Although all the big economic powers are competing in the development of these technologies, they haven't all agreed on the necessity of reducing world's greenhouse gas emissions. Actually the main difference is that, on the one hand, EU is developing renewable technologies as a support to policies of reduction of greenhouse gas emissions while the other big economic powers, on the other hand, are only competing for technological lead and diversity of energy supply. In the future, although it is difficult to predict how and when it will happen, it makes no doubt that humanity will have to face its responsibility for global warming and will have to agree on limitations of greenhouse gas emissions. Meanwhile, the run for technological lead will go on and renewable energy will have to develop while evolving in a difficult economic context and competing against cheaper technologies. A shift toward a de-carbonized future will imply considerable efforts and social changes. Considering the importance of the challenges linked to renewable, it is clear that their development is not a luxury and has to go on. The problem is stated but uncertainty makes it difficult to predict what will exactly happen. One thing is sure, renewable technologies will be at the center of lots of challenges and the end promises to be very exciting.

1.3 Thesis Layout

This paper aims at providing an overview over calculation of levelized cost of energy from generation and from storage in different renewable energy sources with. In the first part the general discussion with introduction and motivation about the importance of using renewable energy expressed deeply. On the second portion we expressed about different renewable energy like solar, wind, water, biomass etc description briefly with particular figure, actually about the resources act as, should utilize as with all of their net properties as possible. For storage it is assumed that solely the cumulated stored energy determines the LCOE of the storage system. It turned out that Carbon rate is the most important parameter for the LCOE of storage. In contrast, the efficiency plays a less dominant role as often assumed in current technology discussions cause the resources are unlimited. The derived model was then used to compare different technologies too. This comparison could easily be expanded to more technologies to foster technology comparison. Well, we have discussed about renewable energy and its history, why we are now concentrating on alternative resources at chapter 2. And in chapter 3, we focused on LCOE for Solar PV and also for Energy storage and also we have shown the comparisons on Solar PV+ Storage Energy for their corresponding LCOE.

Chapter 2
Renewable Energy Resources

2.1 Introduction

Renewable energy sources also called non-conventional energy are sources that are continuously replenished by natural processes. For example, solar energy, wind energy, bio-energy -bio-fuels grown sustain ably), hydropower etc., are some of the examples of renewable energy sources. A renewable energy system converts the energy found in sunlight, wind, falling-water, sea-waves, geothermal heat, or biomass into a form, we can use such as heat or electricity. Most of the renewable energy comes either directly or indirectly from sun and wind and can never be exhausted, and therefore they are called renewable. However, most of the world's energy sources are derived from conventional sources-fossil fuels such as coal, oil, and natural gases. These fuels are often termed non-renewable energy sources. Although the available quantity of these fuels are extremely large, they are never the-less finite and so will in principle 'run out' at some time in the future. Renewable energy sources are essentially flows of energy, whereas the fossil and nuclear fuels are, in essence, stocks of energy.

Various forms of renewable energy (Non-Conventional):

There are five major areas of renewable energy for being tapped for power generation. They are-

- Solar power
- Water/Hydro-electric power (dams in rivers)
- Wind power
- Biomass (burning of vegetation to stop it producing methane)
- Geothermal Energy

And the conventional sources of Thermal Energy includes:

- Coal
- Petroleum
- Natural Gas

We hope that all the conventional sources will become rare, endangered and extinct, as they produce lots of carbon dioxide that adds to the greenhouse effect in the atmosphere (Uranium leaves different dangerous byproducts).

And we similarly hope that all the non-conventional sources will become conventional, common, and every day, as they are all free, green and emit no carbon dioxide (well, biomass does, but it prevents the production of methane which is a greenhouse gas 21 times more dangerous that CO2).

2.2 Solar Energy:

Fig.2.1 The Floating solar farm on Godley Reservoir near Manchester, UK.

Most of the renewable energy is ultimately “Solar energy” that is directly collected from sunlight. Energy is released by the Sun as electromagnetic waves. The energy reaching earth’s atmosphere consists of about-

- 8% UV radiation
- 46% visible light
- 46% infrared radiations

Solar energy storage is as per figure below:

Solar Energy can be used in two ways:

- Solar heating
- Solar electricity

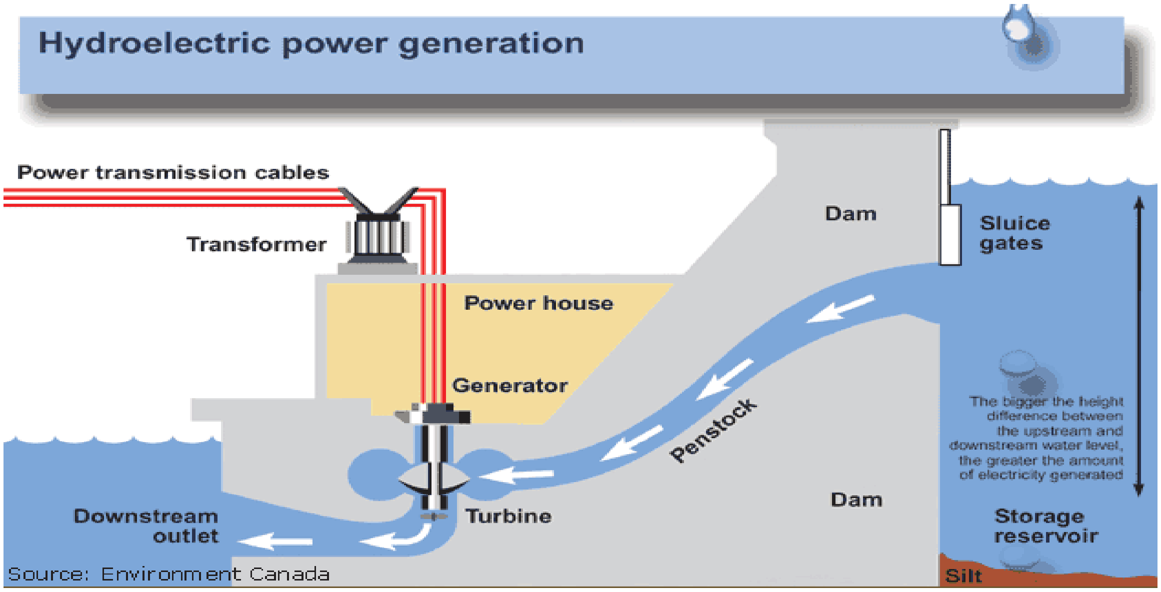
Solar Heating is to capture/concentrate sun’s energy for heating buildings and for cooking/heating foodstuffs etc. solar electricity is mainly produced by using photovoltaic solar cells which is made of semi conducting materials that directly converts sunlight into electricity. Obviously the Sun doesn’t provide constant energy at any spot on the Earth, so it’s use is limited. Therefore often Solar cells are used to charge batteries which are used either as secondary energy source or for other applications of intermittent use such as night lightening or water pumping etc. A solar power plant offers good option for electrification of disadvantageous locations such as hilly regions, forests, deserts and islands where other resources are neither available nor exploitable in techno economically viable manner.

2.3 Wind Energy:

Fig.2.2 Wind power system

The origin for Wind Energy is Sun. When sun ray falls on the earth, it’s surface gets heated up and as a consequence unevenly winds are formed. Kinetic energy in the wind can be used to run wind turbines but the output power depends upon the wind speed. Turbines generally require a wind in the range of 20km/hr. In practice relatively few land areas have significantly prevailing winds. Otherwise wind power is one of the most cost competitive renewable energy today and this has been the most rapidly-growing means of electricity generation at the turn of 21st century and provides a complement to a large scale base load power stations. Its long term technical potential is believed to be 5 times current global energy consumption or 40 times current electricity demand.

2.4 Water Power



Source: Environment Canada

Fig. 2.3 A modern technology of generating Hydro-electric power in Canada.

Energy in the water can be harnessed and used in the form of motive energy or temperature difference. Since water is about 1000 times heavier than air, even a slow flowing stream of water can yield great amount of energy.
There are many forms:

- Hydroelectric energy, a term usually reserved for hydroelectric dam
- Tidal power, which captures energy from the tides in horizontal direction. Tides come in, raise water levels in a basin, and tides roll out. The water is made to pass through turbine to get out of the basin. Power generation through this method has a varying degree of success.

- Wave power which uses energy in waves.

The waves will usually make large pontoons go up and down in the water. The wave power is also hard to tap. Hydro electrical energy is therefore only viable option. However, even probably this option is also not there with the developed nations for future energy production because most major sites within these nations with potential for harnessing gravity in this way are already being exploited or are unavailable for other reasons such as environmental consideration. On the other side, large hydro potential of millions of megawatts is available with the developing countries but major bottleneck in the way of development of these large hydro projects is that each site calls for the huge investment.

- Micro/Small hydro-power

This is non-conventional and renewable source and is easy to tap. Quantitatively small volume of water, with large falls and quantitatively not too large volumes of water, with small fall, can be tapped. This force of flowing and falling water is used to run water turbines to generate electricity.

2.5 Biomass

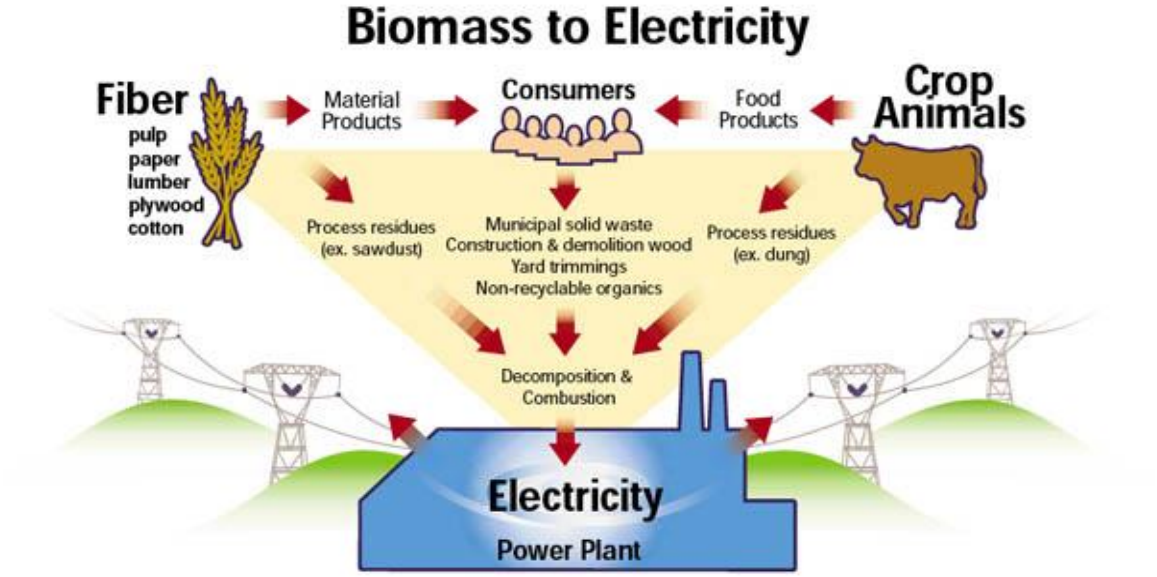


Fig. 2.4 A flow diagram of generating Electricity from Biomass

Plants use photosynthesis to store solar energy in the form of chemical energy. The easiest way to release this energy is by burning the dried up plants. Solid biomass such as firewood or combustible field crops including dried manure is usually burnt to heat water and to drive turbines. Field crops may be grown specifically for combustion or may be for other purposes and the processed plant waste then used for combustion. Most sort of biomass including sugarcane residue, wheat chaff, corn cobs and other plant matter can be, and is, burnt quiet successfully. Currently biomass contributes 15% of total energy supply throughout the world.

Biomass is biological material derived from living, or recently living organisms. It most often refers to plants or plant-derived materials which are specifically called lignocellulosic biomass. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of bio-fuel. Conversion of biomass to bio-fuel can be achieved by different methods which are broadly classified into: thermal, chemical, and biochemical methods. Wood remains the largest biomass energy source today. Examples include forest residues – such as dead trees, branches and tree stumps, yard clippings, wood chips and even municipal solid waste. In the second sense, biomass includes plant or animal matter that can be converted into fibers or other industrial chemicals, including bio-fuels. Industrial biomass can be grown from numerous types of plants, including miscanthus, switchgrass, hemp, corn poplar, willow, sorghum, sugarcane, bamboo, and a variety of tree species, ranging from eucalyptus to oil palm (palm oil).

Bio-fuels include a wide range of fuels which are derived from biomass. The term covers solid, liquid, and gaseous fuel. Liquid bio-fuels include bio-alcohols, such as bio-ethanol, and oils, such as biodiesel. Gaseous bio-fuels include biogas, landfill gas and synthetic gas. Bio-ethanol is an alcohol made by fermenting the sugar components of plant materials and it is made mostly from sugar and starch crops. These include maize, sugarcane and, more recently, sweet sorghum. The latter crop is particularly suitable for growing in dry land conditions, and is being investigated by International Crops Research Institute for the Semi-Arid Tropics for its potential to provide fuel, along with food and animal feed, in arid parts of Asia and Africa.

A drawback is that all these biomass needs to go through some of these steps: It needs to be grown, collected, dried and fermented and burned. All of these steps require resources and an infrastructure.

Fig.2.5 Sugarcane plantation to produce ethanol

Fig.2.6 CHP power station using wood to supply 30,000 households in France

- Bio-fuel

Bio-fuel is any fuel that derives from biomass- recently living organisms or their metabolic byproducts, such as manure from cows. Typically bio-fuel is burnt to release it’s stored chemical energy. Biomass can be directly used as fuel or to produce liquid bio-fuel. Agriculturally produced biomass fuels, such as bio-diesel, ethanol and biogas (often byproduct of sugarcane cultivation) can be burnt in internal combustion engines or boilers.

- Biogas

Biogas can easily be produced from current waste streams, such as paper production, sugarcane production, sewage, animal waste and so forth. The various waste streams have to be slurred together and allowed to naturally ferment, producing 55% to 70% inflammable methane gas. Biogas production has the capacity to provide us with about half of our energy needs, either burned for electrical productions or piped into current gas line for use. This has to be done and made a priority. The payback period of biogas is around 2-3 years, rather in case of community and institutional Biogas plant is even less. Therefore biogas electrification at community level is required to be implemented.

With advanced technology being developed, cellulosic biomass, such as trees and grasses, are also used as feed stocks for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form, but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Bio-ethanol is widely used in the United States and in Brazil. The energy costs for producing bio-ethanol are almost equal to, the energy yields from bio-ethanol. However, according to the European Environment Agency, bio-fuels do not address global warming concerns. Biodiesel is made from vegetable oils, animal fats or recycled greases. It can be used as a fuel for vehicles in its pure form, or more commonly as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons from diesel-powered vehicles. Biodiesel is produced from oils or fats using transesterification and is the most common bio-fuel in Europe. Bio-fuels provided 2.7% of the world's transport fuel in 2010. Biomass, biogas and bio-fuels are burned to produce heat/power and in doing so harm the environment. Pollutants such as sulphurous oxides (SO_x), nitrous oxides (NO_x), and particulate matter (PM) are produced from the combustion of biomass; the World Health Organization estimates that 7 Million premature deaths are caused each year by air pollution. Biomass combustion is a major contributor. The life cycle of the plants is sustainable, the lives of people less so.

2.6 Geothermal energy

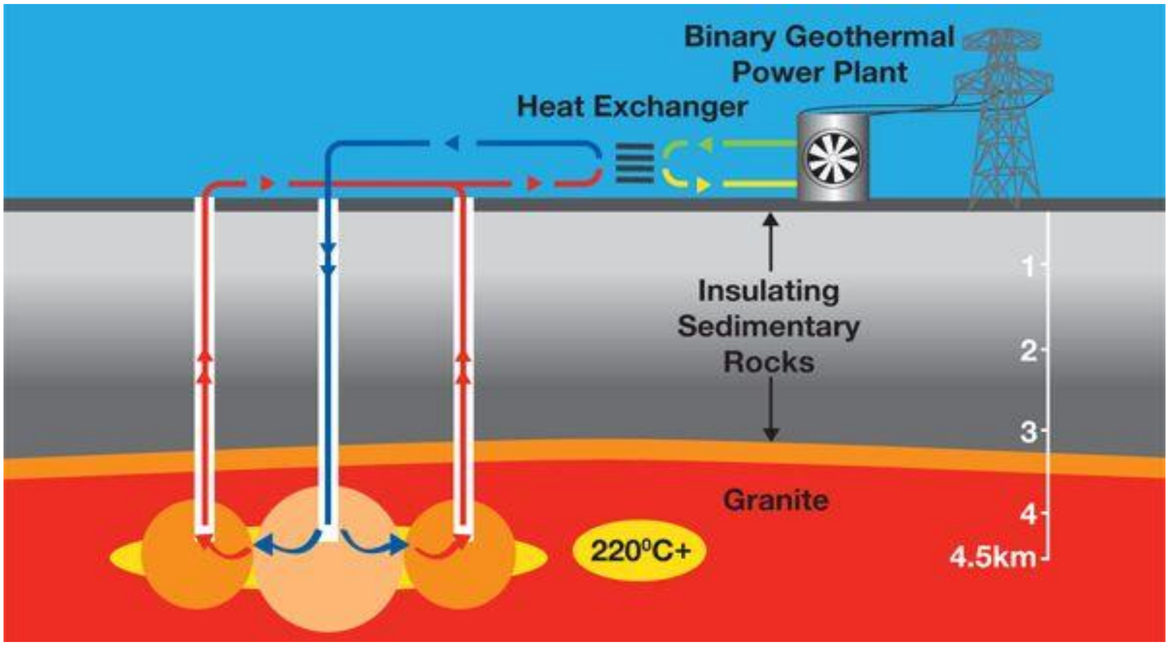


Fig.2.7 A flow diagram of Geothermal Energy

Geothermal energy is from thermal energy generated and stored in the Earth. Thermal energy is the energy that determines the temperature of matter. Earth's geothermal energy originates from the original formation of the planet and from radioactive decay of minerals. The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface.

The heat that is used for geothermal energy can be from deep within the Earth, all the way down to Earth's core – 4,000 miles (6,400 km) down. At the core, temperatures may reach over 9,000 °F (5,000 °C). Heat conducts from the core to surrounding rock. Extremely high temperature and pressure cause some rock to melt, which is commonly known as magma. Magma convects upward since it is lighter than the solid rock. This magma then heats rock and water in the crust, sometimes up to 700 °F (371 °C).
From hot springs, geothermal energy has been used for bathing since Paleolithic times and for space heating since ancient Roman times, but it is now better known for electricity generation.

Fig.2.8 Nesjavellir Geothermal Power Station, Iceland

Low Temperature Geothermal refers to the use of the outer crust of the earth as a Thermal Battery to facilitate Renewable thermal energy for heating and cooling buildings, and other refrigeration and industrial uses. In this form of Geothermal, a Geothermal Heat Pump and Ground-coupled heat exchanger are used together to move heat energy into the earth (for cooling) and out of the earth (for heating) on a varying seasonal basis. Low temperature Geothermal (generally referred to as "GHP") is an increasingly important renewable technology because it both reduces total annual energy loads associated with heating and cooling, and it also flattens the electric demand curve eliminating the extreme summer and winter peak electric supply requirements. Thus Low Temperature Geothermal/GHP is becoming an increasing national priority with multiple tax credit support and focus as part of the ongoing movement toward Net Zero Energy. New York City has even just passed a law to require GHP anytime is shown to be economical with 20 year financing including the Socialized Cost of Carbon.

Chapter 3
Levelized Cost of Electricity (LCOE)

3.1 Introduction

For more than three decades, utility-scale solar generated electricity has been dismissed as too costly. But the cost of solar generated electricity is consistently coming down, while the cost of conventional electricity is increasing. Advances in solar cell technology, conversion efficiency and system installation have allowed utility scale photovoltaic (PV) to achieve cost structures that are competitive with other peaking power sources. The calculation of the levelized cost of electricity (LCOE) provides a common way to compare the cost of energy across technologies because it takes into account the installed system price and associated costs such as financing, land, insurance, transmission, operation and maintenance, and depreciation, among other expenses. Carbon emission costs and solar panel efficiency can also be taken into account. The LCOE is a true apples-to-apples comparison.

Around the globe, the solar industry has installed approximately 10 giga-watts of solar PV systems. Pacific Gas & Electric Co. has announced more than 2 giga-watts of agreements involving both solar thermal and PV technologies, including 800 megawatts of photovoltaic power – the largest utility-scale contracts for PV in the world. Sun-Power's 250 megawatt central station, high-efficiency, PV power plant in California Valley will be the first to deliver utility-scale PV power to PG&E. These solar power plants are vivid examples of how the electricity production landscape is changing rapidly to embrace a much broader portfolio of renewable resources. The LCOE equation sorts through the relative costs of such systems and pinpoints the increasingly positive economics for harvesting the world's most abundant energy resource – sunshine.

The economies of scale inherent in utility-scale solar systems are similar to those found with other power options, but PV has the benefit of being completely modular – PV works at a 2 kilowatt residential scale, at a 2 megawatt commercial scale or at a 250 megawatt utility scale. PV has the unique advantage among renewable resources of being able to produce power anywhere: deserts, cities or suburbs. Smaller scale PV costs more on an LCOE basis, but it can be selectively deployed on the grid wherever and whenever needed to reduce distribution capacity constraints and transmission congestion while producing pollution-free power. All PV can be constructed quickly and even utility-scale power plants can begin delivering power within a few quarters of contract signing – a major advantage when compared to conventional power plants. At Sun-Power, we serve customers across the spectrum, from small-scale to utility-scale solar, because each application has distinctive advantages and will contribute to driving solar power to become a major source of carbon-free power.

3.2 What is LCOE

LCOE can be referred as a metric that attempts to allow a fair evaluation of electricity produced by renewable sources (in this case solar) with other fuel-based electricity production. In fact, such a metric attempts to create a level economic field regardless of how the energy is produced allowing comparisons among all methods of electricity production.

It takes into account capital costs, ongoing system costs, financial rates (discount rates, taxes etc.), utilization and fuel costs (if any). All this is taken into account over the lifetime period of the power plant while considering the total amount of energy that is produced over this period.

The LCOE is a measure of lifetime costs, divided by total lifetime energy production. The less a system costs and the more energy it produces, the lower the LCOE. In addition, installment costs, LCOE measures costs over the lifetime of the power plant.

The mathematical definition of LCOE is conceptually simple:

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Energy Production}}$$

Total lifetime costs consist of four parts:

-Initial project costs
-Depreciation
-Annual operating costs
-Residual value (the tax rate is also factored into this)

An initial project cost can be affected by federal and state tax credits as well.

3.3 Factors affecting LCOE

What drives LCOE reduction for PV?

Both capital costs and operating and maintenance costs are driven by the choice of technology and the area of the solar system. We outline in this paper how the following key factors drive the LCOE for solar PV power plants.

Panel Efficiency:

Sun-Power's high-efficiency solar panels generate up to 50 percent more power than conventional technology and up to four times as much power as thin film technologies, thereby lowering area-related costs.

Capacity Factor:

Sun-Power's tracker technology can increase energy production from solar panels by up to 30 percent, further reducing area-related costs and contributing more high-value energy during afternoon hours than fixed-tilt systems.

Reliable System Performance and Lifetime:

Sun Power's established crystalline silicon technology, with its history of consistent, predictable performance, reduces power plant financing costs lowering the LCOE. Square Miles of PV panels per 1TWh.

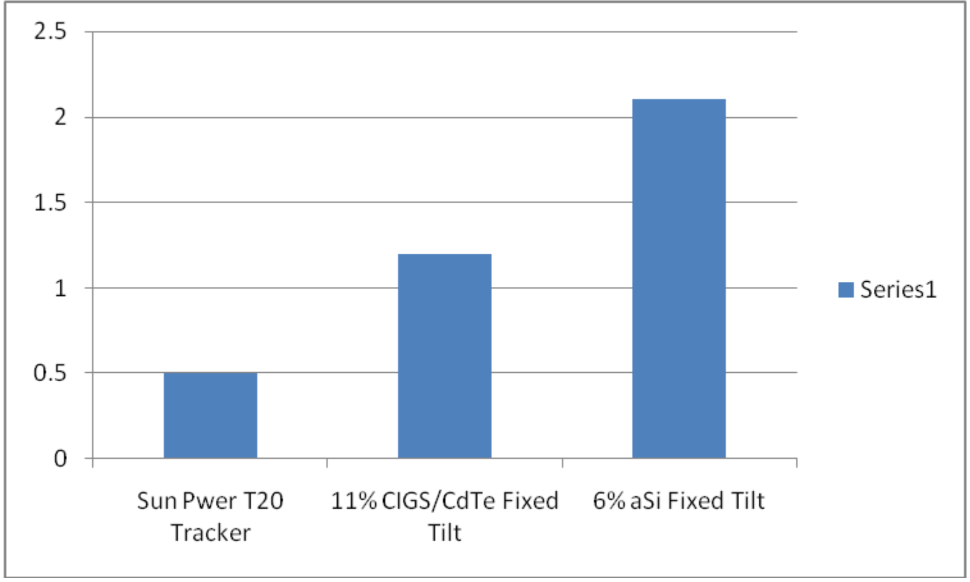


Fig. 3.1 PV panel area required for 1TWh Annual Production

Sunlight is a diffuse energy resource. Maximizing energy production per panel area is critical to achieve the best LCOE in a utility-scale PV power plant. As shown in Figure 3.1, if a PV power plant with 1 terawatt hour (TWh) of annual energy production is built with Sun-Power high-efficiency PV panels mounted on solar trackers, up to 75 percent less panel area is required when compared with thin film technology mounted in a fixed tilt configuration. This energy production density leverages almost all PV power plant fixed plant and operation and maintenance (O&M) costs, directly reducing the system LCOE. Based on the LCOE, Sun-Power's high-efficiency power plants generate energy at a price competitive with other peak power resources. Given our technology roadmap and LCOE forward cost curve, we expect our high-efficiency silicon PV technology to maintain that competitive position.

3.4 LCOE of different Renewable Energy Sources (for PV and energy storage)

3.4.1 LCOE of Solar PV

The following formula calculates the LCOE of PV generation under the assumption that only some amount X of the generated energy will be used.

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Energy Production}}$$

With the directly used actual energy output per period being a function of X and LCOE the standard- calculated levelized cost of energy for PV. This models the direct usage of generated energy. For X= 1, the formula reduces to the commonly known formula for calculating the LCOE of PV generation. The parameter X will become meaningful in combined model.

Modeling the levelized Cost of Energy

The Levelized Cost of Energy (LCOE) is defined as the total lifetime cost of an investment divided by the cumulated generated energy by this investment. For a discussion of the underlying assumptions. An alternative (but mathematically identical) approach is the definition by means of the net present value (NPV). The LCOE is the (average) internal price at which the energy is to be sold in order to achieve a zero NPV. In order to derive the model for combined power plant, the LCOE of PV generation and storage must be expressed. A fair comparison of different technologies on the basis of LCOE is suggested. The following convention shall be applied to simplify the calculations:

$$\sum_{t=0}^{T} Value_t \cdot (1+i)^{-t} = \sum Value,$$

The notation of the discounted sum from period 0 with T the assumed project lifetime. This calculation implicitly assumes a constant discount rate of *i* for the time period. However, the model can be calculated with varying discount rates. It is obvious that the project lifetime is crucial for the result. By default, a lifetime of 25 years is assumed.

Sun-Power Corporation recently produced a whitepaper that details a simplified LCOE equation for utility-scale PV. It can be represented as:

$$LCOE = \frac{\text{Project cost} + \sum_{n=1}^{N} \frac{AO}{(1+DR)^n} - \frac{RV}{(1+DR)^n}}{\sum_{n=1}^{N} \frac{\text{Initial kWh} \times (1-SDR)^n}{(1+DR)^n}}$$

Where, AO is the annual operations cost, DR is the discount rate, RV is the residual value, SDR is the system degradation rate, and *N* is the number of years the system is in operation. Equation 2 computes the economic LCOE. This formulation can be modified to include financial considerations such as 70 taxes, subsidies, and other complexities. An equation taking some of these additional factors into account was recently reported:

$$LCOE = \frac{PCI - \sum_{n=1}^{N} \frac{DEP + INT}{(1+DR)^n} TR + \sum_{n=1}^{N} \frac{LP}{(1+DR)^n} + \sum_{n=1}^{N} \frac{AO}{(1+DR)^n}\Big)(1-TR) - \frac{RV}{(1+DR)^n}}{\sum_{n=1}^{N} \frac{\text{Initial kWh} \times (1-SDR)^n}{(1+DR)^n}}$$

Where, PCI is the project cost minus any investment tax credit 75 or grant, DEP is depreciation, INT is interest paid, LP is loan payment, and TR is the tax rate.

3.4.2 LCOE of a Storage Energy

The levelized cost of energy for storage systems is calculated in a similar manner as for PV generation. The total cost of ownership over the investment period is divided by the delivered energy (Note: This is a definition.) and hence calculates to:

$$LCOE_{St} = \frac{\sum C_{St} + \sum p_{int,t} \cdot E_{IN,St}}{\eta_{St} \cdot \sum E_{IN,St,t}} = \frac{\sum C_{St} + p_{int,0} \cdot K_T \cdot \sum E_{IN,St}}{\eta_{St} \cdot \sum E_{IN,St,t}} = \frac{\sum C_{St}}{\eta_{St} \cdot \sum E_{IN,St,t}} + K_T \frac{p_{int,0}}{\eta_{St}}.$$

The cost consists of a term similar to PV, in which total cost during lifetime is divided by the cumulated energy delivered by the system. Due to the fact, that no energy is generated a second term exists that models the energy purchase from generation plants or from the grid. The energy input into the storage system will be a certain amount of the total generated energy output. The energy output of the storage system is the energy input reduced by the average energy roundtrip efficiency *ηSt* of the storage system over the lifetime. Sometimes it is more convenient to consider the output energy of the storage system.

The levelized cost of energy is then calculated as:

$$LCOE_{St}\left(\sum E_{OUT}, T\right) = \frac{\sum C_{St,t} + \sum p_{int,t} \cdot E_{IN,St,t}}{\sum E_{OUT,St,t}} = \frac{\sum C_{St,t} + p_{int,0} \cdot K_T \cdot \sum E_{IN,St,t}}{\sum E_{OUT,St,t}} = \frac{\sum C_{St}}{\sum E_{OUT,St,t}} + K_T \frac{p_{int,0}}{\eta_{St}}$$

with

$$K_T = \frac{\sum_{t=1}^{T} E_{int,t} \frac{\left(1+PIF_{p_{int}}\right)^t}{(1+i)^t}}{\sum_{t=1}^{T} E_{int,t} \frac{1}{(1+i)^t}} \approx \frac{\sqrt[T]{\prod_{t=1}^{T}\left(1+PIF_{p_{int}}\right)^t} + \frac{1}{T}\sum_{t=1}^{T}\left(1+PIF_{p_{int}}\right)^t}{2},$$

Approximately the average of geometric and arithmetic average price increase factor (PIF) over the considered period *T*. The maximum error for a *PIF = 9%* is below 5% (Note: This approximation is derived empirically), see Figure 3.2.

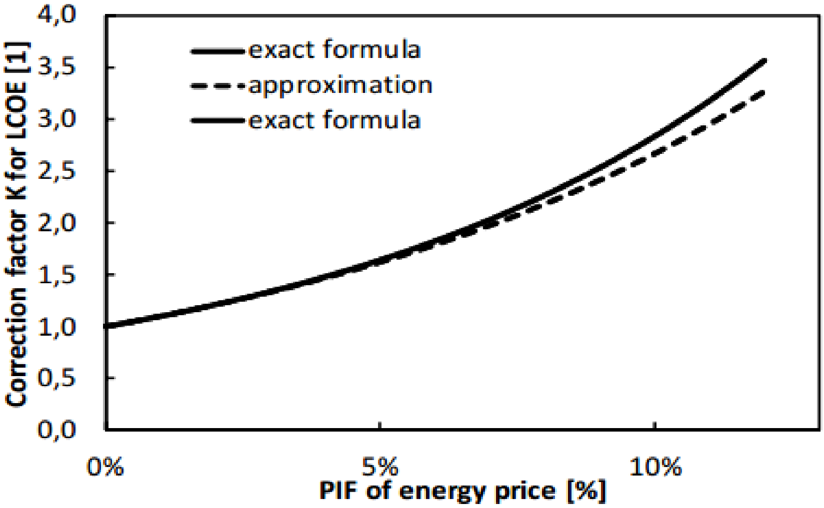


Fig.3.2 Correction factor K for LCOE calculation. Comparison between exact formula with approximation formula.

It is reasonably valid for price increase rates up to 6%. The approximation has the clear advantage of not depending on the discount interest rate or stored energy leading to a much easier calculation. A storage device, by definition, cannot generate energy. Therefore, an internal transfer price *pint, t* weighs the value of the stored energy per period and *pint,0* is the internal price at the beginning of the period. In other words, it defines the internal cost at which the storage system “buys” the energy from the generation system, from the grid or any other source. The factor *K* describes the price change over the years if a constant *PIF* is assumed. The lower limit for the LCOE is determined by the maximum energy turnover during lifetime. This state shall be defined as 100% utility of the storage device. Every deviation inevitably leads to higher LCOE. Fig.3.3 depicts the behavior of the LCOE for a given but arbitrarily chosen technology.

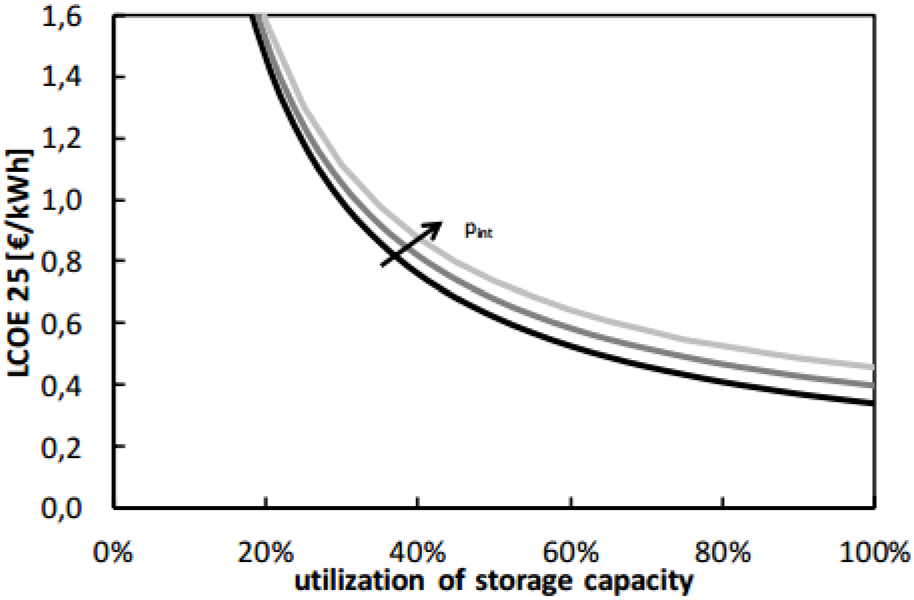


Fig.3.3 LCOE 25 (T=25 years) as function of utilized storage capacity per cycle with varying energy price for charging as parameter.

The C rate has major influence on the LCOE of the storage technology. This behavior is depicted in Figure 3, clearly showing the fact to reduce c-rate in order to improve LCOE. However, one must consider the fact, that this holds only true if the number of full cycles per year is not affected, i.e. a full cycle per day must be physically possible and it is only true since the model evaluates the cumulated stored (and released to some purpose) energy over the whole lifetime.

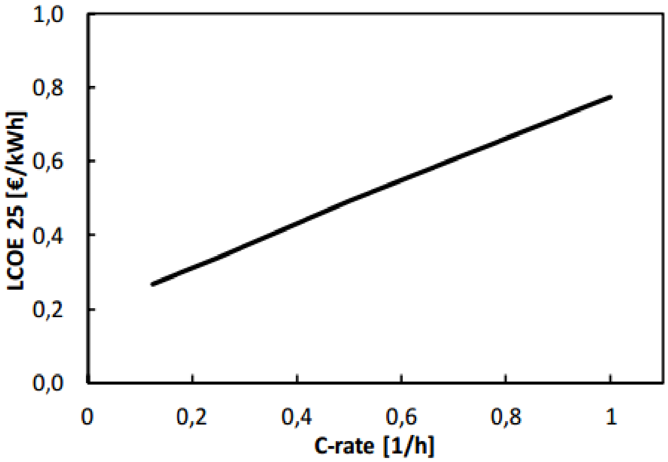


Fig.3.4 LCOE 25 (T=25 years) as function of c rate for chosen technology. Every c rate implies specific investment cost. All other parameters are as given in Table 1.

When discussing performance of energy storage systems it is often assumed that energy efficiency has a great impact. The derived model takes into account the energy efficiency. The influence of efficiency can be seen in the second term. It serves as “acceleration factor” for the energy price, since the price is divided by the energy efficiency and increasing prices are accounted for by factor *KT*. With all parameters equal, Fig.3.5 shows the influence of ac energy efficiency on LCOE at different initial price levels. Two important things can be observed: a) the influence is more pronounced at elevated energy prices. b) the influence is biggest at very low efficiencies below 50%. Above 50%, the effect has much lower impact, e.g. the difference between a technology with 90% efficiency and 70% efficiency is not too important. This is a very important result of this modeling.

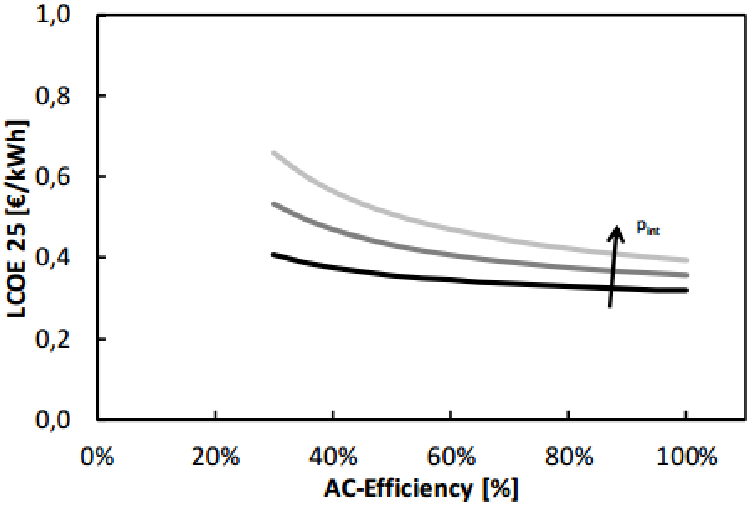


Fig.3.4 LCOE as function of AC-efficiency of storage system with energy price for charging as parameter, see Table 1/Technology

3.4.3 Comparison of different storage technologies

The chosen methodology allows for quick and easy assessment of different storage technologies. It emphasizes the fact that not up-front investment cost but total cost of ownership over the project lifetime are important (Of course, investment cost play a vital role when it comes to financing and risk assessment for investments). An example comparison with all model parameters is given in Table 1.

Table 1: Comparison of LCOE 25 (T=25 years) for different exemplary storage technologies-

Parameter	Redox-Flow	Lithium-Ion	Lead-Acid
Project-specific parameters			
Installed storage power [MW]	1.0	1.0	1.0
Investment Cost [Mio. €]	5.0	2.4	1.2
C-Rate (nominal)	0.25	1	1
Utilization of usable storage capacity	100%	100%	100%
Number of cycles per year	365	365	365
External parameters			
Energy price [€/kWh]	0.03	0.03	0.03
PIF energy price	2%	2%	2%
Loan period	10 years	10 years	10 years
WACC	3.5%	3.5%	3.5%
Storage specific parameters			
Residual value after end of lifetime (discounted) of invest cost	15%	0%	0%
Efficiency	70%	80%	65%
Maintenance Cost of Investment	2%	1%	5%
Degradation storage capacity per year	0.1%	2.0%	3.7%
Calendar lifetime	25	7	3
Usable storage capacity	100%	80%	50%
LCOE of storage [€/kWh]	0.338	1.678	3.072

As can be clearly seen, Redox-Flow with by far the highest initial investment cost turns out to be the most economic one when the cumulated energy over the investment period is considered. It outperforms the second-best (The given numbers are not related to specific products. They reflect the best knowledge of the author while he's aware of very different opinions in the field. Besides the investment cost, the most disputed parameters are lifetime (cycle lifetime) and usable storage capacity (DoD). A change of the C-rate for Li-Ion from 1.0 to 0.25 gives a LCOE of 0.455 €/kWh. On the other hand, a C-rate change from 0.25 to 0.5 for Redox Flow gives a LCOE of 0.653 €/kWh. All readers are encouraged to collaborate in the discussion.) technology Li-Ion by a factor of 6.

However, it should be pointed out, that in reality not just the cumulated energy may be economically relevant, e.g. for power quality purposes. By definition, the LCOE metric disregards any generated revenues from the investment. For that reason a net present value calculation is suggested to gain better insight into the underlying business case of the planned investment. Now let us consider an example for application of the derived model.

3.4.4 LCOE PV + Storage

The combination of a PV plant with storage is considered a PV & Storage Power Plant. The simple model is shown in Figure 3.5. By means of such a model one can compare the energy cost of PV & storage with alternative methods to provide energy, e.g. diesel generation. It consists of a PV park, a storage system, an energy management system (which can be part of the storage system). The total lifetime cost is the sum of the cost of PV energy generation and the cost of storage. The energy output of the PP is the sum of directly used energy from PV and the amount that is taken from PV to the storage system and then released to the output of the PP. What can be used directly should be used directly leading to a minimization of the storage system. This principle is an immediate consequence from the LCOE considerations where the effect of 100% utilization of the installed storage capacity on LCOE is clearly outlined. If a storage system is considered it might be uneconomical to dimension it so big to use the total generated energy either directly or via storage system. The model parameter *Eout*, *pv* is the amount of energy that cannot be stored. It could instead be used for feed into the grid.

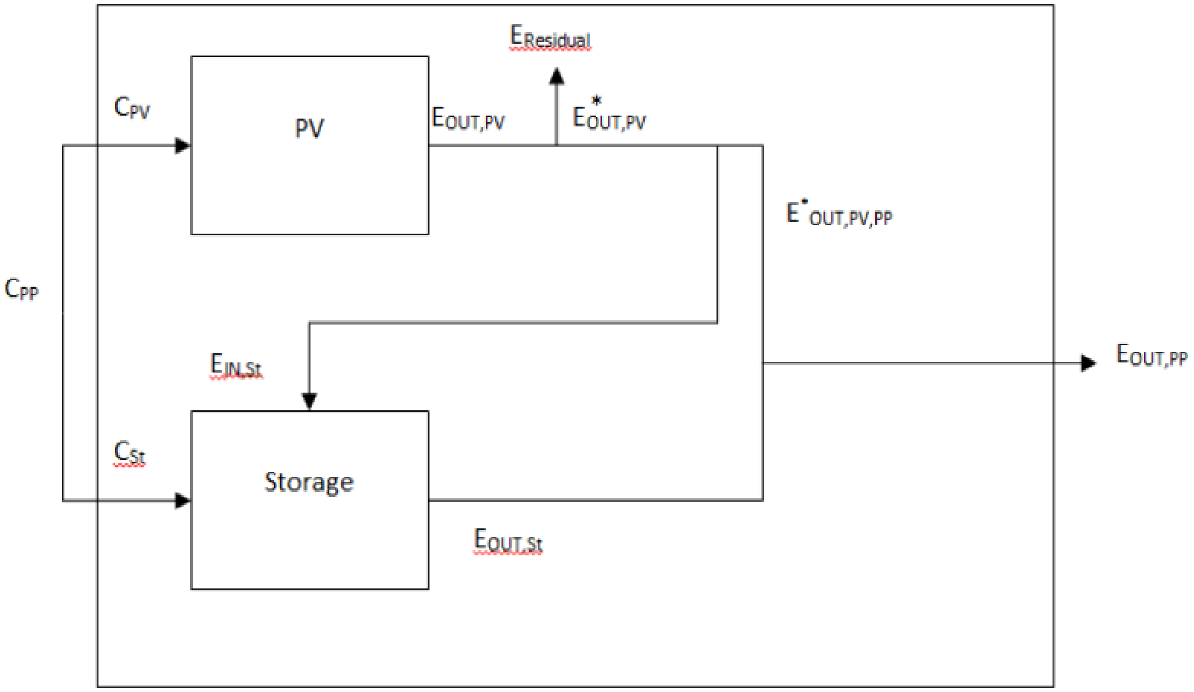


Fig.3.5: Model of combined PV and storage Plant

The usable energy is therefore:

$$E^{*}_{OUT,PV} = E_{OUT,PV} - E_{Residual}.$$

Of this effective energy only a certain amount will be stored, since it cannot be used directly:

$$E_{IN,St} = A \cdot E^{*}_{OUT,PV},$$

With *A*, the usage of PV factor into storage. The remainder of the energy will be used directly:

$$E_{OUT,PV,PP} = (1 - A) \cdot E^{*}_{OUT,PV,PP}.$$

For a PV & Storage Power Plant (Index PP), we have the following relationship for the levelized cost of energy:

$$LCOE_{PP} = \frac{\sum C_{PP}}{\sum E_{OUT,PP}}.$$

The total cost of the power plant is the sum of PV generation and storage:

$$\sum C_{PP} = \sum C_{PV} + \sum C_{St,total}.$$

The total output of the system is the direct output of PV and the output of the storage system:

$$\sum E_{Out,PP} = \sum E_{Out,PV,PP} + \sum E_{Out,St} = \sum E_{Out,PV,PP} + \eta_{St} \cdot \sum E_{IN,St}.$$

By means of eq. 2,3,10,11 eq. 9 can be expanded resulting in:

$$LCOE_{PP} = \frac{\sum C_{PV} + \sum C_{St} + p_{int} \cdot \sum E_{IN,St}}{\sum Eout_{PV,PP} + \eta_{St} \cdot \sum E_{IN,St}}.$$

Taking into account eq. 6-8 yields:

$$LCOE_{PP} = \frac{\sum C_{PV} + \sum C_{St} + p_{int} \cdot A \cdot \sum E^{*}_{Out,PV}}{(1-A) \cdot \sum E^{*}_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^{*}_{Out,PV}}.$$

After some calculation and rearrangement the following formula for the LCOE of the combined PV & storage Power Plant can be derived :

$$LCOE_{PP} = LCOE_{PV} \underbrace{\frac{1}{1 - A(1 - \eta_{St})}}_{PV\ factor} + LCOE_{St}\left(A; E^{*}_{Out,PV}\right) \underbrace{\frac{A \cdot \eta_{St}}{1 - A(1 - \eta_{St})}}_{storage\ factor} .$$

In the obvious case of no storage system the formula simply reduces to the LCOE of the PV plant alone. Let’s have a look on the two terms of the equation separately with their respective LCOE equal to 1 depicted in Figure 3.6.

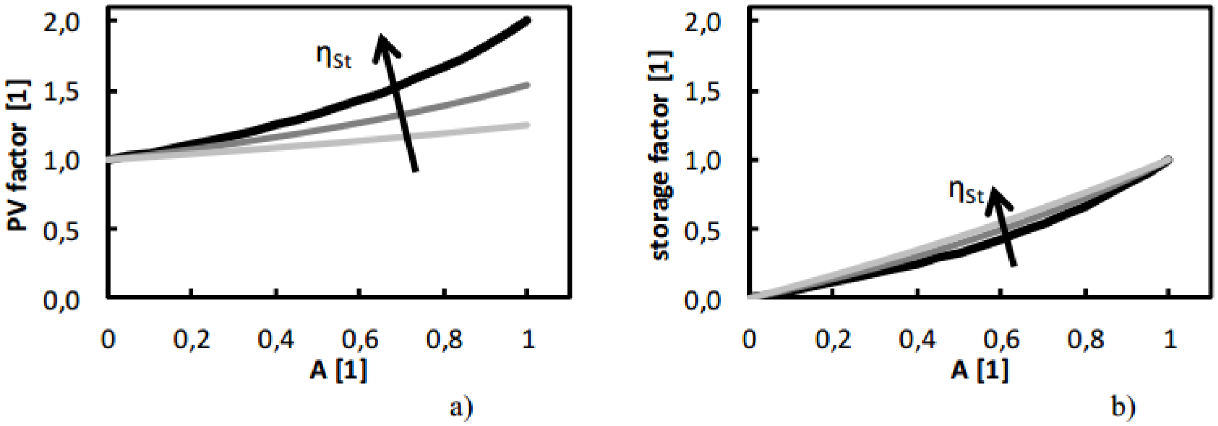


Fig.3.6 Dependency on the ratio of stored PV energy with ac efficiency of storage system as parameter. a) PV factor b) storage factor

It is obvious, that without storage the levelized cost will equal that of PV alone. On the other extreme, for a very high ratio of storage, the total levelized cost is much higher and consists of the cost of storage (factor of 1) and the geared cost of PV due to efficiency losses§.

With *LCOESt = 0.338* €/kWh (taken from Table 1/Technology 1) and *LCOEPV = 0.1* €/kWh one can sketch the implied cost of energy for the complete system under the underlying assumptions, see Figure 3.6. It is assumed that for each value of *A* the optimal storage size is selected and LCOE of storage is constant for each value of *A*. For small storage sizes, the influence of storage efficiency can be neglected. The effect becomes more pronounced as the storage size increases. This is very important for micro grid layouts, e.g. substitution of power generation by means of diesel gensets.

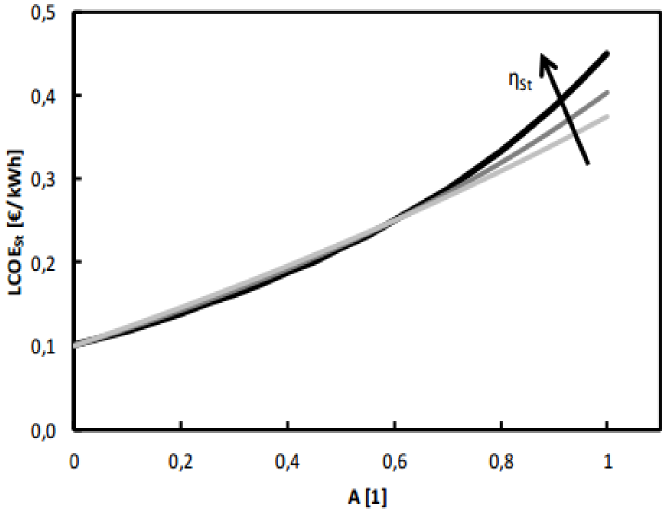


Fig.3.7 LCOE of the combined power plant (PV and storage) for different ratios of storage and with a efficiency of storage system as parameter. It is assumed that for each value of A the optimal storage size is selected and LCOE of storage is constant.

It is very important to point out that the cost curve in Figure 3.7 establishes a lower limit (optimal case) for the LCOE of storage. The parameter ‘Utilization of usable storage capacity’ in Table 1 models this effect. The results are given in Table 2.

Table 2: Influence of the utilization factor of the storage system on total LCOE of the power plant (PV & storage).

Table 2 Ratio of storage A = 0.5, ηSt = 65%.

Uitilization of usable storage capacity	100%	75%	50%
LCOESt [€/kWh]	0.339	(+27.7%) 0.433	(+82.9%) 0.620
LCOEPP [€/kWh]	0.255	(+14.5%) 0.292	(+43.1%) 0.365

In the combined system, the effect of under-utilization of the storage system is significantly lower compared to the respective LCOE. This emphasizes the need to consider the aggregated cost of energy when comparing different and maybe mutually exclusive solutions. The discount rate undoubtedly has major influence on any calculation based on discounted cash-flow (DCF). In this paper we assumed the weighted average cost of capital (WACC) to be the appropriate discount rate. The commonly known formula to calculate the WACC is:

$$WACC = \frac{E}{E+D} c_E + \frac{D}{E+D} c_D \cdot \left(1 - Tax_{Corp}\right).$$

With *E* and *D* equity and debt, *CE* and *CD* the associated cost of equity and cost of debt and the corporate tax of Taxcorp. Respectively(With ac energy efficiency $\eta St = 1$, the total levelized cost are simply the sum of cost of PV and cost of storage.).

Figure 3.8 illustrates the effect of discount rate on the LCOE of storage. It turns out to be a very strong dependency. A 5% change in discount rate implies a 50% change in LCOE. This underlines the necessity to carefully choose the appropriate discount rate. However, the correct calculation of WACC is somewhat complicated procedure with several methodologies and may be outlined in future publications in greater detail.

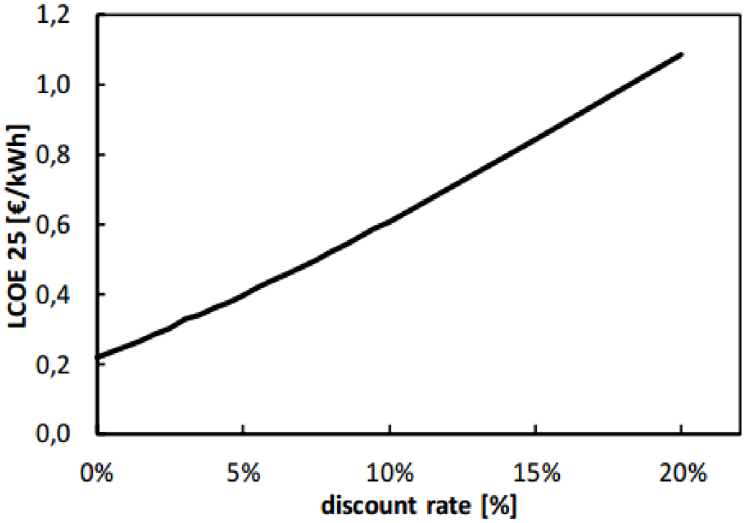


Fig.3.8 Influence of discount rate on levelized cost of energy for storage. Parameters from Table 1/Technology 1.

Chapter 4
Conclusion

Conclusion:

This paper aims at providing an overview over calculation of levelized cost of energy from generation and from storage in particular. In the first part the general relations for PV and storage were derived and various parameter variations were discussed for both systems separately. For storage it is assumed that solely the cumulated stored energy determines the LCOE of the storage system. It turned out that C rate is the most important parameter for the LCOE of storage. In contrast, the efficiency plays a less dominant role as often assumed in current technology discussions. The derived model was then used to compare different technologies. This comparison could easily be expanded to more technologies to foster technology comparison. In reality, project assessment should not be solely based on LCOE calculations but rather one should involve the expected revenue of the project to derive a net present value of the project. However, in this paper, revenue considerations were omitted. Instead, a model for the calculation of LCOE for a PV and storage combined power plant was derived and some aspects of parameter variation were discussed. The derived model is applied to a combined PV and storage power plant in order to derive an analytical expression. The derived model enables quick comparison of combined PV and storage power plants with other forms of energy generation, for example diesel generation. This could prove helpful in the current discussion about diesel substitution in off-grid applications. No cumbersome and time-consuming simulations are needed. Simply put the combined levelized cost of energy lies between the LCOE of PV and LCOE of storage. The next steps are the systematic analysis of business opportunities related with energy storage and their quantitative assessment using the framework and assumptions outlined in this paper and the detailed investigation of cost of capital calculations for different projects and its influence on project realization and financing.

We are venturing into the era of renewable energy, and photo-voltaics (PV) will represent an increasing share of this sector. Countless decisions associated with solar energy technologies 80 rely on financial calculations, ranging from investors to regulators to technologists, yet the established method of comparing costs between electricity generating technologies—LCOE—is being misused in virtually all cases in the context of photovoltaics. There are many assumptions 85 that underlie an LCOE calculation, and anyone performing such a calculation or utilizing the results must fully appreciate the influence of these assumptions. It is unadvisable to input single numbers into the calculation 90 and receive a single LCOE number as a result. This carries with it an unfounded and potentially misleading sense of certainty. Rather, input parameter distributions based on the best available data should be employed, resulting in a LCOE distribution that far more accurately reflects cost uncertainty 95 associated with a solar project.

Here we have used Monte Carlo simulations to produce such a distribution, and we have focused on assumptions revolving around (decoupled) sunlight variation, panel performance, operating costs, and inflation. The distributions used here are relatively crude approximations with no interdependence used to demonstrate the Monte Carlo approach to LCOE. Even within this limited scope, it is clear that the LCOE output can vary substantially from a single value, giving enhanced guidance to all stakeholders in the solar energy arena.

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