IJESG

INTERNATIONAL JOURNAL OF ENERGY AND SMART GRID

Volume: : 3
Issue : 2
Year : 2018
ISSN : 2548-0332
e-ISSN : 2636-7904

INESEG

Email (for orders and customer services enquiries) : info@ineseg.org, ijesg@ineseg.com
Visit our home page on www.ineseg.org

INESEG

IJESG *Vol 3, Number 1, 2018*
International Journal of Energy and Smart Grid
ISSN: 2548-0332 e-ISSN: 2636-7904
Doi: 10.23884/IJESG.2018.3.1.

INESEG

CONTENTS

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

INESEG

TECHNO-ECONOMIC ANALYSIS OF 1 MWE SOLAR POWER PLANT USING COMBINED RANKINE CYCLE IN IZMIR, TURKEY

***Alain C. BIBOUM*[1,*], *Ahmet YILANCI*[2]**

[1] Graduate School of Natural and Applied Sciences, Ege University, Izmir, Turkey

[2] Institute of Solar Energy, Ege University, Izmir, Turkey

*[*]Corresponding author; e-mail: biboumalain@gmail.com

Abstract

In the last decades, there is an increasing attention on renewable energy sources to overcome energy related problems such as global warming/climate change, security of energy supply, depletion of fossil fuels, unpredictable energy prices, conflictions on energy sources etc. Solar energy is an abundant source of renewable energy readily available on the earth. With the recent developments in solar energy conversion technologies, concentrating solar power (CSP) systems for heat and power productions have become attractive solutions. Currently, CSP systems using parabolic trough collectors (PTCs) are dominated the global CSP market since there are the most mature technology and the most installed CSP systems in the world. Turkey is one of the countries benefiting from good solar radiation, so CSP systems may be one of the solutions for the renewable energy production. In this study, techno-economic analysis of a small (1 MWe) PTC-CSP power plant using combined Rankine cycle for electricity production in Izmir, Turkey, is presented as a case study for an example of PTC-CSP power plant utilization in the locations in Turkey with high solar radiation values. Levelized cost of electricity (LCOE), internal rate return, net present value and payback period of the power plant for three different layout configurations of the PTCs in the solar field are calculated by using System Advisory Model (SAM), MATLAB and Excel softwares. The results show that for 1MWe PTC-CSP power plant in İzmir, the initial investment cost is approximately 3.9 Million USD with LCOE of 135 USD/MWh, and the annual operational cost of 37.5 USD/MWh with a payback period of 11.5 years. Also, the required cost for site optimization (RCO) per kW_{th} of exergy destruction and energy loss for the solar field configuration #1 is found to be 1830.2 USD and 1887.5 USD respectively. These results figure out that there are some possible improvements to be achieved. However, the values for the solar field configuration #2 and #3 are closed to the minimal RCO per kW_{th}. This means that no further improvement can be achieved.

Key words*: Solar energy, Concentrating Solar Power, Parabolic Trough Collectors, Techno-economic analysis, Exergy, Combined Rankine cycles.*

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

Nomenclature

A_{ap}	Aperture area (m^2)
C_{net}	Net installed capacity (MW)
c_p	Specific heat (kJ/kgK)
E	Energy (kW)
F'	Collector efficiency factor (-)
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
N_{loop}	Number of loop (-)
$\dot{Q}_{abs}$	Useful energy output (kW_{th})
$\dot{Q}_{solar}$	Solar power input (kW_{th})
$\dot{Q}_{use,in}$	Absorbed energy input (kW_{th})
O_{net}	Net energy generation (MWh)
s	Specific entropy (kJ/kgK)
T	Temperature (K)
T_o	Dead state temperature (K)
T_{sun}	Apparent sun temperature (K)
U_L	Heat loss coefficient (W/m^2K)
U_o	Overall heat transfer coefficient (W/m^2K)

Greek symbols

η	Collector energy efficiency (-)
η_{ex}	Exergy efficiency (-)
η_o	Optical efficiency (-)
η_{th}	Energy efficiency (-)
π	Heat exchanger effectiveness (-)
ψ	Exergy (kW)

Subscripts

eva	Evaporator
con	Condenser
Th	Therminol VP-1
sf	Solar field
in	Inlet
out	Outlet

Acronyms

AOE	Annual Operating Expenses
CER/TAX	Certified Tax Carbon
CR	Central Receiver
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiation
EAIT	Earning after Interest and Tax
EBIT	Earnings before Interest and Tax
EPC	Engineering Procurement and Construction
FiT	Feed in Tariff
HTF	Heat Transfer Fluid
ICC	Capital Cost
IHE	Intermediate Heat Exchanger
IRR	Internal Rate Return
ISG/DSG	Indirect/Direct Steam Generation

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

IT	Initial Investment
LCOE	Levelized Cost of Electricity
LFR	Linear Fresnel Reflectors
MENA	Middle East North Africa
NPV	Net Present Value
O&M	Operations and Maintenance
ORC	Organic Rankine Cycle
PBP	Payback Period
PD	Parabolic Dish
PTC	Parabolic Trough Collector
RCO	Required Cost for the Optimization
SAM	System Advisor Model
STPP	Solar Thermal Power Plant
SRC	Steam Rankine Cycle
TDC	Total Direct Cost
TES	Thermal Energy Storage
TIC	Total Installed Cost

1. Introduction

Solar energy is the most abundant source of renewable energy which is readily available in earth. It is basically used as a heat source to produce thermal energy at desired temperature range (typically up to 1200^{o}C) for different utilization purposes in various ways/technologies. Concentrating solar power (CSP) systems such as parabolic trough solar collectors (PTCs), solar towers (ST), and solar dishes, linear Fresnel reflectors, can be used to produce thermal energy at high temperatures (from 150^{o}C to 1200^{o}C) for heating, cooling and power demands. These systems require high solar direct normal irradiance (DNI) to obtain such temperatures. The PTCs are considered to be one of the most mature and lowest cost CSP systems [1]. Therefore, PTCs are the most widely used for the CSP plant constructions. This technology was developed in 1912 in Cairo, Egypt, and the first commercial CSP plant using PTC was installed in Grenada, 2008 named Andasol-1 [2]. PTC is one of the concentrated solar power technology containing large mirrors used to reflect the solar radiation onto a receiver. The collector field contains loop which have more than one solar collector assemblies (SCA) each and are placed in parallel rows aligned on a north-south axis. The solar field configuration tracks the sun trajectory which move from east to west throughout the day. The aim of the tracking system is to ensure that the solar radiation is continuously focused on the absorber pipes containing inside of receiver. The receiver or absorber tube has to achieve the maximum absorbed solar irradiation and reduce the heat losses in the receiver during this process in order to transfer significantly the heat to the heat transfer fluid which move through receiver. According to some parameters such as steam generation system types and thermodynamic cycle used to generate electricity, the heat transfer fluid can be water, thermal oil, such as diphenyl oxide, Therminol VP-1, Xcelterm-MK1 or molten salt and the others which are a kind of mixture with different percentages. The absorber has to be designed with a high absorption coefficient through its focal line, to ensure an efficient heating process of the working fluid. Contrary to the output heating value of the HTF which depends on the parameters like a local direct normal irradiation (DNI), absorption and emittance coefficient and others. Its output temperature value is related to a type of thermal oil used for heat transfer process. The solar-to-electric efficiency depends on the yearly amount of energy produced, the field layout and the annual DNI, its value is approximately 15% for the CSP system using PTC technology [3]. When the solar field system

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

is integrated with a steam-turbine power plant, the process is called direct steam generation (DSG) technology and uses water/stem as a heat transfer fluid. If the transfer fluid is not water and an intermediate heat transfer system is used to connect the solar field and the power block like in our case, the technology is called indirect steam generation (ISG) using water as a working fluid [4]. The biggest advantages of ISG system are: the heat transfer fluid such as molten salt which can be stored and used during sunlight unavailable period, the thermal energy storage (TES) system which can be built anytime to generate electricity during the night, the operation and maintenance works which can be done in short periods without a negative impact in the energy production. The major disadvantage is its initial investment and O&M cost, which are influenced by the use of the IHE and TES system.

Silva et al. [5] did thermo-economic design optimization of a parabolic trough solar plant for industrial processes with memetic algorithms. The authors carried out a levelized cost of energy of 5 cent€/kWh. Mokheimer et al. [6] studied performance and cost of a solar thermal power plant using the EuroTrough solar collector (ET-100) and for Luz solar collector (LS-3). This study showed that the specific cost for a PTC field per unit aperture area and the specific cost of different mechanical works can be cut by about 46% and 48% on 10 hectares. Khalilpour et al. [7] analyzed various designs and steam extraction design configurations of a hybridized power plant using CSP –biomass hybrid technology while using System Advisor Model (SAM) as the main software for simulation. The results showed that series design configuration had the lowest Levelized Cost of Electricity while parallel design presented the highest installed capacity. Solar energy is this most abundant source of energy which can be combined as a suitable alternative to fossil energy. It can be converted to electricity using different conversion and thermodynamic cycles. Calise et al. [8] did a dynamic simulation model of a solar–geothermal polygeneration system and its exergy and exergoeconomic analyses. The thermal power plant generally combine thermodynamic cycles to generate electricity in order to perform the plant efficiencies. They found that the levelized cost of electricity is between 0.1475–0.1722 €/kWh. Zare and Hasanzadeh [9] studied a closed Brayton cycle combined with Organic Rankine cycle for solar power tower plants in order to optimize electricity generation, in their study they found the efficiencies of the system to be 23.2%. They studied a solar power plant which uses central receiver technology combined with Rankine cycle for electricity generation. The solar energy converted to electricity can be done by different processes and thermodynamic combined cycles or not. A study of a combined Rankine cycle using water and R134a as a working fluid and Therminol VP-1 as a heat transfer fluid was done by Biboum et al. [10]. In the analysis, overall energy efficiency of the system is found to be 23.2%. Adibathla and Kaushick [11] attempted to integrate a solar aided system to existing 500 MWe coal-fired thermal power plant. This study is conducted to elaborate an exergoeconomic analysis of a 500MWe studied system. The results showed that the solar field and boiler have the maximum exergy destruction ratios 78.90% and 56.52% respectively. Ahmadzadeh et al. [12] studied thermodynamic performance and thermo-economic analysis of the proposed system, in order to develop a genetic algorithm optimization. This algorithm is conducted to 25% improvement in thermal energy, 21.3% in exergy efficiency and 7.7% reduction in total cost of the proposed system, PTC has been shown as the best technology among CSP Technologies for main criteria related to commercial electricity generation based on site characteristic and adopted configuration. Bishoyi and Sudhakar [13] studied a configuration of 100 MWe solar thermal power plant using 16 modules of linear Fresnel technology per SCA able to generate 264 GWh per year. LCOE is one of the main values of the economic analysis. A recent study presented by Bonyadi et al. [14] studied solar-geothermal power plant based on the hybridization of an existing geothermal and a solar-powered steam-Rankine. In the study, they used Meteonorm

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

Software to collect DNI meteorological data. The results show that a levelized cost of energy (LCOE) for each configuration is in the range of 163–172 USD/MWh.

The purpose of this study is to highlight the cost of the optimization work per kW capacity for 1 MWe solar plant. This consists of taking into account the cost of the site improvement in order to reduce the energy losses and exergy destruction, which may be due to various factors such as the transport of heat and working fluids, the quality of equipment and others. This work establishes the relationship existing between the site configuration and the necessary cost for its optimization; comparison of the expenditure due to the optimization work of the solar field according to the type of configuration. The two points mentioned show the particular aspect of the work that is generally carried out and implemented for large and medium-sized plants and justifies its limits for small installations.

2. Description of the System

Schematic view of the proposed system is shown in Figure 1. The annual thermal energy and electricity needs of the industry have been assessed to cover them as a priority. The system containing the solar field consisting of parabolic trough collectors (PTCs), the intermediate heat exchanger, the piping system, the combined Rankine cycles as a power block and the other auxiliary equipment such as pumps, recuperator, valves, mixing tank, water tank etc. In the study, PTC-CSP system is designed without thermal storage. In this system, solar radiation is concentrated by parabolic through collectors in the solar field to produce high temperatures. Therminol VP-1 used as a heat transfer fluid is transported to the solar field circuit for transferring the thermal energy while water and the R134a as the working fluids circulate in the high pressure and low pressure (power block) circuit. A pump circulates Therminol VP-1 with a certain mass flow rate to maintain the temperature as 391 °C at the outlet of the solar field. Thermal energy from the solar field to the power block is transferred by an intermediate heat exchanger to produce water vapor for Steam Rankine Cycle (SRC). The water from the tank is sent under pressure, it first passes through to the heat recovery to increase its temperature before entering the intermediate heat exchanger. The saturated steam is immediately transmitted to the turbine to generate electricity, while the non-saturated steam from the turbine is used to feed the recuperator and the low-pressure power circuit (Organic Rankine Cycle - ORC). Thus, electricity generation is obtained based on combined steam Rankine cycle (SRC) and organic Rankine cycle (ORC). ORC can be defined as a recovery system to perform electricity generation of the solar power plant. Generally, an important portion of wasted heat can be used for power generation using ORC [9]. Usually, there are two arrangement types in CSP plant using parabolic trough collectors, I and H. This study also shows which configuration can provide a better-required cost for optimization to perform plant capacity through an acceptable expenditure for exergy destruction and energy loss recovery as possible.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

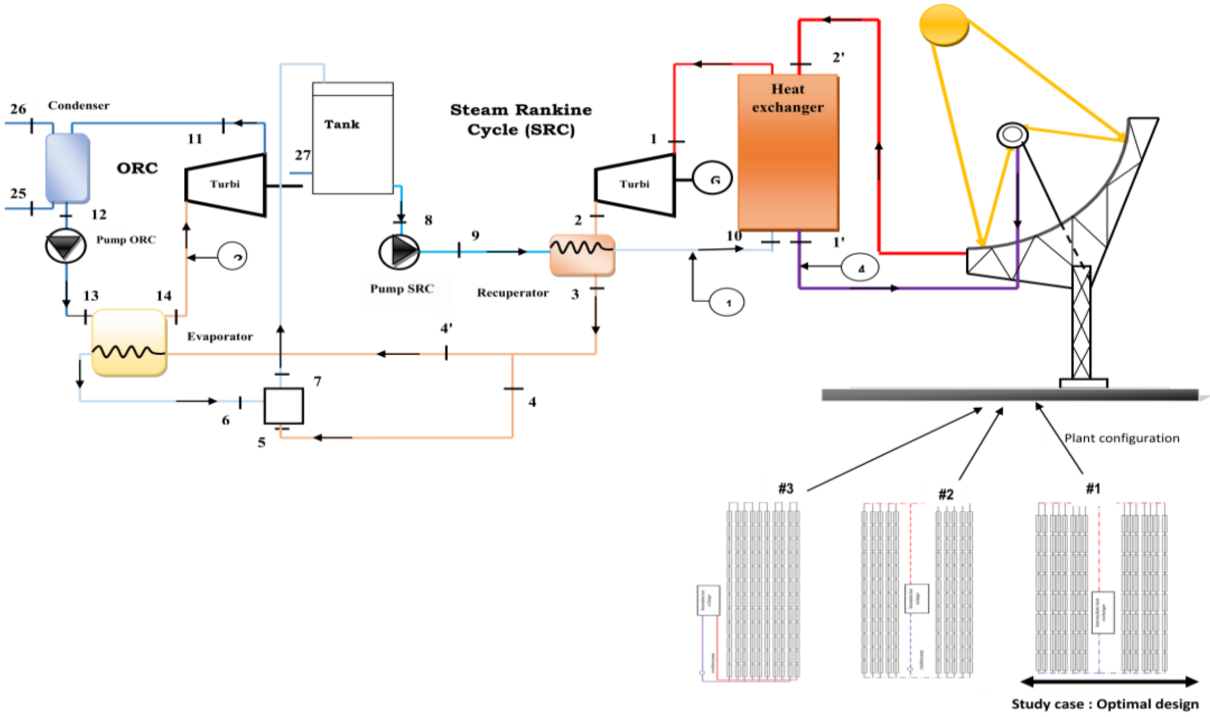


Figure 1. Schematic view of 1 MWe solar power plant containing three different solar field configurations (#1 and #2 are H type and #3 is I type)

The monthly average DNI value in the study area is estimated at 523.7 W/m^2, and the other meteorological data are avaliable in Table 1. The annual energy production can be performed using the meteorological data for Izmir, Turkey (38.25°N latitude and 27.14°E longitude) extracted from a TMY3 format file provided by Meteonorm Software.

Table 1. Meteorological data of Izmir [15]

Months	Monthly global solar radiation (kW.h/m^2)	Daily sunshine duration (h/day)	Av. solar radiation during sunshine hours (W/m^2)	Ambient temperature (°C)	Wind speed (m/s)
January	65	4.1	395.5	6.8	2.7
February	74	4.8	403.2	8.1	3.2
March	124	6	453.6	11.9	3.2
April	163	7.8	473.7	15.8	2.7
May	204	9.7	544.3	21.2	2.7
June	222	11.2	726.8	26.4	3.4
July	236	12	751.5	28.4	3.8
August	211	11.3	685.1	27.7	3.5
September	163	9.1	605	22.5	2.8
October	116	7.0	513.3	18.0	2.5
November	75	5.3	394.7	12.5	2.3
December	55	4.2	333.7	8.2	2.6
Av. values	**5.78**	**7.08**	**523.7**	**17.3**	**3.0**

3. Technical and Economic Analysis

3.1. Energy and Exergy Analyses

For a control volume at steady state, the energy and exergy balance equations are expressed as below.

$$\dot{E}_{in} = \dot{E}_{out} \tag{1}$$

$$\dot{\psi}_{in} - \dot{\psi}_{out} = \dot{\psi}_D \tag{2}$$

where $\dot{E}_{in}$ and $\dot{E}_{out}$ are the total energy rates entering and exiting to the control volume respectively; $\dot{\psi}_{out}$ and $\dot{\psi}_{int}$ are the total exergy rates entering and exiting to the control volume respectively, while $\dot{\psi}_D$ is the exergy destruction rate within the component. The exergy rate of a fluid can be obtained from the following equation:

$$\dot{\psi} = \dot{m}[(h - h_o) - T_o(s - s_o)] \tag{3}$$

For each subsystem, thermodynamic models are developed based on the equations above, and each subsystem are analyzed thermodynamically by using MATLAB program.

3.1.1 Solar field

The arrangement of solar field consists of solar collectors so as to create a SCA, and SCAs have a tracking system to follow the sun. In this study, Therminol VP-1 is used as heat transfer fluid at the outlet temperature of 391°C. The energy received by solar field system can be written as follow using the equation given by Shahin et al. [17]:

$$\dot{Q}_{input} = DNI.A_{ap} \tag{4}$$

Petela's equation [18] can be used to determine the exergy rate from solar radiation:

$$\dot{E}_{x,sf} = DNI.A_{ap}.\left(1 + \frac{1}{3}\left(\frac{T_o}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_o}{T_{sun}}\right)\right) \tag{5}$$

where A_{ap} is the aperture area of the solar field recovered by parabolic mirror; DNI is direct normal irradiation which is the irradiation value received on the solar field aperture; T_o and T_{sun} (5739 K) are dead state temperature in the location and apparent sun temperature as an equivalent heat source temperature [18]. The parameters such as the area of PTCs, the number of loops, the mass flow rate of the HTF, type of absorber, turbine size and HTF pipe and many others specifications presented in Table 1 are taken from SAM software. Thermodynamic analysis via Matlab software is done to determine the mass flow rate of HTF which affects considerably the value of heat transferred to SRC. The value of the useful energy, the exergy and the exergy destruction are given by:

$$\dot{Q}_u = \dot{m}_{Th}.C_{P,Th}.\left(T_{Th,out} - T_{Th,in}\right) \tag{3}$$

$$\dot{E}_{x,sf\_use} = \dot{m}_{Th}.\left[\left(h_{Th,out} - h_{Th,in}\right) - T_o\left(s_{Th,out} - s_{Th,in}\right)\right] \tag{4}$$

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

$$\dot{E}_{x,D,sf\_use} = N_{loop}.\dot{m}_{Th}.[C_{P,Th}.(T_{Th,out} - T_{Th,in}) - (h_{Th,out} - h_{Th,in}) + T_o(s_{Th,out} - s_{Th,in})] \quad (5)$$

The exergy efficiency of solar field is given by: $\eta_{ex\_sf} = \frac{\dot{Q}_u}{\dot{E}_{x,sf}}$ (6)

3.1.2 *Steam (SRC) and Organic Rankine cycles (SRC) (Power block)*

As described in Figure 1, SRC contains a steam turbine which produces electricity. The mass flow rate of water can be changed according to operating conditions closely related to meteorological data. Energy analysis and exergy balance of SRC can be found using these equations as follow:

$$\dot{W}_{net\_Solar\_SRC} = \dot{m}_w.(h_1 - h_2) - \dot{m}_w(h_9 - h_8) \quad (6)$$

ORC's working fluid used to recover low temperature of SRC's wasted heat in this study is R134a.Thermodynamic analysis of ORC can be written as follow:

$$\dot{Q}_{eva} = \dot{m}_{w1}(h_{4'} - h_6) \quad (7)$$

$$\dot{E}_{x\_eva} = (\dot{\psi}_{14} - \dot{\psi}_{13}) \quad (8)$$

$$\dot{Q}_{cond,orc} = \dot{m}_{R134a}(h_{12} - h_{11}) \quad (9)$$

$$\dot{W}_{net\_ORC} = \dot{m}_{R134a}.((h_{14} - h_{11}) - (h_{13} - h_{12})) \quad (10)$$

Exergy destruction can be obtained from this equation:

$$\dot{\psi}_{D,Eva} = (\dot{\psi}_{14} - \dot{\psi}_{13}) - (\dot{\psi}_{4'} - \dot{\psi}_6) \quad (11)$$

$$\dot{\psi}_{D,Cond} = (\dot{\psi}_{11} - \dot{\psi}_{12}) - (\dot{\psi}_{26} - \dot{\psi}_{25}) \quad (12)$$

$$\dot{E}_{x,D\_ORC} = \dot{E}_{x,eva} - \dot{E}_{x,work\_ORC} \quad (13)$$

Main equations and assumptions to find out the overall performance parameters of the power plant is presented in Table 2.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

Table 2. Equations and assumptions for the performance analysis

Equations	Assumptions
Energy yields from the solar collectors: $EP_{SF}=DNI \times Solar\ Field\ aperture\ area$	It depends on the DNI of the plant location (1702 kWh/m^2) and the area allocated to the plant size according to CSP technology used during construction (SAM).
Solar field land use efficiency: $LU_{SF} = \frac{\text{Solar field aperture area}}{\text{Site area}}$	The solar field land use efficiency is the main data during ESIA and feasibility studies to optimize the use of an available natural resource like water, land etc. This ratio has to be above 0.3.
Energy production efficiency: $\eta_{STPP} = \frac{\text{Annual Electricity Production (GWh)}}{\text{Yearly thermal energy produced by aperture Solar field (GWh)}}$	The power plant production and overall efficiency are key values in developed and developing countries with high demography. Despite the necessity to use renewable energy it is also important to optimize production. Then, we assumed that η_{STPP} and ψ_{STPP} have to be more than 27% and 10%, respectively.
Overall energy efficiency of the system: $\psi_{STPP}=\frac{\text{System capacity (MWe)}}{\text{Solar field thermal output (MWth)}}$	
Thermal energy production of the system: $TEP_{STPP} = \text{Annual electricity production (GWh)} \times \frac{1}{\psi_{STPP}}$	Thermal energy produced by the system depends essentially on the type of CSP technology used. To carry out suitable power plants we suggested to analyze a thermal efficiency of the solar field. We assumed that for our further studies the thermal efficiency of the solar field has to be: 41.66%.
Thermal efficiency of the solar field: $\eta_{th-SF} = \frac{TEP_{STPP}}{\text{Annual DNI received by the solar field aperture area}}$	
Thermal energy transferred by the solar power plant: $TET_{STPP} = \frac{\text{Solar field thermal output (MWth)}}{\text{Annual DNI received by the solar field aperture area}}$	The thermal energy transferred rate has to exceed 0.8.
Capacity factor: $CF = \frac{\text{Annual electricity produced}}{\text{Installed capacity} \times 24 \times 365}$	The capacity factor is the main value used by experts to evaluate the hybridization option of the installed plant.

3.2. Economic Analysis

The aim of a techno-economic analysis is to find the total system costs through thermodynamic and economic analyses of a system together. It is important for the optimization of PTC-CSP plants both technically and economically. In this section, economic analysis based on financial parameters are explained briefly.

The net earnings of the consecutive years are discounted to year zero with the rate selected to satisfy Marginal Average Rate of Return. The investment is deducted from the present sum of benefits. The NPV is written as:

$$NPV = -S + \sum_{j=1}^{i} \frac{CF_i}{(1+r)_i} \quad (14)$$

Internal Rate of Return (IRR) discounts all the cash back, thereby giving zero NPV during the investment life of a project, is expressed as:

$$-S + \sum_{j=1}^{i} \frac{CF_i}{(1+r)_i} = 0 \quad (15)$$

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

A set of projects that can earn maximum benefits can be easily selected by the management when the IRR is superior to the discount rate, r.
The payback period (PBP) can be defined as a number of years that the project takes to recover its total investment by the earnings after interest and tax (EAIT) deducted, it can be written as follow:

$$PBP = \frac{TI}{EAIT} \quad (16)$$

For the economic analysis, Feed-in-Tariff (FiT) prices for solar thermal power plants provided by the government in Turkey are listed in Table 3. The base rate is 13.3 USD/kWh for the solar thermal power plant. A specific bonus tariff for the domestic contribution is also provided for specific technologies and environmental considerations. Radiation collection tubes, sun tracking systems and the use of mechanical accessories for the steam generation systems increase the FiT prices with 2.4 USDcent/kWh, 0.6 USDcent/kWh and 2.4 USDcent/kWh respectively.

Table 3. Feed in tariff prices for concentrating solar power generation technologies in Turkey

Concentrating Solar Power Generation Technologies	**Domestic Contribution (USDcent/kWh)**
1- Radiation collection tube	2.4
2- Reflective surface plate	0.6
3- Sun tracking system	0.6
4- Mechanical accessories of the heat energy storage system	1.3
5- Mechanical accessories of the steam production system for the solar tower	2.4
6- Stirling engine	1.3
7- Structural mechanics	0.6
Production facility based on renewable energy	**Feed-in-tariff Prices (USDcent/kWh)**
Solar power system	13.3

4. Results and Discussion

The main characteristics of the system at design conditions are summarized in Table 4. In this study, commercial available PTCs (Luz-S2 and PTR Schott technologies) are used since they are able to provide heat around 500^{o}C depending on different criteria such as site assessment and configuration, heat transfer fluid (HTF), thermal properties of the raw materials of the collectors and receivers.

In the study, the following assumptions have been considered**:**

- The electricity need is 975 MWh annually with an average at 95 MWh per month.
- The system is operating in steady state conditions.
- Pressure drops in all the heat exchangers and the pipes are neglected.
- Heat losses from the components (excluding PTSC) are neglected.
- Thermal oil is considered as an incompressible fluid.
- The kinetic and potential energies and exergies are neglected, due to absence of chemical reactions in the considered system and also in heat transfer fluid. (Chemical exergy can be also cancelled).

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

- Turbine and pump used in Rankine cycle have isentropic efficiencies of 0.8,
- Energy efficiency for the recuperator is equal to 0.91,

Table 5 presents the total direct cost (TDC) containing the solar field cost and the power block cost; the total indirect cost including land cost and engineering procurement and construction (EPC) work cost, and the total installed cost (TIC). A power block has a high operation and maintenance expenditure cost because of its main components such as exchangers, turbine, and condenser. Prices of other units are relatively low as mentioned in Table 5.

Table 4. Design parameters of PTC-CSP plant for configuration #3 [16]

Sub-system	Parameter	Value
Solar Field	Aperture /active area	17800 m^2/7285 m^2
	Average irradiation	523.7 W/m^2
	Heat transfer fluid	Therminol VP-1
	Loop outlet temp.	391.1 ℃
	Number of module per SCA	12
	Number of loops	7
	Configuration type	I type (Figure 1)
	Collector	Luz LS-2
	Receiver	Schott PTR80
Power block	Capacity	1 MWe
	Efficiency	0.336
	Outlet temp.	391℃
	HTF mass flow rate	12.4 kg/s
Parasitic	Parasitic loss ratio	0.02273
	Other parasitic losses	-

Table 5 presents the installation and system costs of the 1 MW_e Concentrated solar power plant. The operation and maintenance (O&M) costs are divided between variable cost and fixed cost of the studied plant. Annual O&M cost is estimated as 23USD/MWh in the case of annual energy generated or 25 USD/kW-yr if the total installed cost of solar power plant is considered. The contingency of solar power plant construction is estimated at 6% of the total direct cost (TDC). The total area of the plant is 17.800m^2 and the estimated installed cost per kW is 3875.25 USD. Solar power plant technologies vary widely with DNI availability and conversion processes. Likely with a direct combustion-based plant, a solar thermal plant using ISG system run a steam turbine and can store a part of thermal energy produced during the day. Thus, the investment cost varies substantially with technology, operating conditions and the used working fluid and heat transfer fluid. The working fluid and a HTF are an important factor in solar power generation. The fluids characteristics can affect the plant efficiencies. Another important factor is the system cost (constructions, parabolic trough collectors, piping system and power block) because their price are directly related to thermal properties, such as inlet/outlet temperatures of different fluids.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

Table 5. Economic parameters of PTC-CSP plant for configuration #3 [16]

System cost	Unit	Values
Site improvement	USD/m^2	15
Solar field	USD/m^2	80
HTF system	USD/ m^2	40
Power plant	USD/kWe	750
Balance of plant	USD/kWe	60
Contingency	-	0.06
Total direct cost	USD	3111566.50
Total indirect cost	USD	613799.81
Total cost	USD	3725366.25
Total cost per kW	USD/kW	3725.25
Fixed O&M cost by capacity	USD/kW-yr	25
Variable O&M cost by generation	USD/MWh	2.3

Table 6 shows the main technical parameters considered for techno-economic analysis of the solar power plant in Izmir, Turkey.

Table 6. Technical parameters of solar thermal power plant.

Capacity (MW_e)	0.9	Design gross output	1 MW_e
Yearly DNI (kWh/m^2)	1702	Total annual DNI received by the land and solar field aperture area (GWh)	30.3 12.4
Thermal output of the solar field (MW_t)	2.81	Yearly electricity production (GWh_e)	1.622GWh_{ei}
Power plant production efficiency (%)	13.1	Power block rated conversion (%)	35.6
Annual water usage (m^3) – (times per year)	667 (52)	Capacity factor (%)	20.6

Thermodynamic analysis of the system (energy and exergy analyses) has been done in order to show the performance of the power plant. The solar power plant is divided into two subsystems namely, solar field and power block (Steam and Organic Rankine Cycle). These subsystems are considered as one block containing many components studied individually using MATLAB program for simulation. Results of the analysis for the optimized solar field configuration #3 are given in Table 7. Exergy destruction and energy loss are 2101.3 kW_{th} and 2052.8 kW_{th} respectively. The exergy destruction values of the system components are shown in Table 7. Table 7 shows that maximum exergy destruction occurs in the solar field. The fans and pumps impose a load to operate themselves. The developed power plant model handles also the parasitic loads. These parasitic loads are estimated as a percent of gross capacity for the calculation of net generating capacity (MW) and net energy output (MWh) of the solar power plant.

Table 7. Energy and exergy analyses of the CSP plant

		Energy Analysis				Exergy Analysis			
System	**Component**	Input (kW)	Output (kW)	Losses (kW)	En. Eff. (-)	Input (kW)	Output (kW)	Dest. (kW)	Ex. Eff. (-)
Subsystem1	CSP field	3093.8	1899.8	1194	0.609	3093.8	1790	1303.6	0.5786
	Abs. heat	1899.8	1468.2	431.6	0.772	1790.2	1383	407.5	0.7724
	Piping syst.	1468.2	1427.8	40.4	0.972	1382.7	1237.	145.6	0.8946
Subsystem2	Power cycle	1427.8	1047.9	379.9	0.706	1237.1	1005	231.8	0.7269
	Low cycle	244.3	19.4	224.9	0.0793	200.3	3.7	196.6	0.0186
	Comb. cycle	1427.8	1067.3	360.5	0.720	1237.1	1009	228.1	0.7429
	Overall plant	**3093.8**	**1041**	**2052.8**	**0.327**	**3093.8**	**992.5**	**2101.3**	**0.3207**

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

The annual energy production of the plant is presented in Table 6, part of this production is intended for the energy needs of the industry estimated at 975.02MWh. The remaining electricity production estimated at 696.02 MWh is for sale with a feed-in-tariff price of 19.6 USDcents/kWh. The profits are related to the quality of production and the type of technology used. Furthermore, the thermal energy produced for manufacturing industrial processes are not take into account in the profit calculation. To produce electricity, the quality of production through the use of solar energy has been controlled to protect the grid stability and the sustainability of the environment by combining solar with other energy sources which cannot produce tons of CO_2. Table 6 and 8 give an estimated value of the bonuses achieved for each MWh produced with the preservation of the environment (51.41 USD /MWh). The use of CSP-PTC and the Rankine Combined Cycle help to obtain a bonus on each kWh of electricity produced at approximately 5.14 USD cent/kWh. Table 8 presents, a cash flow analysis of the solar power plant using Credit-Carbon bonus and the discount rate is equal to 7%. The economic analysis of the plant leads to the determination of the following values: internal rate of return (IRR) 19.4%, the net present value approximately equal to 667,869USD for an equal payback period 9.55 years. Table 9 presents a cash flow analysis of the CSP plant with 20% loan and using Credit-Carbon bonus. In the economic analysis, it is found that IRR decreases by 3.6% compared to the value obtained from the preliminary analysis. Furthermore, the value of the NPV decreases to reach the value of 513797 USD and a payback period of 11.5 years as seen in Table 9. The value of IRR is closely related to the annual income of the plant and the initial investment. When the project is done without obtaining a loan from a financial institution, the IRR value is greater than 10% for the solar power plant project's bankability study. On the other hand, if the project is financed by a financial institution, the value of the IRR decreases considerably. The economic parameters such as present values, internal rate of return, and Payback-Period are calculated for different financing conditions using factors such as a loan, Credit-Carbon bonus and a discount rate. The gross profit margin is calculated by deducting the cost of goods sold from the revenue generated by the sale of the energy produced. The cash flows before interest and tax (EBIT) are calculated by deducting the operating cost from the gross profit and the cost related to grid connection and electricity transportation. After interest and tax (EAIT) are calculated by adding CER/Tax bonus (51.41 USD/MWh) and deducting loan payment from EBIT.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

Table 8. Annual cash flow analysis of the CSP plant without a loan

Year	Yearly prod. (kWh)	Surplus (kWh)	Revenue (USD)	Cost of good sales (USD)	The annual saving of manufacture (USD)	Gross profit (USD)	OPEX (USD)	EBIT (USD)	CER/Tax USD/MWh	EAIT (USD)	C. Earning (USD)
1	1671020	696020	92571	43849	202414	338834	27890	310944	81011	391954	-3453828
2	1671020	696020	92571	43849	212534	348954	27890	321064	85890	406955	-3046873
3	1671020	696020	92571	43849	213041	349460	27890	321570	85890	407461	-2639412
4	1671020	696020	92571	43849	213041	349460	27890	321570	85890	407461	-2231951
5	1671020	696020	92571	43849	213066	349486	30121	319365	85890	405255	-1826696
6	1659323	684323	91015	43112	215757	349885	30724	319161	85289	404450	-1422246
7	1647708	672708	89470	42381	218564	350414	31338	319076	84692	403768	-1018478
8	1636174	661174	87936	41654	221357	350947	33845	317102	84099	401201	-617277
9	1624720	649720	86413	40932	224131	351476	36553	314923	83511	398434	**-218843**
10	1613347	638347	84900	40216	226885	352001	39477	312524	82926	395450	176607
r = 7%	**IRR= 19.4%**	**PBP(Y) = 9.55**	**NPV=667869 $**								

Table 9. Revised assessment of annual cash flow analysis of the CSP plant with a loan (20%) at 2.5% after 3 years

Year	Yearly prod. (kWh)	Surplus (kWh)	Revenue (USD)	Cost of good sales (USD)	The annual saving of manufacture. (USD)	Gross profit (USD)	OPEX (USD)	EBIT (USD)	Loan Pay. (USD)	CER/Tax USD/MWh	EAIT (USD)	C. Earning (USD)
1	1671020	696020	92571	43849	202414	338834	27890	310944	-	81011	391954	-3453828
2	1671020	696020	92571	43849	212534	348954	27890	321064	-	85890	406955	-3046873
3	1671020	696020	92571	43849	213041	349460	27890	321570	-	85890	407461	-2639412
4	1671020	696020	92571	43849	213041	349460	27890	321570	197096	85890	210365	-2429048
5	1671020	696020	92571	43849	213066	349486	30121	319365	197096	85890	208159	-2220889
6	1659323	684323	91015	43112	215757	349885	30724	319161	197096	85289	207354	-2013535
7	1647708	672708	89470	42381	218564	350414	31338	319076	197096	84692	206672	-1806863
8	1636174	661174	87936	41654	221357	350947	33845	317102	-	84099	401201	-1405662
9	1624720	649720	86413	40932	224131	351476	36553	314923	-	83511	398434	-1007228
10	1613347	638347	84900	40216	226885	352001	39477	312524	-	82926	395450	-611778
11	1602054	627054	83398	39504	229620	352523	42635	309888	-	82346	392233	**-219545**
12	1590840	615840	81907	38798	232336	353041	46046	306995	-	81769	388764	169219
r = 7%	**IRR= 15.8%**	**PBP(Y)= 11.5**	**NPV=513797 $**									

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

INESEG

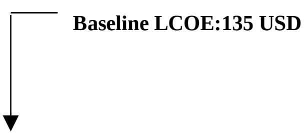
4.1. Cost of Electricity

For the financial analysis, an excel sheet was used to calculate the levelized cost of energy, initial capital cost per kW, capacity factor, annual operating expenses (AOE) cost per kW and acceptable discount rate after tax. These results can be illustrated in Table 10 and Figure 2. The economic model assumes that the capacity factor of the solar power plant can't reach 21.7 % according to the annual solar energy received on the site and the annual energy produced by the studied system. The study reveals that a slight variation of LCOE between the two simulated projects can be confronted using the variation of the maintenance and operating cost and the interest due to the loan from the bank. Annual cash flows are presented in Table 8-9.

Table 10: Overall performance and economic outputs of the solar power plant

	Data	Unit	Izmir-1MWe
	Overall energy efficiency (η)	-	32.7 %
	Solar thermal power input	MWth	3.12
	Annual operating hours	hours	6810
Performance metrics	Annual generating energy production	GWh/year	1.56
	Installed electricity capacity	MWe	1.04
	Parasitic losses	kWe	0.95
	Annual gross energy generated	GWh/year	1.67
	Gross capacity	MW	1.1
	Capacity Factor	GWh/GWh_e	13.46
	Annual water usage	m^3	3533
	LCOE (nominal)	USDcents/kWh	13.49
	LCOE (real)	USDcents/kWh	19.3
Financial metrics	IRR	%	[19.4 – 15.8]
	r	%	7
	PBP	Years	[9.55- 11.55]
	NPV	USD	[667869-513797]
	CER/TAX	1 tCO_2 - 7.2 USD	1MWh - 7.14 tCO_2

The average nominal and real LCOE are estimated to be equal to 193 USD/MWh and 135.1 USD/MWh respectively. Additionally, AOE, operating life per year and applicable values of discount rate are evaluated in Table 8. The calculated value of the cost per kW installed is less than 4000USD, this value is not related to other economic parameters. But the value of AOE depends on the annual production of electricity, the duration of intervention on the site and yearly fixed cost of O&M. Generally, the value of the discount rate is 8% according to the literature. For this study, we have exceptionally used the value 7% as the value of the discount rate to cover the difficulties related to the bankability study. The amount and physical characteristic of Water, R134a and Therminol VP-1 used in the power block and the solar field respectively have a direct impact on the LCOE in such a way that the variables will lead to energy output and then lower LCOE.



IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

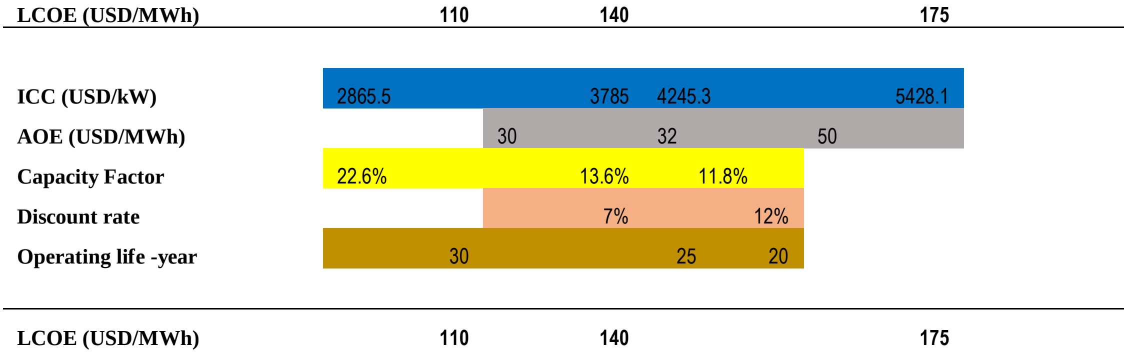


Figure 2. Sensitivity analysis of LCOEs of the CSP plant

This value of the DNI has a non-desirable impact on the annual electricity production and LCOE. Several studies, like a research carried out by Abbas et al. [19] for an assessment of CSP using PTCs in the MENA region has conducted to obtain some specific data for the project bankability in the area. During this work, the authors carried out a value of the cost per kW installed, a real LCOE and a capacity factor which are between 5940 USD and 6320 USD per kW, 119.3 USD/MWh and 296USD/MWh and 44.2-21.1% respectively. Moreover, the research done by Turchi et al. [20] showed that, the use of a heat storage system contributes significantly to the increase of the capacity factor and the LCOE through its high cost. Furthermore, the cost per kW installed of the studied project by the authors is above 4600USD with a capacity factor between 26% - 60% and a LCOE between 179 USD/MWh and 99USD/MWh. In this terms it can be said that, the system studied in this work does not contain a storage system to supply electricity when sun rays aren't available. Due to the absence of the storage system in our study case, the capacity factor can't reach 22%. On the other hand, this absence has conducted to obtain a low cost per kW installed (3725USD /kWh) and an acceptable LCOE (135USD/MWh). The IRENA's report shown that a suitable commercial power plant can be developed on the site with a direct normal irradiation between 2700 kWh/m^2/year and 2100 kWh/m^2/year [21].

4.2. Sensitivity Analysis

In this section, the sensitivity analysis both financial and performance outputs of the main system are considered. During this study, we also focused on the effects of the differences of configurations (#1, #2 and #3) in order to predict optimization of the solar field. Calculated technical parameters of three different configurations are seen in Table 11.

Table 11. Calculated technical parameters of the configurations

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

Parameters	Configuration #1	Configuration #2	Configuration #3
Net electiricty capacity (kW)	701	843.2	869
Net exergy rate (kW)	687.3	840.3	864.9
Estimated thermal production (GWh_t)	6.51	5.41	5.23
Thermal production efficiency (%)	52.5	43.6	41.2
Overall energy efficiencies (%)	24.94	30.01	30.9
Overall exergy efficiencies (%)	24.4	29.9	30.7

The improvement of solar field arrangement has a direct effect on annual energy production, initial capital cost per kW, required cost for optimization (RCO) of the exergy destruction, energy loss and capacity factor. The previous research [10] showed that the energy output of the solar power plant depends on different input variables such as the mass flow rate of working fluid and HTF, the inlet and outlet temperature of steam water in a steam turbine. Therefore, the sensitivity analysis of the energy output variables is studied, in order to carry out a possibility to optimize solar field configuration #1 and #2 through required cost for optimization (RCO) as presented in Figure 3. The mass flow rate and physical properties of the heat transfer fluid are important data for a suitable heat transfer.

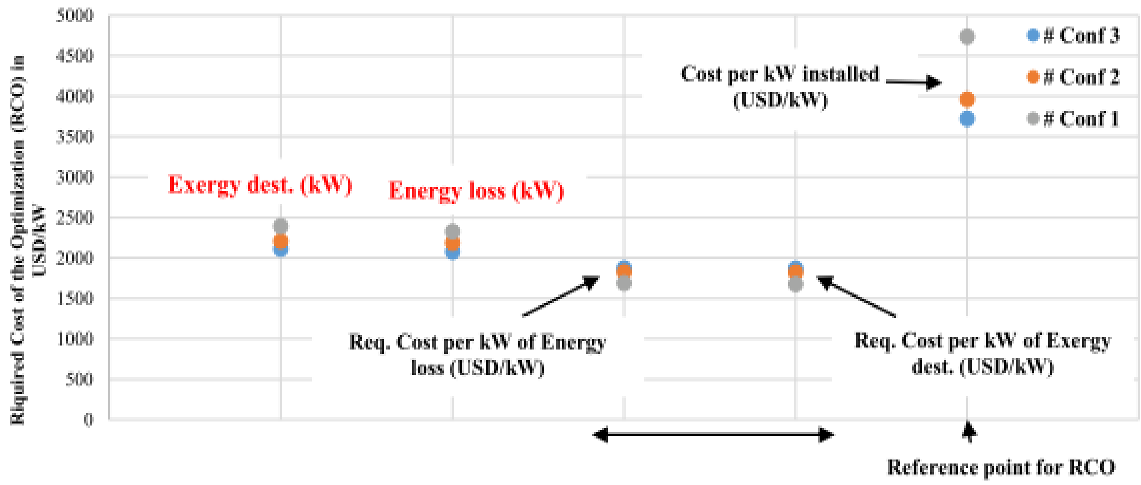


Figure 3. Required costs for plant optimization of kW of energy losses and exergy destruction and installed cost per kW

The sensitivity analysis of solar field configuration leads to reduce energy losses and exergy destruction of the solar power plant. This analysis is characterized by required cost for optimization (RCO) of exergy destruction and energy losses. RCO should be less than the half of the estimated cost per kW installed (1863 USD/kW) in order to face economic considerations related to bankability of the project. Figure 3 show the RCO values in the configuration #1 and #2, for the energy loss, these values are 1690.2 and 1822.6 USD per kW_{th} respectively and for exergy destruction, these values are 1677 and 1820 USD per kW_{ex} respectively. The analysis of solar field configuration #3 showed that we need to spend more than 1873.4 USD to recover 1 kW_{th} of energy loss. This RCO value corresponds to the recovered thermal energy. If we need to generate electricity after recovering this energy, we have to consider other parameters such as conversion, transport and generation process with various losses of equipment used during these processes. For the conversion we have to remind that, the efficiency of solar power plant

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

is 32.7%. Then we are going to spend 5729.1 USD per kWe recovered in configuration #3. This study reveals to us, the necessity of the exergoeconomic sensitivity before the construction of solar power plant. In order to determine a suitable solar field arrangement combined with the initial investment of the solar power plant, Figure 2-3 and Table 8-9 contribute to holding a final decision able to find a compromise between quality and managing total installation cost (TIC). From this figure, we can see that the solar field configuration#3 does not need to be optimized due to a high cost of RCO per kW_{th}. But configuration#1 which has a RCO of 5128.4 USD per kWe can be optimized.

5. Conclusion

An investigation for the techno-economic analysis of a small solar power plant with various solar field configurations on the same site has been done in this study in order to carry out plant optimization. For a 1 MWe concentrated solar power, parabolic trough collector technology is chosen for the simulation in the case study. For the technical and economic parameters, SAM software, Meteonorm7 and an elaborated program on Microsoft Excel has been used conjointly for simulation and to find necessary values in the studied location. On the other hand, thermodynamic analysis is done by using Matlab software and an Excel datasheet is used to find out the financial values. The combined analysis in this study allows us to solve the current problem related to feasibility report and optimization of existing power plant using installed cost, O&M cost and rehabilitation cost . The availability of DNI depends on the region where the study is taking place, then the importance of such kind of work has to be shown before any intervention in the solar field. The required cost for optimization (RCO) can be considered as one key data for any techno-economic analysis. Furthermore, discount rate, Credit Carbon bonus (CER/TAX), levelized cost of energy and internal rate of return are the main data of the bankability report. These results show that when the required cost for optimization (RCO) is higher than half of the cost per kW installed, the optimization work is still possible but might not be recovered soon during the plant exploitation. Then, the owners can consider a possibility to increase the plant capacity and technology used during the feasibility study. If the credit carbon bonus increases, CSP technologies could become a very successful area for independent power producers in Turkey since a payback period is closed to 11.5 years for 1 MWe without taking into account the thermal energy generated. Furthermore, renewable energy policies in Turkey can increase the value of carbon credit (CER/TAX) for CSP in order to encourage independent power producers to invest more in solar energy by using CSP technologies. It is planned that comparison of different CSP technologies or consideration of these technologies installed in another region with higher DNI per year will be analyzed for future study.

References

[1] Behar O., Khellaf A., Mohammedi K., Ait-Kaci S., A review of integrated solar combined cycle system (ISCCS) with a parabolic trough technology, Renewable and Sustainable Energy Reviews, 39, pp. 223-250, 2014.

[2] Ummadisingu A, Soni M.S., Concentrating solar power–technology, potential and policy in India, Renewable and Sustainable Energy Reviews, 15 (9), pp. 5169-5175, 2011.

[3] Fernández-García A., Zarza E., Valenzuela L., Pérez M., Parabolic-trough solar collectors and their applications, Renewable and Sustainable Energy Reviews, 14 (7), 1695–721, 2010.

[4] IEA, Technology Roadmap: Concentrating Solar Power, International Energy Agency – IEA, 2010. (Available from: https://www.iea.org/publications/freepublications/Publication/csp_roadmap.pdf⟩ [Accessed on January, 2019].

[5] Silva R., Berenguel M., Pérez M., Fernández-Garcia A., Thermo-economic design optimization of parabolic trough solar plants for industrial process heat applications with memetic algorithms, Applied Energy, 113, pp. 603–614. 2014.

[6] Mokheimer E.M.A, Dabwan Y.N., Habib M.A., Said S.A.M., Al-Sulaiman F.A., Techno-economic performance analysis of parabolic trough collector in Dhahran, S.Arabia, Energy Conversion and Management, 86, pp. 622–633, 2014.

[7] Khalilpour R., Milani D., Qadir A., Chiesa M., Abbas A., A novel process for direct solvent regeneration via solar thermal energy for carbon capture, Renewable Energy, 104, pp. 60-75, 2017.

[8] Calise F., Denticed'Accadia M., Macaluso A., Piacentino A., Vanoli L., Exergetic and exergoeconomic analysis of a novel hybrid solar-geothermal polygeneration system producing energy and water, Energy Conversion and Management, 1, pp. 200–220, 2016.

[9] Zare V. and Hasanzadeh M., Energy and exergy analysis of a closed Brayton cycle-based combined cycle for solar power tower plants. Energy Conversion and Management, 128, pp. 227–237, 2016.

[10] Biboum A.C., Mwanza M., Yilanci A., Performances analysis of combined Rankine and absorption refrigeration cycles for a small size solar power plant, IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry, ISES Solar World Congress, Abu Dhabi, 2017.

[11] Adibhatla S. and Kaushik S.C., Exergy and thermoeconomic analyses of 500 MWe sub-critical thermal power plant with solar aided feed water heating, Applied Thermal Engineering, 123, pp. 340–352, 2017.

[12] Ahmadzadeh A., Salimpour M.R., Sedaghat A., Thermal and exergoeconomic analysis of a novel solar driven combined power and ejector refrigeration (CPER) system, International Journal of Refrigeration, 83, pp. 143-156, 2017.

[13] Bishoyi D. and Sudhakar K., Modeling and performance simulation of 100 MW LFR based solar thermal power plant in Udaipur India, Resource-Efficient Technologies, 3(4), pp. 365–377, 2017.

[14] Bonyadi N., Johnson E., Baker D., Techno-economic and exergy analysis of a solar-geothermal hybrid electric power plant using a novel combined cycle, Energy Conversion and Management, 156, pp. 542–554, 2018.

[15] Meteonorm, Typical Meteorological Years, TMY-3, 2019. (Available from: https://meteonorm.com/typical-meteorological-years

[16] System Advisor Model (SAM), NREL, 2019. (Available from: https://sam.nrel.gov/download)

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.01

INESEG

[17] Shahin M.S., Orhan M.F., Uygul F., Thermodynamic analysis of parabolic trough and heliostat field solar collectors integrated with a Rankine cycle for cogeneration of electricity and heat, Solar Energy, 136, pp. 183–196, 2016.

[18] Petela R., Exergy of undiluted thermal radiation, Solar Energy, 74, pp. 469–488, 2003.

[19] Abbas M., Belgroun Z., Aburidah H., Merzouk N.K., Assessment of a solar parabolic trough power plant for electricity generation under Mediterranean and arid climate conditions in Algeria, Energy Procedia, 42, pp. 93–102, 2013.

[20] Turchi C., Mehos M., Ho C., Kolb G.J., Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market, NREL/CP 5500-49303, 2010. (Available from: https://www.nrel.gov/docs/fy11osti/49303.pdf) [Accessed on January, 2019].

[21] IRENA, Renewable Power Generation Costs in 2012: An Overview, International Renewable Energy Agency, IRENA Report, 2013. (Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/Overview_Renewable-Power-Generation-Costs-in-012.pdf) [Accessed on January, 2019].

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

INESEG

ENERGY STORAGE IN MICROGRIDS: CHALLENGES, APPLICATIONS AND RESEARCH NEED

Hamidreza Nazaripouya[1], Yu-Wei Chung[2*], and Abbas Akhil[3]

[1] University of California, Riverside Winston Chung Global Energy Research Center.
hamidn@ucr.edu

[2] University of California, Los Angeles Smart Grid Energy Research Center (UCLA SMERC),
*Corresponding author: ywchung@ucla.edu.

[3] Renewable Energy Ventures: abbas@revtx.com

Abstract

This paper studies various energy storage technologies and their applications in microgrids addressing the challenges facing the microgrids implementation. In addition, some barriers to wide deployment of energy storage systems within microgrids are presented. Microgrids have already gained considerable attention as an alternate configuration in electric power systems that can operate in grid-connected mode or islanded mode. Host grid reliability, electricity rate uncertainty, electricity demand beyond installed capacity, and regulatory and market incentives are some of the drivers motivating the deployment of microgrids. Microgrids offer greater opportunities for including renewable energy sources (RES) in their generation portfolio to mitigate the energy demand reliably and affordably. However, there are still several issues such as microgrid stability, power and energy management, reliability and power quality that make microgrids implementation challenging. Nevertheless, the energy storage system is proposed as a promising solution to overcome the aforementioned challenges.

Keywords: *microgrid, energy storage system, microgrid stability, power and energy management, reliability and power quality*

1. Introduction

Microgrids have attracted significant attention and interest in their remarkable features including operation in grid-connected and islanded modes which perfectly adapts to the modern power grid. The modernization is largely driven by the widespread deployment of Renewable Energy Resources (RES) in response to the growing power demand, depletion of fossil fuels, and increasing environmental concerns. Microgrids reliably offer a promising configuration that integrates RES as Distributed Energy Resources (DER) and mitigates the growing energy demand.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

The definition of a microgrid with respect to the size, geographic area or energy demand is not universally and uniquely stated. A broader definition of a microgrid describes it as a single controllable entity consists of interconnected loads and DER within defined electrical boundaries which operates in both grid- connected and islanded modes [1].
The features of dynamic reconfiguration and flexible operation make microgrids as a reliable and resilient source for load supplying. Microgrids can supply un-interruptible power to critical loads even during contingencies including those resulting from severe weather and natural disasters [2], [3]. In addition, microgrids play an important role in providing secure and high-quality power for end users. However, design, control, and operation of microgrids are still challenging due to the RES intermittency, load profiles uncertainties, and low or lack of mechanical inertia introduced by inverter-interfaced DER. A growing body of operational experience has shown that concerns associated with operation and control of microgrids include voltage and frequency stability, reliability, and power quality, which can be addressed by incorporating energy storage into the mixed generation of the microgrid [4], [5].
Energy storage systems have been proposed as a promising solution for the operational issues of microgrids including power quality, dynamic stability, reliability, and controllability especially in the presence of RES [6]. Energy storage systems act as an energy buffer to compensate renewable intermittency, mitigate load uncertainties, and improves the microgrid stability by providing virtual inertia. The presence of energy storage in the microgrid also enhances its efficiency by managing the power flow and reducing operational losses.
This paper benefiting from the accumulated experience of real-world microgrid projects, overviews the existing challenges in control and operation of microgrids. It also studies various energy storage technologies, their characteristics and related services they can offer to microgrids. The role of energy storage systems within a microgrid to improve the stability, reliability, resiliency, and power quality as well as facilitating the energy management within microgrids is also addressed. Finally, this paper discusses the barriers need to be coped in order to expand the utilization of energy storage in microgrids.
This paper is structured as follows: Section II reviews microgrid challenges. Section III presents energy storage technologies based on their capabilities. Section IV studies the application of energy storage in microgrids along with real-world case studies. Challenges and barriers are discussed in Section V. The concluding remarks are given in Section VI.

2. Microgrid challenges

Although microgrid is a promising solution to provide reliable and secure power and facilitates the integration of DER units into the power systems in an economic manner, there are still some operational concerns. In this section, the challenges including system stability, power management, power quality, and system reliability are discussed.

2.1. Microgrid Stability

Microgrids stability characteristics are different from those of traditional grids due to the lack of inertia in the inverter-interfaced distributed generation (DG) [7], [8]. The deployment of inverter-interfaced DGs in microgrids has led to the major operating differences between a microgrid and a traditional grid in time response and inertia. These differences lead to complication in operation and stability of microgrids.
A traditional power grid stores a significant amount of kinetic energy in the rotating mass which contributes to grid stability, while inertia-less DGs do not. The kinetic energy compensates for the short timescale mismatches of demand and supply and thus maintains the stability of the grid voltage and frequency.

Since a microgrid operates in grid-connected and islanded mode, the microgrid stability is studied in these two modes [8] and discussed separately.
In mode of grid-connected, microgrid absorbs energy from the main grid when there is a deficit in its internal energy balance and sends it back to the grid when it has a surplus generation. In this case, the maingrid balances the mismatch between the generation and load and ensures the system frequency stability. Therefore, in grid-connected mode, rather than rotor angle and frequency stability, voltage stability is the main issue. To this end, small and large disturbances (transient) analysis are performed only for the voltage.
In islanded mode, since a microgrid is electrically independent of the main grid, it has the responsibility to maintain both voltage and frequency stability.
The transient stability of a microgrid at the time of islanding is investigated in [9], and the results show that the microgrid can lose stability very easily due to the power imbalance while even load shedding might not be an effective solution to stabilize the system.

2.2. Microgrid Power Management

A robust and autonomous power management system is of vital importance to enable the deployment of microgrids within the current grid and accelerate their adoption by utilities and customers. The role of a power management system is to control the power flow while optimizes an objective function such as fuel consumption, efficiency, and overall operation costs [10, 11]. However, the hybrid AC/DC architecture [12] and multi- operational modes of a microgrid make the microgrid power management complicated. Firstly, AC/DC hybrid microgrids require proper coordination among the AC and DC generators. Secondly, supply and demand balancing during the transition from grid- connected to islanded mode should be effective to make the transition seamless. Finally, the incorporation of intermittent RES such as solar and wind as well as stochastic and uncertain loads such as electric vehicles (EVs) into microgrids[13] pose challenges to microgrid power management. The above- mentioned physical configuration and components of a microgrid impose several constraints for power management and thus, turn it into a complex multi-objective optimization problem[14].

2.3. Microgrid Power Quality and Reliability

Power quality in electric grid is defined as maintaining the magnitude and frequency of the voltage within the allowable range of rated value in a sinusoidal waveform [15]. In a microgrid comprised of a collection of DGs, providing high power quality can be challenging due to the following reasons. First, most DGs usually interconnect via power electronics. The nonlinear voltage-current characteristic of these inverter-interfaced DGs generates harmonics in the system, negatively affects the power quality. Second, high penetration of DGs in the microgrid, which are mostly RESs such as solar or wind power, can degrade the power quality significantly because of their nature of intermittency and the reverse power flow. Lastly, nonlinear and stochastic loads, loads with considerable reactive power, and transition between grid- connected and islanded modes are other factors that lead to power quality issues in microgrids. All of those may result in the issues including power variation, voltage and frequency deviation, voltage sag, voltage swell, voltage flicker, poor power factor, Total Harmonic Distortion (THD), and unbalanced voltage and current, which are power quality concerns in microgrids [16].
The initial motivation of developing and deploying microgrids is to improve power system reliability. The capability of microgrids to improve reliability relies on the availability of DERs and dynamic response of local generation units to withstand sudden disturbances or faults. However, the reliability improvement in microgrids is still challenging as the DERs are

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

stochastic and non- dispatchable resources. That is, complex scenarios including multi-stochastic factors such as loads, supply, and failure events should be managed to ensure system reliability [17].

3. Energy Storage Technologies

Energy storage is a device that is capable of converting the electrical energy to a storable form and convert it back to electricity when it is needed. Based on the form of stored energy, there are four main categories for energy storage technologies: Electrical Energy Storage (EES), Mechanical Energy Storage (MES), Chemical Energy Storage (CES), and Thermal Energy Storage (TES) as depicted in Table 1.

Table 1. The Classification of Energy Storage Technologies.

Electrical Energy Storage (ESS)	Mechanical Energy Storage(MES)
1 Magnetic/Current Energy Storage e.g. Superconducting Magnetic Energy Storage (SMES)	1 Kinetic Energy Storage e.g. flywheel
2 Electrostatic Energy Storage e.g. capacitor/ supercapacitor	2 Potential Energy Storage e.g. Compressed Air Energy Storage (CAES) or Pumped Hydroelectric Storage (PHS)
Chemical Energy Storage (CES)	**Thermal Energy Storage(TES)**
1 Electrochemical Energy Storage e.g. conventional batteries (lead-acid, lithium ion) and flow-cell batteries (vanadium redox)	1 Low Temperature Energy Storage e.g. cold aquifer thermal energy storage and cryogenic energy storage
2 Chemical Energy Storage e.g. fuel cell	2 High Temperature Energy Storage e.g. steam or hot water accumulators, graphite, hot rocks and concrete, and latent heat system
3 Thermochemical Energy Storage e.g. solar hydrogen, solar metal	

The functionalities and applications of energy storage technologies depend on their characteristic including rating characteristic, dynamics, space requirement, and performance. The rating characteristic is determined by power and energy rating. Power rating refers to the charge/discharge rate while energy rating represents the discharge duration. The dynamics can be evaluated by response time and ramp rate. The response time is the time duration that energy storage goes from zero discharge to full and the ramp rate is the rate at which the output power can change. The space requirement depends on power and energy densities, and the performance can be expressed as the efficiency of the energy storage. Table 2 shows the common energy storage technologies deployed in microgrids and their characteristics.

4. Applications of Energy Storage in Microgrids

The integration of intermittent RES within a microgrid has turned the traditional power generation from controllable and dispatchable recourses into uncontrollable and non-dispatchable ones. In addition, stochastic EV loads make the power demand unpredictable. Therefore, microgrids encounter a big challenge for balancing the power demand and supply. Energy storage, however, becomes a capable solution for microgrids to address the mismatch of the unpredicted power demand and generation. Energy storage system also plays an indispensable role in microgrids to ensure the system stability, reliability and power quality

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02
INESEG

while lower the operation cost and enhance the power efficiency. In this section, different capabilities and applications of energy storage that can address the challenges mentioned in section II are discussed and presented.

4.1. Stability Enhancement

Energy storage systems connected to power electronic device can be utilized to improve both voltage and frequency stability by exchange active and reactive power with a microgrid.
Under incidents such as reactive power shortage, dynamic variation of load and generation, and operation of load tap changers and voltage regulators, as the main sources of voltage instability, there is a need for a mechanism to maintain the voltage within an allowable range for stable operation of microgrids. It should be noted that since in a microgrid, the line resistance to line reactance ratio (R/X) unlike the transmission system is considerable, the impacts of active and reactive power on frequency and voltage are not decoupled [18]. Fortunately, the battery energy storage system as a source of active and reactive power can be controlled to compensate the imbalance of active and reactive powers with fast dynamics.

Table 2. Characteristics of various energy storage technologies utilized in microgrids.

Energy Storage Technology	Characteristics						
	Rating Characteristic		Dynamics		Space Requirements		Performance
	Discharging/ Charging rate (MW)	Discharging duration	Response time	Ramp rate	Energy Density (Wh/kg)	Power Density (W/kg)	Efficiency (%)
Battery Energy Storage(BES)	0-40	ms - hrs	ms	MW/sec	10 - 250	70 - 300	70 - 90
Capacitors (Supercapacitors)	0.01–0.05 (0.01–0.3)	Ms -1 hr	ms	MW/sec	0.05 - 5 (0.1 - 15)	100, 000 (500 - 10,000)	60 - 90 (75 - 95)
Flywheel Energy Storage(FES)	0.002–0.25	ms -15 min	Instantaneous	MW/min	5 - 130	400 - 1500	90 - 95
Fuel Cell	0.001–50	Sec - 24+ hr	ms	MW/min	800 - 10,000	500+	20 - 90
Compressed Air Energy Storage (CAES)	0.1-300	1 - 24+ hr	min	MW/min	3 - 60	-	42 - 89
Superconducting Magnetic Energy Storage (SMES)	0.1–10	ms - 10 sec	Instantaneous	MW/ms	0.5 - 5	500 - 2000	> 97
Pumped Hydroelectric Storage (PHS)	0.1–5000	1 - 24+ hr	sec – min	MW/sec	0.5 - 1.5	-	IV. - 85

An energy storage system can also act as virtual inertia in a microgrid to enhance the frequency stability by compensation the low inertia of RES [19, 20]. That is, the energy stored in the storage systems emulates the kinetic energy stored in the rotor of synchronous generator which can be released in the events of disturbance or drastic demand- supply imbalance. Battery energy storage systems, supercapacitors, superconducting magnetic energy storage (SMES), and flywheel Energy Storage (FES) are suitable candidates for dampening the frequency oscillations in microgrids due to their fast dynamics.

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

4.2. Energy Management

Energy management in a microgrid is an economical strategy of dispatching DERs and managing the loads. Energy management not only minimizes the operation cost but also meets the load demand within the microgrid operational constraints. Energy storage can be viewed as a dispatchable source and controllable load in energy management systems. Since it is a challenge to balance the power supply and demand in a microgrid with its unpredictable RES generation and stochastic loads, energy storage system plays an indispensable role to provide more flexibilities for relaxing the energy management constraints and optimizing the objective function [21].
Energy storage can offer different services to facilitate microgrid energy management. Firstly, as a dispatchable and controllable prosumer, they can be used to ease the complexity of energy management problem in the presence of intermittent RES and stochastic loads by smoothing the RES power generation and managing the demand [22]. Secondly, energy storage systems are capable of shifting the time of power generation and demand. Many of RES might generate a considerable amount of energy when the demand is low, and thus result in energy generation surplus [23]. Without energy storage, the surplus energy may be curtailed. Therefore, an energy storage system can store the energy when the demand is low (extra generation) and release the energy when the demand is high (energy shortage). With this capability, energy storage systems can provide microgrids with services such as peak shaving, load leveling, and energy arbitrage. They can also prevent curtailment of renewable energy [23]. Lastly, with optimal placement of energy storage systems within a microgrid, they can help to reduce power loss and improve efficiency through maximizing the local energy utilization and reducing the transferred power from the main grid [18]. In addition, since in microgrids the energy loss in conductors and electrical equipment is proportional to current squared (RI^2) , distributing loads evenly over time and reducing the peak demand by energy storage can reduce the energy loss. Finally, energy storage systems by providing reactive power locally, can also decrease the current drawn by loads from resources and reduce the loss over lines.

4.3. Power Quality Improvement

Load characteristics, variability in power generation, operation of switching devices, and malfunctioning of equipment within a microgrid may degrade the power quality and thus negatively affect the operation of system through reducing the efficiency and increasing the maintenance cost in microgrids. Energy storage systems can be deployed to assist power quality improvement by offering services such as renewable intermittency compensation, voltage support, power factor correction, phase balancing, and harmonic compensation, which are described below.

4.3.1 Renewable Intermittency Compensation:

The intermittency in power generation can be effectively mitigated with a fast response energy storage system integrated with RES [24]. An energy storage unit can automatically smooth the variation in RES by controlling the ramp-rate through instantaneous energy exchanging. Figure 1 depicts the obtained result from using energy storage to smooth solar power in Borrego Spring microgrid [25].

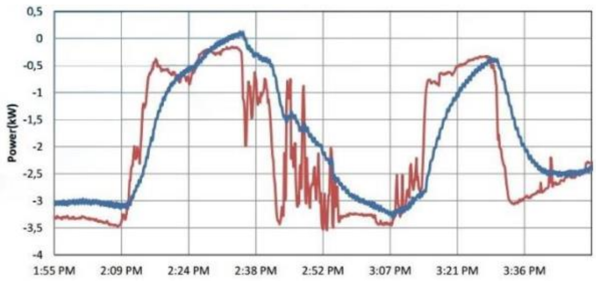


Figure 1. Smoothing the power of PV solar using energy storage in Borrego Spring microgrid [25]

4.3.2 Voltage Support:

Voltage sag/rise is considered as a power quality issue in microgrids. Voltage sag occurs when the capacity of the system in delivering the required energy is not adequate to meet the demand. Voltage rise is due to reverse power flow when the local generation exceeds the consumption. Voltage variation may cause shutting down or malfunctioning of electric equipment. The inverter-interfaced energy storage systems by operating in four-quadrant (charging, discharging, leading or lagging) and controlling active and reactive power in the microgrid can effectively regulate the voltage [18].

4.3.3 Power Factor Correction:

Energy storage systems equipped with power electronic converters are valuable assets within a microgrid to improve power factor and compensate the effects from local reactance. In [26] distributed battery energy storage systems are optimally scheduled to mitigate marginal loss through power factor correction.

4.3.4 Phase Balancing:

A three-phase microgrid might contain single-phase loads and generation. Therefore, for a safe and efficient operation of the system, balancing loads and generation among phases is needed. Single-phase energy storage systems can mitigate the phase imbalance if they are separately integrated to each phase and exchange active and reactive power independently [27].

4.3.5 Harmonic Compensation:

The widespread deployment of intermittent RES and nonlinear loads such as fluorescent lamp, motor drivers, and electric vehicle chargers leads to current and voltage harmonics in the system. The harmonics can be compensated by proper switching of energy storage power electronic converters to act as an active filter and producing the inverse of harmonics in the system [28].

4.4. Reliability Improvement

Power reliability can be defined as the ability to provide sustainable power to meet the consumer's electricity demand. According to reliability indices defined by Institute of Electrical and Electronics Engineers (IEEE) [29], one of the key factors in reliability degradation is power interruption. Microgrids with the support of energy storage system is a promising solution to improve the power reliability. In the event of the outage, the energy storage system provides the consumers with the required power to ride-through the outage until the backup generation

starts up and the system continues the normal operation [30]. The microgrid energy storage in order to prevent power interruption during the transition into the islanded mode of operation can also offer the ride-through and bridging services.
The other influential factors in microgrid reliability include capacity availability and resources adequacy. The required generation capacity for a microgrid usually is about 115 percent of its forecasted peak demand. Adding more dispatchable generation is the common practice to provide generation capacity. However, the energy storage system is a competitive alternative to provide resource adequacy.

4.5. Resiliency Improvement

Microgrid resiliency can be defined as the ability to endure and recover from disruptive events and to minimize the duration, intensity, and the negative impacts of disruptions [31]. Energy storage can be controlled properly to manage the network power flow and balance the supply and demand in order to stabilize the system during the contingencies [32]. To sustain the sudden changes, energy storage systems can provide virtual inertia to the microgrid, which enhances the robustness of the entire system. In addition, the integration of RES with energy storage system turns the intermittent RES generation into a reliable energy source to provide power during grid outages.

5. Challenges and Barriers

The barriers and challenges for widespread deployment of energy storage system in a microgrid are discussed in this section.
There are three major issues for the extensive deployment of energy storage. The first issue is the deployment cost. Due to the high cost of energy storage systems, the value stream and revenue created by energy storage systems within a microgrid should be clearly identified and quantified. It should be noted that besides the cost of energy storage technology, the cost of ancillary equipment as well as system installation, integration, and commissioning should be reduced. Sometimes, the secondary cost reaches up to 60-70 percent of the total cost [32].
Choosing the proper type, sizing and placement of energy storage within a microgrid is the second challenge. The first difficulty that users may encounter is to decide the best fit technology for their application from a wide range of selections of different energy storage systems with different characteristics. Even if they select one, the sizing of the energy storage capacity would be challenging. Therefore, to facilitate energy storage utilization, creating a comprehensive standard to be able to evaluate and compare the quality and performance of different technologies is inevitable. Next step is to develop a clear guideline to help energy storage users with the optimal selection of energy storage type and size and optimal placement in order to gain the maximum benefit. Lastly, appropriate rules and regulation should be formed to promote energy storage deployment in the microgrids and encourage stakeholders' investment. Clear market models, as well as adequate incentives should be provided by regulatory entities for investors, while the regulatory restrictions that prevent stakeholders to collect revenue need to be removed. Moreover, a clear and accurate evaluation of energy storage systems performance is required for stakeholders to assess the investment. To this end, desired performance criteria should be defined through establishing appropriate codes and standards and also a unified framework for analysis and reporting the performance of energy storage should be developed to alleviate the uncertainties over capabilities of energy storage and make the stakeholders confident to invest.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

6. Conclusion

This paper provides an overview of microgrid challenges including stability, power and energy management, reliability and power quality. The paper also studies and compares various energy storage technologies based on their characteristics such as rating characteristics, dynamics, space requirement, and performance. The role of energy storage systems in microgrids and services that they can offer to address the challenges are discussed. Finally, the barriers of promoting energy storage system in microgrids are discussed. Technical barriers such as determining the best technology fit, sizing and placement problems, along with non-technical barrier including high cost, lack of rules, standards, and regulation are the issues need to be overcome in order to allow widespread propagation of energy storage. There is no question that the energy storage system will be an indispensable component of future microgrids. Once conquering the barriers, new markets and applications will be opened for energy storage.

7. References

[1] Dan T. Ton and Merrill A. Smith, *The U.S. Department of Energy's Microgrid Initiative.* The Electricity Journal, 2012. 25(8): p. 84-94.

[2] Models Microgrids-Benefits, *Barriers and Suggested Policy Initiatives for the Commonwealth of Massachusetts.* KEMA Inc.: Burlington, MA, USA, 2014.

[3] Nikos Hatziargyriou, Hiroshi Asano, Reza Iravani, and Chris Marnay, *Microgrids.* IEEE power and energy magazine, 2007. 5(4): p. 78-94.

[4] Sina Parhizi, Hossein Lotfi, Amin Khodaei, and Shay Bahramirad, *State of the art in research on microgrids: A review.* IEEE Access, 2015. 3: p. 890-925.

[5] Mariya Soshinskaya, Wina HJ Crijns-Graus, Josep M Guerrero, and Juan C Vasquez, *Microgrids: Experiences, barriers and success factors.* Renewable and Sustainable Energy Reviews, 2014. 40: p. 659-672.

[6] Qiang Fu, et al., *The Role of Energy Storage in a Microgrid Concept: Examining the opportunities and promise of microgrids.* IEEE Electrification Magazine, 2013. 1(2): p. 21-29.

[7] Ramon Zamora and Anurag K Srivastava, *Controls for microgrids with storage: Review, challenges, and research needs.* Renewable and Sustainable Energy Reviews, 2010. 14(7): p. 2009-2018.

[8] Zhikang Shuai, et al., *Microgrid stability: Classification and a review.* Renewable and Sustainable Energy Reviews, 2016. 58: p. 167-179.

[9] Ritwik Majumder, *Some aspects of stability in microgrids.* IEEE Transactions on power systems, 2013. 28(3): p. 3243-3252.

[10] Yubo Wang, Bin Wang, Chi-Cheng Chu, Hemanshu Pota, and Rajit Gadh, *Energy management for a commercial building microgrid with stationary and mobile battery storage.* Energy and Buildings, 2016. 116: p. 141-150.

[11] Yubo Wang, Wenbo Shi, Bin Wang, Chi-Cheng Chu, and Rajit Gadh, *Optimal operation of stationary and mobile batteries in distribution grids.* Applied Energy, 2017. 190: p. 1289-1301.

Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

[12] Farzam Nejabatkhah and Yun Wei Li, *Overview of power management strategies of hybrid AC/DC microgrid.* IEEE Transactions on Power Electronics, 2015. 30(12): p. 7072-7089.

[13] Bin Wang, et al., *Predictive Scheduling Framework for Electric Vehicles With Uncertainties of User Behaviors.* IEEE Internet of Things Journal, 2017. 4(1): p. 52-63.

[14] CM Colson and MH Nehrir. *A review of challenges to real-time power management of microgrids*. in *Power & Energy Society General Meeting, 2009. PES'09. IEEE*. 2009. IEEE.

[15] Ewald Fuchs and Mohammad AS Masoum, *Power quality in power systems and electrical machines*. 2011: Academic press.

[16] Arangarajan Vinayagam, KSV Swarna, Sui Yang Khoo, and Alex Stojcevski, *Power Quality Analysis in Microgrid: An Experimental Approach.* Journal of Power and Energy Engineering, 2016. 4(04): p. 17.

[17] Scott Kennedy and Mirjana Milosevic Marden. *Reliability of islanded microgrids with stochastic generation and prioritized load*. in *PowerTech, 2009 IEEE Bucharest*. 2009. IEEE.

[18] H Nazaripouya, Y Wang, P Chu, HR Pota, and R Gadh. *Optimal sizing and placement of battery energy storage in distribution system based on solar size for voltage regulation*. in *Power & Energy Society General Meeting, 2015 IEEE*. 2015. IEEE.

[19] Sumiti Lamichhane, H Nazaripouya, and S Mehraeen. *Micro grid stability improvements by employing storage*. in *Green Technologies Conference, 2013 IEEE*. 2013. IEEE.

[20] Toshinobu Shintai, Yushi Miura, and Toshifumi Ise, *Oscillation damping of a distributed generator using a virtual synchronous generator.* IEEE transactions on power delivery, 2014. 29(2): p. 668-676.

[21] Yubo Wang, et al. *Optimal energy management for Microgrid with stationary and mobile storages*. in *Transmission and Distribution Conference and Exposition (T&D), 2016 IEEE/PES*. 2016. IEEE.

[22] Hasan Geramifar, Majid Shahabi, and Taghi Barforoshi, *Coordination of energy storage systems and DR resources for optimal scheduling of microgrids under uncertainties.* IET Renewable Power Generation, 2016. 11(2): p. 378-388.

[23] Alireza Majzoobi and Amin Khodaei, *Application of Microgrids in Supporting Distribution Grid Flexibility*. IEEE Transactions on Power Systems, 2016.

[24] MJE Alam, KM Muttaqi, and D Sutanto, A novel approach for ramp-rate control of solar PV using energy storage to mitigate output fluctuations caused by cloud passing. IEEE Transactions on Energy Conversion, 2014. 29(2): p. 507-518.

[25] Neal Bartek, *Borrego Springs Microgrid Demonstration Overview*. 2015: Society of American Military Engineers, San Diego, CA.

[26] Ali Moeini, Innocent Kamwa, and Martin de Montigny, *Power factor-based scheduling of distributed battery energy storage units optimally allocated in bulk power systems for mitigating marginal losses.* IET Generation, Transmission & Distribution, 2016. 10(5): p. 1304-1311.

IJESG International Journal of Energy and Smart Grid
Vol 3, Number 2, 2018
ISSN: 2548-0332 e-ISSN 2636-7904
doi: 10.23884/IJESG.2018.3.2.02

INESEG

[27] Sun Sun, Ben Liang, Min Dong, and Joshua A Taylor, *Phase Balancing Using Energy Storage in Power Grids Under Uncertainty*. IEEE Transactions on Power Systems, 2016. 31(5): p. 3891-3903.

[28] Sharad W Mohod and Mohan V Aware, *A STATCOM-control scheme for grid connected wind energy system for power quality improvement.* IEEE systems journal, 2010. 4(3): p. 346-352.

[29] Transmission and Distribution Committee, *IEEE Guide for Electric Power Distribution Reliability Indices.* IEEE Std 1366™-2003, 2003.

[30] R Arghandeh, Manisa Pipattanasomporn, and Saifur Rahman, *Flywheel energy storage systems for ride-through applications in a facility microgrid.* IEEE Transactions on smart grid, 2012. 3(4): p. 1955-1962.

[31] Sayonsom Chanda and Anurag K Srivastava, *Defining and enabling resiliency of electric distribution systems with multiple microgrids.* IEEE Transactions on Smart Grid, 2016. 7(6): p. 2859-2868.

[32] C Gouveia, J Moreira, CL Moreira, and JA Pecas Lopes, Coordinating storage and demand response for microgrid emergency operation. IEEE